A computer simulation of groundwater salinization risk in Salento peninsula (Italy)

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Abstract

The main source of water for civil purposes in Salento peninsula is the coastal karst aquifer. It is formed by Cretaceous units, essentially limestones and dolomitic limestones highly fractured and karstificated. The groundwater is intensively withdrawn and, as a consequence, the risk of contamination of existing wells due to salinization is high. In order to evaluate the level of such a risk, a procedure is proposed that, taking into account the essential features of the underground circulation like the principal conductive fractures and karstic conduits, leads to a predictive model based on the generation by computer of artificial systems of fractures and conduits. Very preliminary results are presented to show the capability of such a procedure.

1 Introduction

Groundwater quality in Salento peninsula is compromised by a human-induced salinization, due to uncontrolled exploitation (Federico, 1999). The public authorities are now concerned about the protection of this resource and studies aiming to the prediction of salinization are considered of great importance.

In karstic aquifers groundwater flows in pipelike conduits as well as through fractures. The aperture of the karst openings ranges from few millimeters up to many meters of major conduits (caves). Conduit systems are often developed in several levels, reflecting successive stages of formation. Due to the randomness of the geometry of the network of fractures and conduits, the flow circulation and the transport of solute are predictable.
only on a statistical basis. In what follows a procedure is outlined leading to a predictive model based on computer generated artificial networks of fractures and conduits through a tossing process of their geometrical and hydrological properties.

2 Geological and hydrological features of Salento peninsula

To start at least from the Upper Cretaceous, the geological history of the Salento has been characterized by several emersions alternate with submergences by the sea, due to tectonic or eustatic phenomena. The former determined fault systems with the main tectonic axes oriented NNW-SSE (Figure 1). As a consequence, the units forming the stratigraphic series are separated by sedimentary hiatus and angular discordance. Cretaceous limestones and dolomitic limestones - their thickness exceeds 6000 m - were raised by tectonic movements at the end of Cretaceous. During Tertiary
and Quaternary marine ingressions, mainly calcareous limestones have been formed. Several tectonic phases generated the fracture networks. During the dry land conditions, underground waters took place into the Cretaceous units, floating over salt water coming from the sea. Some tectonic fractures were enlarged by karstic dissolution, becoming large pipelike conduits. This phenomenon was strongly active along the brackish zone, where fresh water and salt water are continuously mixed and replaced (Forti, 1991). By virtue of this speleogenetic condition, in Salento the mean karstificated levels are sub-horizontal (Delle Rose et al., 1998).

In coastal karstic aquifers, the altimetrical position of the brackish zone is related to the position of the coastline, and, as a consequence, the hydrological features of the aquifer must be strongly determined by its changes (Figure 2).

In general, karstic aquifers can have different hydrological characteristics, depending on the hydrogeologic setting. Two extremes can be recognized: conduit aquifers, in which the groundwater flows essentially along the conduit system, and diffuse flow aquifers, in which conduit systems are either absent or so poorly integrated that they have little influence on the groundwater circulation. Many carbonate aquifers contain both elements (White, 1988) and Salento coastal aquifer can be considered of this kind. Up to now no particular attention has been paid to the discrete nature of this aquifer and the prediction of flow and transport has been carried out by means of porous-like medium models, leading to erroneous evaluations. A correct predictive model should reply the inherent medium inhomogeneity and anisotropy, the existence of turbulent non-Darcy flow along the karstic conduits and the fast response to short term events (White, 1988).

In karstic fractured aquifers a wellbore is too small to capture all the heterogeneities of the rock mass; moreover, the geometry and nature of the probed fracture network are unknown. Values obtained from pumping
tests vary widely over short distances; therefore they have to be considered as samples of population of random variables, and can be utilized in the framework of a stochastic predictive model.

3 The modeling

Generally speaking, fractured karstic aquifers are characterized by high level of randomness. This can be experienced when analyzing pumping tests in different boreholes within the rock mass: the results are usually not regular and this discourages their interpretation. An example of evidence of this characteristic is shown in Figure 3. The randomness is due to several factors, all logically connected to the nature of fracture system and, when dealing with karstic aquifers, also to the system of karstic conduits. The response of each well would depend roughly on the number of conductive fractures intercepted by the well itself, the geometry of the network of connected fractures and their apertures or hydrological properties. The authorities that commission executions of well tests in such aquifers usually do not require any information about the fracture system close to the wells, neither they care about the existence of karstic cavities or other major hydrological features in the vicinity of the probed zone. The authorities involved in water resources management in Salento have always behaved in this way and collected an impressive amount of data that were subsequently considered useless. Had we an appropriate method of interpretation, such data would constitute an important basis for management purposes. A method aiming to retrieve these data is proposed, based on hierarchical models of discrete fracture networks (DFN). Such models are gaining acceptance as practical tools when dealing with problems of fluid flow in fractured media. Applications of DFN in reservoir engineering and waste depository design are well documented, while, to the Authors knowledge, such applications are missing in water resources management.

A DFN is the outcome of a tossing process of the essential features of any fracture in the generated network (i.e. orientation of the fracture plane, size, hydrological properties). The number of generated fractures can be expressed in terms of fracture density or fracture area per volume. The fractures are elliptical or rectangular and can terminate or not against other fractures.

The essential fracture features derive from sampling of fracture traces on outcrops or caves. Collected data are essentially two-dimensional, and inference procedures are needed in order to get the three-dimensional features.

A powerful package for generating DFN is FracMan of GOLDER Associates (Dershowitz et al., 1995), that allows also a post analysis of a generated network. The code is able to 'probe' the network with boreholes and define several global parameters associated to the network. A valu-
Figure 3: Drawdowns (m) measured in 25 wells in the sample area for 20 and 40 l/s pumping rates

A valuable hydrological parameter is the connectivity between the boreholes and any other geometrical figure inside the generation region. There are several definitions for connectivity; in this case we limit the analysis to identify the more conductive pathway existent between an imaginary borehole and a plane. The code can retrieve the fractures involved in a pathway and roughly calculate its global conductance.

If one approximated the fresh water - sea water interface to a plane, the global conductance of the more conductive pathway between a borehole and the interface itself would give a measure of the risk of salinization associated to that borehole.

For the above-mentioned, an approach to evaluation of risk of salinization in fractured karst aquifers can be outlined in the following steps:

- collect data about the discontinuity field on outcrops and cavities;
- based on geological considerations, define the position of the main sub-horizontal karstificated levels inside the aquifer;
- define statistical distributions for the essential geometrical features of the fractures and beddings;
- collect data in inspectionable karstic cavities about the spatial evolution of their aperture and estimate the occurrence of such cavities in the rock mass;
- define distribution of transmissivity by analyzing pumping well tests by means of Osnes et al. (1988) procedure or other similar procedures;
• generate several DFN based on the same distributions; such networks should contain a number of cavities consistent with the measurements;

• evaluate in a preliminary stage the global conductances of the more conductive pathways between wells of fixed length and the interface and collect the data in hystograms;

• perform several numerical simulations of fluid flow and transport of solute between a pumping well of fixed length and pumping rate and the interface and collect eventually the results in terms of salinity of pumped water at steady-state in hystograms;

• the distributions of pathway conductances and salinity of pumped water derived from the related hystograms will lead to a judgement about the risk of salinization in the fractured karstic aquifer of a well of fixed length at a fixed pumping rate.

4 A simplified application of the approach in Nardó sample area

In this area, located in the north-western part of Salento (Figure 1), salinization problem is particularly strong, since many wells are already salsificated.

From the geological point of view, tectonically raised and lowered coastal blocks of Cretaceous limestones and dolomitic limestones are locally covered by Miocene, Pliocene and Pleistocene mainly calcareous sandstones, whose thickness vary from few to about 30 metres.

Nine sets of discontinuities are evident: eight are due to tectonical stresses (S# with # from 1 to 8) and one is the bedding (B), which dips no more than 10-15 degrees toward SW or NE. Every fracture system dips around 85 degrees; medial trends of dip directions measured from N to E are: 0, 15, 45, 60, 90, 115, 135 and 150 degrees. The coastal portion, where brackish water flows toward the sea, is actually place of strongly karst phenomena that form a conduit and doline-like system. Some conduits, called "polle-inghiottiti", open under sea (Carlin et al., 1968); these alternatively outflow fresh water and absorb salt water following the tide fluctuations. As a consequence, the conduit openings must have an high importance on the water circulation. By speleological point of view, this area has been object of several explorations. Twenty-five karstic caves are known, most of them opening in the upper portion of the vadose zone (Orofino, 1987).

Submerged caves have been located between 0 and 20 metres below sea level; it seems that other caves are not present at deeper levels. Main trunks of these caves develop preferentially along the strikes of the fracture sets 0, 45, 90 and 150 degrees (Figure 4).
Twentyfive wells bored in this area showed a vast range of drawdowns during pumping tests (Figure 3). Wells penetrate 12-15 metres into karstic aquifer. At large scale, it seems possible to recognize some portions with different transmissivity, perhaps related to various karst system developments.

In order to show the capability of the previously described approach, an example of the possible results follows.

Running FracMan code, three realizations $R_1$, $R_2$ and $R_3$ ($300 \times 300 \times 50 m^3$) were produced, based on the data shown in Table 1. Sets $S\#$ were considered, along with the bedding $B$ and two randomly located vertical cavities $C_1$ and $C_2$ of $100 \times 10 m^2$, whose plane strikes are 45 and 90 degrees. A bivariate normal distribution of given mean trend and plunge of dip direction and standard deviation equal for both is applied to each fracture set. For fracture length and width an uniform distribution is applied with given mean values and one maximal deviation for both. Due to the lack of information, the authors point out that such data are absolutely hypothetical and are here utilized just as an academical exercise.

A picture of one of these realizations is shown in Figure 5. Nine boreholes 15 meters deep per realization were located on the top of the prismatic region. Relative values of transmissivity were imposed as follows: 1 to $S\#$ fracture sets, 5 to $B$ and 100 to the karst cavities.

The randomness of the fracture network is consistently simulated by the realizations. In fact we have 5, 5, 5, 6, 3, 2 and 1 cases respectively for 1 to 7 fractures captured by the boreholes. If one assigns to each borehole a transmissivity given by the sum of the intercepted fracture transmissivities, the simulation would give back a pattern of borehole transmissivities consistent with the irregular pattern of drawdowns per fixed pumping rate.

As to the risk of salinization, the interface was located at the bottom of the generation region. For each borehole a rough calculation of maximal

![Circular histogram of the lengths of the main cave trunks](image)
### Table 1: Fracture data for the generations; $\alpha_m$ and $\beta_m$ mean values of trend and plunge of dip directions

<table>
<thead>
<tr>
<th>set</th>
<th># of frac.</th>
<th>$\alpha_m$</th>
<th>$\beta_m$</th>
<th>st.dev.</th>
<th>length</th>
<th>width</th>
<th>max.dev.</th>
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<td>5</td>
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</tr>
<tr>
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<td>200</td>
<td>60</td>
<td>85</td>
<td>5</td>
<td>20</td>
<td>10</td>
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</tr>
<tr>
<td>S3</td>
<td>300</td>
<td>105</td>
<td>85</td>
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<td>20</td>
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</tr>
<tr>
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<td>150</td>
<td>85</td>
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<td>20</td>
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<td>5</td>
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<tr>
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<td>0</td>
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</tr>
<tr>
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<td>0</td>
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<td>20</td>
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</table>

### Figure 5: One of the realizations utilized for connectivity evaluation
pathway conductance was performed. For a fracture slab of length $l$ and width $w$ perpendicular to the flow path, fracture conductance $C$ is defined as $C = Tw/l$, where $T$ is fracture transmissivity. As to a pathway of fractures, the portion of the pathway in a single fracture is a slab of length $l'$ equal to the trace-to-trace distance and width is the mean $w'$ between the trace lengths, where traces are the intersections of the fracture with the previous and subsequent fracture of the pathway. A pathway conductance $C_p$ is the conductance of a series of fractures, i.e.:

$$C_p = \frac{1}{\sum_{i=1}^{n_f} \frac{1}{C_i} = \frac{1}{\sum_{i=1}^{n_f} \frac{l_i'}{T_iw_i'}}}$$  \hspace{1cm} (1)$$

where $n_f$ is the number of fractures in the pathway, and $C_i$, $T_i$, $l_i'$ and $w_i'$ refer to a generic fracture $i$.

There are several pathways potentially leading salt water from the interface to the boreholes, but the maximal one is considered the only one relevant. Furthermore, for a very rough estimation the ratio $l_i'/w_i'$ is equal to the aspect ratio of each fracture in the pathway.

The maximal pathway conductance was evaluated for each borehole. In Table 2 the calculated values per classes are shown. The mean value is $0.105 \text{m}^2/\text{s}$ and the standard deviation is $0.076$.

The groundwater salinization risk can be roughly estimated by utilizing a 'discrete' version of Dagan & Bear (1968) solution for the upconing under a point sink in a three-dimensional flow above an initially horizontal and stable interface:

$$\zeta(t) = - \frac{\gamma_f}{2\pi K_f}\left[1 + \frac{1}{d + tK_f/n(2 + \delta)}\right]$$  \hspace{1cm} (2)$$

where $\zeta(t)$ is the upconing measured from the initial level of the interface at time $t$, $\delta$ is equal to $\gamma_f/\left(\gamma_s - \gamma_f\right)$ with $\gamma_f$ and $\gamma_s$ unit weights of fresh water and sea water respectively, $Q$ is the pumping rate, $K_f$ is the hydraulic conductivity of the homogeneous isotropic porous medium, $d$ is the distance
between the point sink (in this case located in the middle of the well) and
the interface and $n$ is the medium porosity.

If one impose a dimensional analogy and consider $\zeta/d$ as a measure of
salinization risk at time $t$ for a fixed pumping rate $Q$, the previous equation
comes to:

$$\frac{\zeta(t)}{d} = \frac{\delta Q}{C_p d} \left[ 1 - \frac{1}{1 + tC_p l_p/d(2 + \delta)(ew)_{av}} \right]$$

(3)

where $l_p$ is the total pathway length, $(ew)_{av}$ is the mean value along the
pathway of the product of $e$ (aperture) and $w$ (width).

The previous equation would give back the upconing for each analyzed virtual borehole leading to the definition of distribution of probability. Matching it with the value of 1.0, one can derive a judgement about the risk of salinization for a borehole of specific length at a fixed pumping rate after a certain period of time.

5 Preliminary conclusion

In the previous a general description of hydrogeological features of Salento
aquifer is given, aiming to the definition of a conceptual model for risk
evaluation of groundwater salinization. The model is based on the Dis-
crete Fracture Network (DFN) concept, that requires a quantitative and
sistematic knowledge of the fracture field as well as the occurrence and the
evolution of karstic openings in the rock mass. An example of the capa-
bility of the model is shown through a very simplified model. The typical
randomness of the karstic fractured aquifer is simulated.

The DFN leads to the definition of the probability density function by
a Monte Carlo procedure of any tested variable. From the point of view of
engineer, probability density functions are more effective tools for design,
given that they provide an expected value with the reliability of the measure
and this would strengthen the decision.

In any case, as to karstic fractured aquifers, the application of DFN
seems mandatory, given that a porous-like conceptualization would not al-
low to simulate the inherent randomness of the aquifer response, especially
when dealing with rock masses of scale-dependent density (vide Dershowitz,
1996).

Acknowledgments: This study has been supported by Italian National
Research Council - Contratto n. 94.01741.PF42, Gruppo Nazionale per la Difesa
dalle Catastrofi Idrogeologiche, Pubbl. n. 2185. The authors would like to
thank Gruppo Speleologico Neretino for the information about the caves in
Salento and Consorzio di Bonifica Arneo for the data about pumping tests.
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