

Drought risk analysis applied to porous Swiss aquifers

Francesco Kimmeier¹, Mahmoud Bouzelboudjen¹,
Laurent Eisenlohr², Yvan Rossier³

¹ CHYN - Centre d'Hydrogéologie, Université de Neuchâtel, Emile-Argand 11, 2007 Neuchâtel, Suisse

² CETE Environnement, 25 avenue François Mitterrand, Case n°1 F-69674 BRON Cedex France

³ ATE, 17 rue du Perigord, 69330 Meyzieu, France.

ABSTRACT

The impact of hydrogeological drought on groundwater has been studied in the context of natural flow systems. The aim of this article is to find the relative resistance of 18 unconfined aquifer systems in porous media to a prolonged shortfall in recharge. A synthetic relative drought resistance indicator has been calculated for each of the aquifer systems based on 4 variables which are the half-recession time, the specific regulatory capacity, the drainage density and the aquifer system area.

The analysis shows that 33% of the chosen aquifer systems are weakly resistant. By contrast, 22% have a high drought resistance. The other aquifer systems are of moderate resistance (22%) or of good resistance (22%).

Keywords : Hydrogeologic resistance, alluvial aquifer, porous medium, stage hydrograph, recession, Switzerland.

1. INTRODUCTION

No region in Europe is safe from hydrogeological drought, or less so, from a prolonged precipitation shortage [Grillot & Razack 1983, Margat 1989, Gennai and al. 1993, Marsh and al. 1994]. The droughts in Europe are specifically of random character, non-seasonal and often localized by the division of the landscape. According to the season in which a drought occurs, the latter will have variable aspects and wide ranging socio-economic consequences [Zilliox 1992].

One can consider there to be a drought when there is a significant shortage in water supply, over a sufficiently long period (seasonal, annual, or pluriannual) in comparison to the averages (of at least 10 years) and over a sufficiently large area.

The impact of extreme climatic variations, droughts and floods, on the regime and chemical quality of groundwaters can be important [Bouzelboudjen, Kimmeier and al. 1997, Bultot and al. 1988, Cooper and al. 1995, Eagleson 1996].

For a decade, global scale studies have shown an increase in the concentration of carbon dioxide and rare gases [Clark 1982]. One of the consequences of these increases is a climate change which is shown by an increase in temperatures [Berger

1981, Marsh and al. 1994], by a change in precipitation patterns [Washington and Mehl 1983] and finally by changes in parameters linked to sunshine [Chou and al. 1982].

Only recently have studies tried to show the impact of these climatic changes on natural resources at a local or a regional scale [Gleick 1989]. Most of these studies do not mention the effects on groundwater, with only a small number dealing with the impact of climatic modifications at a large scale on water resources [Zekster and Loaiciga 1993]. We should nevertheless mention the local study of Wilkinson and Cooper from 1993, which gives indications on the impact of climatic changes on a few aquifers in England.

This contribution aims to study the reaction of unconfined aquifer systems faced with a prolonged shortfall in recharge. We have developed a synthetic relative hydrogeologic drought resistance indicator to do this for 18 porous aquifer systems in Switzerland.

2. MATERIALS AND METHODS

2.1 Material

We have used 25 piezometers spread all over Switzerland with daily records over 10 to 15 years (Fig. 1 and 2). We have also chosen 20 rain gages in the neighborhood of the piezometers to be able to identify the drought periods.

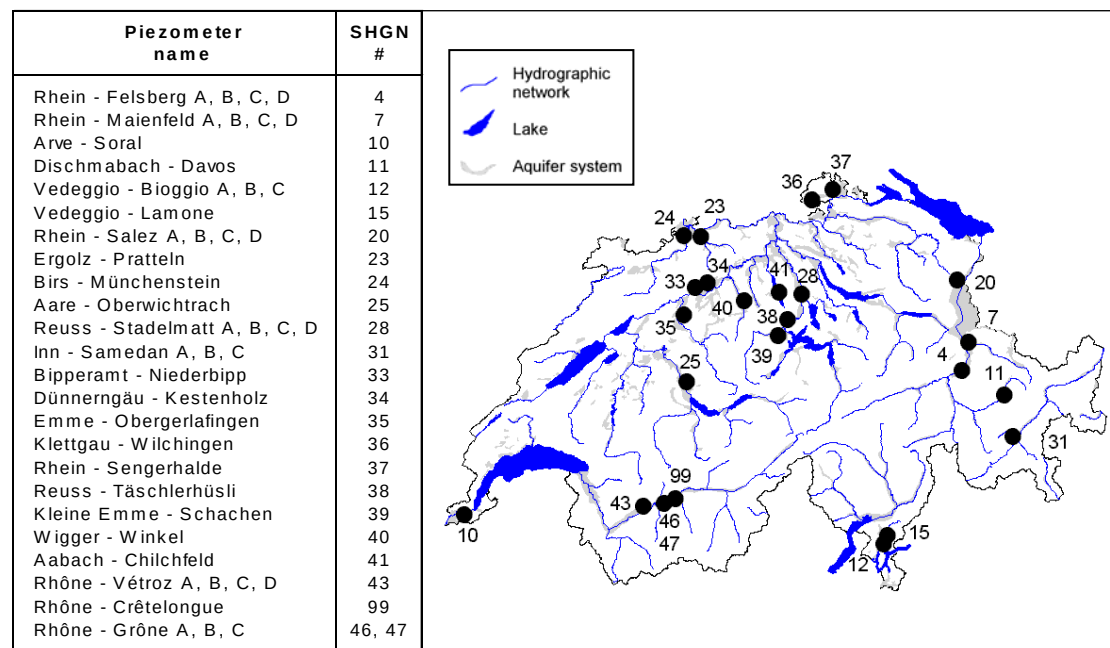


Figure 1: Location of the 25 piezometers used for the drought resistance study of the 18 aquifer systems in porous media.

We have chosen piezometers from the Swiss National Network (SHGN : Service Hydrologique et Géologique National) as much as possible [Buttet and Eberhard, 1995], which show the regional conditions of the aquifer system as well as possible. The piezometers too near to fixed level limits have been discarded.

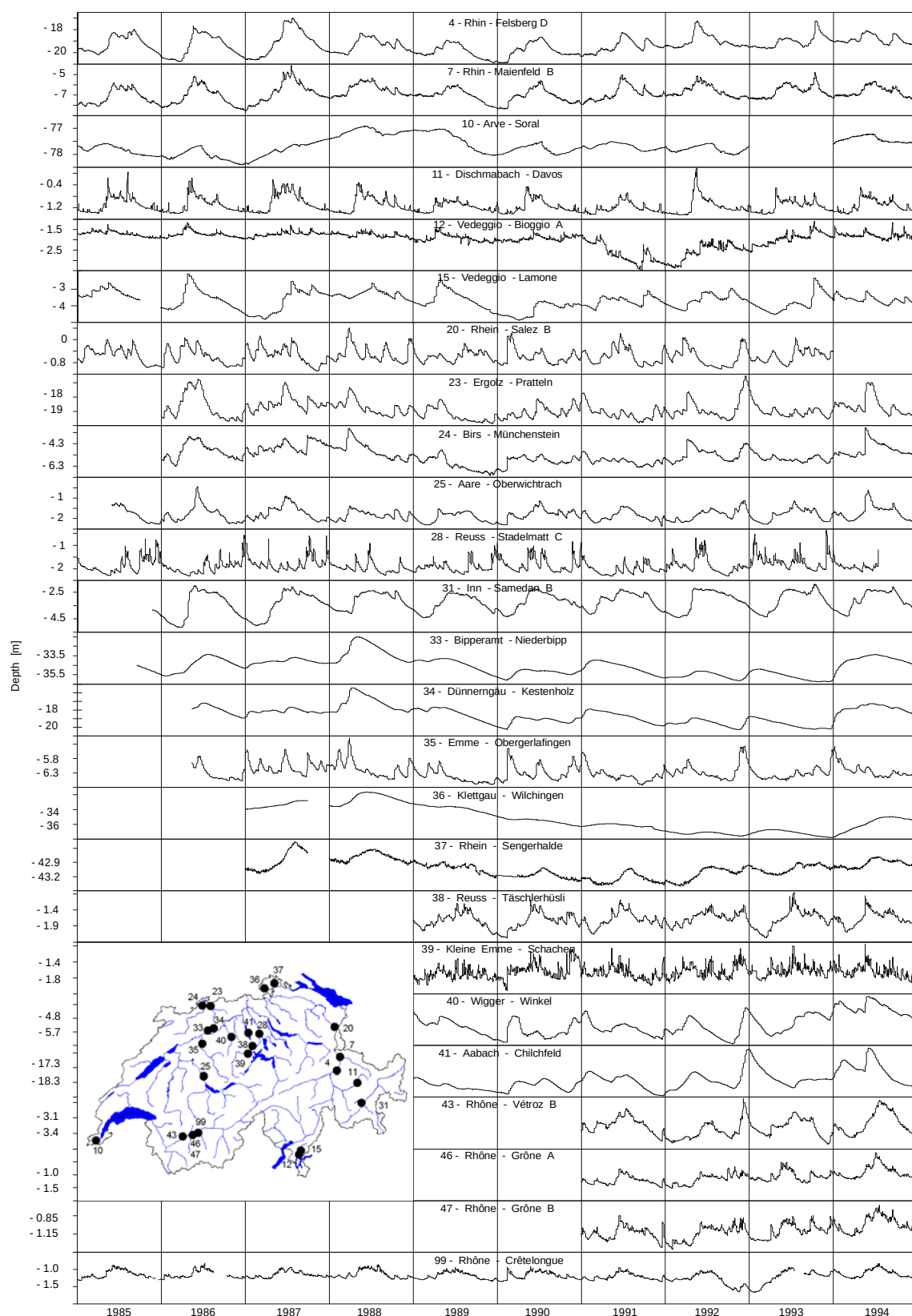


Figure 2: Daily stage hydrographs for the 25 selected piezometers in porous media (see locations in figure 1).

Figure 2 shows the principal characteristics of the form of the stage hydrographs used and the difference in resistance of these systems to drought.

From 1989 to 1993, (piezometer 36) and from 1989 to 1992 (piezometer 37) we detect between 4 and 5 successive years with a falling trend of the water table of Wilchingen and Sengerhalde. Similar characteristics are seen for piezometer 33 (Bipperamt) and piezometer 34 (Dünnergau) set in the Gaü groundwater body.

A second noticeable fact is the high incidence due to the deficit year of 1988-89. Nearly half the piezometers show a strong fall in level. The incidence of the shortage year 1992 on groundwater is generally less significant.

The incidence of the surplus year of 1987 on groundwater is marked in 3 piezometers (4, 7 and 37). These piezometers show significant recharge. Otherwise, 11 of the 18 aquifers show no effect whilst in 3, the incidence is retarded.

Aquifer systems with an annual regime without any noticeable pluri-annual trend are found at piezometers 4, 7 and 31.

For the aquifers linked to the Rhine (piezometers 4 and 7) and to the Rhône (piezometers 43, 46, 47, and 99) the levels stay generally stable over the whole recorded period.

A special regime is seen for the groundwater aquifers whose levels are shallow, linked to the fact that the imposed capacity limits are very close (piezometers 11, 12, 28, 38 and 39). Figure 3 shows that more than half of the piezometers indicate an unconfined aquifer level of less than 5 meters depth. Moreover, figure 3 shows the pluriannual cycle (extreme minimum and maximum values) of the aquifer systems.

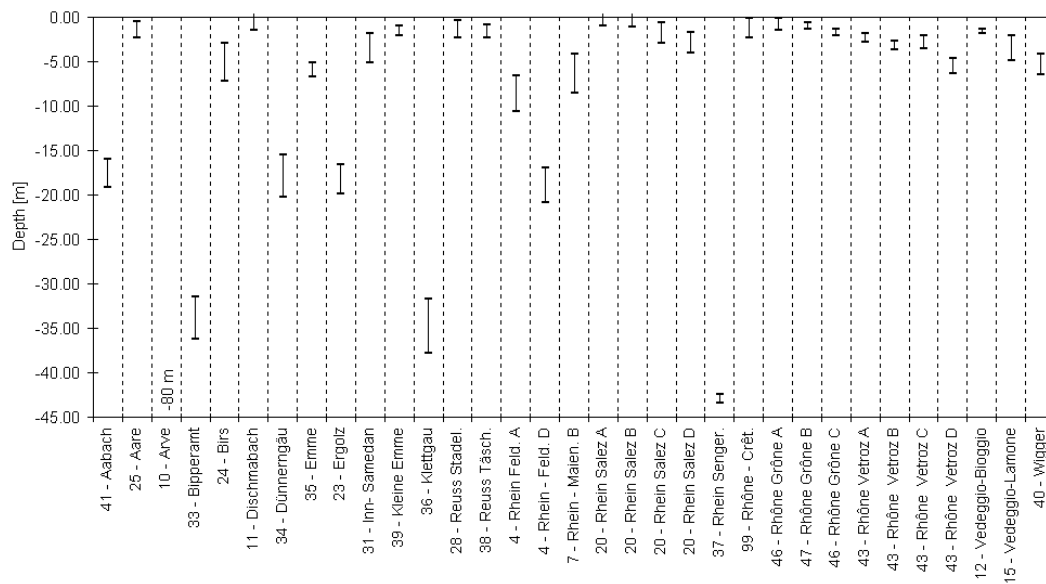


Figure 3: Depth and movements of the free groundwater surface of the 18 Swiss aquifers.

2.2 Method

To calculate the synthetic relative drought resistance indicator (SRDRI) of aquifer systems during a prolonged recharge shortage, we need piezometric records, on average over 10 to 15 years.

The SRDRI [Gennai 1992, Gennai and al. 1993, Fig. 4) which defines the relative resistance of aquifer systems to drought is determined by the following equation:

$$\text{SRDRI} = 5(T/2) + 2(\text{SRC}) + 1(\text{DD}) + 1(\text{A}) \quad (1)$$

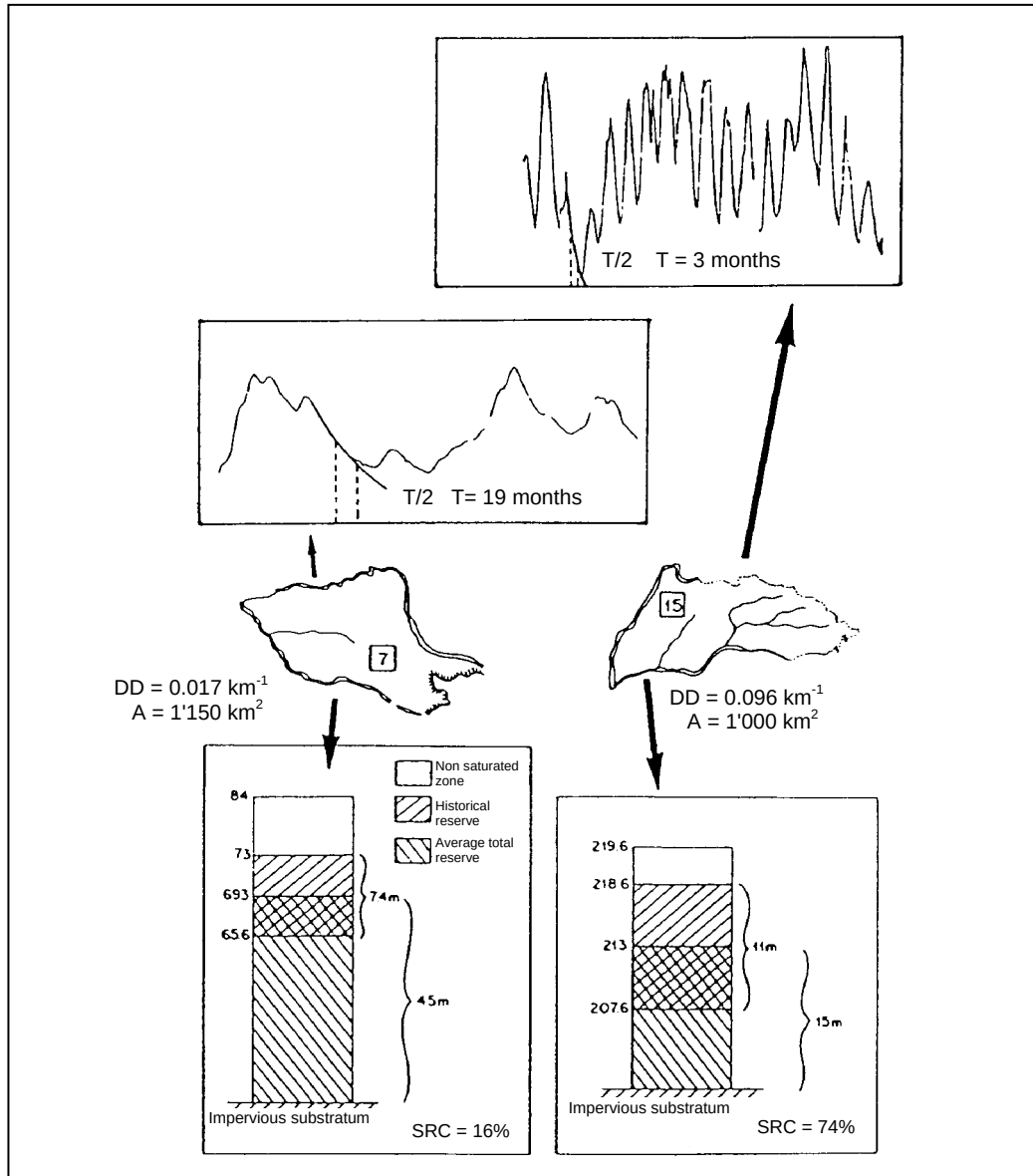


Figure 4: Illustration of the 4 variables for the study of the relative drought resistance of the aquifer systems: examples of application in Northern France [Gennai, Margat and Collin, 1993]

The 4 variables in the formula are defined as follows:

$T/2$ = the half recession time (in months) and is found by hydrogram analysis [Birtles 1978]. The method of calculation was developed in part by Degallier 1975 and by Margat and Forkasiewicz in 1978.

SRC = the specific regulatory capacity (in %) corresponds to the ratio of the historical reserve to the total average reserve (Fig. 4).

DD = the drainage density (in km⁻¹) represents the length of the surface hydrographic network (L) divided by the area of the aquifer system ($L^{-1}/L^2 = L^{-1}$).

A = the area of the aquifer system (L²) expressed in km².

The half-recession time, which depends uniquely on the structural conditions of the aquifer system, is the most representative variable for determining the capacity of aquifer systems to resist drought [Margat and Forkasiewicz 1978, Degallier 1975, 1976, Pointet 1975].

The specific regulatory capacity is well representative of the groundwater body dynamics, in other words the regulatory potential of the aquifer. This is the most difficult variable to evaluate as a function of the available database.

The area and the drainage density of the aquifer system are variables of less importance, but which nevertheless allow one to separate aquifer systems whose SRDRI values would be too close if one only considered half recession times and specific regulatory capacity.

Calculation of SRDRI for each aquifer system relies on finding the magnitude of the 4 previously mentioned hydrogeologic variables.

The values found for each variable have to be divided into homogeneous groups of number and intensity of observed phenomena, which allows the characterization of hydrogeological drought. 4 classes have been chosen to show increasing drought resistance (weak, moderate, good, and high). The weighting factors (see equation 1) used for the SRDRI calculation of each variable are given arbitrarily, and according to the previous considerations as follows:

Variables	Weighting factor
Half recession time (T/2)	5
Specific regulatory capacity (SRC)	2
Drainage density (DD)	1
Area (A)	1

Table 1: Weighting factors of the 4 variables.

3. APPLICATION OF THE METHOD IN SWITZERLAND

3.1 Half recession time (T/2)

In table 2 we have divided results into 4 classes. For a high recession value, there is a corresponding high drought resistance (class 4 with a half recession time greater than 6 months). The piezometric records used show that 40% of the aquifer systems are weakly resistant to drought and 20% have moderate resistance. 24% of aquifers show good resistance whilst 16% show high resistance (Fig. 5).

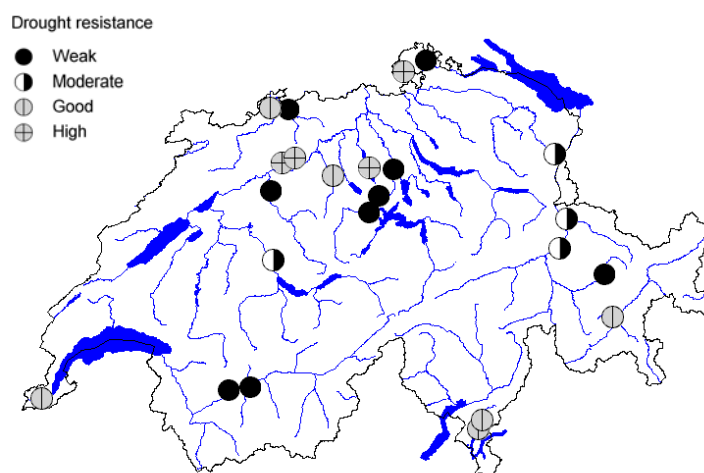


Figure 5: The relative drought resistance of the 18 Swiss aquifer systems using only the half recession time (months).

Half-Recession Time T/2 [month]		Min 0.4 Max 7.2 Average 3.1 Classification: high drought resistance for high T/2				
Classification	Class value	Class designation	Aquifer system #	Piezometer #	Piezometer name	T/2 value
1	≤ 1.5	Weak S=10 => 40%	18	47	Rhône - Grône B	0.4
			18	43	Rhône - Vétroz B	0.4
			15	39	Kleine Emme - Malters, Schachen	0.5
			9	28	Reuss - Hüenenberg, Stadelmatt C	0.6
			9	38	Reuss - Emmen, Täschlerhüsli	0.7
			3	11	Dischmabach - Davos, Boden	0.7
			18	99	Rhône - Crêtelongue - Valais	0.9
			14	37	Rhein - Shaffhausen, Sengerhalde	1.0
			12	35	Emme - Obergerlafingen	1.2
			6	23	Ergolz - Pratteln	1.3
2	1.5-3	Moderate S=5 => 20%	5	20	Rhein - Sennwald, Salez B	1.6
			1	7	Rhein - Maienfeld B, année 1989	1.7
			8	25	Aare - Oberwichtlach	2.0
			1	4	Rhein - Felsberg D	2.2
			1	7	Rhein - Maienfeld B, année 1986	2.3
3	3-6	Good S=6 => 24%	4	12	Vedeggio - Bioggio A	4.4
			7	24	Birs - Münchenstein	4.7
			10	31	Inn- Samedan B	5.2
			4	15	Vedeggio - Lamone	5.4
			16	40	Wigger - Nebikon, Winkel année 1989	5.5
			2	10	Arve - Soral	6.0
4	> 6	High S=4 => 16%	13	36	Klettgau - Wilchingen, Tobel	6.5
			17	41	Aabach - Ermensee, Chilchfeld	7.1
			11	34	Dünnergau - Kestenholz	7.1
			11	33	Bipperamt - Niederbipp, Autobahn	7.2

Table 2: Classification of the 18 Swiss aquifer systems according to half-recession times (HRT in months).

3.2 Specific Regulatory Capacity (SRC)

In table 3, we see that the drought resistance is higher as the regulatory capacity is lower. The values are distributed into 4 classes expressed as percentages. 22% fall into the high resistance category, 39% into good resistance and 17% and 22% respectively in the moderate and weak resistance categories.

Specific Regulatory Capacity SRC [%]		Min 1.3% Max 86% Average 17.1% Classification : high drought resistance for weak SRC				
Classification	Class value	Class designation	Aquifer system #	Piezometer #	Piezometer name	SRC value
4	≤ 4	High Σ=4 => 22%	16	40	Wigger - Nebikon, Winkel année 1989	2.4
			1	4	Rhein - Felsberg D	2.7
			18	99	Rhône - Crêtelongue - Valais	3.0
			5	20	Rhein - Sennwald, Salez B	3.6
3	4-12	Good Σ=7 => 39%	12	35	Emme - Obergerlafingen	4.1
			14	37	Rhein - Shaffhausen, Sengerhalde	4.2
			10	31	Inn- Samedan B	4.2
			15	39	Kleine Emme - Malters, Schachen	5.8
			3	11	Dischmabach - Davos, Boden	8.7
			2	10	Arve - Soral	9.9
			11	34	Dünnergau - Kestenholz	10.0
2	12-20	Moderate Σ=3 => 17%	13	36	Klettgau - Wilchingen, Tobel	13.7
			8	25	Aare - Oberwichtlach	15.2
			17	41	Aabach - Ermensee, Chilchfeld	17.5
1	> 20	Weak Σ=4 => 22%	9	28	Reuss - Hüenenberg, Stadelmatt C	22.4
			4	12	Vedeggio - Bioggio A	24.6
			6	23	Ergolz - Pratteln	53.7
			7	24	Birs - Münchenstein	85.5

Table 3: Classification of the 18 Swiss aquifer systems according to their specific regulatory capacity (SRC in %).

3.3 Drainage Density (DD)

The drought resistance is high for a low drainage density. The aquifer systems studied (table 4) show 33% of cases with a high resistance against 17% with good resistance, 17% moderate resistance and 33% low resistance.

Drainage Density DD [km ⁻¹]		Min 0.5 Max 2.7 Average. 1.4 Classification : high drought resistance for weak DD				
Classification	Class value	Class designation	Aquifer system #	Piezometer #	Piezometer name	DD value
4	≤1	High Σ=6 => 33%	14	37	Rhein - Shaffhausen, Sengerhalde	0.6
			2	10	Arve - Soral	0.6
			1	4	Rhein - Felsberg D	0.7
			7	24	Birs - Münchenstein	0.7
			5	20	Rhein - Sennwald, Salez B	0.7
			11	34	Dünnergau - Kestenholz	0.8
3	1.0-1.4	Good Σ=3 => 17%	13	36	Klettgau - Wilchingen, Tobel	1.0
			8	25	Aare - Oberwichtlach	1.2
			17	41	Aabach - Ermensee, Chilchfeld	1.4
2	1.4-1.8	Moderate Σ=3 => 17%	12	35	Emme - Obergerlafingen	1.6
			18	43, 99	Rhône - Vétroz B + Crêtelongue	1.6
			16	40	Wigger - Nebikon, Winkel année 1989	1.7
1	> 1.8	Weak Σ=6 => 33%	9	28	Reuss - Hünenberg, Stadelmatt C	1.9
			6	23	Ergolz - Pratteln	2.2
			15	39	Kleine Emme - Malters, Schachen	2.3
			10	31	Inn- Samedan B	2.4
			4	15, 12	Vedeggio - Lamone + Bioggio A	2.7
			3	11	Dischmabach - Davos, Boden	3.3

Table 4: Classification of the 18 Swiss aquifer systems according to their drainage density (DD in km).

3.4 Aquifer system area (A)

The aquifer system area was determined using 1:100,000 scale hydrogeological maps. In table 5 we have divided the results into 4 classes of increasing drought resistance. This classification gives 22% weakly resistant, 33% moderate resistance, 22% good resistance and 22% high resistance.

Aquifer system area A [km ²]		Min 4.0 Max 788.5 Average 108.4 Classification : high drought resistance for high A				
Classification	Class value	Class designation	Aquifer system #	Piezometer #	Piezometer name	A value
1	≤20	Weak Σ=4 => 22%	3	11	Dischmabach - Davos, Boden	4.0
			4	12	Vedeggio - Bioggio A	8.6
			17	41	Aabach - Ermensee, Chilchfeld	8.6
			7	24	Birs - Münchenstein	18.9
2	20-50	Moderate Σ=6 => 33%	15	39	Kleine Emme - Malters, Schachen	22.3
			6	23	Ergolz - Pratteln	23.8
			10	31	Inn- Samedan B	24.6
			2	10	Arve - Soral	30.0
			14	37	Rhein - Shaffhausen, Sengerhalde	36.7
			11	34	Dünnergau - Kestenholz	46.9
3	50-80	Good Σ=4 => 22%	13	36	Klettgau - Wilchingen, Tobel	57.3
			16	40	Wigger - Nebikon, Winkel année 1989	60.4
			9	28	Reuss - Hünenberg, Stadelmatt C	61.1
			8	25	Aare - Oberwichtlach	64.0
4	> 80	High Σ=4 => 22%	18	99	Rhône - Crêtelongue - Valais	113.4
			1	4	Rhein - Felsberg D	144.3
			12	35	Emme - Obergerlafingen	202.4
			5	20	Rhein - Sennwald, Salez B	788.5

Table 5: Classification of the 18 Swiss aquifer systems according to their area (A in km²).

3.5 Drought resistance of 18 porous aquifer systems in Switzerland

The analysis shows (table 6) that 33% of the selected aquifers are weakly resistant. In contrast, 22% of the aquifer systems have a high drought resistance. The other aquifer systems are of moderate resistance (22%) or resistant (22%).

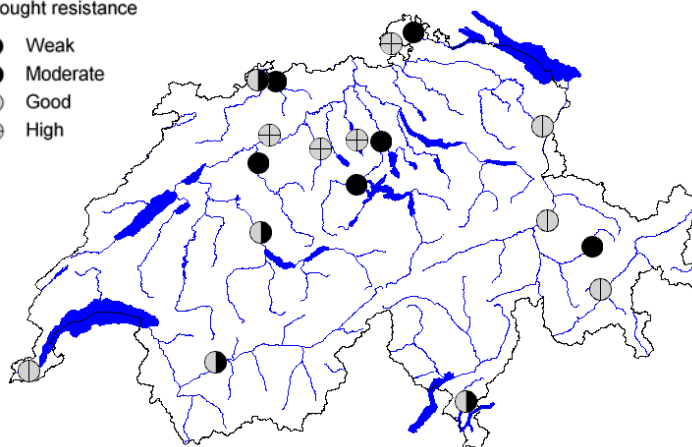
SRDRI classification	SRDRI class	Aquifer system #	Piezometer #	Piezometer name	SRDRI value
Weak $\Sigma=6$ => 33%	$SRDRI \leq 18$	6	23	Ergolz - Pratteln	10
		9	28	Reuss - Hünenberg, Stadelmatt C	11
		3	11	Dischmabach - Davos, Boden	13
		15	39	Kleine Emme - Malters, Schachen	14
		12	35	Emme - Obergerlafingen	17
		14	37	Rhein - Schaffhausen, Sengerhalde	17
Moderate $\Sigma=4$ => 22%	$18 < ISR$	4	15, 12	Vedeggio - Lamone, Bioggio A	19
		18	43, 46 47, 99	Rhône - Vétroz B + Crêtelongue	19
		8	25	Aare - Oberwichtlach	20
		7	24	Birs - Münchenstein	22
Good $\Sigma=4$ => 22%	$23 < ISR$	10	31	Inn- Samedan B	24
		1	4	Rhein - Felsberg D	26
		5	20	Rhein - Sennwald, Salez B	26
		2	10	Arve - Soral	27
High $\Sigma=4$ => 22%	$SRDRI \geq 28$	16	40	Wigger - Nebikon, Winkel année 1989	28
		17	41	Aabach - Ermensee, Chilchfeld	28
		13	36	Klettgau - Wilchingen, Tobel	30
		11	33, 34	Bipperamt + Dünnerngau	32

Table 6: Synthetic relative drought resistance indicator (SRDRI) of the 18 Swiss aquifers.

The SRDRI calculation for each unconfined aquifer system allows the drawing of a drought resistance map (Fig. 6). Due to their size and boundary conditions, the major

Drought resistance

- Weak
- ◐ Moderate
- ◑ Good
- ⊕ High



aquifer systems studied, which are the most exploited water resource in Switzerland, are relatively resistant to prolonged shortfalls in recharge.

Figure 6: Representation of the relative drought resistance of the 18 Swiss aquifer systems using all 4 variables.

4. DISCUSSIONS AND CONCLUSIONS

Due to their extent and boundary conditions, the major aquifers studied representing the most exploited water resource, are relatively resistant to climatic variations if we compare them to European aquifers.

Although the Swiss aquifer systems chosen are relatively resistant to climatic variations, it was interesting to classify them as a function of their relative resistance to prolonged recharge shortfalls.

The method of mapping of unconfined aquifer system resistance to drought was carried out in the light of all the piezometric data of the federal network. However, we have discarded piezometers too close to fixed potential limits (rivers, lakes) and/or of zero flux (nearness of watertight limits). The determination of the half recession time and of the specific regulatory capacity requires a study on the representativeness of the piezometers of the national network. In effect, these two variables are the most important in the determination of the synthetic drought resistance indicator.

Acknowledgments: This study was funded by the Swiss National Foundation for Scientific Research in the framework of National Research Programme NRP 31. Climate changes and natural disasters (research project N° 4031-33148).

5. REFERENCES

- Berger A., 1981. *Climatic variations and variability: Facts and Theories*. Nato advanced Study Institutes Series. Serie C: Mathematical and Physical Sciences. Reidel, Dordrecht, 795 p.
- Bouzelboudjen M., Kimmeier F., Rossier Y., Eisenlohr L., Király L., Zwahlen F., 1997. *Impact des changements climatiques sur le comportement des systèmes aquifères*. PNR 31 - Programme National de Recherche du Fonds National de la Recherche Scientifique (FNRS) Suisse. Changements climatiques et catastrophes naturelles. 116p, 46 fig., 24 tab., vdf, Hochschul Verlag AG, ETH Zürich.
- Birtles A.-B., 1978. *Identification and separation of Major Base Flow Components From a Stream Hydrograph*. Water Res. Research, 14, n° 5, 791-803.
- Bultot F., Coppens A., Dupriez G.-L., Gellens D., Meulenberghs F., 1988. *Repercussions of a CO₂ doubling on the water cycle and on the water balance. A case study for Belgium*. J. Hydrol. 99: 319-347.
- Buttet P., Eberhard A., 1995. *Das Eidgenössische Grundwasser Beobachtungsnetz*. Hydrologische Mitteilungen N° 22, 162s. Landeshydrologie und -geologie. Bern.
- Chou M.-D., Peng L., Arking A., 1982. *Climate Studies with a Multilayer Energy Balance Model. Part II: The Role of Feedback Mechanisms in the CO₂ Problem*. J. Atmos. Sci. 39: 2657-2666.
- Clark W.-C., 1982. *Carbon Dioxide Review*. Oxford University Press, New York, NY.
- Cooper D.-M., Wilkinson W.-B., Arnell M.W., 1995. *The effects of climate changes on aquifer storage and river baseflow*. Hydrological Sciences - J. Sc. Hydrol., 40,5, 615-631.
- Degallier R., 1975. *Interprétation des variations naturelles du niveau des nappes souterraines*. Thèse Université de Montpellier et Rapport Inédit BRGM 75 SGN 383 AME.
- Degallier R., 1976. *Interprétation des variations naturelles du niveau des nappes*. Bulletin BRGM Fr. (2), III, n° 2.

- Eagleson P.-S., 1986. *The emergence of global scale hydrology*. Water Resources Research, 22: 6-14.
- Gennai A., 1992. *Elaboration d'une carte de résistance à la sécheresse des systèmes aquifères libres: Application au Nord de la France*. Mémoire Dipl. 3ème cycle Centre d'hydrogéologie, Université de Neuchâtel, 117 p, 36 fig., 16 tabl., 3 ann.
- 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.
- Gleick P.-H., 1989. *Climate change, hydrology and water resources*. Rev. Geophys., 27: 329-344.
- Grillot J.-C., Razack M., 1983. *Evolution spatio-temporelle d'un système aquifère alluvial sous l'effet d'une sécheresse pluriannuelle exceptionnelle, littoral méditerranéen, Hérault, France*. J. Hydrol. 82 (1-2), 155-173.
- Margat J., Forkasiewicz J., 1978: *Analyse des fluctuations naturelles de niveau de nappes libres en France. Essai de prédiction déterministe de niveaux d'étiage en 1976*. Bulletin du BRGM (deuxième série). Section III, n° 3, 247-258.
- Margat J., 1989. *La sécheresse et eaux souterraines*. La Houille Blanche 7/8.
- 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.
- Pointet T., 1975. *Essai de caractérisation du coefficient de tarissement des nappes*. Thèse de Doct-Ing. Université de Nancy I, 115 p, 9 ann., 63 fig.
- Washington W. M., Mehl G. A., 1983. *General circulation model experiments on the climatic effects due to a doubling and quadrupling of carbon dioxide concentration*. J. Geophys. Res. 88 (611): 6600-6610.
- Wilkinson W.-B., Cooper D.-M., 1993. *The response of idealized aquifer/river systems to climate change*. Hydrological Sciences - J. Sc. Hydrol., 38,5, 379-390.
- Zektser I.-S., Loaiciga H. A., 1993. *Groundwater fluxes in the global hydrologic cycle: past, present and future*. J. Hydrol., 144, 405-427.
- Zilliox L., 1992. *Les ressources en eau du fossé rhénan: des études aux actions de sensibilisation*. Hydrogéologie (Orléans), n° 4, 175-179, 2 fig.

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