Vulnerability of the aquifer system: considerations on a methodological approach

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Abstract: - The protection of groundwater, now exposed to contamination and over-exploitation in the industrialised world, is one of the major issues in modern groundwater resource planning. In particular, in the semi-arid areas of the Mediterranean basin, for a better management and protection of the water resources, it is very important the assessment and the mapping of groundwater vulnerability to contamination. In this paper, we present the result and the problem relative to realization of vulnerability maps in different geological-hydrogeological and human-pressure conditions. Firstly, in order to define the conceptual hydrogeological model of the area, geological, stratigraphic, geomorfological, hydrological and hydrogeological data are collected and elaborated. Secondly, by using the most suitable method for the local hydrogeological condition, among those available from the literature, the created database is implemented in a GIS to estimate the intrinsic vulnerability of the aquifer systems.

Key-Words: - vulnerability, carbonate aquifer, alluvial aquifer, Italy, Kerkyra Island

1 Introduction

The worldwide development of past civilisations as well as the recent socio-economical evolution of Nations is based and strongly controlled by the availability of water. The Mediterranean Basin that during the last decades has been characterised by a semi-arid climate is not an exception.

In this area, the occurrence of wide aquifers both in limestone rocks and alluvial deposits favour the accumulation of important amounts of water resources. However, this opulence in underground waters is often compromised by an abuse of pumping and by local but diffused polluting phenomena having several causes (urban, farming, factories, etc.).

In Italy, only the 40% of the total amount of the potentially exploitable water resources, both superficial and underground, is effectively exploited. In fact, the remaining 60% is in practice not used because of qualitative and economical problems. Due to the general setting and the specific characteristics, the aquifers are frequently vulnerable to superficial polluting sources. In particular, the vulnerability of the underground resources is a function of a) the hydrolithological, hydrostructure and hydrogeological conditions of the system; b) the pedological characteristics of the soils; c) the recharge conditions; d) the groundwater inflow-outflow processes and e) the physical and hydrochemical processes that influence the natural quality of waters.

In the last decades, several methods to evaluate the intrinsic vulnerability of the aquifer system have been development based on a) the zonation of homogeneous areas with a similar degree of vulnerability [1] and b) the parametric systems separated in a matrix system, a point count system, a point count system model and an environmental evaluation system ([2], [3], [4], [5]).

The present research is devoted to the evaluation of the intrinsic vulnerability to pollution for three case studies characterised by a different density and overall quality of basic information (Figs. 1, 2, 5). The first area is represented by the carbonate aquifer of the High Basento Valley (Basilicata, Southern Italy), the second case study is represented by the alluvial system surrounding the town of Ferrara, characterised by an unconfined aquifer (Eastern Po Plain, Northern Italy), while the third area is represented by the carbonate aquifer system of the Gouvia (central sector of the Kerkyra island, Greece). For all areas, we define the conceptual hydrogeological model before applying the more suitable methodological approach allowing us to recognise the sectors characterised by the higher degree of pollution risk.

2 Intrinsic vulnerability maps

2.1 Basento Valley carbonate aquifer system

One of the major carbonate aquifer systems of the Basilicata region is represented by the wide Arioso-Pierfaone morphostructure, located in the higher sector of the Basento Valley. This aquifer is characterized by abundant groundwater resources, quantified in about 107 m^3/y, which flow from several springs, many of which are captured although not fully exploited, whereas others are not captured, even though characterized by considerable discharges [6].

From the geological point of view, in the study area we can distinguish the follow formations (Fig. 1a):

Monte Facito formation (Lower-Middle Triassic), subdivided in the a) terrigenous (siliciclastic) unit, made up of a succession of quartz-rich calcarenites and mudstones, marls, shales and green micaceous sandstones, strongly deformed and frequently associated with gravels; and b) an organogenic unit, made up of grey massive limestones and heavily fractured black limestones and marls.

Calcari con Selce formation (Upper Triassic), conformably lying on the Monte Facito formation, which is made up of centimetres-to-decimetres-thick layers of grey limestones with beds and nodules of black and white chert, marls and calcareous marls, mudstones and marly clays. This succession is well layered and strongly fractured.

Scisti Silicei formation (Jurassic), formed by thin-layered and fractured variegated cherty shales, partially cherty marls, green and red Radiolarites and graded pebbly limestones.

Galestri formation (Lower-Middle Cretaceous) consisting of the clay and marly thinly bedded rocks.

From the structural point, the area is characterized from the presence of numerous faults and thrusts. As a consequence, the permeability of the carbonate aquifer system shows a large variability.

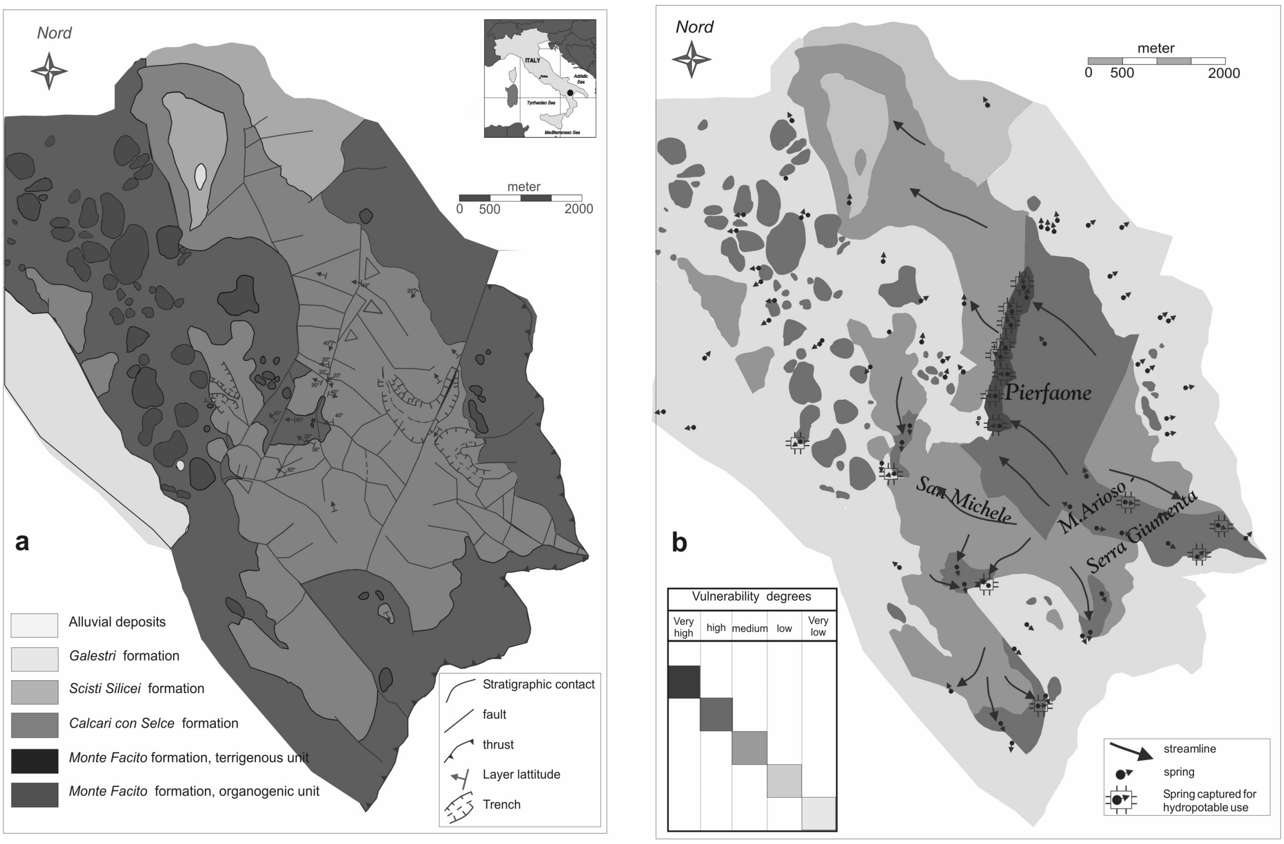

Fig. 1: Basento Valley carbonate aquifer system: a) geological map and b) vulnerability map.

The presence of these structures strongly influences the underground circulation, while in general the tectonic features represent important underground divides therefore playing an important role in the hydrogeological behaviour. Along one of the principal fault zones we have the manifestation of the numerous springs with the important Fossa Cupa springs system (about 32 springs) with a mean discharge for the period 1969-1999 of about 160 l/s and the San Michele spring system with a mean discharge of about 143 l/s (Fig. 2).

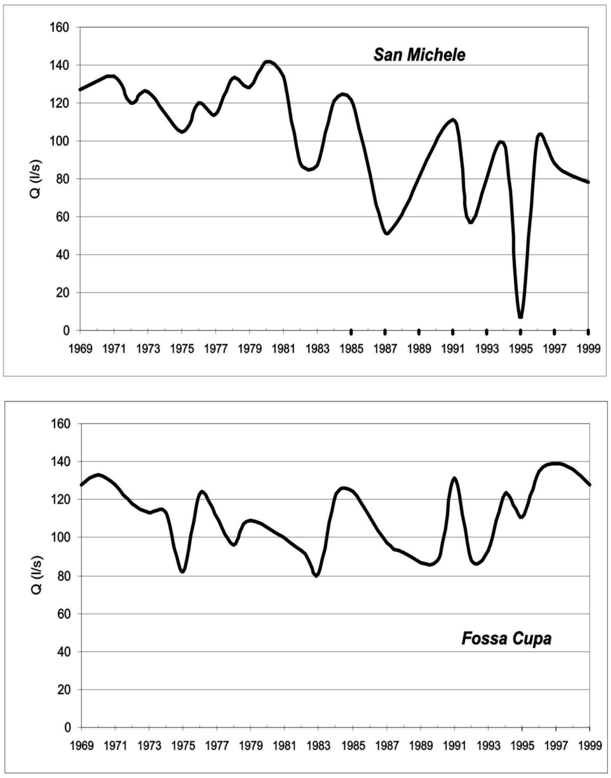

Fig. 2: Discharge (Q) of the San Michele and Fossa Cupa spring system.

For the evaluation of the intrinsic vulnerability of the Basento Valley carbonate aquifer system, a complex and hydrogeologic setting approach was selected obtained using the GNDCI-CNR method [7]. This method supplies a protocol of standard hydrogeological contest based on the comparison between the situation of interest and the reference ones proposed by the method for the different degrees of vulnerability. Accordingly, this allows the recognition of homogeneous zones articulated from the morphological, hydrogeological and structural point of view.

The application of the GNDCI-CNR method also permits to evaluate the intrinsic vulnerability to contamination of the carbonate system varies between low and very high (Fig. 1b). These high values of vulnerability is mainly due to the density of the fractures, the petrographic composition of the permeated geological formations and the depth of the water table.

2.2 Gouvia carbonatic aquifer system

One of the major aquifer systems of the Kerkyra island (Western Greece) is represented by Gouvia carbonate aquifer system located in the central sector of the island (fig. 3).

In the geodyamical framework, Kerkyra Island belongs to the external Hellenides and, in particular, to the Ionian Zone [8]. The geological formations that outcrop in the study area are ([9], figure 3):

Triassic dolomitic breccias and dolomitic limestones that outcrop in most of the study area. This formation shows high permeability and is characterized by several wide dolines. In places, also deposits of gypsum are present (figure 3; 7);

Triassic Foustapidima Limestones, outcropping in the eastern side of the island, that are black, massive to well stratified, with evident white strata due to the occurrence of Cardita Gumbeli (figure 3; 6);

Jurassic Vigla Limestones (figure 3; 5) and Upper *Cretaceous calcareous breccias* (Fig. 3; 4) outcropping in the northern sector;

Miocene marls with thick gravel-to-conglomeratic beds (Fig. 3; 3);

Pliocene plastic blue marls with sand-to-gravel intercalations (Fig. 3; 2);

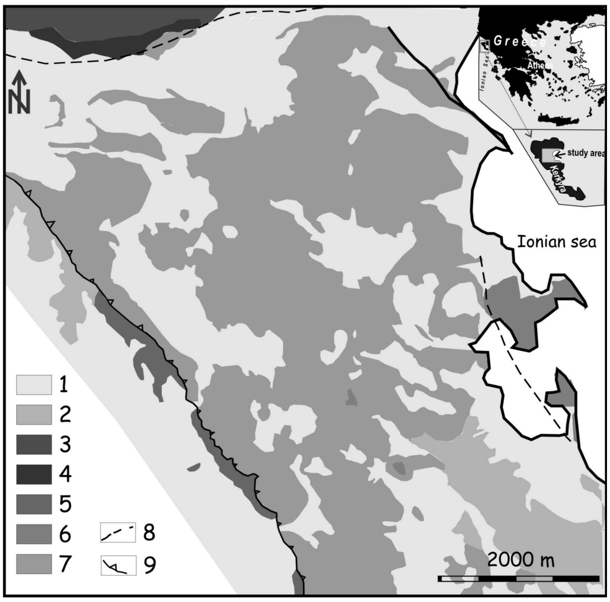

Fig. 3: Geological map of Gouvia aquifer system. 1: Alluvial deposits; 2: marls (Miocene-Pliocene); 3: calcareous breccias (Cretaceous); 4: Vigla Limestones (Jurassic); 5: Posidonia shales (Jurassic); Foustapidima Limestones (Triassic); 7: dolomitic limestones (Triassic); 8: fault; 9: thrust.

Quaternary alluvial deposits (Fig. 3; 1).
The compressive tectonics that has been affecting the study area since Miocene time caused the faulting and deformation of all the above-mentioned geological formation.

2.2.1 Vulnerability of the aquifer system

A huge carbonate aquifer develops inside the dolomitic breccias, as testified by the several springs gushing all over this territory (Fig. 4). These are principally sporadic springs due to the outcropping of the piezometric surface, that show a low water capacity. The average permeability of this aquifer is in the order of 10^{-2} cm/s.
From a climatic point of view, the mean annual precipitation relative to the period 1955-2004 is 1095 mm, with November and December as most rainy period (187 mm) and summer months as least rainy one. As concerns the average annual temperature during the same reference period, it ranges from 10°C, in winter, and 26°C, in summer.

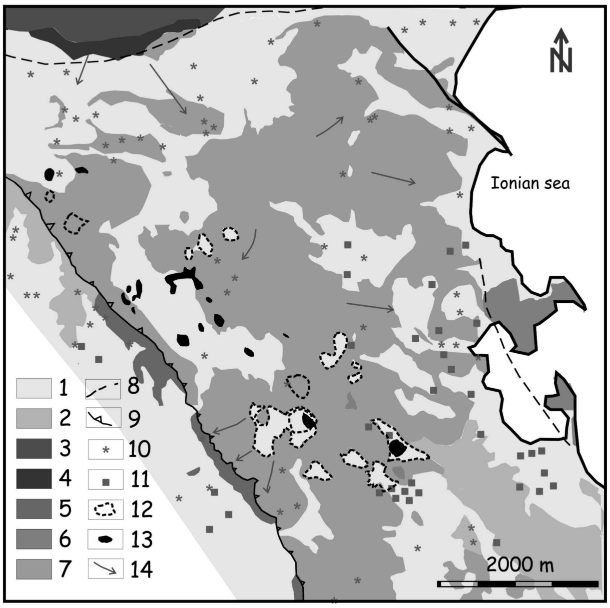

Fig. 4: Gouvia aquifer system: hydrogeological map. 10: spring; 11: well; 12: dolines; 13: lake; 14:groundwater flow direction (from 1 to 9 point can you see the figure 3).

In order to evaluate the vulnerability of the area, the GNDCI-CNR method proposed by Civita 1994 [7] has been used. In the geological and hydrogeological framework of the area, the application of this method allowed us to the definition of the following degrees of intrinsic vulnerability (Fig. 5):
a) low, in the marls with low permeability;
b) medium, in the alluvial deposits;
c) high, in the dolomitic breccias, Vigla and Foustapidima Limestones, due to the high permeability and low depth to water;
d) very high, in those areas where the dolomitic breccias are characterized by the occurrence of dolines.

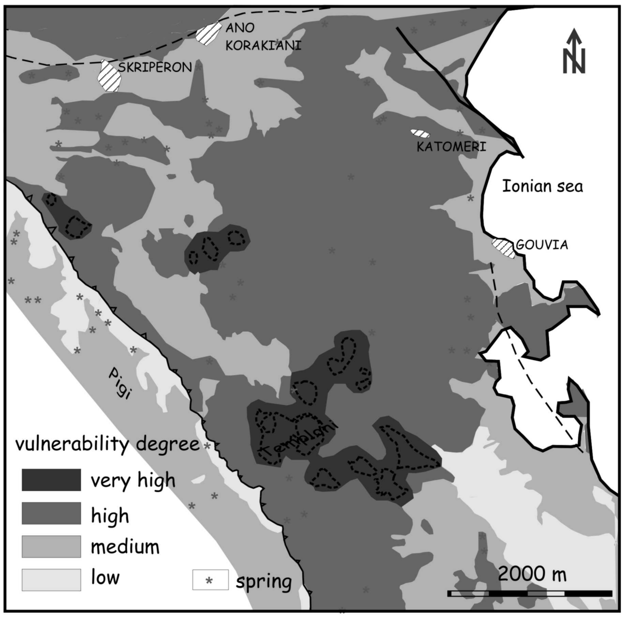

Fig. 5: Vulnerability map of the Gouvia aquifer

2.3 Ferrara alluvial aquifer system

In the eastern sector of the Po plain, in the Prefecture of Ferrara, the highly dynamic palaeogeographic evolution of the River Po deeply influenced the morphological and lithological variability of the area an its underground. As a consequence, the western sector near the town of Ferrara shows altimetric variations as high as 6 m, while absolute quote variability is restricted to only -1 m in the eastern sector.
In this flat territory, in the fluvial sediments we can distinguish an unconfined aquifer system consisting of sandy lenses with variable texture, while silty-sandy materials locally crop out. A low permeability layer consisting of silt and clay sometimes alternating with peat separates the unconfined aquifer from the underlying one. The exploitation of this unconfined aquifer is performed by using numerous wells of about 1 m in diameter excavated since historical times down to a depth of 7 m. The geometric characteristics of these highly heterogeneous aquifers are mainly influenced by the geomorphological evolution of the territory and

particularly by the occurrence and the pattern of the palaeo-river channels and the outflow cones [10].
Moreover, the measurements carried out in the about 400 monitoring wells, indicate that the water level of this aquifer stands at a depth between 1.5 and 2.0 m below the field surface.
The lithological composition of the unsaturated zone presents a large variability. In particular, in the study area down to a depth of 1.5 m, we can distinguish six soil units varying from sandy along the principal palaeo-channel axes to silty-clayely in the interfluvial zones [10].

Based on a detailed knowledge of the hydrological, lithological and hydrogeological characteristics of the system and following a SINTACS point count system model [5] implemented in a GIS, the intrinsic vulnerability of the aquifer is then calculated. The parameters considered to estimate the intrinsic vulnerability of the aquifer systems are: i) the depth to water table, ii) the effective infiltration, iii) the soil and the unsaturated zone attenuation capacity, iv) the hydrological characteristics and the hydraulic conductivity of the aquifer and finally, v) the topographic surface average slope.
The index of the intrinsic vulnerability is obtained according to the equation:

$$\boldsymbol{I}_{SINTACS} = \sum_{j=1}^{7} \boldsymbol{P}_j \times \boldsymbol{W}_j$$

where P, is the rating of the SINTACS parameters that the method considers and W, the correlated weight inside the selected string.
For the evaluation of the vulnerability the territory is subdivided in square cells with 500 m sides and where the index of the intrinsic vulnerability is calculated for each cell barycentre.
The results of this application presents in figure 6b. The vulnerability of the unconfined aquifer system vary between medium and extreme high (Fig. 6b). The low depth of the water level and the presence of the palaeo-channels mainly influenced the vulnerability of the aquifer (Fig. 6a). In the areas characterized by high vulnerability we have observed a geochemical degradation of the underground resources emphasised by high values in NO_3 and SO_4 due to the intense agricultural activities.

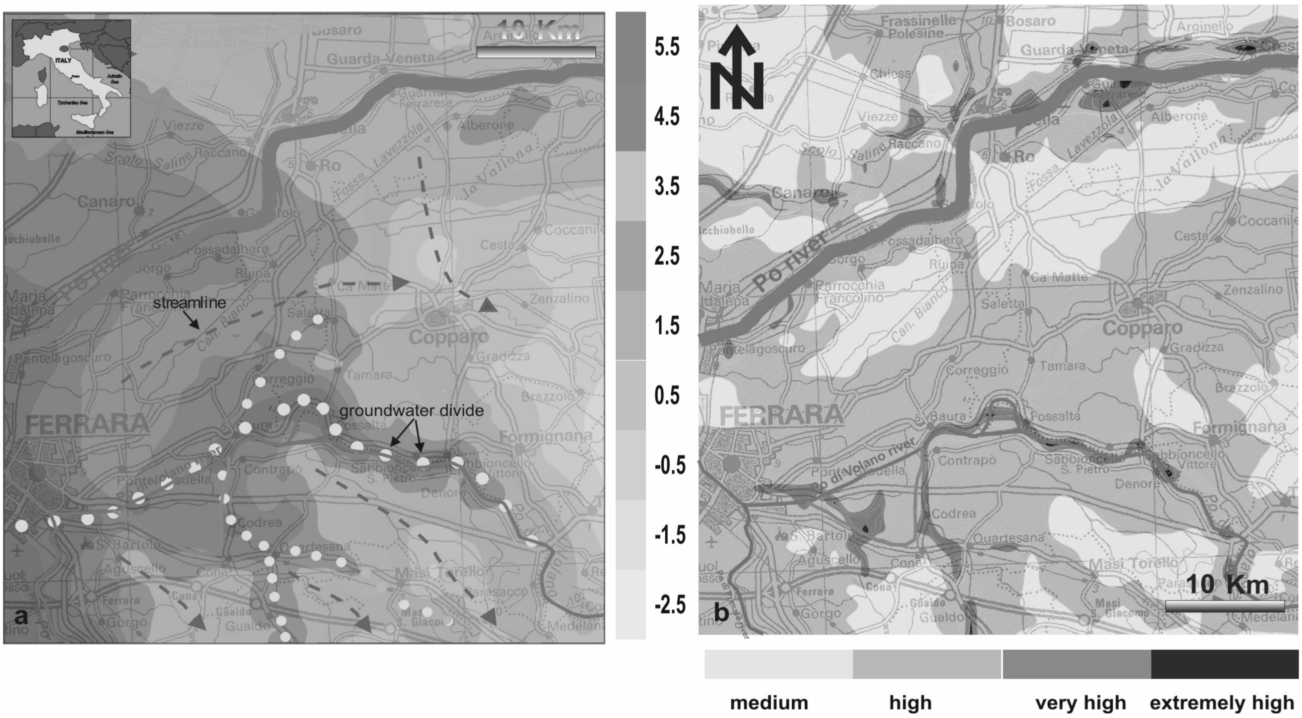

Fig. 6: Unconfined alluvial aquifer system in the Ferrara plain: a) piezometric level and b) vulnerability map.

3 Discussion
The construction of vulnerability-to-contamination maps of aquifers is an operative instrument for territorial planning and protection of the underground patrimony. In the present research, the choice of the methodological approach for the evaluation of the vulnerability of the aquifers is based on the local hydrogeological characteristics

and on the amount of available geological information.
In particular, the realization of vulnerability maps for three important aquifers allowed to recognise and characterise the occurrence of sectors with high values of vulnerability to local polluting sources. In the karstic systems, this vulnerability is mainly influenced by the local tectonic setting and by the depth of the water table, while in the alluvial aquifer the lithological composition and variability of the unsatured zone are the principal factors governing the distribution of the vulnerability index.

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