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Estimation of conduit network geometry of a karst aquifer by the means of groundwater flow modeling (Bure, Switzerland)

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ABSTRACT

A steady-state two-dimensional groundwater flow model was developed using the combined discrete channel and continuum approach in order to estimate the spatial configuration and hydraulic properties of the karst conduit system in the Bure Aquifer, Ajoie, Switzerland.

The research site is 83 km^2 in area and is located in NW Switzerland. It is underlain by gently folded layers of limestones and marls of Malm age. The aquifer is 300-400 m thick, delimited from below by a thick sequence of marls, and it contains three marl intercalations. The Malm plateau is dissected by normal faults, which form a succession of elongated horst and graben structures.

A 10 km long section of the entire conduit system was explored. The flow model was calibrated by changing conduit spatial configuration and conductivity. A uniform average hydraulic conductivity derived from borehole tests was applied to the fissured rock matrix. Measured average hydraulic heads, average spring discharges and catchment boundaries were used as model control parameters. Catchment boundaries were designated from tracing tests.

Flow simulations suggest the existence of extended karst systems, each extending to the catchment boundaries, having a hydraulic conductivity proportional to the measured spring discharges.

Key words: Bure (Switzerland), conduit network geometry, groundwater, karst aquifers, numerical modeling

Estimación de la geometría de la red de conductos de un acuífero kárstico mediante un modelo de flujo hidrogeológico (Bure, Suiza)

RESUMEN

Un modelo bidimensional para el flujo de agua subterránea ha sido desarrollado utilizando la aproximación de medio continuo con canales discretos, para evaluar la configuración espacial y las propiedades hidráulicas del sistema de conductos kársticos en el acuífero de Bure, Ajoie, Suiza.

El área de investigación ocupa una superficie de 83 km^2 en el NO de Suiza. Es una región formada por calizas y margas del Malm ligeramente plegadas. El espesor del acuifero es de 300-400 m, está limitado en la base por una potente secuencia de margas y contiene tres intercalaciones margosas. La altiplanicie de rocas del Malm está cortada por fallas normales que originan una sucesión de horst y gráben.

Se ha explorado una sección de 10 km de largo del sistema de conductos; el resto continúa desconocido. Se ha calibrado el modelo de flujo cambiando la configuración espacial de los conductos y su conductividad hidráulica. Para la matriz de roca fisurada se ha considerado una conductividad hidráulica media uniforme obtenida a partir de pruebas en sondeos. Se han utilizado como parámetros de control del modelo la media de la carga hidráulica medida, la media de las descargas de los manantiales y los límites de la cuenca de alimentación. Estos últimos fueron asignados a partir de ensayos de trazadores. Las simulaciones de flujo sugieren la existencia de extensos sistemas kársticos que pueden alcanzar los bordes de la cuenca de alimentación, con una conductividad hidráulica proporcional a las descargas medidas en los manantiales.

Palabras clave: acuífero kárstico, agua subterránea, Bure (Suiza), modelo numérico, geometría de red de conductos

Introduction

One of the most significant characteristics of karst systems is strong heterogeneity due to the presence of high permeability dissolution voids. A karst aquifer can be considered as an interactive unit of a low permeabiliy matrix of fissured limestone with a hierarchical network of karst conduits immersed within it.

The spatial configuration of the conduit network and the hydraulic properties of either the low permeability matrix or the karst conduits have a strong influence on the hydraulic behavior of the aquifer and of the karst springs to which it discharges. The influence of conduit network geometric and hydraulic properties on the hydraulic head distribution and on the spring discharges has been demonstrated by Kiraly and Morel (1976) and later by Eisenlohr (1996). Both studies used numerical models specifically to qualitatively demonstrate the effect of aquifer parameters alteration.

Speleological exploration may provide information on the extension, spatial geometry, and diameter of certain karst conduits. Because the minimum diameter of conduits accessible by this method is limited to the size of the human body, and also because of technical difficulties involved in subterranean exploration, speleological methods only provide spatially limited information on the geometry of conduit networks. Although this information can be further extended by the application of surface geophysical methods and borehole logging, knowledge of conduit geometry still remains spatially limited and uncertain.

The aim of this study is to estimate the spatial configuration and hydraulic characteristics of the conduit network in karst aquifers compared to available field observations, by the means of numerical modeling of a real aquifer. For this purpose, a set of steady-state two-dimensional groundwater flow models of the Bure Aquifer (Ajoie, Switzerland) are developed, using the combined discrete channel and continuum approach. Although a section of the conduit system of the Bure Aquifer over 10 km long has been explored by speleologists, the majority of the entire network remains uninvestigated. For estimating the spatial configuration and hydraulic properties of the entire conduit network, several conceptional models were tested from pure observed conduit network configuration until extended systems, and also equivalent porous media models.

A uniform average value of conductivities derived from borehole tests was assigned to the low permeability matrix. The preliminary value of conduit conductivity was obtained from field observations and previous models (Jeannin and Maréchal 1995). The approximate density of the conduit network was estimated from cave maps. Measured average hydraulic potentials, average spring discharges and catchment boundaries designated from tracing experiments served as control parameters for the calibration process. For data transfer between reality, conceptual models and numerical models, and also for data exploitation, GIS tools (ArcView/ArcInfo) were used. Finite element mesh was generated by Feflow 4.8. Flow equations were solved making use of the groundwater modeling code FEN1 (Kiraly, 1985).

Research site geological and hydrogeological settings

The Bure plateau is located at the Swiss-French border in Ajoie, canton Jura, NW Switzerland at the southern margin of the Plateau Jura, to the west of the southern end of the Rhine Graben (Fig. 1). The research site is bordered by the Allaine river at the West and an extended dry valley at the South. Several springs are located along the Allaine river, and also along the North-Western boundary of the Plateau. The Bure plateau is 83 km^2 in area. It is characterized by various types of karstic forms (dolines, dry valleys and shafts). There are no significant surface streams throughout the site.

The Bure-plateau consists of gently folded layers of shallow marine limestones and marls of Triassic - Upper Jurassic age (Lambhart and Decrouez, 1997). Malm limestones form the aquifer, having a total thickness up to 320 m (Kovács and Jeannin, 2003). Aquifer contains three marl intercalations (Fig. 2). The lowermost Sequanian "Astarte marls" formation (also called "Natica marls") has a considerable thickness (40 m) while Kimmeridgian marl layers are relatively thin (10 m). The aquifer is bounded from below

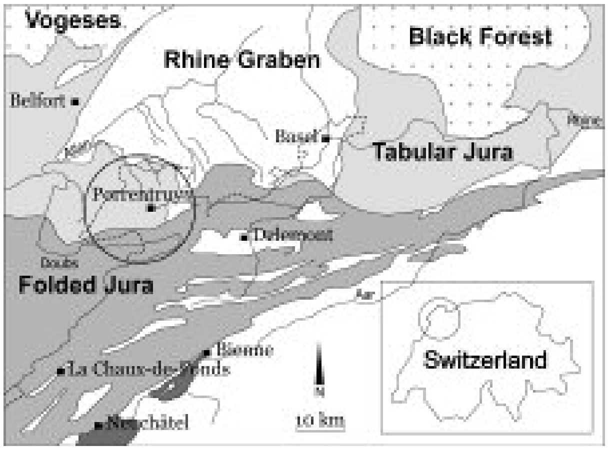

Fig. 1. Geographical situation of the Bure plateau, Ajoie, Switzerland. Research site is located at the southern margin of the Plateau-Jura, to the west of the Rhine Graben termination

Fig. 1. Situación geográfica de la Meseta de Bure, Ajoie, Suiza. El área de estudio está localizada en el borde sur de la meseta del Jura, al oeste de la fosa tectónica del Rhin.

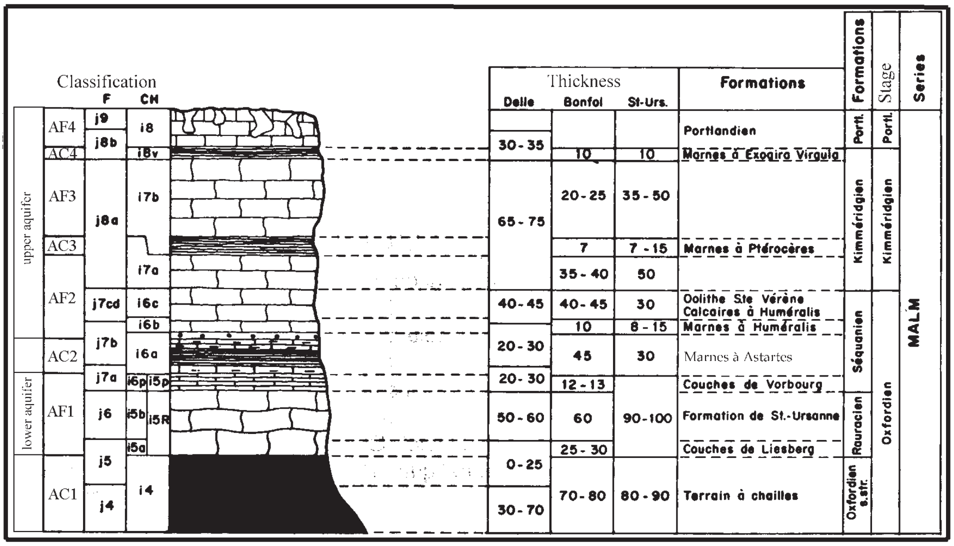

Fig. 2. Research site hydrostratigraphy after Gretillat (1996). The Malm calcareous aquifer contains three marl intercalations, the Sequanian Astarte Marls Formation having the greatest thickness (40 m)

Fig. 2. Hidroestratigrafía del área de estudio tomado de Gretillat (1996). El acuífero calcáreo del Malm contiene tres intercalaciones de margas; la Formación Jenonense de margas con Astarte tiene el espesor mayor (40 m)

by the massive layers of Oxfordian Marls. The underlying sediments of Dogger age are hydraulically independent (Gretillat, 1996). Terciery sediments are very rare in the area. Quaternary loess sediments cover about 30% of the Mesozoic rocks. Quaternary alluvial sediments are present along riverbeds and dry valleys with a thickness of 10-20 m and they form separate aquifer bodies interacting with the Malm calcareous aquifer.

The Bure-plateau is dissected by N-S, NW-SE and NE-SW oriented faults, which form a succession of elongated horst and graben structures (Kiraly *et al.*, 1971). The vertical displacement along faults is generally in the range of 20-40 meters (Figs. 3 and 4).

Hydrogeological data on the Bure site is relatively abundant, due to several years of karst research being performed in this area. This data comprise of piezometric and spring discharge measurements, hydrochemical analyses, surface geophysical survey, and speleological exploration.

The mean piezometric surface (Fig. 5) has been obtained by the interpolation between average piezometric levels and spring topographic elevations. Two boreholes have been used as reference points during the modeling process. The water table fluctuations throughout the aquifer are slight. Figure 5 provides a good approximation of the general hydraulic head distribution. According to this map, a piezometric dome extends to the south of Bure with a maximum piezometric head at 580 m above sea level. In accordance with the tracer flow directions, a NW-SE oriented regional groundwater flow divide can be estimated for this region. To the north of this zone, the general flow direction is NE, and to the south of it groundwater flow tends to the ESE.

Tracing experiments (Fig. 6) performed throughout the Bure-plateau allowed the delineation of drainage basins corresponding to karst springs (Gretillat, 1996, Grasso and Jeannin, 1994; Favre, 2001; Kovacs and Jeannin, 2003). The largest catchment belongs to the Beuchire spring and the most detailed information on sub-catchments delineation is available for the Milandrine karst system, which discharges to the Saivu spring. The total length of this system exceeds 10 km, and it contains a 4.6 km long underground river. Some segments of the Beuchire system were explored to a limited extent (2 km), and indicate the presence of a more extended cave system. The conduit systems belonging to other springs of the region remain completely unexplored.

The hydraulic conductivity of either the Rauracian or the Sequanian and Kimmeridgian limestones, measured from borehole tests, is in the range of 10^{-6} - 10^{-7} m/s (Fleury and Allemann, 1991; Jeannin, 1995).

The hydraulic conductivity of the Milandrine conduit system was estimated by Jeannin and Maréchal (1995). Its average value is 1 m^3/s. The average spacing of explored karst conduits is approximately 200 m.

Conceptual and numerical models

The development of a conceptual model of the study area involved several simplifications of the real system, which were adjusted to the aim of this study.

Although the hydraulic functioning of karst aquifers is a typically transient phenomenon, the aim of this study is to investigate the spatial configuration of the conduit system and not the temporal variations of the water table or of spring discharges. For this reason a steady-state flow model was employed. Both model input and control parameters are average values, and simulation results correspond to a long-term generalization of the processes taking place in the aquifer.

In spite of the considerable thickness (40 m) of the Sequanian Astarte marls, on the evidence of several tracing tests, the underlying and overlying aquifer volumes communicate hydraulically. None of the three marl layers interrupt hydraulic continuity, and all of the malm sediments superposed on the Oxfordian Marls can be considered as an integral whole (Kovács and Jeannin, 2003). The vertical flow processes taking place in the unsaturated zone are not of our interest. Consequently, aquifer geometry can be simplified to a two-dimensional sheet (Fig. 7) with spatially varying transmissive properties.

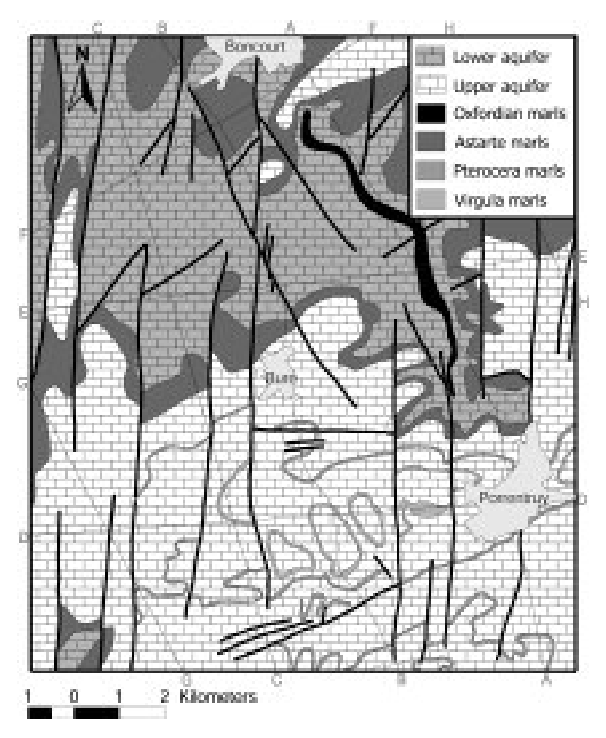

Fig. 3. Hydrostratigraphic map of the Bure-plateau. The Malm aquifer can be lithologically subdivided into lower and upper aquifers, separated by the Astarte marls. On the evidence of tracing experiments these two aquifer units behave hydraulically as one. Kovács and Jeannin (2003)

Fig. 3. Mapa hodroestratigráfico de la meseta de Bure. El acuífero de Malm puede subdividirse litológicamente en un acuífero superior y en otro inferior, separados por las margas de Astarte. En experimentos con trazadores estas dos unidades acuíferas se comportaron hidráulicamente como uno. Kovács y Jeannin (2003)

An average of the measured hydraulic conductivity as a uniform value was assigned to the fissured rock matrix over the entire model domain. Transmissivity values were set proportional to the varying thickness of the saturated zone calculated from interpolated piezometric surface and aquifer bottom maps. Hydraulic conductivities of the conduit systems were estimated by Jeannin and Maréchal (1995). This value was later modified during the calibration process for each karst subsystem. Darcian flow was calculated in both the low permeability blocks and in the conduits.

Observed hydraulic head distribution, average spring discharges and drainage basin boundaries were taken into account during calibration. A uniform effective recharge (500 mm/y) was distributed throughout the domain. This value is based on the calculations of Jeannin and Grasso (1995).

The eastern boundary of the model domain is delimited by the Allain river, and by karst springs which are located along the riverbank. In this zone, Dirichlet type boundary conditions are imposed (Fig. 7). The same type of boundary conditions is imposed along the southern boundary of the domain. This boundary is delimited by a dry valley, below which an underground river flows with known water surface elevations. Dirichlet boundary conditions are defined also along the northern part of the western boundary, which follows a surface stream. Along the rest of the western model boundary, Neumann (no flow) type boundary conditions are defined following the topographic high.

Groundwater flow simulations were based on the combined discrete channel and continuum approach (Kiraly and Morel, 1976; Kiraly, 1985,1998). This approach allows for the combination of 1-D, 2-D and 3-D linear or quadratic finite elements to be used. The code FEN1 facilitates the simulation of saturated, steady-state groundwater flow in two or three dimensions. The formulation of the finite elements is based on the Galerkin weighted residuals approach. The resulting system of linear equations is solved by the frontal elimination technique.

During the calibration of different flow models, two of the piezometric data points, borehole BUR-7 and FN-1 were used as reference points, and also the maximum observed hydraulic head was considered.

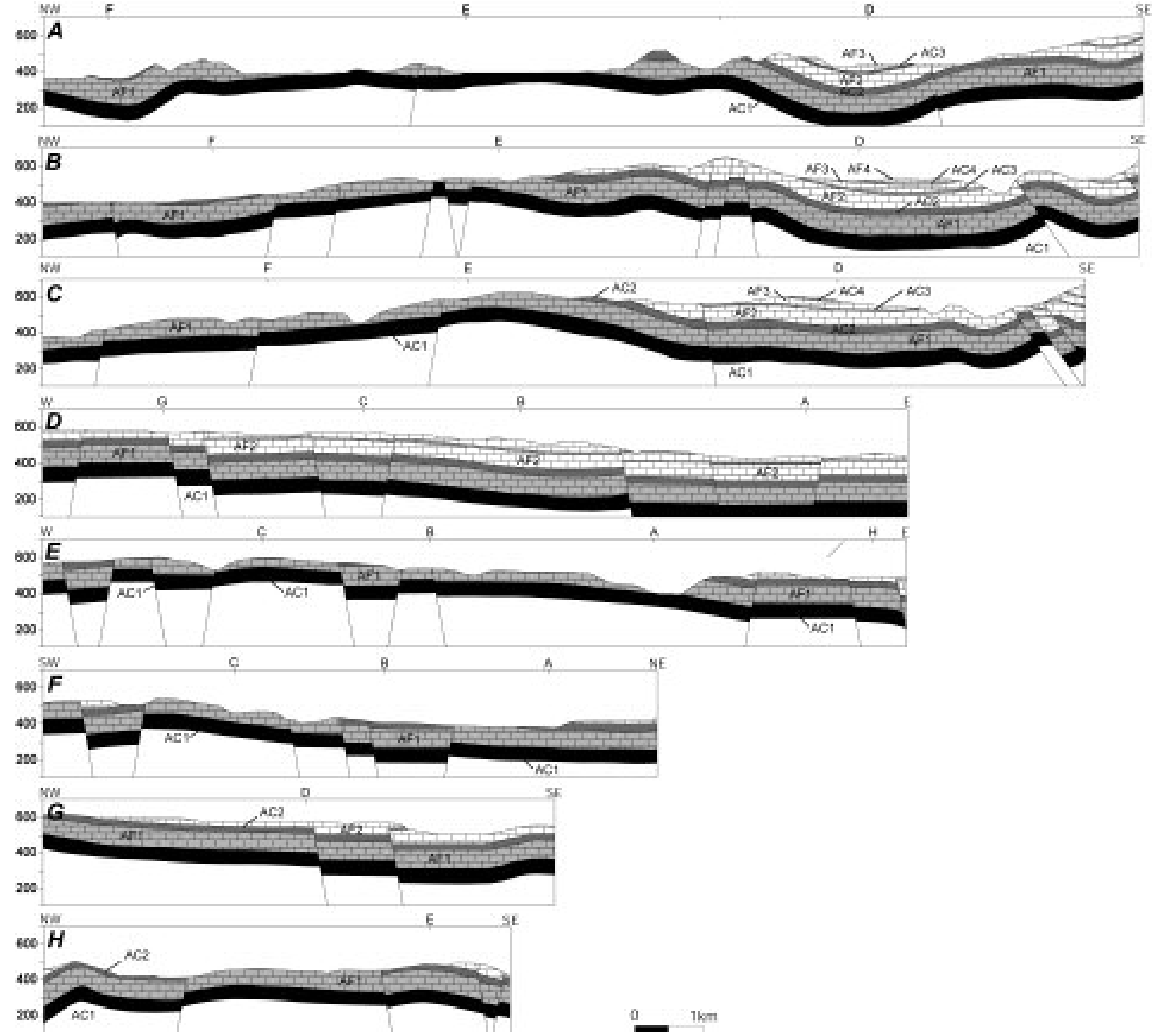

Fig. 4. Cross sectional profiles. The Bure-plateau corresponds to the eastern periclinal termination of an E-W oriented anticline. Kovács and Jeannin (2003)

Fig. 4. Cortes geológicos. La meseta de Bure corresponde a la terminación periclinal este de un anticlinal de orientación E-O. Kovács y Jeannin (2003)

The aim of approximate model calibration was to show the limitations and suitabilities of a given concept, rather than to precisely reflect measured hydraulic data. Consequently, the uniform conductivity field was not subdivided in the course of the calibration process, and model results may differ slightly from field measurements.

Disscussion of model results

In the course of modeling process several conceptual models and realizations of conduit network geometry were tested. In order to obtain indirect information on the structure of karst conduit systems, two different parameter distributions were assigned to each model

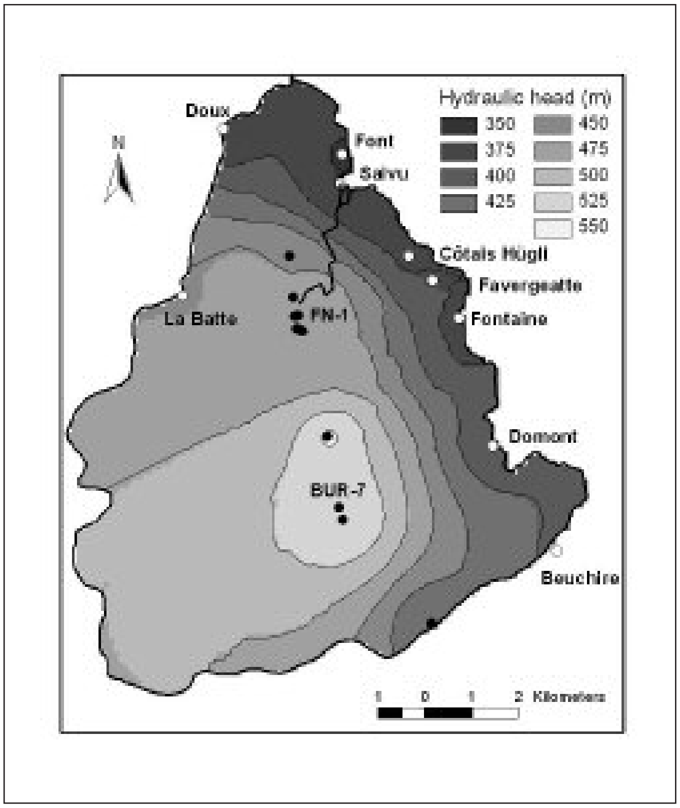

Fig. 5. Piezometer (white dots) and spring (black dots) locations and average piezometric surface obtained by interpolation among these observation points. Solid line indicates the explored conduit system called Milandrine. The boreholes FN-1 and BUR-7 were used as reference points in the course of model calibration
Fig. 5. Localización de piezómetros (puntos blancos) y manantiales (puntos negros) y superficie piezométrica media obtenida por interpolación sobre estos puntos de observación. La línea llena indica el sistema de conducto explorado llamado Milandrine. Los sondeos FN-1 y BUR-7 fueron usados como puntos de referencia en la calibración del modelo

conception. One distribution is consistent with measured hydraulic conductivity, while the other is calibrated to observed piezometric data.

As an initial scenario, discrete features were omitted in order to investigate the applicability of the equivalent porous medium approach for modeling the Bure test site. According to Figure 8a, realistic parameter model (PMref) yields enhanced hydraulic heads and unrealistically low spring discharges. This is the direct consequence of the lack of the drainage system which drains infiltrating waters and focuses them towards karst springs.

In order to roughly calibrate simulated head values to observed piezometric surface (Fig. 8b), an increase in the measured matrix conductivity by more than one order of magnitude became necessary (Table 1). Although this porous equivalent model (EPMcal) of the aquifer is capable of revealing measured hydraulic heads in a steady state, spring discharges could not be simulated by using this scenario. As the simulation of transient phenomena taking place in strongly heterogeneous media is even a more challenging task, the equivalent porous medium approach is hardly suitable for modeling karst aquifers.

The Milandrine cave was incorporated in models CDocnref and CDocncal (Fig. 9), in order to check whether explored conduit network is sufficient for simulating hydraulic behavior of the entire system. Exclusively field observations are integrated in model CDocnref: It contains the entire observed conduit system, and measured hydraulic conductivity is assigned to the low permeability fissured matrix. This model yields extremely enhanced hydraulic heads (Fig. 9a) and feeble spring discharges for every springs except that belonging to the explored conduit system. Consequently, pure field observations are insufficient for modeling an aquifer containing unexplored conduit subsystems.

Fig. 6. Delineation of karstic catchment areas based on tracing experiments. Thin lines join tracer injection points (quadrangles) and monitoring points (dots). Kovács and Jeannin (2003)
Fig. 6. Cuencas de drenaje kárstico, basadas en experimentos con trazadores. Las líneas delgadas vinculan los puntos de inyección del trazador (cuadrados) con los puntos de control (círculos). Kovács y Jeannin (2003)

Fig. 7. Finite element mesh and boundary conditions. Solid line designates Neumann no-flow type boundary conditions, and dashed line indicates Dirichlet boundary conditions. Mesh refinement along tectonic features serves other flow models than those presented in this paper

Fig. 7. Malla de elementos finitos y condiciones de contorno. La línea continua indica una condición de contorno de tipo Neuman y la línea discontinua una condición de tipo Dirichlet. La malla se refinó a lo largo de los rasgos tectónicos

In order to adjust head distribution, the hydraulic conductivity of the fissured matrix had to be increased (Table 1). Although the calibrated matrix conductivity of model CDocncal (Fig. 9b) is smaller than that of the equivalent porous medium model (EPMcal), it is still more than one order of magnitude greater than measured values. Moreover, simulated spring discharges are far lower than measured ones.

It is important to emphasize that exclusive increase of observed conduit network hydraulic conductivity can slightly decrease hydraulic heads and increase the discharge of the observed conduit system. However this cannot permit either remaining spring discharges or hydraulic heads to be calibrated.

As explained above, the simultaneous simulation of measured spring discharges and observed hydraulic heads is not possible by applying exclusively the explored karst conduits in the numerical model. An extension of observed conduit network is a logical necessity. Consequently the observed conduit network was extended to the catchment boundaries, and further networks have been added to every single catchment in model CDecn. Manually constructed synthetic networks follow a hierarchical structure, converging on karst springs. Initial conduit conductivity was estimated to be 1 m^3/s (Jeannin and Maréchal, 1995). Conduit network density was increased until excessive heads disappeared. Steep gradients between adjacent karst systems were smoothed, heads were calibrated and spring discharges were regulated by adjusting conduit system conductivities (Fig.10).

Although the conduit system geometry implemented in model CDecn is only one possible realization of the infinite number of possibilities, this model clearly shows that simultaneous simulation of observed hydraulic heads and measured spring discharges is only possible by the extension the observed conduit network. The extended conduit network model gives a good approximation of observed water table and yields spring discharges comparable to those measured (Table 2). Since the catchment area of the Beuchire spring extends outside of the model domain, simulated discharge is considerably less than measured value. The model CDecn clearly suggests the existence of extended conduit systems over the model domain (This assumption is supported by strongly fluctuating spring discharge data).

MODEL	K_m (m/s)	K_c (m^3/s)	Conduit network	H (m) Bur-7	H (m) Fn-1	Q (m^3/s) Saivu	Q (m^3/s) Beuchire
reference	7.0E-07	1	observed	550	480	1.55E-01	8.00E-01
PMref	7.0E-07	-	omitted	1741	2102	9.02E-03	9.91E-03
EPMcal	1.8E-05	-	omitted	500	485	5.72E-03	9.91E-03
CDocnref	7.0E-07	1	observed	1715	1536	1.76E-01	9.87E-03
CDocncal	1.5E-05	1	observed	490	490	7.82E-02	9.26E-03
CDecn	7.0E-07	0.1-30	extended	526	508	2.05E-01	6.04E-01

Table 1. Comparative table of reference data, hydraulic parameters, and model results

Table 1. Tabla comparativa de datos de referencia, parámetros hidráulicos y resultados del modelo

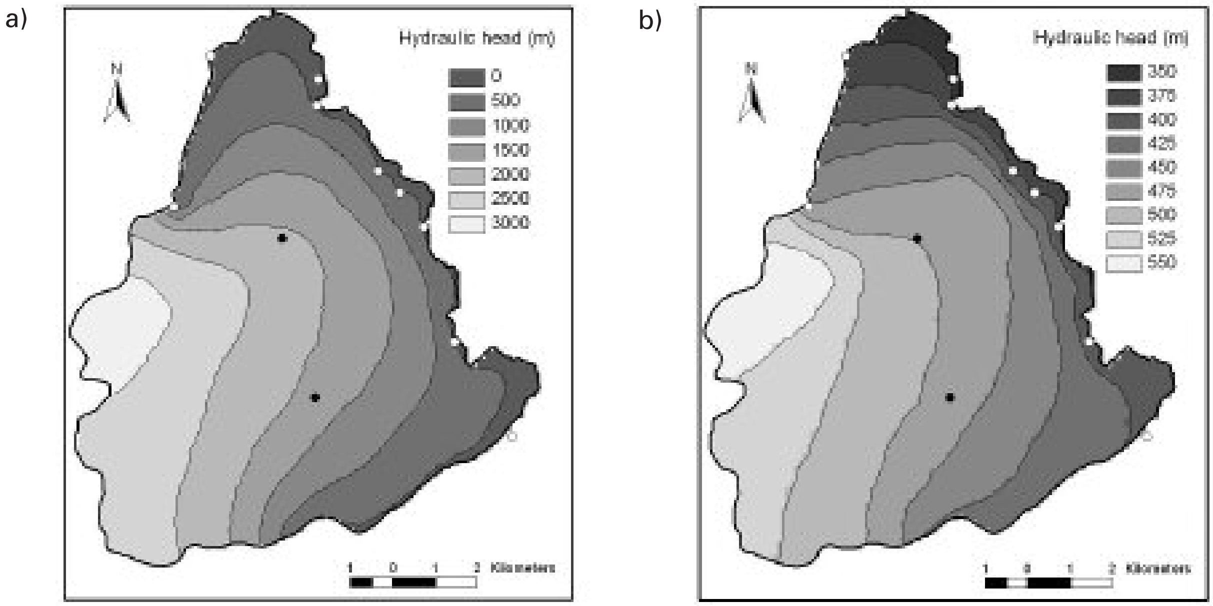

Fig. 8. Porous medium models. The realistic parameter model PMref (a) yields excessive hydraulic heads. The equivalent porous medium model EPMcal (b) results in realistic hydraulic heads but unrealistically low spring discharges

Fig. 8. Modelos del medio poroso. El modelo de parámetros realistas PMref (a) produce niveles piezométricos excesivos. El modelo del medio poroso equivalente EPM cal (b) ofrece niveles piezométricos realistas pero caudales de descarga en los manantiales excesivamente bajos

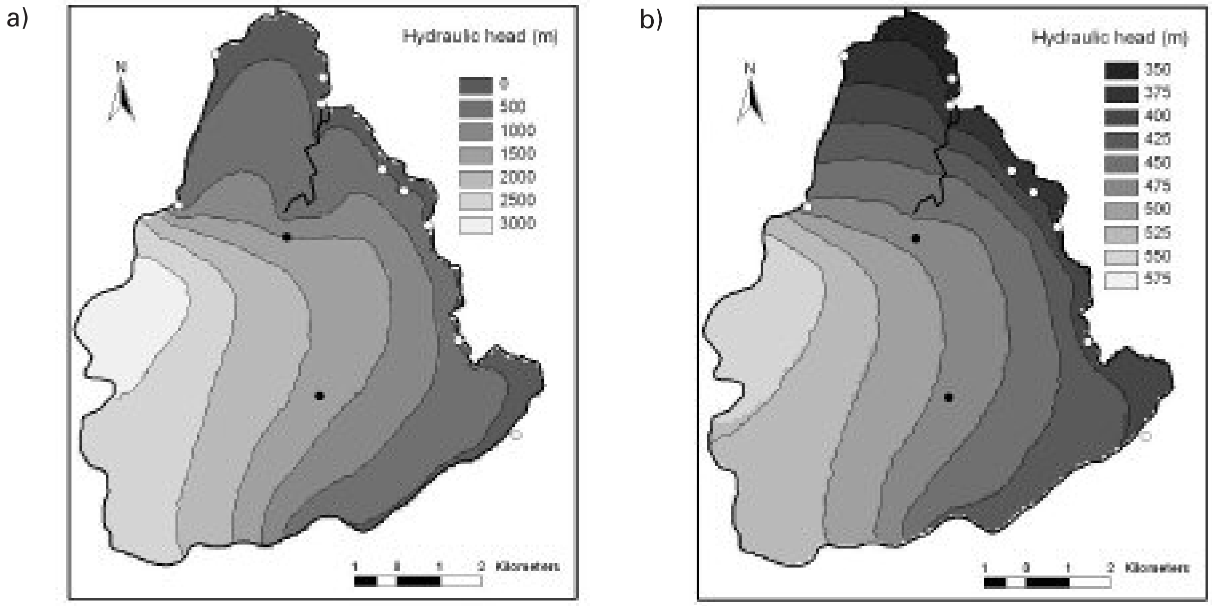

Fig. 9. Observed conduit network models. Matrix conductivity of model CDocnref (a) is derived from borehole tests; that of model CDocncal (b) is adjusted to observed hydraulic heads. Although model CDocncal roughly reveals observed piezometric surface, none of these models can simulate spring discharges except at the Saivu spring

Fig. 9. Modelos de la red de conductos. La matriz de conductividad del modelo CDocnref (a) se define a partir de los ensayos en los piezómetros. El modelo CDocncal (b) está ajustado para los niveles piezométricos observados. Aunque el modelo CDocncal reproduce groseramente la superficie piezométrica observada, ninguno de estos modelos puede simular la descarga de los manantiales excepto el de la fuente de Saivu

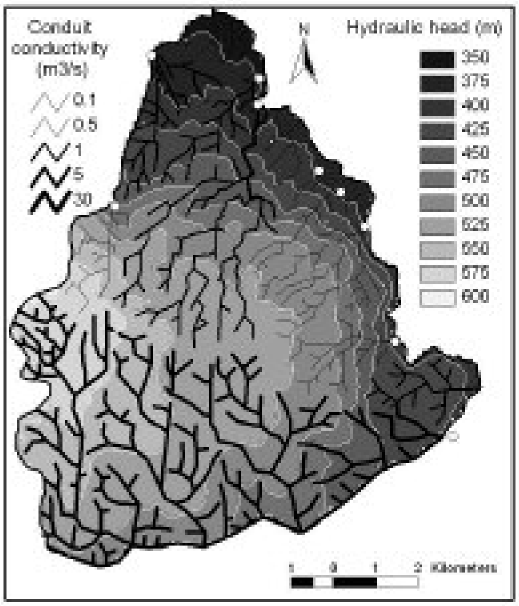

Fig. 10. Extended conduit network model (CDecn), conduit geometry and calculated hydraulic heads. Calibrated conduit conductivities are numerical values and refer to darcian flow conditions
Fig. 10. Modelo de la red de conductos extendida (CDecn), geometría de los conductos y niveles piezométricos calculados. Las conductividades de los conductos calibradas son valores numéricos y están referidas a las condiciones de flujo darciano

spring	measured discharge (m^3/s)	calculated discharge (m^3/s)
SAIVU	0.155	0.205
COTAIS-HUGLI	0.010	0.019
FAVERGEATTE	0.030	0.025
FONTAINE	0.065	0.077
DOMONT	0.040	0.060
BEUCHIRE (*)	0.800	0.600
BATTE	0.020	0.053
DOUX	0.150	0.060
FONT	0.050	0.050

Table 2. Measured and calculated spring discharges. Calculated values originate from the extended conduit network model (CDecn). The catchment area of the Beuchire spring extends outside of the model domain
Table 2. Descarga en manantiales medidos y calculados. Los valores calculados se obtienen del modelo de la red de conductos extendida (CDecn). El área de recarga del manantial de Beuchire se extiende fuera del dominio del modelo

Conclusions

Indirect information on the spatial extension of the conduit network in the Bure Aquifer has been obtained by the means of numerical modeling. Steady-state two-dimensional models have been constructed making use of the combined discrete channel and continuum approach. This method facilitated testing of different simulations of hydraulic parameter distribution and the spatial geometry of the high conductivity karst channel network, by allowing for the implementation of one-dimensional elements into the two-dimensional element network.

The equivalent porous medium approach is inappropriate for modeling karstified medium, since it yields systematically lower spring discharges than those measured due to the lack of a drainage network.

The implementation of observed conduit system into the model is insufficient for retrieving measured spring discharges. Simultaneous simulation of mean water levels and average spring discharges requires the extension of the observed conduit system to the whole model domain where effective infiltration takes place. Each karstic spring ought to have a conduit network discharging to it; otherwise the simulation of spring discharges fails even under steady-state conditions.

Flow simulations suggest the existence of karst systems extending up to the catchment boundaries, that have hydraulic conductivities roughly proportional to measured average spring discharges.

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