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The vulnerability of complex karst hydrostructures: Problems and perspectives[3]

Franco Cucchi[1], Paolo Forti[2] and Luca Zini[1]
[1] *Dipartimento de Scienze Geologiche, Ambientali i Marine, Univ. di Trieste, Italy*
[2] *Dipartimento de Scienze della Terra e Geologico Ambientali, Univ. di Bologna, Italy*

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RESUMEN

En los últimos 15 años, algunos de los más grandes acuíferos cársticos italianos han sido estudiados con el fin de realizar mapas de vulnerabilidad intrínseca e integrada a la contaminación utilizando el método SINTACS. La búsqueda ha evidenciado que algunas características peculiares de los acuíferos cársticos pueden llegar a dificultar la definición de un valor fijo para los 7 parámetros SINTACS. Entre estas características, las más importantes son: el diferente nivel de heterogeneidad del sistema de drenaje, el diferente nivel de carstificación sea a nivel superficial o profundo, el espesor de la zona no saturada (a menudo de poco espesor, pero altamente carstificada). Por lo tanto para obtener una mejor conexión del mapa de la vulnerabilidad con la situación real existente en un determinado acuífero cárstico, los valores SINTACS para algunos parámetros han sido en ocasiones cambiados respecto a los valores oficiales. En este trabajo se presenta una propuesta preliminar de nueva puntuación, para obtener una mejor concordancia entre los mapas de vulnerabilidad intrínseca e integrada a la contaminación y a las condiciones hidroestructurales que pueden cambiar en los acuíferos cársticos.

PALABRAS CLAVE: Acuíferos cársticos, vulnerabilidad a la contaminación, modelo SINTACS.

ABSTRACT

In the last 15 years some large karst aquifers of Italy were studied to realize maps of intrinsic and integrated vulnerability to pollution on the basis of the point count system model SINTACS. The most important characteristics are: the heterogeneity levels of the drainage networks; the level of karst evolution both on the surface and deep into the aquifer; the thickness of the unsaturated zone (which is often highly karstified). In order to obtain a better fitting of the intrinsic vulnerability map with the real situation, the SINTACS values for some of the parameters were sometimes changed with respect to the official ones. The present paper proposes tables in order to obtain a better fitting between the map of integrated and intrinsic vulnerability to pollution and the hydrostructural conditions.

KEY WORDS: Karst aquifers, pollution vulnerability, SINTACS model.

INTRODUCTION

In the last 15 years the Operative Units 4.7 and 4.9 of the GNDCI (National Group for the Prevention of Natural Catastrophes in Italy) studied some of the largest karst aquifers of Italy (Civita *et al*. 1991, Forti *et al*., 1999, Forti *et al*., 2000; Cucchi *et al*., 2000; Ayub *et al*., 2001, Cucchi *et al*., 2002) to realize maps of intrinsic and integrated vulnerability to contamination on the basis of the point count system model SINTACS (Civita and De Maio, 2000). This research showed that some characteristics of the karst aquifers may hardly affect the possibility to define, as normally required, a fixed value for most of the seven SINTACS parameters.

Karst develops complex and different discontinuities both on the surface and underground, resulting in an anisotropy and heterogeneity of the hosted aquifers. Therefore all the methods used to quantify the vulnerability degree to contamination for the waters stored in a karst aquifer are not able to ensure a result fully compatible with the specific hydrogeological characteristics which may vary dramatically from point to point. All the general methods to define the vulnerability to pollution, among which the DRASTIC (Aller *et al*., 1987), SINTACS and EPIK (Doerfliger and Zwahlen, 1995; Doerfliger *et al*., 1999) are presently the most utilized, have vantages and defects, which may be summarized as follow.

DRASTIC was the very first method to evaluate vulnerability to contamination by an using point count system: therefore both SINTACS and EPIK, which were elaborated starting from DRASTIC, represent a important step ahead in

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the acknowledge of natural heterogeneity within different types of aquifers. EPIK is more simple and easier to use than SINTACS, because it is based on a lower number of parameters, considering only what happens within the epikarst (percolation) zone: in fact it assumes that nothing will change in the saturation zone, but this is not always true, in particular when karst aquifer should be considered. Therefore, even more complex, SINTACS seems to be the best for karst aquifers, because it takes into consideration the whole aquifer and not a single part of it, giving also wide possibilities to adapt the parameters to the real situation.

The first vulnerability map of a karst area realized with the SINTACS method was that of the Apuan Alps in Italy (Civita *et al*., 1991); after this first application several other karst aquifers in Italy and abroad where studied, covering most of the possible karst types from alpine to tropical, from young and rather homogeneous to very old and completely hierarchized (Adorni and Aureli, 1990, Ayub *et al*., 2001, Aureli, 1997, Civita *et al*., 1991, Forti *et al*., 1999, Forti *et al*., 2000; Cucchi *et al*., 2000, Cucchi *et al*., 2002). In the last ten years some SINTACS values were sometimes changed with respect to the official ones to obtain a better fitting of the intrinsic vulnerability map with the real punctual situation in a given karst aquifer.

The proposal of numerical tables herewith presented (Figure 2 to 5) has the aim to improve the validity of the SINTACS model in the karst environment: it has to be regarded as a first attempt to solve the problems and not a definitive statement. The aim is that to stimulate discussions among the scientists to reconsider the whole problem of the karst aquifers and their "singularity", therefore the proposal is open to further suggestions and contributes.

Karst processes cause the evolution of peculiar forms thus inducing in the rocks a dramatic variability in the hydraulic conductivity, which may be controlled point to point by fracturing and/or karstification degree. Then depending on the peculiar characteristics of its drainage network, a karst aquifer may be subdivided into 3 different types (Civita, 1975): with disperse, unhierarchized, drains (type 1), with partially hierarchized, but still interdependent, drains (type 2) and with a few well hierarchized dominant drains (type 3) (Figure 1). It is relatively easy the practical differentiation of these 3 categories:

Karst type 1 *(young karst)*: spread embryonic surface forms, dissolution dolines not very deep, covered or scarcely uncovered karst, few caves, absence of well developed deep drains, diffuse risings each of which with a scarce yield and hydraulic characteristics similar to those of an aquifer with permeability due to fractures and porosity.

Karst type 2 *(rather developed karst)*: frequent surface forms, wide and deep dissolution dolines, spread corrosional forms over uncovered rock, like karren fields, caves with large drainage galleries, few springs with a constant base flow but high in time variations of their hydrochemistry and/or hydrodynamics.

Karst type 3 *(holokarst)*: extremely developed karst landscapes (sometimes with residual forms like mogotes and cockpits), wide and deep dissolution and/or breakdown dolines, scarce cover, complex karst systems with presence of large horizontal galleries and huge vertical pits, single spring or single rising area with scarce base flow but sudden tremendous in time variations of its yield and chemistry.

Therefore, in order to obtain a better fitting of the intrinsic vulnerability map with the real situation in a given aquifer, the SINTACS values for each parameter should be, to be time by time, changed with respect to the official ones on the basis of the different type of karst representative of the point situation.

SINTACS PARAMETERS FOR KARST AQUIFERS

The GNDCI O.U. 4.7 (Trieste University) and 4.9 (Bologna University) tried to define a preliminary proposal to settle up special tables for most of the SINTACS parameters, which are herewith shortly discussed.

Depth to ground water: the SINTACS rating, this is the same as for DRASTIC, lowers with a hyperbolic shape, being 10 for the surface waters, 5 at –10 m, 2 at –40 and 1 at –90. In the karst the piezometric surface cannot be represented by a flat plane but it consists of a variously bended surface, the shape of which is strictly controlled by the different hydraulic transmissivity of the drains with respect to the less karstified block. Therefore the suggested variations are (Figures 2 and 3):

- to define the piezometric surface the plain joining the springs to the normal water/air interface inside the karst aquifer, not considering at all the values related to floods.

- to multiply the hyperbolic rating by a factor 3 for karst type 1 (rating being 10 for the surface waters, 5 at 30 m, 2 at 120 and 1 only over 200 m), by a factor 5 for type 2 (rating being 10 for the surface waters, 5 at 50 m, 2 at 200 and 1 only over 300) and by 10 for type 3 (rating being 10 for the surface waters, 5 at 100 m, 2 at 400 and 1 over 500).

Effective infiltration action: the SINTACS rating requires that the effective precipitation should be multiplied by an

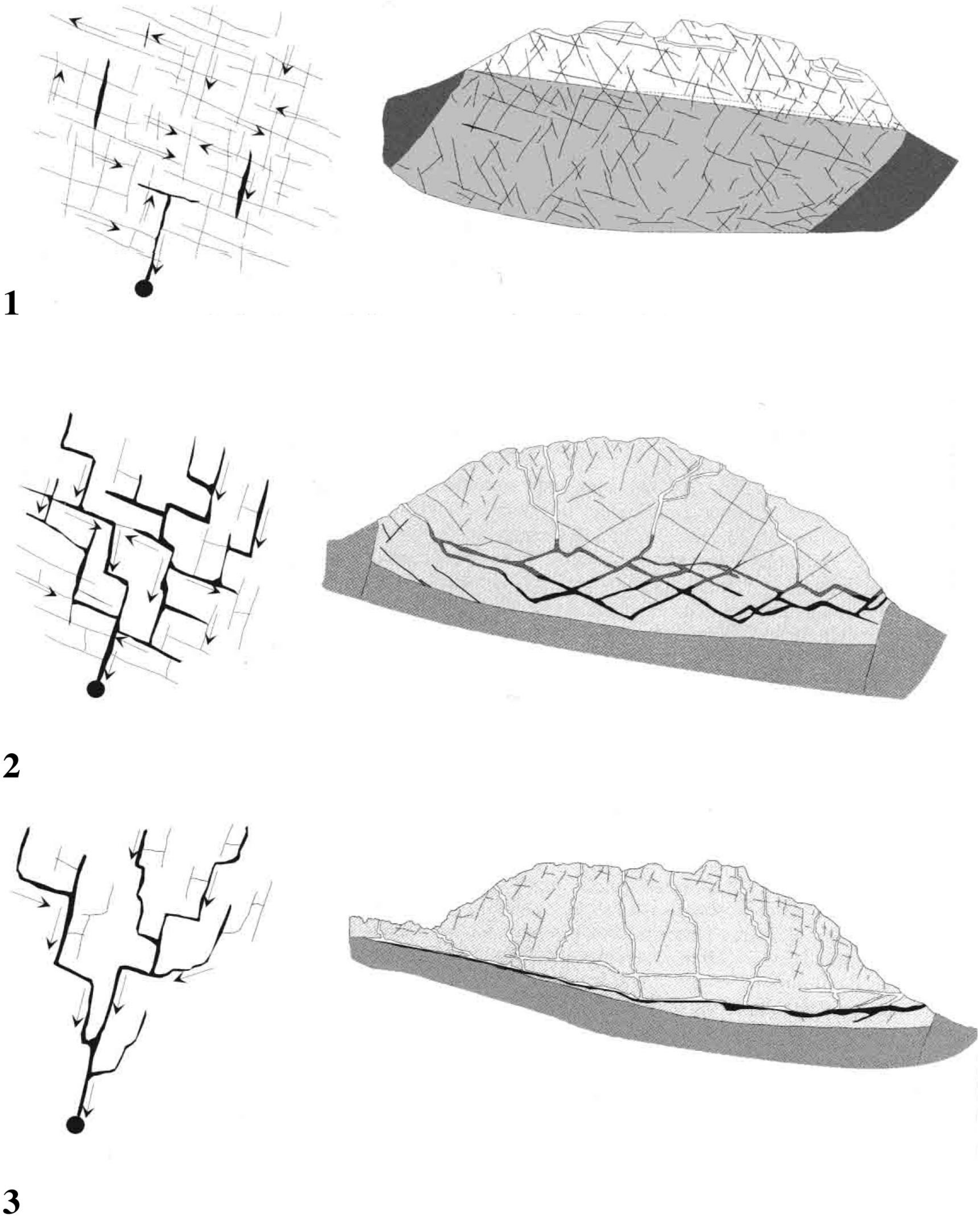

Fig. 1. The three types of karst and their relative drainage pattern: 1 - karst type 1 or young karst with a disperse drainage, 2 - karst type 2 or developed karst with interdependent drains, 3 - karst type 3 - or holokarst with a dominant drain.

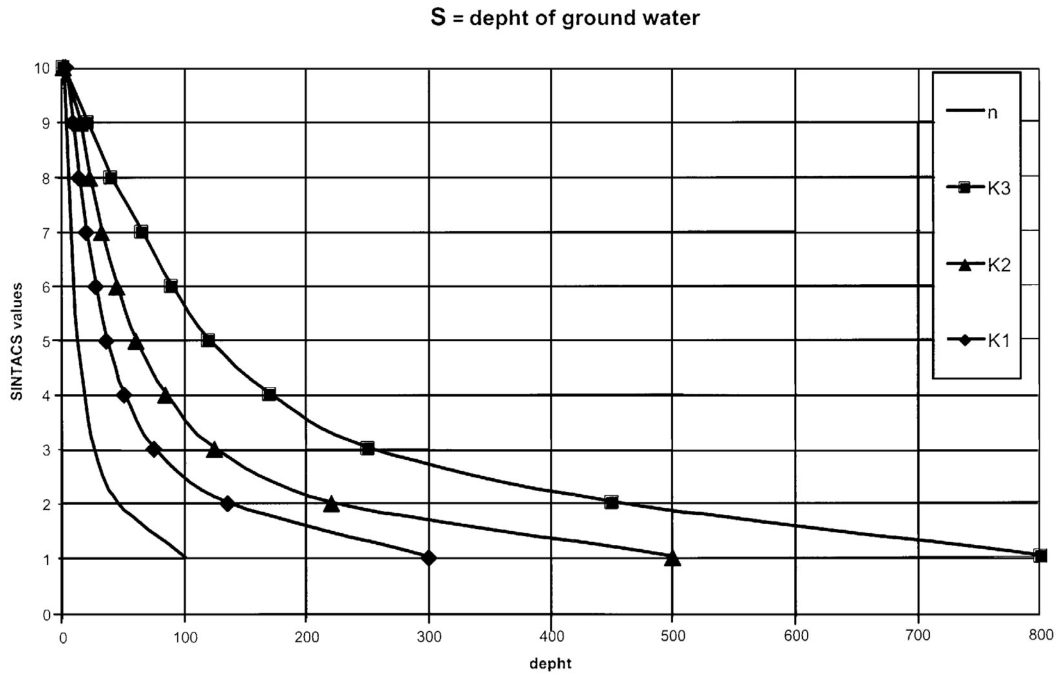

Fig. 2. The original SINTACS rates (*n*) for depth to water and the proposed new ones for the three proposed different karst types: *K1* young, *K2* developed, *K3* holokarst. The graph was made with simple corrective algorithms to multiply the hyperbolic rating (*n*) by a factor 3 for karst type 1 (*K1*), by a factor 5 for type 2 (*K2*) and by 10 for type 3 (*K3*).

infiltration coefficient (function of the soil texture and thickness). The soil cover of Italian karst areas is normally very thin or absent, while evapotranspiration ranges between 20 and 40%), therefore the suggested variation consists in increasing the coefficient value respectively of 10, 20 and 30% according with the karst type.

Moreover, the soil coefficient has to be used only if the cover is really thick, but, as normally happens, if the cover is less than 1 m in average thickness, it has to be used the coefficient for karstified limestone (from 1 to 0.75 for SINTACS) instead of that of the soil.

Unsaturated zone attenuation capacity: actually this effect is always considered practically absent in karstified limestones, without any reference to their thickness and/or karstification. In reality their behaviour is more complex and sometimes the karst attenuation capacity may result even important as in the case of a thick unsaturated zone, where the waters may flow in direct contact with the atmosphere for many hours. In fact a fundamental role is played by the karst homogeneities: a disperse karst (type 1) behaves as a homogeneously fractured aquifer and therefore the related SINTACS values are correct.

The situation is rather different when considering aquifer with dominant drains (type 3): the higher the heterogeneity, the faster the transfer toward the saturate zone, but in the mean time the turbulent flow in aerate conditions allows for efficient attenuation (mainly via oxidation) at least of some pollutants. Anyway, even at the same karst degree, it is necessary to evaluate if the transfer occurs mainly along vertical or horizontal drains to evaluate correctly this parameter. In the first case the attenuation capacity will remain rather null because the transfer time becomes very short, while in the second may become really important: therefore to assess the correct value to the unsaturated zone the different kind of hosted drains must be considered.

The proposal is to widen the range (from 8-10 to 7-10) in order to weight also the amount of sub horizontal flow and of the presence of filtration through incoherent deposits (breakdowns, uncemented sediments, …).

Soil/ overburden attenuation capacity: the SINTACS ratings need no changes.

Hydrogeologic characteristics of the aquifer: this parameter is considered only in the SINTACS and DRASTIC, while the other methods take into consideration only the epikarst. The SINTACS rating for karst aquifers is fairly adequate ranging from 8 (hydrogeological complex in fractured limestone, corresponding to karst type 1) to 9 or 10 (karstified limestone, corresponding respectively to type 2 and 3).

Hydraulic conductivity range of the aquifer: this parameter is considered only in the SINTACS and DRASTIC, while the other methods take into consideration only the epikarst.

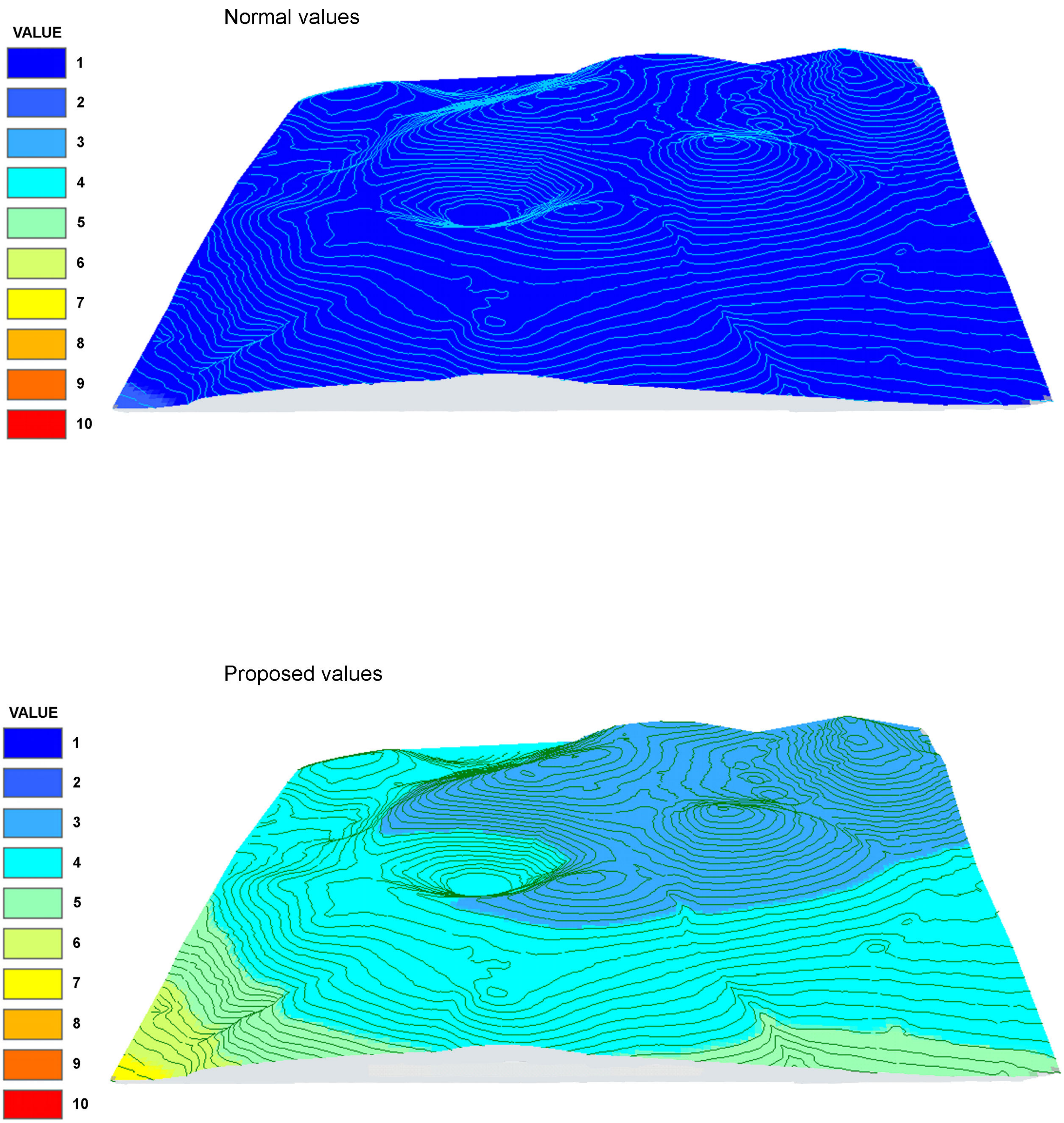

Fig. 3. The original SINTACS rates for the depth to water parameter (above) compared to the proposed one (below) for a holokarst (karst type 3) with surface between 60 m a.s.l. and 295 m a.s.l., and groundwater at 2 m a.s.l.. The figure was obtained projecting on a 3D model the values of the S parameter (depth to water) obtained by using the standard model (above) and the new proposed method (below).

The SINTACS rating for karst aquifers may vary over the full range (1-10): therefore the problem is not to change the rating procedure but to choose the correct value for each elementary square grid. In karst type 1 and 2, even in presence of a slightly high heterogeneity between the main drains and the poorly karstified blocks, an average value for the whole formation may be assumed on the basis of the available data on its hydraulic conductivity.

This should not be done while considering a type 3 karst, where the conductivity of the large few drains may result so high with respect to that of the rather not karstified blocks (which in turn represent over the 90% of the whole aquifer) thus avoiding any exchange between these two components within the saturated zones. In these conditions the contribution to the springs is, rather completely, confined to drains and the exchanges between blocks and drains may occur only in the unsaturated and epiphreatic zones. In this case it would be correct, if possible (depending upon the detailed knowledge of exact location of the drainage tubes), to differentiate the drains from the block areas, giving to each of them the pertinent conductivity value.

Information on the groundwater flow may be obtained by comparing the spring regimen to the rainfalls and analysing the apparent flow velocity from dye tracing tests performed in different flow conditions, moreover a rough evaluation of the geometry of the groundwater surface and of its vertical variations can be done if other hydrogeological parameters of the aquifer are known. Finally a grid of geological sections makes possible to reconstruct in detail the geometry of the aquifer, while geomorphological analyses on the surface and inside the cavities allow to estimate the degree of karst hyerarchization. If all these data were available, it should be possible to define a relative hydraulic conductivity value for each of the different square grid in which the aquifer is subdivided. Obviously this evaluation is neither easy nor simple, but it must be stressed that it is the single method to obtain reliable values for this parameter in presence of an aquifer hosted in a karst of the 3rd type.

Hydrologic role of the topografic slope: in karst areas runoff is confined where the cover is thick enough, moreover some surfaces, even with an exalted acclivity, may allow for fast infiltration: it is the case of the doline and/or polje flanks or other slopes with totally uncovered karren fields. The proposal is to assign a value of 10 to the bottom of any karst depressions, a very high value should also be imposed to the surroundings of the sinkholes (9 to 10 depending upon their morphology and hydraulic characteristics). A value of 8, 9, 10 should be given to any flank of doline and/or any uncovered karrenfield, depending of their relative karst type, but disregarding their actual slope. Finally 10 slope intervals should be considered (0-2%, 2-5%, 5-10%, 10-15%, 15-20%, 20-40%, 40-80%, 80-120%, 120-200%, 200%-sv) with an hyperbolic rating (Figures 4 and 5).

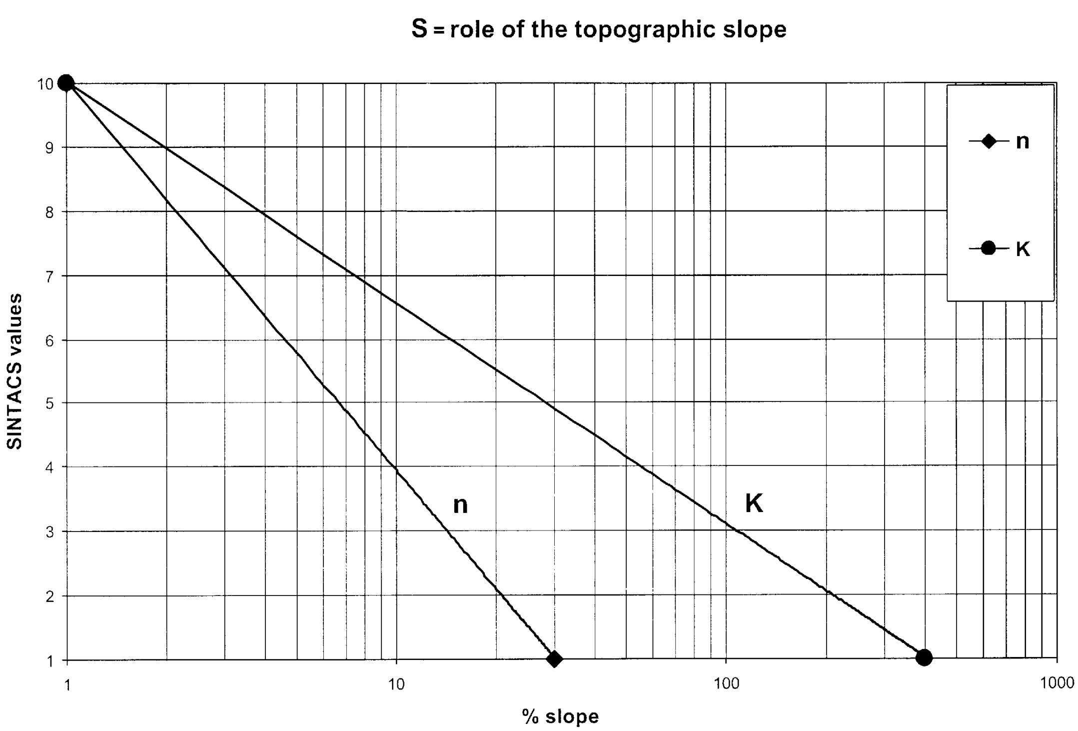

Fig. 4. The original SINTACS rates for the slope parameter (n) compared with the proposed ones (k) for an holokarst (karst type 3). The graph was made with simple corrective algorithms for the newly proposed 10 intervals value.

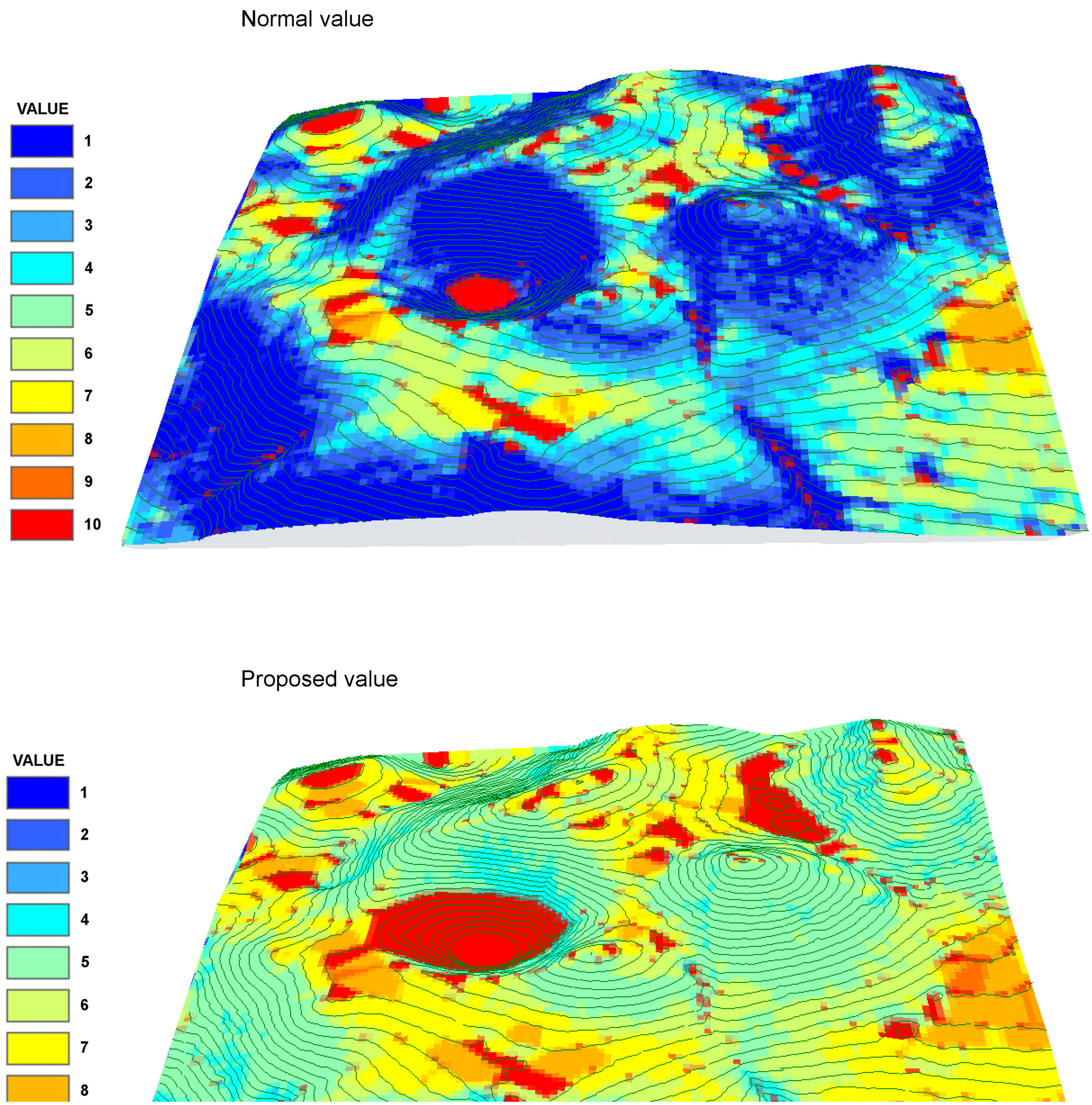

Fig. 5. The original SINTACS rates for slope values parameter (above) compared to the proposed one (below) for a holokarst (karst type 3, the same holokarst of Figure 3). The figure was obtained projecting on a 3D model the values of the S parameter (slope) obtained by using the standard model (above) and the new proposed method (below).

CONCLUSIONS

The just outlined proposals of variation of the SINTACS values have been assessed on the direct experience made by GNDCI O.U. 4.7 and 4.9 in the study of karst aquifers in the last 20 years. Their aim is to make the methods more elastic and therefore more adaptable to the dramatic differences in behavior the karst aquifer evidences due to its level of evolved anisotropy. For this reason it is fundamental to have a very detailed knowledge of the hydrogeological characteristics (lithology, structural settlement, geomorphology, geological evolution, and hydrodynamics) of the whole karst hydrostructure as well as of the feeding or discharging areas and of their environmental conditions. In fact only the accurate definition of the amount and type of karst evolution present in each elementary grid of the studied area may allow for a correct definition of the values to be given to each SINTACS parameters.

Finally it must be stressed that this proposal has to be regarded as a first attempt to solve the problems and not a definitive statement: in fact different experiences in other karst areas, in Italy and/or abroad, may suggest further or different changes. The present paper wants just to stimulate discussions among the scientists to reconsider the whole problem of the karst aquifers and their “singularity”.

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Franco Cucchi[1], Paolo Forti[2] and Luca Zini[1]

[1] Dipartimento de Scienze Geologiche, Ambientali i Marine, Univ. di Trieste GNDCI U. O. 4.7, Italy
Email: cucchi@univ.trieste.it
[2] Dipartimento de Scienze della Terra e Geologico Ambientali, Univ. di Bologna GNDCI U. O. 4.8, Italy