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Karst Geomorphology

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GEOMORPHOLOGICAL HERITAGE EVALUATION IN KARSTIC TERRAINS: A METHODOLOGICAL APPROACH BASED ON MULTICRITERIA ANALYSIS

ABSTRACT: BOYER L., FIERZ S. & MONBARON M. *Geomorphological Heritage Evaluation in Karstic Terrains: a Methodological Approach Based on Multicriteria Analysis.* (IT ISSN 0391-9838, 1998).

Confronted with the problem of geomorphological heritage evaluation for applied research, the authors have developed an evaluation process based on the principles of systemic approach and multicriteria analysis in the context of their research project. They establish several procedures in order to standardize both the observation and the evaluation of geomorphological heritage. In so doing, they strive for more strictness, yet wish to maintain considerable maneuverability. Lastly, the authors test the method in a concrete case: sink-hole evaluation at the Froidevaux site in the Swiss Jura Mountains.

KEY WORDS: Geomorphological Heritage, Geotope, Multicriteria Analysis, Landuse Planning, Karstic Geomorphology.

INTRODUCTION

The Earth Sciences are currently concerned with the preservation of objects and sites belonging to our Earth Heritage. Its importance for academic circles lies in fundamental research, whereas public administrations and their private collaborators have an interest from a landuse planning and environmental protection point of view. All the professionals working in this area must solve the same methodological problem: How does one evaluate this heritage? Which object merits preservation? Which object does not? A flexible and adaptable method has been developed to address these questions. It's purpose is to evaluate geomorphological heritage, especially karst forms. This method can be used for inventories, environmental impact reports or site evaluations. Two distinct steps are involved: first, standardizing observations and second, standardizing the evaluation process.

Standardizing Observations – This step involves standardizing the process of observing geomorphologic objects in the field. This is an essential step, as geomorphological heritage evaluation requires that one considers not only the object itself, but also the relations this object has with its environment. To simplify reality's complexity, a model of the karst morphosystem has been developed, which will be used as a frame of reference in the process of observing, and later evaluating, geomorphological heritage. This approach to observing the karstic landscape leads quite naturally to mapping the links that an object has with its environment.

Standardizing the Evaluation Process – Using the principles of multicriteria analysis, this step defines a series of criteria satisfying the author's particular requirements for geomorphological heritage evaluation. Multicriteria analysis techniques are also useful in solving problems involving value scales, weighting criteria or grouping results.

A practical application of the method is presented at the end of the article. This concrete example, the evaluation of sink-holes at a particular site (Froidevaux, Swiss Ju-

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ra Mountains), allows the reader to better perceive the potential, as well as the limits, of the method.

STANDARDIZING OBSERVATIONS

In all disciplines, reality's complexity requires scientists to employ models in order to highlight essential elements and to eliminate less important details. Every model is developed on the basis of a formal approach, according to precise aims and rules. The geomorphologic map is no exception, presenting a good example of reality abstraction and formalization of field observations. This type of document is created after inventorying, describing and comprehending a region's morphogenic forms and processes. However, for problems of evaluation, its precision is insufficient, as a map does not provide explicit enough information about the relations between an object and its environment-particularly concerning the functioning of morphogenetic processes. New models have therefore been developed, the general model of the karst morphosystem and the «object-relation» model, which complement the geomorphologic map, but which reveal certain criteria that are indispensable for the evaluation of the geomorphological heritage.

General Model of the Karst Morphosystem

Karst relief presents itself as an excellent example of geomorphological heritage. A karst landscape develops numerous typical forms whose characteristics vary according to geological and climatic conditions (e.g. caves, sink-holes, karren, poljes, etc.). Karst topography, however, is also a complex and dynamic «whole» – a single karstic object can only be considered in relation to this overall entity.

Exposing the invisible elements which contribute to the development of karst forms is therefore a necessary first step. Based on the literature and our experience, a model of the karst morphosystem (fig. 1) has been created using the symbology developed for systems modelling in economics and computer science (Pillet, 1993; Bycer, 1976; Shannon, 1975).

In order to model the karst morphosystem, its limits must first be determined (fig. 1). The inputs and outputs of the system are precipitation, watercourses, springs and evapotranspiration. The flows of water and matter which cross the system from one end to the other constitute the central element of the model. These flows cross one or two filter-environments whose characteristics influence several types of operations: infiltration processes, flow concentration, water storage or chemical and/or physical reactions. Certain operations can then exert an action or feedback, positive or negative, on other up- or downstream operations, thereby enhancing or hindering them.

The complexity of these links emphasizes the importance of situating a geomorphological heritage object in relation to its context. In the field, however, there is access only to the surface reality (except in areas with previosly explored endokarst). For this reason, surface objects are

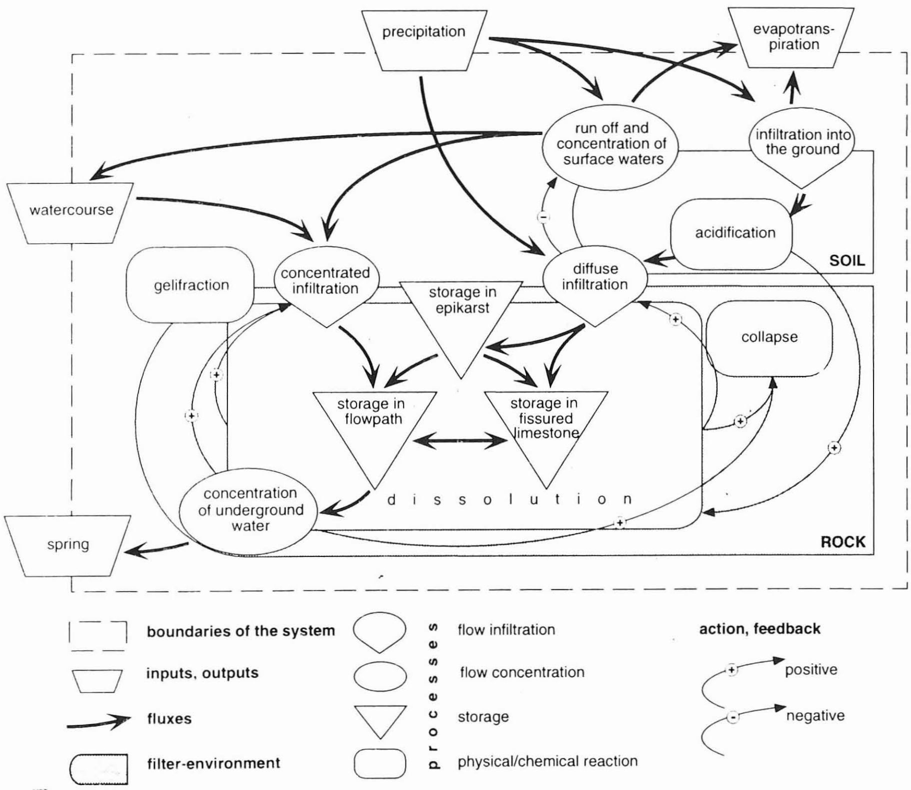
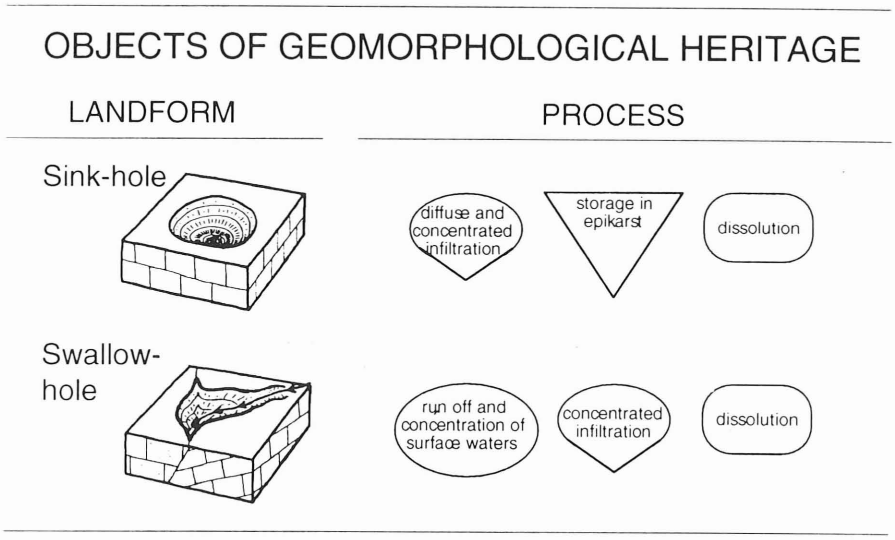


FIG. 1 - The karst morphosystem model.

FIG. 2 - Identification of the operations.



first identified and then placed into their morphogenic, three-dimensional context. The model allows an investigation of the processes which shape them, and provides information on the central or peripheral role an object has in the morphogenesis of a sector, at a local and a regional scale (fig. 2).

The «Object-Relation» Model

Based on these morphogenetic relationships, a network of links is then established between the different objects observed. This process aims to evaluate an object according to the type and number of links it has with its environment. Two types of relationships between objects are thus distinguished.

– «Operational relationships» express dependency links between different objects. Studying them allows us to determine what position an object has in the chain of processes, i.e. which objects it is dependent on and which objects' existence it governs (e.g. swallow-hole and spring).

– «Topological relationships» exist when several ob-jects are located in a spatially characteristic manner (alignment, adjacency, superimposition) due to their formation process or a particular lithological, tectonic, or climatic control (e.g. alignment of sink-holes along a fault).

In order to display these two types of relationships, a simple graphic representation is used, which serves not only as a formal tool for the evaluation of geomorphological heritage, but also as an explanatory complement to a conventional geomorphological map (fig. 3). This manner of appraising reality provides structure to the observations and a logic for evaluating geomorphological heritage elements. It also allows to distinguish between objects, mentioned above, and sites. The latter are composed of an ensemble of objects in operational and/or topological interaction within a defined sector. This approach has an undeniable advantage: adaptability. Its users can create an infinite network of links or limit themselves to the precise aim of the study. This degree of liberty requires the geomorphologist to fully utilize his or her ability to describe and interpret the natural environment, in order to justify the choices made.

The Tuileries site is located in the folded Jura, in a syncline oriented approximately NE-SW. The bottom of this depression is still partly covered with tertiary sediments. The impermeability of this rock favored the development of domed peat-bogs from which acidic water drains peripherally. Upon contact with karstified limestones (lower Portlandian), the water is rapidly engulfed in a series of sink-holes. These different objects are parts of a system, evolving together in close relation. The map in fig. 3 points out these different links. There are, for example, functional links between the peat-bog and the various infiltration points. The topological links show the repetition of this pattern (peat-bog-swallow-hole) along the syncline. In ano-ther case, the topological links show the series of sink-holes that become apparent after recession of the peat-bog.

STANDARDIZING THE EVALUATION PROCESS

In order to reach the best possible decision (e.g. protection, landuse recommendation), scientists or decision-makers must take into account a maximum number of elements. In the context of geomorphological heritage evaluation, naturalists are not an exception to the rule; however, they often restrict themselves to detailed description of objects without providing a basis for comparison. In order to ensure clarity and coherency, it is recommended that the evaluation process should be more rigorous. Multicriteria analysis is one approach to solve the problem.

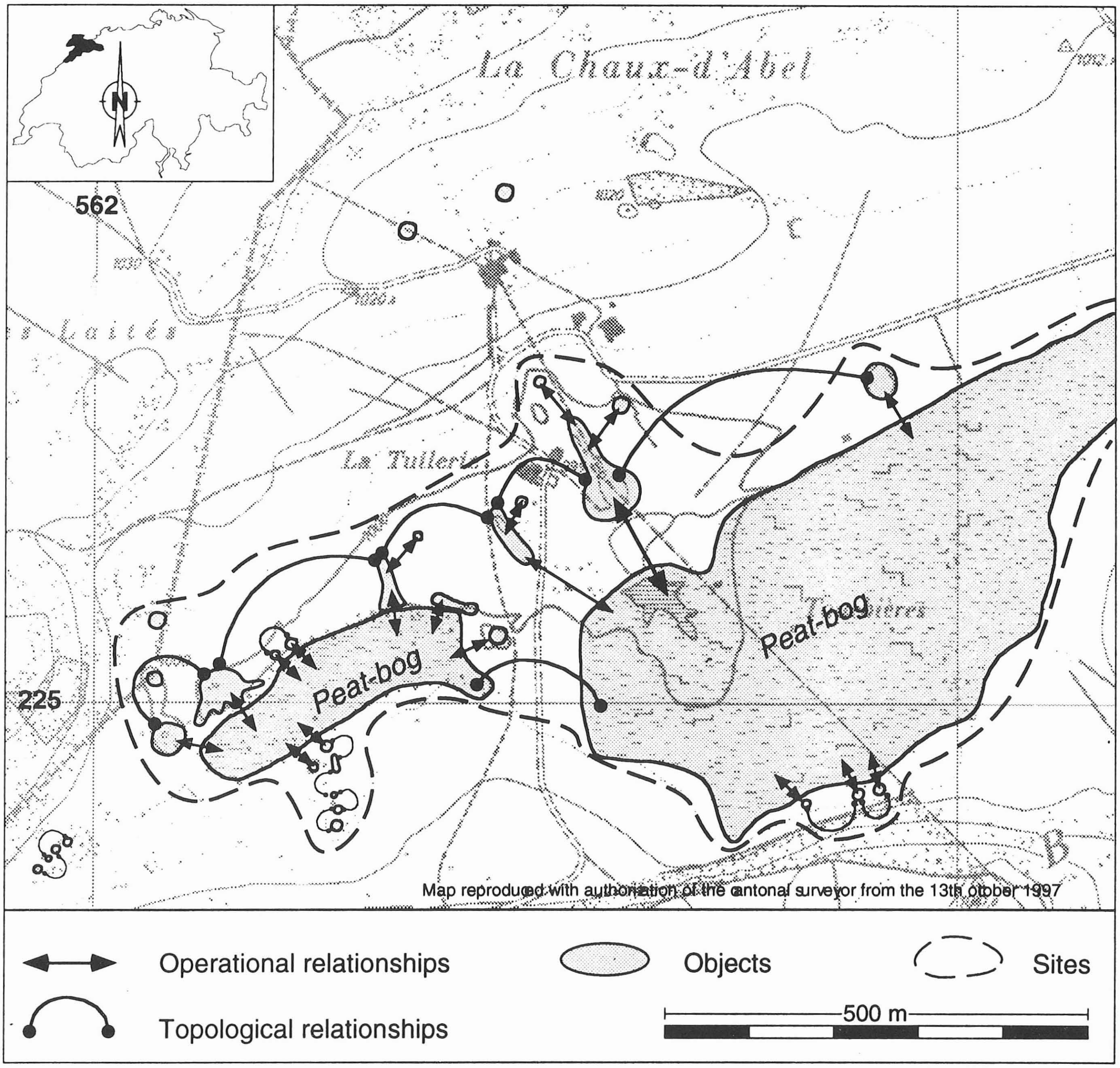


FIG. 3 - Mapping relationships between objects or sites: Les Tuileries, Swiss Jura Mountains.

Definition of the Evaluation Criteria

Creating a list of criteria is the foundation of multicriteria analysis. In order to be valid, the criteria must completely address the question being asked, without being redundant. Despite this strictness, the criteria still express the value system of the evaluator. In order to reduce this weakness, a version of the set of criteria developed by the authors was submitted to thirty Earth Science specialists. In conjunction with the French Association of Karstology was organized by the present research group a workshop with this theme on October 8, 1995, at the annual meeting of the Swiss Society for Geomorphology (Boyer & Fierz, 1996). This pursuit of intersubjectivity, an intermediate between subjectivity and objectivity, allowed to validate part of the process and to improve the coherence of the criteria.

11 criteria grouped into 3 categories have been selected. Each criterion was created in order to attribute scores according to a preference scale adapted to the study's re-

quirements. This list is the product of ideas expressed in specialized literature in combination with personnel experience. For each criterion, the main bibliographical sources used to create it are cited. The three categories of criteria are as follows (table 1):
- The «object» criteria, which refer only to the process and form in question;
- The «morphosystem» criteria, which characterize the nature and intensity of the object's links with other objects and with the overall morphosystem;
- The «context» criteria, which put into perspective the value of the object in relation to its environment (other objects, geomorphologic, geological, or climatic context).

TABLE 1 - Synthesis of geomorphological heritage evaluation criteria Legibility

EVALUATION CRITERIA OF GEOMORPHOLOGICAL HERITAGE		
OBJECTS	MORPHOSYSTEM	CONTEXT
Legibility	Operational Relationships	Type Rarity
Illustration		
Activity		Specific Rarity
Paleomorphologic Marker	Topological Relationships	
Morphochronologic Archive		Geodiversity
Human-induced Damage		

- LEGIBILITY

The object gets a higher score if identification is easy, and if the limits of its form are clear. «Legibility» only concerns the natural action of the process and does not take human interventions into account (Schlegel, 1987, p. 158); (Monbaron, 1993, p. 125); (Wilson, 1994, p. 219); (Gsteiger, 1995, p. 157).

- ILLUSTRATION

An object gets a higher score if its form and/or the process of its formation illustrate particularly well a morphogenetic model described in the literature, and/or a particular lithologic, tectonic, or climatic control of the process studied (Schlegel, 1987, p. 158); (Kienholz, 1988, p. 196); (Monbaron, 1993, p. 125); (Kreutzer, 1994, p. 246); (Wilson, 1994, p. 219); (Grandgirard, 1995, p. 126); (Gsteiger, 1995, p. 157); (Strasser & *alii*, 1995, p. 21).

- ACTIVITY

The object gets a higher score if it is more active, allowing the observer to understand the evolution of the phenomenon, or even to model its entire cycle of existence. For this criterion, the different operations involved (see fig. 2) and the rate of evolution of associated forms are taken into account. This criterion gives no value to fossil forms (Schlegel, 1987, p. 158); (Kienholz, 1988, p. 196); (Monbaron, 1993, p. 125); (Wilson, 1994, p. 219); (Grandgirard, 1995, p. 127); (Gsteiger, 1995, p. 157).

- PALEOMORPHOLOGIC MARKER

The object gets a higher score if the information it contains allows the reconstitution of a paleomorphology at a certain moment during the history of the Earth. Such an object must have been described in this light in the literature, or expressly for the requirements of the evaluation (Kienholz, 1988, p. 196); (Monbaron, 1993, p. 126); (Kreutzer, 1994, p. 246); (Wilson, 1994, p. 219); (Droste zu Hülshoff (von), 1995 p. 339); (Grandgirard, 1995, p. 127); (Gsteiger, 1995, p. 156); (Strasser & *alii*, 1995, p. 21).

- MORPHOCHRONOLOGIC ARCHIVE

The object gets a higher score if the information it contains allows the chronological reconstitution of the evolution of paleoecological conditions in which morphogenesis occurred, for a certain lapse of time. This «morphochronologic archive» value - parameter record - should have been described in the literature or for the requirements of the evaluation. It can also be estimated by the geomorphologist when the object in question contains potential or presumed information, but that has not yet been described and cannot be described in the context of the evaluation (Schlegel, 1987, p. 135); (Kienholz, 1988, p. 196); (Monbaron, 1993, p. 126); (Kreutzer, 1994, p. 246); (Wilson, 1994, p. 219); (Droste zu Hülshoff (von), 1995 p. 339); (Grandgirard, 1995, p. 127); (Gsteiger, 1995, p. 156); (Strasser & *alii*, 1995, p. 21).

- HUMAN-INDUCED DAMAGE

The object gets a lower score if damage to its form and/or functioning is human-induced: this implies that the information contained by the object has been dissimulated or destroyed. One makes a distinction between irreversible and reversible damage, for which remedial measures can be suggested. Irreversible damage is more strongly penalized (Schlegel, 1987, p. 135); (Lagally, 1994, p. 257 or Lagally & *alii*, 1994, p. 48), (Grandgirard, 1995, p. 127); (Gsteiger, 1995, p. 157); (Strasser & *alii*, 1995, p. 21).

- OPERATIONAL RELATIONSHIPS

The object gets a higher score if it presents a large number of operational links with its environment. This signifies that it occupies a central role in the morphosystem and that its influence on the morphogenesis of a defined sector is important. It is also possible, depending on the degree of detail used to evaluate this criterion, to take into account the strength of these links by estimating matter and energy flows between various objects (Monbaron, 1993, p. 125); (Kreutzer, 1994, p. 246); (Gsteiger, 1995, p. 157).

– Topological Relationships

The object gets a higher score if it can be linked to one or several objects having a characteristic spatial distribution (e.g. alignment) determined by a common formation process or particular geological or climatic conditions. This criterion is evaluated in a binary manner, through the presence or absence of links (Monbaron, 1993, p. 125); (Grandgirard, 1995, p. 124).

– Rarity of the Type of Object

The object gets a higher score if there are few objects of similar type in a given reference space. This criterion therefore concerns the category of objects considered (e.g. a polje, a sink-hole, etc.). Rarity can be estimated in relation to each reference space (e.g. local, regional, global), the results of which are then grouped to obtain a rarity index. This criterion, nevertheless, does not evaluate the rarity of an object relative to other objects of the same type, for which the criterion «specific rarity» applies (Schlegel, 1987, p. 135); (Monbaron, 1993, p. 124); (Lagally, 1994, p. 257 or Lagally & *alii*, 1994, p. 48); (Grandgirard, 1995, p. 126); (Gsteiger, 1995, p. 157); (Strasser & *alii*, 1995, p. 21).

– Specific Rarity of an Object

An object gets a higher score if it already scores highly for one of the «object» or «morphosystem» criteria, and there are few objects of the same type in the reference area with such a strong performance for that particular criterion. Suppose a karst cavity, which is a frequent type of object at all scales (see rarity of the type of object), performs weakly in all criteria except its «morphochronologic archive» value; the cavity contains sediments constituting the only evidence of glaciers in the sector in question and therefore merits being valued. This object would then score higher in the «specific rarity-morphochronologic archive» criterion. It is important to judge the rarity of an object's performance in each different criterion, in order to avoid immersing it in a global rarity value. The «specific rarity» criterion satisfies this requirement (Kienholz, 1988, p. 196); (Lagally, 1994, p. 257; Lagally & *alii*, 1994, p. 48); (Grandgirard, 1995, p. 127); (Gsteiger, 1995, p. 156).

– Geodiversity

This criterion is different from the above in that it does not concern the objects. It can be applied to groups of objects which are operationally and/or topologically interactive: sites, as defined above. A site gets a higher score if it presents a high diversity of objects. Geodiversity is important due to the existence of a large number of different objects in a given space, but also because it facilitates studying, visiting and protecting a site due to the concentration of objects in a limited area (Monbaron, 1993, p. 124); (Kreutzer, 1994, p. 246); (Lagally, 1994, p. 257 or Lagally & *alii*, 1994, p. 48); (Grandgirard, 1995, p. 127); (Gsteiger, 1995, p. 156).

APPLICATION OF THE METHOD

Context

A working group in Switzerland is currently compiling an inventory of geotopes of national significance (Groupe de travail suisse pour la protection des géotopes). In the Jura, the karstic geotopes (sink-holes, swallow-holes, lapies, caves, canyons,...) will be particularly important. The practical application described here serves to demonstrate that the present method can help in the selection of the geomorphological objects to be included in this inventory. For this application, the examination of sink-holes will be focused upon.

The selected test-site is located on the Franches-Montagnes plateau in the Swiss Jura Mountains (fig. 4). Geologically, the study area is characterized by folded layers of alternating marl and limestone. The particular topography of Froidevaux is the result of karstic erosion of a rounded anticlinal summit. Numerous sink-holes aligned along a contact between marl (in black) and limestone (in brick symbol on the profiles) are evident along the edge of the depression.

Procedure

The first step of the procedure is the evaluation in the field. All the sink-holes are individually mapped and evaluated. For each evaluation criterion, the possible scores that a sink-hole can be given have been defined (table 2). «Legibility», «activity», «human-induced damage» and all the «rarity» criteria are scored from 0 to 3 (for ex. 0 = not or poorly legible; 1 = weak legibility; 2 = good legibility; 3 = very good legibility). «Illustration», «paleomorphologic marker» and «morphochronologic archive» can receive scores from 0 to 2 (0 = does not illustrate; 1 = illustrates; 2 = illustrates very well), and the «relationships» criteria either 0 or 1 (0 = absence, or 1 = presence of relationship).

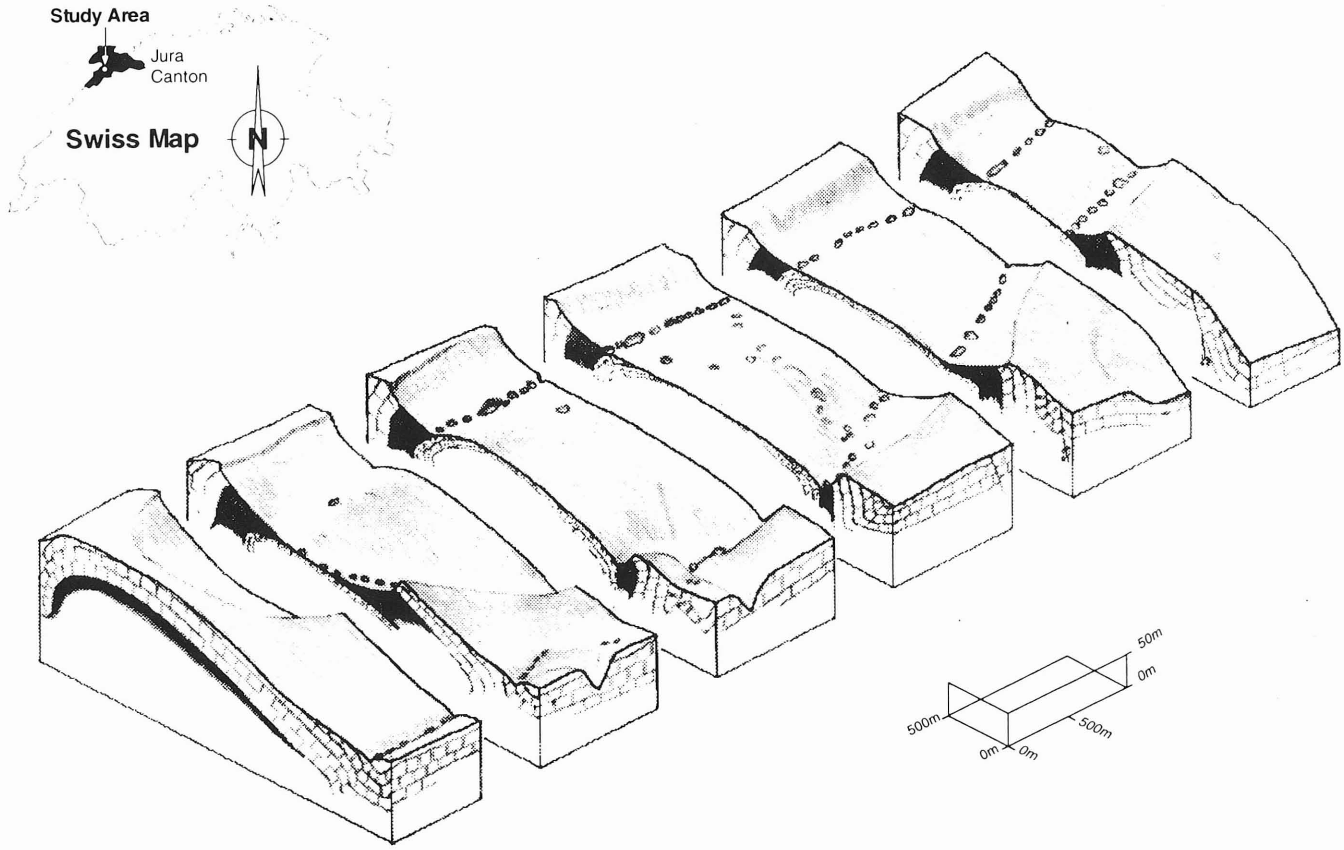


Fig. 4 - Geomorphological context of the test sector.

TABLE 2 - Possible scores for each criterion

EVALUATION CRITERIA	POSSIBLE SCORE
Legibility	0 to 3
Illustration	0 to 2
Activity	0 to 3
Paleomorphologic Marker	0 to 2
Morphochronologic Archive	0 to 2
Human-induced Damage	0 to 3
Operational Relationships	0 or 1
Topological Relationships	0 or 1
Type Rarity	0 to 3
Specific Rarity	0 to 3
Geodiversity	0 to 3

After this stage of considerable field work, the data are entered into the computer to be processed using multicriteria analysis. At this point, one must choose the weight to be given to each criterion. Four different test classifications are proposed, each time changing the weight assigned to different criteria (table 3). These different weighting configurations translate the preferences of those creating the geotope inventory (for example, the Environmental Office of the Canton of Jura, the scientists behind the study, nature preservation groups,...). In test A, the people creating the inventory judge that all the criteria are equally important. Thus, all criteria have the same weight. Then, others suggest that objects deemed as geotopes should be quite visible, not altered and very didactic. To translate this preference, test B attributes doubled weight to the «object» criteria. Since all karstic landforms develop in conjunction with eachother, another participant finds that it is important to consider the relationships between objects. For this reason, test C has the same weighting as test B, except for tripling the weight of the «morphosystem» criteria (here, «topological relationships»). In the fourth case, the participants find that the first criteria are useful, but that considering rarity is of little use. Test D, then, has a zero weighting for all the «rarity» criteria.

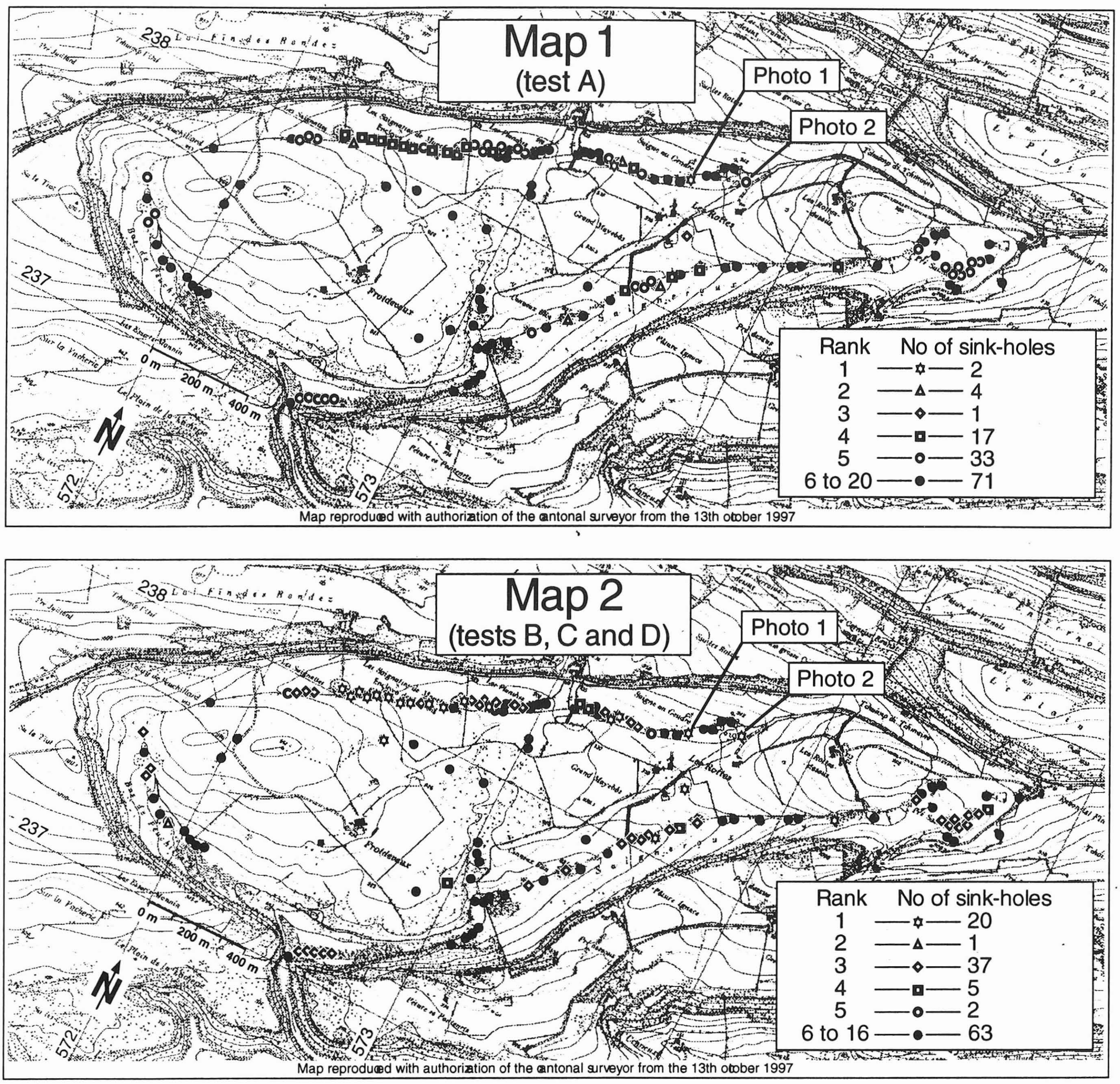


FIG. 5 - Maps showing the sink-hole classification for test A (Map I, above) and tests B, C and D (Map II, below).

According to its definition, the «specific rarity» criterion is evaluated on the score the sink-holes received for the first criteria («object» and «morphosystem» criteria). Note that in this example, the «paleomorphologic marker», «morphochronologic archive» and «operational relationships» criteria (as well as «specific rarity» based on these criteria) were excluded since all the sink-holes had the same score. «Type rarity» (we have only sink-holes!) and «geodiversity» (one single site) were also eliminated.

TABLE 3 - Weighting of the criteria in the four tests

	Test A	Test B	Test C	Test D
Legibility	x 1	x 2	x 2	x 1
Illustration	x 1	x 2	x 2	x 1
Activity	x 1	x 2	x 2	x 1
Human-induced Damage	x 1	x 2	x 2	x 1
Topological Relationships	x 1	x 1	x 3	x 1
Specific Rarity / Legibility	x 1	x 1	x 1	x 0
Specific Rarity / Illustration	x 1	x 1	x 1	x 0
Specific Rarity / Activity	x 1	x 1	x 1	x 0
Specific Rarity / Human-induced Damage	x 1	x 1	x 1	x 0

x 2 = double the weight
x 3 = triple the weight

Now that all the parameters are defined, the actual evaluation can take place. It was decided to use the program Electre III[1], because it establishes a classification (called the «gamma» approach in multicriteria language). Electre III establishes the classification by comparing the sink-holes pair-wise and answering these two questions:

– does sink-hole X perform equally well as sink-hole Y on the «legibility» criterion, on the «illustration» criterion,...?

– which criterion shows the maximum difference between sink-hole X's and sink-hole Y's scores?.

The first question is used to calculate the similarity index, and the second for the discordance index. Electre III uses these two indices to establish the sink-hole classification. The results are presented in classes (see Maps I and II below) because Electre can not give a different ranking order to objects with the same total score.

Results

Map I presents the results of test A. Map II presents the results of the three tests B, C and D, since they are all exactly the same. The fact that Electre produces the same sink-hole classification in three tests may appear curious; but if one considers the weighting chosen in the three cases (Table 3), it becomes evident that the weighting favored the four «object» criteria over the other criteria.

After comparing the two resulting maps, one notes that two sink-holes are ranked first in both situations (Photo 1 shows one of these sink-holes.). In both maps, the objects fall into more or less identical groups of equally ranked sink-holes. The difference between the two maps is in the different ranking of these sink-hole groups. This may explain why the number of sink-holes according to rank varies significantly: Map I has only two objects with the highest rank, whereas Map II has 20 first-rank objects (see, for example, the sink-hole in photo 2). A comparison of the two maps also shows that the criteria's weighting does not completely modify the classification: of all the sink-holes ranked 1st to 5th on both maps, (57 on Map I and 65 on Map II), 54 are the same.

In a final instance, it is legitimate to ask which weighting scheme is most suitable for selecting sink-holes for a geotope inventory. In the past, attempts to evaluate geomorphological objects often select the most rare or simply the most «beautiful» objects (the most legible, the most illustrative, the most active,...). The authors believe that the «relationships» criteria should never have less weight than the others. In the context of this small study, it is recommended to use the weighting of test C. But it is possible that others users would disagree, which would open up the weighting scheme for discussion.

This small and fictive example of an application shows how the method works and the advantages that it can offer. One sees that it is of interest in cases where several participants must make choices together, such as for an inventory of geomorphological geotopes. However, this particular case does not illustrate all of the method's possibilities, notably, using the «geodiversity» criterion to compare sites (an ensemble of linked objects, see fig. 3).

CONCLUSION

In the perspective of environmental management, the method suggested here presents a tool for the systematic evaluation of geomorphological heritage. Obviously, this process does not attempt to eliminate subjectivity. It does, however, allow the correct presentation of a problem of geomorphological heritage evaluation, providing a framework that ensures the user's awareness of the choices being made.

This method can be useful in that it allows one to compare different types of objects (sink-holes, lapies, cavities, dry valleys,...) and different sites (the example above does not, unfortunately, illustrate this advantage). In addition, it is flexible enough that it can be adapted to the user's needs, working scale, research questions, etc. Clearly, considerable field work is required for the evaluation of each object.

Standardizing the observation procedure is an essential preparatory step for the evaluation. In this paper, a possible standard approach for karst landform development is proposed (general model of karstic morphogenesis and the «object-relation» model). Note that the user is not limited to these models of karstic landform development; in order to produce a coherent evaluation, however, one should strive to define the observation model(s) as precisely as possible.

[1] Developed by Dominique Vallée, Lamsade, University of Paris Dauphine, Place du Maréchal de Lattre de Tassigny, F-75775 Paris Cedex 16 and Roman Slowinski, Poznan University of Technology, Institute of Computing Science, Piotrowo 3a, 60-695 Poznan, Poland.

PHOTO 1
Sink-hole ranked 1st on both Map I and Map II
Score given to this sink-hole:
Legibility: 3
Illustration: 2
Activity: 3
Human-induced Damage: 2
Topological Relationships: 1
Spec. Rarity / Legibility: 2
Spec. Rarity / Illustration: 1
Spec. Rarity / Activity: 1
Specific Rarity / Human-induced Damage: 0

PHOTO 2
Sink-hole ranked 5th on Map I and 1st on Map II
Score given to this sink-hole:
Legibility: 2
Illustration: 2
Activity: 1
Human-induced Damage: 2
Topological Relationships: 1
Spec. Rarity / Legibility: 0
Spec. Rarity / Illustration: 1
Spec. Rarity / Activity: 0
Specific Rarity / Human-induced Damage: 0

Using multicriteria analysis (Electre III) provides an opportunity to make the evaluation process more methodical. These methods should be used only as a decision making aid, and not as a magic device that provides the solution. It is up to the user to refine the classification, taking new criteria into account. Such a method offers advantages for long term management of our geomorphological heritage. Once these data (the objects thus evaluated) are digitized, they can be used in diverse contexts: inventory, environmental impact study, nature trail design, etc. For each purpose, one has only to change the weighting given to the different criteria.

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