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Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods

R.C. Gogu · A. Dassargues

Abstract The concept of groundwater vulnerability is a useful tool for environmental planning and decision-making. Many different methods have been developed for assessing this vulnerability. Hydrogeologists have failed to reach a consensus concerning the definitions of and reference terms for groundwater vulnerability assessment. Therefore, a review of vulnerability assessment and mapping methods providing a new classification system is necessary. This is focused on techniques that use the overlay and index class methods. New research challenges in vulnerability assessment are identified, especially the need for developing dynamic links between numerical models and overlay and index methods.

Key words Groundwater · Vulnerability · Overlay and index methods

General concepts for groundwater vulnerability assessment

Vulnerability assessment of groundwater, as used in many methods, is not a characteristic that can be directly measured in the field. It is an idea based on the fundamental concept "that some land areas are more vulnerable to groundwater contamination than others" (Vrba and Zaporozec 1994). Nevertheless mapping the degree of groundwater vulnerability to contaminants, as a function of hydrogeological conditions, shows that effective protection provided by the natural environment may vary drastically from one place to another.

Often, the groundwater contamination level is determined by the natural attenuation processes, occurring within the zone located between the pollution source and the aquifer. Various natural, physical processes, and chemical reactions that operate in the soil, unsaturated, and saturated zones, may cause the pollutant to change its physical state and chemical form. These changes may attenuate the degree of pollution or change the nature of the contamination. Especially in soil and the unsaturated zone, some mechanisms may affect the contaminant concentration much more than in the saturated zone.

Chemical processes can be very complex and may work individually or in combination with other processes to provide varying attenuation degrees. These reactions depend on site specific soil and aquifer characteristics as well as on the particular geochemical properties of each pollutant. Although the importance of these chemical reactions for attenuation of pollution is widely recognized and sometimes modelled, attenuation processes can be partially or completely bypassed depending on geochemical conditions in the aquifer and the infiltration conditions.

Pollution sensitive areas

Pollution sensitive areas can be divided into three groups: naturally vulnerable areas, well-protection zones, and potential problem areas.

Naturally vulnerable areas are more sensitive zones where the soils, subsoil, and bedrock do not provide adequate protection and the potential exists for rapid transfer of pollutants to groundwater. Areas of concern are, for example, the recharge zones of shallow aquifers.

In the vicinity of pumping wells, each pollutant can potentially contaminate the pumped groundwater relatively quickly. In many countries, the methods for delineating well-protection zones are standardised using different criteria, based on the piezometric heads, on the advective transport time, on the advective-dispersion transport time or other parameters.

Overlaying maps of the most vulnerable zones, with maps showing the location of each potential contamination sources or polluting land-use activities, generates the map of potential problem areas (risk maps).

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Concepts and methods of vulnerability assessment

The aquifer vulnerability concept mainly entails two particular notions: intrinsic vulnerability and specific vulnerability. European specialists of the COST Action 620 "vulnerability and risk mapping for the protection of carbonate (karst) aquifers", agreed on the fact that intrinsic vulnerability is a "term used to define the vulnerability of groundwater to contaminants generated by human activities", taking "account of the inherent geological, hydrological and hydrogeological characteristics of an area", but being "independent of the nature of contaminants". On the contrary, specific vulnerability notion is used "to define the vulnerability of groundwater to a particular contaminant or group of contaminants", taking "account of the contaminant properties and their relationship with the various components of intrinsic vulnerability".

In relation to groundwater protection, three main approaches can be distinguished in the assessment of groundwater vulnerability to contamination:

1. Vulnerability assessment considering only the soil and unsaturated zone without taking into account the transport processes within the saturated zone. In this case, the assessment is limited to the relative probability that troublesome concentrations of contaminants reach the saturated zone. Many classical vulnerability methods, are based on this approach : the GOD method (Foster 1987), the Irish approach (Daly and Drew 1999) or AVI method (Van Stempvoort and others 1993).
2. The approach based on delineation of protection zones for groundwater supply systems, where groundwater flow and contaminant transport processes within the saturated zone are considered to some extent (including dispersion transport as it is done in Walloon Region of Belgium, Derouane and Dassargues 1998).
3. An approach, targeting the soil and unsaturated zones as well as the aquifer medium.

Based on these different approaches, various methods of groundwater vulnerability assessment have been developed. They range from sophisticated numerical models simulating the physical, chemical and biological processes occurring in the subsurface, to techniques using weighting factors affecting vulnerability and also to statistical methods. Coupled, physically-based models considering soil, unsaturated and saturated zones in order to compute contaminant transport time in the system and at the opposite various empirical vulnerability methods like DRASTIC (Aller and others 1987), SINTACS (Civita 1994), EPIK (Doerfliger and Zwahlen 1997) could be cited here.

In this paper, only the current methods used for groundwater vulnerability assessment are discussed. Most often they are based on overlay and index techniques. The combination of maps with spatial distributions of specific attribute data (soil, geology, depth to water, etc.) leads to an assigned numerical index or score for each attribute. They are combined to produce a vulnerability score. Attempts are made to obtain values as quantitative as possible.

Current trends in vulnerability assessment using overlay and index methods

Overlay and index methods rely mainly on the quantitative or semi-quantitative compilation and interpretation of mapped data. Starting from the fundamental concept of vulnerability of the U.S. Committee on Techniques for Assessing Ground Water Vulnerability (National Research Council 1993) and from the definitions of the International Association of Hydrogeologists (Vrba and Zaporozec 1994), some general characteristics of these methods must be emphasised:

- Groundwater vulnerability is a relative, non-measurable, dimensionless property.
- The main attributes used for the intrinsic vulnerability assessment are recharge value, soil properties and characteristics of unsaturated and saturated zones. Attributes of secondary importance include topography, groundwater/surface water relation, and the nature of the underlying unit of the aquifer.
- Specific vulnerability is mostly assessed in terms of danger for the groundwater system becoming exposed to specific contamination. The most important parameters in specific vulnerability assessment are: contaminant travel time within the unsaturated zone and its residence time inside the aquifer medium, attenuation capability of the soil-rock-groundwater system with respect to the properties of individual contaminants.
- The assessment of groundwater vulnerability is site or area specific.

A summary of some significant methods used for groundwater intrinsic vulnerability assessment can be found in Table 1. The existing methods can be grouped into two basic categories: hydrogeological complex and settings methods, and parametric system methods.

Hydrogeological complex and settings methods (HCS)

This kind of method implies a qualitative assessment. First, one must decide the hydrogeological, hydrographical and morphological conditions that correspond to each class in a vulnerability scale. Then the entire area is analysed and divided following the criteria established (Albinet and Margat 1970). Generally, a map overlay procedure is used. Large areas with various hydrographical and morphostructural features are best suited for assessment through these methods and thematic maps are produced from medium to large scale.

Parametric system methods

These are the Matrix Systems (MS) and Rating Systems (RS) methods and the Point Count System Models (PCSM) for the groundwater vulnerability assessment. For all parametric system methods the procedure is almost the same. The system definition depends on the selection of those parameters considered to be representative for groundwater vulnerability assessment. Each pa-

Table 1
Significant methods for the assessment of the intrinsic vulnerability of groundwater, Explanation: HCS hydrogeological complex and settings methods, MS matrix system methods, RS rating systems methods, PCSM point count system models (rating and weighting systems)

METHOD	TYPE	BASIC PARAMETERS													
REFERENCE		Topo-grafic surface slope variability	Stream flow net-work density	CHARACTERISTICS OF SOILS				Aquifer connect to surface water	Net recharge	Charac-teristics unsaturated zone	Depth to water	Hydro-geological features	Aquifer hydraulic conduc-tivity	Thickness of the aquifer	Landuse type[a]
				Thickness texture and mineralogy	Effective moisture	Perme-ability	Physical and chemical properties								
Albinet and Margat 1970	HCS							•		•	•	•	•		
Goossens and Van Damme 1987	MS			•			•				•	•			
Carter and Palmer 1987	MS			•		•	•					•			
GOD, Foster 1987	RS									•	•	•			
DRASTIC, Aller and other 1987	PCSM	•		•					•	•	•	•	•		
SEEPAGE	RS	•		•	•	•	•			•	•	•			
SINTACS, Civita 1994	PCSM	•	•	•				•	•	•	•	•	•		•
AVI -Van Stempvoort and others 1993	RS			•		•				•	•				
ISIS, Civita and De Regibus 1995	RS	•		•			•		•	•	•	•		•	•
EPIK, Doerfliger and Zwahlen 1997	PCSM Karst aquifers	•		•				•	•	•		•			•

[a] The land use parameter characterise the human activity impact as effect on the runoff coefficients and not as the nature of contaminants

rameter has a defined natural range divided into discrete hierarchical intervals. To all intervals are assigned specific values reflecting the relative degree of sensitivity to contamination.

Matrix Systems (MS) methods are based on a restricted number of carefully chosen parameters. To obtain a quantified degree of vulnerability, these parameters are combined following a number of strategies developed by different research groups. These research applications are site-specific methods developed for local case studies, such as the method selected for the Flemish Region of Belgium (Goossens and Van Damme 1987) and the system used by Severn-Trent Water Authority in some areas of Central England (Carter and others 1987).

Rating Systems (RS) methods provide a fixed range of values for any parameter considered to be necessary and adequate to assess the vulnerability. This range is properly and subjectively, divided according to the variation interval of each parameter. The sum of rating points gives the required evaluation for any point or area. The final numerical score is divided into intervals expressing a relative vulnerability degree. The rating systems are based upon the assumption of a generic contaminant. Examples are GOD system (Foster 1987), AVI Method (Van Stempvoort and others 1993), and the ISIS method (Civita and De Regibus 1995).

Point Count System Models or Parameter Weighting and Rating Methods (PCSM) are also a rating parameters system. Additionally, a multiplier identified as a weight is assigned to each parameter to correctly reflect the relationship between the parameters. Rating parameters for each interval are multiplied accordingly with the weight factor and the results are added to obtain the final score. This score provides a relative measure of vulnerability degree of one area compared to other areas and the higher the score, the greater the sensitivity of the area. One of the most difficult aspects of these methods with chosen weighting factors and rating parameters remains distinguishing different classes of vulnerability (high, moderate, low etc.), on basis of the final numerical score. Examples are the DRASTIC method developed by U.S. EPA in 1985 (Aller and others 1987), SINTACS method (Civita 1994), and the EPIK method used in karst groundwater protection strategy developed by Doerfliger and Zwahlen (1997).

Uses and limitations

Groundwater vulnerability predictions are made in a relative, not an absolute, sense.

In many cases vulnerability maps are created to obtain a fast assessment of pollution risk, however they could be used as a meaningful tool in the environmental decision-making process. Methods applied to obtain groundwater vulnerability maps, have to portray a correct view on the site vulnerability and subsequent site-specific investigations are essential in many situations.

The UK National River Authority recognised that a full assessment of aquifer vulnerability and groundwater pollution risk can only be achieved by local studies (Robins and others 1994). These kinds of methods can reduce the number of areas to be studied in detail by identifying the most vulnerable areas. However, vulnerability assessment is a useful management concept for guiding decisions on groundwater protection tasks. It requires co-operative efforts of policy makers, natural resource managers, technical and scientific experts.

Main methods

GOD rating system

This method (Foster 1987) has a simple and pragmatic structure. It is an empirical system for quick assessment of the aquifer vulnerability to pollution. Three main parameters are considered: the groundwater occurrence, the lithology of the overlying layers, and the depth to groundwater (in unconfined or confined conditions). The vulnerability index (Fig. 1) is the result of the values assigned to these three parameters. Following the GOD flowchart, the area vulnerability index is computed by choosing first the rating of groundwater occurrence parameter and then multiplying by the overlying lithology rating as well as with the depth to water parameter rating. The overlying lithology parameter contributes to the vulnerability index only in the case of unconfined aquifers.

Because the parameters can only take values from 0 to 1, the computation result is usually a value less than the score assigned to each parameter. In the particular case where two parameters have a value equal to 1, the vulnerability score is equal to the score of the third parameter.

DRASTIC point count system model

The U.S. Environmental Protection Agency (EPA) developed DRASTIC (Aller and others 1987) as a method for assessing groundwater pollution potential. This method considers the following seven parameters: depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity. Each mapped factor is classified either into ranges (for continuous variables) or into significant media types (for thematic data) which have an impact on pollution potential. The typical rating range is from 1 to 10. Weight factors are used for each parameter to balance and enhance their importance. The final vulnerability index (D_i) is a weighted sum of the seven parameters and can be computed using the formula:

$$D_i = \sum_{j=1}^{7} (W_j \times R_j) \quad (1)$$

D_i = DRASTIC Index for a mapping unit
W_j = Weight factor for parameter j
R_j = Rating for parameter j

DRASTIC provides two weight classifications (Table 2), one for normal conditions and the other one for conditions with intense agricultural activity. This last one, called pesticide DRASTIC index, represent a specific vul-

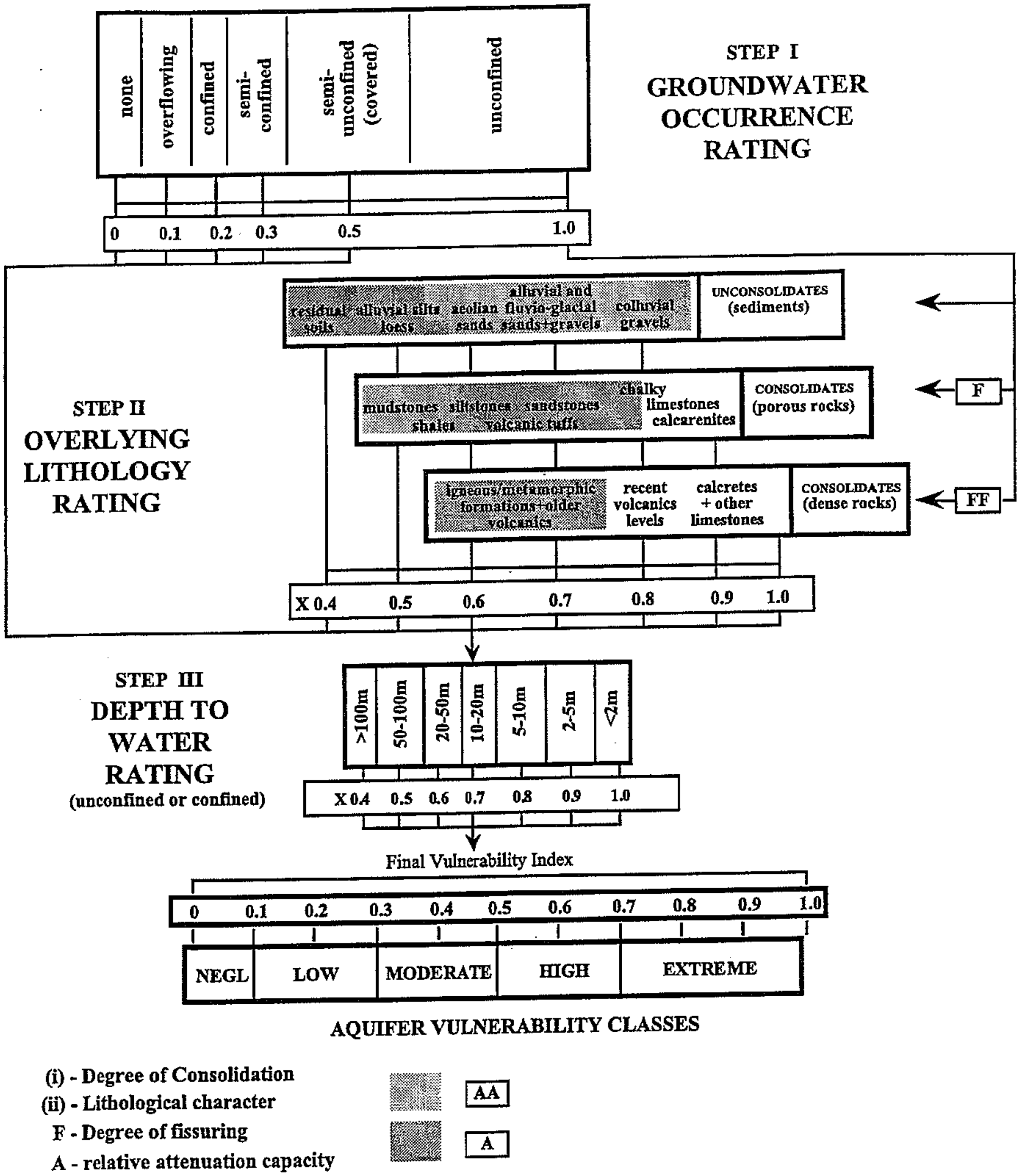

Fig. 1
The GOD parameters rating method, from Foster (1987)

nerability assessment approach. In a specific area only one weight classification should be selected for the whole area.

Once DRASTIC indices have been computed, it is possible to identify areas that are more susceptible to groundwater contamination than others. The higher the DRASTIC index, the greater the groundwater contamination

Table 2
Weight factors for DRASTIC and Pesticide DRASTIC

Parameter	DRASTIC weight	Pesticide DRASTIC weight
Depth to ground water	5	5
Net recharge	4	4
Aquifer media	3	3
Soil media	2	5
Topography	1	3
Impact of vadose zone	5	4
Hydraulic conductivity	3	2

potential. The DRASTIC index provides only a relative evaluation tool and is not designed to provide absolute answers. Moreover, the values generated by DRASTIC index and pesticide DRASTIC index are not similar.
To facilitate interpretation, some users have tried to divide the final index into vulnerability classes such as: low, moderate, high, and very high potential (Corniello and others 1997).

SEEPAGE method

The system for early evaluation of pollution potential of agricultural groundwater environments (SEEPAGE) considers various hydrogeologic settings and soil physical properties that affect groundwater vulnerability to pollution potential (Navulur KCS and Engel BA, unpublished data). It is also a numerical ranking model analysing contamination potential from both concentrated and dispersed sources. The SEEPAGE model considers the following parameters: soil slope, depth to water table, vadose zone material, aquifer material, soil depth, and attenuation potential. Attenuation potential takes into account the texture of surface soils, texture of subsoil, surface layer pH, organic matter content of the surface, soil drainage class and soil permeability.
To each parameter a weight factor ranging from 1 to 50 is assigned, based on its relative significance. A weight factor of 50 is assigned to the most significant parameter affecting the water quality and a weight factor of 1 is assigned for the least significant. These weights are different for concentrated sources and dispersed ones. As with DRASTIC, each parameter can be divided into ranges, but the rate value assigned for each parameter vary from 1 to 50. The ratings of the aquifer media and vadose zone are subjective and can be changed for a particular region. Once the scores for the six parameters are obtained, these are summed to get the SEEPAGE Index Number (SIN). SIN numbers are ordered in four categories of pollution potential: low, moderate, high, and very high. A high or very high SIN category indicates that the site is highly vulnerable.

AVI rating system

This method (Van Stempvoort and others 1993) estimates the aquifer vulnerability index (AVI) using only two parameters: the thickness of each sedimentary unit above the uppermost aquifer (d); and the estimated hydraulic conductivity of each of these layers (k). The hydraulic resistance is given by:

$$c = \sum_{i=1}^{n} d_i/k_i; \qquad (2)$$

c = the hydraulic resistance given by AVI rating system
n = the numbers of layers
k = estimated hydraulic conductivity of each of the n layers

The c or $\log(c)$ value is related to a qualitative Aquifer Vulnerability Index by a relationship table. The authors suggest calculating c for each well or test hole and then to generate the iso-resistance contour to classify the study area in AVI zones.

SINTACS method

Derived from DRASTIC model, this method has been developed for vulnerability assessment and mapping requirements (medium and large-scale maps) by Italian hydrogeologists (Civita 1994). The SINTACS point-count system has a complex structure (Fig. 2). A number of weight strings are used in parallel, to define the existing conditions. These parameter values are then rated and divided into intervals. The final results outline six vulnerability classes.
In fact, SINTACS proposed by Civita (1994) uses the same seven parameters as DRASTIC but the rating and weighting procedure is more flexible. It provides four weight classifications but it also allows the creation of new ones. The user encodes the input data as functions of local conditions in each area, and has the possibility of using different classifications depending on circumstances.
SINTACS vulnerability index can be computed as follows:

$$I_v = \sum P_{(1,7)} \times W_{(1,n)}; \qquad (3)$$

I_v = vulnerability index by SINTACS method
$P_{(1,7)}$ = the rating of each of the seven parameters used
$W_{(1,n)}$ = the associated weight
n = the number of weight classification arrays

ISIS method

This method is a synthesis of various studies on aquifers intrinsic vulnerability assessment (Civita and De Regibus 1995) and can be classed with the rating systems group of methods.
ISIS is a hybrid method, based on the comparative evaluation of the existing hydrogeological situations. It has been developed taking into account the rating and weighting systems of DRASTIC and SINTACS methods and the GOD method for the general structure design. Parameters used by ISIS method are: the annual mean of the net recharge (it is possible to introduce the rainfall value and the mean annual temperature or other related parameters), topography, soil type, soil thickness, lithology of the unsaturated zone, thickness of the unsaturated zone, aquifer medium, and aquifer thickness.

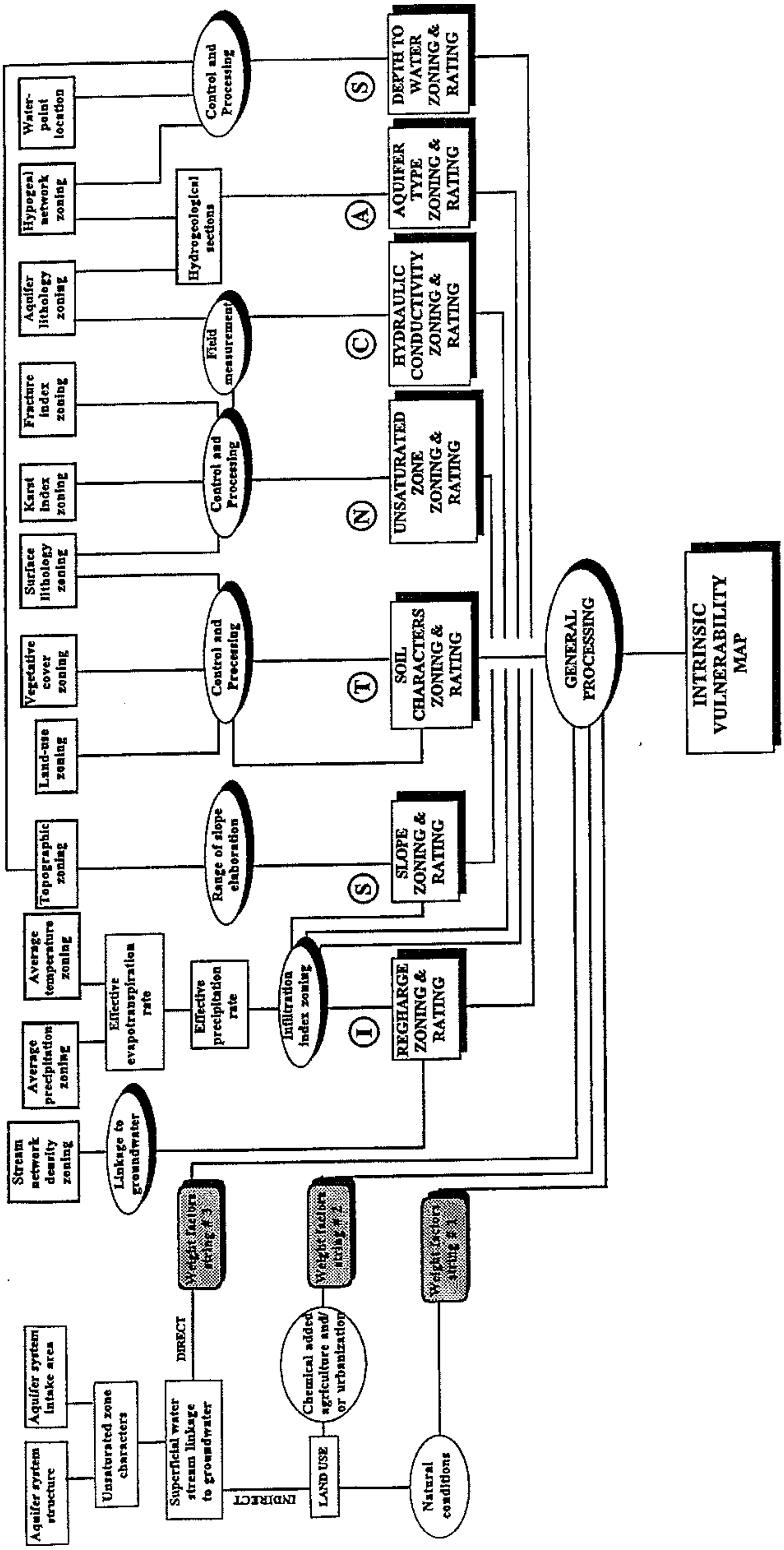

Fig. 2
SINTACS method recipe, adapted from Vrba and Zaporozec (1994)

The land-use parameter, as the human activity impact feature, has been adopted from the SINTACS methodology and quantified. It has been divided in three areal units: areas with normal conditions, strong contaminated agricultural area, strong superficial drained area. This parameter is used as a weighting element for modulating the relative importance of the direct used parameters, as a function of the different land use conditions.

To estimate the vulnerability index I_v, ISIS method is using the following formula:

$$I_v = p_{Inf} \times f_{Inf} + p_{Su} \times f_{Sus} \times f_{Su} + p_{Ins} \times f_{Si} \times f_{Ins} + p_{Sat} \times f_{Ss} \times f_{Sat} \quad (4)$$

Where:

p_{Inf} = the rating values for ranges on the net recharge;
f_{Inf} = infiltration coefficient dependent on land use;
p_{Su} = the rating values for the soil media;
f_{Sus} = soil coefficient dependent on land use;
f_{Su} = weighting coefficient dependent on soil thickness;
p_{Ins} = the rating values assigned to the vadose zone;
f_{Si} = weighting coefficient dependent on the unsaturated zone lithology and thickness;
f_{Ins} = vadose zone coefficient dependent on land use;
p_{Sat} = the rating values assigned to aquifer media;
f_{Ss} = weighting coefficient dependent on the aquifer thickness;
f_{Sat} = aquifer coefficient dependent on land use.

The final vulnerability index, varying between 24 and 180 is divided in 6 vulnerability classes: extreme (141–180); very high (124–140); high (88–123); medium (64–87); low (44–63); very low (24–43).

EPIK method

EPIK method has been specifically created for the vulnerability assessment of the karst aquifers (Doerfliger and Zwahlen 1997) in Switzerland. It is a clear and original parameter weighting and rating method (Fig. 3). Four main parameters are considered: epikarst (*E*), protective cover (*P*), infiltration conditions (*I*), and karst network development (*K*). Considering the impact on pollution potential, each parameter is classified into ranges (Table 3). Weighting factors are used for each parameter to balance their importance. The final "protection factor" (vulnerability index) is calculated with the following basic formula:

$$F_p = (\alpha \times E_i) + (\beta \times P_j) + (\gamma \times I_k) + (\delta \times K_l) \quad (5)$$

F_p = vulnerability Index in the EPIK method
E_i = rating value for the "epikarst" parameter
P_j = rating value for the "protective cover" parameter
I_k = rating value for the "infiltration conditions" parameter
K_l = rating value for the "karst network development" parameter
$\alpha, \beta, \gamma, \delta$ = weight factors for EPIK parameters

Assigned relative weights for EPIK parameters are: $\alpha = 3$, $\beta = 1$, $\gamma = 3$, $\delta = 2$

Table 3
Rating values for E, P, I, and K parameters, note: the lower the rating value, the higher the vulnerability

E_1	E_2	E_3	P_1	P_2	P_3	P_4	I_1	I_2	I_3	I_4	K_1	K_2	K_3
1	3	4	1	2	3	4	1	2	3	4	1	2	3

The vulnerability index is found in an interval of values from 9 to 34 and is divided in four categories of vulnerability degree: high (9–19); medium (20–25); low (26–34) and very low (in conditions of a soil protective cover of thick detrital layers with very low hydraulic conductivity – having a thickness of minimum 8 m).

Comparison studies

One of the few cases where an attempt has been made to compare methods was by an Italian research team in "Piana Campana" region, Southern Italy (Corniello and others 1997). To assess the vulnerability of the aquifer in this area, four methods were tested: DRASTIC, SINTACS, GOD, and the AVI model. For an operational qualitative comparison, specific aspects of vulnerability classes were considered.

It was shown that the SINTACS method, compared with the others, generates "very high vulnerability zones in the areas concerned with surface waters and aquifer interactions. This result is strongly influenced by the aquifer identification and by different weight classification series used for the area affected by drainage. A similar result was obtained in a vulnerability assessment study made on the alluvial cone Prahova – Teleajen (Gogu and others 1996), by applying the SINTACS method together with a matrix system method locally developed by a Romanian research team.

Using the DRASTIC model, the low vulnerability class was wider than within SINTACS. At the same time, SINTACS model seems to give more importance to the land-use parameter, because of using different weight classification strings. In areas where the degree of vulnerability has modest variations, the GOD method provided homogeneous distributions of values. In consequence this method can only be used in areas with high contrasted vulnerability. Even with fewer parameters, the vulnerability map generated through AVI method was similar to those obtained from DRASTIC and SINTACS models. Moreover, a statistical comparison of all vulnerability maps showed the greatest similarity between the DRASTIC and SINTACS methods as well as a good correlation between those two and the AVI method.

Civita and De Regibus (1995) performed another significant comparative study of five methods of groundwater vulnerability assessment. To cover different hydrogeological situations, the study targeted three specific areas in Northern Italy, respectively flat, hilly and mountainous regions. The methods considered were DRASTIC, SINTACS, GOD, the Flemish Method (Goossens and Van Damme 1987), SINTACS, ISIS, and the CNR – GNDCI

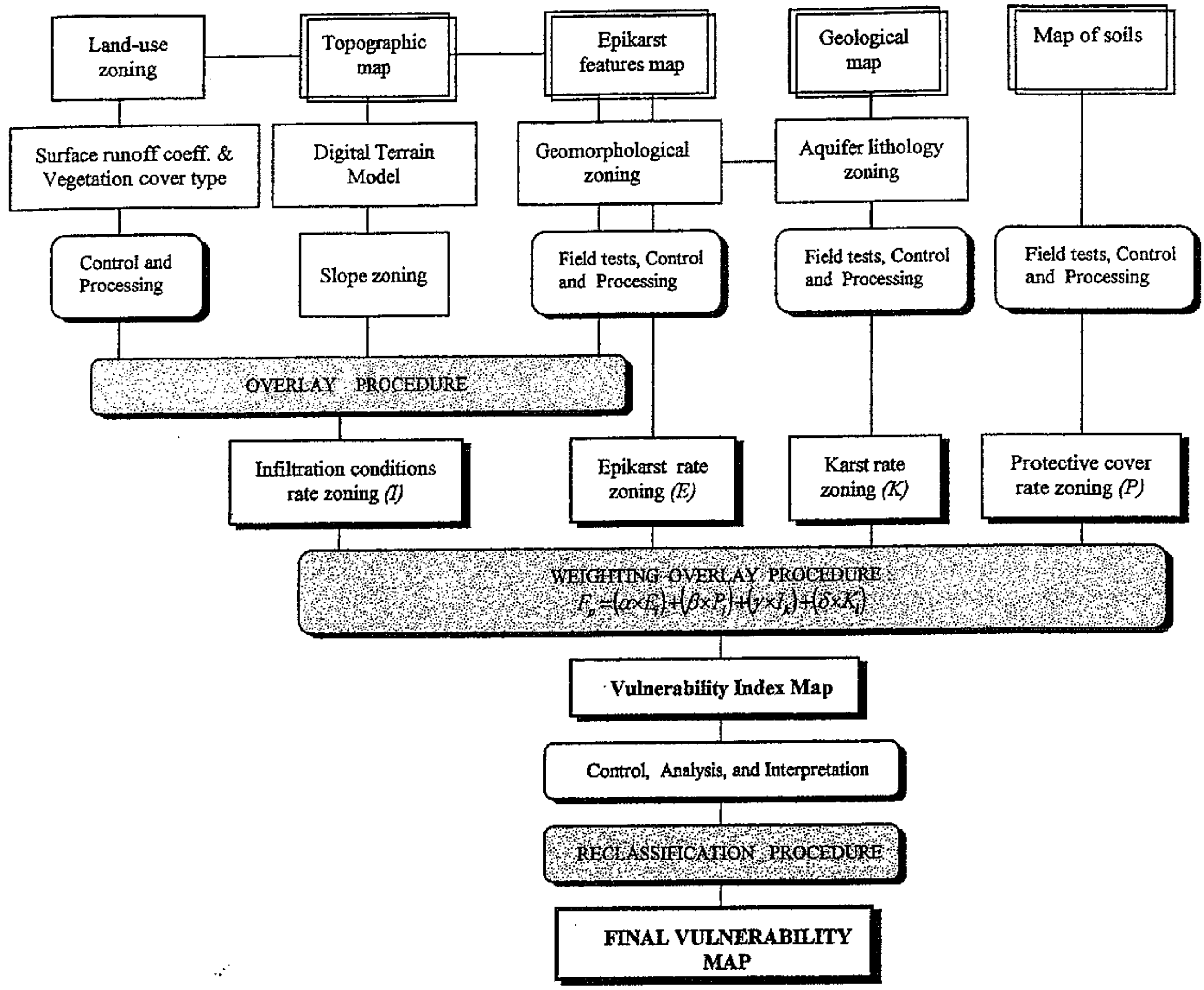

Fig. 3
The main steps of the EPIK method

method based on direct confrontation with hydrogeological predefined situations (Civita 1990).

Applying different methods to the same zone and using the same data showed that the relatively simple methods could provide similar results to the complex ones. It could be confirmed that these methods (as GOD for example) are best suited for designing large areas (used in land management). Having a good precision and flexibility, DRASTIC and SINTACS methods are much more effective in detailed studies. Other methods, such as the Flemish one, were not able to be adapted to situations other than those they were designed for.

A sensitivity analysis to evaluate a single parameter influence on the aquifer vulnerability assessment was performed on the same "Piana Campana" region by Napolitano and Fabbri (1996). Comparing SINTACS and DRASTIC methods, they observed that removing each of the seven parameters one by one, created relevant and significant changes in the vulnerability maps. They concluded that all the seven DRASTIC parameters are important in assessing aquifer vulnerability.

Comparing vulnerability methods using different parameters is not a comfortable operation however it represents the single manner to estimate their efficiency on a case study. This can be done mainly by examining the resulted vulnerability maps obtained with each method. A confrontation between them as well as with the initial hydrogeological information is always very interesting. In general, a method providing more contrasted results for a specific area can be considered as presenting a higher sensibility, so that results can be used and interpreted.

Future challenges in groundwater vulnerability assessment

Hydrogeologists are trying to agree on issues concerning intrinsic and specific vulnerability, on the different models and assessing methods, and on risk mapping and management aspects. For improvement of the vulnerability assessment analysis, research challenges can be found in the following aspects:

- To determine circumstances in which properties of the intermediate vadose zone are critical to vulnerability assessment and to develop methods for characterising this zone with more accuracy. A better quantification of physical and chemical processes that are taking place in this zone as well as the relationship with the other important factors influencing vulnerability will result in better results of the assessment procedure.
- To develop methods for accounting preferential flow pathways (for examples, soil macropores, fissure network, etc.) that can affect severely the vulnerability.
- To gather more information on uncertainty associated with vulnerability assessments and to develop ways to handle and display this aspect.
- To improve the hydrochemical database structures, and to find ways of introducing them in specific vulnerability assessments.
- To define more meaningful categories of vulnerability and determine which processes are most important to be incorporated into vulnerability assessment at different spatial scales. For instance, the UK National review on aquifer vulnerability defines the relative vulnerability of aquifers in terms of land zonation, based on the average time taken by infiltrating water to reach the aquifer. The accompanying maps, therefore, have classes of 1 week, 1 year, 20 years, greater than 20 years, plus three other categories (multizone, no information and no aquifers). The multizone category was designed to overcome the limitation of detail at the used map scale (Robins and others 1994).
- To set up unified models integrating the soil and geologic information in vulnerability assessment models. Also, the land-use and census data integration can improve the quality of groundwater overlaying vulnerability assessment by creating the potential risk maps. This correlation should be done by integrating information associated to potential contaminators (for example, industrial activity, highways' traffic parameters, etc.) and data about indirect influence of the human activities (artificial drainage created by agricultural activities).
- To create tools for merging data obtained at different spatial and temporal scales into a common scale for vulnerability assessment.
- To seek for useful comparative techniques and procedures to evaluate assessment methods and groundwater quality monitoring data. For instance, it was attempted in some overlay and index methods to address contamination (that might occur by wells and boreholes) by mapping those features in combination with results derived from other assessment methods. In these kinds of approaches, an essential point is the fact that contaminant load distribution is taken into account.
- To improve analytical tools in GIS software for effective integration of assessment methods with spatial attribute databases as well as with statistical and process based modelling techniques.

Process-based simulation models are used to predict groundwater flow and contaminant transport in both space and time. They mostly include a comprehensive description of the physical, chemical, and biological processes affecting groundwater vulnerability, they require extensive data sets, which often are not available. When missing data are estimated by indirect means, these models are not as reliable as they are in theory. Moreover based on the Representative Elementary Volume (REV) concept, these models simulate the flow and transport processes at the spatial scale of the chosen REV. In addition, most of them do not consider cases where preferential groundwater flow exists. (The assumption of considering a karst aquifer as a continuous porous medium is made in order to use numerical procedures developed for continuum mechanic).

One of the main future challenges of hydrogeology is to establish conceptual and operational basis for combining vulnerability methods and the results of process based models. This should be achieved, first at the theoretical level and later as a complex expert tool that could merge the data from spatial databases, vulnerability methods and process-based and statistical models into an integrated assessment concept.

To meet such a challenge, it will be necessary to use numerical model results in order to provide values of parameters in vulnerability assessment analysis (for DRASTIC: hydraulic conductivity, aquifer media, impact of the vadose zone, recharge of the aquifer). Integration of the "transfer time zones", related to the aquifer media, as rating parameter in the vulnerability assessment methods is also needed.

Conclusions

Trying to reach consensus on the terminology (vulnerability, hazards, risks), comparing methods, establishing models, discussions on weighting and rating, development of sensitivity analysis, could be accomplished by dedicated workshops and meetings. In this topic, the work being done in the scope of the COST620 Action on "vulnerability and risk mapping for the protection of carbonate (karst) aquifers", is not only useful for future research development but also needed for immediate practical purposes.

New challenges for hydrogeologists will consist in the integration of results from process based numerical model in the vulnerability mapping techniques. Using the existing software, GIS packages and interfaces the problem could theoretically be solved, but real integrated tools are expected and according to needed parameters data are to be collected and better quantified.

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