Geochemical indicators to determine relations between spring behaviour and water losses of a divergence tunnel

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ABSTRACT

Hydraulic and geochemical relations between a subthermal, SO_4-rich spring (Q6) and water losses of a divergence tunnel indicate that both features are hydraulically connected. The divergence tunnel, crossing the evaporite rocks of the Penninic Pontis-Nappe (anhydrite, gypsum, dolomitic limestones) in the Rhone River valley (Central Wallis, Switzerland), deviates water from the Rhone River at a rate of up to 62 m³/s. The recharge rate of weakly mineralized water exfiltrating from the divergence tunnel and flowing to the Q6 spring varied between 0.5 and 5 l/s, depending on seasonal variations of the discharge in the divergence tunnel. Methods used to determine the degree of connection included discharge measurements, continuous and monthly water quality measurements, and geochemical modelling. Hydrochemical indicators of particular significance include major inorganic ions, as well as temperature, pH, calcite and gypsum saturation indices. Following the divergence tunnel decommissioning in August 17 1998, simultaneous rises in spring temperature from 13.0 to 13.7 °C and electrical conductivity from 2430 to 2600 µS/cm were recorded. A decline in spring discharge from 10 to 6.7 l/s was also observed.

ZUSAMMENFASSUNG

Eine hydraulische und geochemische Beziehung konnte zwischen den Wasserverlusten eines Wasserkraftwerk-Freispiegelstollens und einer subthermalen, SO_4-reichen Quelle (Q6) festgestellt werden. Der Freispiegelstollen, der sich in evaporitischen Gesteinen der penninischen Pontis-Decke (Anhydrit, Gips, dolomitische Kalke) im Rhonetal (Zentralwallis, Schweiz) befindet, leitet von der Rhone bis zu 62 m³/s Flusswasser ab. Der in der Quelle Q6 gemessene, vom Freispiegelstollen exfiltrierte Wasseranteil betrug, je nach dem sai-

sonalen Abfluss im Stollen, zwischen 0.5 und 5 l/s. Die verwendeten Methoden sind Schüttungs- und Abflussmessung, kontinuierliche und monatliche Wasserqualitätsmessung und geochemische Modellierung. Die untersuchten hydrochemischen Indikatoren sind die inorganischen Hauptionen, sowie die Temperatur, der pH-Wert, die Kalzit- und Gipssättigung. Der Freispiegelstollen wurde am 17. August 1998 definitiv ausser Betrieb gestellt. Daraus resultierte in der Quelle Q6 eine Zunahme der elektrischen Leitfähigkeit von 2430 bis 2600 µS/cm. Gleichzeitig nahm die Wassertemperatur von 13.0 bis 13.7 °C zu und die Quellschüttung von 10 bis 6.7 l/s ab.

RESUME

Des relations hydrauliques et géochimiques ont été déterminées entre des pertes d'eau d'une galerie d'amenée et une source subthermale, riche en sulfate (Q6). La galerie d'amenée, détournant un débit maximal de 62 m³/s des eaux du Rhône jusqu'à une usine électrique, est localisée dans des roches évaporitiques penniques de la Nappe des Pontis (anhydrite, gypse, calcaires dolomitiques) dans la vallée du Rhône (Valais central, Suisse). L'apport d'eau peu minéralisée percolant de la galerie d'amenée à la source Q6 varie entre 0.5 et 5 l/s, selon les variations saisonnières du débit de la galerie. Les méthodes utilisées sont la mesure du débit, ainsi que la mesure en continu et mensuelle de la qualité de l'eau et la modélisation géochimique. Les indicateurs hydrochimiques étudiés ont été les ions inorganiques majeurs, la température, le pH, ainsi que les indices de saturation en calcite et en gypse. La galerie a été définitivement mise hors service le 17 août 1998. Il en est résulté une augmentation de la conductivité électrique de la source Q6 de 2430 à 2600 µS/cm. Simultanément, la température a augmenté de 13.0 à 13.7 °C et le débit a diminué de 10 à 6.7 l/s.

Introduction

The Finges / Pfyn area is situated in the upper Rhone River valley, 20 km east of the town of Sion, Wallis Canton, Switzerland. Locations are shown in Figure 1. Because the boundary between French and German languages crosses this area, two names appear on the maps, but only French names are used in this paper. The Finges area is composed of various Quaternary geological environments: the Rhone alluvial sediments, the Ill-

graben alluvial fan deposits, the Sierre rockslide deposits (Burri 1997) and the debris deposits of the south valley side (Fig. 1). The unconfined alluvial aquifer of the Rhone River valley is characterized by a hydraulic conductivity larger than 10^{-3} m/s corresponding to sandy gravel deposits with an important flow velocity of about 20 m/d and an average hydraulic gradient of 3.5‰. During high-water period, between June and August, the Rhone River strongly recharges this aquifer with a

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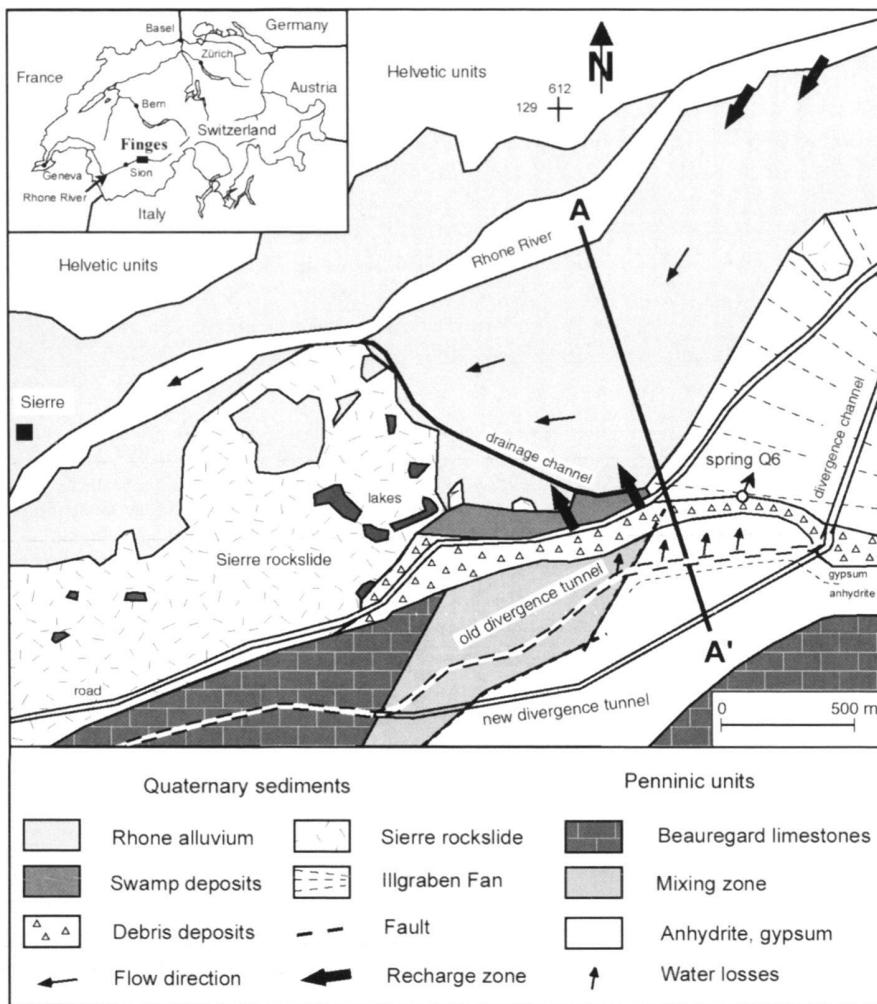
Fig. 1. Location of the investigation area and schematic geological map with the position of the old and new divergence tunnels, water losses and the observation spring Q6, as well as of recharge zones and flow direction of the Rhone River alluvium. Cross section A-A' is shown in Figure 2.

weakly mineralized water of type Ca, Mg-HCO₃, SO₄. Another component of type Ca, Mg-SO₄ is flowing from Triassic rocks of the south valley side into the Rhone alluvial sediments. On the other hand, during low-water period (November till April), the aquifer of the Rhone alluvium is exclusively recharged by SO₄-rich water from the south valley side, because the Rhone River bed is almost dry in winter (Schürch & Vuataz 2000). The unconfined alluvial aquifer of the Rhone River valley yields large amounts of water suitable for drinking water or agricultural supply, but it is also vulnerable to contamination. Moreover, this alluvial aquifer is subject to numerous possible environmental constraints, including the town of Sierre, industrial and agricultural activities, gravel pits, dump sites, roads, and a planned national highway.

Water losses from a divergence tunnel into groundwater were so important for the hydropower plant using this water, that this tunnel was abandoned after a new one was built. The divergence tunnel, transporting cold, weakly mineralized water of the Rhone River, is situated about 200 m to the south of a monitored spring (Q6) on the southern side of the Rhone

River valley, which is characterized by a subthermal, SO₄-rich water. The old divergence tunnel crosses evaporite rocks (anhydrite, gypsum, and dolomitic limestones) and loses water at a rate of several 100 l/s. The locations of the divergence tunnel and the spring Q6 are shown in Figure 1. Along the southern side of the valley, the spring Q6 is the only spring with a flow rate higher than 10^{-2} l/s.

This study of the relations between Q6 spring behaviour and the divergence tunnel water losses is a small part of a 4-year research project of the Swiss National Science Foundation. The objective of this research project was to identify the source, type and quantity of various components of groundwater of the Finges area, and to describe their spatial and temporal variations, by using various hydrochemical, hydrogeological and geophysical methods. The hydrochemical and hydrogeological studies were carried out at the Centre of Hydrogeology, University of Neuchâtel (Schürch 2000, Schürch & Vuataz 2000), whereas the geophysical research was realized by the Institute of Geophysics, University of Lausanne (Monnet et al. 2000).

Tunnelling activities require a very narrow collaboration between geology and engineering. Consideration of the local and regional lithology, the stratigraphy and the geological structure influence not only the choice of the tunnel position but also excavation and support methods. Some of the most disastrous experiences in tunnelling have been the result of interception of large water inflows in highly fractured, water-saturated or soluble rocks. In an aquifer, chemical processes such as mineral dissolution can influence the strength of geological and artificial materials. In some cases where dissolution of soluble rocks was not recognized, major accidents up to a total failure of dams and tunnels were observed (James 1992, Wahlstrom 1973). Important leakage of water from divergence tunnels can inundate large areas and threaten cultivated land, houses, streets and people.

The use of geoindicators in groundwater, such as physical and chemical parameters, is generally aimed to measure accurately and precisely the key parameters that can best describe long term trends and effects on the environment (Edmunds 1995). Measurements of relatively few, well-chosen parameters on appropriate time and space scales give decisive results at a reasonable cost. The aim of this paper is to present different physical and chemical indicators, which were used to study relations between Q6 spring behaviour and the water losses of the divergence tunnel. The methods used were water sampling, continuous temperature and electrical conductivity monitoring, as well as geochemical modelling, whereas the studied geoindicators are major inorganic ions, temperature, pH, calcite and gypsum saturation indices.

Methodology

Monthly water samples were collected from the Q6 spring over a three-year period and from the Rhone River over a one-year period to determine chemical variations. Field measurements for water temperature, electrical conductivity at 25°C, dissolved oxygen, redox potential (Eh) and pH were carried out. All samples were filtered in the field using 0.45 μm filters. The discharge of the spring was measured with a 30 l bucket and a chronometer.

The laboratory analysis program was as follows: bicarbonate was analysed by titration less than 12 h after sampling, whereas calcium and magnesium were determined by titration not later than 48 h after sampling. Analyses of sodium, potassium, strontium, sulphate, chloride and nitrate were carried out 3-4 weeks after sampling by ion chromatography at the Laboratory of Geochemical and Environmental Analyses (GEA), University of Neuchâtel. Water chemistry is classified into various chemical types, according to the cations and anions reaching ≥10 % of the sum of all the ions.

The saturation indices and mass transfer values for gypsum and calcite reported in this article were calculated with the hydrochemical computer code NETPATH (Plummer et al. 1993), whereas the mixing proportions of the Q6 spring three-component mixing system were calculated with PHREEQCI

(Charlton et al. 1997). The saturation index (SI) is defined as logarithm of the ratio of ion activity product (IAP) vs the thermodynamic solubility product of the solid species K_S [SI = $\log(IAP/K_S)$]. Mass transfer is equal to the dissolved or precipitated minerals brought into contact with the solution.

In order to study the relations between the behaviour of the Q6 spring and the divergence tunnel water losses, the Q6 spring was equipped with an automatic data acquisition system between December 1997 and November 1998 which recorded water temperature and electrical conductivity every three hours. During the same period, the discharge of the divergence tunnel was manually measured three times per day.

Geology

The geology of the Finges area consists of Helvetic units on the north side of the Rhone River valley, dominated by marly limestone of Jurassic age (Bugnon 1986, Burkhard 1988), and of Penninic units on the south side (Fig. 1). The Penninic at the Finges area contains the Houillere-Zone, the Pontis-Nappe and the Siviez-Mischabel-Nappe described by Escher (1988). The Houillere-Zone outcropping in the southwest of the Finges area is composed of anhydrite, porous calco-dolomite, meta-arkoses and conglomerates of Carboniferous to Triassic age. The Pontis-Nappe, in which the divergence tunnel is situated, contains Triassic rocks, a tectonic mixing zone and Beauregard limestones (Fig. 1). The tectonic mixing zone is a complex geological formation of Triassic rocks, composed of anhydrite, dolomitic limestone, partly gypsum-bearing rocks (cornieules) and marl (Stempfel & Schaeren 1997). The Siviez-Mischabel-Nappe is essentially composed of quartzites and conglomerates of Permo-Carboniferous age (Escher 1988).

The Quaternary sediments consist of alluvial sandy gravels that fill the Rhone trough; alluvial deposits of the Illgraben fan; the Sierre rockslide, which includes only Helvetic rocks; debris deposits dominated by Penninic rocks and swamp deposits (Fig. 1). The Illgraben fan in the eastern part of the area has diverted the Rhone River bed to the northern side of the valley. The fan consists of a silty and sandy upper part and of sandy gravels below (Fig. 2). The gigantic Sierre rockslide (about 1 km^3) occurred at the end of the last glaciation, about 10'000 years ago, when the mountain sides became unstable after the retreat of the Rhone glacier (Burri 1997).

The divergence tunnel

The old freesurface divergence tunnel of the Finges area, constructed between 1908 and 1911, deviates water from the Rhone River at a rate of up to 62 m^3/s in order to produce electricity in a hydropower plant. First an open channel crosses the Illgraben fan on a 2922 m-long section, and then the freesurface divergence tunnel crosses the southern hillside on about 5000 m length (Fig. 1). The divergence tunnel is oriented east-west and crosses the following rock sequence (Stempfel & Schaeren 1997, Escher 1988): debris deposits of the hillside,
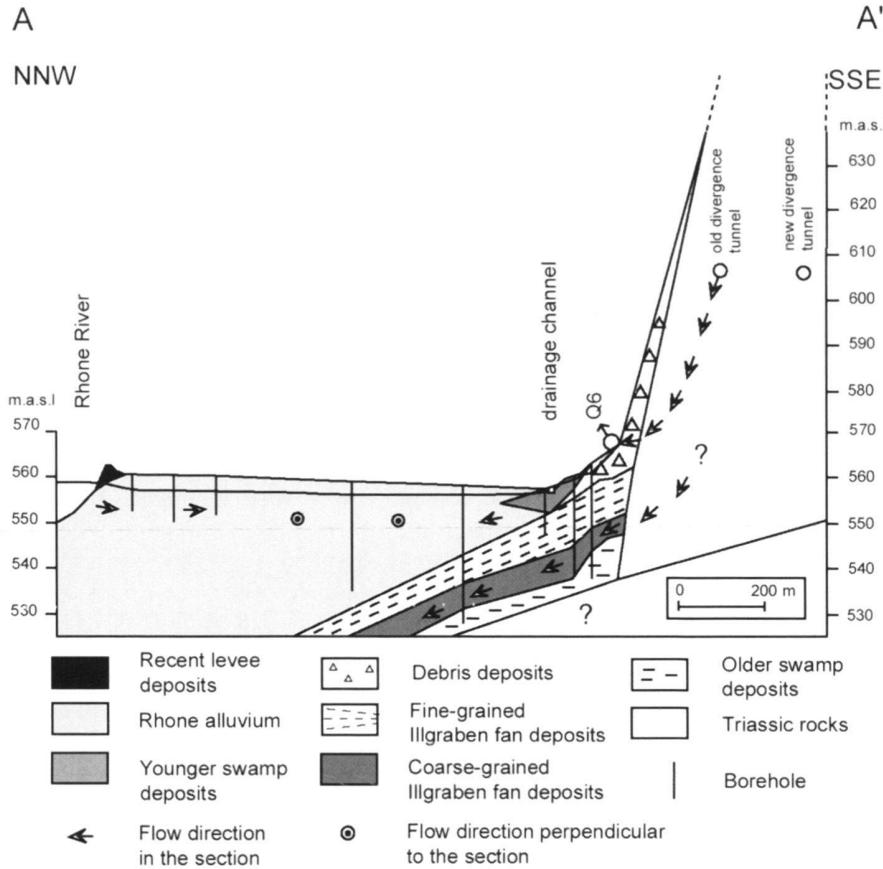
Fig. 2. Geologic section through the alluvial deposits of the Rhone River valley and through the Triassic rocks of the southern valley side showing spring and divergence tunnel positions. Position of section is shown in Figure 1.

Triassic rocks (anhydrites, gypsum), a tectonic mixing zone and Beauregard limestones (Fig. 1). The tectonic mixing zone is characterized by major groundwater inflows in the old divergence tunnel (Stempfel & Schaeren 1997). The old divergence tunnel is situated 200 m in the south (Fig. 1), and about 40 m higher than the Q6 spring (Fig. 2).

In certain locations, the lining of the old divergence tunnel contains natural stone masonry, which collapsed because of the cavity formations due to anhydrite and gypsum dissolution behind the lining. Resulting water losses of several 100 l/s, measured at the outfall of the divergence tunnel, threatened cultivated land, houses and streets, and reduced the electricity production capacity. Consequently, the owner of the tunnel, the RHOWAG company, decided to construct an alternative divergence tunnel in the anhydrite section (Jacquod 1995, Stempfel & Schaeren 1997). The use of the old tunnel finally ended on August 17, 1998. These events allowed the hydraulic and geochemical relations between the old divergence tunnel and the Q6 spring behaviour to be subsequently studied.

The Triassic aquifer

The tectonic mixing zone, situated between the Beauregard limestones and the anhydrite / gypsum unit, is a complex geo-logical formation of Triassic rocks, composed of anhydrite, dolomitic limestone, partly gypsum-bearing rocks and marl (Stempfel & Schaeren 1997). The mixing zone is characterized by a dual aquifer hydraulic conductivity consisting of a very low permeability matrix (anhydrite and dolomitic limestone) cut by high hydraulic conductivity fissures which allow important groundwater flow rates. This feature is the consequence of recent active tectonics, which created or reactivated fractures in the Triassic rocks (Sartori 1993). The cellular dolomites next to the fractures (Masson 1972) show high hydraulic conductivity conduits, which can attain a diameter larger than 10 cm. During the construction of the new divergence tunnel, groundwater inflows in the tunnel of about 33 l/s were observed in these high hydraulic conductivity conduits, which often contain silty sand composed of phyllosilicates and quartz (Jacquod 1995).

Furthermore, water leakage of the old divergence tunnel has created karstic conduits because of the high solubility of gypsum (Lloyd & Heathcote 1985). In fact, the solubility product of gypsum attains 0.86 g $(CaSO_4-H_2O)/l$, while including complexes and activity corrections leads to a solubility of 3.15 g $(CaSO_4-H_2O)/l$ (Appelo & Postma 1999). It should be mentioned that the solubility of gypsum decreases with increasing temperature. The dissolution of gypsum, anhydrite
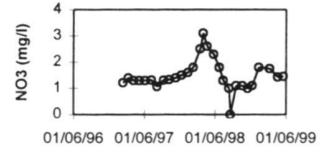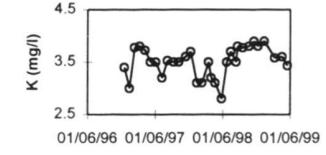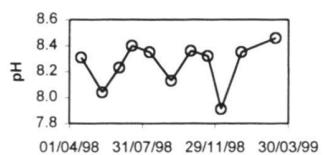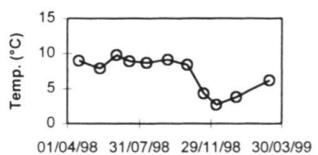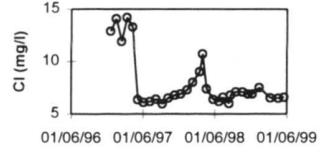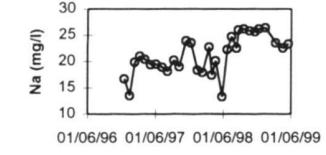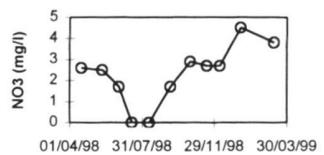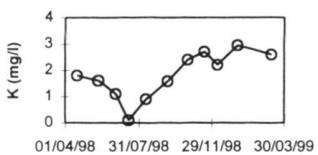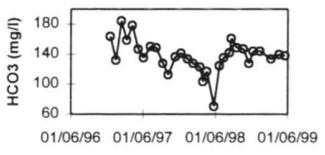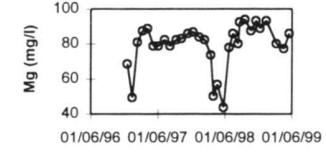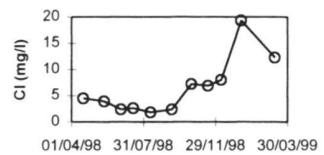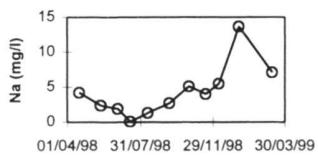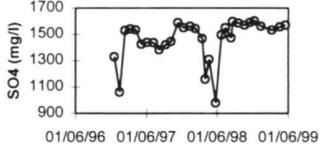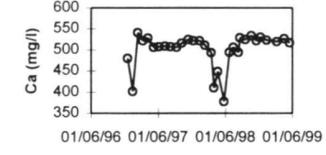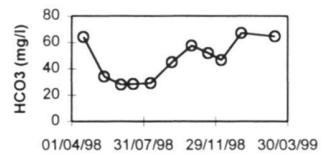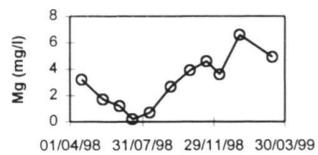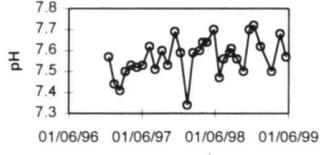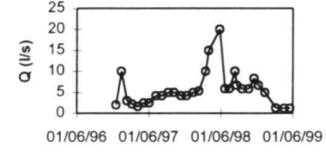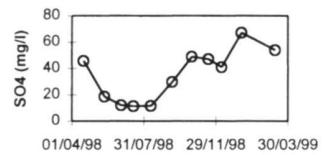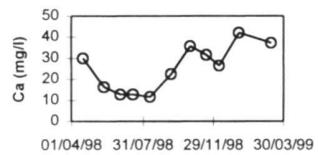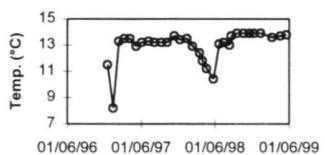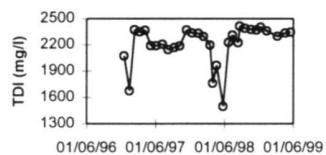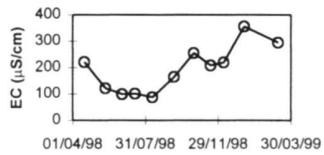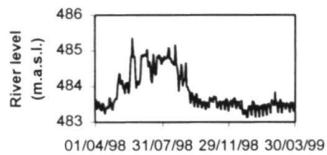
Fig. 3. Seasonal evolution of selected physical and chemical parameters of the Rhone River at Finges between April 1998 and March 1999. The Rhone River level was recorded in Sion, at a station of the National Hydrological and Geological Survey. Electrical conductivity (EC) is measured at 25°C.

Fig. 4. Seasonal evolution of selected physical and chemical parameters of Q6 spring between December 1996 and May 1999. TDI = Total Dissolved Ions (mg/l); Q = flow rate (l/s).

and dolomitic limestones are responsible for most of the groundwater mineralization. Aquifers in Triassic evaporite rocks of the upper Rhone River valley were studied in detail by Mandia (1993).

Seasonal evolution of hydraulic, physical and chemical parameters

The Rhone River

The Rhone River represents a glacio-nival flow regime, which is characteristic for streams with a high elevation catchment, partially covered with glaciers (SNHGS 1998). As a result, the

hydrological cycles of the Rhone River and of the deviated flow in the divergence tunnel are characterized by a low discharge between November and April, and a high discharge between May and October during snowmelting. The weekly and daily discharge variations, induced by the exploitation of hydropower plants of the upper Rhone River basin, occur in the Rhone River every day, except during the weekend. However, the divergence tunnel reflects these daily variations only during low-water periods, because it is almost always working at the maximum flow rate of 62 m³/s during high-water periods.

The temperature of the Rhone River, measured at the entrance of the divergence tunnel, varies from 2.5 to 4.5 °C in winter and from 8.5 to 10 °C in summer. The low temperature

Table 1. Physical and chemical data of the Q6 spring and of the Rhone River. The selected samples reflect the seasonal mineralization variability.

Name	Date	Temp. °C	EC µS/cm	pH	Eh mV	O$_2$ mg/l	Q l/s	TDI mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	Sr mg/l	SO$_4$ mg/l	HCO$_3$ mg/l	Cl mg/l	NO$_3$ mg/l	Bal. %
Q6	26.05.98	10.4	1881	7.70	458	9.0	20.0	1497	378.0	43.8	13.3	2.8	3.8	980	70.5	6.4	2.3	3.0
Q6	06.08.97	13.2	2460	7.51	469	9.1	4.2	2145	507.6	78.8	18.1	3.5	6.9	1381	148.5	6.4	1.1	2.0
Q6	20.10.98	13.9	2610	7.50	529	9.1	5.8	2377	534.0	87.5	25.8	3.8	6.2	1571	147.0	7.1	1.1	-0.4
Rhone	26.05.98	7.9	122	8.04	460	12.3	-	81	16.4	1.7	2.4	1.6	<0.1	19	34.0	3.9	2.5	0.3
Rhone	17.11.98	4.3	208	8.32	504	11.1	-	151	31.6	4.6	4.0	2.7	0.2	47	51.8	6.9	2.7	3.1
Rhone	12.01.99	3.8	356	8.35	432	11.9	-	223	42.0	6.6	13.7	3.0	0.3	67	67.0	19.3	4.5	3.1

EC = electrical conductivity at 25°C; Q = discharge; TDI = total dissolved ions;

Bal. = ionic balance = [($\sum$ cat. + $\sum$ an.)/($\sum$ cat. - $\sum$ an.)] * 100 (%).

values in winter correspond to low Rhone River discharge and low air temperature values. Figure 3 presents the seasonal variations of selected physical and chemical parameters of the Rhone River, determined between April 1998 and March 1999.

The Rhone River water shows its maximum electrical conductivity value in January and its minimum value in August. As the electrical conductivity reflects the total dissolved ions (TDI), the winter chemical composition is characterized during this low-water period by larger concentrations of sodium, chloride and nitrate (Tab. 1), due to the increase of groundwater contributions. At this period, the Rhone River water is a Ca-Na-Mg-SO$_4$-HCO$_3$-Cl type, and its TDI reaches 223 mg/l. On the other hand, the lower electrical conductivity of the Rhone River water in summer reflects water dilution due to snow and glacier melt water. In summer, during high-water period, the Rhone River water is a Ca-Mg-HCO$_3$-SO$_4$ type, and its TDI attains only 81 mg/l (Tab. 1). Furthermore, the concentrations of nitrate, potassium, sodium and magnesium are very low, due to the increase of snowmelt water contribution.

The Q6 spring

To determine the interactions between the Q6 spring and the divergence tunnel water losses, it is very important to understand the flow system of the spring. The Q6 spring discharge varies between 1.2 and 20 l/s. The spring water temperature attains a maximum value of 13.5 °C during low-water periods on the Rhone River in November 1997 and November 1998, but decreased to 7.5 °C in January 1997 after the important precipitations in December 1996. Figure 4 shows the seasonal variations of selected physical and chemical parameters of the Q6 spring observed between December 1996 and May 1999.

The Ca-Mg-SO$_4$ geochemical water type characterizes the Q6 spring emerging from the Triassic aquifer (Tab. 1). A significant concentration decrease of the chemical parameters during precipitation events reflects a piston flow process in the system (Richter et al. 1993). The infiltrated precipitation, channelled by fracture networks, recharges the Triassic aquifer. Consequently, the hydraulic head in the aquifer and the spring flow rate increase with dilution of the emerging wa-

ters. Figure 2 shows the hydraulic head difference between the Q6 spring, the divergence tunnel and groundwater of the Rhone River alluvial aquifer.

Following a precipitation event in January 1998, nitrate and chloride concentrations have abruptly increased. Nitrate was probably washed out of the soil into the aquifer and transported towards the Q6 spring. The reaction time of the Q6 spring on significant precipitation events is in the order of two months.

Selected chemical parameters and the saturation indices of calcite and gypsum of the Q6 spring are presented in Figure 5 relative to sulphate concentrations. The values of Na+K, HCO$_3$, pH and the calcite saturation index show a triangular distribution on the Figure 5, indicating a three-component mixing system with the following end-members:

1. Triassic aquifer groundwater characterized by a large SO$_4$ concentration (about 1550 mg/l) and by a calcite saturation index of 0.6.
2. Waters infiltrated during precipitation events containing SO$_4$ concentrations of about 1000 mg/l and a calcite saturation index of 0.2.
3. Waters exfiltrated from the divergence tunnel showing large SO$_4$ concentrations (about 1550 mg/l) and a calcite saturation index of 0.3.

Continuous monitoring of temperature and electrical conductivity in the Q6 spring

Temperature and electrical conductivity were recorded every three hours at the Q6 spring by an automatic monitoring and recording system. The short time variations of these two observed parameters have been compared with divergence tunnel discharge and daily precipitations measured in Sierre at the Swiss Institute of Meteorology station #7360 during 11 months, from December 1997 to November 1998 (Fig. 6).

Spring water temperature and electrical conductivity follow the weekly and daily discharge variations of the divergence tunnel induced by the exploitation of hydropower plants, and therefore indicate a hydraulic connection between the spring and the divergence tunnel (Figure 2). The diver-
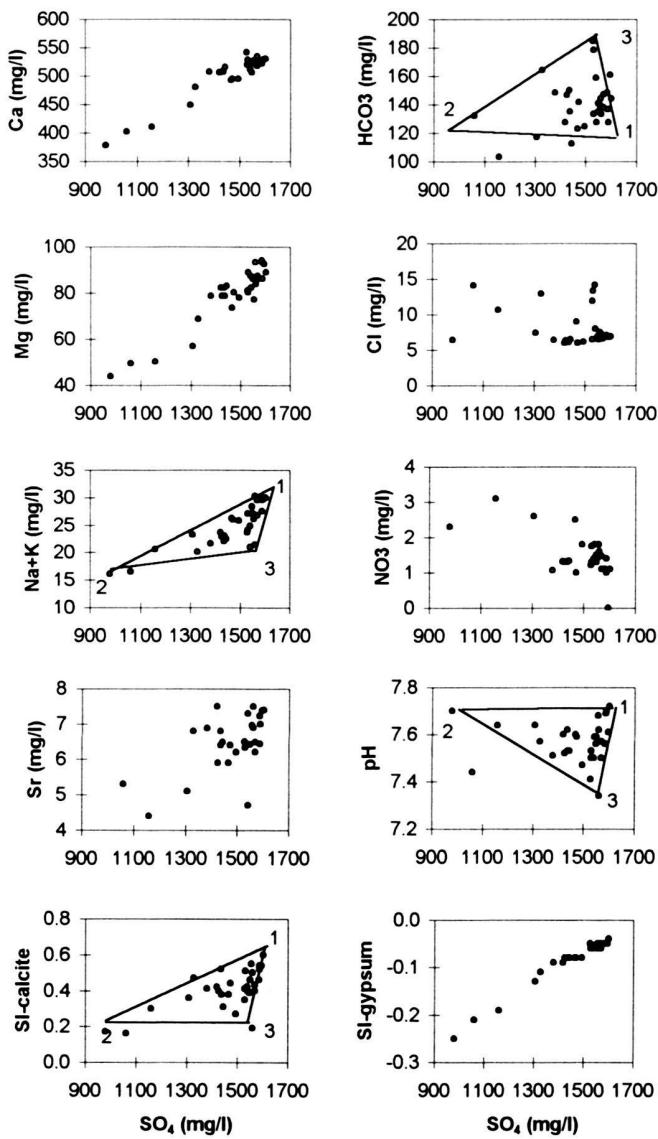
Fig. 5. Relations between major groundwater ions, pH, calcite and gypsum saturation indices versus dissolved sulphate concentration for the spring Q6. These parameters were determined monthly between December 1996 and May 1999. Triangles and numbers 1, 2 and 3 represent a three-component mixing system, as explained in the text.

gence tunnel water losses attain several 100 l/s. The recharge rate from the divergence tunnel which flows to the Q6 spring varied between 0.5 and 5 l/s, depending on seasonal variations of the discharge in the divergence tunnel. An increase of the divergence tunnel discharge induces a rapid decrease of the conductivity and temperature at the spring. On the other hand, recovery of conductivity and temperature at the spring is distinctly slower during periods of decreased discharge in the tunnel. During periods, when the divergence tunnel is dry, con-

ductivity and temperature of the spring rise to their maximum value (Fig. 6). Monthly spring discharge measurements display a strong negative correlation with temperature and conductivity (Fig. 4). During the observation period, the divergence tunnel was shortly dry twice for two-day periods (April 28-29 and June 3-4, 1998). Automatic measurements in the spring show that the interventions executed in order to reduce leakage in the divergence tunnel were very successful after June 3-4, 1998. As a result, tunnel leakage and dilution effects in the Q6 spring decreased simultaneously.

The divergence tunnel was finally decommissioned on August 17, 1998. As a result, the electrical conductivity of the spring increased from 2430 to 2600 μS/cm. At the same time, the temperature augmented from 13.0 to 13.7 °C, whereas the spring discharge diminished from 10 to 6.7 l/s. The spring conductivity and temperature, recorded by the automatic monitoring system after August 17, no longer showed the weekly and daily variations observed in the divergence tunnel (Fig. 6). The new divergence tunnel was first put in operation on November 4, 1998. Then, discharge, temperature and conductivity of the observed spring showed no more variations.

Quantification of recharge rates

For the period between April 14 and May 6 1998, the temperature and conductivity values of the Q6 spring are plotted together and show two different mixing lines (Fig. 7):

1. Upper mixing line between cold, weakly mineralized water of the divergence tunnel and subthermal SO_4-rich aquifer water.
2. Upper mixing line between cold, infiltrated precipitation water and subthermal SO_4-rich aquifer water.

This feature confirms that the water chemistry of the Q6 spring represents a three component mixing system. On the one hand, mixing processes with a) water losses of the divergence tunnel, cool b) groundwater of the Triassic aquifer and, on the other hand, c) infiltrating precipitations also cool the groundwater. The temperature of the end-member of infiltrating precipitations was estimated with the help of the Swiss Hydrologic Atlas (SNHGS 1992). Moreover, the maximum groundwater mineralization, observed after the old divergence tunnel was decommissioned (sample 20.10.1998, Tab. 1), was considered to represent the end-member for the subthermal SO_4-rich water. A synthetic end-member of the Rhone River was calculated as an average value of 12 samples measured over a complete hydrological cycle. However, since water losses from the old divergence tunnel reached their maximum flow rate during high-water periods, the sample of May 26, 1998 was used as the Rhone River end-member to simulate mixing proportions between the spring and the divergence tunnel waters. The mixing proportions simulated with the code PHREEQCI (Charlton et al. 1997) vary between 0.6 and 0.9, which correspond to a value of 40 to 10% of tunnel water for the total spring dis-
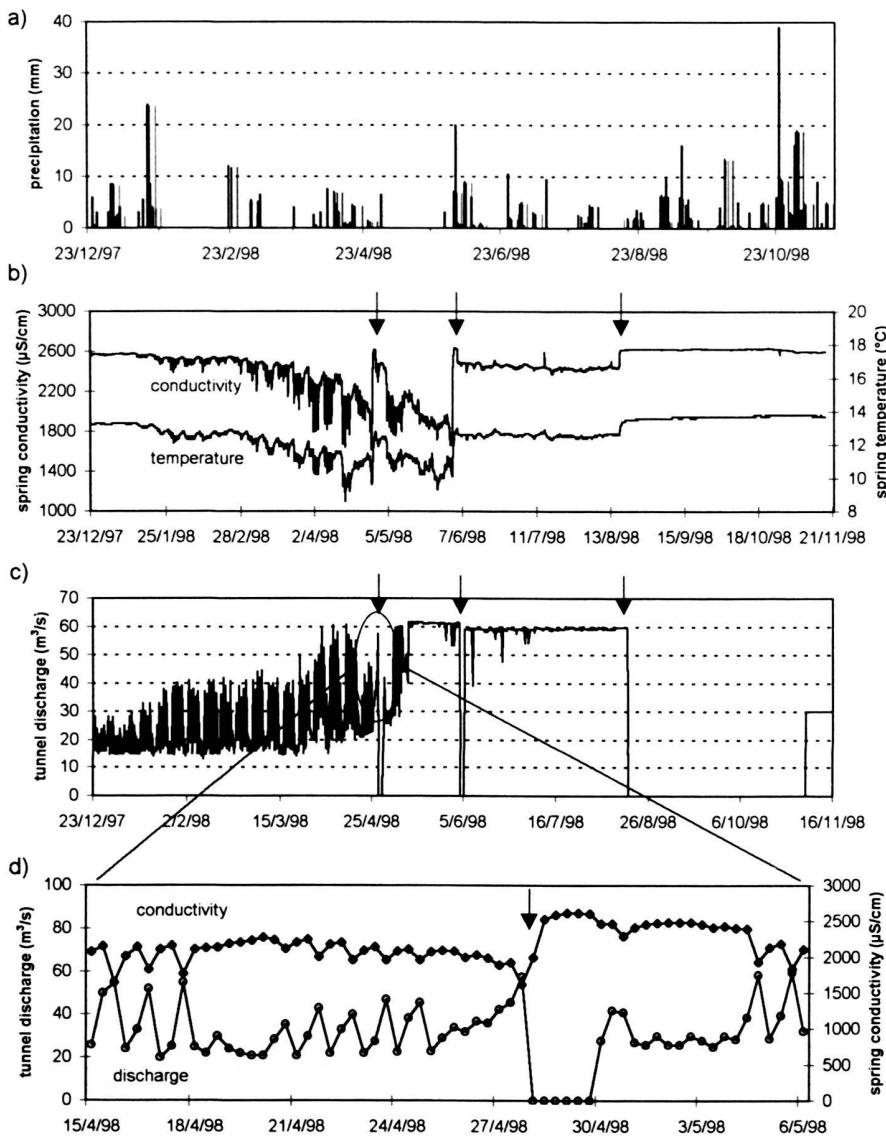
Fig. 6. Relations between the old divergence tunnel and Q6 spring. a) Daily precipitation measured in Sierre at the station #7360 of the Swiss Institute of Meteorology; b) Electrical conductivity and temperature of the spring; c) Divergence tunnel discharge and d) Comparison between the tunnel discharge and the spring conductivity during 23 days. The two first arrows indicate the time, when the flow in the divergence tunnel was temporarily stopped, and the last arrow shows, when the tunnel was decommissioned.

charge. During the low-water period in November 1997, the discharge of the Q6 spring reached 5 l/s, and with a mixing of about 10% of tunnel recharge at the spring, the flow rate, occurring from the divergence tunnel towards the spring, attains 0.5 l/s. During the high-water period between March and May 1998, the average Q6 spring discharge rose to about 12.5 l/s, and with a mixing of about 40 % of tunnel recharge at the spring, it represents 5 l/s.

Mass transfer

Thermodynamic equilibrium models like NETPATH (Plummer et al. 1993) and PHREEQCI (Charlton et al. 1997) mainly deal with complex compounds equilibria and minerals equilibria. In these codes, the species distribution is calculated using thermodynamic constants for many important inorganic complexes and saturation indices are calculated for about 300 minerals. The primary minerals, when brought into contact with the solution, dissolve until their equilibrium ion activity is reached, or, if the primary minerals are not the thermodynamically most stable phase, they dissolve completely and the stable phase is precipitated till equilibrium is established.

Here, the principal objective of the geochemical modelling is to calculate the mass transfer rates in mmol/kg H_2O between water of the divergence tunnel (= Rhone River water) and the Q6 spring, which allow dissolution and precipitation processes in the Triassic aquifer to be quantified. Mass transfer is equal to the dissolved or precipitated minerals. Spring water is saturated with respect to gypsum, calcite and dolomite, whereas Rhone River water is undersaturated in respect to all minerals.
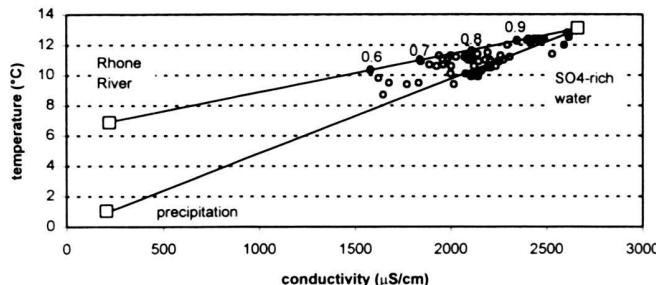
Fig. 7. Correlation between electrical conductivity and temperature of Q6 spring for the observation period from April 14 to May 6, 1998 (measure interval = 3 h). The four black dots represent simulated mixing proportions from 0.6 to 0.9 between the Rhone River and SO₄-rich water.

Table 2 shows the saturation indices for selected minerals of the Q6 spring and of the Rhone River. For this simulation, the geochemical code NETPATH (Plummer et al. 1993) was chosen, because it can simulate the geochemical evolution of a water A to a water B along a flowpath. The conceptual model used considers that water losses of the divergence tunnel exfiltrate and percolate through the Triassic aquifer before emerging at the observed spring. Along the flowpath, water reacts with the host rocks. Processes such as dissolution of gypsum and dolomite, as well as precipitation of calcite are mostly responsible for the mineralisation of the Q6 spring. Here it is important to say that during the construction of the new divergence tunnel, cellular dolomites were detected along the major groundwater flow conduits located in the tectonic mixing zone. Table 3 shows the simulation conditions and the results. For the simulation, water samples of the Rhone River and of the spring were used, collected on May 26, 1998, which corresponds to a high-water period. Consequently, divergence tunnel water losses were considered to have reached their maximum flow rate at this time. The tunnel water losses occurred punctually, where the lining collapsed because of the formation of cavities due to anhydrite and gypsum dissolution behind the lining.

The simulation provides the following mass transfer rates between water infiltrated from the divergence tunnel (122 μS/cm) and spring water (1881 μS/cm): 10.34 mmol/l of gypsum, 1.73 mmol/l of dolomite and –2.84 mmol/l of calcite. The negative sign of the mass transfer for calcite indicates a precipitation process. The recharge rate of weakly mineralized water exfiltrated from the divergence tunnel varies at the spring between 0.5 and 5 l/s following seasonal flow variations in the divergence tunnel. Considering a maximum recharge rate of 5 l/s at the spring during high-water period, the mass transfer rates correspond to gypsum and dolomite dissolution rates of respectively 280 and 50 t/y, and to a calcite precipitation rate of 45 t/y.

The distance between the sections of the divergence tunnel with significant water losses and the spring varies between 200 and 1000 m (Fig. 1). The underground transit time, during

Table 2. Saturation indices for selected minerals of Q6 spring water and Rhone River water, calculated with the code NETPATH (Plummer et al. 1993).

Name	Spring Q6		Rhone River	
Date	May 26, 1998	Oct. 20, 1998	May 26, 1998	Jan. 12, 1999
calcite	+0.17	+0.40	-0.83	+0.03
aragonite	+0.01	+0.25	-0.99	-0.13
dolomite	-0.46	+0.22	-2.56	-0.74
gypsum	-0.25	-0.05	-2.69	-1.85
anhydrite	-0.51	-0.30	-2.94	-2.11
strontianite	-1.29	-1.01	-2.49	-1.52
celestite	-0.54	-0.28	-3.19	-2.27

+ oversaturation; 0 saturation ; - undersaturation

Table 3. Mass transfer between weakly mineralized Rhone River water and SO₄-rich groundwater of Q6 spring, calculated with the code NETPATH (Plummer et al. 1993).

Model conditions and input data	Results
Sampling date: 26.5.1998 Initial solution = Rhone River Final solution = spring Q6 Constraints: C, Ca, Mg, Na, K, Sr, Cl Phases: gypsum (±), calcite (±), dolomite (±), halite (±), magnesite (±), celestine (±), cation exchange (±), K-montmorillonite (±)	Mass transfer (mmol /kg H₂O): gypsum = +10.34 calcite = -2.84 dolomite = +1.73 halite = +0.07 celestine = +0.04 cation exchange = +0.20 K-mont. = +0.09 magnesite = 0

+ dissolution; - precipitation; ± dissolution or precipitation

which water is in contact with the evaporite rocks, depends mainly on the hydraulic head, which is a function of the divergence tunnel discharge rate. From Figure 6d, the reaction time of the Q6 spring to hydraulic head changes in the divergence tunnel was estimated to be less than 3 h. Therefore, mean water losses velocity between the old divergence tunnel and the spring is inferred to be in the range of 60 to 300 m/h.

Discussion

Major inorganic parameters, as well as temperature and pH-value reflected the relations between the Q6 spring and the old divergence tunnel, allowing to decipher the different end-members of the spring flow system. The discharge rate of weakly mineralized water exfiltrated from the divergence tunnel varied at the spring between 0.5 and 5 l/s, following the seasonal variations of the tunnel discharge. Mean water losses velocity between the divergence tunnel and the spring is inferred to be in the range of 60 to 300 m/h.

The spring water temperature and electrical conductivity, recorded by an automatic monitoring system, followed the

weekly and daily discharge variations occurring in the divergence tunnel, induced by the exploitation of hydropower plants, and reflect a hydraulic connection between the spring and the divergence tunnel. Due to progressive water losses, an increase of the tunnel discharge induces a rapid decrease of conductivity and temperature in the spring. The divergence tunnel was finally decommissioned on August 17, 1998. As a result, the electrical conductivity of the spring increased from 2430 to 2600 μS/cm. At the same time, the temperature augmented from 13.0 to 13.7 °C, whereas the spring discharge decreased from 10 to 6.7 l/s. The conductivity and temperature of the spring, recorded after August 17 by the data acquisition system, no longer show weekly and daily variations induced by the old tunnel. The new divergence tunnel was put into operation on November 4, 1998. Since then, discharge, temperature and conductivity of the Q6 spring have shown no relation with those observed at the new divergence tunnel.

During the period following the decommissioning of the old divergence tunnel, the relation between the tunnel and the groundwater of the alluvial plain on the south valley side was studied by Kleiner (1998). He observed that groundwater levels decreased of several centimeters in the first 48 h after the decommissioning of the old divergence tunnel.

Conclusions

To determine the interactions between a spring and water losses from a divergence tunnel, it is mandatory to understand the flow systems of the spring and of the tunnel, respectively. Simultaneous measurements of discharge rate, temperature and electrical conductivity of the spring, as well as of the flow rate of the tunnel allow to determine the short- and long-term relations between the spring and the tunnel. Measurements of relatively few, well-chosen parameters on appropriate time and space scales give decisive results at a reasonable cost. Major inorganic parameters, determined in the spring and in the tunnel water allow to study geochemical processes such as dissolution and precipitation of minerals in the host rock, as well as to determine groundwater transit time and velocity in function of time. Future research should concentrate on finding specific indicators for rivers and for groundwaters, such as krypton-85, chloro-fluoro-carbon compounds and dissolved carbon.

Acknowledgements

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