

Map of the vulnerability to pollution of the Apuo-Versilia aquifer (Tuscany - Italy)

Carta della vulnerabilità all'inquinamento dell'acquifero della Pianura Apuo - Versiliese (Italia)

Giovanni Pranzini, Francesco Di Martino, Riccardo Fanti, Katia Fontanelli

Riassunto: La Carta della Vulnerabilità all'inquinamento degli acquiferi della pianura costiera Apuo-Versilia è stata redatta con il metodo SINTACS. La disponibilità di un gran numero di dati di sottosuolo (colonne litostratigrafiche e indagini piezometriche) integrate in un ambiente GIS, ha permesso di ottenere una mappa di elevato dettaglio su un'area molto estesa (circa 152 km²). I tassi di vulnerabilità da alta a molto alta prevalgono in gran parte della pianura, il che costituisce un rischio per le risorse idriche sotterranee, che rappresentano una importante risorsa per l'approvvigionamento idrico civile.

Abstract: *The authors have drawn up the Map of Vulnerability to Pollution for groundwater of the Apuo-Versilia coastal Plain using the SINTACS method. The availability of a large number of subsoil data (stratigraphic columns and piezometric surveys) integrated in a GIS environment, has allowed to obtaining a large detail map on an extended area (about 152 Km²). Vulnerability rates from high to very high prevail in much part of the Plain; this poses a risk for groundwater, which represent an important resource for civil water supply.*

Keywords: *vulnerability mapping, coastal aquifer, Apuo-Versilia Plain (Tuscany).*

Parole chiave: carta della vulnerabilità, acquifero costiero, pianura Apuo-Versiliese.

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Introduction

The Authors drafted this Map of Vulnerability to groundwater pollution of the Apuo-Versilia Plain under a research agreement between GAIA, Water Service of ATO 1, Tuscany North (Provinces of Lucca and Massa-Carrara), and the Department of Earth Sciences of the University of Florence. The general objective of the research was to assess the water resources of the entire territory of the ATO 1, both current and in the near future in relation to the forecasts of climate changing. The protection of groundwater quality of the Apuo-Versilia Plain is very important, as GAIA draws through the wells 16.1 million cubic meters of water per year (average of 2010-2012), about one third of the total water provided by civil aqueducts of the Plain.

The Map was carried out using the parametric point count system SINTACS (Civita 1990), which is the method officially adopted in Italy according to the National Group from the Defense Against Hydrogeological Disasters of the National Research Council.

If we compare an intrinsic vulnerability map with the groundwater contamination status, we can often observe that waters are contaminated also in areas with very low vulnerability. This could lead us to conclude that this type of document does not work. Indeed, pollutants can infiltrate in highly vulnerable areas and migrate into zones less vulnerable according to the groundwater flow. We must always take into account the fact that the vulnerability maps obtained by methods such as SINTACS refers to vertical infiltration of pollutants. Therefore, we should consider vulnerability maps primarily as a land use planning tool: we can use them to prevent potentially polluting infrastructures (factories, landfills, etc.) from being located in vulnerable areas. Furthermore, we should use vulnerability maps in agriculture to regulate the use of fertilizers, herbicides and pesticides according on the soil's ability to attenuate pollutants or prevent their leaching to groundwater.

Geographic and morphological overview

The Apuo-Versilia coastal plain (Fig. 1, hereinafter Plain), in Tuscany, is about 34 km long from the NW limit of the municipality of Carrara to the SE limit of the municipality of Viareggio. The north part of the coastal plain (Apuan Riviera) belongs to the Province of Massa Carrara, the south (Versilia) to the Province of Lucca. The Plain has a width that increases from three to five km from North to South.

The morphological and climatic characteristics of the Plain, with the Apuan Alps sheltering it from the cold winds from

north, have favored urban settlement and the development of productive activities. The oldest settlements are located on the slopes of the Apuane, at more easily defensible position; the cities of the plain (Carrara, Massa, and Pietrasanta) developed later, at the vertex of the alluvial fans.

The anthropic occupation of the coastline took place in the nineteenth century: the various “marine” have had a dizzying development after the last war, when the coast became a summer vacation area of great appeal. Currently, holiday homes and hotels occupy the entire marine band, virtually without any continuity solution.

The main industrial activity is the processing of marble extracted in the Apuan Alps, but also of different stone materials (granites and others) of external origin.

In the Apuan Riviera, metallurgical and chemical industries were well developed, but, in the last 25 years, these activities have considerably reduced, while flourishing handicraft and small building-related industries have grown.

Agriculture had a great development in the last century; currently, a large part of the intermediate and the inner strips are engaged in specialized agriculture: mostly vegetables, fruit and flowers. Presently, this activity is also regressive. Tourism, especially in summertime, is now the main source of income in the coastal plain. For this activity, some concerns come from the erosion of the beaches.

Geological overview

The Apuo-Versilia coastal plain was built in the Quaternary with sediments carried by watercourses that descend from the Apuan Alps and with the materials brought to the sea by the rivers Magra, Serchio and Arno and distributed by the coastal currents. In the Plain, there are three morphological bands almost parallel to the coastline.

The fans of the rivers descending from the Apuan Alps form the inner band. In the Apuan Riviera, the main fans are those of the Frigido River and of the Carrione Creek. Fan



Fig. 1 - The Apuo-Versilia coastal plain, study area.

Fig. 1 - La pianura costiera Apuo-Versiliese, area di studio.

deposits mostly consist of carbonate gravel of Apuan origin (Marmi and Grezzoni), somewhere partially cemented.

In Versilia, the major fan is formed by the Versilia River, while that of the Camaiole River is less developed and less prominent; this depends on the fact that most of the sediments carried by the river stop in the Camaiole basin, of karst origin.

These river deposits are terraced, with the higher escarpments, until eight meters, in the Apuan Riviera. In the distal part, the fans appear truncated by a scarp up to 5 meters running parallel to the coast. This is the limit reached by the sea during the Versilian transgression (Sestini 1957).

In Versilia, the fan band is considerably narrower, and there are no evident terraces, witnessing that the southern half of the Plain has continued to subsiding after the last glaciation.

The intermediate strip is the topographically lower, being in some areas below the sea level. This strip corresponds to the lagoon and marshy areas isolated from the sea by the development of sandy coastline and dunes. The wetlands have been largely "reclaimed": now, the water mirrors are limited to Lake Massaciuccoli and Lake Porta, the latter now reduced to a small wetland entirely covered by cane thicket. Lime and clay, even with peat, mainly form the ground.

The Versilia Reclamation Consortium operates in this area, crossed by several channels of "low water" and "high waters". Waters of the low channels arrive in small basins, where the level water is below sea level (-1.5 ÷ -2 m); from here they are lifted by water-scooping machines and poured into the "high water" channels, and hence to the sea.

Beach and Aeolian sand form the coastal band. The dunes, which did not exceed the height of 4-5 m, were almost all deleted by intense urbanization that has affected the coastline over the last 80 years. The width of this band grows from NW to SE: about 1 km in Marina di Carrara, it arrives at 3-4 km to Lido di Camaiole. The coastal strip has grown by the contribution of the sediments of the Magra and Arno Rivers, distributed by the coastal drift.

The whole Plain has rapidly increased over the last 4,000 years because of deforestation and the introduction of agriculture: this caused an increase in land erosion and a strong increase in the solid flow rate of the watercourses. This led to marine regression despite the rising of the sea level (about a meter over the last 3,000 years). The trend reversed following the construction of the port of Marina di Carrara in the 1920s, which resulted in the interruption of coastal sediment transport from the north. Extraction of gravel and sand from the Magra River bed, started after the last war, has further increased the coastal erosion. We are currently facing a beach erosion that by Marina di Carrara proceeds south rather quickly despite the interventions performed (mainly orthogonal groynes) and partly because of the fact that these interventions have had the effect of moving the erosion southward.

Less is erosion of the beach in Versilia, where the construction of the port of Viareggio has interrupted the drift to north of the sand brought by the Arno River.

Hydrogeological Features

The multi-layer aquifer of Versilia and Apuan Riviera is one of the main groundwater bodies in Tuscany (Regione Toscana - CNR, Istituto di Geoscienze e Georisorse 2011). The complex of quaternary sediments, both continental and marine, attains the thickness of several hundred meters near the coastline.

The alluvial deposits are mostly composed of gravels and pebbles with lenses of sand and clayey silts. This powerful sedimentary body is an aquifer with medium-high permeability and, due to its thickness, of high transmissivity. The alluvial gravel and sand form an unconfined aquifer in the piedmont band, and passes to confined aquifer in the central strip of the plain, where palustrine clays cover it. At various depths, carbonate-cement conglomerates are present. Such a conglomerate is poorly permeable and, where continuous, it subdivides the aquifer into more confined overlapping aquifers. This aquifer forms the plain's main aquifer, exploited by deep wells (up to 100 m and more). Groundwater is used for drinkable and agricultural purposes; well exploitation for industry was important in the north (industrial area of Massa and Carrara), but the crisis of big industries at the end of the past century has dramatically reduced groundwater withdrawal.

Proceeding towards the coast, the alluvial deposits dive under the sand of the "Versilian" transgression. The coastal and Aeolian sands represent an unconfined aquifer of medium permeability, which in the northern part of the Plain (the Apuan Riviera) attains a thickness of 30-35 meters. In some areas the sand rest directly on the alluvial gravel, forming a single aquifer. In others, a layer of silt or conglomerate separates the two aquifers.

In the southern half of the Plain (the Versilia), the marine sands extend more towards the Apuane Alps and have greater thickness: near the coastline, even the deepest wells do not reach the continental deposits. This testifies that, in the Quaternary, the subsidence of Versilia was much greater than that of the Apuan Riviera. Moreover, in Versilia the strip of marsh and lagoon deposits is wider and a vast lagoon (Lago di Massaciuccoli) occurs in Versilia.

The Aeolian and marine sands of the coastal belt form an unconfined aquifer with medium permeability. Currently, domestic and agricultural wells exploit this aquifer. In summertime, many shallow wells (usually less than 10 meters deep) supply water to beach resorts, hotels and summerhouses.

The marine intrusion affects the aquifer of the coastal sands, to a different extent in the different areas (Fig. 2), as well as the aquifer of alluvial gravels (Pranzini 2002). The presence of areas topographically below the sea level also favors the salinization of groundwater. However, the reduction in the withdrawals for industries in the last decades and the techniques of saving water in agriculture have led to a substantial stabilization of groundwater salinization in the Plain.

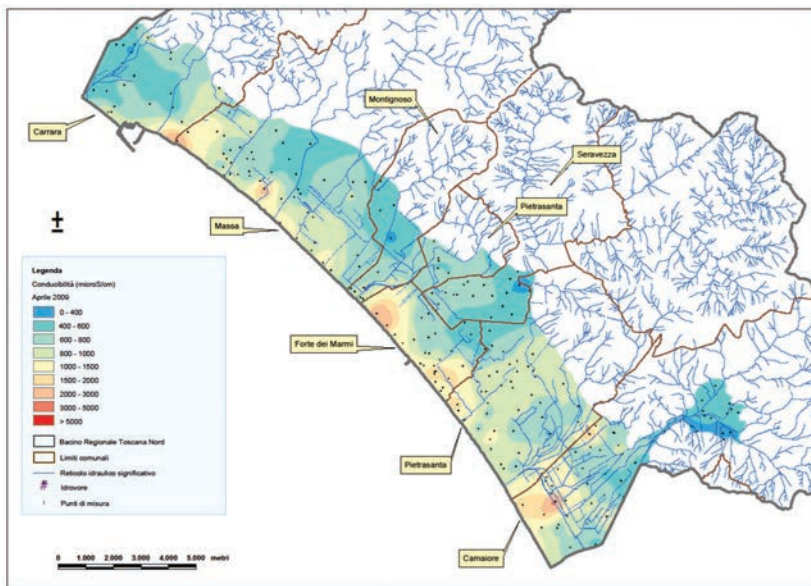


Fig. 2 - Electric conductivity of groundwater, measures of April 2009. The yellow to orange areas have groundwater with salinity beyond the limits for drinking water (University of Florence DST 2016).

Fig. 2 - Conducibilità elettrica dell'acqua di falda, misure dell'aprile 2008. Le aree dal giallo all'arancione hanno acqua di falda con una salinità oltre i limiti di potabilità (Università di Firenze DST 2016).

Vulnerability map

The SINTACS method, partially derived from the DRASTIC method (Aller et al. 1987), takes into account the following seven parameters, resulting in the acronym (in Italian):

1. Depth to ground water;
2. Effective infiltration;
3. Self-attenuation capacity of unsaturated zone;
4. Type of soil cover;
5. Type of aquifer;
6. Hydrogeological characteristics of the aquifer;
7. Hydraulic conductivity of the aquifer;
8. Slope of land surface.

A different weight has assigned to each parameter for specific situations (Table 1). Obviously, each parameter has a different weight depending on whether we are in a karst environment, in fissured rocks instead of in sediments, in areas with important superficial drainage. In our case, the chosen weight string is that of relevant impact considering that in the Plain there are many potentially polluting agricultural and industrial activities.

For each parameter, a score from one to ten is attributed to each area unit, depending on the different situations.

Tab. 1 - Strings of weights (from ISPRA 2001).

Tab. 1 - Stringa dei pesi (da ISPRA 2001).

| Parameter | ordinary | relevant | drainage | karst | fissured |
|-----------|-----------|-----------|-----------|----------|-----------|
| Parametro | ordinario | rilevante | drenaggio | carsismo | fessurato |
| S | 5 | 5 | 4 | 2 | 3 |
| I | 4 | 5 | 4 | 5 | 3 |
| N | 5 | 4 | 4 | 1 | 3 |
| T | 2 | 5 | 2 | 3 | 4 |
| A | 3 | 3 | 5 | 5 | 4 |
| C | 3 | 2 | 5 | 5 | 5 |
| S | 1 | 2 | 2 | 5 | 4 |

Therefore, the product weight x score varies, theoretically, from 26 to 260. Based on this product, areas of differing degrees of vulnerability, from extremely high to low, are delimited.

It is important to note that the method SINTACS calculates the degree of vulnerability to pollution of the first aquifer present in the subsoil, regardless of its value and its use. Therefore, it is important to have a detailed geological conceptual model to decide whether a layer forms an aquifer or not.

The drafting of the Vulnerability Map of such a large area (about 152 km²) was possible by the availability of homogeneous and reliable geological and hydrogeological data. In particular:

- 230 stratigraphic logs of wells and geognostic surveys, 181 present in the database of the Tuscany Region (<http://sira.arpat.toscana.it/sira/>) and 49 provided by GAIA or collected by drilling companies and professional geologists.
- data of the head contouring performed twice a year (April and September) by the Tuscany Region from 2002 to 2009. On average, the operators measured 235 wells or piezometers in each survey.

By means of a GIS, each SINTACS parameter was computed in distributed shape, obtaining seven raster maps. The grid is made up of about 16,000 square units with a hundred-meter side.

Depth to ground water S (weight 5)

The higher the depth of the water table the less likely it is that a pollutant infiltrates down to the groundwater. If the aquifer is confined the thickness of the terrain above the aquifer must be taken into account.

For the calculation of this SINTACS parameter S, we have interpolated the piezometric levels of April 2009, the more recently measured in the season of high groundwater condition, to obtain the piezometric map. We have then compared the piezometric surface with the available stratigraphic columns: where the piezometric surface was within the aquifer, we have

assumed the piezometric level for the calculation of the S parameter; where it was above the top of the aquifer we have considered the thickness of the ground above the aquifer. Figure 3 shows the layout of depth to ground water. We assigned the scores according to Table 2.

Tab. 2 - Values of depth to ground water and corresponding ratings (ISPRA 2001).
Tab. 2 - Valori della soggiacenza e punteggi corrispondenti (ISPRA 2001).

| Depth to ground water (m) Soggiacenza (m) | Rating Punteggio |
|--|---------------------|
| 0 - 1 | 10 |
| 1 - 3 | 9 |
| 3 - 5 | 8 |
| 5 - 7 | 7 |
| 7 - 10 | 6 |
| 10 - 15 | 5 |
| 15 - 20 | 4 |
| 20 - 25 | 3 |
| >25 | 2 |

The scores are almost everywhere high (Fig. 4) because the depth of the water table is generally small. The piezometric level is deeper only in the areas of the fans, due to both the morphology and the aquifer pumping.

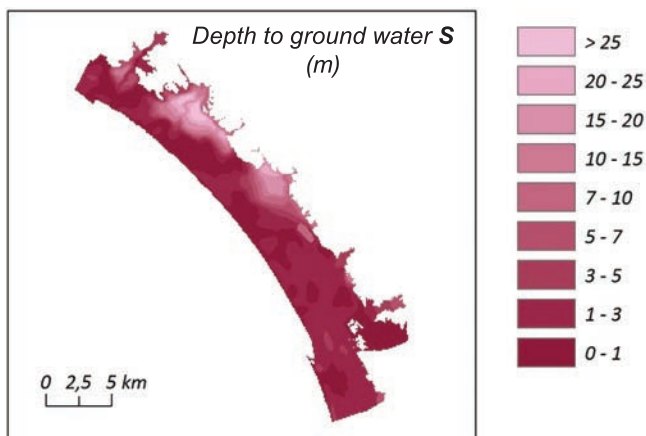


Fig. 3 - Layout of depth to ground water (water table or top of aquifer).

Fig. 3 - Distribuzione del parametro soggiacenza (tavola d'acqua o tetto dell'acquifero).

Actual infiltration I (weight 5)

The SINTACS score increases with rainwater infiltration, because increased infiltration favors the transport of pollutants; but over 275 mm/year, the score is considered decreasing because the dilution effect is presumed to prevail (Fig. 4).

We have calculated this parameter with the formula

$$I = (P - Er) * Cie$$

where P is the mean annual precipitation of the decade 2003-2012 (data provided by the University of Parma 2016), Er the actual evapotranspiration calculated with the Turc formula (Turc 1954), Cie is the actual infiltration coefficients $I / (P - Er)$,

$$Er = \frac{P}{\sqrt{0,9 + \frac{P^2}{L^2}}}$$

where $L = 300 + 25T + 0,05T^3$; with T mean annual temperature in °C

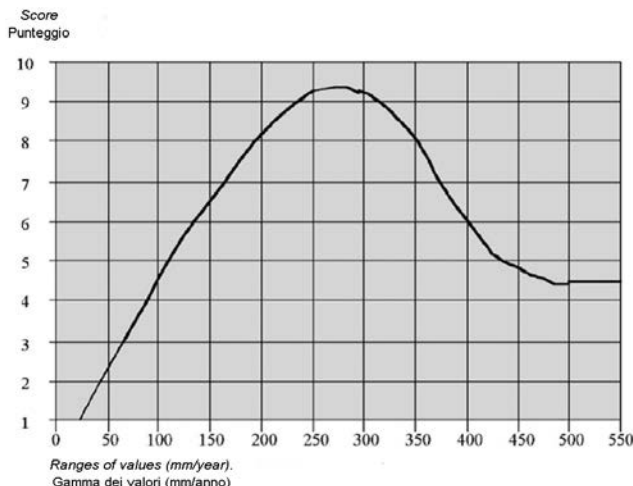


Fig. 4 - SINTACS rating of the actual infiltration (ISPRA 2001).

Fig. 4 - Punteggi SINTACS dell'infiltrazione efficace (ISPRA 2001).

In the plain, the average annual temperature of the decade considered is between 14.5° and 17.0 °C, while the average annual precipitation is between 900 and 1350 mm. Actual precipitation P-Er results between 268 mm and 655 mm.

Cie is different for differing soil types. Table 3 contains the Cie for the geological units of the Apuo-Versiliese Plain. We have taken these values from the study of Pranzini (2004) on the hydrogeological balance of the Plain aquifer.

Tab. 3 - Values of the Cie for the geological unit outcropping in the Plain.
Tab. 3 - Valori del Cie per i terreni della Pianura.

| Sign Sigla | Geological formation Formazione geologica | Granulometric composition Composizione granulometrica | Cie Cie |
|---------------|---|--|------------|
| b | Modern alluvial deposits | b) Gravel prevailing | 0.50 |
| | | c) Gravel and sand | 0.45 |
| | | d) Sand prevailing | 0.40 |
| bna | Recent alluvial deposits (terraced and not terraced). | b) Gravel prevailing | 0.45 |
| | | c) Gravel and sand | 0.40 |
| | | d) Sand prevailing | 0.35 |
| | | e) Sand and silt | 0.20 |
| | | f) Silt and clay prevailing | 0.15 |
| bnb | Alluvial terraced deposits | g) Gravel with silt | 0.25 |
| | | c) Gravel and sand | 0.35 |
| | | e) Sand and silt | 0.25 |
| da | Aeolian deposits | g) Gravel with silt | 0.30 |
| | | Without granulometric description | 0.6 |
| e2a | Lacustrine deposits | a) Sand prevailing | 0.75 |
| e3a | Marshy deposits | | 0.15 |
| g2a | Beach deposits | | 0.08 |
| | | | 0.90 |

In continuous urban fabric, we have reduced infiltration to half to take into account the presence of waterproofed areas and sewage (data source: Corine Land Cover 2006; ISPRA – SINAnet); in discontinuous urban fabric, we have reduced it by one third.

The ratings for the parameter I are in Table 4.

Tab. 4 - Rainwater infiltration and related rating.

Tab. 4 - Infiltrazione da pioggia e relativo punteggio.

| Infiltration (mm/year) Infiltrazione (mm/anno) | Rating Punteggio |
|---|---------------------|
| 0-30 | 1 |
| 30-60 | 2 |
| 60-80 | 3 |
| 80-100 | 4 |
| 100-125 | 5 |
| 125-150; 380-410 | 6 |
| 150-180; 360-380 | 7 |
| 180-220; 320-360 | 8 |
| 220-320 | 9 |

The distribution of infiltration values reflects well geology (Fig. 5): the highest values are at the beach and aeolian sand, the lowest ones at the marsh deposits.

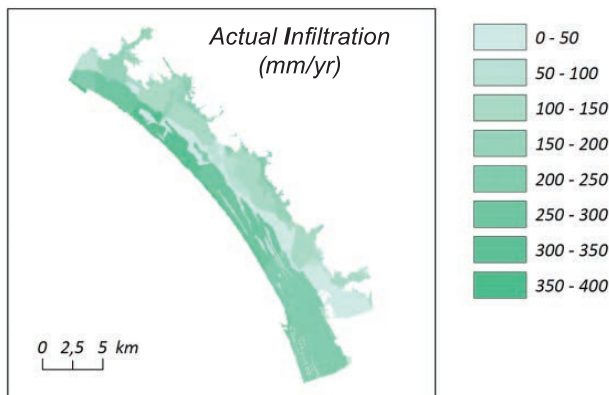


Fig. 5 - Layout of infiltration values.

Fig. 5 - Distribuzione dei valori dell'infiltrazione.

Attenuation capacity of the unsaturated zone N (weight 4)

The vertical permeability and the mineralogical composition of the unsaturated terrain over the aquifer are the characteristics to consider in evaluating the degree of attenuation of contamination. For a free aquifer, the unsaturated zone is the subsoil between the base of the soil and the water table level. If the aquifer is confined, the lower limit of the unsaturated zone corresponds to the top of the aquifer.

In order to calculate the distributed values of the parameter N, we have placed the piezometric levels recorded in April 2009 in each of the 230 available stratigraphic columns: if the unsaturated zone came out composed of different

granulometric layers, we have calculated the thickness-weighted average.

The SINTACS ratings assigned are in Table 5.

Tab. 5 - SINTACS scores assigned to terrains of unsaturated zone.

Tab. 5 - Punteggi SINTACS assegnati ai terreni non saturi.

| Terrains of unsaturated zone Terreni non saturi | Rating Punteggio |
|--|---------------------|
| Gravel | 9 |
| Sand | 8 |
| Gravel with sand | 8 |
| Gravel with silt | 6 |
| Sand with silt | 6 |
| Sandy silt | 5 |
| Silt | 4 |
| Clayey silt | 2 |
| Clay, peat | 1 |

Geognostic surveys, however, do not cover the whole plain: large parts, especially in the foothills strip, are without direct information on the nature of the subsoil. In these areas, we have assumed for the unsaturated zone the prevailing granulometric composition of the geological units, according to the Geological Map of the Tuscan Region (Table 6).

Tab. 6 - SINTACS rating assigned to aquifers.

Tab. 6 - Punteggi SINTACS assegnati alle unità geologiche.

| Sign Sigla | Geological formation Formazione geologica | Granulometric composition Composizione granulometrica | Cie Cie |
|---------------------|---|--|----------------------------|
| b | Present alluvial deposit | b) Gravel prevailing | 9 |
| | | c) Gravel and sand | 9 |
| | | d) Sand prevailing | 9 |
| bna | Recent alluvial deposits (terraced and not terraced). | b) Gravel prevailing | 8 |
| | | c) Gravel and sand | 7 |
| | | d) Sand prevailing | 7 |
| | | e) Sand and silt | 5 |
| | | f) Silt and clay prevailing | 2 |
| | | g) Gravel with silt | 6 |
| | | bnb | Alluvial terraced deposits |
| e) Sand and silt | 5 | | |
| g) Gravel with silt | 6 | | |
| da | Aeolian deposits | Without granulometric description | 8 |
| | | a) Sand prevailing | 8 |
| e2a | Lacustrine deposits | | 3 |
| e3a | Marshy deposits | | 2 |
| g2a | Beach deposits | | 10 |

The highest scores are where beach and Aeolian sand outcrop (Fig. 5): these deposits have little effect on the attenuation of pollutants. In other areas, the score depends both on the thickness and the content of clay and silt of the unsaturated zone

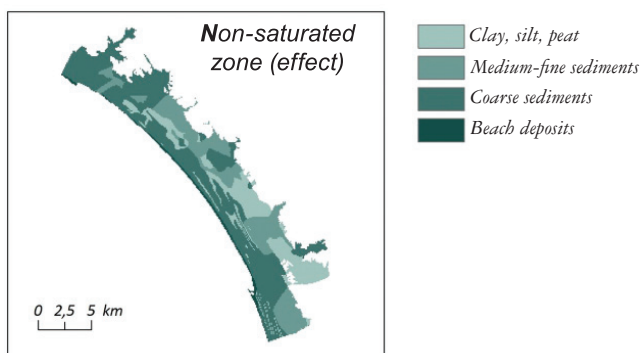


Fig. 6 - Layout of non-saturated geologic sediments.

Fig. 6 - Distribuzione dei tipi di terreno.

Type of soil cover T (weight 5)

Because of the filtering action and the significant chemical and biochemical activity of the soil, this parameter is one of the most important for the evaluation of intrinsic vulnerability.

A map of soils is not available for the Apuo-Versiliese Plain. Therefore, we have derived the soil types from the characteristics of outcropping sediments. For this attribution, we used the data of the Livorno coastal plain between Rosignano and San Vincenzo. Here the land is similar, and a Soil Map, performed by Tuscany Region, is available. Frullini et al. (2007) have linked the different types of soil to the different outcropping geological formations. We assigned these types of soil to the corresponding geological formations of the Apuo-Versilia Plain (Table 7).

Tab. 7 - Soil types of geological units and assigned SINTACS scores.

Tab. 7 - Tipi di suolo delle unità geologiche e punteggi SINTACS assegnati.

| Sign Sigla | Geological formation Formazione geologica | Granulometric composition Composizione granulometrica | Cie Cie |
|---------------------|---|--|----------------------------|
| b | Present alluvial deposit | b) Gravel prevailing | 9 |
| | | c) Gravel and sand | 8 |
| | | d) Sand prevailing | 8 |
| bna | Recent alluvial deposits (terraced and not terraced). | b) Gravel prevailing | 8 |
| | | c) Gravel and sand | 8 |
| | | d) Sand prevailing | 8 |
| | | e) Sand and silt | 5 |
| | | f) Silt and clay prevailing | 5 |
| | | g) Gravel with silt | 5 |
| | | bnb | Alluvial terraced deposits |
| e) Sand and silt | 5 | | |
| g) Gravel with silt | 5 | | |
| da | Aeolian deposits | Without granulometric description a) Sand prevailing | 7 8 |
| e2a | Lacustrine deposits | | 3 |
| e3a | Marshy deposits | | 2 |
| g2a | Beach deposits | | 9 |

The distribution of the scores (Fig. 7) is, as expected, in good correspondence with the geology of outcropping sediments.

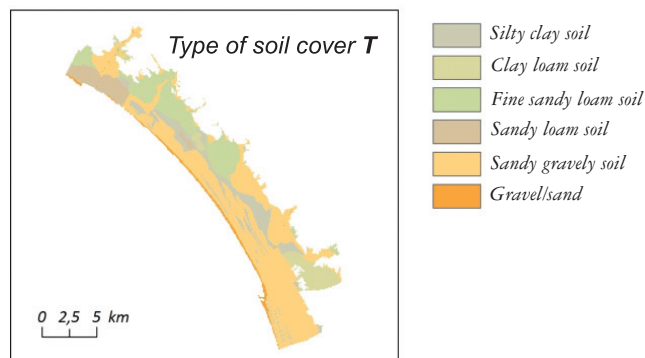


Fig. 7 - Distribution of types of soil.

Fig. 7 - Distribuzione dei tipi di suolo.

Hydrogeological characteristics of the aquifer A (weight 3)

The characteristics of the aquifer, in particular its permeability, play a fundamental role in defining the degree of vulnerability: the greater the permeability the more easily a contaminant moves from the point of entry to the potential target, well or spring.

Also for this parameter, we analyzed the 240 available stratigraphic columns to extract the characteristics of the aquifer. We have assigned the scores as in Table 8.

Tab. 8 - SINTACS scores assigned to the different lithotypes of the aquifer.

Tab. 8 - Punteggi SINTACS assegnati ai diversi litotipi di acquifero.

| Aquifer granulometric composition Composizione granulometrica dell'acquifero | Rating Punteggio |
|---|---------------------|
| Gravel | 9 |
| Gravel with sand | 8 |
| Sand | 8 |
| Gravel with silty sand | 7 |
| Gravel with silt | 6 |
| Sand with silt | 6 |
| Silty sand | 5 |
| Silt with sand | 4 |
| Silt | 2 |

In areas without geognostic surveys, we preferred to attribute the type of aquifer based on the knowledge of stratigraphy and sedimentary evolution of the Plain, rather than assigning it to the granulometric composition indicated in the Geological Map; the latter, in fact, concerns the outcropping lithology, which may be different from the aquifer.

The highest scores are at beach sands and alluvial fans (Fig. 8).

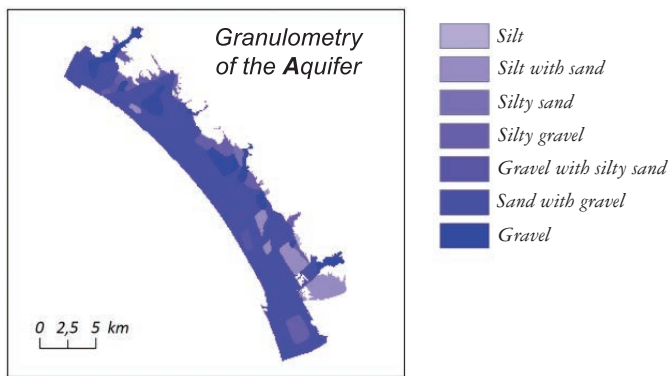


Fig. 8 - Layout of types of aquifers.

Fig. 8 - Distribuzione dei tipi di acquifero.

Hydraulic conductivity of the aquifer C (weight 2)

For aquifers with primary porosity, such as those of the plains, this parameter has about the same meaning as the previous parameter A. Based on this consideration, some authors (Gargini et al 1995; Frullini et al. 2007) have replaced this parameter with the thickness of the aquifer: since an aquifer is contaminated when the pollutant exceeds a certain concentration, contamination depends not only on the quantity of pollutant that reaches it, but also on the volume of the aquifer, and therefore its thickness. However, we preferred to follow the CNR's official method, so that our Vulnerability Map can be properly compared to others of the same type.

As is well known, the hydraulic permeability, or conductivity coefficient K , varies in many orders of magnitude, and samples of the same lithotype can have very different values. Only a few measurements of the coefficient K , derived from pumping tests, are available in the plain. Therefore, after assigning these K values to the corresponding aquifers, it was necessary to refer to literature data. Table 9 contains the mean values of K for the different lithotypes and the corresponding SINTACS score.

As done for the parameter N (attenuation capacity of the unsaturated zone), if the aquifer is composed by different granulometric layers, we calculate the thickness-weighted average.

Tab. 9 - Aquifer granulometry, corresponding K medium values, and SINTACS rating.Tab. 9 - Granulometria dell'acquifero, K media corrispondente e punteggi SINTACS.

| Aquifer Acquifero | K medium interval (m/s) Intervalli di K media (m/s) | Rating Punteggio |
|-----------------------|---|---------------------|
| Clean gravel | $10^{-2} - 10^{-3}$ | 9 |
| Clean Sand | $10^{-3} - 10^{-4}$ | 8 |
| Gravel and sand | $10^{-3} - 10^{-4}$ | 8 |
| Gravel/Sand with silt | $10^{-4} - 10^{-5}$ | 5 |
| Silt with sand | $10^{-5} - 10^{-6}$ | 3 |
| Silt | $10^{-6} - 10^{-7}$ | 2 |

Figure 9 shows that rating 8, corresponding to K between 10^{-3} and 10^{-4} m/s, prevails in the Plain.

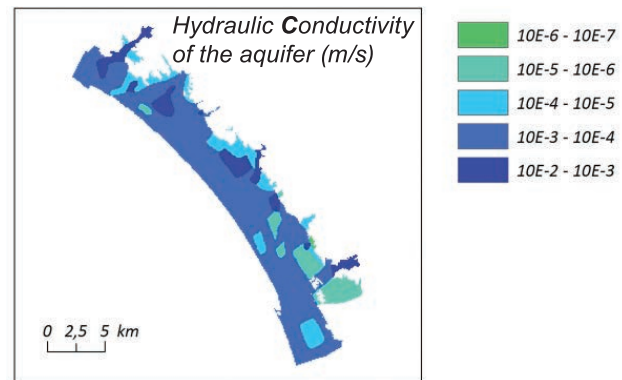


Fig. 9 - Layout of the aquifer hydraulic conductivity.

Fig. 9 - Distribuzione della conducibilità idraulica degli acquiferi.

Slope of the land surface S (weight 2)

The slope of the topographic surface is a factor to be considering in assessing vulnerability, as a higher slope increases the velocity of overland flow, thus decreasing the chance that a pollutant infiltrates the subsoil.

By means of the DTM of the land, the areas belonging to the different slope classes were distinguished. The SINTACS method assigns the score as in Table 10. Obviously, most of the Plain falls into the lower acclivity class (Fig. 10).

Tab. 10 - Ratings of the slope classes.

Tab. 10 - Punteggi delle classi di acclività.

| Slope (%) Acclività (%) | Rating Punteggio |
|----------------------------|---------------------|
| 0 - 2 | 10 |
| 2 - 4 | 9 |
| 4 - 6 | 8 |
| 6 - 9 | 7 |
| 9 - 12 | 6 |
| 12 - 15 | 5 |
| 15 - 18 | 4 |

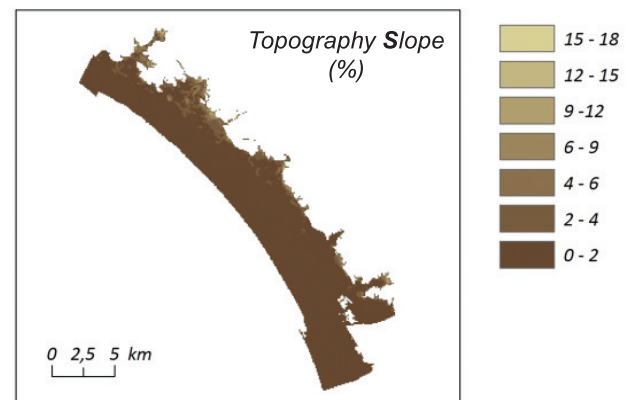


Fig. 10 - Layout of the slope classes.

Fig. 10 - Distribuzione dei terreni a diversa acclività.

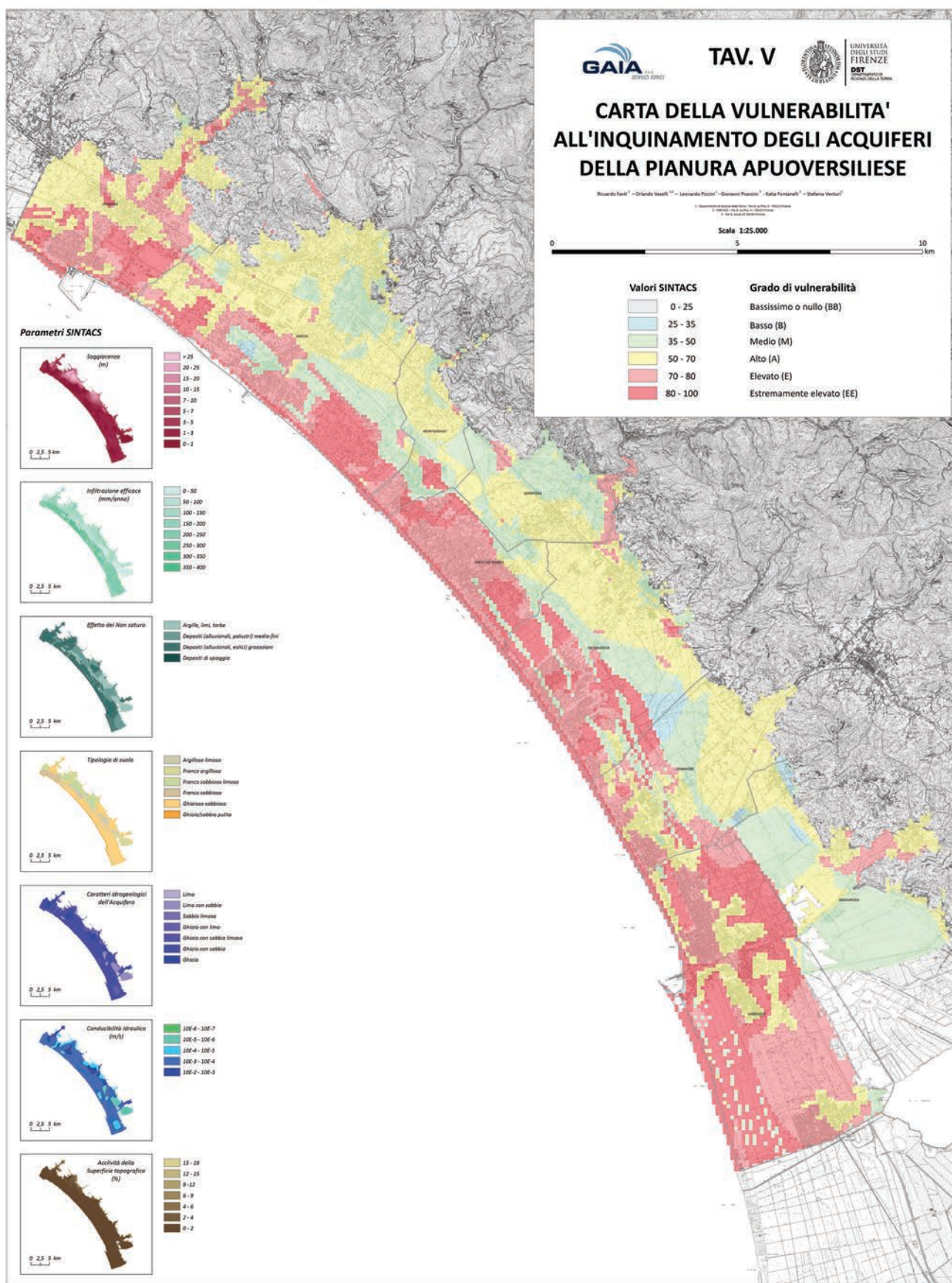


Fig. 11 - Vulnerability Map of the Apuo-Versilia Plain.
 Fig. 11 - Carta di vulnerabilità della Pianura Apuo-Versiliese.

Using the GIS, we have calculated for each element of the grid the sum of the seven scores for their weights

$$I_{SINTACS} = \sum_{i=1}^7 P_i \cdot W_i$$

where P and W are respectively the score and the weight of the string considered for the i-th parameter.

The raw values of the index, $I_{SINTACS}$ (raw), were then normalized to 100 by the formula:

$$I_{SINTACS(norm)} = \frac{I_{SINTACS(raw)} - I_{SINTACS(min)}}{I_{SINTACS(max)} - I_{SINTACS(min)}} \cdot 100 = \frac{I_{SINTACS(raw)} - 26}{260 - 26} \cdot 100$$

The normalized index was then subdivided into six classes (Table 11).

Figure 11 shows the layout of the vulnerability degree in the Plain (see on the previous page).

Tab. 11 - Ranges of the normalized SINTACS Index and Vulnerability Degrees, with relative color scale.

Tab. 11 - Intervalli dell'indice SINTACS normalizzato e gradi di vulnerabilità, con relativa scala di colore.

| Range of $I_{SINTACS}$ Intervallo dell'indice SINTACS | Vulnerability degree Grado di vulnerabilità |
|--|--|
| 0 – 25 | Very low , BB |
| 25 – 35 | Low, B |
| 35 – 50 | Medium, M |
| 50 – 70 | High, A |
| 70 – 80 | Very high, E |
| 80 – 100 | Extremely high, EE |

Conclusions

In the Apuo-Versilia Plain we find almost all the degrees of vulnerability to pollution of aquifers. The highest degrees (from high to extremely high) are in the outer strip of the Plain, in correspondence of aeolian and beach sands, where almost all parameters assume the highest values. In these areas, there is an unconfined free aquifer, mainly exploited for agriculture and for hotel and holiday gardens. Somewhere the water quality is not good due the infiltration of nitrates of agricultural and civil sewer system origin and saltwater intrusion from the sea.

In the interior, the degrees from high to medium prevail, mainly depending on the type of cover and the depth of groundwater. Groundwater quality is generally good. Here we have most of the wells for civil public water supply; therefore, it is very important that all caution must be taken not to disperse let pollutants leak into the ground, and that the well protection areas are correctly dimensioned according to local vulnerability degree.

Only in few areas, where swamp deposits outcrop, the degree of vulnerability is low.

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