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Single-parameter sensitivity analysis for aquifer vulnerability assessment using DRASTIC and SINTACS

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Abstract This paper deals with the application of sensitivity analysis to evaluate the influence of single parameters on aquifer vulnerability assessments using DRASTIC and SINTACS. The procedure to implement the map removal and the single-parameter sensitivity analysis is described in this contribution and is tested in a part of the Piana Campana, southern Italy, where the aquifer vulnerability was assessed. A GIS-based approach with the use of "unique condition subareas" and with the implementation of batch files allows easy and fast analysis. The presentation of the results through tables and classified raster maps allows an efficient interpretation also to non-GIS specialists.

INTRODUCTION

This paper deals with the application of sensitivity analysis to evaluate the influence of single parameters on aquifer vulnerability assessments using DRASTIC (Aller *et al.*, 1987) and SINTACS (Civita, 1994), two parametric methods based on the weighted sum of seven parameters thought to be critical for the analysis.

Subjectivity is unavoidably associated with the selection of ratings and weights that have to be assigned to the seven base maps which represent the seven parameters. Such a selection strongly affects the result of the final vulnerability map. Because it is not possible at present to avoid subjectivity, one way is to deal with it is by performing a sensitivity analysis which characterizes the distribution of individual variables and of input parameters on the resultant output of an analytical model. From a practical point of view, because vulnerability maps are tools used by planners for socio-economic decisions, sensitivity analysis is useful for validation and consistency evaluation of the analytical result and for a correct interpretation of the vulnerability maps.

The process strategy described in this contribution for the development of a systematic analytical procedure uses geographic information systems (GIS). In particular, ILWIS (ITC, 1993), which was used in this contribution, is a PC-based GIS with the capability to iterate operations between spatial datasets and the associated non-spatial data. The method was tested in a study area which is part of the Piana Campana near Naples, southern Italy, where the aquifer vulnerability has been assessed using both DRASTIC and SINTACS (Napolitano, 1995; Corniello *et al.*, 1995; Napolitano & Fabbri, 1995).

BACKGROUND

The DRASTIC and SINTACS methods

DRASTIC, proposed by the US Environmental Protection Agency (Aller *et al.*, 1987) and its modification termed SINTACS (Civita, 1994) are two methods to evaluate the vertical vulnerability based on the following seven parameters: **D**epth to water, net **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of the vadose zone, and hydraulic **C**onductivity. 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. Weight multipliers are then used for each factor to balance and enhance their importance. The final vulnerability index is a weighted sum of the seven factors.

The DRASTIC index (D_I) can be computed using expression (1):

$$D_I = D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w \qquad (1)$$

where D, R, A, S, T, I, and C are the seven parameters, r is the rating value of the analysed subarea, and w is the weight associated to each parameter.

Differently from DRASTIC, with SINTACS it is possible to use, at the same time and in different subareas, different weight classes corresponding to different situations. The SINTACS vulnerability index (I_v) is computed using expression (2):

$$I_v = \Sigma P_{(1,7)}\, W_{(1,n)} \qquad (2)$$

where $P_{(1,7)}$ is the rating of each of the seven parameters used and $W_{(1,n)}$ is the corresponding weight in each class, which can vary from 1 to n.

The main differences between DRASTIC and SINTACS are the values of the ratings, the selection of classes of weights, and the strategy used to assign them. Establishing ranges and assigning ratings and weights are the most delicate tasks.

Sensitivity analysis

Sensitivity analysis studies the contribution of individual variables and of input parameters, on the resultant output of an analytical model. In GIS modelling the "effect" of single input data on the final overlay map has been studied by several authors. It depends on many factors such as the type of overlay operation performed, the value of the weights, the number of data layers and of map units in each layer, and on the error or the uncertainty associated to each map unit (Bailey, 1988; Heuvelink *et al.*, 1989). In this contribution we deal only with those aspects related to the influence of ratings and weights assigned to the single parameters.

The analysis performed here was based on the use of unique condition subareas and partially inspired by the theory developed by Lodwick *et al.* (1990). That method was preferred because it tests the sensitivity of operations between map layers. In particular, it was developed for weighted sum intersection overlays and can be easily applied to the expression to compute both the DRASTIC and the SINTACS indexes.

METHOD IMPLEMENTATION

The procedure developed to perform the sensitivity analysis is shown in Fig. 1 and is described in the following paragraphs. The seven classified maps are overlayed using expressions (1) or (2) to obtain the vulnerability map. With a "crossing" operation all the possible combinations of the seven layers are recorded both in a crossing map and in a crossing table representing the unique condition subareas. The map removal and the single-parameter sensitivity analyses are done using the crossing table and the results are also processed to obtain a table of statistical values. The parameter sensitivity table is then used to reclassify the seven input maps obtaining seven output maps representing the effective weight of each layer.

The final interpretation is based on the analysis and comparison of the seven input maps, the vulnerability map, the seven output maps representing the real weight for each subarea and the associated tables with resulting statistics.

The unique condition subareas

The procedure to test the sensitivity depends on the spatial data structure and on the capability of GIS to manipulate large tables. To overcome the problem related to the

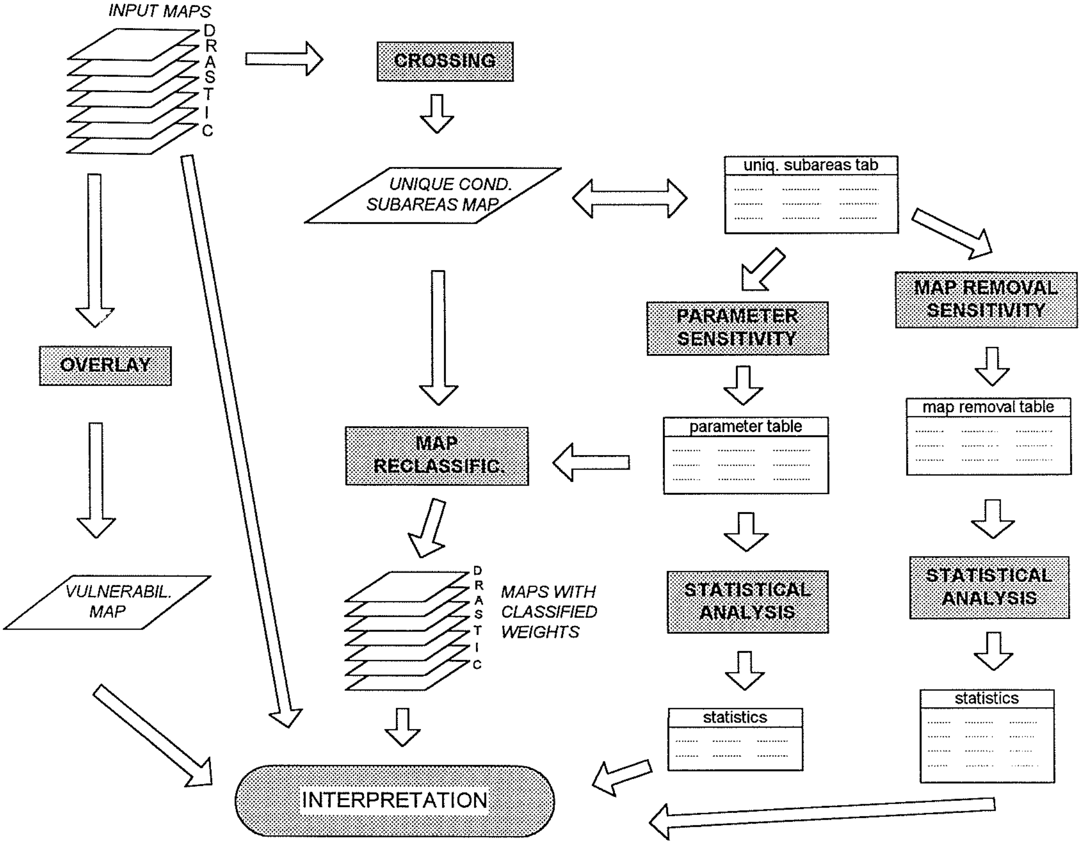
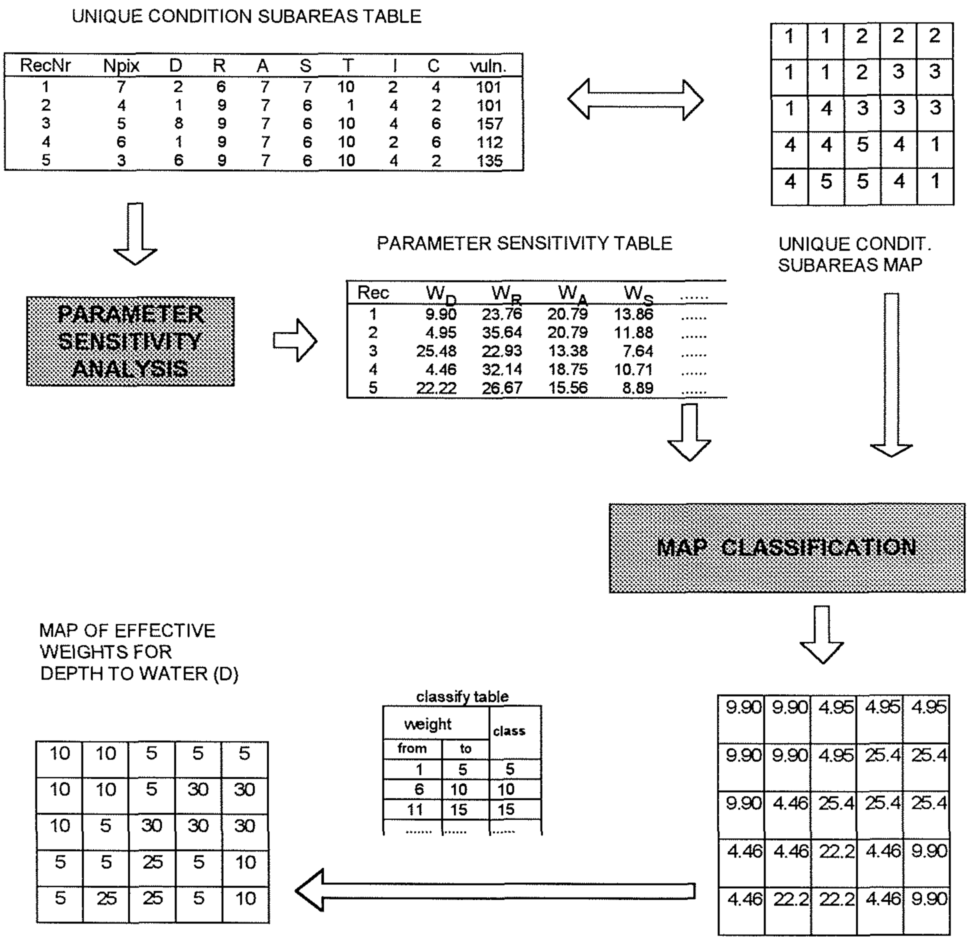


Fig. 1 Processing strategy used to implement the sensitivity analysis.

individual analysis of a large number of pixels, 455 203 pixels in the study area, smaller sets of "unique condition subareas" were used. A "unique condition subarea" is one or more polygons consisting of pixels with a unique combination of D_i, R_i, A_i, S_i, T_i, I_i, and C_i, where D_i, R_i, A_i, S_i, T_i, I_i, and C_i are the rating values of the seven layers used to compute the vulnerability index, and $1 \leq i \leq 10$. The weights are not considered because in DRASTIC they are constant for each parameter. A combination of eight layers is necessary with SINTACS because the weights assigned to each layer can be different in some subareas.

In theory, the possible combinations of the seven layers can be computed using an "*m* dimensional contingency table" containing all the possible combinations of the thematic classifications of the *m* input layers. With our dataset the seven dimensional contingency table contained 81 000 slots, which still represented a very high number of units to be handled. Most of these theoretical unique combinations are not present in the study area, and the number of units to be considered can be furthermore reduced. In practice, the unique condition subareas were obtained crossing the seven layers two at



UNIQUE CONDITION SUBAREAS TABLE

RecNr	Npix	D	R	A	S	T	I	C	vuln.
1	7	2	6	7	7	10	2	4	101
2	4	1	9	7	6	1	4	2	101
3	5	8	9	7	6	10	4	6	157
4	6	1	9	7	6	10	2	6	112
5	3	6	9	7	6	10	4	2	135

1	1	2	2	2
1	1	2	3	3
1	4	3	3	3
4	4	5	4	1
4	5	5	4	1

UNIQUE CONDIT. SUBAREAS MAP

PARAMETER SENSITIVITY TABLE

Rec	W_D	W_R	W_A	W_S	......
1	9.90	23.76	20.79	13.86	......
2	4.95	35.64	20.79	11.88	......
3	25.48	22.93	13.38	7.64	......
4	4.46	32.14	18.75	10.71	......
5	22.22	26.67	15.56	8.89	......

9.90	9.90	4.95	4.95	4.95
9.90	9.90	4.95	25.4	25.4
9.90	4.46	25.4	25.4	25.4
4.46	4.46	22.2	4.46	9.90
4.46	22.2	22.2	4.46	9.90

classify table

weight		class
from	to	
1	5	5
6	10	10
11	15	15
....	......	......

MAP OF EFFECTIVE WEIGHTS FOR DEPTH TO WATER (D)

10	10	5	5	5
10	10	5	30	30
10	5	30	30	30
5	5	25	5	10
5	25	25	5	10

Fig. 2 Single-parameter sensitivity analysis: procedure to compute the effective weights of the *D* layer (depth to water).

a time obtaining a map of the subareas and an associated cross table. Such computations and the followings were performed by constructing "batch" files in ILWIS (ITC, 1993) to automate the procedure. In the cross table, shown in Fig. 2, each record (entry on row) represents a unique condition subarea containing the following information: record number, values of the input maps, number of pixels, area covered by the pixels. The vulnerability value of each subarea is also added to the table.

With such a representation, 536 subareas were obtained in contrast with the 455 203 pixels or the 81 000 slots of the contingency table. The subareas containing less than 10 pixels where found to be very small and corresponding to unavoidable "slivers" or positional noise at the edge of the initial polygons (subareas). Such small subareas were not considered in the sensitivity and statistical analysis. The subareas containing more than 10 pixels and therefore analysed are 391.

This strategy allowed us to reduce drastically both the computation time and complexity using a table with the relatively small number of unique condition subareas for the computation instead of the raster maps. The attribute data of the tables, linked to the spatial data of the raster map by the subarea number identifier, can be easily represented on the map.

Map removal sensitivity analysis

The next step in the analysis was to evaluate whether it was really necessary to use all the seven parameters. In spite of its success, many criticisms have been moved to the DRASTIC model. In particular, the problem related to the influence of each single parameter on the final vulnerability value was subject of research by other authors and several approaches used less than seven parameters. A discussion on vulnerability assessment methods is in Barber *et al.* (1993). Merchant (1994), in a critical review of the DRASTIC model, argued that a DRASTIC-equivalent result might be obtained using fewer parameters, with several advantages in accuracy, precision and costs. On the contrary, Rosen (1994), analysing the statistical properties of the interrelations between the DRASTIC parameters in a study in some sites of Sweden, found that in the swedish study area the seven parameters were quite independent and, therefore, representative enough to assess pollution vulnerability.

The map removal sensitivity measure, defined by Lodwick *et al.* (1990), represents the sensitivity (S) associated with removing one or more maps from a suitability analysis and is defined as follows:

$$S = \sum_p s_p \left| r_p/N - \bar{r}_p/n \right| \tag{3}$$

where s_p is a weight given to the pth polygon, r_p and $\bar{r}_p$ are the unperturbed and perturbed output values of the pth polygon, respectively, while N is the number of the maps used in the primary suitability and n is the number of the maps used in the perturbed suitability. The output attribute values are divided by the number of maps in order to remove the bias due to a different number of maps. Another computation made consisted in re-scaling the attribute values resulting from the fewer maps so that the attribute values of both analyses were made comparable. Later, for each subarea the new vulnerability index was compared with the initial one and the variation index, VP, for removal of parameter P was computed as follows:

$$VP_i = \frac{vulni_i - vulnP_i}{vuln_i} 100 \tag{4}$$

where $vuln_i$ is the vulnerability computed with expression (1) on the ith subarea and $vulnp_{Pi}$ is the vulnerability index of the ith subarea without considering the parameter p, and $1 \leq i \leq 391$. The analysis was performed on each of the 391 subareas removing one-by-one the seven parameters. The variation index can be positive or negative, depending on the influence of the single parameter in decreasing or increasing, respectively, the vulnerability index. The value of this index gives an idea of the magnitude of such a variation. In this study the result showed that the seven parameters are all significant for the analysis. In particular, the significance depended not only on the "theoretical weight" assigned by the DRASTIC and SINTACS methods, but mainly on the value of the parameter in the context of the other parameter values within a same area.

Single-parameter sensitivity analysis

With the map removal sensitivity analysis it was concluded that no one parameter could be removed: all of them were significant. An analysis was then made to compare the "effective" or "real" weight that each parameter had in each subarea with the theoretical weight assigned by the DRASTIC and SINTACS methods. Also in this situation the analysis was performed only on the 391 most significant subareas. The effective Weight (W_{pi}) in %, for each subarea, was computed as follows:

$$W_{pi} = \frac{P_{Ri} P_{Wi}}{vuln_i} 100 \tag{5}$$

where P_{Ri} and P_{Wi} are the ratings and the weights respectively of the parameter P assigned to the subarea i, and $vuln_i$ is the vulnerability index as computed in expression (1) or (2).

A statistical analysis was performed to analyse and display the results of each DRASTIC parameter. Table 1 shows the theoretical weight assigned by the method, the same weight normalized to 100, the average real weight computed on the 391 subareas, the standard deviation, the median, and the minimum and maximum values.

Table 1 Statistical analysis of the parameter sensitivity of unique condition subareas. The analysis deals only with the 391 subareas considered significant (npix > 10).

Parameter	Theoretical weight	Theoretical weight (%)	Average weight (%)	Standard deviation (%)	Median (%)	Minimum value (%)	Maximum value (%)
D	5	21.7	18.165	10.542	22.321	4.237	34.722
R	4	17.4	26.590	4.992	24.161	16.107	44.444
A	3	13.0	16.687	3.217	15.217	11.765	25.926
S	2	8.7	9.847	3.551	9.459	1.282	21.053
T	1	4.3	7.630	1.658	6.993	0.935	11.111
I	5	21.7	11.484	2.618	11.976	6.757	24.272
C	3	13.0	9.597	3.205	8.219	4.054	22.857

The map representing the unique condition subareas was reclassified according to the attribute values of the effective weight of each parameter. The real percentage weights were then grouped into classes of 5%. Those computations were used to obtain seven maps representing the effective weight of each parameter in each subarea. Figure 2 shows the procedure to compute the effective weights of depth to water (*D*).

DISCUSSION OF THE RESULTS

The last step of the procedure, the interpretation, is based on the analysis and comparison of the vulnerability maps, the maps representing the seven layers, the maps representing the real weight for each subarea with the associated tables, and the tables with resulting statistics.

A general consideration on this analysis is that the removal of each of the seven parameters generates a relevant variation in the resulting vulnerability map. This confirms the impression that the seven DRASTIC parameters must be considered together being all important. Such a conclusion is in contrast with the views of some authors that it may be useful to consider a lesser number of parameters (less than seven).

The "effective weight" of each parameter in each subarea is dependent not only on the "theoretical weight" assigned by the DRASTIC or SINTACS method, but on the value of the single parameter in the "context" of the values of the other parameters. In particular, in the Piana Campana study area, some results confirm what could be expected, that depth to water is a parameter that strongly affects vulnerability in the area where the aquifer is unconfined or semi-confined, while it is less important where it is confined. The most unexpected result, shown in Table 1, is that net Recharge mostly influences the vulnerability index, with an average weight of 26.59% against the theoretical weight that is of 17.4%. In particular its removal tends to decrease the vulnerability index. On the contrary, the parameter "impact of the vadose zone), that together with "depth to water" has the highest theoretical weight, has a low effective weight with an average value of 11.5%, a little higher where the soil presents sandy loam or loamy texture.

CONCLUDING REMARKS

The sensitivity analysis, conveniently performed using an "analytical" GIS, becomes very useful when, given the theoretical weight assigned to each parameter in DRASTIC and SINTACS, we want to know the effective or real weight that each parameter gets in a given subarea in relation to the value of the other parameters. In particular, because the effective weight of each parameter depends on the value of the single parameter in the "context" of the values of the other parameters, it is not possible to draw general conclusions on the optimal weight of each single parameter. Such observation leads to reconsideration of the approaches in DRASTIC and SINTACS in terms of the parameter relationships to perform more realistic fine-tuning of those models of the vertical vulnerability index.

With a GIS-based approach, the method described in this paper is not time-consuming and has low costs. In particular, the implementation of batch files for repetitive tasks in a GIS allows easy and fast analyses of the influence of the single data on the final result.

Single-parameter sensitivity analysis is important both for the experts that implement a vulnerability model and for the users of vulnerability maps. The former can use sensitivity analysis for validation and consistency evaluation of the analytical results. In addition, they can select the layers and the subareas which are more critical for the analysis and require more detailed information and accuracy. The latter can use the result of such an analysis for a more efficient interpretation of the vulnerability index. In particular, the production of maps representing the effective weight of each parameter helps decision-makers, usually not GIS-specialists, in understanding and using the model results.

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