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Hydrochemical multiparameter log analysis in a shallow, heterogeneous alluvial aquifer (Wallis Canton, Switzerland)

with 11 figures and 2 tables

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Key words/Mots-clés/Stichwörter

multiparameter borehole logging, hydrochemistry, alluvial aquifer, groundwater, flow system, Switzerland

diagraphie multiparamètres, hydrochimie, aquifère alluvial, eau souterraine, régime d'écoulement, Suisse

Multiparameter-Bohrlochmessung, Hydrochemie, alluvialer Grundwasserleiter, Grundwasser, Fliesssystem, Schweiz

Abstract

With the help of a hydrochemical multiparameter logging system, the vertical evolution of temperature, electrical conductivity, dissolved oxygen, as well as redox potential and pH were determined in five shallow boreholes in a heterogeneous alluvial aquifer of the upper Rhone River valley, Wallis Canton, Switzerland. The multiparameter logging was carried out both with and without pumping using a suction pump at a flow rate ranging between 58 and 86 m^3d^{-1}. In order to study the seasonal fluctuations of these groundwater physico-chemical parameters, the logs were repeated in two boreholes at three different seasons. The variations in the multiparameter logs generally coincide with lithologic boundaries and with groundwater flow zones in the boreholes. Thus, the integration of lithology and multiparameter hydrochemical logs was crucial for the successful characterisation of the heterogeneous alluvial aquifer, of the vertical distribution of its groundwater quality and of its groundwater flow system.

Résumé

A l'aide d'une sonde multiparamètres hydrochimiques, l'évolution verticale de la température de l'eau, de la conductivité électrique, de l'oxygène dissous, ainsi que du pH et du potentiel redox a été déterminée dans cinq forages peu profonds dans un aquifère alluvial hétérogène de la vallée supérieure du Rhône, Canton du Valais, Suisse. Les diagraphies multiparamètres ont été éffectuées avec et sans pompage utilisant une pompe aspirante avec un débit de 58 à 86 m^3d^{-1}. Dans le but d'étudier les fluctuations saisonnières de ces paramètres physico-chimiques, les diagraphies ont été répétées dans deux forages à trois différentes saisons. Dans les forages, les fluctuations des logs multiparamètres correspondent généralement aux interfaces lithologiques et aux zones d'écoulement. L'intégration de la lithologie et des logs multiparamètres hydrochimiques était déterminante pour la caractèrisation de l'aquifère alluvial hétérogène, de la distribution verticale de sa qualité d'eau et du régime d'écoulement.

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Zusammenfassung

Mit Hilfe einer hydrochemischen Multiparametersonde wurde in fünf Bohrungen in einem alluvialen, heterogenen Grundwasserleiter des oberen Rhonetales (Kanton Wallis, Schweiz) die vertikale Verteilung der Grundwassertemperatur, der elektrischen Leitfähigkeit, des gelösten Sauerstoffes, des Redoxpotentials und des pH-Wertes bestimmt. Die Multiparameter-Bohrlochmessungen wurden unter natürlichen statischen und dynamischen Fliessverhältnissen mittels einer Ansaugpumpe mit einer Fliessrate von 58 bis 86 m^3d^{-1} durchgeführt. Um die saisonalen Veränderungen dieser physikalischen und chemischen Grundwasserparameter nachzuvollziehen, wurden die Multiparameter-Bohrlochmessungen in zwei Bohrungen in drei verschiedenen Jahreszeiten wiederholt. Vertikale Veränderungen in den Multiparameterlogs stimmen im allgemeinen mit lithologischen Grenzen und Grundwasserfliesszonen überein. Die Integration von Lithologie und hydrochemischer Multiparameter-Bohrlochmessung war Voraussetzung für eine erfolgreiche Charakterisierung des heterogenen, alluvialen Grundwasserleiters, der vertikalen Wasserqualitätsverteilung und des Grundwasserfliesssystems.

1. Introduction

The geographical area studied, called Finges area, is situated in the upper alpine Rhone River valley, 20 km east of the town of Sion, Wallis Canton, Switzerland (Fig. 1). In the Finges area, the unconfined alluvial aquifer of the Rhone River valley is composed of surficial glacial outwash deposits. This aquifer yields large amounts of water suitable for drinking or agricultural supply, but is vulnerable to contamination from urban, industrial and agricultural sources, including effluent from the town of Sierre, gravel pits, dump sites, roads and a planned national highway. In the Finges area, the Rhone River decreases 88 m in altitude along its 7-km course. The steepness of the slope of the Rhone River bed, which ranges from 6-12%, favours the deposition of coarse material with a high hydraulic conductivity, which promotes surface-groundwater exchange (Schürch & Vuataz 2000). The bed of the river is 2-8 m above the water table. With an annual average precipitation of 587 mm, the Finges area is one of the driest regions of Switzerland. Water exchange between the river and the aquifer is a function of the potential difference, the leakage factor, and the section of the river-aquifer interface (Edmunds et al. 1976; Hötzel & Reichert 1992; Briechle 1997).

Predicting the quantity and quality of groundwater flowing in shallow subsurface systems requires accurate information on the geometry and hydraulic properties of aquifers (Domenico & Schwartz 1997). This information is commonly obtained by description of sediments obtained as cores or cuttings from boreholes, by aquifer testing and geophysical logging (Keys 1990; Paillet & Reese 2000). One of the principal limitations of lithologic and geophysical logs is that they cannot give a direct estimate of hydraulic properties of aquifer materials. Geophysical logs can be interpreted in terms of porosity and permeability on the basis of various formation models (Jorgensen 1991). Multiparameter hydrochemical borehole logging permits determination of the vertical evolution of the groundwater quality in the aquifer. In this study, a multiparameter hydrochemical data transmitter was lowered into five shallow boreholes to measure simultaneously electrical conductivity, temperature, dissolved oxygen, redox potential, as well as pH and turbidity.

This study of multiparameter logging was a small part of a 4-year research project of the Swiss National Foundation for Scientific Research. 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). The geophysical research was carried out at the Institute of Geophysics, University of Lausanne (Monnet et al. 2000).

2. 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, and of Penninic units on the south side (Fig. 1). The Penninic units are composed of anhydrite,

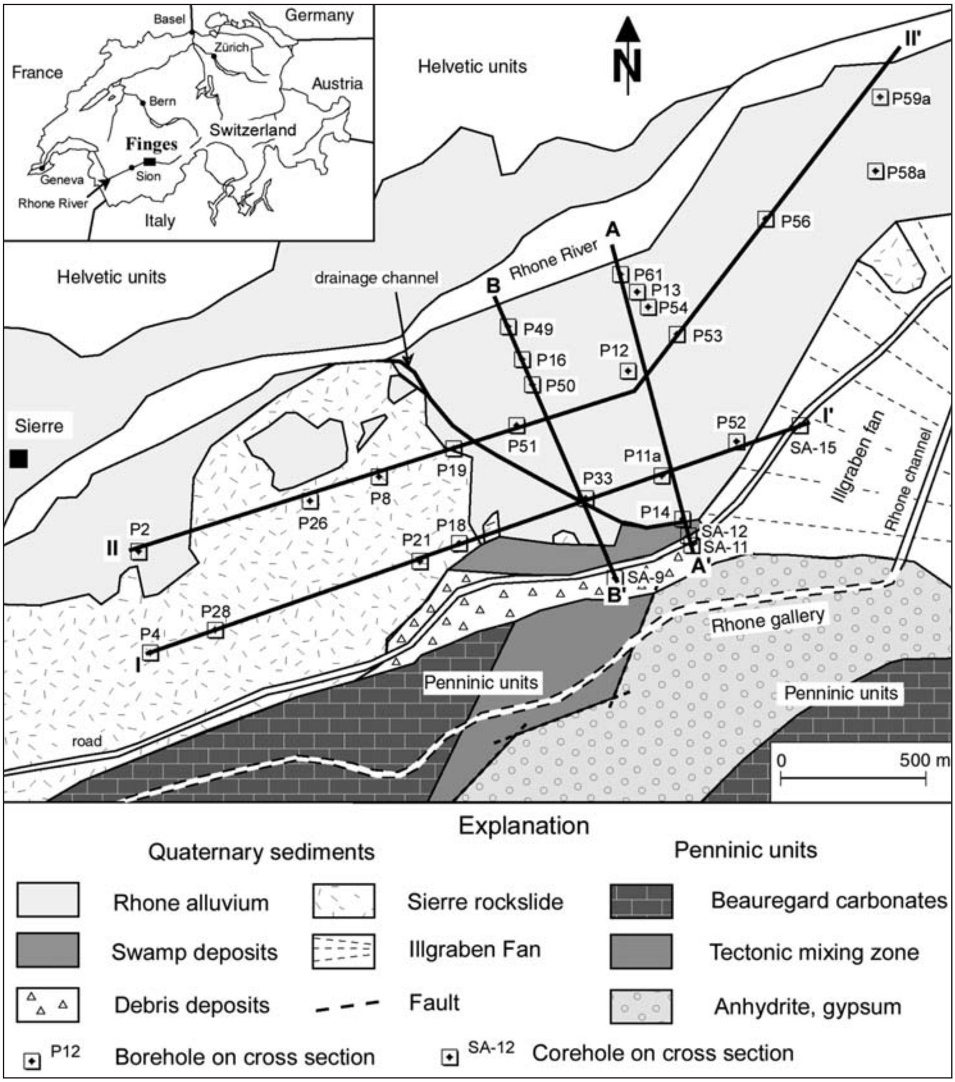

Fig. 1: Location and schematic geologic map of the Finges area, Wallis Canton, Switzerland. Cross sections I-I' and II-II' are shown in Figure 2, and A-A' and B-B' in Figure 3.

porous calco-dolomite and marl of Triassic age; quartzite, sandstone, and conglomerate of Permo-Triassic age; and schist and arkose of Permo-Carboniferous age (Escher 1988).

The Quaternary sediments consist of alluvial sandy gravel which fills 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; Burri 1997). The Illgraben fan in the eastern part of the area consists of a silty and sandy upper part and sandy gravel below. This fan has a 5% slope to the northwest and dips under the Rhone sediments; a depth of 15.20 m to the top of the fan deposits was measured in P11a borehole (Fig. 2a). The heterogeneous Rhone River gravel sediments are the major aquifer in the Finges area. The thickness of this major aquifer increases from the fan deposits in the southeast towards the northwest side of the Rhone River valley, as shown in Figures 2b and 3a. Locally, on the south side of the valley, fan deposits and debris deposits are intercalated with Rhone gravel sediments and rockslide deposits, as shown in the section of Figure 3b. The 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).

3. Hydrogeology

Patterns of groundwater circulation in the southern part of the Finges area are shown for August 8, 1996 in Figure 4. This was a time of high flow on the Rhone River, when groundwater recharge to the Rhone alluvial aquifer occurred in two main areas. At the northeastern limit of the study area, surface water moved from the Rhone River bed, on a broad front about 700 m wide, southward into the alluvium; the water then followed a path through the alluvium towards the drainage channel across the centre of the area (Fig. 2b and 4). The second recharge area is at the base of the southern side of the valley in the east-central part of the area, where subsurface flow enters the Rhone alluvium and underlying units (Fig. 3a and 4). This recharge flow is along a front about 800 m wide perpendicular to the main groundwater flow in the aquifer.

The contour map (Fig. 4) was also used for flow simulation experiments after the model of Schürch et al. (1999). These experiments show that 75% of the total recharge originates from the Rhone River and 25% from the water source on the south side of the valley. The Illgraben fan does not contribute to recharge of the valley aquifer during high-water period.

Hydraulic conductivity was determined from pumping tests and piezometric readings in the boreholes (Jawecki 1996). The average hydraulic conductivity of the Rhone River alluvial aquifer is 10^{-3} ms^{-1}, whereas the hydraulic conductivity ranges from 10^{-4} to 10^{-6} ms^{-1} in the deposits of the Sierre rockslide. The swamp deposits and debris deposits have hydraulic conductivities of 10^{-5} and 10^{-3} ms^{-1} respectively. An average groundwater velocity of the Rhone aquifer was determined by tracer tests in borehole P11a (Kennedy et al. 2001, Fig. 1). The velocity ranged from 1.44 to 11.04 md^{-1} and from 6.96 to 55.20 md^{-1} under low and high water conditions, respectively.

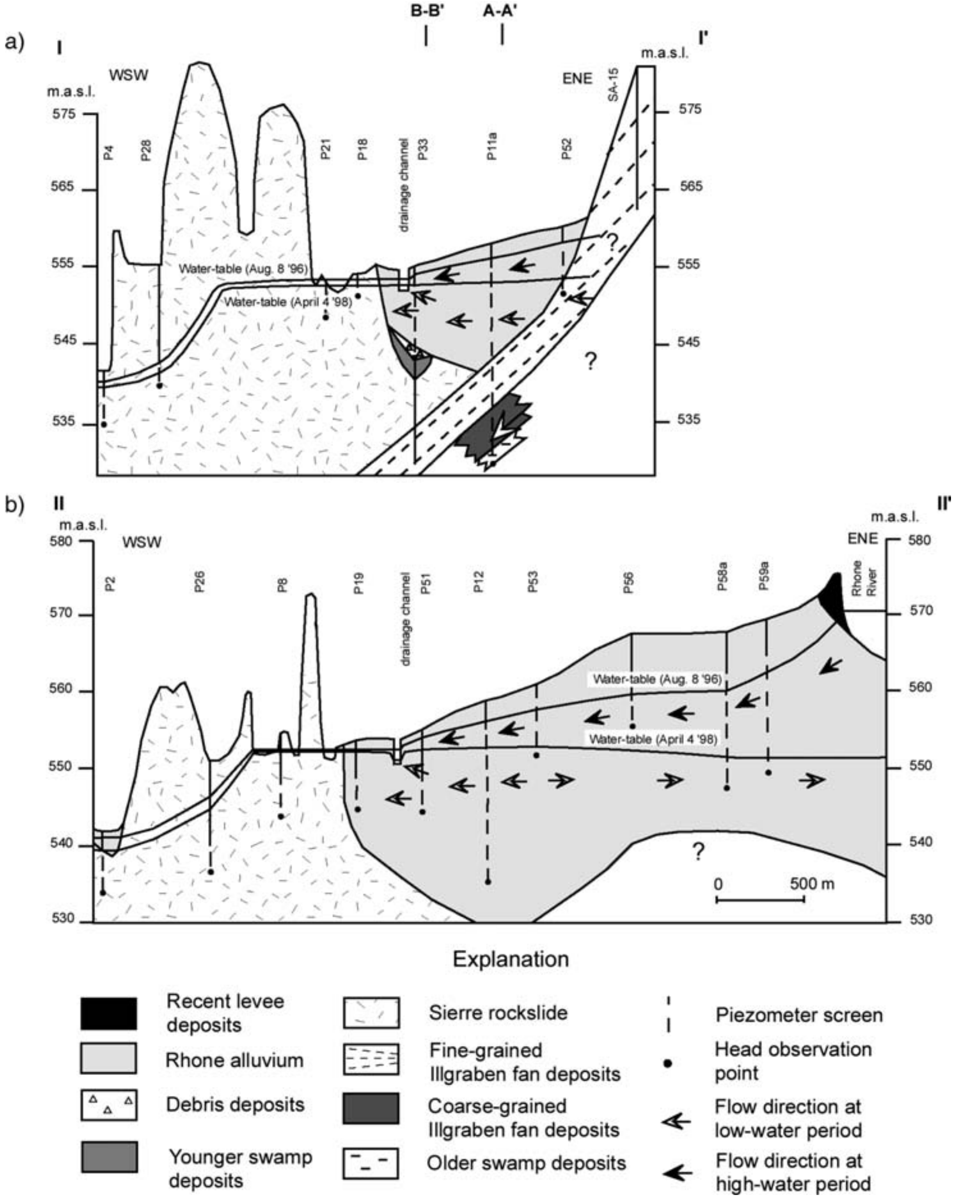

Fig. 2: Geologic cross sections a) I-I' and b) II-II' along the Rhone River valley and along the principal groundwater flow path. Line of section and borehole locations are shown in Figure 1.

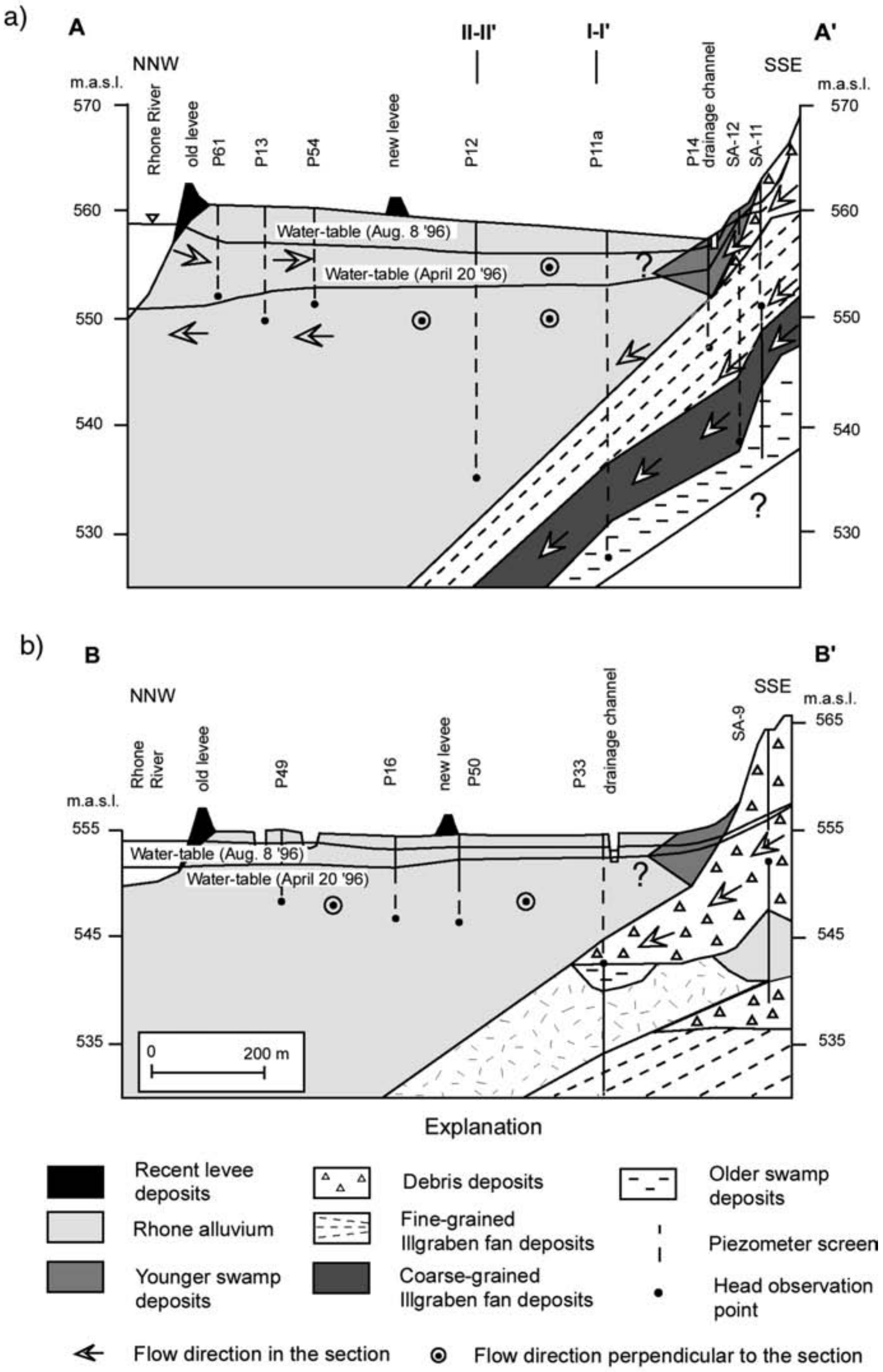

Fig. 3: Geologic cross sections a) A-A' and b) B-B' through the Rhone River alluvial deposits perpendicular to the principal groundwater flow path. Line of section and borehole locations are shown in Figure 1.

4. Groundwater Chemistry

The chemical characteristics of groundwater in the Finges area, as well as seasonal variations are described in detail in Schürch & Vuataz (2000). The chemical water types are classified by the cations and anions that compose ≥20% of the total dissolved solids (Appelo & Postma 1999). During high-water period, the Rhone River water that recharges the Rhone aquifer on the northeastern border of the studied area is a Ca-Mg-HCO_3-SO_4 water type and includes only 77 mg l^{-1} total dissolved solids (TDS). The groundwater of the Rhone River gravel is a Ca-Mg-SO_4-HCO_3 type with a TDS between 300 and 600 mgl^{-1}, increasing with distance from the Rhone River. The water of the recharge zone at the base of the south valley side in the east-central part of the area is of Ca-Mg-SO_4 type with TDS of about 2700 mg l^{-1}. This water is flowing from anhydrite- and gypsum-bearing rocks of Triassic age (Fig. 1; Schürch & Vuataz 2000).

5. Hydrochemical multiparameter logging method

A TURO T-611 water quality analyser (Turo Technology 1996) was lowered into five boreholes to log simultaneously temperature, electrical conductivity, dissolved oxygen (O_2), redox potential (Eh), pH and turbidity. The TURO T-611 analyser consists of six sensors and a data transmitter mounted in a 5 cm diameter housing,

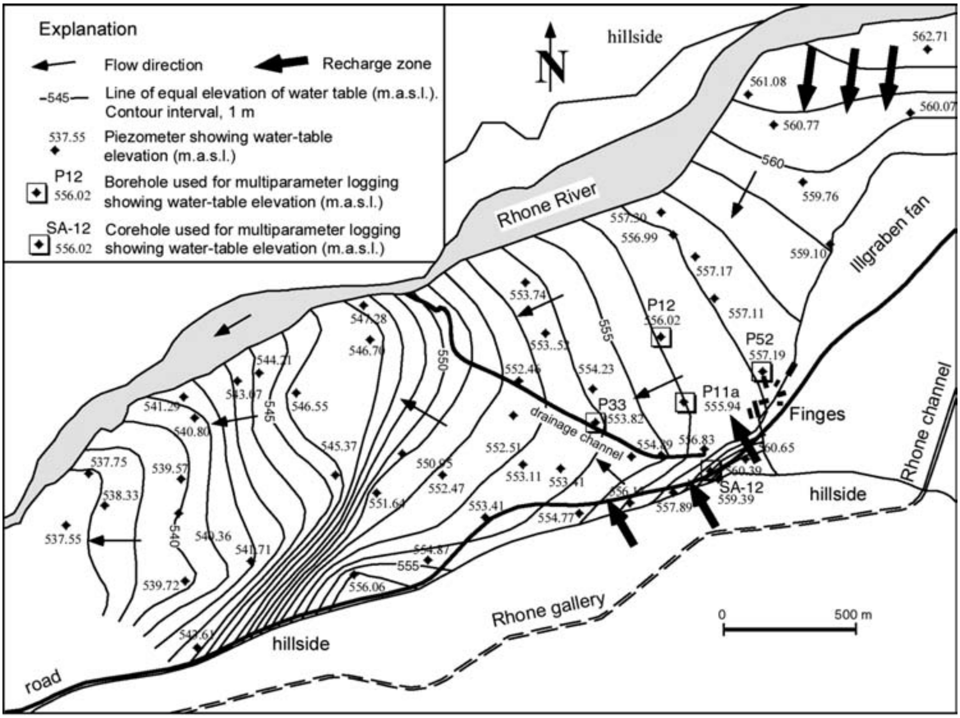

Fig. 4: Configuration of water table on August 8, 1996 during high flow on the Rhone River and borehole locations of the multiparameter loggings.

Sensor	Unit	Range	Resolution	Accuracy
Temperature	°C	-5 - + 50	0.1	±0.05
Electrical conductivity	µS/cm at 25°C	0 - 8000	2	±5
Dissolved oxygen	% O_2 at saturation	0 - 200	0.1	±0.5
Redox potential	mV	-900 - +900	1	±2
pH	pH unit	0 - 14	0.01	±0.03
Turbidity	ntu	0 - 600	0.3	±0.5

Tab. 1: Characteristics of the TURO T-611 water quality analyser (Turo Technology 1996).

of a 50 m long underwater cable, as well as of an automatic data acquisition recorder at the ground surface. Table 1 shows the unit, range, resolution and accuracy of each sensor. The redox potential (Eh) was corrected to the standard H^+ electrode potential. The logging was carried out by lowering manually the multiparameter probe to a given water depth, where the six physico-chemical parameters were recorded simultaneously after a 5 min wait. These parameters were acquired every 50 cm in the boreholes P12, P33, P52, P11a and SA-12. The localities of these five boreholes are shown in Fig. 4, and their characteristics are described in Table 2. The hydrochemical log measurements were made under natural conditions (no pumping) and under pumping conditions using a suction pump at a flow rate ranging between 57.6 and 86.4 m^3d^{-1}. To study the seasonal fluctuations of the physico-chemical groundwater parameters in the boreholes P12 and P33, the multiparameter logging was repeated at three different periods: July 15, 1997, September 16, 1997 and November 19, 1997. The logging of the boreholes P52, P11a and SA-12 was carried out on July 15, 1997, October 3, 1997 and July 15, 1997 respectively.

Well	Swiss coordinates X [m]	Swiss coordinates Y [m]	Z soil [m.a.s.l.]	Screen interval [m]	Total depth [m]	Type of drilling
P11a	612'210	127'685	557.97	4.0 - 30.0	30.20	coring
P12	612'120	127'924	558.98	5.0 - 22.0	24.00	coring
P33	611'867	127'591	554.80	2.5 - 10.0	30.00	coring
P52	612'502	127'795	560.88	2.0 - 9.0	9.00	destructive
SA-12	612'309	127'428	559.08	4.0 - 20.0	20.00	coring

Tab. 2: Characteristics of the five boreholes used for multiparameter logging at the Finges area. All boreholes are cased with a 10.16 cm diameter casing.

6. Results

6.1 Borehole P12

The borehole P12 is entirely located in the Rhone River alluvial deposits (Fig. 2b and 4). The Rhone River alluvium in the borehole P12 consists of a sandy gravel upper part and clayey and silty gravel below, the interface occurring at about 14 m depth. The hydraulic conductivity determined from pumping tests shows a higher value in the upper part ($2.5 * 10^{-3}$ ms^{-1}) than in the lower part ($1.2 * 10^{-3}$ ms^{-1}).

The first hydrochemical logs in the borehole P12 were run on July 15, 1997 without pumping (Fig. 5). The sandy gravel deposits of the upper part contain groundwater with an electrical conductivity of about 950 µS/cm and a dissolved oxygen content larger than 90%, whereas the clayey and silty gravel lower part contains a slightly less mineralised water (880 µS/cm) with a O_2-content smaller than 80%. The pH-value is around 7.10 in the upper part and 7.40 in the lower part. The turbidity increases at the base of the sandy gravel upper part, probably due to a water inflow with a higher suspended load. The logs were repeated on July 15, 1997 with pumping at about 57.6 m^3d^{-1} (Fig. 5). Under pumping conditions, the hydrochemical limit between the two different lithological formations, observed by pH- and electrical conductivity-logs, occurred about 3 m higher, indicating a water inflow at 11 m depth. This 3 m shift of the hydrochemical step can be explained by a downward movement of the more mineralised water.

Figure 6 shows the repeated multiparameter logs measured under natural conditions (no pumping) at three different periods of 1997: July 15, September 16 and November 19. The groundwater conductivity decreased progressively from July to

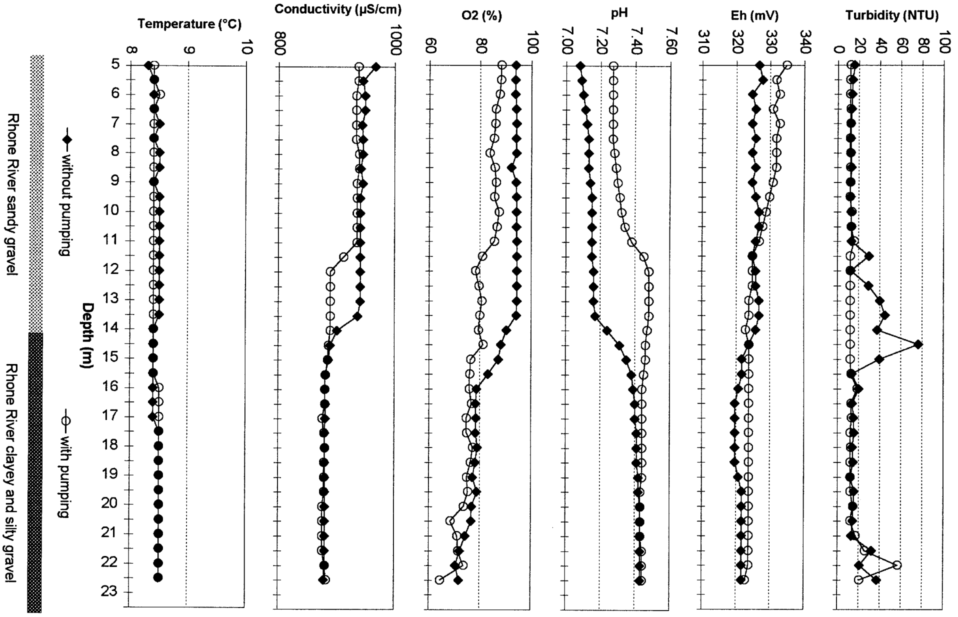

Fig. 5: Multiparameter logging in borehole P12 on July 15, 1997 under natural conditions (no pumping) and under pumping at about 57.6 m^3d^{-1}.

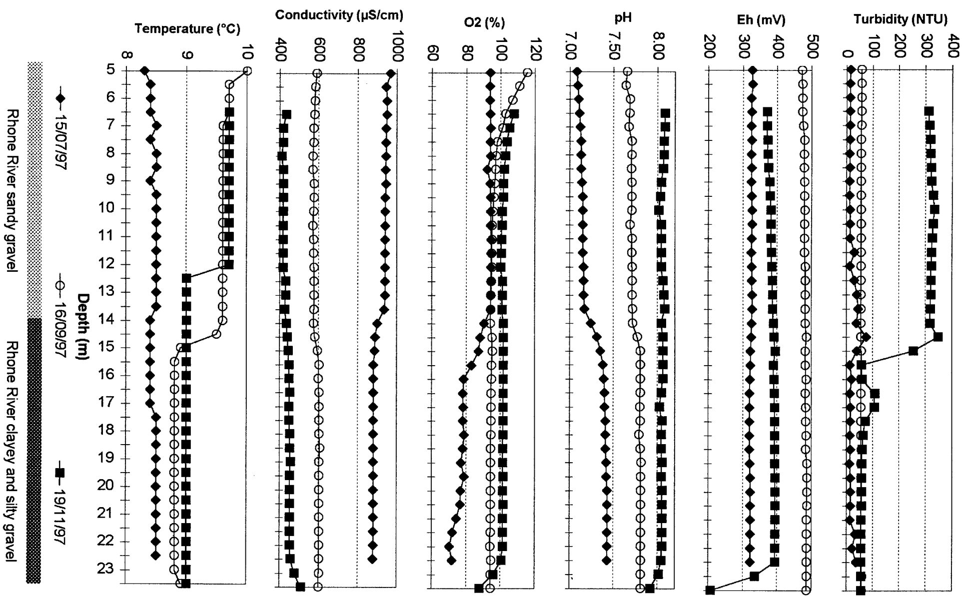

Fig. 6: Three multiparameter loggings in borehole P12 under natural conditions (no pumping) executed on July 15, September 16 and November 19, 1997.

November 1997, and the logs of September and November showed broadly inverse trend to that for July (Fig. 6). During September and November, the upper formation shows a less mineralised water with a 0.8°C higher temperature than the lower part. The weakly mineralised water, infiltrated in the northeast from the Rhone River during the summer high-water period (Fig. 2b), circulates faster in the sandy gravel upper part with a higher hydraulic conductivity, than in the less permeable lower formation. As a result, groundwater dilution by weakly mineralised water, infiltrated from the Rhone River, occurs faster in the upper part at a time of high water. During low-water period however, between October and March, when no water moves out from the Rhone River into the alluvium, the groundwaters of the two different lithological formations in borehole P12 reach a kind of equilibrium. The turbidity attains about 300 ntu in the upper part in November 1997, whereas it remains at 80 ntu in the lower part. The high turbidity in the upper part indicates an important suspended load of the groundwater.

6.2 Borehole P33

The borehole P33 is located on the east sight of the drainage channel (Fig. 1). This 30 m deep borehole is equipped only with a 10 m deep piezometer, penetrating the Rhone River alluvium (0 - 8 m) and the debris deposits (8 - 10 m), as shown in Figure 3b. Figure 7 displays the multiparameter logs executed on July 15, 1997 under natural conditions and with pumping at 72.0 m^3d^{-1}. Inflections in the temperature, conductivity and pH logs indicate the interface of the two different lithological formations at 8 m depth. The Rhone River sandy gravels of the upper part contain a highly mineralised water (>1550 µS/cm) with a temperature of about 11.5 °C,

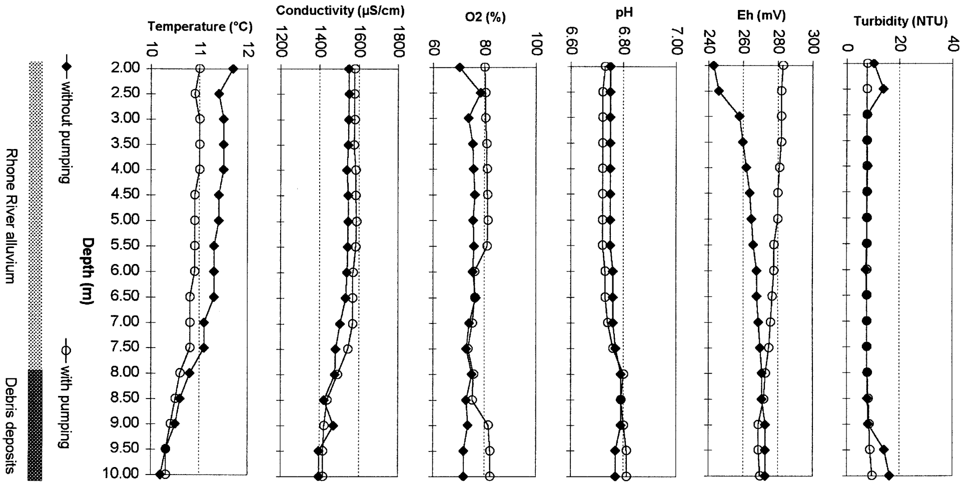

Fig. 7: Multiparameter logging in borehole P33 on July 15, 1997 under natural conditions (no pumping) and under pumping at about 72.0 m^{3}d^{-1}.

whereas the debris deposits of the lower part show a lower conductivity of about 1400 µS/cm and a lower temperature of about 10.5 °C. Under natural conditions, the dissolved oxygen content is almost constant over the whole borehole length. Under pumping conditions however, the O_2 log shows two hydrochemical steps:

i) at the top of the debris deposits,

ii) at 5.50 m depth, situated within the Rhone River alluvium.

Figure 8 shows the repeated multiparameter logs measured under natural conditions (no pumping) at three different periods of 1997: July 15, September 16 and

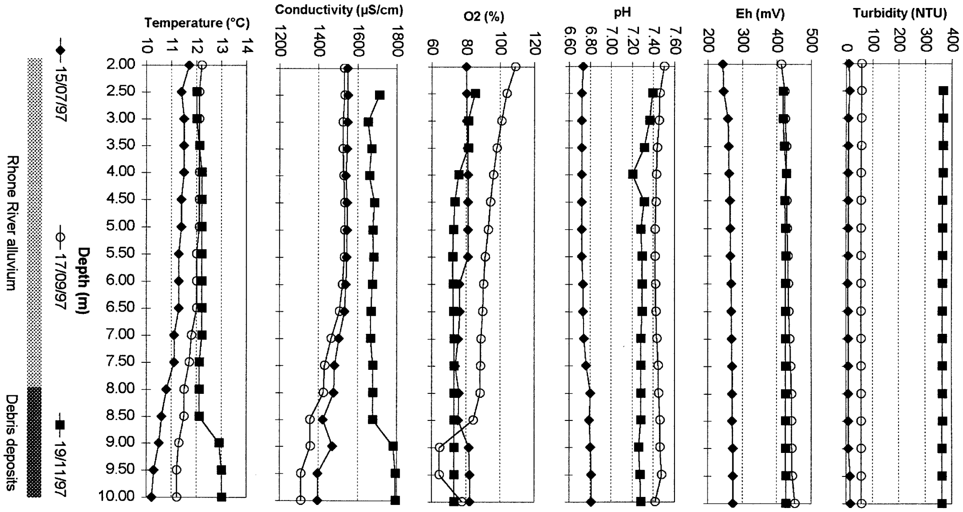

Fig. 8: Three multiparameter loggings in borehole P33 under natural conditions (no pumping) realised on July 15, September 16 and November 19, 1997.

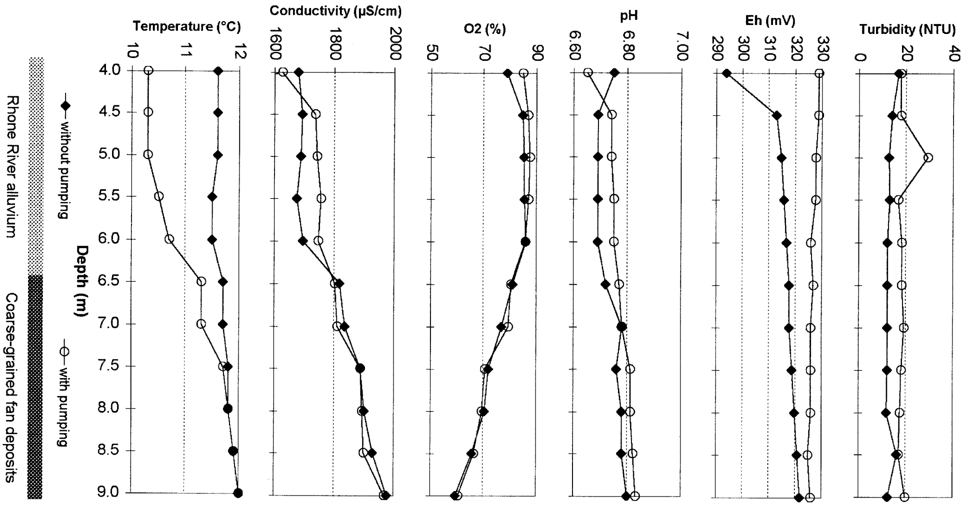

Fig. 9: Multiparameter logging in borehole P52 on July 15, 1997 under natural conditions (no pumping) and under pumping at about 86.4 m^3d^{-1}.

November 19. The temperature rises slightly from July to November, whereas electrical conductivity first decreases from July to September and then increases in November. A computer simulation of the groundwater flow during the high-water period of August 8, 1996 (Schürch et al. 1999) shows that water infiltrating from the Rhone River in the northeastern part of the study area takes almost 2½ months to reach borehole P33, a distance of 1860 m from the river. This travel time corresponds to a groundwater flow velocity of 25 m d^{-1}. During low-water period between September and March, no weakly mineralised water moves out from the Rhone River into the alluvium. As a result, the groundwater mineralization in the Rhone River alluvium of borehole P33 first decreases with the arrival of weakly mineralised water flowing from the Rhone River and then increases during winter, when no water infiltrates from the river. At this winter low-water period, the Rhone River alluvium is exclusively recharged by SO_4-rich water, flowing from the southern side of the valley (Fig. 4). On the other hand, snowmelt water, as well as rainwater and SO_4-rich water, flowing from the southern side of the valley into the debris deposits in borehole P33, determine their groundwater composition (Fig. 3b).

6.3 Borehole P52

The borehole P52 is situated in the southeastern part of the Rhone River plain, where Illgraben fan deposits, dipping under the Rhone River alluvium, attain 6.50 m depth from ground surface (Fig. 2a). Figure 9 displays the multiparameter logs measured on July 15, 1997 under natural conditions and with pumping at 86.4 m^3d^{-1}. The results show the interface of the two lithological formations at a depth of 6.50 m. The Rhone River alluvium of the upper part contains a highly mineralised water (>1650 µS/cm) with a O_2- content larger than 80%, whereas the Illgraben fan deposits show a less oxygenated water (60-70%) with a higher conductivity of about 1900 µS/cm. Under pumping conditions, the temperature decreases

significantly in the Rhone River alluvium of the upper part, reflecting a colder groundwater inflow at 5 m depth (Fig. 9).
During the winter low flow on the river, the Rhone River alluvium of borehole P52 is completely unsaturated, because the water-table level is situated at 7.50 m depth. The computer simulation of the groundwater flow during the high-water period of August 1996 (Schürch et al. 1999) showed that water infiltrating from the Rhone River in the northeastern part of the study area takes almost 1½ months to reach borehole P52, a distance of 1270 m from the river. This travel time corresponds to a groundwater flow velocity of 28 m d^{-1}.

6.4 Borehole P11a

The borehole P11a is situated in the south-central part of the Rhone River plain (Fig. 2a and 4). The results of the multiparameter logging, carried out under natural conditions (no pumping), confirm the presence of three different lithologic horizons (Fig. 10): the Rhone River alluvial sandy gravel sediments (0-15.20 m), the Illgraben fan alluvial silty sand deposits (15.20-26.70 m) and the swamp deposits (26.70 - 30.20 m). The groundwaters of these three horizons are characterised by important variations of their physical and chemical parameters. The Rhone River alluvium shows a highly mineralised water (>1900 µS/cm) with a pH > 7.35, whereas the Illgraben fan deposits contain a poorly oxygenated water with a higher conductivity (2300 µS/cm), a higher pH-value (pH = 7.58) and a low redox potential of -50 mV. The values of redox potential decrease further in the swamp deposits beneath the Illgraben fan deposits, where the fluid reaches its highest dissolved minerals content and its highest pH-value. Two peaks occur in the turbidity log: i) at 6.5 m depth within the Rhone River alluvium and ii) at 18.5 m depth within the Illgraben fan deposits. The turbidity peak at 6.5 m depth corresponds to observed temperature and pH variations at the same depth, representing the limit between two lenses of different alluvial composition.

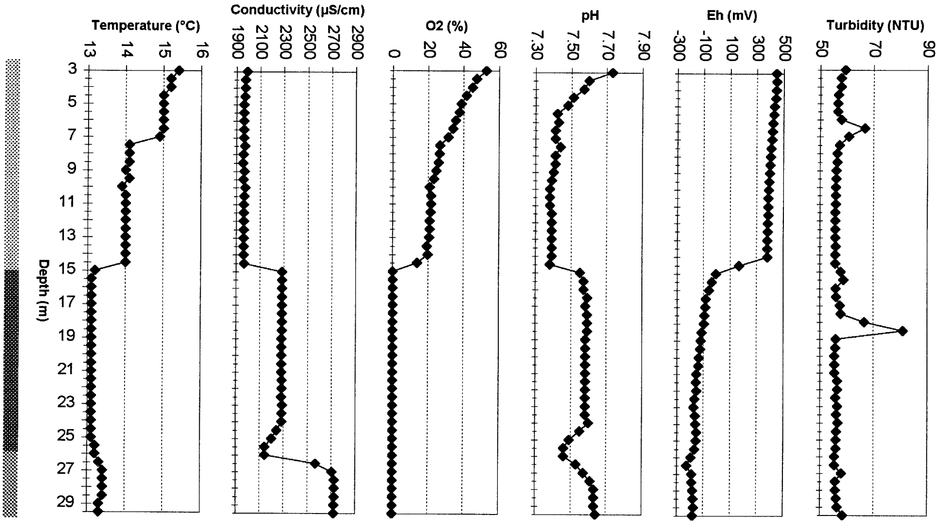

Fig. 10: Multiparameter logging in borehole P11a on October 3, 1997 under natural conditions (no pumping).

The vertical evolution of electrical conductivity and pH indicates a groundwater flow into the borehole from the Illgraben fan deposits between 25 and 26 m. This recharge zone at the base of the fan deposits brings a groundwater with a lower conductivity (about 2150 µS/cm) and a lower pH-value (pH = 7.47). The major change at 15 m also corresponds with the bottom of an outflow zone of the alluvial Rhone aquifer, as is confirmed by a flowmeter log (Monnet et al. 2000). It certainly seems that flow controls the vertical distribution of the fluid chemistry, and that the formation properties control the flow. In case of vertical flow in the borehole, the quality of the water in the column at a given depth is not representative of the formation pore water at the same depth. Instead, it represents the quality of water in the formation at the outflow zone.

6.5 Borehole SA-12

The borehole SA-12, situated in the southeasthern part of the Rhone River plain (Fig. 4), shows the following lithologic formations (Fig. 3a): swamp deposits (0 - 2.50 m), debris deposits (2.50-3.80 m), upper Illgraben fan deposits (3.80-14.60 m) and lower Illgraben fan deposits (14.60-20.00 m). The screen length is exclusively situated in the Illgraben fan deposits between 4 and 20 m depth. The results of the multiparameter physical and chemical logging, measured on July 15, 1997 under natural conditions and with pumping at 86.4 m^3d^{-1}, confirm the position of the interface between the lower and upper parts of the Illgraben fan deposits at about 15 m depth. This interface is represented by a decrease in the O_2-content, as well as in the pH and Eh-values (Fig. 11). The turbidity increases to attain a maximum value at 16 m depth and then decreases towards the bottom of the borehole. The silty and sandy upper part of the fan deposits contains water with a high electrical conductivity (>2500 µS/cm) and a pH lower than 7.0. In the fine-grained upper part, the log results are similar under static and pumping conditions. In the sandy gravel lower part of the fan, the logging carried out under static conditions shows a higher elec-

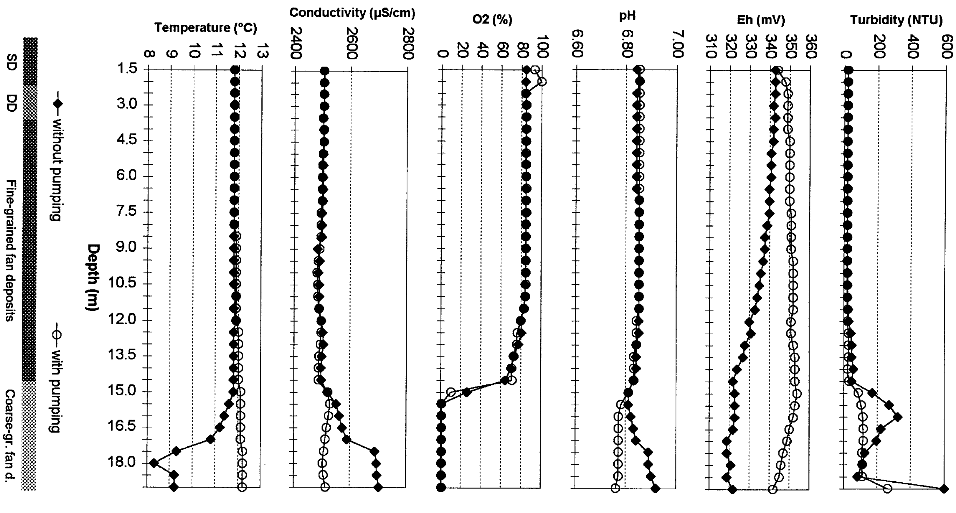

Fig. 11: Multiparameter logging in borehole SA-12 on July 15, 1997 under natural conditions (no pumping) and under pumping at about 86.4 m^3d^{-1}. SD = Swamp Deposits; DD = Debris Deposits.

trical conductivity of about 2700 µS/cm and a lower temperature of about 9 °C. This cold, highly-mineralised water at the bottom of the borehole can be explained by cold water infiltrated during winter precipitations or snow melting, then flowing in the debris deposits and in the sandy gravel deposits of the lower fan. During logging with pumping, warmer water was flowing into the borehole at the base of the sandy gravel lower part of the Illgraben fan (Fig. 3a), corresponding to that recharge zone observed in borehole P11a between 25 and 26 m (Fig. 10).

7. Hydrogeological synthesis

By using geological information and multiparameter log results, three-dimensional flow system and water quality distribution were determined in the Finges area. The unconfined alluvial aquifer of the Rhone River is delimited in the south-east by Illgraben fan deposits and in the south-west by Sierre rockslide deposits. Major groundwater flow occurs in this highly permeable Rhone River aquifer from the Rhone River in the north-east towards the drainage channel in the south-west, induced by weakly mineralised river water infiltrating in the north-west. At the second recharge area at the base of the southern side of the valley in the east-central part of the area, highly-mineralised water is flowing into the Rhone River aquifer and into underlying Illgraben fan deposits (boreholes P11a, P52 and SA-12) and debris deposits (borehole P33). In summer during high flow on the Rhone River, the sandy gravels of the Rhone River contain dissolved oxygen-rich water with a temperature of about 8.5 °C. The electrical conductivity ranges from 950 µS/cm in the central part of the Rhone River aquifer (borehole P12) to about 1950 µS/cm in the south-central part (borehole P11a). The Illgraben fan deposits, underlying the alluvial Rhone River aquifer, are yielding highly-mineralised water of about 1900 µS/cm and a dissolved oxygen content of 60-75% in the southeastern part (borehole P52). In the south-central part at a depth of 15.20 m to the top of the fan deposits (borehole P11a), they contain an anoxic water with an electrical conductivity of 2300 µS/cm.

8. Conclusions

With the help of a multiparameter hydrochemical logging system, the vertical evolution of groundwater electrical conductivity, temperature, dissolved oxygen, redox potential, pH and turbidity was studied in five boreholes. These boreholes are situated in different Quaternary sediments: Rhone River alluvium; silty sand deposits of the Illgraben fan; deposits of the Sierre rockslide; debris deposits and swamp deposits. The steps in the multiparameter logs generally coincide with lithologic boundaries. These steps correspond to flow zones where groundwater is moving into the borehole. It certainly seems that flow controls the vertical evolution of the fluid chemistry, and that the formation properties control the flow. In case of vertical flow in the borehole, the quality of the water in the column at a given depth is not representative of the formation pore water at the same depth. Instead, it represents the quality of water in the formation at the outflow zone. Thus, the integration of geological information and multiparameter hydrochemical logging was helpful in identifying the heterogeneous nature of the alluvial aquifer, of the vertical distribution of its groundwater quality and of its flow system.

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