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Assessing and mapping groundwater vulnerability to contamination: The Italian "combined" approach

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RESUMEN

En la década de los ochentas la comunidad científica Italiana, junto con tomadores de decisiones institucionales, se dieron cuenta de la urgencia de proteger los recursos ambientales. El Proyecto VAZAR fue iniciado en 1984, como parte del contexto científico de la GNDCI CNR, línea de investigación 4, "Evaluación de Vulnerabilidad Acuífera". La contaminación acuífera fue examinada en este proyecto. La forma Italiana para evaluar y mapear la vulnerabilidad acuífera a la contaminación está basada en: a) El método básico GNDCI un tipo HCS que puede ser usado para cualquier tipo de situación hidrogeológica Italiana, aun con un limitado número de datos b) El método SINTACS, un desarrollo PCSM para usar preferentemente en áreas con una buena cobertura de datos. La metodología descrita en este artículo ahora constituye la norma italiana incluida en la ley Italiana (152/99) ratificada en las guías nacionales producidas por ANPA, la Agencia Nacional Italiana para la Protección Ambiental.

PALABRAS CLAVE: Aguas subterráneas, vulnerabilidad, contaminación, GIS, SINTACS.

ABSTRACT

Early in the eighties the Italian scientific community, together with institutional decision-makers, realized the urgency of protecting environmental resources. The VAZAR[1] project was set up in 1984, as part of the GNDCI-CNR[2] scientific context, Research Line, 4 "Aquifer Vulnerability Assessment". Groundwater contamination was examined in this project. The Italian approach to assessing and mapping groundwater vulnerability to contamination is based on: a) the GNDCI Basic Method, a HCS type approach that can be used for any type of Italian hydrogeologic situation, even where there is a limited number of data. A unified legend and symbols are also defined for each hydrogeologic level. b) The SINTACS method, a PCSM developed for use prevalently in areas with a good data base coverage. The methodological approach described in this paper now makes up the Italian standard in Italian Law (152/99[3]) ratified in the national guide lines produced by ANPA, the Italian National Agency for Environment Protection.

KEY WORDS: Groundwater, vulnerability, contamination, GIS, SINTACS.

MAIN METHODS FOR INTRINSIC VULNERABILITY EVALUATION

The intrinsic (*i.e.* natural) aquifer vulnerability to contamination is the specific susceptibility of aquifer systems, in their parts, geometry and hydrodynamic settings, to receive and diffuse fluid and/or hydro-vectored contaminants, the impact of which, on the groundwater quality, is a function of space and time (Civita, 1987). The intrinsic vulnerability depends on three main factors:

- the ingestion process and the time of travel of water (and/or a fluid contaminant) through the unsaturated zone down to the underlying saturated zone of the aquifer system;
- the groundwater (and/or a fluid contaminant) flow dynamics in the saturated zone;
- the residual concentration of the contaminant as it reaches the saturated zone, compared to the original concentration, which indicates the aquifer attenuation capacity of the contaminant impact.

The previously mentioned factors in turn depend on the different possible synergies of several parameters of a hydrogeologic and anthropogenic nature, and which are therefore subject to change in each area (Table 1).

The attenuation process that takes place inside an aquifer system (*i.e.* soil + vadose zone + saturated zone) as it

[1] *The acronym stands for "Vulnerability of Aquifers in High Risk Zones".*
[2] *GNDCI-CNR stands for National Group for the Defence against Hydrogeologic Disasters, of the Italian National Council of Research.*
[3] *Law Decree n. 152, May 11 1999 "Orders on the protection of water against contamination" and acknowledgements of the 91/271/CEE Directive regarding the treatment of urban wastewater and the 91/676/CEE Directive regarding the protection of water against contamination by nitrates from agricultura sources.*

Table 1

The main factors and basic parameters of intrinsic vulnerability

MAIN FACTORS	BASIC PARAMETERS
TIME OF TRAVEL	Depth to groundwater (thickness of unsaturated zone); Thickness, texture, porosity, effective moisture, soil permeability; Lithology, stratigraphy, grain size, fracture index, karst index, geometry, structure, vertical permeability of unsaturated zone; Average total net recharge; Density, viscosity, solubility of the contaminants.
GROUNDWATER FLUX	Aquifer type, structure and geometry; Effective porosity, pore size and distribution, hydraulic conductivity, transmissivity, storage coefficient, flow velocity, hydraulic gradient, dispersion and molecular diffusion; Groundwater and matrix (rock) temperature; Density, viscosity and solubility of the contaminants.
ATTENUATION CAPACITY OF THE CONTAMINANT IMPACT	Depth to groundwater; Average net recharge; Topographic surface slope; Stream network density and linkage to underlying aquifer system(s); Thickness, mineral composition and texture, effective moisture, physical and chemical characteristics of soil and unsaturated zone of the aquifer system.

receives a contaminant (fluid and/or water vectored) depends on the properties and primary concentration of each contaminant but also on the reactivity of the system, which can be reduced or, in the long term, completely depleted in time. Thus, when a CSC impact persists for a long time or if a contaminant is persistent and mobile, the attenuation capacity of the soil dwindles and vulnerability increases in time. In these cases, ground water protection is only aided by the time of travel, that is, by the thickness of the vadose zone; it is also inversely related to the ingestion capacity, vertical percolation velocity and to the mechanical dispersion that are typical of the medium. During the traveling, many interactions take place between the soil, subsoil, groundwater and the contaminants, the overall result being an attenuation of the contaminant impact. A further and surely not negligible dampening effect takes place as the residual concentration of the contaminant dilutes, in the saturation zone, to a lower degree, due to the flow velocity, unit flow rate and hydrodynamic dispersion.

The evaluation of the specific vulnerability of an aquifer should be made case by case, taking into account all the chemical and physical features of each single contaminant that is present (or of a group of similar contaminants), the type of source (punctual or diffused), quantity, means and rates of contaminant applications (Andersen and Gosk, 1987; Foster and Hirata, 1988; Bachmat and Collin, 1987). This approach, although scientifically valuable and adequate for the case of the evaluation of a potential contamination of a CSC in small areas, is quite impracticable where the goal is the assessment of aquifer vulnerability for large areas or when it is carried out as part of contamination prevention and aquifer protection planning.

In the last 30 years, some techniques have been developed for the general treatment of data (Tab. 2). These techniques vary considerably, according to the physiography of the tested areas, to the quantity and quality of the data, and to the aim of the study.

A division into two distinct classes is therefore important: use for any physiographic scenario, or use for a particular area. For the sake of simplicity, the terms universal and local are proposed. However, these two classes can also be subdivided into three basic groups (Civita, 1994; Vrba and Zaporozec[edit], 1995):

* Homogeneous area zoning (hydrogeologic complex and setting assessment - HCS);

* Parametric system assessment: Matrix Systems [MS]; Rating Systems [RS] and Point Count System Models [PCSM]

* Analogical relation (AR) and numerical model assessment.

As has been widely verified from a comparison of several different approaches applied to the same sample-area (Civita, 1994), the choice of the method that is most suitable to build a vulnerability map for a certain area should initially depend on a strictly realistic evaluation of the number, distribution and reliability of the available (and/or surveyable) data. It should there fore be underlined that an aquifer vulnerability map is an environment planning document. The map must be an integrant part of a land planning scheme for any order and degree of the administrative territory: it cannot depend on the morphology as it must cover a wide mix-

Table 2

Methods of assessing the aquifer vulnerability to pollution and the relative basic information

METHODOLOGY		BASIC INFORMATION													
					CHARACTERISTICS OF SOIL										
REFERENCE AND/OR NAME	TYPE	PRECIPITATION RATE & CHEMICAL COMPOSITION	TOPOGRAPHIC SURFACE & SLOPE VARIABILITY	SURFICIAL STREAMFLOW & NETWORK DENSITY	THICKNESS, TEXTURE & MINERALOGY	EFFECTIVE MOISTURE	PERMEABILITY	PHYSICAL & CHEMICAL PROPERTIES	AQUIFER CONNECTIONS TO SURFICIAL WATERS	NET RECHARGE	HYDROGEOLOGIC FEATURES OF INS. ZONE	DEPTH TO WATER	PIEZOMETRIC LEVEL CHANGES	AQUIFER HYDROGEOLOGIC FEATURES	AQUIFER HYDRAULIC CONDUCTIVITY
Albinet & Margat (1970) BRGM (1970)	HCS								●		●	●		●	●
Vrana (1968) Olmer & Rezac (1974)	HCS										●			●	
Fenge (1976)	RS				●					●	●	●	●	●	●
Josopait & Swerdtfeger (1976)	HCS									●	●	●		●	●
Vierhuff, Wagner & Aust (1980)	HCS										●	●		●	●
Zampetti (1983) Fried (1987)	AR										●	●			
Villumsen, Jacobsen & Sonderskov (1983)	RS				●						●	●	●	●	●
Haertle' (1983)	MS										●	●			
Vrana (1984)	HCS	●			●						●			●	
Subirana, Asturias & Casas Ponsati (1984)	HCS								●		●	●		●	●
Engelen (1985)	MS								●		●	●		●	
Zaporozec (edit., 1985)	RS				●	●	●	●			●	●		●	
Breeuwsma et al. (1986)	HCS				●	●	●	●	●	●	●	●			●
Sotornikova & Vrba (1987)	RS						●					●	●		●
Ostry et al. (1987)	HCS				●			●				●		●	
Minstr. Flemish Comm (1986) Goossens & Van Damme (1987)	MS				●							●		●	
Carter et al. (1987) Palmer (1988)	MS				●		●	●						●	
Marcolongo & Pretto (1987) method. 1	RS				●					●	●	●			
Marcolongo & Pretto (1987) method. 2	AR					●				●	●	●			
GOD Foster (1987, 1988)	RS										●	●		●	
Schmidt (1987)	RS				●				●		●	●			
Troyan & Perry (1988)	PCSM	●	●				●			●	●	●		●	
GNDCI BASIC (Civita, 1990)	HCS								●		●	●		●	●
DRASTIC Aller et al. (1985 - 1987)	PCSM		●		●					●	●	●		●	●
SINTACS (Civita, 1991; Civita & De Maio, 1997, 2000)	PCSM		●	●	●				●	●	●	●		●	●
ISIS (De Regibus, 1994)	PCSM		●		●					●	●	●		●	

ture of plain, hilly and mountain areas, as can be found throughout Italy.

Considering the recent Italian experience, it is possible, although only in a qualitative form at present, to indicate the correlation between the three main factors to map vulnerability, namely the density of surveyed points, the amount of information secured for any point and the scale denominator (SD) at which the map can be constructed. The diagram in Figure 1 shows that:

* only when there are a great number of information points per unit area (for any of which a variety of ground data are attainable) can complex low SD models be applied;

* for a medium information point density with a fair distribution, a more complex or less complex parametric system (depending on the number of data available per point) can be used;

* if the specific basic information is inadequate and/or scarce and scattered throughout the area, as is often the case, an HCS method fitted to a medium-large SD must be used.

One important consideration that must be done when choosing a vulnerability assessment method is the reliability of the basic data, as the inadequate reliability of data can give rise to a false precision. Even worse, it can completely falsify the results, making them quite useless.

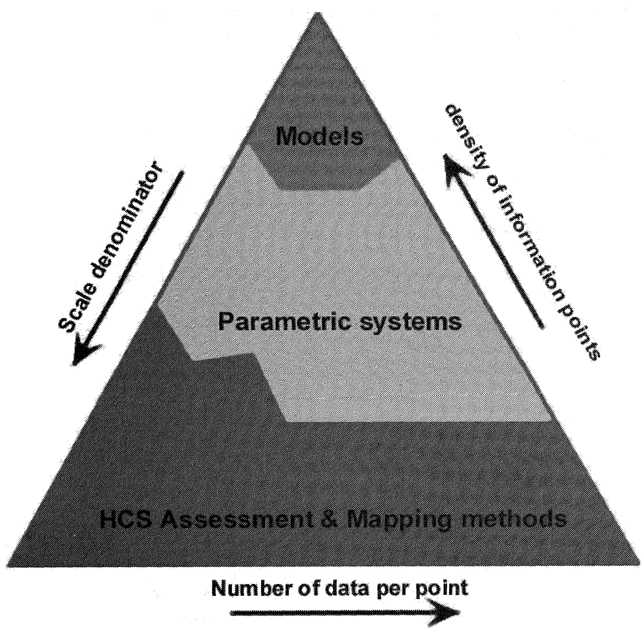


Fig. 1. Interaction between the SD, the density of the surveyed points and the number of parameters/amount of surveyed/available data for each point. [after Civita (1994)].

The reliability of data, moreover, can vary widely with a mean elevation of the investigated area. If a data reliability ranging between 1 to 10 is given, a variation curve of this reliability versus the mean elevation can be plotted. Figure 2 shows a sharp decrease in the reliability of re sults above a comparatively low altitude (300-400 m a.s.l.) due to the increasing scarcity of data in mountain areas, a problem which can only be partially resolved through the use of extrapolation techniques. This is true for hydrogeologic and hydrostructural data (piezometric levels, vadose zone, flow directions, hydraulic conductivity, aquifer geometry), but no less so for pedologic and climatological data (rainfall, evapotranspiration, wind, temperatures, etc.).

In mountain regions and in most hilly areas it may be necessary to avoid the more complex techniques, using HCS or MS systems coupled to medium-high SD mapping, instead of the more sophisticated parametric systems. The validity of these is greater in plain areas with high data density and reliability, but they are also suited to adequately low SD mapping.

On the basis of this consideration, it was realized that it is impossible to elaborate an aquifer vulnerability map using a single method. A new approach (named combined approach) was studied and tested, for use in any part of the Italian territory, which was based on the overlapping of two different methodologies:

1. a parametric method (a highly advanced PCSM - i.e. SINTACS Release 5 [Civita and De Maio, 2000]), which has been improved for plain areas, where the amount and reliability of data, measurements, tests and analysis can be sufficient for the mapping scale;

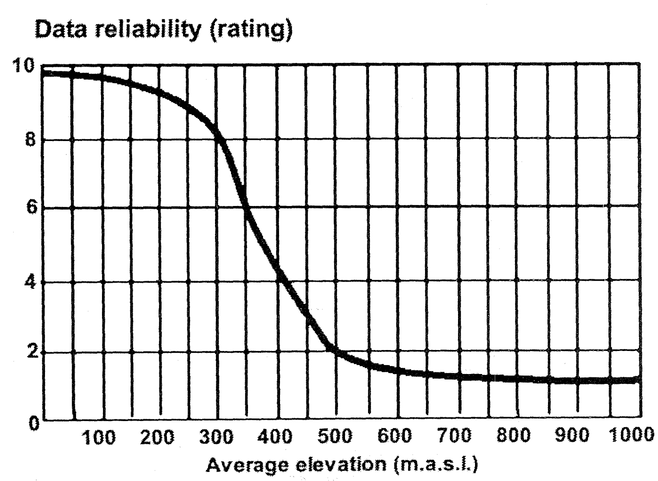


Fig. 2. Variations of the reliability of the basic data with a variation of the mean height in the investigated area [after Civita (1994)].

2. homogeneous areas zoning, based on the survey of hydrogeologic complexes, characteristics and settings (**HCS**), to be used in mountainous and hilly areas where a scarcity or lack of underground information is normal (GNDCI-CNR Basic Method).

THE METHODS PCSM SINTACS R5

The vulnerability of a groundwater body is a function of several parameters, the most important of which are lithology, structure, geometry of the hydrogeologic system, the type of overburden, the recharge-discharge process, the interaction of the physical and hydrochemical processes that regulates the quality of the groundwater, and the fate of the contaminants that impact the system.

Where the data base is complete and the frequency of the available information is adequate, the factors that are used to assess the aquifer vulnerability to contamination are selected; a subdivision into value intervals and/or declared types is applied to each selected factor; a progressive rating (**P**, ranging 1 – 10) is given to each interval as a function of the importance in the final assessment (Table 3); the selected ratings of each factor must be multiplied for a choice of weight (**W**) strings, which are used in parallel and not in series (Table 4), each one describing a hydrogeologic and impact setting that emphasizes the action of each parameter.

The acronym SINTACS comes from the Italian names of the factors that are used, *i.e.* Soggicenza (depth to groundwater); **I**nfiltrazione (effective infiltration); **N**on saturo (unsaturated zone attenuation capacity); **T**ipologia della copertura (soil/overburden attenuation capacity); **A**cquifero (saturated zone characteristics); **C**onducibilità (hydraulic conductivity); **S**uperficie topografica (topographic surface slope). A vulnerability index is calculated for each cell of a discretization grid that is overlaid on the basic map of the study area:

$$\mathbf{I}_{\mathrm{SINTACS}} = \sum_{J=1}^{7} \mathbf{p}_J \mathbf{w}_J \,. \qquad (1)$$

The types of basic information, the steps to transform them in SINTACS factors and the definition of the hydrogeologic and impact settings used to select the weight strings can be found in Civita (1994) and in Civita and De Maio (2000), together with a number of application tests.

GNDCI-CNR BASIC METHOD

This method [Civita M., *In*: AA. VV. (1988); Civita M. (1990.b)] is based on a standard in which a number (about 20 – see Table 5) of hydrogeologic settings that can be found in the Italian territory is collected and the intrinsic vulnerability characteristics of the aquifer are identified. This method is highly flexible and can be adapted, if necessary, to other situations that are not dealt with in the standard. The lithological, structural, piezometric and hydrodynamic indexes are not rigorously quantified. Starting from a complete examination of the main Italian hydrogeologic settings, the representative sites were extracted from those that best define the settings, *e.g.* the Po river Plain, the carbonatic massifs of the Apennine ridge, the karst settings of Apulia and Trieste, the volcanic terrain of central Italy, the ancient basement of the Alps, and so on. The main factors of the aquifer vulnerability (*e.g.* depth to groundwater, porosity, fracturing index, karst index, linkage between stream and aquifer, and so on) were identified for each site. Bearing in mind the dynamics and frequency of the contamination cases that were collected and previous similar experience at an international level, the settings were distributed over the 6 degrees of intrinsic vulnerability (*i.e.* contamination potential) that form the synoptic legend of the maps.

THE COMBINED APPROACH

In many zones where it is necessary to cover vast areas identified by administrative (*i.e.* Municipalities, Provinces, Regions) or physical boundaries (interregional watershed) with a Vulnerability Map, the parametric models that have been set up cannot be applied due to a lack of data at those points where the terrain changes from a plain morphology to a hilly or mountain area. In these situations, in the past, a simple method was chosen that was able to perform a less refined and detailed evaluation, but with good results.

The experience gained recently has led to a reconsideration of the methodological problem: why renounce to the detail that can be offered by point and weight parametric models (Civita, 1990, 1994) in areas with moderate relief where the majority of the CSCs and the DCA[4] s and many of the supply springs are concentrated (that is, the subjects at risk - SAR)? On the other hand, how can we carry out the evaluation of vulnerability and the risk to contamination in areas with great depth to water, areas that can be described in less detail on the basis of hydrogeologic situations and complexes?

The solution that has been found for this problem and which has been tested, is the combined approach. This approach allows the GNDCI-CNR Basic method to be combined with the PCSM SINTACS method without continuity solutions: the latter in areas where the data that are necessary and sufficient to apply a parametric model exist; the first in areas where the great depth to water, the hydrolithologic and hydrostructural complexity and the lack

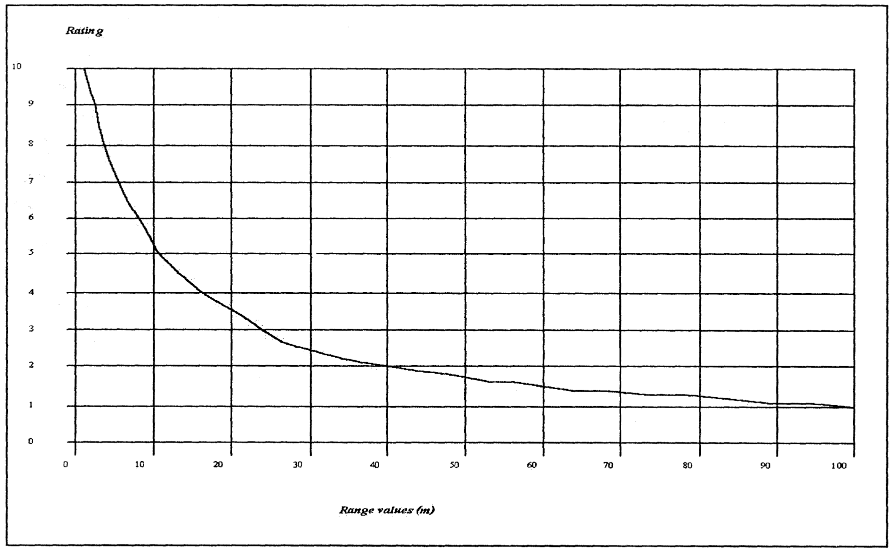
[4] *DCS = Diffused Contamination Sources.*

Table 3

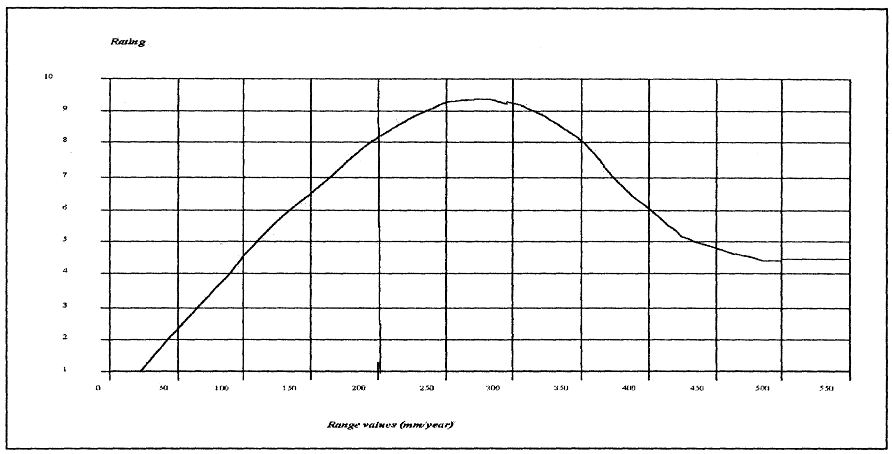
Description of the parameters and related rating graphs for PCSM SINTACS

DESCRIPTION	RATING DEFINITION

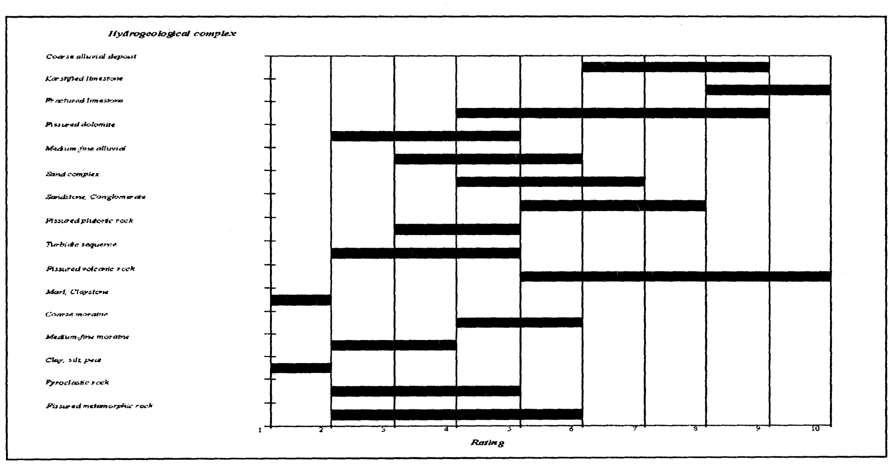
S DEPTH TO GROUNDWATER: is defined as the depth of the piezometric level (both for confined or unconfined aquifers) with reference to the ground surface and it was a great impact on the vulnerability because its absolute value, together with the unsaturated zone characteristics, determine the time of travel (TOT) of a hydro-vectored or fluid contaminant and the duration of the attenuation process of the unsaturated thickness, in particular the oxidation process due to atmospheric O2. The SINTACS rating of depth-to-groundwater therefore decreases with an increase of the depth, i.e. with an increase of the thickness of the unsaturated zone within the range 10 ÷ 1.



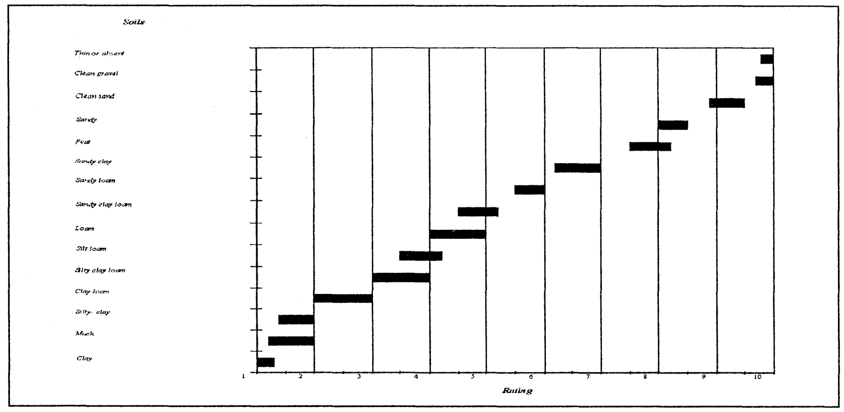
I EFFECTIVE INFILTRATION ACTION: The role that the effective infiltration plays in aquifer vulnerability assessment is very significant because of the dragging down surface of the pollutant but also their dilution, first during the travel through the unsaturated zone and then within the saturated zone. Direct infiltration is the only or widely prevalent component of the net recharge in all the areas where there are no interflow linking aquifers or surficial water bodies or no irrigation practices using large water volumes.



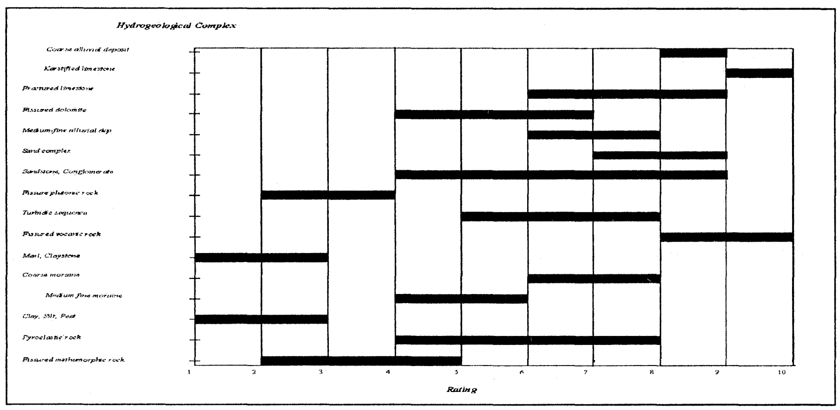
N UNSATURATED ZONE ATTENUATION CAPACITY: The unsaturated zone is the "second defense line" of the hydrogeologic system against fluids or hydro-vectored contaminants. A four dimension process takes place inside the unsaturated thickness in which physical and chemical factors synergically work to promote the contaminant attenuation. The unsaturated zone attenuation capacity is assessed starting from the hydro-lithologic features (texture, mineral composition, grain size, fracturing, karst development, etc.).



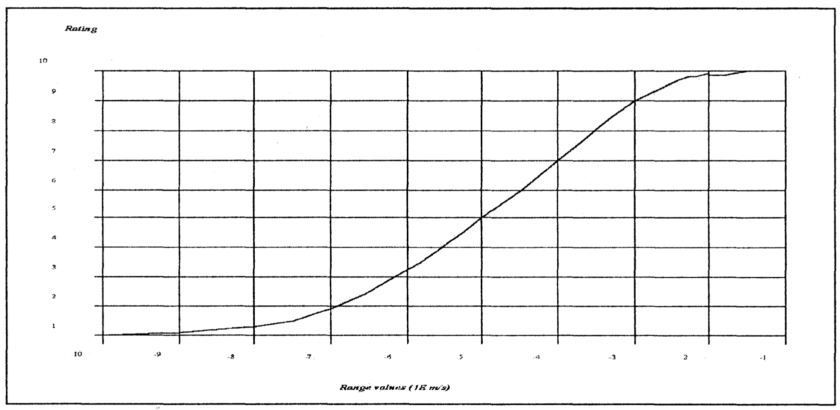
T SOIL/OVERBURDEN ATTENUATION CAPACITY This is the "first defense line" of the hydrogeologic system: several important processes take place inside the soil that built up the attenuation capacity of a contaminant travelling inside a hydrogeologic system and therefore in aquifer vulnerability assessment and mapping. Soil is identified as an open, three-phase, accumulator and transformer of matter and an energy sub-system which develops through the physical, chemical and biological alterations of the bottom lithotypes and of the organic matter that it is made up of.



A HYDROGEOLOGIC CHARACTERISTICS OF THE AQUIFER: In vulnerability assessment models, the aquifer characteristics describe the process that takes place below the piezometric level when a contaminant is mixed with groundwater with a loss of a small or more relevant part of its original concentration during the travelling through the soil and the unsaturated thickness. Basically these processes are: molecular and cinematic dispersion, dilution, sorption and chemical reactions between the rock and the contaminants.



C HYDRAULIC CONDUCTIVITY RANGE OF THE AQUIFER: Hydraulic conductivity represents the capacity of the groundwater to move inside the saturated media, thus the mobility potential of a hydro-vectored contaminant which as a density and viscosity almost the same as the groundwater. In the SINTACS assessment context, the hydraulic gradient and the flux cross section being equal, this parameter determines, the aquifer unit yield and flow velocity that go toward the effluences or the tapping work that indicates the of risk targets.



S HYDROLOGIC ROLE OF THE TOPOGRAPHIC SLOPE: The topographic slope is an important factor in vulnerability assessment because it determines the amount of surface runoff that is produced, the precipitation rate and displacement velocity of the water (or a fluid and/or hydrovectorable contaminant) over the surface being equal. A high rating is assigned to slight slopes i.e. to surface zones where a pollutant may be less displaced under gravity action or even stop in the outlet place favoring percolation. The slope may be a genetic factor due to the type of soil and its thickness, and can indirectly determine the attenuation potential of the hydrogeologic system.

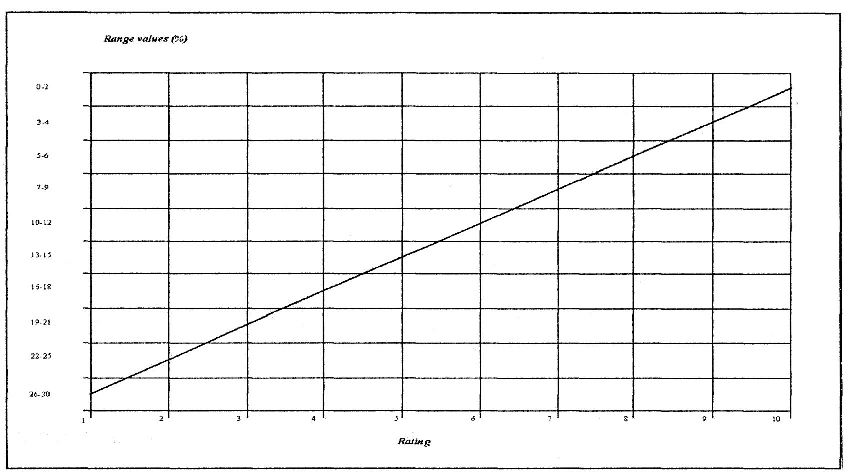


Table 4

Strings of multiplier weights given for SINTACS

Parameter	Normal I	Severe I.	Seepage	Karst	Fissured	Nitrates*
S	5	5	4	2	3	5
I	4	5	4	5	3	5
N	5	4	4	1	3	4
T	3	5	2	3	4	5
A	3	3	5	5	4	2
C	3	2	5	5	5	2
S	3	2	2	5	4	3

* Under evaluation

Table 5

Standards of Italian hydrogeologic settings (GNDCI-CNR basic method)

Vulnerability degrees	Hydrogeologic complexes and setting features
Extremely high	Unconfined (water table) aquifer in alluvial deposits: streams that freely recharge the groundwater body; well or multiple well systems that drawdown the water table to under the stream level (forced recharge). Aquifer in carbonate (and sulphate) rocks affected by completely developed karst phenomena (holokarst with high karst index [**KI**]).
Very high	Unconfined (water-table) aquifer in coarse to medium-grained alluvial deposits, without any surficial protecting layer. Aquifer in highly fractured (high fracturing index [**FI**]) limestone with low or null **KI** and depth to water <50m.
High	Confined, semiconfined (leaky) and unconfined aquifer with impervious (aquaculture) or semipervious (aquitard) superficial protecting layer. Aquifer in highly fractured (high fracturing index) limestone with low or null **KI** and depth to water >50m. Aquifer in highly fractured (but not cataclastic) dolomite with low or null **KI** and depth to water <50m Aquifer in highly clivated volcanic rocks and non-weathered plutonic igneous rocks with high **FI**.
Medium	Aquifer in highly fractured (but not cataclastic) dolomite with low or null **KI** and depth to water >50m. Aquifer in medium to fine-grained sand. Aquifer in glacial till and prevalently coarse-grained moraines.
Medium - Low	Strip aquifers in bedded sedimentary sequences (shale-limestone-sandstone flysch) with layer by layer highly variable diffusion rates. Multi-layered aquifer in pyroclastic non indurated rocks (tuffs, ash, etc.): different diffusion degrees layer by layer close to the change in grain size.
Low	Aquifer in fissured sandstone or/and non carbonatic cemented conglomerate. Aquifer in fissured plutonic igneous rocks. Aquifer in glacial till and prevalently fine-grained moraines. Fracture network aquifer in medium to high metamorphism rock complexes.
Very low or null	Practically impermeable (aquifuge) marl and clay sedimentary complexes (also marly flysch): contamination directly reaches the surface waters. Practically impermeable (aquifuge) Fine-grained sedimentary complexes (clay, silt, peat, etc.) contamination directly reaches the surface waters. Meta-sediment complexes or poorly fissured highly tectonized clayey complexes low metamorphism complexes, almost aquifuge: contamination directly reaches the surface waters.

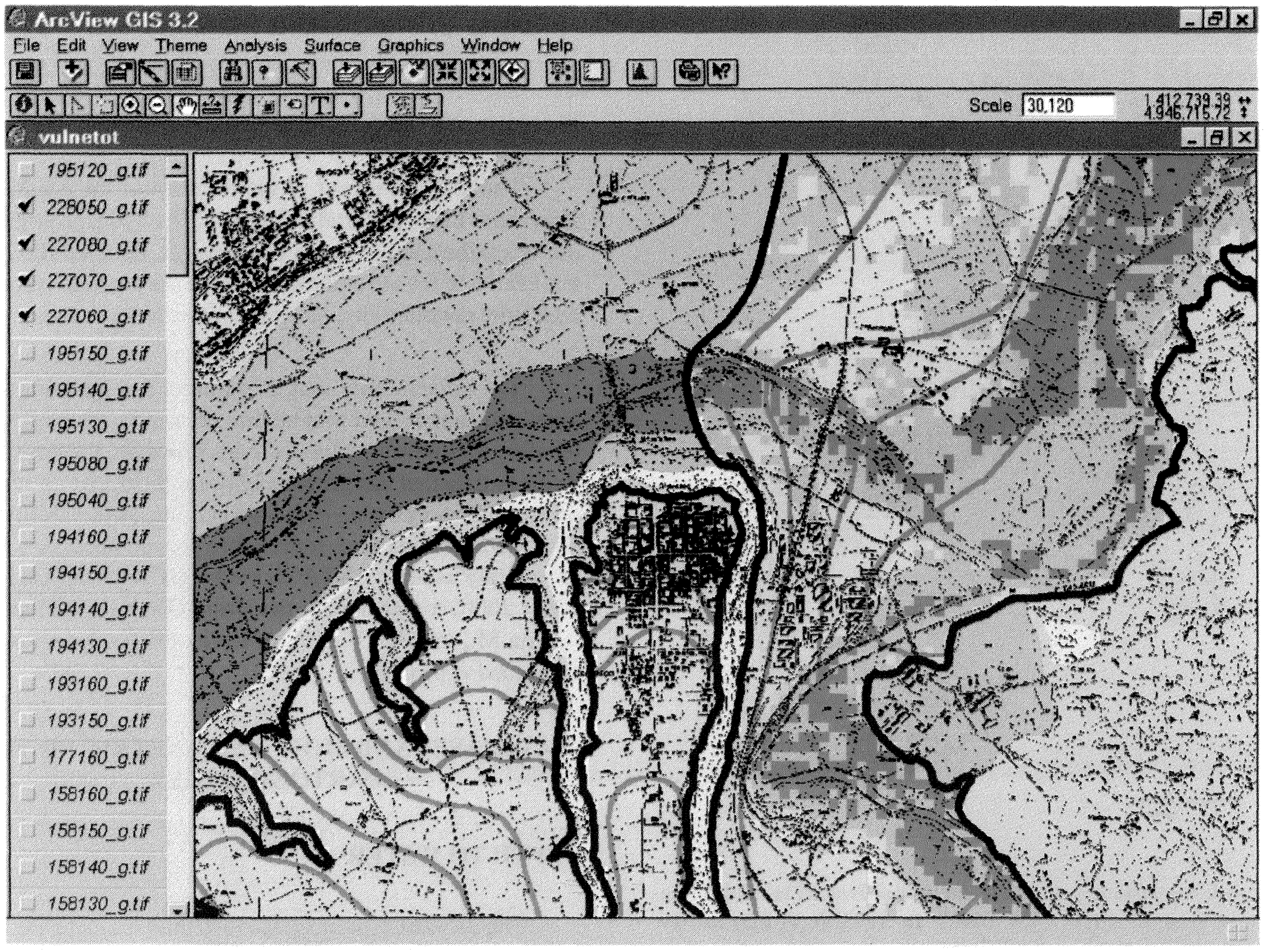


Fig. 3. Vulnerability Map: (Red) Extremely elevate Degree; (Orange) Elevated Degree; (Yellow) High Degree; (Green) Medium Degree and (Cyan) Low extremely Degree of vulnerability.

of certain data on the terrains, the hydraulic conductibility and active recharge do not allow details to be obtained that can be compared with those that can be obtained using SINTACS.

The necessary connection, whether conceptual or cartographic, between adjacent areas where different methodologies should be applied, is supplied by the parametric evaluations. In practice, for those complex ones where a parametric evaluation already exists, the same degrees of vulnerability are applied but the changed slope and water table conditions are also taken into account. All this is possible thanks to the fact that the calibration with SINTACS was carried out by comparing and crossing, as already mentioned, the SINTACS evaluation with that obtained with the GNDCI-CNR Basic method, on over 600 test-sites distributed throughout the different Italian areas and territories (Figure 4). The division of the numerical index into 6 degrees of vulnerability, the same as those used for the Basic Method, makes the two methods comparable and the results optimally combinable.

The application of the combined approach has given excellent results in the Tanaro Project area (Regione Piemonte, 2000) and led to a complete covering being obtained without any loss of basic information or accuracy of synthesis. The same numbers of cartographic examples of the vulnerability carried out using the Combined Approach of the two methods are shown in Figure 3. The thick black line in the figure represents the dividing line between the areas treated with the two methods. The homogenization that the approach involves can clearly be seen.

CASE STUDY

INTRODUCTION

The study of the aquifer vulnerability in the Tanaro Valley, Piedmont (Italy) was initially set up and planned on a very large territorial basis. It was considered that not only the areas that were directly involved by the 1994 flood event should be considered, but also the remaining territory be-

Fig. 4. Geographical position of the test sites used to control the subdivision of SINTACS index in several vulnerability degrees.

longing to the Municipalities that were involved in the catastrophe. The application of this afore mentioned approach to a part of the large area covered by the study (Regione Piemonte, 2000) is presented in this work as an example.

The test site is part of the territory of the Alessandria Province - Piedmont, Italy (Figure 5). Its hydrogeologic layout is synthesized in Table 6. However, detailed data were not available for the external areas on the depth to water, the hydraulic conductivity, the soil characteristics, etc.

The vulnerability map of aquifers is a planning document and cannot therefore be limited to only the parts of the territory that were involved. Given, however, the cover conditions - data that has previously been illustrated - it was not possible to carry out an elaboration of the vulnerability map with a uniform method. It therefore proved necessary to appropriately use the SINTACS method (Civita and De Maio, 1997, 2000) together with the Basic GNDCI CNR method (Civita M., in AA.VV. (1988); Civita (1990c)) applied in a combined approach.

DATABASES AND MONOPARAMETRIC SINTACS CARTOGRAPHIES

DEPTH TO WATER

The SINTACS points relative to this parameter decrease with an increase of the depth, vadose zone, and they take on

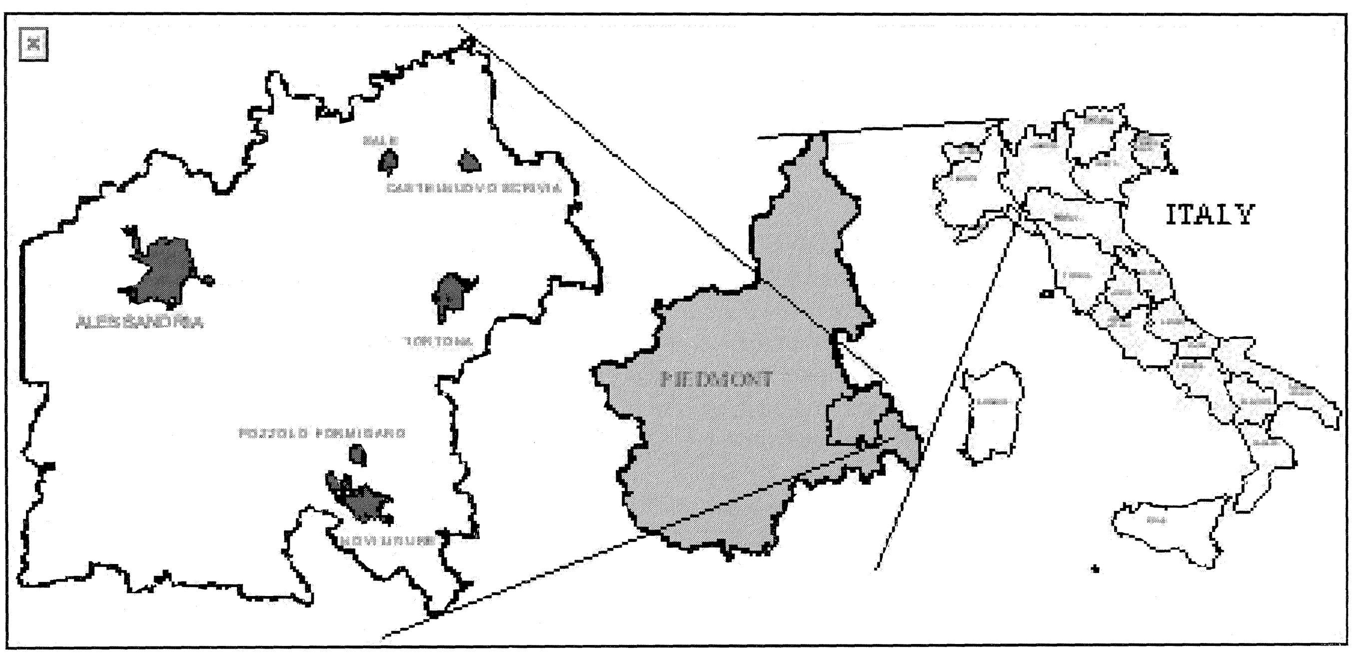


Fig. 5. Geographical location.

Table 6

Hydrogeologic characteristics of the complexes

Hydrogeologic Complexes	**Subcomplexes**	**Era**	**Tickness (m)**	**Lithology**	**Relative K**	**Hydrogeologic Role**
Actual alluvial	Main Plain	Holocene	1÷6	Coarse gravel with sandy matrixes	EE	Secondary unconfined aquifer
		Holocene	5÷50	Gravel with sandy matrixes, clayey gravel, sands and extended clay bodies	M	Main unconfined aquifer
Gravely-clayey alluvial	Intermediate terraces	Pleistocene	5÷50	Gravel with sandy matrixes, clayey gravel, sands and extended clay bodies	M	Main unconfined aquifer
	High terraces	Pleistocene	5÷50	Gravel with clayey matrixes, gravel and clayey sands and clay lenses	M	Main unconfined aquifer
Gravely-clayey	Prevalently clayey	Upper Pliocene	1÷50	Important clayey bodies with gravel and sand horizons	L	Secondary aquifer under pressure
Sandy-gravely	Sands	Middle lower	30÷50	Coarse sand, silty sand with silty-clayey hori zons	M	Unconfined aquifer under pressure
	Gravel	Middle lower Pliocene	30÷100	Locally cemented gravel and sand and silty horizons	M-E	Aquifer under pressure
Marly-sandy		Lower Pliocene	100÷200	Prevailingly marl and silty sand horizons	I - M	Limits of permeabi-lity (aquifer locally under pressure)
Clayey-sandy-conglomerate		Lower Pliocene	100÷200	Important clay bodies with sand horizons, prevalently sand and arenaceous-conglomera-te bodies (varying from zone to zone)	I - M	Limits of permeabi-lity (aquifer locally under pressure)
Terrigenous-evaporitic		Messinian	20÷100	Chalk lenses, arena-ceous-conglo meratehorizons, important clayey bodies (varying from zone to zone)	I - E	Limits of permeabi-lity (unconfined aquifer and under pressure)
Calcareous-arenaceous-clayey		Paleocene, Eocene, Oligocene, Miocene	≈ 100	Minute conglomerates and sandstone, calcareous and arenaceous thin layers, marl, marl-sandstones, mar-clays and multicoloured clays	I - L	Permeability sill
Clayey		Tortonian	200÷300	Important succession of marls and marly clays	I	Impermeable, limits of permeability

values between 10 and 1. Therefore, when selecting the data to use in SINTACS it was necessary to consider the minimum depth to water value from the survey campaign, in order to be in the most cautionary conditions when evaluating the vulnerability, the value of which, in all cases, is inversely proportional to the Time of Travel (TOT). The raw depth to water data were elaborated in an ARC/INFO ambient, first to obtain a satisfactory and descriptive territorialisation[5], while taking into consideration the limits of the system and the georeferenced position of the 0 depth to water descriptions. Then the spaces were reclassified on the basis of the SINTACS points and cartography was obtained relative to the **S** parameter, which was plotted on a raster basis (Regional Technical Map) at a 1:100.000 scale.

The depth to water map was obtained automatically from subtractions of the height grids of the topographic surfaces and from the piezometric surface height grid. The topographic surface was obtained using the DTM (Digital Terrain Model) of the Regione Piemonte. This is not compatible with ARC/INFO: this led to a software prepared in DOS environment to transform the original files into ASCII files which are instead compatible with ARC/INFO with the Gauss-Boaga co-ordinates (x,y,z) of the points that make up the DTM. The thus obtained file was imported and appropriately elaborated (Figura 6) so as to obtain a covering of the quoted points on which to apply the 50 m side grid. GRID 1 was obtained in this manner.

The piezometric surface was obtained from the surveyed point piezometric data. The Isopie zometric Map ($\Delta h = 1m$) was generated from these data through linear interpolation. It was digitized in ARCVIEW and imported into ARC/INFO as a shape file. The creation of the topology made possible to attribute the mean height of the piezometric level to the iso-value areas. GRID2 was obtained from the thus obtained cover.

The elaboration that was made also constitutes a remarkable innovation of the traditional techniques used for the drawing up of depth to water maps. These traditional techniques do not supply great precision, even in the case of situations with moderate variability, and, above all, the automatic elaboration makes it possible to obtain maps almost in real time. The thus obtained depth to water map was then reclassified using the RECLASS command of GRID in the intervals foreseen by the SINTACS method. This allowed a grid with the depth to water parameter points to be obtained.

INFILTRATION

The evaluation and territorialisation method of this parameter in the latest SINTACS versions (Civita and De Maio, 2000) is based on the inverse hydrogeologic balance technique. The parameter is calculated from the effective rainfall territorialised using a grid square numerical model and from the surface hydrogeologic conditions that are incorporated in the infiltration index (χ).

In the study case, the historical series registered in 208 pluviometric stations and 11 thermometric stations distributed over the area under examination and in the vicinity were examined for the periods 1931-1941 and 1954-1964. Five homogeneous areas were identified on the basis of the mean rainfall/elevation ratio; four homogeneous areas were identified on the basis of the mean corrected temperature/elevation ratio.

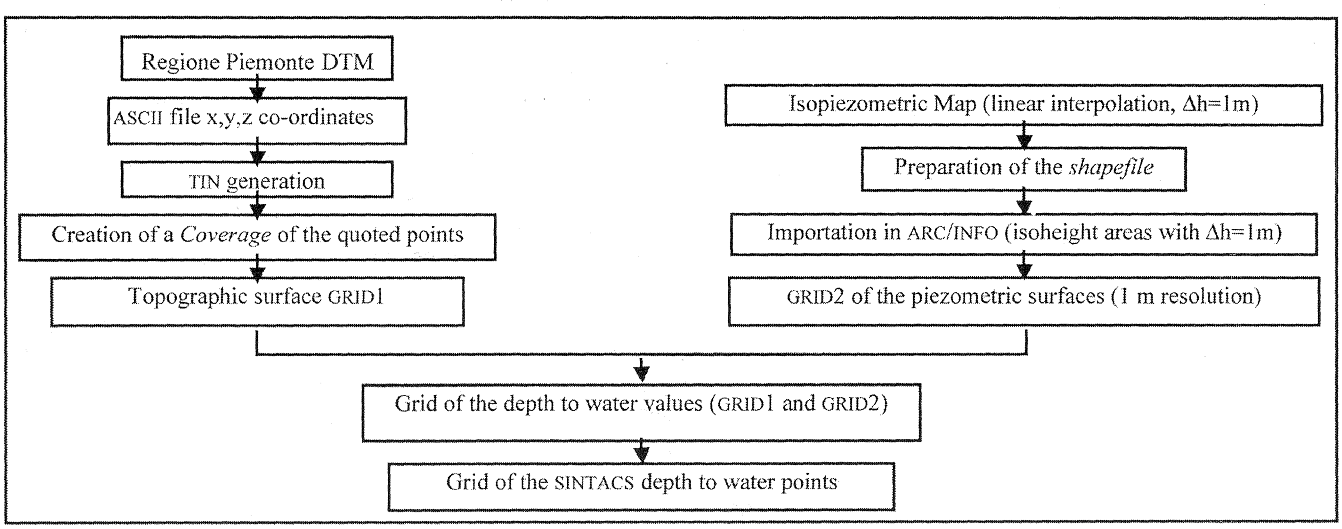


Fig. 6. Flow chart of the depth to water map.

[5] See Civita and De Maio: *Assessing and Mapping groundwater vulnerability to contamination: the Italian "combined" approach* (in the volume of these proceedings).

On the basis of the points obtained from the DTM, of the mesh defined for the studied area, from cover of the χ performed for the entire studied area and constructed in ARCVIEW as a polygonal shape file, through an AML script in the ARC/INFO GRID ambient, the following data are automatically calculated for each cell:

- the specific rainfall ($\overline{\mathbf{P}}$);
- the specific corrected temperature ($\overline{\mathbf{T}}_c$);
- the specific evapotranspiration ($\overline{\mathbf{Er}}$);
- the specific effective rainfall ($\overline{\mathbf{Q}}$);
- the specific active (infiltration) charge ($\overline{\mathbf{I}}$);
- the specific surface run off ($\overline{\mathbf{R}}$).

Once the value of the potential infiltration had been calculated for each grid element, a reclassification can be made according to the point intervals defined by the method and with the redrawing up of the Map for parameter **I**, in a 1:100.000 scale on a raster basis.

EFFECT OF THE AUTO-DEPURATION OF THE UNSATURATED ZONE

The values of the parameter **N** were obtained point by point from stratigraphy profiles inte grated with about 700 wells and geological and geophysical surveys. Once the depth to water is known, it is possible to make an initial sub division into unsaturated or saturated zone for each point. Once the unsaturated thickness and the relative lithologic are known, it is possible to proceed with the elaboration of the pondered mean of the SINTACS **N** point for each point. A heterogeneous substrate with **N** parameter values between 1 and 9 is indicated in the Alessandria sector, with a dominance of 4 in the plain south of the Alessandria-Spinetta Tortona alignment. A value **N** = 8 was assigned to the recent alluvial complex (prevalently gravel).

The lowest value, 3, was assigned to the prevalently insistent clay complex west of the sector under examination. The Map relative to the auto-depuration effect of the unsaturated zone was obtained using traditional mapping of the data derived from the hydrogeologic survey and from drillings. Data relative to subsoil on which the parameterization of the vadose zone is based, are derived from drillings and from geognostic and geophysical investigations.

The different items of punctual information, which were placed in a specific database con taining about 15.000 data, were subjected to cross-checking and homogenization in order to construct the greatest number of hydrogeologic profiles, and to obtain a correct zoning of the hydrolithologic information.

The next step was the importing of treated data to the ARCVIEW ambient where the points foreseen by the SINTACS method for the unsaturated thickness of heterogeneous composition were attributed to homogeneous areas. The information relative to **N** was reclassified according to the foreseen points and the Map relative to the 1:100.000 scale was redrawn on a raster basis. This elaboration was then imported to ARC/INFO. The normal mesh was applied to this cover and the grid of the SINTACS points for the unsaturated zone was obtained.

TYPOLOGY OF THE COVER

The SINTACS **T** parameters were derived from an analysis of 106 soil samples obtained from the 1998 sampling campaign carried out in the province of Alessandria through a correlation diagram of the **T** parameter and the organic matter contents in the soil (SO) and fine mud clayey particles (AL) (Civita and De Maio, 2000; Civita and Persicani, 1996). Given the re markable extension of the area (1042 km^2), the Map of the Capacity of use of Soils and their Limitations (IPLA-Regione Piemonte, 1982) was analyzed to have an adequate pedologic knowledge of the entire area. The whole area was then pedologically zoned thanks to this map and to the hydrogeologic complexes map. The zoning was defined according to parameter **T** through the use of the correlation diagram between the textural characteristics of the soils and the relative points for the evaluation of the mitigating action of the contaminants. The dominant value of **T** in the Alessandria plain area was 6, while in the hilly areas south and south east of the Alessandria sector, a **T** value 7 was obtained.

The Thematic map was obtained using traditional methods. The obtained map was acquired as a polygonal ARCVIEW shape file in which the relative points were assigned according to the reference abacuses of the SINTACS method. The shapefile was then imported into ARC/INFO where the usual 50 meter side grid was applied.

THE AQUIFER CHARACTERISTICS

The elaboration of the data relative to the SINTACS **A** parameter followed the same course of the parameter **N**. Given the partial heterogeneity of the saturated zone, which also occurred for the analysis of the vadose zone, the mean pondered technique (with respect to the thicknesses) of the value assigned to the point datum was applied. This reflected the real typology of the saturated zone.

The Alessandria sector is dominated by high **A** values (7-8-9), an indication of an elevated permeability type aquifer; a limited central zone in correspondence to the Frugarolo village diverges from this analysis with a SINTACS point equal to 5, as well that other areas.

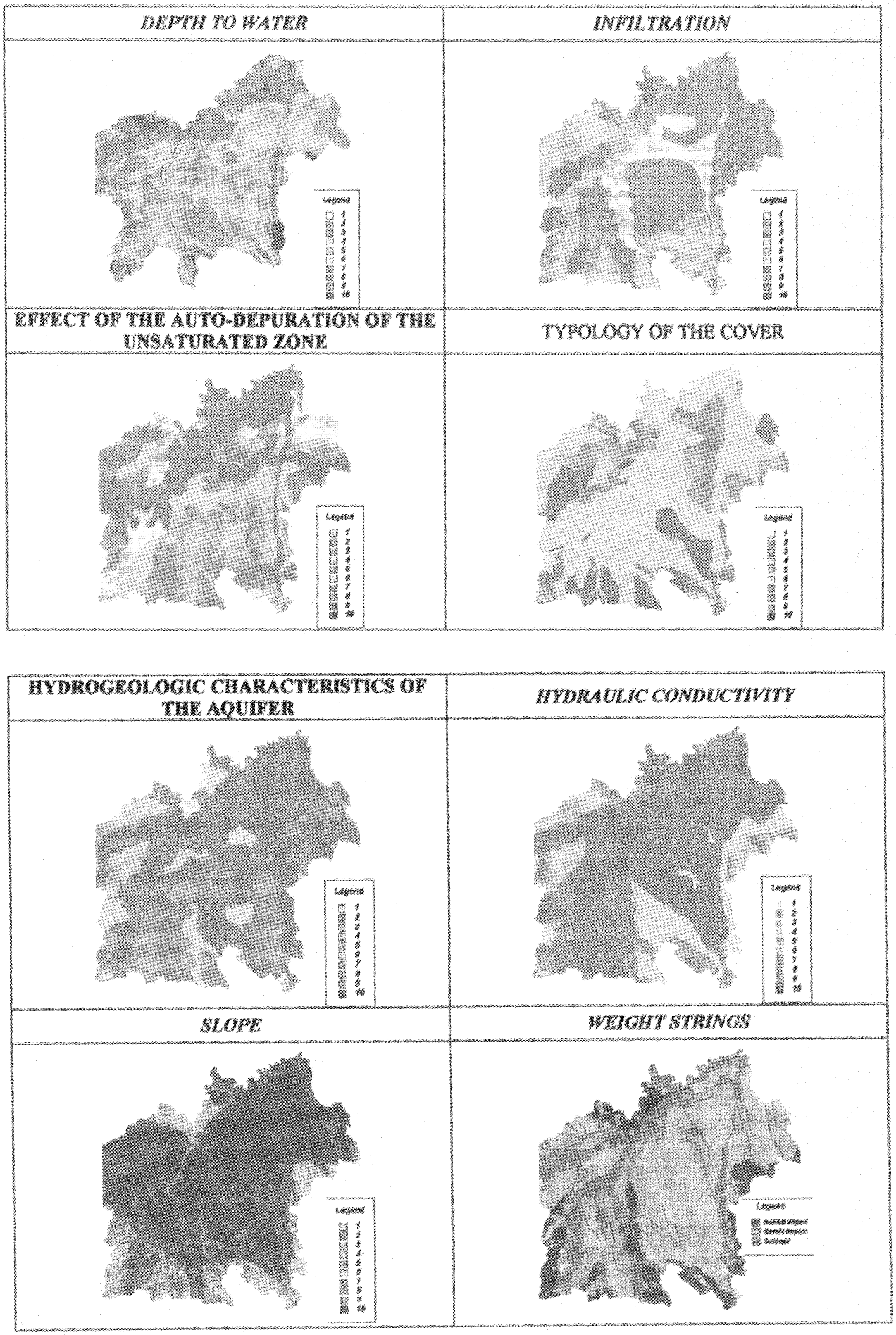


Fig. 7. Alessandria plain: Parametric Maps.

The Map of the hydrogeologic characteristics of the aquifer was obtained by attributing the SINTACS points, according to the abacuses reported for the method.

HYDRAULIC CONDUCTIVITY

The determination of the SINTACS **C** parameter was mainly based on the elaboration of the hydraulic conductivity data obtained from *in situ* tests (Slug test, recovery test, LeFranc test) and from the use of the Q_{SPEC} program (Civita, 1997) using the input data extracted from well stratigraphy and where the data were insufficient, the correspondence between the hydraulic conductivity intervals of the main aquifer complexes and the corresponding **C** parameter points was taken into consideration.

The hydraulic conductivity of the aquifers in the Alessandria sector is medium-high and the values of **C** therefore vary from a minimum of 5, relative to the high terraces of the southern sector, to 6 for the intermediate central sectors of the Alessandria plain. The highest values occur in the sub-complex of the main plain and for the present alluvial complex with **C** = 7 and **C** = 8, respectively. The hydraulic conductivity in the western sector of the area, in correspondence to the gravely-clayey-prevalently Clayey sub-complex, is medium-low and the corresponding **C** value is 3.

The Hydraulic Conductivity Map of the aquifer was prepared for each area under study by attributing the hydraulic conductivity value determined from slug tests and recovery tests and calculating the data of the specific discharge. The procedures for the creation of the covering of the hydraulic conductivity and the SINTACS point grid are similar to those carried out for the covering type Map. The following tests were carried out in the studied area when there was a lack of specific data:

- recovery tests on agricultural wells;
- slug tests in piezometry;
- analysis of the specific discharge data, connected to the stratigraphy of about 250 wells, with a Q_{SPEC} numerical calculation program specifically set up for the evaluation of the SINTACS **C** parameter.

The characterization of the parameter in the areas that are not sufficiently covered by the afore mentioned data was obtained using a protocol that is based on international statistics that allows the order of magnitude of the permeability of the different rock formations (hydrogeologic complexes) to be appraised, together with the SINTACS method (Civita and De Maio, 2000). The different items of information relative to **C**, appropriately reclassified according to the SINTACS points, have allowed the drawing up of the relative Map, via GIS, at a 1:100.000 scale on a raster basis.

SLOPE

The different classes of slope (between 0 and 30 %) were directly obtained from the Regional DTM in the ARC/INFO ambient and were then reclassified according to the SINTACS points. The relative Map of the **S** parameter was thus prepared on a raster basis.

The Map, 1:100.000 scale, was prepared in an automatic way. A grid of the heights was generated from the DTM and the grid of the topographic surface slope was generated from this, using the SLOPE command. The range of the slope classes is defined by the user through a file in which the percentage slope intervals to map are specified. The SINTACS method indicates the slope intervals and the points that are assigned to them. The polygonal cover of the slope from which the area of interest was cut was obtained using overlay operations with the cover of the border of the municipality area. A 50 m side mesh was applied to the slope cover and the thus obtained grid was reclassified with the assignment of the relative SINTACS points.

SELECTION AND CARTOGRAPHY OF THE WEIGHT STRINGS

The structure of the SINTACS method was thought up in order to be able to use various weight strings to attribute to parameters in function of different hydrogeologic and impact situations. In the present case, the conditions to apply 3 of the 6 strings, were encountered:

→ *areas subject to normal impact:* barren areas, uncultivated or with spontaneous cultiva tions which however do not require the use of plant protection products or chemical fertilizers, unless in small doses, or irrigation practices. The breeding of a few wild animals, whether permanent or seasonal, often occurs in these areas.

→ *areas subject to relevant impact:* areas with cultivation that foresee abundant treatments with plant protection products, fertilizers, applications of fert-irrigations, sewage spreading, uncontrolled dumping of waste materials, lagoons, petrol pipelines, sewage deposits, etc.; active and abandoned industrial areas, urban areas or similar.

→ *areas subject to drainage:* from surface water bodies and shallow aquifer; depth to water areas subject to natural and man-made drainage networks; irrigation areas with large quantities of water, continuous or periodic outcropping areas of the unconfined piezometric surface.

The map and the relative grid were prepared using the standard procedures: traditional mapping, construction of the polygonal shapefile in ARCVIEW and application of the usual ARC/INFO mesh.

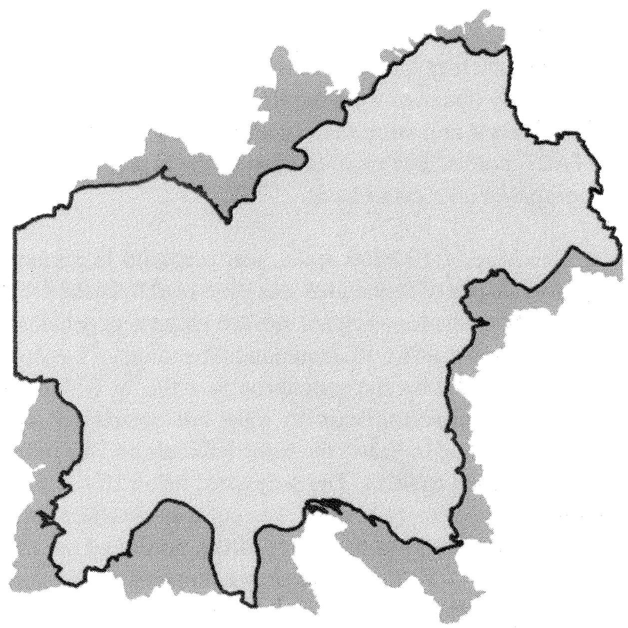


Fig. 8. Light Grey restricted Area elaborated with SINTACS, dark grey enlarged area.

DRAWING UP OF THE INTRINSIC VULNERABILITY MAP

The combined approach was used to draw up the Intrinsic Vulnerability Map. The evaluation was carried out, for the so-called restricted area, using PCSM SINTACS where the necessary data were available. The GNDCI Basic method, suitably calibrated for the specific hydrogeologic situation, (combined approach), was used for the so-called enlarged area (Figure 8).

VULNERABILITY MAP OF THE ENLARGED AREA

The implementation of the SINTACS method to a GIS foresees: a) Importation of the basic elaborations and production of the 8 basic thematic point maps to draw up the Vulnerability Map, relative to 7 SINTACS parameters and to the hydrogeologic and impact situation; b) Production of the Vulnerability Map.

The Vulnerability Map (Figure 9) was obtained through implementation of a cell by cell proce dure in a GRID ambient that foresees the verification of the value of the cell in

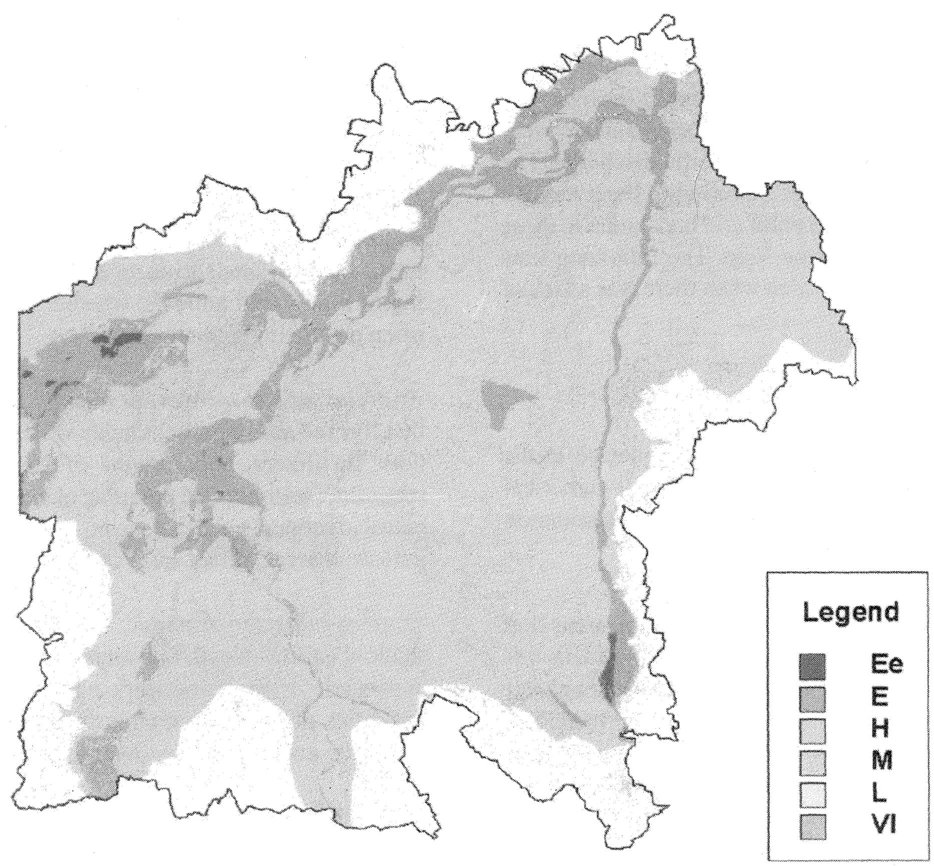


Fig. 9. Vulnerability Map. (Ee: Extremely Elevated; E: Elevated; H: High; M: Midium; L: Low).

Table 7

Hydrogeologic complexes and their Vulnerability degree (Basic GNDCI CNR method)

VULNERABILITY DEGREES	HYDROGEOLOGIC COMPLEXES AND SETTING FEATURES
Extremely High	Unconfined aquifer in gravely and sandy matrixes.
Very High	None
High	Unconfined aquifer in gravel with sandy, clayey gravel, sands with clayey lens matrixes extended to various degrees
Medium	Unconfined aquifer in gravel with clayey, gravel and clayey sand with clay lens matrixes. Unconfined aquifer or under pressure in gravel and sand, coarse sand, muddy sand with silty-clayey horizons. Unconfined aquifer or under pressure in chalk lenses with arenaceous-conglomeratic horizons.
Low	Aquifer under local pressure in prevalently marl with sandy silty horizons; important clay bodies with sand, prevalent sand horizons and arenaceous-conglomerate bodies. Permeability threshold in minute conglomerates and sandstone.
Very low or null	Aquifer under pressure in important clay bodies with gravel and sand horizons. Important permeable succession of marls and clayey marls.

the hydrogeologic impact characteristic grid and identification of the relative weight strings.

And also the application of :

$$I_{SINTACS} = \sum_{J=1}^{7} p_J w_J \,.$$

The value of the SINTACS index of the single cells was then normalized through the implementation of another application of the relation cell by cell procedure (Civita, 1994):

$$I_{norm} = (I_{sintacs} - 26)/2.34.$$

The Grid of the normalized intrinsic vulnerability was thus obtained and it was put on a raster basis and produced in three sheets at a 1: 50.000 scale. It was necessary to insert a thick black line to define the border between the area that was only elaborated with the SINTACS model and the so-called "enlarged" area which was elaborated with the Basic GNDCI-CNR Method.

VULNERABILITY MAP OF THE ENLARGED AREA

The classical method for discrete Hydrogeologic Complexes and Situations (HCS), which for many years was adopted for all the test sites studied as a part of the P.S. VAZAR program of GNDCI-CNR, was used for this map. Details of this treatment can be found in the previous sections. Table 7 shows the code that was attributed to the individual Complexes and Sub-Complexes, as far as the intrinsic vulnerability degree is concerned (Figure 10).

The congruence with the SINTACS evaluation was confirmed with the criteria of the combined approach (Civita M. *et al.*, 2001), introducing some corrections in some points that were however produced by the use of the estimation carried out with the rougher methodology.

INTRINSIC VULNERABILITY MAP

The method that was applied to prepare the Intrinsic Vulnerability Map (Figure 11) has already been fully described in the previous sections.

From this Map it is possible to remark the following in the Alessandria sector:

- the vast Alessandria plain is characterized, with large extensions, by a **high** (**H**) degree of aquifer vulnerability ;
- the degree of vulnerability is just slightly lower (**medium M**) in the less depressed areas (terraces) of the low Tortona area; in the southern part of the Alessandia area; in the strip

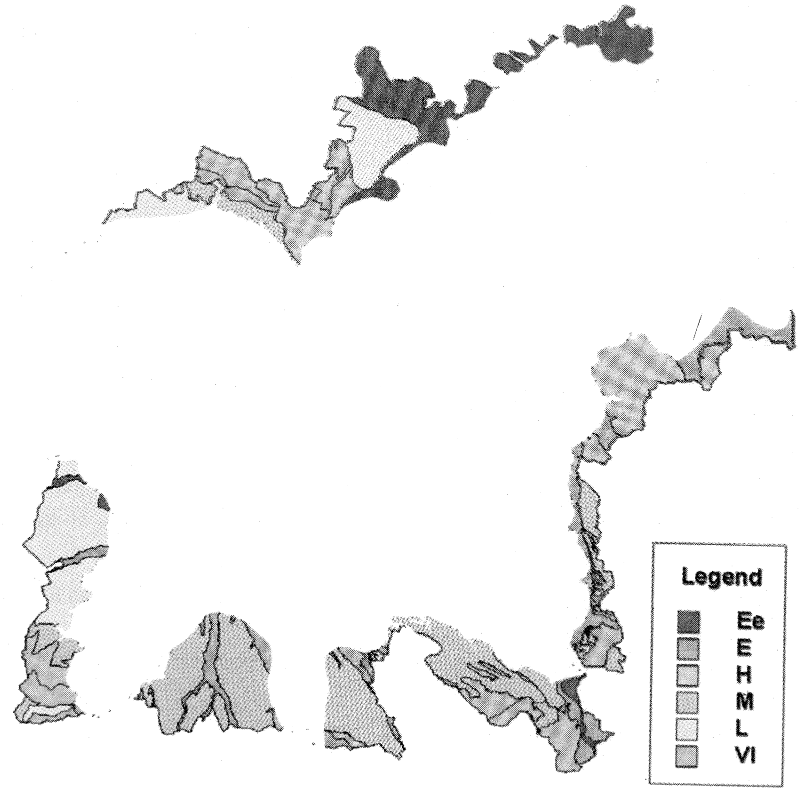


Fig. 10. Vulnerability Map of the enlarged zone.

Fig. 11. Vulnerability Map of the entire zone.

north of Solero; in the area east of Capriata d'Orba; in Castelferro-Mantovana and Sez-zadio;

- In correspondence to the most important riverbeds and the relative floodable areas, the SINTACS index is greater than 70 (**E - elevated vulnerability**) and is often close to the border with the higher class (**Ee - extremely elevated**) for the area of Castellazzo Bormida - Frugarolo - Sezzadio; to the south of the Quattordio - Solero line; north east of Alessandia, next to the Tanaro river up to the convergence with the Po river;

- All the flooded area of the Scrivia river is, likewise, in **elevated (E)** vulnerability conditions with some points in the higher degree **(Ee)** in the apical area of the fan (NW Cassano Spinola): many uncontrolled waste disposal dumps of toxic and harmful materials were found in this area and structures subject to great risks are present in this area; for example the water intake system of the Novi Ligure aqueduct;

- the waters from the Scrivia river derive in great part from numerous irrigation channels on the left that distribute the water from the river to areas with **high** to **elevated** vulnerability;

- The hilly Tortonese areas, of Monferrato and the Alessandria part of the Langhe are usually characterised by a **medium** (**M**) to **low** (**L**) vulnerability degree.

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