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AQUIFER VULNERABILITY ASSESSMENT: IMPROVEMENT OF THE NEW PARAMETRIC MODEL W.A.T.ER.

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An improvement is proposed for the W.A.T.ER. model, a parametric model for the assessment of aquifer vulnerability to pollution developed within the National Group for Hydrogeological Hazard Prevention of the National Research Council of Italy. The original methodology has been modified to evaluate separately the "intrinsic vulnerability" of every permeable layer, which provides a more reliable representation for a complex aquifer. Insertion of data into a Geographical Information System has made possible a finer calibration of the weight of the different parameters, through several simulations and critical analysis of the results. In particular, the number and distribution density of wells is the most important parameter in the evaluation of aquifer vulnerability. The modeling time has been drastically reduced, and more precise answers are given to the public institutions managing groundwater resources and, broadly speaking, the environment.

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INTRODUCTION

In the last decade the water supply needs for drinking and industrial purposes have increased remarkably, requiring the exploitation of deeper aquifers as a consequence of the poor quality and reduced quantity of shallower resources.

Intensive exploitation focuses first on alluvial plains, characterized by both high productivity of groundwater resources (frequent presence of multi-layered complex aquifers), and a dense human settlement model, with industrial and agricultural activities particularly sensitive to the use of pollutants. Therefore, the need arises for adequate instruments to solve and manage the problems connected with the vulnerability of groundwater resources.

This Research Unit, which belongs to National Group for Hydrogeological Hazard Prevention of the National Research Council of Italy, has been involved since 1996 in developing a new approach for the estimation of aquifer vulnerability. We have proposed a new parametric model, called **W.A.T.ER.** (**W**ells, **A**quifer, **T**ransmissivity and Cov**ER**). This model is based on a parametric system that includes groundwater table depth (S), effective infiltration (I), the purifying effect of the unsaturated zone (N), type of cover (T), aquifer lithology (A), hydraulic conductivity (C), and surface slope (S). The model falls in the category of "point count system models" and takes into account four significant aspects linked to wells and aquifer characteristics (Marcolongo B. et al., 1999). Its application to a specific study area marked by hydrogeological complexity, like the alluvial plain of Pisa (Figure 1), is carried out to determine the reliability of the procedure, and its results compared with other accepted models, such as SINTACS (Civita and De Maio, 1997).

In addition, the present research aims to give a concrete solution to the institutional demand for exploitation of natural resources for sustainable economic growth in an already heavily industrialized zone.

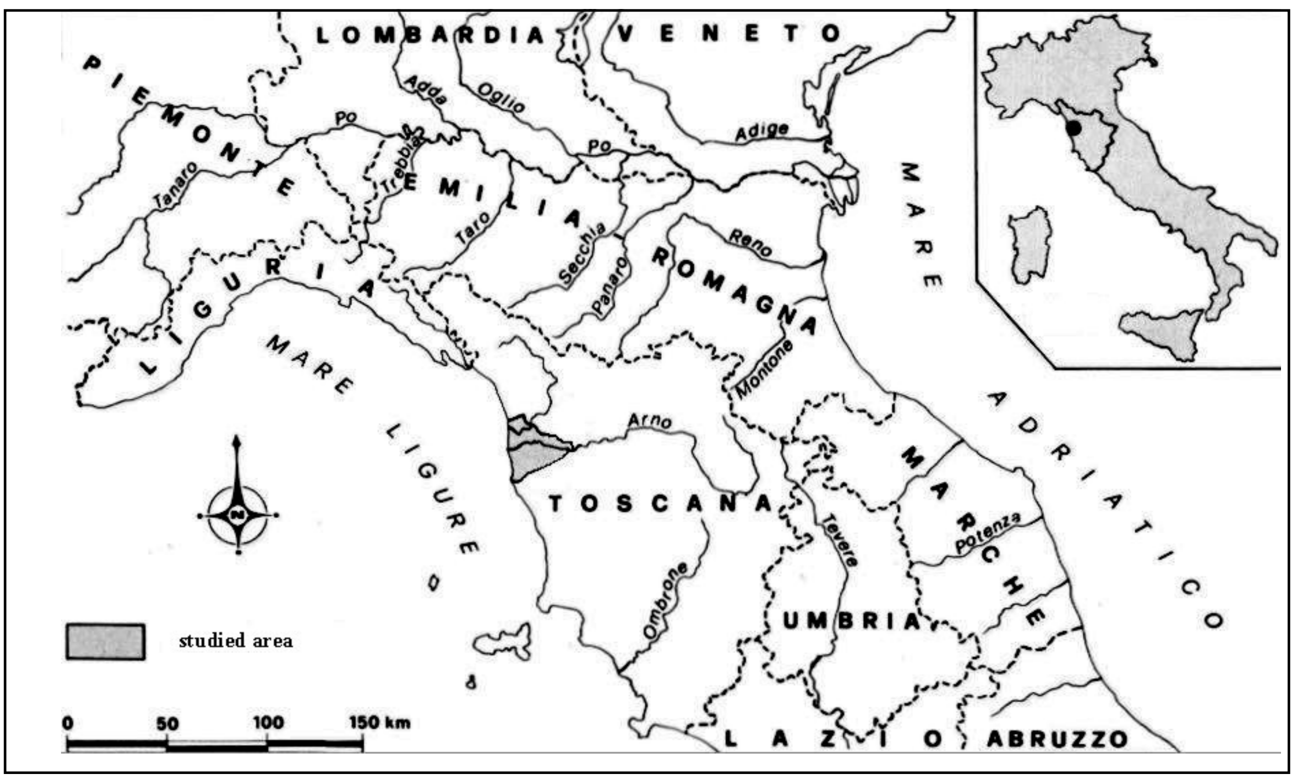

Figure 1. Map showing the study area.

METHODOLOGICAL IMPROVEMENT OF W.A.T.ER

The most prominent modification to the original model consists of the separate evaluation of intrinsic vulnerability for each single productive horizon, composing a multi-layered aquifer. This overcomes various problems, mainly linked to the availability and completeness of data. In other words, the description of the qualitative potential exposure to pollution of a specific exploited aquifer horizon is not precluded by a lack of information relative to the entire aquifer.

With the previous method, the global vulnerability assessment in alluvium depends strongly on the well depth, which may introduce high uncertainty where the well does not penetrate to the base of the alluvium. Moreover, the computation of a single intrinsic vulnerability value may be complicated by the requests of the end users, who are often interested in managing only a part of the groundwater resources, rather than the entire aquifer.

A second improvement is a better weight attributed to each parameter, on the basis of a larger set of information gathered in the plain of Pisa, followed by a series of computational simulations.

(W)ELLS

A well, here considered as a "stable landscape element", naturally increases the intrinsic vulnerability of the exploited confined aquifer, generating an influence inversely proportional to its distance.

The initial draft of W.A.T.ER. includes all the existing wells, either those reaching only the first confined layer of the aquifer or those penetrating to the deeper layers, which as a rule present a greater risk. In this revised version only wells placed in a specific permeable horizon contribute to the specific intrinsic vulnerability, in accordance with the following hyperbolic function:

$$P_w = 1000/d \qquad (1)$$

where P_w is the decimal weighted score attributed to the well and d the distance from the well itself (Figure 2).

Here the coefficient 1000 elevates the value of 200 initially proposed by Marcolongo et al., (1999), to the maximum distance foreseen by Italian legislation for protecting groundwater resources. In fact, thisis an increase in the zone of influence that has been dictated by new data

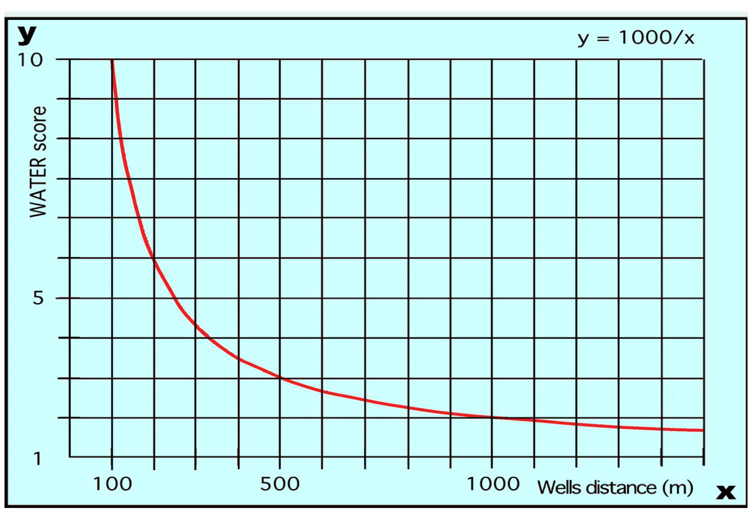

Figure 2. Rating curve for computing vulnerability scores due to (W)ell distance.

acquired by our group in the Pisa plain about the diffusion velocity of pollutants carried by groundwater. The different categories of score obtainable are listed below (Table 1).

Table 1. Score Categories as a Function of Distance from (W)ells

distance from wells	WATER score
> 1000	0
500 - 1000	1
333 - 500	2
250 - 333	3
200 - 250	4
167 - 200	5
143- 167	6
125 - 143	7
111 - 125	8
100 - 111	9
0 - 100	10

(A)QUIFER EXPLOITABLE LAYERS

In the former proposal, all the known potential horizons of a complex aquifer were considered for the vulnerability assessment, while now only the number of permeable layers effectively exploitable before reaching the given stratum enters into the calculation. In other words, more influence is attributed to shallow layers than to deeper ones in the pollution migration process (phreatic aquifers normally show the worst quality of resources).

Addition of vulnerability due to this parameter is described by the following exponential function:

$$P_A = a \; x \; e^n \tag{2}$$

where P_A is the decimal weighted score, n the number of exploitable layers above the datum horizon, and a is a conversion coefficient equal to 0.183. The asymptotic curve approaches the maximum value when the number of exploitable layers is four or more (Figure 3).

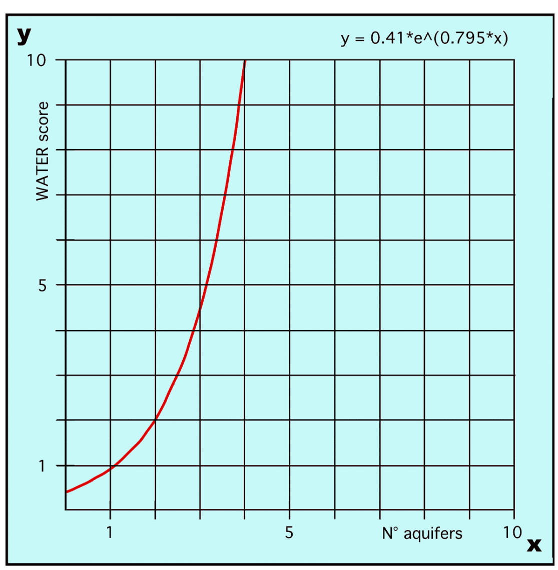

Figure 3. Rating curve for computing vulnerability scores due to (A)quifer exploitable layers.

The relative map is computed attributing to every elementary grid cell a specific score, as listed below in Table 2.

Table 2. Score Categories as a Function of the Number of (A)quifer Exploitable Layers

N. of explotable layers	WATER score
1	1
2	2
3	4
4	10

(T)RANSMISSIVITY

The first version of W.A.T.ER. utilizes the inclusive transmissivity of the entire multi-layered aquifer, which is sometimes difficult to estimate with sufficient precision due to poor information on the effective thickness. Now, the evaluation of this parameter for every single horizon overcomes the problem and permits the correct contribution to vulnerability of the different layers.

The variation of vulnerability depending on transmissivity is described by means of a linear direct function within the interval $10^{-1} – 10^{-3}$ m^2/sec, which can be taken as the normal range for commonly exploited groundwater resources:

$$P_T = (7T + 0.191)/0.099 \quad (3)$$

where P_T is the decimal weighted score attributed to the layer transmissivity, and T is the specific transmissivity of the horizon (Figure 4). Table 3 shows scores for each transmissivity class.

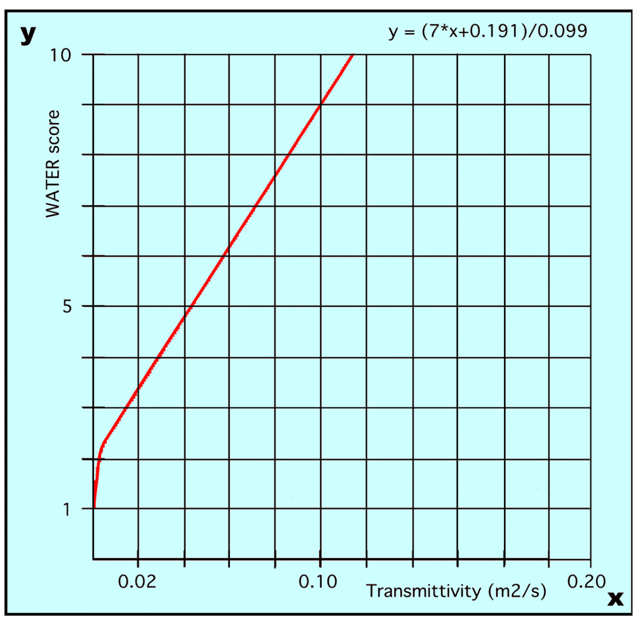

Figure 4. Rating curve for computing vulnerability scores due to (T)ransmissivity.

IMPERMEABLE COV(ER) THICKNESS

In the original elaboration, only the first impermeable layer thickness, confining the deeper horizons, is considered to play a role for vulnerability. This improved version uses the sum of all the clayey horizons, defined as alluvial deposits with permeability coefficient equal to or greater than 10^{-8} m/sec (clayey silt, sandy clay, etc), encountered before reaching the productive layer.

Table 3. Score Categories as a Function of (T)ransmissivity

Transmissivity	WATER score
< 0.0001	1
0.0001 - 0.001	2
0.001 - 0.015	3
0.015 - 0.029	4
0.029 - 0.043	5
0.043 - 0.058	6
0.058 - 0.072	7
0.072 - 0.086	8
0.086 - 0.1	9
> 0.1	10

Here a linear inverse function represents the best mathematical operator for calculating vulnerability scores:

$$P_{ER} = - a\, S + b \tag{3}$$

where P_{ER} is the decimal weighted score attributed to the impermeable cover thickness, S is the total thickness of all impermeable levels shallower than the datum horizon, and a and b are respectively equal to 0.30 and 10, such that the minimum value of 1 is for 30 or more meters of thickness (with the very low permeability coefficient, equal to or less than 10^{-8} m/sec, a groundwater transported polluting element needs more than 100 years to cross 30 m of clay).

The distribution map is built labelling each elementary cell of the selected grid with the scores indicated in succession (Figure 5). Table 4 shows scores for cover thickness.

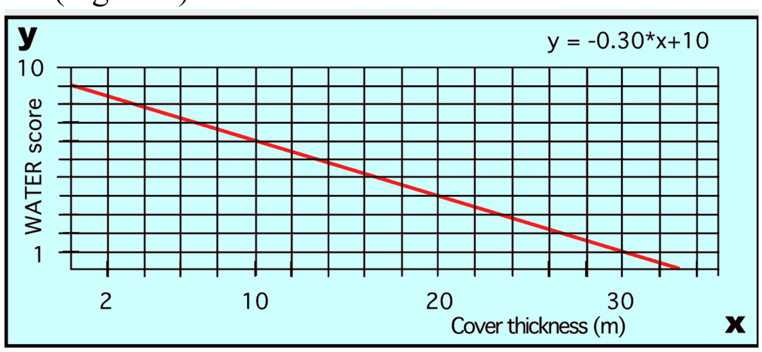

Figure 5. Rating curve for computing vulnerability scores due to impermeable cov(ER) thickness.

Table 4. Score Categories as a Function of Impermeable Cov(ER) Thickness

impermeable cover's thickness	WATER score
< 3.3	10
3.3 - 6.7	9
6.7 - 10	8
10 - 13.3	7
13.3 - 16.6	6
16.6 - 20	5
20 - 23.3	4
23.3 - 26.6	3
26.6 - 30	2
> 30	1

PARAMETER HIERARCHY

W.A.T.ER. foresees weighted coefficients being applied to the calculated scores, to develop a correct hierarchy among the four parameters that is more suitable to describe their effective influence in the formation of vulnerability.

The "weight string" for calibration is partially changed in the second version with respect to the first one, because various simulations done in a GIS (ArcView) have shown a better agreement with reality. Therefore, a major emphasis has been placed on the (W)ells effect, recognizing that groundwater extraction points are the main conduit for the penetration and migration of polluted substances into a complex aquifer (Table 5).

Table 5. Weight String for the Hierarchy Calibration of W.A.T.ER. Parameters

parameters	weight
(W)ells	4
(A)quifer's layers	1
(T)ransmissivity	2
impermeable cov(ER)	2

Intrinsic vulnerability index, I_{WATER}

The following relation gives the index of intrinsic vulnerability for each single grid cell or QDE (quadratic discrete element) covering the entire study area:

$$I_{\mathrm{WATER}} = S^{4}_{j=1} P_j W_j , \tag{4}$$

where P_j is the score for every specific parameter and W_j the relative weighted factor of hierarchy.

It becomes clear that the simple application of the proposed equations inevitably determines decimal values, which must be transformed to integers before calibration. So, features for I_{WATER} have been found with values ranging from a minimum of 5 to a maximum of 90. Then, after normalization to 100, they have been correlated to vulnerability classes as indicated in Table 6.

Table 6. Intrinsic Vulnerability Classes

Iw	vulnerability's classes
0 - 25	VL (very low)
25 - 35	L (low)
35 - 50	M (medium)
50 - 70	H (high)
70 - 80	E (elevate)
80 -100	VE (very elevate)

APPLICATION TO THE PISA PLAIN

The Pisa plain, lying between the Pisani Mountains to the east, Livorno Province to the south and Lucca Province (Serchio river) to the north, has been selected as the test area for the application of the revised W.A.T.ER. parametric method. A large amount of data exists, gathered over a long period, and the complex hydrogeological structure of the plain is particularly well known (Figure 6).The presence of dense and locally heavy exploitation of some aquifer horizons, especially in coarse loose alluvium, demands a correct assessment of groundwater resource vulnerability for a sustainable future exploitation.

Thus, following the request of the local Public Institutions, interest has been focussed on two main productive and exploited layers, the upper being confined in sands (average depth 40 m, average thickness 35 m), the lower one in gravels (average depth 80 m, average thickness 10 m).

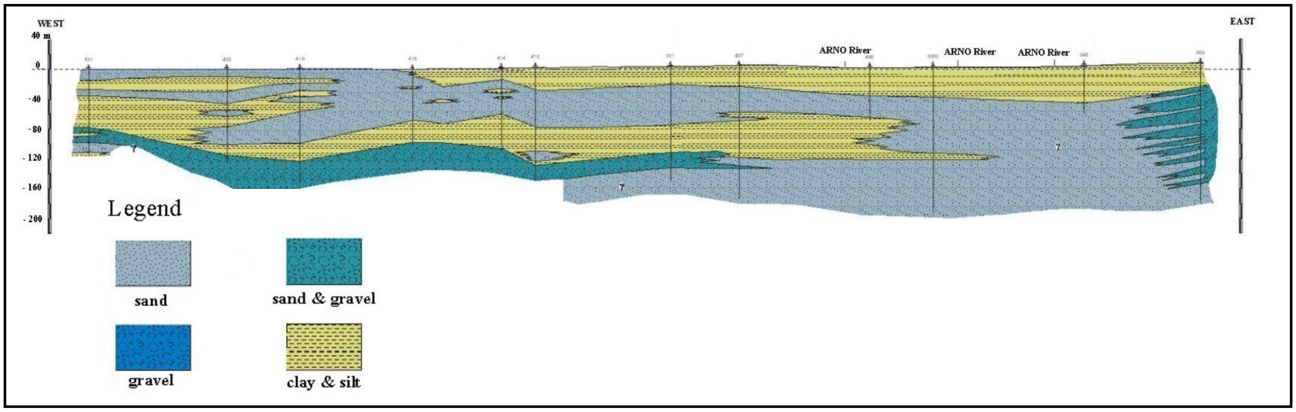

Figure 6. Typical hydrogeological cross section through the central part of the study area.

The numerous wells observed and inserted in W.A.T.ER. are those classified in the digital archive of the administrative headquarters of Pisa Province, updated to the end of 1999 (more than 170 for the sand horizon, and more than 150 for the gravel horizon).

These reliable data have made possible the calculation of the intrinsic vulnerability of both the confined aquifers with a very accurate resolution, based upon an elementary grid cell, the so-called "quadratic discrete element" (QDE), of 100 m on a side equivalent to 1 hectare. Only for limited boundary zones the precision is slightly reduced, and the real extension of the two horizons may be wider than that assumed.

RESULTS

The intrinsic vulnerability maps of the main productive and exploited horizons of the Pisa plain have been drawn, after superposition of the four intermediate maps describing the weighted contribution of each single parameter. A GIS programme have been selected (*ArcView*) as the best means to refer any information to a selected reference topographic grid, and then to operate the necessary intersections cell by cell.

For the first sandy confined aquifer, the vulnerability map (Figure 7) shows in general relatively low values, except for two concentrated bands flanking the Arno and Serchio rivers where, since the beginning, industrial activity has resulted in a major exploitation of groundwater resources. A few spots of high and elevated degree of vulnerability are also located in the industrial zone to the southwest of Pisa, mainly due to the density of the drilled wells.

The vulnerability map of the first gravely confined horizon, which lies below the previous one, presents also a general low vulnerability distribution but, on the other hand, is dotted by small spots of higher value, linked to the presence of one or more exploitation points. These spots are distributed first of all along the Arno river and secondarily around the heavily urbanized and tourist beach of Tirrenia.

It is here worthwhile to underline that in the intersection band, common to both the horizons (a zone of about 400 km^2 around the city of Pisa), the map classes quantify correctly vulnerability values in accordance with either the the hydrogeological context, or the intuitive lowering of vulnerability itself with increasing depth. In fact, they look higher in the first shallower confined sandy layer and lower in the underlying confined gravely layer, protected by thicker clayey levels. While limited vulnerability in the deeper horizon is guaranteed by the absence of wells and thick impermeable levels of clayey alluvium.

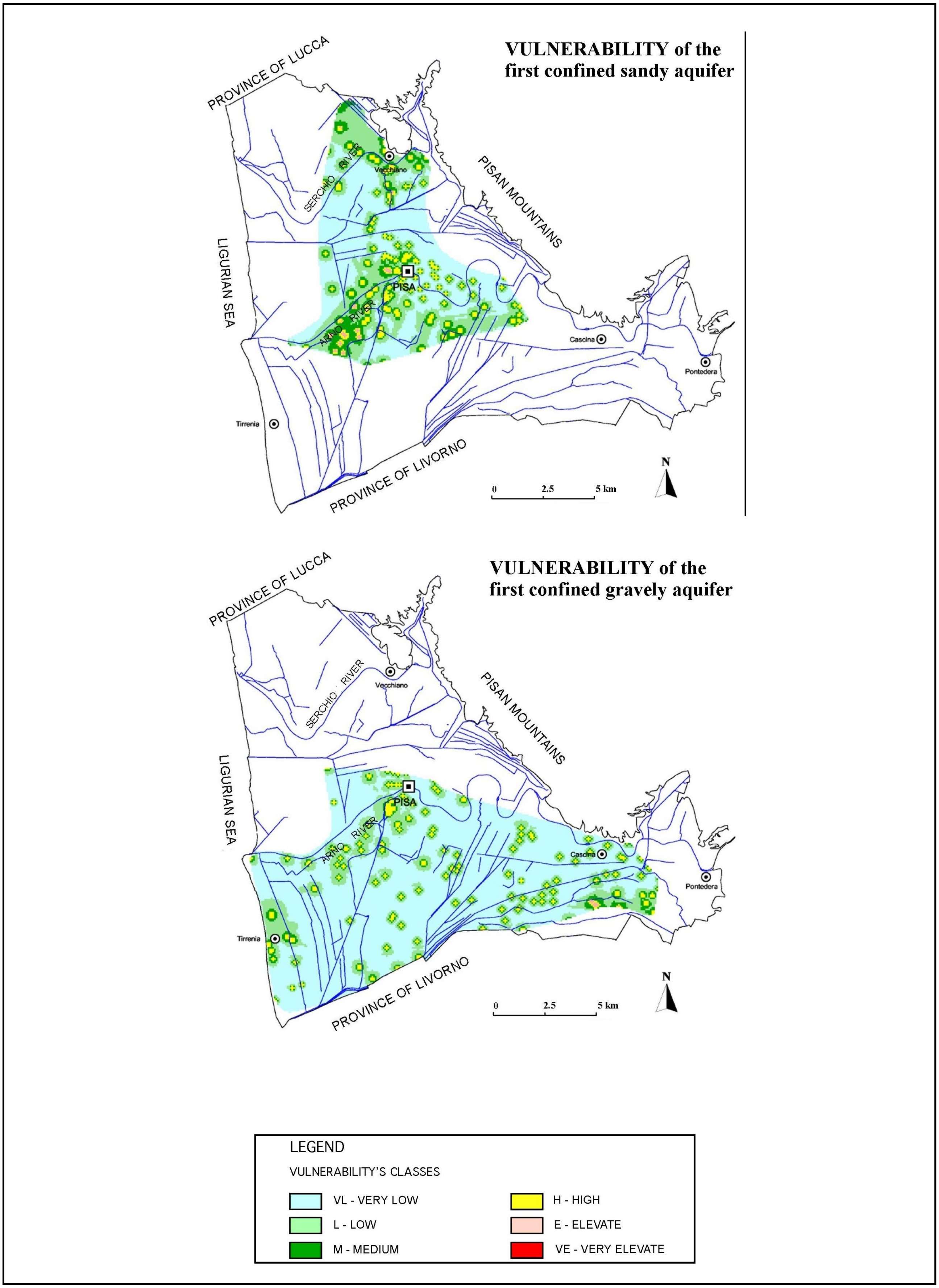

Figure 7. Aquifer vulnerability maps.

CONCLUSIONS

The more peculiar feature of the proposed W.A.T.ER. parametric method, for computing vulnerability of multi-layered complex aquifers lodged in alluvial plains, is the treatment of the groundwater resources exploitation points (Wells) as a "natural" environment characteristic, better than a human factor amplifying pollution risk.

The main advantage of W.A.T.ER. is its simplicity of application and ease of gathering the needed data, which normally are found in the well logs stored in the archives of public organizations.

The modifications brought to this revised version (new weight string and more precisely calibrated rating curves) aim to render the results more reliable, which also have to match the real hydrogeological conditions of the area being investigated. Moreover, the vulnerability computation applied separately to each single productive horizon encounters the demand of the public water users for managing specific strategies of quality recovery, and planning a sustainable use of natural resources.

A major emphasis is attributed to the wells, recognized as one of the major vehicles of entry of pollutants into the groundwater resources. Many recent episodes of aquifer pollution have occurred in several Italian provinces through this pathway.

The water approach presents the limits inherent to any parametric method, essentially due to a discrete representation of otherwise continuous entities either in space or in time. Furthermore, the vulnerability assessment is based on the assumption that vertical water filtration movements are carrying down pollution (through permeable and semi-permeable layers, or along well casings) and other types of processes or sources of pollution are not taken into account (deeper sources or pollutants not carried by water).

Consequently, for a more complete coding, W.A.T.ER. must be tested in other hydrogeological contexts showing structures and boundary conditions complementary to those found in the Pisa plain.

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