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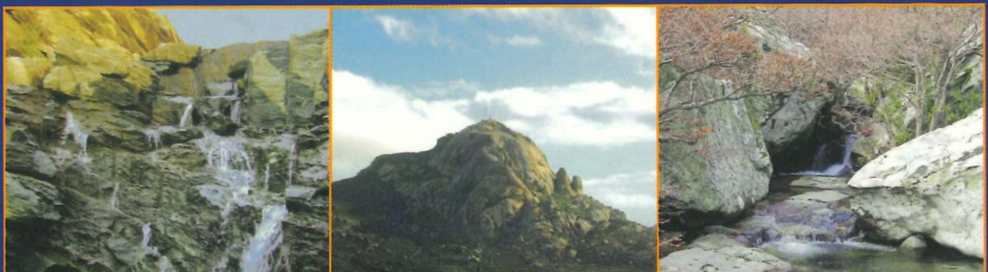

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INDEX OF AUTHORS

QUANTITATIVE ANALYSIS OF GROUNDWATER FLOW IN ALPINE ENVIRONMENT

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Abstract

Knowledge of effective groundwater resources in the Alpine Piedmont area (Italy) is typically differentiated between target areas (object of special monitoring plans of springs) and larger areas poor of quantitative and direct discharge data. The paper tries to identify a methodologic approach from local to sub-regional scale, based on a statistical-deterministic analysis, showing major relations between dynamic parameters that describe recharge and recession curves into shallow/local "slope/detritic" aquifer.

1. Introduction

Monitoring groundwater resources in Alpine catchments provide basic informations for design of recession-curve of springs, during different time-period and seasons. Estimation of groundwater resources leads to quantitative classification of spring discharge and aquifer vulnerability, designing a method that could be easily applied over large areas in order to estimate the real amount of water available for civil utilization, and foresee limitations due to climate change.

2. Use of springs in the Alpine area

Water supply from springs represent in northern regions of Italy (Piedmont) 20% of total water consumption for human use. Official databases of Public Administration contains more than 3100 records of spring-points, the estimated average discharge is about 165 Mm^3/year.

Information concerning measured volumes flowing from springs on annual basis is available for about 40% of them; yearly minimum discharge is actually unknown for more than 50% of the springs. Authomatic hydrometers are active especially in the karst springs of South Piedmont, because of their potential use in the future.

In this context, an open problem is related to the effective amount of groundwater flow available during periods of drought: in the summer of 2003 – the latest critical event – 34.000 citizens belonging to 150 municipalities were involved (at different levels) in reduction of water distribution for human consumption, in response also to depletion of spring discharge in shallow local aquifers along the mountain slopes. Moreover, reduction of recharge during springtime is getting more and more evident in the last years from rain gauges on the Alps (Nimbus, 2005).

In the following chapters, an example of quantitative analysis of groundwater flow is described, with reference to a representative catchment placed in the central western side of the Alpine range (district of Turin).

Picture n°1 showns the regional distribution of springs in Piedmont, with reference to the geological and structural pattern.

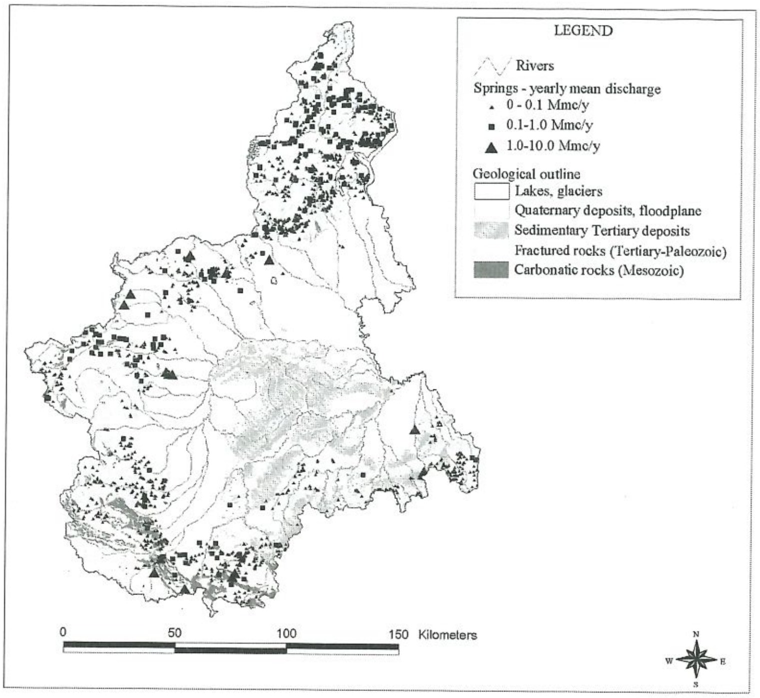

Fig.1 – Distribution of springs in the Piedmont region

3. Quantitative analysis of spring flow and recession curves

A selected set of 20 springs has been monitored during a time period ranging between 8 months and 5 years with monthly measurement of discharge (volumetric method) and "in situ" tests of geochemical parameters (pH, temperature, specific electric conductivity at 20°C); from november 2004 a program of water sampling for hydrogeochemical and microbiological analysis started, in the context of "ante-operam" monitoring of water resources along the trace of the "pilot-tunnel" for transalpine Turin-Lyon railway.

Monitored springs are distributed over an elevation range of more than 1000 meters (from 600-1700 m above sea level), between the hydrographic basin divide of Dora Riparia and Cenischia rivers; most of them are intercepted by capture structures for water supply (uptake of geological outflowing point, horizontal drains into the aquifer), even if fountains and natural springs are included in the monitoring program too. Detailed geological, geo-structural and hydrogeological studies and investigations has been carried out for this project in the last 10 years (Sacchi *et al.*, 2001), focusing on the design of the "Base Tunnel" in terms of geo-mechanical and hydraulic behaviour of rocks. Prediction of expected reduction in spring discharge during the tunnel drilling phase has been evaluated out too, so this task will be not considered in this paper.

The object of discussion is concentrated on the analysis of dynamic parameters of spring's outflow, used as a method for the assessment of groundwater resources in Alpine areas. The proposed method of analysis is of interest also along projected tunnels, since "natural" regime of groundwater flow from springs can be expressed with a set of quantitative parameters, surely different from the drawdown curves resulting from aquifer drainage during underground excavations. In the following table are listed the observed hydrodinamic parameters, referred to the number of measurements available in the reference time-period:

- average discharge
- maximum discharge
- minimum discharge
- variability index (Meinzer)

Spring ID	N° of measurements	Qaverage (l/s)	Qmax (l/s)	Qmin (l/s)	Iv –Variability Index
S1 Arnot – Poisattoni	18	2.52	10.50	0.10	413
S2 Boscocedrino	65	8.86	31.02	1.22	337
S3 Contraerea 4	6	0.05	0.17	0.00	352
S4 Escosa	40	11.50	66.70	0.01	580
S5 Fontanì	70	0.49	3.00	0.01	615
S6 Pratovecchio	64	9.57	22.40	0.50	229
S7 S.Chiara – Pra Piano	15	0.13	0.33	0.04	232
S8 S.Chiara – Tubo	15	0.98	3.33	0.21	319
S9 Supita	59	1.16	5.30	0.28	435
S10 Tre Merli	6	0.068	0.07	0.063	10
F1 Contraerea 2	6	0.09	0.17	0.04	157
F2 Contraerea 3	6	0.052	0.19	0.0034	354
F3 Perino	6	0.081	0.10	0.066	42
F4 S.Antonio	6	0.0583	0.073	0.037	62
F5 S.Chiara Fontana	15	0.43	0.75	0.06	161
F6 Tornari	6	0.053	0.12	0.00	226

Table 1 – List of main hydrodinamic factors of the springs

As listed before, the springs considered cover a wide distribution of average discharge values (ranging over 4 order of magnitude); with some exception, most of the springs are characterized by strong fluctuations in discharge (very high Meinzer index), showing that seasonal vertical recharge in the context of subsurface slope circulation system is quite important. Typical distribution of discharge values during the year can be recognized by a first maximum discharge at the beginning of the spring (in response to the snowmelt), and a secondary maximum during the autumn period (corresponding to high precipitation rates, mostly in a liquid phase).

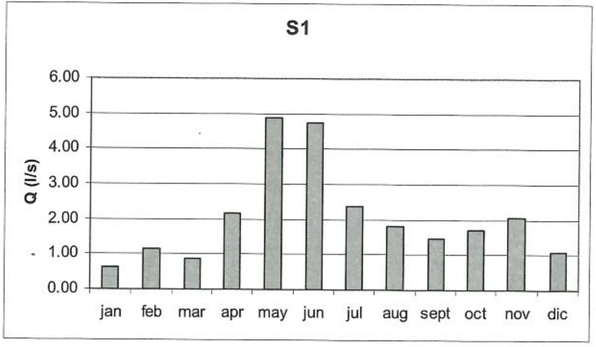

Fig.2 – Average monthly discharge, spring S1

Recession periods are usually distributed during the winter time and in the middle – late summer (july-september). Recession curves of the springs have been computed with reference to the available time-series of monthly measured discharges; analysis is mostly developed for the springs, since the fountains have been only recently included in the monitoring program. For all the situation considered, exponential function of Maillet reaches the highest degree of approximation of the theoretical curve to observed discharge values.

The general reference function is:

$$[1] \qquad Q^{t=}Q_0\,e^{-\alpha t}$$

where

Q_t = discharge at time t (l/s)
Q_0 = discharge at beginning of drawdown (l/s)
α = recession coefficient (1/day)
t = time after beginning of drawdown (days)

When all the parameters in the [1] are determined, it is possible to proceed to the computation of dynamic storage "W" as follows:

$$[2] \qquad W=Q_0\,86400/\alpha$$

where W correspond to the volume of water stored into the aquifer at the beginning of the recession period, after the recharge phase has been completed. In the following table are listed the dynamic parameters of recession curves, computed for different springs and seasons; column r^2 refers to the correlation coefficient of experimental data, interpolated with the exponential function of Maillet.

Spring	Season	t_0	t_f	t_f- t_0 (g)	Q_0 (l/s)	α	r^2	W ($10^3 m^3$)
S1 Arnot-Poisaton	W	nov-98	mar-99	123	3.05	0.0112	0.715	23.5
	S	giu-99	ott-99	119	7.04	0.0118	0.7714	51.5
	S	mag-00	set-00	124	5.23	0.0167	0.9559	27.1
	S	mag-03	set-03	119	5.24	0.0134	0.9795	33.8
	W	nov-04	feb-05	83	0.88	0.0042	0.9533	18.1
S2 Boscocedrino	W	nov-00	gen-01	75	9.50	0.0129	0.9548	63.6
	S	lug-03	ott-03	92	16.10	0.0085	0.8203	163.7
	W	dic-03	mar-04	91	16.10	0.0295	0.9599	47.2
S3 Contraerea 4	W	gen-05	apr-05	84	0.059	0.0373	0.9927	0.1
S4 Escosa	A	set-02	dic-02	101	10.00	0.0098	0.925	88.2
	S	lug-03	nov-03	125	5.20	0.007	0.9271	64.2
	W	nov-04	mar-05	113	4.2	0.0186	0.9823	19.5
S5 Fontanì	W	nov-97	mar-98	147	0.38	0.0085	0.9455	3.9
	W	dic-98	apr-99	119	0.08	0.0046	0.797	1.6
	S	lug-02	ott-02	88	1.67	0.0111	0.842	13.0
	W	nov-02	mar-03	117	0.70	0.0038	0.6999	15.9
	W	nov-04	mar-05	113	0.23	0.0056	0.9673	3.5
S6 Pratovecchio	W	gen-03	apr-03	91	22.4	0.009	0.8049	215.0
S7 Santa Chiara Pra Piano	S	mag-99	ago-99	98	0.33	0.0063	0.9377	4.5
	S	mag-00	ago-00	97	0.35	0.0102	0.9923	3.0
S8 S.Chiara – Tubo	S	mag-03	lug-03	64	2.00	0.0255	0.8614	6.8
S9 Supita monte strada	S	mag-00	set-00	124	2.1	0.0094	0.9685	19.7
	W	nov-00	gen-01	75	2.7	0.0088	0.9696	26.1
	S	mag-03	set-03	119	1.4	0.0114	0.9582	10.8
	W	nov-04	mar-05	113	0.59	0.0076	0.8834	6.7
F5 S.Chiara Fontana	S	mag-03	lug-03	64	0.17	0.0165	0.8643	0.9

Table 2 – Description of the most important recession curves of the springs (S= summer,A=autumn, W=winter)

Note that a quantitative feature of direct interest in the evaluation of available groundwater resources (in terms of order of magnitude) is here specified in the last column of the table – the dynamic storage "W".

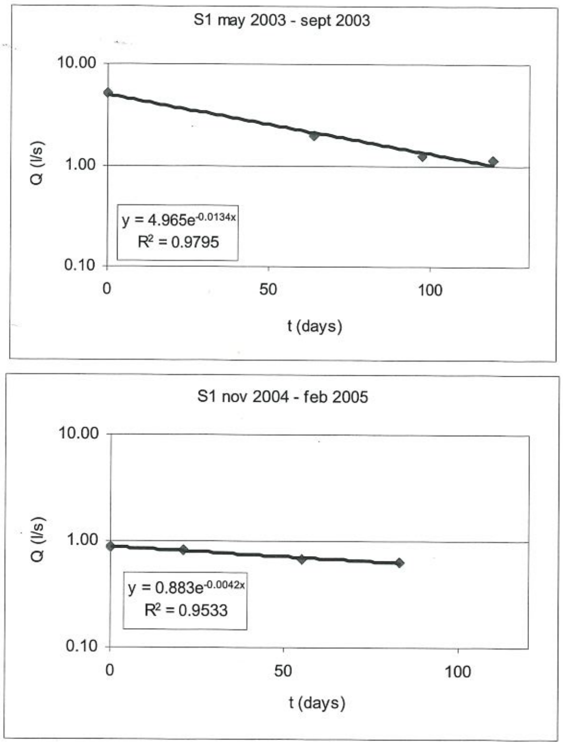

Fig. 3 – Comparison between recession curves of the same spring in different seasons

The observation of fig.3 indicates that aquifer outflow dynamic is clearly controlled by the hydrogeological conditions typical after recharge peak has been reached: in the example, the highest the amount of recharge, the highest slope of the recession curve. The function Q = f(t) depends by the peak discharge at the end of the recharge phase and by the slope coefficient of the recession curve, α, as easily derived from the [1], written in logaritmic format

$$\log Q^t = - \alpha t * \log Q_0$$

and

$$\alpha = - \log Q^t / (\log Q_0 * t)$$

With reference to the group of springs considered in the test-area (table 2), statistical relationships between Q_0 (discharge at beginning of drawdown) and α (recession coefficient) have been studied with reference to available dataset of (Q_0, α) values. The following picture shows the distribution of (Q_0, α) in logaritmic form; the linear correlation factor for this set of experimental data ($r \approx 0.75$) assume values that encourage this kind of analysis in the next future, getting new (Q_0, α) values with monitoring program in selected homogeneous hydrogeological environment.

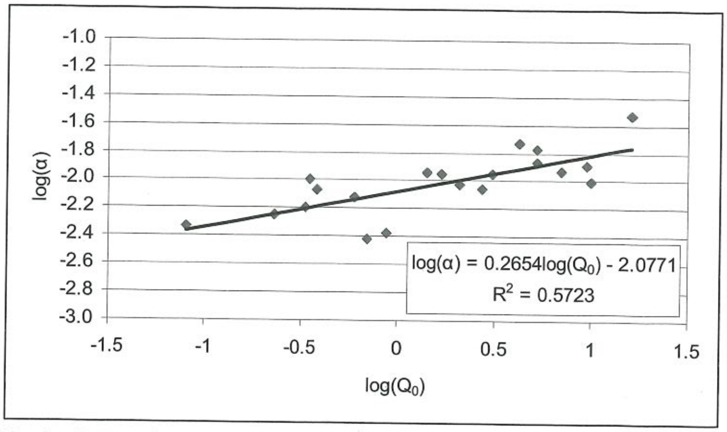

Fig. 4 – Dynamic of aquifer outlfow, visualized in the logα – logQ_0 plane

Setting up of experimental functions $\alpha = f(Q_0)$ can be obtained monitoring spring discharge initially with monthly frequency for 2-3 years, supporting reasonable estimations about the available groundwater resources outflowing from springs after dry periods of 3-4 months.

4. Using recession curves for estimation of aquifer vulnerability

The use of the half-decay time of maximum discharge has been introduced in the 90's as a method for evaluation of spring's aquifer vulnerability and related design of capture-zone (Civita, 1988) according to 4 different situations, called "A", "B", "C", "D" (listed with decreasing order of vulnerability). The method is now accepted in the italian national regulamentation. The practical use of this method requests the analysis of spring hydrographs (from measured data-series) and evaluation of the time after which maximum discharge is reduced of 50% (t_d).

Spring	Q_0 (l/s)	t_d (g)
S1 Arnot-Poisaton	3.05	61
	7.04	58
	5.23	42
	5.24	52
S2 Boscocedrino	9.50	54
	16.10	81
S4 Escosa	10.00	81
	5.20	99
S5 Fontanì	0.38	82
	1.67	74
	0.23	130
S6 Pratovecchio	22.4	77
S7 Santa Chiara Pra Piano	0.35	68
S8 S.Chiara tubo	2	35
S9 Supita monte strada	2.1	74
	2.7	75
	1.4	60
	0.59	75
F5 S.Chiara Fontana	0.17	50

Table 3 – Determination of half-decay time of maximum spring discharge

It is of specific interest to visualize the statistical relations between the recession coefficient "α" and t_d, as obtained from the observed hydrographs in the selected springs.

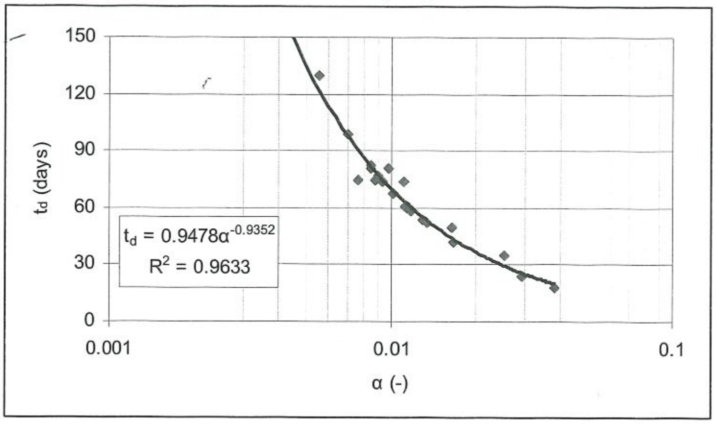

Fig. 5 – Relation between t_d (half-time of decay of maximum spring discharge) and recession coefficient - synthesis of experimental data

The high values of the power regression function ($r^2 = 0.9633$) can be explained considering that the numerical computation of coefficient "α" (from experimental data) and estimation of t_d are substantially comparable. Computation of "α" and t_d - using respectively the functions reported in the figures n°4 and n°5 (with limitation to the springs for which at least 3 couple of Q_0-α observed values are available) - leads to the conclusion that difference with "observed" values is only about 5% (see figure 6 below). This low discrepancy does not affect the classification of the springs into the same degree of vulnerability ("situation D").

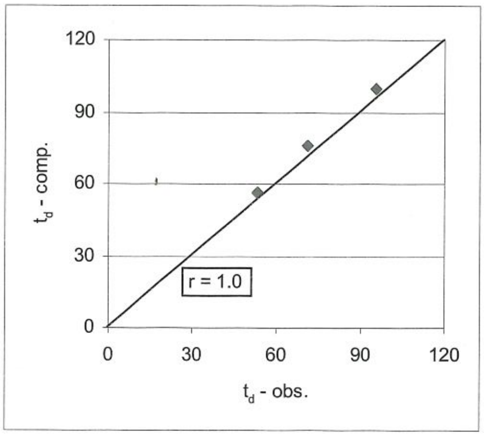

Fig. 6 – Correlation between computed and observerd values of t_d

Spring	Td observed (days)	Td predicted (days)	Diff.
S1 Arnot-Poisaton	53	56	5%
S5 Fontanì	95	99	4%
S9 Supita monte strada	71	76	7%

Table 4 – Comparison between observed and computed t_d values

The last picture summarizes the succession of activities presented in this paper, with a differentiation between data collecting in "target" / "focus" areas (initially choosen for special reasons), and extrapolation of dynamic functions governing groundwater resources availability to adiacent or similar areas on a larger scale.

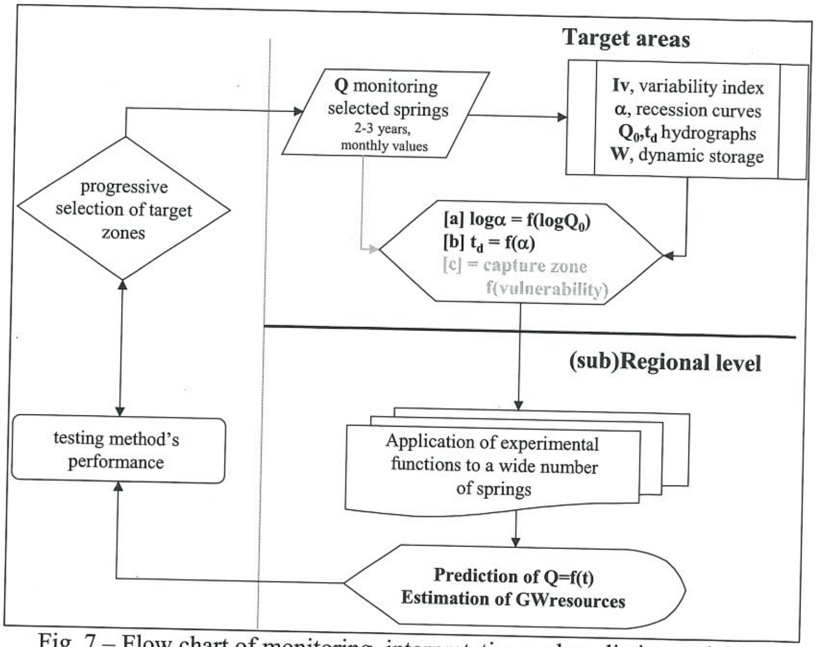

Fig. 7 – Flow chart of monitoring, interpretation and prediction activities

5. Conclusions

Evaluation of groundwater resources outflowing from springs in the Alpine Piedmont area is today problematic at the regional scale, since a very high number of spring-uptake points is poor of discharge time-series and experimental hydrographs. Monitoring surveys in specific target-areas sustain deterministic analysis of aquifer "natural" depletion during recession periods after peak recharge.

The knowledge of residuals groundwater resources after long dry periods is becoming more and more important also in relation to climate change / deficit of recharge.Simple discharge monitoring on monthly basis for a 2-3 years in homogeneous hydrogeological areas would enable to obtain basic parameters for the understanding of aquifer dynamic, recharge and depletion: maximum discharge Q_0, regression coefficient "α", half-decay of maximum discharge (t_d).

These features are strictly necessary also for a correct estimation of dynamic storage volume and spring aquifer degree of vulnerability. Since slope subsurface flownets have similar features in terms of recharge/discharge dynamic, empirical relation among the basic parameters ($Q_0 - \alpha - t_d$) could be used in statistical terms for a first set-up of groundwater resources at the subregional scale, if sufficiently detailed data are acquired in a significant number of springs in target-areas (order of magnitude $n > 10^2$).

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