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Application of the Vulnerability Estimator for Spring Protection Areas (VESPA index) in mountain quaternary aquifers / Banzato, Cinzia; Vigna, Bartolomeo; Galleani, Lorenzo; LO RUSSO, Stefano. - ELETTRONICO. - (2011). ((Intervento presentato al convegno GeoHydro2011 - CANQUA-IAH tenutosi a Quebec City (CA) nel 28-31 August 2011.

Availability:
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08 February 2023

Application of the Vulnerability Estimator for Spring Protection Areas (VESPA Index) in mountain Quaternary aquifers

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ABSTRACT
We propose the use of a Vulnerability Estimator for Spring Protection Areas (VESPA) index developed by Galleani et. al. (2011) to quantify spring vulnerability. The VESPA index is based on a joint analysis of discharge, temperature, and electrical conductivity derived from monitoring. The method requires 1 year of data measured on the spring, and estimates the spring vulnerability for several hydrogeological contexts. No infiltration data in the catchment area is required by the VESPA index. The analyzed springs are supplied by aquifers constituted by coarse grained alluvial fans and slope deposits (Balmetta spring), glacial and predominantly coarse-grained slope deposits (Fontanas and Marguareis springs). The protection areas were determined according to local technical guidelines.

RÉSUMÉ
Nous proposons l'utilisation d'un estimateur de la vulnérabilité de sources (VESPA) élaboré par Galleani et. al. (2011). Le VESPA est basé sur une analyse conjointe de la décharge, la température et la conductivité électrique provenant de la surveillance. La méthode nécessite une année de données mesurées sur la source. Aucune donnée d'infiltration dans la zone d' alimentation n'est requis par le VESPA. L'étude présentée analyse les sources alimentées par les cônes alluviaux et des débris (source Balmetta), et des dépôts glaciaires grossiers(sources Fontana et Marguareis). Les zones de protection ont été déterminées selon les directives techniques locales.

1 INTRODUCTION

Aquifers are recharged from precipitation and surface waters that percolate through the land surface and become part of the groundwater flow system. This water may become contaminated as a result of land use practices (Powell et al., 2003; Barry et al., 2009; Schijven et al., 2010). In identifying the level of territorial protection required to preserve a spring from polluting activities in the recharge area, the practical problem is whether a significant proportion of the freshly infiltrated water can quickly reach the spring (high spring vulnerability) or not (low spring vulnerability) during or just after a recharge event.

Springs with different aquifer types display different hydrographs (Barnes, 1939; Brutsaert and Nieber, 1977; Mangin, 1982; Amit et al., 2002; Malvicini et al., 2005). The aquifer drainage system can be characterized by an impulse function that transforms the input (e.g., rainfall or snowmelt) into spring hydrograph responses in terms of discharge, temperature, and EC variations. The impulse functional analysis can then be related to the drainage ‘‘effectiveness’’ (i.e. network connectivity) (Plagnes and Bakalowicz, 2001; Vigna, 2007; Kresic and Stevanovic, 2009).

To assess the spring vulnerability level, we used the Vulnerability Estimator for Spring Protection Areas (VESPA) index, a vulnerability estimator based on the analysis of spring hydrographs (Galleani et al., 2011). The VESPA index uses the discharge (flow) rate Q, groundwater temperature T, and electrical conductivity EC, and requires 1 year of data derived from the spring monitoring. Using the VESPA index, one can detect the spring vulnerability level or, alternatively, verify the vulnerability determined by means of other hydrogeological investigation techniques. The results show that the VESPA index correctly identifies the vulnerability of the analyzed springs.

2 METHODOLOGY

Analysis of the spring hydrograph responses with respect to the infiltrative events in the recharge area forms the basis for VESPA procedure to quantify spring vulnerability. The joint analysis of water flow discharges, temperature, and EC potentially offers a useful and replicable way to identify the spring vulnerability. To determine the vulnerability index, 1 year of data sampled by automatic sensors every 1 or 2 h and stored in an opportune data logger was considered. This minimum time interval helps limit the possible errors associated with the loss of information provided by the main flood events during the hydrological year (spring and autumn events).

The VESPA index is defined as

$$V = c(\rho)\beta\gamma \qquad [1]$$

where $c(\rho)$ is the correlation factor, β is the temperature variability, and γ is the discharge factor.

2.1 Correlation Factor

The correlation factor is defined by

$$c(\rho) = [u(-\rho) + \alpha u(\rho)]|\rho| \qquad [2]$$

where ρ is the correlation coefficient between discharge and electrical conductivity, computed on the reference time interval t_0 = 1 year (one hydrologic year) as

$$\rho = \frac{\int_0^{t_0} Q(t)\sigma(t)dt}{\sqrt{\int_0^{t_0} Q^2(t)dt}\sqrt{\int_0^{t_0} \sigma^2(t)dt}} , \qquad [3]$$

and $u(\rho)$ is the Heaviside step function

$$u(\rho) = \begin{cases} 1, & \rho \geq 0 \\ 0, & \rho < 0 \end{cases} \qquad [4]$$

This formula can be rewritten in simpler terms as follows

if $\rho \geq 0$, then $u(\rho) = 1$ and $u(-\rho) = 0$ [4a]

else if $\rho < 0$, then $u(\rho) = 0$ and $u(-\rho) = 1$ [4b]

The parameter α is a scaling coefficient constrained by $0 \leq \alpha \leq 1$. Since all terms in Eq. (2) are non-negative, $c(\rho)$ is also non-negative. The key element of the correlation factor is the correlation coefficient, which can vary in the interval

$$-1 \leq \rho \leq 1 \qquad [5]$$

2.2 Temperature Variability Factor

The temperature variability is defined as

$$\beta = \left(\frac{T_{\max} - T_{\min}}{1°\mathrm{C}} \right)^2 \qquad [6]$$

where $T_{\max}$ and $T_{\min}$ refer to the maximum and minimum values, respectively, of the temperature *T* on the reference time interval t_0 (explored data set: 1 year). Division by 1°C is performed to ensure that β is dimensionless. Since temperature stability over time indicates a high aquifer residence time and low vulnerability, the maximum temperature variation is a fundamental parameter for estimating the spring vulnerability. Hence, we use its squared value to enhance the corresponding weight in the vulnerability index *V*.

2.3 Discharge Factor

The discharge factor measures the variability of the discharge time series, and it is defined as

$$\gamma = \frac{Q_{\max} - Q_{\min}}{Q_{\mathrm{m}}} \qquad [7]$$

where $Q_{\max}$ and $Q_{\min}$ are the maximum and minimum values, respectively, of the discharge *Q* on the reference time interval t_0, and Q_{m} is the average discharge given by

$$Q_{\mathrm{m}} = \frac{1}{t_0} \int_0^{t_0} Q(t)dt \qquad [8]$$

Table 1. VESPA index intervals for the identification of the spring vulnerability level.

Vulnerability	VESPA index
Very High	$V \geq 10$
High	$1 \leq V < 10$
Medium	$0.1 \leq V < 1$
Low	$0 \leq V < 0.1$

3 BEHAVIORAL MODELS OF THE DRAINAGE NETWORK EFFECTIVENESS

Qualitative analysis of the hydrographs and observed correlations between the flow rate, temperature, and EC as a function of infiltration input revealed three broad behavioral categories (types A–C), based on the drainage network effectiveness.

In the highly effective drainage system (type A) during high water levels (e.g., flood or snow melting period), most of the freshly infiltrated water reaches the spring very quickly, due to the presence of open fracture systems, well-developed karst conduits, or highly permeable horizons, according to the local hydrogeological situation. Freshly infiltrated water of low salinity tends to replace the groundwater supplying the spring during the baseflow. Therefore, the water chemistry response is usually characterized by a fast and intense reduction in mineralization, highlighted by decreased EC values corresponding to the flood peaks. The behavior of the groundwater temperature is relatively similar to that of the EC: its intense variability is almost synchronous with the flood peaks, and it recovers rapidly after the end of the infiltrative processes.

In the moderately effective drainage system (type B), the spring hydrodynamic response can display impulsive behaviors. Freshly infiltrated water increases the hydraulic head in the saturated zone, and induces a pressure increase in the saturated fractured portions of the rock mass (fractures and/or karst conduits). This pressure increase and the corresponding pushing effect tend to mobilize the resident groundwater. The groundwater is near thermal equilibrium with the aquifer and is characterized by a higher salinity than the freshly infiltrated water. Therefore, an increase of flow discharge, EC, and temperature is observed by monitoring the spring (piston effect). After the infiltrative peak, the system is dominated by a mixing process between the resident pre-event groundwater and the freshly infiltrated water.

In a low effective drainage system (type C), the hydrodynamic impulsive response to the infiltrative processes is almost absent The discharge flow displays slow and modest fluctuations that are delayed up to several months relative to the main rainfall events. Chemical parameters (salinity) and the discharge water temperature usually display a similar trend, with slow and minor variations. Freshly infiltrated water moves slowly in the unsaturated and saturated zones, thereby reaching equilibrium with the aquifer and the resident pre-event circulating groundwater. Homogenization occurs due to the aquifer characteristics, and the external output due to the infiltrative process (low salinity and cold water) is strongly reduced.

Table 2. Intervals spanned by the correlation coefficient and correlation factor for the three basic types of spring described above.

Spring type and prevailing phenomenon	Correlation coefficient (ρ)	Correlation factor $c(\rho)$
Type A - Replacement	$-1 \le \rho \le -0.2$	$0.2 \le c(\rho) \le 1$
Type B - Piston	$0.2 \le \rho \le 1$	$0.1 \le c(\rho) \le 0.5$
Type C - Homogenization	$-0.2 \le \rho \le 0.2$	$0 \le c(\rho) \le 0.2$

4 TEST SITES RESULTS

The VESPA methodology has been applied on three mountain springs located in the SW Alps in the Piemonte region (Italy – Fig. 1) supplied by Quaternary aquifers.

The region is characterized by the arcuate orogenic belt of the Western Alps (crystalline and carbonate rocks) on its west side, morphologically connected by extensive alluvial and morainic fans to the continental plain area in the central and eastern parts. Most springs in the mountain sector are generally supplied by detritus aquifers covering the crystalline bedrock. These diffuse, high quality water resources typically provide moderate to low yields of 1–30 L/s, and are employed for human consumption in most mountain villages.

The analyzed springs are supplied by aquifers constituted by coarse grained alluvial fans and slope deposits (Balmetta spring), glacial and predominantly coarse-grained slope deposits (Fontanas and Marguareis springs).

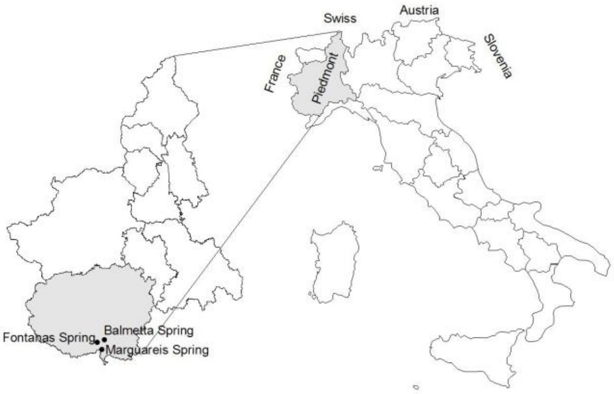

Figure 1. Location of test sites

Table 3. Springs geographical coordinates

Spring	Coord N	Coord E
Balmetta	44°15'06"	7°43'00"
Fontanas	44°14'03"	7°38'26"
Marguareis	44°10'53"	7°41'26"

4.1 Balmetta spring

The Balmetta test site is situated in the Ellero valley (Roccaforte Mondovì municipality) at 960 m amsl. The supplying aquifer consists of a thin coarse Quaternary detritus with high permeability, without a significant protective soil cover. The aquifer overlays a crystalline substrate constituted by impermeable porphyroids (Permian-Trias) that outcrop extensively in the catchment area. The saturated and unsaturated zones are limited in width. The spring catchment area is characterized by a lack of vegetative cover. Only in the upper part summer grazing pastures are present. Significant fluctuations in spring discharge, water temperature and EC have been observed. Flood peaks are very quick and correspond to significant depletions of temperature and EC, highlighting a prevailing replacement phenomenon, operated by the freshly infiltrated water in the aquifer. Consequently, the Balmetta spring appears to be highly vulnerable to contamination. The monitoring data set starts on June 2006, while we use only the 2008 data for the VESPA processing (Fig. 2). The yearly maximum temperature variation is 2.5°C (average 7.6°C) and the EC variation is ~ 80 µS/cm (average 84 µS/cm). The yield is strongly variable, with an average discharge rate close to 20 L/s.

The VESPA index shows a very high vulnerability for the spring, while the correlation factor confirms a replacement prevailing phenomenon.

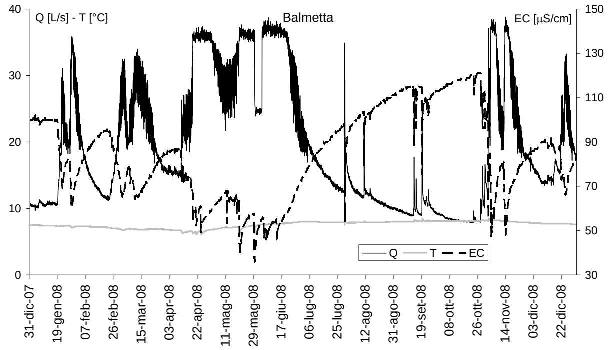

Figure 2. Behavior of Q, T, and EC of Balmetta spring in the hydrological year 2008.

Figure 3. Balmetta spring tapping system.

4.2 Fontanas Spring

The Fontanas Spring is situated in the Pesio valley (Chiusa Pesio municipality) at 1200 m amsl.

The catchment area (little more than half a square kilometer) is characterized by quartzite and porphyry slopes which are partly covered with a less powerful blanket of Quaternary glacial and slope deposits. The aquifer is hosted in the Quaternary sediments with medium-high permeability, without a significant protective soil cover. The saturated and unsaturated zones are limited in width.

Similarly to Balmetta, during an infiltrative input, Fontanas spring shows weighty variations in spring discharge, temperature, and electrical conductivity parameters.

Flood peaks correspond to quick and significant decrease in temperature and EC, underling a prevailing replacement phenomenon, due to new infiltrated water. Consequently, the Balmetta spring appears to be highly vulnerable to contamination.

The monitoring data set starts on September 2006, while we use only one year of data for the VESPA processing (Fig. 4). The yearly maximum temperature variation is almost 4°C (average 6.2°C), and the EC variation is 66 µS/cm (average 125 µS/cm). The discharge changes between few L/s and 60 L/s

The VESPA index indicates a very high vulnerability for the spring and the correlation factor confirms a replacement prevailing phenomenon.

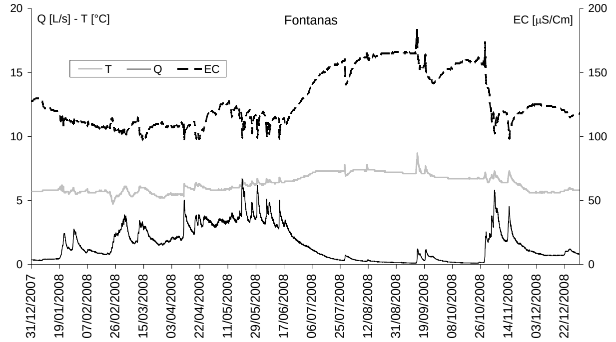

Figure 4. Behavior of Q, T and EC of Fontanas spring in the hydrological year 2008.

Figure 5. Fontanas spring alimentation area.

4.3 Marguareis Spring

The Marguareis Spring is situated in the Pesio valley (Chiusa Pesio municipality) at 1920 m amsl.

The catchment area (a little more than a square kilometer) is characterized by rather steep slopes made of quartzite, porphyry, and limestone which are partly covered by less powerful Quaternary glacial and slope deposits. The aquifer is hosted in the Quaternary sediments with medium-high permeability, without a significant protective soil cover. The saturated and unsaturated zones are limited in width.

During infiltrative input, Marguareis spring shows weighty variations in spring discharge and electrical conductivity, in fact, while the discharge increases, the EC decreases. Conversely, temperature varies little.

The monitoring data set starts on July 2006, while only the 2008 data are used for the VESPA processing (Fig. 6). The yearly maximum temperature variation is a little more than 1°C (average 2.9°C), and the EC variation is 50 µS/cm (average 70 µS/cm). The discharge changes between 35 L/s and 110 L/s

The VESPA index indicates a high vulnerability for the spring and the correlation factor provides a replacement prevailing phenomenon.

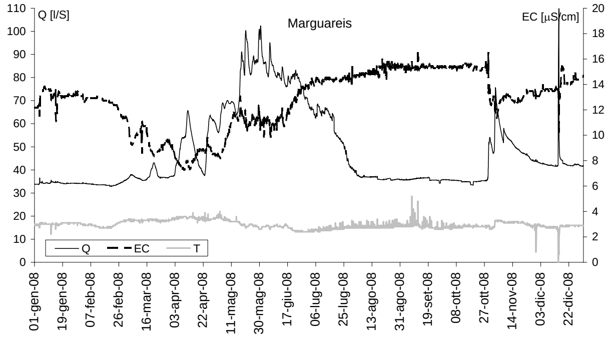

Figure 6. Behavior of Q, T and EC of Marguareis spring in the hydrological year 2008.

Figure 7. Marguareis spring.

Table 4. Summary of VESPA calculated parameters in the three test sites

Spring	Index ρ	Index β	Index γ	Index V
Balmetta	-0.9	14.4	2.1	28.8
Fontanas	-0.6	30.4	11.9	92.7
Marguareis	-0.6	3.2	1.7	3.3

Balmetta and Fontanas springs shows a very high vulnerability, so in according to local regulations, in the overall catchment area the entire recharge zone is identified as the protection area, without differentiation. Marguareis spring has a high vulnerability, so only a portion of the catchment area (2000 m) is subject to protection and restrictions as required by local regulations.

5 CONCLUSIONS

Analysis of the joint behavior of the discharge, temperature, and EC using hydrographs seems to provide a good quantitative estimate of the spring vulnerability. These parameters are also useful for identifying the drainage network effectiveness and the main phenomena occurring in the aquifer after the flood peak (prevailing replacement, piston, or homogenization). Vulnerability assessment can be used to define the groundwater protection zones, according to the hydrogeological situation and the local regulatory framework.

The goal of the VESPA index is to provide a numerical assessment of the spring vulnerability. Subsequently, the protection area can be defined by considering the hydrogeological setting as well as the local regulations. However, we observe that a correct delineation of the spring protection areas must always rely on intensive geological and hydrogeological field investigations of the recharge area, mainly aimed at identifying the preferential infiltration areas, if present. Application of the VESPA method seems straightforward for several reasons. First, the VESPA index allows estimation of the level of vulnerability in a wide range of hydrogeological environments. Second, the spring vulnerability evaluation is based solely on the analysis of the spring monitoring data, and does not involve any other parameter. Furthermore, infiltration data of the catchment area connected to rainfall events, snowmelt, or stream loss, which are difficult to evaluate, are not required to compute the VESPA index. Finally, the VESPA method provides reproducible results with a moderate financial effort.

ACKNOWLEDGEMENTS

The authors wish to thank the environmental authority of the Piemonte region government that partially supported the study.

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