Published in the 3rd International Conference on Future Groundwater Resources At Risk,
Lisbon, Portugal, 63-78, 2001
which should be used for any reference to this work

Geohydrological parameters identification and groundwater vulnerability to pollution : A Swiss case study

Francesco Kimmeier[1], Mahmoud Bouzelboudjen[1], Pascal Ornstein[2],
Isabelle Weber[1], Jean-Daniel Rouiller[2]

[1] CHYN - Centre d'Hydrogéologie, Université de Neuchâtel, Emile-Argand 11, 2007 Neuchâtel, Suisse
[2] CREALP - Centre de Recherche en Environnement Alpin, Rue de l'Industrie 43, 1991 Sion, Suisse

ABSTRACT

The alluvial aquifer of the Rhône valley in Switzerland, which extends over 110 km and occupies an area of 256 km^2, is of great economic importance. Its groundwaters are easily accessible and thus exploitable at low cost. However, its location in an often narrow valley with intense human activity (industry, agriculture, communications network) makes it particularly vulnerable from both a qualitative (industrial and\or agricultural pollution) and quantitative point of view (groundwater flow disturbance following civil engineering works). Since 1995, the Swiss canton of Valais has decided to compile datasets from a number of local studies (water supply, hydro-electricity, and geotechnical studies) into a regional, integrated hydrogeological framework. The realization of the study has shown the importance of GIS tool either for the computing and mapping of the first piezometric map between Brig and Léman Lake or the elaboration of vulnerability maps. The geostatistic tool was also intensively used all over the spatial treatment of data. The comparison of groundwaters NO_3^{--} content (1985 and 1995), has shown that globally the nitrates content in the groundwater is low (< 30 mg/l for 90 % of samples). However it must be notice that the evolution of the NO_3^{--} content degrades during time. The study of vulnerability to pollution for the aquifer situated between Sierre and Vétroz as shown significant differences between the four different methods used. As main results DRASTIC and SINTACS integrated methods are concentrated between Moderate and High vulnerability when NLFB and GOD intrinsic methods are concentrated between Very Low and Moderate vulnerability. Intrinsic methods have the tendency to minimize the vulnerability.

Keywords : GIS (Geographical Information System), geostatistics, vulnerability to pollution, time series, piezometric map

1. STUDY PURPOSE

The Rhône valley alluvial aquifer in Switzerland extends over 110 km and occupies a surface of 256 km^2 and is of great economic importance. Its groundwaters are easily accessible and thus exploitable at low cost. However, its location in an often narrow valley with intense human activity (industry, agriculture, communications network) makes it particularly vulnerable from both a qualitative (industrial and\or agricultural pollution) and quantitative point of view (groundwater flows disturbance following civil engineering works). Since 1995, the Swiss canton of Valais has decided to compile datasets from a number of local studies (water supply, hydro-electricity, and geotechnical studies) into a regional, integrated hydrogeological framework. The management of contaminated sites in Switzerland, and in the canton of Valais in particular, has now become a major concern in terms of water resource protection. Indeed, new legislation (OEaux 1998) now requires the delineation of the zone of influence of all water catchments of public interest that are vulnerable to pollution.

The aims of this paper is to study the Rhône aquifer at different scale and under multiple aspects that are : 1) the piezometry between Brig and Léman lake, 2) the piezometry between Sierre and Vétroz and for the same region 3) the study of piezometric time series, 4) the study of the groundwater hydrochemistry and the nitrates evolution of groundwaters and finally 5) the study of vulnerability to pollution using four methods. This study is carried out with GIS and geostatistic tools.

2. HYDROGEOLOGICAL DATABASE

The creation of a spatial (Arc/Info®, ArcView® ; ESRI, 1996, 1997) and tabular database (Access® ; Microsoft, 1997) represented the first stage of work. This database integrates relevant hydrogeologic data for the study and is subdivided into two complementary parts ; on one hand, a spatial database incorporating various coverages (a set of thematically associated data considered as a unit, e.g. soils, streams, roads, or land use, [ESRI, 1996]). On the other hand a descriptive database including data relating to the structure (boreholes), to the hydrodynamic characteristics (permeability, transmissivity, storage coefficient), to the piezometry (punctual and continuous measurements) and the hydrochemistry of the aquifer system. Before the implementation of this database, validation procedures adapted for each type of data were defined and applied in a systematic way.

In order to make its management easier, a simple structure (tabular files) was adopted for the descriptive database. In its current state, the spatial database covers 11 areas (Annex 1). The descriptive database includes 779 boreholes among of which 283 have associated permeability measurements, more of 15'000 piezometric and physico-chemical measurements (only discrete data : geographic features containing boundaries : point, line or area boundaries, [ESRI, 1996]), 91 automatic measurement stations of groundwater level as well as about 1'000 chemical analyses [Ornstein, 1996]. The Valais canton hydrogeologic database allowed local studies of groundwater simulations to be carried out. The methodology of this kind of study is well described in Bouzelboudjen and Kimmeier [1998]. The description is from the data validation until the elaboration of 3D hydrodynamic models.

3. THE POROUS AQUIFER OF THE VALAIS CANTON IN THE CONTEXT OF POROUS SWISS AQUIFERS

Our study area is located in the Rhône valley, which contains an important alluvial aquifer (110 km of length on an average of 1.5 km of width ; 256 km^2) at the Swiss scale (Fig. 1). The vulnerability study is focused on the Sierre-Vétroz area. Four hydrographs (automatic measurements of the water table depth) from the area are represented on figure 2. On a national scale it is necessary to notice that despite the abundance of geological and hydrological (e.g. river discharge records extends back more than a centenary), the piezometric information concerning unconsolidated aquifers (main element in the knowledge of the groundwaters dynamics) does not

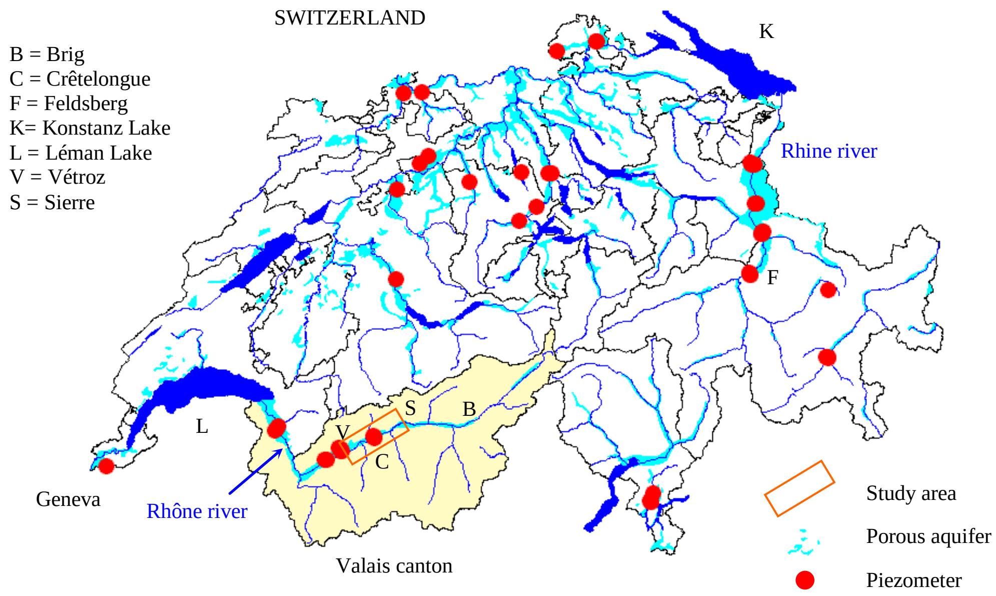

Figure 1 : a) Porous aquifers and piezometers network of SNHGS (Swiss National Hydrological and Geological Survey), b) Study area between Sierre and Vétroz in the Valais canton (Switzerland).

extend back more than 25 years and is inadequately distributed. For consolidated rocks (fissured and karstic), the situation is even less adequate, since the piezometric information remain fragmentary. The first data were collected in 1975, which is relatively recent for the groundwater monitoring.

Important information can be obtained by studying the recession part of

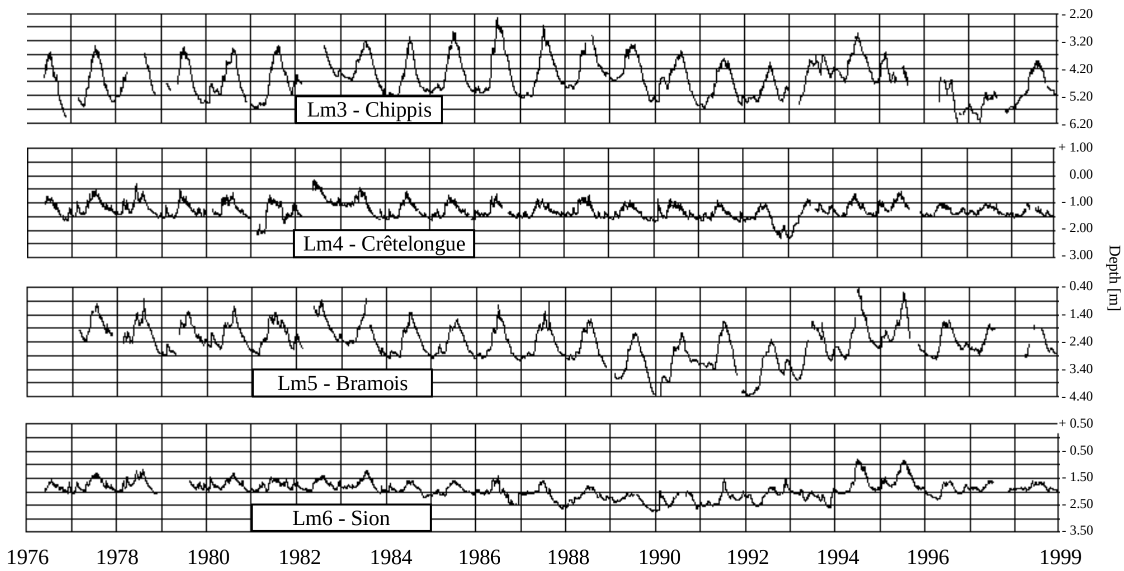

Figure 2 : Hydrographs (daily average) Lm3 (Chippis), Lm4 (Crêtelongue), Lm5 (Bramois), and Lm6 (Sion) of measurement stations (Fig. 4) installed since 1976 by the Cantonal Service of Environmental Protection (Valais canton, Switzerland).

hydrographs. The study of this part of the graph allows information concerning drought resistance or more usually under our latitudes the resistance at a deficit of precipitation. We estimated the half recession time for the Crêtelongue's hydrograph (Fig. 2 and 4 - Lm4) that corresponds to 0.4 month [Bouzelboudjen, Kimmeier & al., 1998]. By comparing this value with that obtained with Feldsberg's hydrograph from a site in the Rhine aquifer upstream to Konstanz Lake (2.2 months) one notices that the Rhône aquifer has a relatively weak resistance in comparison to the Rhine. The Rhône aquifer is situated close to the surface (some meters) while the alluvial Rhine aquifer is relatively deeper (approximately 15 meters). In the vulnerability approach the variable "half recession time" is indirectly taken in account by means of the conductivity of the saturated and non saturated zone as the depth of the water table.

3.1 Hydraulic potential field reconstruction by kriging

The hydraulic potential field is necessary to calculate the depth of the aquifer water table. This is a very important parameter for the evaluation of aquifer vulnerability. Consequently the variable hydraulic potential (H) was regionalized by kriging (Fig. 3) using the 1'160 data points from the high water event of 1997. To reconstruct the H field we used a probabilistic approach developed by Matheron [1970] and applied to the water sciences by Delhomme [1979]. The hydraulic potential variogram presents non-stationary spatial behavior characterized by a parabolic increase. It does not stabilize at great distance reflecting the presence of a drift. Structural recognition is indirect and is made automatically in two steps [Geovariances, 1998]. The first step consists of determining the degree of drift by the least-squares method. The second step consists in adjusting the models of generalized covariance by iterative regression and selection of the optimal model. The hydraulic potentials were regionalized on a grid of 100x100 m using the *Isatis* method of standard kriging. The moving neighborhood method of kriging allows an interpolation to take into account the local variations of the hydraulic potential. Consequently we obtained the first (1997) piezometric numerical map (Fig. 3) with an associated map of kriging estimation error. This map shows that the direction of flow is quite parallel to the valley and is directed from East (Brig) to West (Léman Lake). The map also shows the close relation between the aquifer and the river. As expected, the gradient of the

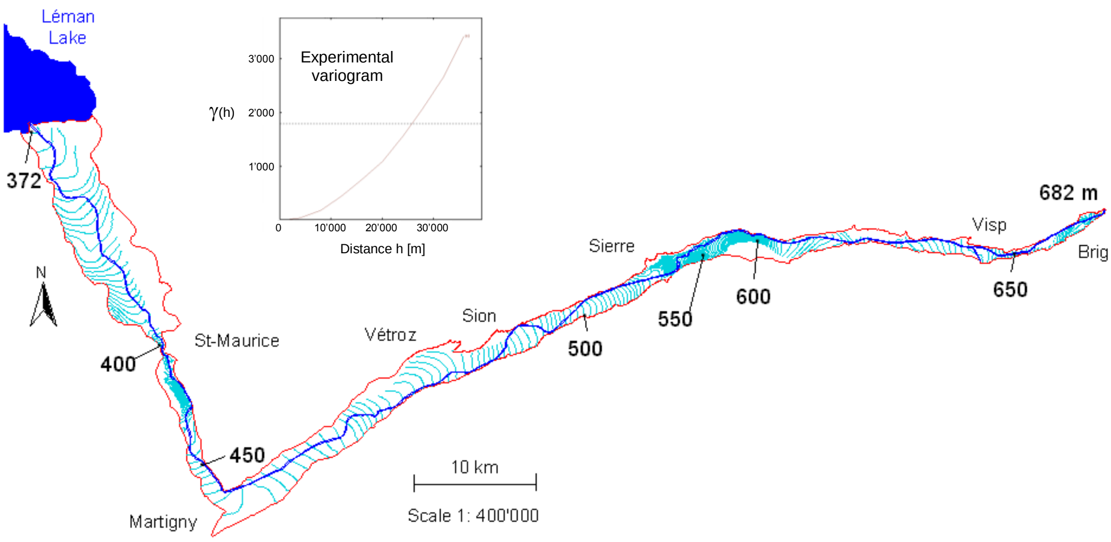

Figure 3 : Kriging contour map of hydraulic potentials H (high water July 1997, 1'160 values) in the aquifer of the Rhône valley from Brig to Léman Lake. The numbers indicate isovalues of estimated H in meters. The variogram of hydraulic potentials is also depicted (inset).

piezometric surface increase before the narrowing in the valley as it is the case at St-Maurice or Sierre.

4. HYDROGEOLOGY OF SIERRE-VÉTROZ AREA

4.1 Aquifer system structure

The topography and the geomorphology of the Rhône alluvial plain between Sierre and Vétroz are strongly conditioned by the factors such as the Rhône course, the talus cones as well as the deposits of the rockfall of Sierre (Fig. 4). An evaluation of the amount of water resulting from precipitation on the study area surface was made by Ebener & al. [1998]. For period 1978-1991 these authors obtained an annual average temperature of 10.2 °C and an annual average precipitation of 570.5 mm. The evapotranspiration, calculated by means of Turc's formula, gives a value about 430 mm/year. Therefore, the potential effective precipitation (EP) value is 140 mm/year.

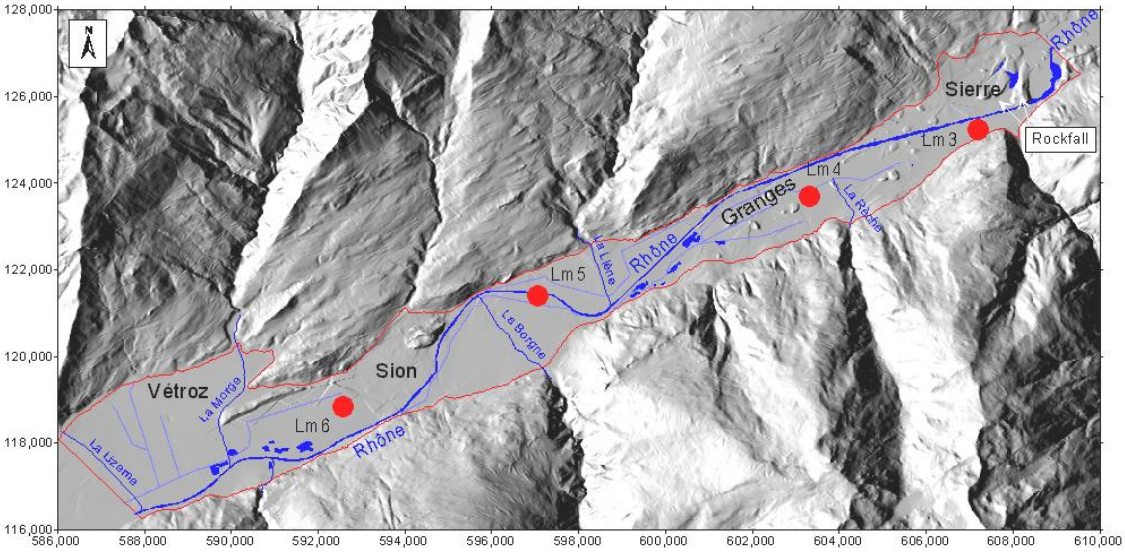

Figure 4 : Digital Elevation Model (DEM : grid 25x25m, © *Federal Office of Topography*), study area boundary in the region of Sierre-Vétroz and location of hydrographs Lm3 to Lm6 (Fig. 2).

The aquifer structure was defined based on 460 borehole logs. The alluvial deposits represent a continuous horizon over almost all the surface of the plain to depth from 20 to 25 meters below ground surface. The permeability of these deposits varies between 10^{-2} and 10^{-3} m/s. It can present locally strong variations with the depth. The main aquifer consists of alluviums of the Rhône. Near valleysides, coarse deposits connected to the talus cones of lateral tributaries can intercalate themselves in alluvium and constitute potentially aquiferous levels.

The sediments above the aquifer mainly consist of Rhône flood deposits to which can be added locally lacustrine and\or anthropogenic deposits. These deposits, which are no thicker than some meters, divide up mainly along the Rhône (current and former beds), along valleyside-slopes and at base of the hills of the Sierre rockfall. The unit has low to moderate permeability and varies from 10^{-5} to 10^{-6} m/s for horizons mainly silty compared to 10^{-4} to 10^{-5} m/s for horizons mainly sandy.

The available borehole logs do not specify the lower limit of the aquifer. Some boreholes reveal intercalations of lacustrine and swamp deposits with very low permeability (<10^{-6} m/s) in fluviatile alluviums of the Rhône. These deposits are situated at variable depths (from 15 to 25 meters) and correspond frequently to intermittent levels. Globally, the alluvial aquifer around Sierre-Vétroz can be compared to a highly heterogeneous single layer [Aviolat & Rey, 1995 ; Ornstein, 1996 ; Ebener, 1998 ; Schürch, 2000].

4.2 Results of piezometric campaigns

Piezometric measurements were taken twice (350 control points) every year, in July (high water) and in February (low water). In our study we used the measurements made in July 1997. The interpretation of piezometric maps shows that the aquifer general flows is parallel to the axis of the Rhône valley with an orientation NE-SW and an average gradient about 2 ‰. A more detailed analysis reveals a higher overall gradient in the upstream half study area that is 2 to 5 ‰ (downstream region : 1 to 2 ‰) with notably a marked effect on the alluvial aquifer flows around the hills of Sierre rockfall (gradient from 4 to 5 ‰). These maps also show the influence of local

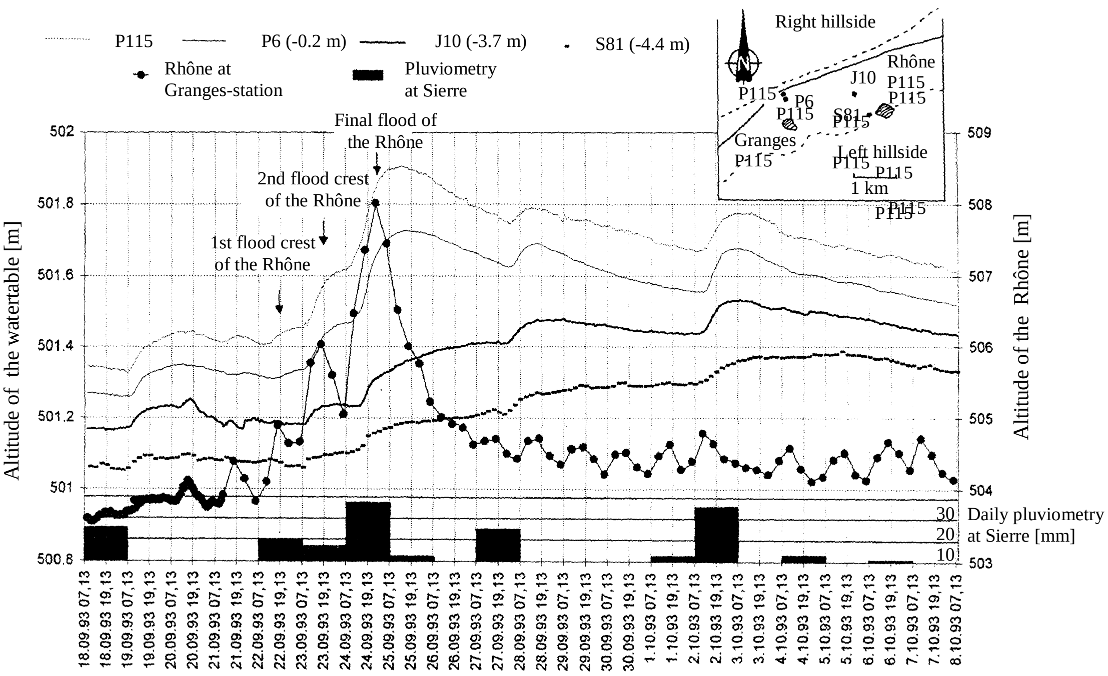

Figure 5 : Effects on the unconfined aquifer of the Rhône flood on the 24-25 septembre 1993 and of the pluviometry between the 18th of septembre and the 8th of october 1993 [Aviolat & Rey, 1995].

factors such as the Rhône, the canals or the valleysides on the general direction of the aquifer flow. The exchanges Rhône-aquifer are conditioned by the relative position of the Rhône with regard to the top of the alluvial aquifer. Overall, around Sierre-Vétroz, the Rhône main infiltrates into the alluvial aquifer. The locally draining effect of the main canals on the alluvial aquifer is clearly visible at high water. Recharge to the aquifer from canals can occur at specific points at low water. The influence of valleysides is very reduced.

The study of the Rhône exceptional flood at the end of September 1993 (Fig. 5) demonstrated its direct influence on groundwaters. The magnitude of the water table reactions decreases when the distance to the river increases. Furthermore, the measurements and the physico-chemical analyses indicate that the infiltration of the river create essentially in left shore an effect of dilution of waters of the alluvial aquifer. The influence of the precipitation on the evolution of the water table level has only a very limited duration, except during precipitations separated by a short time. In case of intense rainfall, the reaction of the water table level marks by a fast ascent. The flood crest of the aquifer, of very short duration, is led of the pluviometric event because of the infiltration delay through the non-saturated zone [Aviolat & Rey, 1995].

4.3 Piezometry time series analysis

A study of piezometry time series (daily measurements) of four measurement stations located between Sierre and Sion (Fig. 2 and 4) provided an understanding on the behavior of the alluvial aquifer during period 1976-1999.

The results obtained show that during the period 1992-1994 there was a continuous rise in the low water level (from 30 to 120 cm). Low water 1995 generally appears at its highest level over the twenty years in the sector Sierre-Sion. The period spring - summer 1995 was marked at the level of the Rhône plain by frequent floods resulting in a marked rise in the maximum groundwater level in aquifer at high water. However this tendency is not as uniform compared to the low water. While in Crêtelongue's region, they join the average of these last twenty years, high water 1994 and 1995 are the highest recorded since 1976 in the region of Sion. In contrast, this analysis highlights the particularly deficient character of the hydrological years 1988 to 1993. This tendency to the drought is not unique to central Valais canton as shown in recent studies carried out at the Swiss and European scale [Bouzelboudjen, Kimmeier & al., 1998 ; Gennai & al., 1993 ; Marsh, 1994].

The temporal analysis of the piezometry (1976-1999) show for the years 1994-1995 important variations of the water table near the Rhône river (positive differences of height from 50 to 150 cm). Nevertheless, these piezometric variations globally remain in the limits of the inter-annual fluctuations (± 20 cm) when the measurement point is located far away the Rhône (see inset Fig. 5).

4.4 Hydrochemistry of groundwater

A principal components statistical analysis (PCA) using 245 observations of high water level (11 standardize variables) was carried out (Fig. 6). The study of the results of this campaign of chemical analyses provided indications of the hydrochemical characteristics of groundwaters of the Rhône valley between Sierre and Vétroz, as well as of local influences on the chemical content of the water. It notably highlights the respective influence of the Rhône and the valleysides. The weakly mineralized feature of alluvial aquifer waters along the Rhône very probably denote an effect of dilution due to the infiltrations of the river at high water level (group 3 in Fig. 6D). Furthermore, the existence of strongly mineralized zones (group 1 : SO_4^{--}, Ca^{++}, Mg^{++}, Kc (Electrical conductivity), DTO (Total hardness) ; group 2 : NO_3^{--}, K^+, Na^+, Cl^-,) at bases of the north and south valleysides provides evidence of the existence of side contributions with strong mineral load mainly acquired. A comparison of groundwaters NO_3^{--} content was established for the years 1985 and 1995 to study its evolution (Fig. 7 and 8). Globally, and with the exception of some atypical points, the nitrates content in the groundwater is low (< 30 mg/l for 90 % of samples), in a region

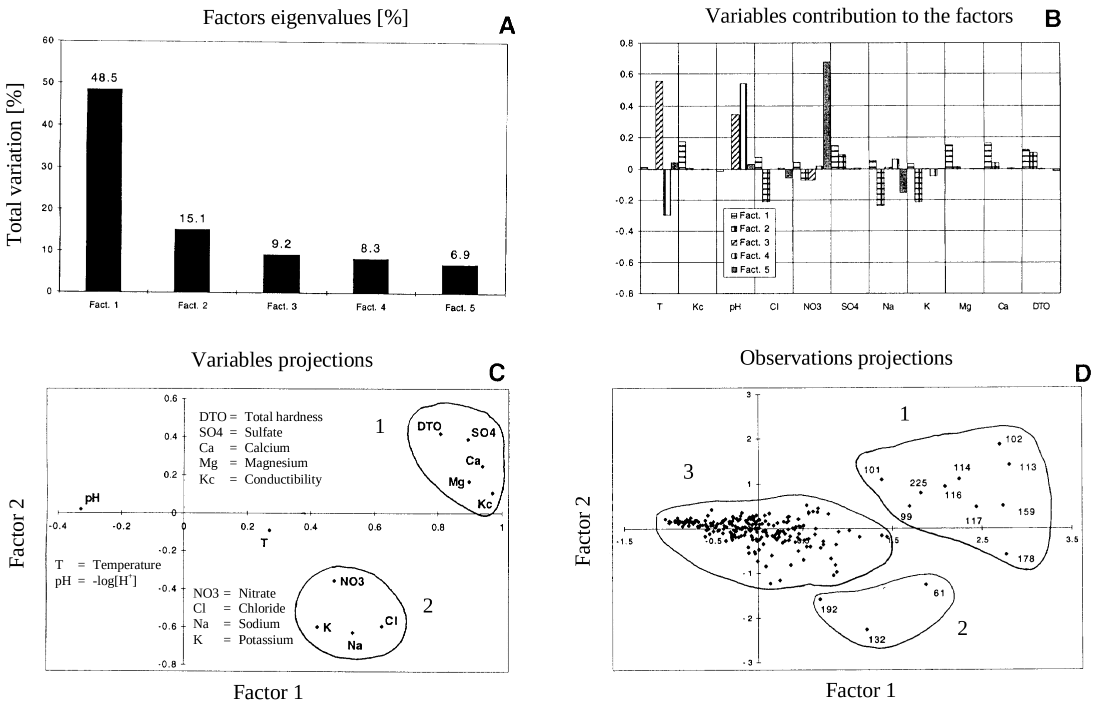

Figure 6 : Principal components statistical analysis (PCA) made on 245 observations in situation of high water 1995 (11 standardized variables).

where the agricultural is significant. It is however necessary to notice that the evolution of the NO_3^{--} content degrades during time. For example the number of points where the content is > 50 mg/l has doubled in the space of ten years, passing from 3 % to 6 %.

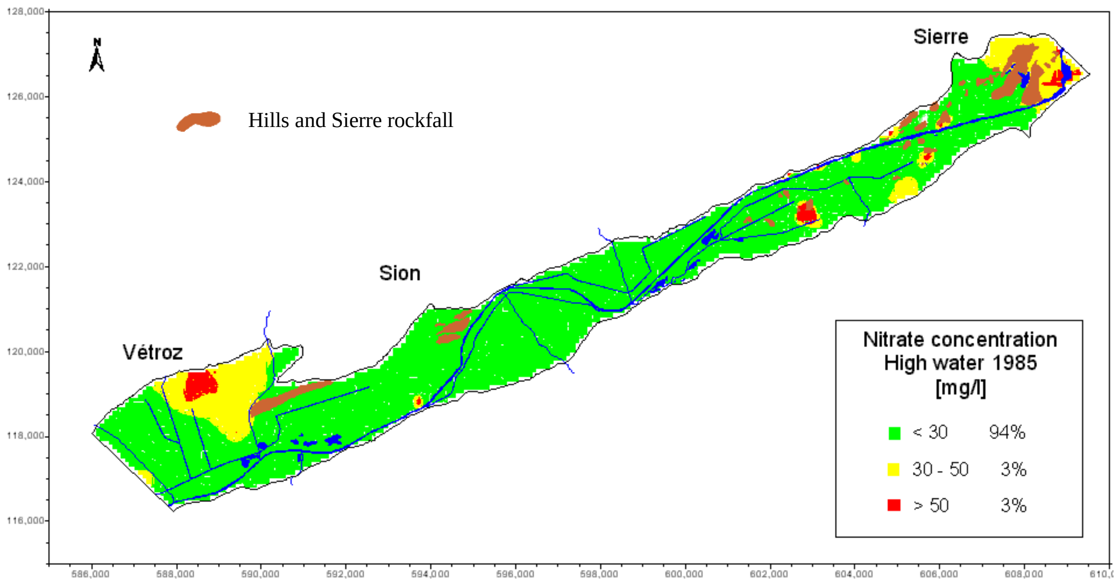

Figure 7 : Nitrate concentration mapping of the Rhône valley aquifer between Sierre and Vétroz. Sampling campaign during high water 1985 (245 values). Data regionalization by linear Kriging (*Surfer 7* - grid 100x100m).

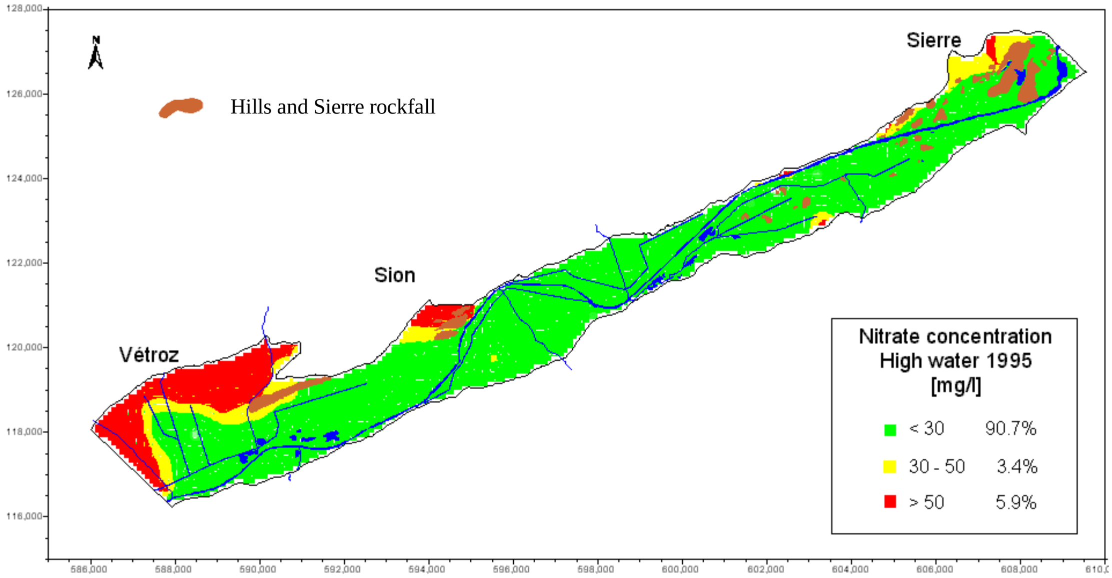

Figure 8 : Nitrate concentration mapping of the Rhône valley aquifer between Sierre and Vétroz. Sampling campaign during high water 1995 (245 values). Data regionalization by linear Kriging (*Surfer 7* - grid 100x100m).

5. VULNERABILITY TO POLLUTION OF THE SIERRE-VÉTROZ ZONE

One of the most recent definitions of vulnerability defines it "as an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and\or natural impacts" [Vrba and Zaporozec, 1994]. The authors admit several types of vulnerability exist. The term of "intrinsic (or natural) vulnerability" is characterized by hydrogeologic factors : the characteristics of an aquifer as well as the overlying soil and geological materials. Apart from the intrinsic properties defined above "integrated vulnerability" includes the potential impacts of specific land uses, that is the sites of risk. "specific vulnerability" defines the vulnerability of an aquifer to the pollution according to specific characteristics of a particular type of pollutant.

5.1 Methods

The techniques can be grouped into three basic groups : hydrogeological setting methods, parametric methods, and analogical relation and numerical model methods. In this study we concentrated on four parametric system methods that may be divided into : (a) matrix systems (MS ; NLFB), (b) rating systems (RS ; GOD), and (c) point count system models (PCSM ; DRASTIC and SINTACS).

NLFB is a parameter method of "matrix system type" that assesses vulnerability by two variables [Hartlé, 1989] : depth of groundwater (D) and overall lithology of aquifer or aquitard (O). The final index is obtained from the formula :

$$I_v = D + O$$

GOD is a rating system method that assesses the vulnerability using three variables [Foster, 1987] : groundwater occurrence (G), overall lithology of aquifer or aquitard (O) and depth to groundwater table (D). The final index is obtained from the formula :

$$I_v = G \cdot O \cdot D$$

DRASTIC is a parameter weighting and rating method that assesses the vulnerability according to seven parameters [Aller and al., 1987] : depth of groundwater (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of the vadose zone media (I) and the hydraulic conductivity of the aquifer (C). The vulnerability index is obtained from the following equation :

$$I_v = D_R D_W + R_R R_W + A_R A_W + S_R S_W + T_R T_W + I_R I_W + C_R C_W$$

where : I_v = Pollution potential, R = rating and W = weight

SINTACS is a parameter weighting and rating method that assesses the vulnerability according to seven parameters [Civita, 2000] : depth of groundwater (S = Soggiacenzia), net recharge (I = infiltrazione), impact of the vadose zone media (N = effeto di autoepurazione del non-saturo), soil media (T = typologia della copertura), aquifer media (A = caratteristiche idrogeologische dell'acquifero), hydraulic conductivity of the aquifer (C = conductibilità dell'acquifero) and, topography slope (S = l'acclivita della superficie topografica). The vulnerability index is obtained from the following equation :

$$I_v = \sum_{j=1}^{7} R_j W_j$$

where : I_v = Pollution potential, R = rating and W = weight

5.2 Results and comparison

In order to compare the maps of vulnerability to pollution resulting from the four methods, five identical vulnerability classes have been chosen : Very Low, Low, Moderate, High and Very High. Furthermore, the surface occupied by each class has been computed and transformed in percentage. These figures are consigned in Table 1

VULNERABILITY	% area (NLFB)	% area (GOD)	% area (DRASTIC)	% area (SINTACS)
Very High	4.0	6.1	9.0	2.1
High	5.2	27.3	44.4	21.1
Moderate	29.1	29.4	36.0	69.5
Low	12.1	11.3	9.7	7.3
Very Low	49.6	26.0	0.9	0.1
	100.0	100.0	100.0	100.0

Table 1: Percentage of surface according to the degree of vulnerability by NLFB, GOD, DRASTIC and SINTACS methods.

The following comments can be made :

- The vulnerability for NLFB is concentrated between Very Low and Moderate (90%) with 50% for Very Low and 30% for Moderate (Fig. 9).
- GOD method has more or less homogenous classes between Very Low and High and is comparable to NLFB method. Both are intrinsic methods. Nevertheless, the area occupied by the class High vulnerability is 5 times higher than for NLFB

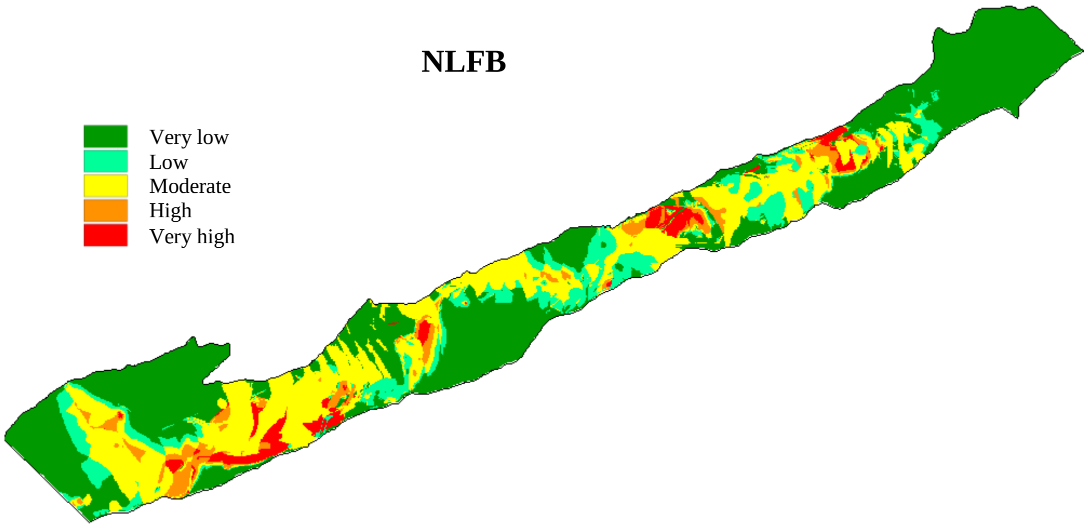

Figure 9 : Map of intrinsic vulnerability according to NLFB method. Zone Sierre-Vétroz. Grid: 25 x 25 m.

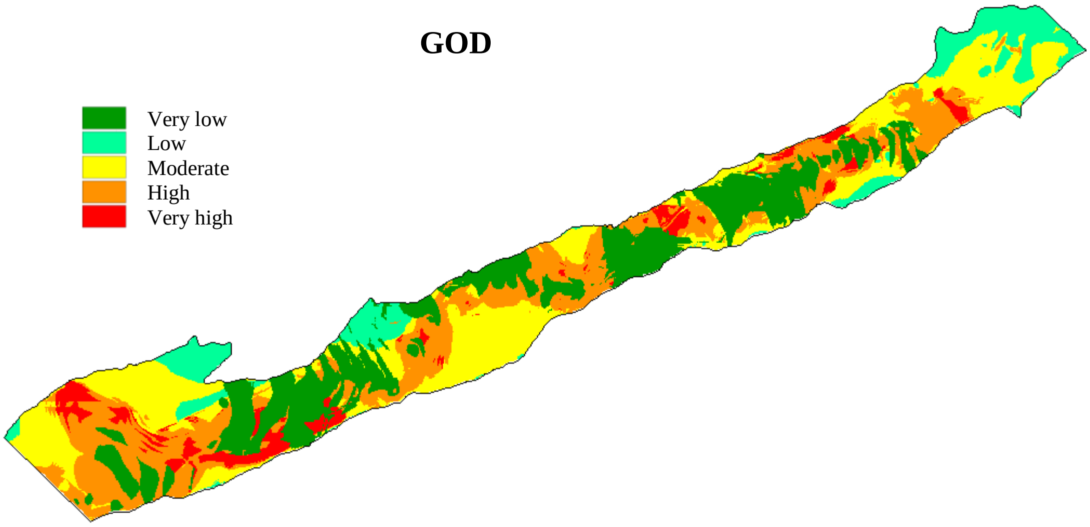

Figure 10 : Map of intrinsic vulnerability according to GOD method. Zone Sierre-Vétroz. Grid : 25 x 25 m.

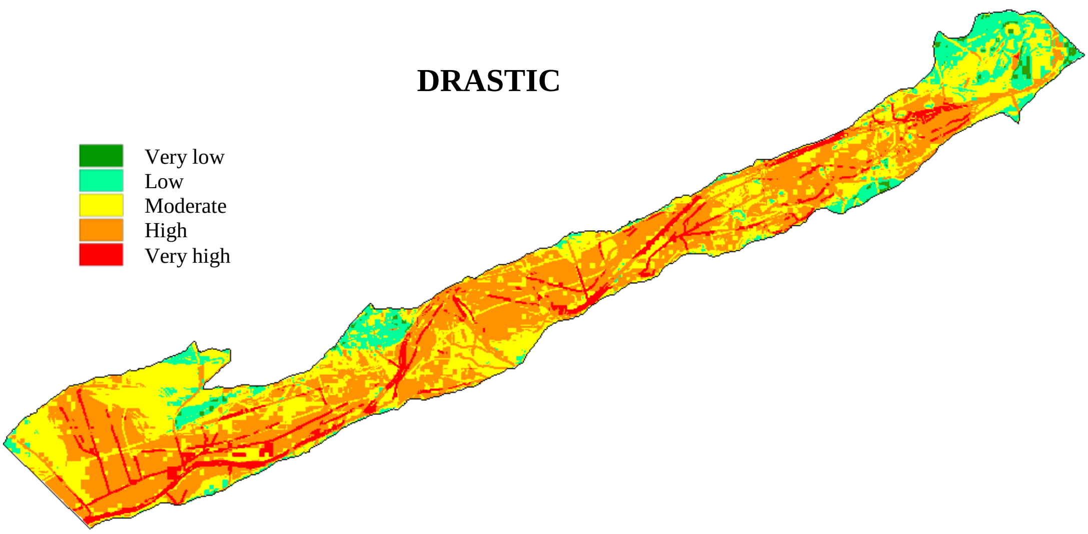

Figure 11 : Map of integrated vulnerability according to DRASTIC method. Zone Sierre-Vétroz. Grid : 25 x 25 m.

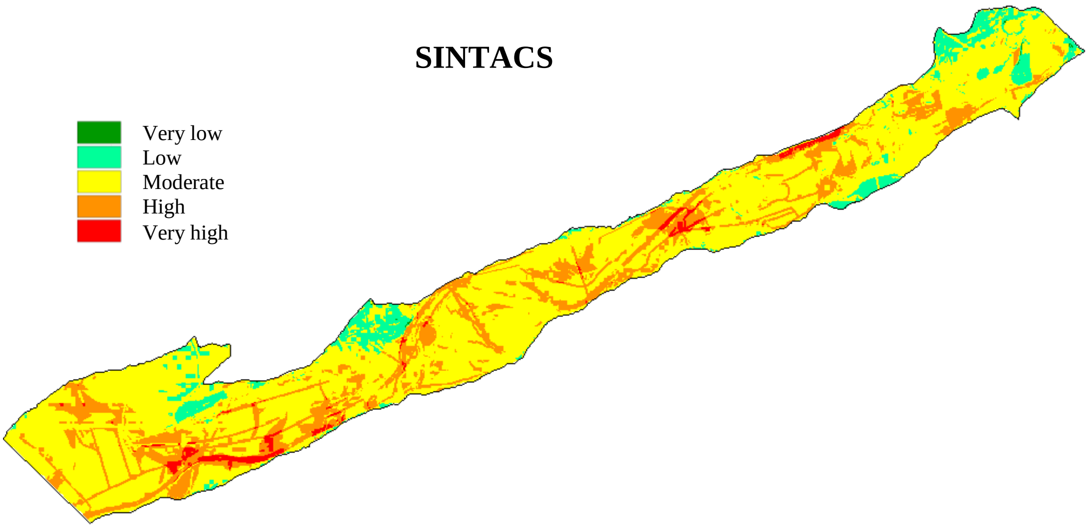

Figure 12 : Map of integrated vulnerability according to SINTACS method. Zone Sierre-Vétroz. Grid : 25 x 25 m.

method. This explains by the fact that GOD accounts the type of aquifer (unconfined or confined) and gives a high weight to unconfined aquifer (Fig. 10).

- DRASTIC method shows a shifted vulnerability towards Moderate and High (80%) by contrast with NLFB and GOD (Fig. 11). This explains by the fact that this method accounts the land use. It is easy to recognize on the vulnerability map the hydrographic network (Very High) and the areas where agriculture is important (High).
- The same remarks can be made for SINTACS (Fig. 12) method than for DRASTIC method. 90% of the vulnerability is concentrated between Moderate and High with 70% for the Moderate class. These 70% of Moderate vulnerability can be compared with the 50% of Very Low for NLFB method.
- DRASTIC and SINTACS integrated methods are concentrated between Moderate and High vulnerability when NLFB and GOD intrinsic methods are concentrated between Very Low and Moderate. Intrinsic methods have the tendency to minimize the vulnerability.
- It can be noticed that the Very High class is weakly represented for each method.

A comparison of the intrinsic (NLFB, GOD) and integrated (DRASTIC, SINTACS) methods show that the integrated methods result in groundwater pollution vulnerability maps with values which are higher than those produced by the intrinsic methods. This is explained as a result of the following : 1) integrated methods account for land use, therefore in this region of intense economic and agricultural activities and with a dense hydrographic network (rivers and canals) that will have as a consequence to increase the vulnerability values and 2) the fact to use raster land use data on a grid of 100x100 m while the precision of the DEM is of 25 m will have as a consequence to overestimate the areas of high vulnerability.

6. CONCLUSIONS

The realization of this study has shown the importance of GIS tool either for the computing and mapping of the first piezometric map between Brig and Léman Lake or the elaboration of vulnerability maps. The geostatistic tool was also intensively used all over the spatial treatment of data.

The study of the Rhône exceptional flood at the end of September 1993 demonstrated its direct influence on groundwaters. Furthermore, the measurements and the physico-chemical analyses indicate that the infiltration of the river create essentially in left shore an effect of dilution of waters of the alluvial aquifer.

The comparison of groundwaters NO_3^{--} content, established for the years 1985 and 1995 to study its evolution, has shown that globally, and with the exception of some atypical points, the nitrates content in the groundwater is low (< 30 mg/l for 90 % of samples), in a region where the agricultural is significant. The pollution by percolation through the non-saturated zone remains weak probably due to the fact that precipitations in this region are very low (about 570 mm/y). It is however necessary to notice that the evolution of the NO_3^{--} content degrades during time. The number of points where the content is > 50 mg/l has doubled in the space of ten years, passing from 3 % to 6 %.

The study of vulnerability to pollution for the aquifer situated between Sierre and Vétroz as shown significant differences between the four different methods used. As main results DRASTIC and SINTACS integrated methods are concentrated between Moderate and High vulnerability when NLFB and GOD intrinsic methods are concentrated between Very Low and Moderate. Intrinsic methods have the tendency to minimize the vulnerability.

Finally, for future works we plan to account the hydrodynamic of the aquifer in the study of vulnerability to pollution. This will be done in incorporating as a new factor other variables as Darcy's velocity or dispersivity. These variables will be provided by the results of either hydrodynamic or transport numerical models.

Acknowledgments : This study was funded by the Swiss National Foundation for Scientific Research (research project N° 21-39357.93 and 20-47064.96)

7. REFERENCES

Aller L., Bennett T., Lehr J.H., Petty R.J. & Hackett G. 1987. *DRASTIC : A standardised system for evaluating ground water pollution potential using hydrogeologic settings*. EPA, Ada, Oklahoma, 622 p.

Aviolat P. & Rey J.-M. 1995. *Hydrogéologie de la plaine alluviale du Rhône entre Sierre ouest et Granges (VS, Suisse)*. Bull. d'Hydrogéol. de Neuchâtel N° 14 : p. 243-244, Editions Peter Lang, Berne.

Bouzelboudjen M., Kimmeier F., Rossier Y., Eisenlohr L., Király L., Zwahlen F. 1998. *Impact des changements climatiques sur le comportement des systèmes aquifères*. Projet Fonds National de la recherche Scientifique Suisse (PNR31, Berne), 136 p., 46 fig., 24 tabl. V/dIf Hochschulverlag AG an der ETH Zürich, Suisse.

Bouzelboudjen M., Kimmeier F., 1998. *GIS vector and raster database, advanced geostatistics and 3-D groundwater flow modelling in strongly heterogeneous geologic media : an integrated approach*. In : The Eighteenth annual ESRI user conference, San Diego, California (USA), 5 p., 18 fig.

Civita M, De Maio M., 2000. *Valutazione e cartografia automatica della vulnerabilità degli acquiferi all'inquinamento con il sestema parametrico. SINTACS R5 a new parametric system for the assessment and automatic mapping of ground water vulnerability to contamination*. QTPA, Q.d.t.d.p.a., vol. 72, Pitagora Editrice, Bologna, 219 p.

Delhomme J.P, 1979. *Spatial Variability and Uncertainty in Grounwater Flow Parameters* : *A geostatistical Approach*. Water Resources Research 15 (2), p. 269-280.

Ebener S., Bouzelboudjen M., Wildi W.,1998. *Eléments hyrogéologiques dans l'étude de l'influence de deux décharges sur le système aquifère de la plaine du Rhône (Valais central, Suisse)*. Archs Sci. Genève Vol. 51, Fasc. 2, pp. 153-170.

ESRI, 1997. *Understanding GIS. The Arc/Info Method*. Version 7 for Unix and Open VMS. Environmental Systems Research Institute, California, USA. Wiley & Sons, New York.

ESRI, 1996. *ArcView GIS, The Geographic Information System for Everyone*. Environmental Systems Research Institute, California, USA.

Foster S.S.D, 1987. *Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy*. Atti Int. Conf. Vulnerab. of soil and Groundw. to Pollutants, RIVM Proc. and Inf. 38. pp. 69-86.

Gennai A., Margat J., Collin J.-J., 1993. *Cartographie de la résistance à la sécheresse des systèmes aquifères à nappe libre*. Rapport inédit BRGM, Orléans, 13 fig., 5 tabl., 5 ann.

Geovariances, 1998. *Isatis 3, The Geostatistical key*. User's Guide, Avon, France.

Golden software, 1999. *User's guide. Surfer For windows, version 7*. Golden software, Inc.

Haertlè T., 1983. *Method of working and employment of EDP during the preparation of groundwater vulnerability maps*. Groundwat. in Wat. REs. Planning, IAHS 142. pp. 1073-1085.

Marsh T.-J., Monkhouse R.A., Arnell N.W., Lees M.L. & Reynard, N.S., 1994. *The 1988-92 Drought*. Institute of Hydrology, British Geological Survey, 78 p.

Matheron G., 1970. *La théorie des variables régionalisées et ses applications*. Centre de Géostatistique, Ecole des Mines de Paris, Fascicule 5, 211 p.

Microsoft, 1997. *User's Guide. Microsoft Access. Relational Database System*. Microsoft Corporation.

Ornstein P., 1996. *Méthodologie d'étude d'un système aquifère dans une vallée alluviale en milieu alpin : exemple de la vallée du Rhône, Valais central*. Swiss National Foundation for Scientific Research (research project N° 21-39357.93 and 20-47064.96, unpublished).

Schürch M. 2000. *Tranchée couverte de Champsec (Valais central, Suisse) : étude hydrogéologique et modélisation mathématique 2-D par éléments finis*. Bull. d'Hydrogéol. de Neuchâtel N° 18 : p. 63-76, Editions Peter Lang, Berne.

Vrba J. & Zaporozec, A. 1994. *Guidebook on Mapping Groundwater Vulnerability*. Int. Assoc. Hydrogeol. 16, 131 p.

Weber I., 1998. *Comparaison de cinq méthodes d'évaluation de la vulnérabilité des aquifères à la pollution : application à la région Sierre-Vétroz (Valais, Suisse)*. Bull. d'Hydrogéol. de Neuchâtel N° 18 : p. 273-274, Editions Peter Lang, Berne.

Corresponding author : Francesco Kimmeier, Institut de Géologie, Centre d'Hydrogéologie, Université de Neuchâtel, 11 rue Emile-Argand, 2007 Neuchâtel.
Tél : +4132/718.26.30 - Fax : +4132/718.26.03
E-mail : francesco.kimmeier@unine.ch

Annex 1: Summary of the coverages implemented in the geographical database.

Coverages	Kind of spatial object	Data format	Data source / owner	Scale	Acquisition type
Hydrographic network	lines (arcs)	Vector	Swiss national map / SNSF project N°21.39357	1 : 25'000	Digitalization by scanner
Lakes, glaciers, wet zones	zones (polygons)	Vector	Swiss national map / SNSF project N°21.39357	1 : 25'000	Digitalization by scanner
Communication ways	lines (arcs)	Vector	Swiss national map / SNSF project N°21.39357	1 : 25'000	Digitalization by scanner
Agglomerations	zones (polygons)	Vector	Swiss national map / SNSF project N°21.39357	1 : 25'000	Digitalization by scanner
Water catchment for potable water supply (sources and wells)	points	Vector	Cantonal Service of Environmental Protection (Sion)	1 : 25'000	AUTOCAD export file
Provisory and definitive protection Zones	zones (polygons)	Vector	Cantonal Service of Environmental Protection (Sion)	1 : 25'000	AUTOCAD export file
Boundary catchments (from Hydrological Atlas of Switzerland)	zones (polygons)	Vector	SNHGS Swiss National Hydrological and Geological Survey	1 : 500'000	Export file Arc/Info
Old river reach of the Rhône	lines (arcs)	Vector	Cantonal Archives of the Valais state / SNSF project N°21-39357	1 : 50'000	Digitalization by scanner
Old wet zones	zones (polygons)	Vector	Valais state - Cantonal Office of cadastral mensuration	1 : 5'000 1 : 10'000	Digitalization by scanner
Land use map grid: 25x25 m (24 modes of utilisation)	zones (polygons)	Raster	Federal Office of Statistics Database GEOSTAT		Export file Arc/Info
Digital Elevation Model (DEM) (partial)		Raster	Federal Polytechnical School of Lausanne (EPFL) / Federal Office of Topography	1 : 25'000	IDRISI image file

SNSF = Swiss National Science Foundation,