Geomorphology 132 (2011) 17–28

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Morphometric analysis of three-dimensional networks of karst conduits

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ARTICLE INFO

Article history:
Received 19 October 2010
Received in revised form 19 April 2011
Accepted 24 April 2011
Available online 30 April 2011

Keywords:
Rose of directions
Z-histograms
Fractal dimension
Semi-variogram of spatial density
Connectivity index
Sinuosity index

ABSTRACT

The main idiosyncrasy of a typical karst system is the presence of a three-dimensional network of conduits behaving as drains in the system and being responsible of both the quick response of karst springs to rainfall events and the complex distribution of solutes in the system. A morphometric analysis of the three-dimensional geometry of conduits provides quantitative measures that can be used in a range of applications. These morphometric parameters can be used as descriptors of the underground geomorphology, they provide information on speleogenesis processes, they can be correlated with karst denudation ratios, they can be used to control the simulation of realistic stochastic karst networks of conduits, and they can be correlated with hydrogeologic behaviour of the karst system. The main purpose of this paper is to define, describe and illustrate a range of morphometric indexes and morphometric functions that can be calculated nowadays because the availability of three-dimensional topographies provided by speleological work and the availability of the computational and graphical power provided by modern computers. Some of the morphometric parameters describe the existence of preferential directions of karstification, others describe the kartification along the vertical and the possible presence of inception horizons. Other indexes describe the shape complexity of the karstic network, whilst other indexes describe spatial variability of the conduit geometry, and other parameters give account of the connectivity of the three-dimensional network. The morphometric analysis is illustrated with a three-dimensional karstic network in Southern France.

1. Introduction

Most of the quantitative research of karst systems (Bakalowicz, 2005) has been based on black-box approaches considering the karst system as a whole (e.g. the system analysis approach of Mangin (1975)). However, the most challenging aspect of karst research is to work with distributed models that are able to provide reliable information of the direction and rates of groundwater flow through the karstic aquifer. The complexity of the karst system is given by its large local heterogeneity, mainly introduced by the presence of a complex system of pipes (known as conduits), their location, their density across the system and the connectivity of the conduit network. It has been widely recognised that because there is never enough spatial experimental information to adequately describe the spatial complexity of the karst system, the future of karst modelling is to increase the understanding of the functioning of the karst system more than to give reliable forecasting of local hydrogeological behaviour (Palmer, 2006). In our opinion, the latter is a pessimistic view of the possibilities of modern approaches to karst research. The hydrodynamics of conduit flow is well defined (Gale, 1984) and the programmers have no difficulty to incorporate the conduit flow into the mathematical models of groundwater flow (for example, Reimann and Hill (2009) describe a new conduit flow process (CDP) for MODFLOW-2005). Additionally, because the network of conduits is unknown (or partially known from speleological investigations) one possibility is to simulate it in the most realistic possible way and to use an ensemble of simulations in an inverse modelling process trying to reproduce the hydrograms, thermograms and chemiograms of springs in order to obtain a spatial distribution of conduits and an associated uncertainty (Fig. 1).

The first step in establishing such a methodology is the morphometric characterization of known three-dimensional geometries of karstic networks in order to give quantitative descriptions of size, shape and spatial variability and connectivity of conduits. Those morphometric parameters and functions have different uses: (i) to generate realistic networks by simulation or (ii) to extrapolate a known network to unexplored areas. The main task of this paper is to describe morphometric parameters to be obtained from the three-dimensional geometries of karst conduits. These parameters will be used for calibrating the simulations of karstic networks in the context of the previous general aim described by the project of inverse modelling in Fig. 1. Additionally the morphometric indexes may have other applications like (i) to correlate the morphometric indexes with hydraulic behaviour, (ii) to correlate with conceptual speleogenesis processes for assisting in conceptual modelling of karst areas with scarce speleological information, (iii) to characterise the degree of development of a karst system, and (iv) to compare different karst systems.

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doi:10.1016/j.geomorph.2011.04.030

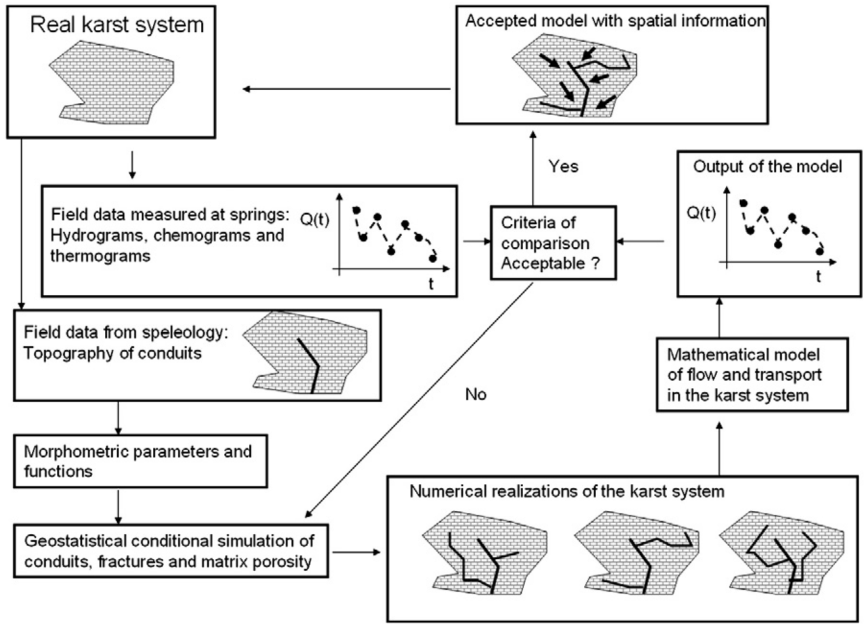

Fig. 1. Flow diagram of a methodology on karst hydrogeology in which spatial detail of the karst system is obtained by an inverse modelling procedure. In this methodology an important stage is the validation of computer simulated networks of conduits. The morphometric analysis (presented in this paper) is used to control and calibrate the synthetic network in order that they are realistic.

In a general geomorphologic context, morphometric analysis provides quantitative descriptors of geometry and topology of geomorphologic features, it provides assistance in the determination of physical laws of patterns, scaling, complexity and variability of geological structures, and it provides numerical indexes that can be correlated with physical parameters of practical interest. The archetype of morphometric analysis in geomorphology is the morphometry of fluvial systems (Horton, 1945). Nowadays morphometric analysis of a wide range of landscapes and its applications have flourished because the availability of digital elevation models (DEMs) and computer algorithms for their spatial analysis (e.g. Ganas et al., 2005). Morphometry of karst systems has usually been limited to landscape features like cellular networks of polygonal karst (Williams, 1972), dolines and other karstic depressions (Denizman, 2003), cockpit karst landscape (Lyew-Ayee et al., 2007), karren and other features of bedrock sculpturing (White and White, 2000), etc.

On the other hand, when considering the underground karst, the most frequent case has been the morphometric analysis of caves (Frumkin and Fischhendler, 2005), trying to establish a relationship between cave architecture and structural, lithological, geomorphological and hydrogeological factors. With respect to conduits, many times there has been a limitation to show the data as plan patterns (many examples may be found in Klimchouk et al., 2000 and Ford and Williams, 2007). These plan patterns may give a clear idea of fracture control and can be used to determine the type of recharge in the system (Palmer, 1991), they also introduce the possibility to establish the type of speleogenesis. However, these plan views, being projections of a three-dimensional network on the x–y plane provide limited morphometric information that, in any case, can be obtained from the original three-dimensional geometry.

In this paper, we use network of conduits and cave system as synonymous terms. The three-dimensional topography provided by speleological investigations have a resolution of around half a metre as the minimum diameter of a conduit that can be mapped given by the minimum width of a karst conduit accessible by a person. In the next section there is a description of the proposed morphometric indexes and functions.

1.1. Morphometric analysis of karst conduit networks

A network of karstic conduits is defined by geometrical and topological information collected usually by the speleologists. The original underground topographic information is referred to a given baseline (for example the entrance to a cave) and a sequence of topographic stations. Between two consecutive topographic stations, the data collected are the distance, azimuth and dip of the line joining both stations. From this original information it is possible to obtain the coordinates $\{x, y, z\}$, absolute or relative, of each topographic station. An introduction to modern techniques to cave mapping may be found in Jeannin et al. (2007). This speleological work provides the basic geometry of the network, defined by the locations of M topographic stations $\{s_i; i=1,\ldots,M\}$ and for each station one has its three spatial coordinates $s_i=\{x_i,y_i,z_i\}$. A summary of all notations is given in Table 1. The topological information gives the connection between the different points of the network. The usual speleological practise is to work with series—a continuous survey line going through several survey stations. Information is provided about how the series are connected. For example, in Fig. 2 there is a plan view of a karstic network with twelve stations where the conduit $\{s_7,s_8,s_9,s_{10}\}$ is connected with the conduit $\{s_1,s_2,s_3,s_4,s_5,s_6,s_7,s_{11},s_{12}\}$, with $\{s_7\}$ being the location of connection. A general k-thm basic conduit c_k is defined as the conduit that connects two consecutive survey stations $c_k=\{s_i,s_j\}$, and the full network of conduits is a set of N basic conduits $\{c_1,c_2,\ldots,c_k,\ldots,c_N\}$. For example, in Fig. 2, $\{s_4,s_5\}$ is a basic conduit and the total number of basic conduits is $N=11$. The length ℓ_k of the k-thm basic conduit c_k is a defined as the Euclidean distance (Fig. 3A):

$$\ell_k = \sqrt{\left(x_i-x_j\right)^2 + \left(y_i-y_j\right)^2 + \left(z_i-z_j\right)^2} \quad (1)$$

It is important to remark that the number and location of surveying stations have been determined to suit the convenience of the cave surveyors rather than following speleogenetic criteria, such as choosing the two ends of one mono-genetic hydrogeologic segment (and the reverse is also true, several basic conduits may be part of the same genetic component). Thus, a basic conduit is defined as the