

## **Hydrogeological exploration with geomathematical tools in karstic and fissured non-karstic aquifers**

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**Abstract** A group of geomathematical tools has been successfully tested in different fractured media in order to: (a) reduce the costs of hydrogeological exploration after the identification of prospective areas for a given water quality and quantity demand; (b) increase the effectiveness of water well drilling in low permeability rocks; (c) optimize the groundwater monitoring network in terms of the minimum number of stations and minimum frequency of measurements allowing equal or greater information; and (d) simulate the development of cave conduits to locate water supply sources or to identify the main flow paths for groundwaters in karstic terrains. Two case studies, one in a karstic aquifer and the other in fissured non-karstic low permeability rocks are briefly described to illustrate applications.

### **Prospección hidrogeológica en acuíferos cársticos y fisurados no cársticos aplicando técnicas geomatemáticas**

**Resumen** Un grupo de técnicas geomatemáticas han sido aplicadas exitosamente en diferentes medios fracturados con el objetivo de: (a) reducir los costos de la prospección hidrogeológica mediante la identificación de las áreas más perspectivas para determinadas demandas de calidad y cantidad; (b) incrementar la efectividad de la perforación de pozos de agua en rocas de baja permeabilidad; (c) optimizar la red de monitoreo de las aguas subterráneas en términos del número mínimo de estaciones y la menor frecuencia de observaciones que permitan la misma o mayor informatividad; y (d) simular el desarrollo de los conductos cársticos (cavernas) para localizar fuentes de abastecimiento de agua o identificar las líneas principales de flujo en terrenos cársticos. Dos casos de estudio, uno en un acuífero cárstico y otro en rocas fisuradas no cársticas de baja permeabilidad se describen brevemente para ilustrar las aplicaciones.

## **INTRODUCTION**

Hydrogeological exploration is an expensive activity in which the probability of success should be carefully balanced. Groundwater research to satisfy the increasing demand of population, industry, agriculture and recreation is the first stage of any programme for social and economic development. The groundwater sources identified after exploration and evaluation, as well as the aquifer and the hydrogeological system to which they belong are thereafter systematically monitored in order to prevent their exhaustion or contamination.

Therefore, exploration and monitoring are strongly linked. Their cost should warrant the maximum efficiency of the information derived from those works. The priority is always to improve the cost-benefit ratio in the research and management of groundwater resources.

Annual payments for research, water well drilling and monitoring are increasing while the demand is not always satisfied. Developing countries with limited or no access to modern technologies suffer the consequences of this unbalanced situation. Figures derived from international specialized agencies indicate millions of dollars of unsatisfied water demand.

The cost-benefit relation is still displaced to the left. The situation has to be reverted in the near future by means, among others, of the optimization of exploration and monitoring techniques. In that sense, the authors have introduced a set of geomathematical tools validated and improved systematically since 1983 leading to:

- optimization of the groundwater monitoring network of Cuba in terms of accounting for the minimum number of stations and the lowest frequency of measurements and observations allowing the same or greater information (Barros *et al.*, 1996; Molerio, 1983, 1992a; Molerio *et al.*, 1996a; Rocamora *et al.*, 1996);
- reduction of the costs of hydrogeological exploration by means of identification of the most favourable areas for a certain demand of groundwater quantity and quality (Guerra & Menéndez, 1996; Jiménez *et al.*, 1992; Núñez *et al.*, 1992; Molerio, 1992a,b; Núñez *et al.*, 1995; Molerio *et al.*, 1996);
- increasing the effectiveness of water well drilling for agricultural and husbandry water supplies in low permeability rocks where, historically, the risk of ineffective drilling and unsatisfied demand is as high as 60% of drilling works (Molerio, 1984a,b,c, 1985a,c, 1986; Núñez *et al.*, 1995; Molerio *et al.*, 1996a,b; Rocamora *et al.*, 1996); and
- mathematical simulation of the spatial development of cave networks to allow the location of water supply sources in zones of difficult access and high hydrogeological complexity, as in the case of the karstic mountains of Cuba (March & Molerio, 1987; Molerio *et al.*, 1984; Molerio, 1985b, 1986, 1989a,b, 1992b, 1995).

## TECHNIQUES APPLIED

To meet the above mentioned objectives the main author and his colleagues have introduced and combined, in the national hydrogeological practice, a set of mathematical processing techniques for existing raw data, thereby allowing a substantial reduction in the cost of acquiring new information. Those techniques: (a) are invariant with respect to time and space scales; (b) allow an increase of information without a necessary increase in the number, kind and frequency of observations or measurements; (c) reduce researcher's subjectivity while numerical methods of information filtering and classification are used; (d) allow an adequate discrimination of variables and objects to be investigated, incorporating a

measurement of information and, therefore, of certainty; and (e) favour discovery of the regularities of the processes, contributing to the establishment of the driven laws and mechanisms.

The main techniques applied are: (a) digital and cartographic processing and interpretation of aerospatial imagery and topographical maps; (b) statistical univariate and multivariate analysis and pattern reconnaissance; (c) theoretical tools from the automatic command of feedback open systems under random inputs; (d) non-equilibrium (irreversible) thermodynamics; (e) techniques from information theory, combinatory non-formalized (Boolean) logic, error theory and uncertainty evaluation and from polyvalent logic; (f) automatic mapping techniques, reducing the spatial uncertainty in inter-extrapolation (kriging, co-kriging and fuzzy sets), and (g) fractal geometry.

Until now these tools have been successfully applied by the authors in the solution of a large number of case studies comprising groundwater exploration, artificial tracer experiments, location of contamination sources, optimization of the Groundwater Monitoring Network of Cuba, optimization of the Groundwater Isotopic Monitoring Network of the country, orientation and design of water well drilling in low permeability rocks and calibration of groundwater mathematical models.

## CASE STUDIES

### **Groundwater exploration in a karstic coastal aquifer: water supply to Cárdenas City, Matanzas, Cuba**

**Identification of the problem** The intention is to identify the feasibility of an increase in  $250 \text{ l s}^{-1}$ , which is the present supply to the city of Cárdenas (Fig. 1). One possibility is to determine whether the present water supply system (water cave) could increase its yield. Another is to identify if other near sources (caves) could provide the yield and quality of water required. The third possibility is the assessment of a more extensive territory that is close to the city, but preventing sea water intrusion or source exhaustion.

**Discussion of results** Processing of hydrogeological raw data, including a radar image of the territory and monochromatic aerial photography allowed identification of the main hydrogeological features of the territory and, particularly, of the most favourable tectonic structures. Therefore the following facts were defined:

- (a) Most of the aquifer fractures that could deliver yields equal to or more than  $50 \text{ l s}^{-1}$ , were oriented  $90\text{--}270^\circ$ ,  $115(295)\text{--}135(315)^\circ$  and  $5(185)\text{--}10(190)$ , while the latter reduce the potential yield to  $30 \text{ l s}^{-1}$ .
- (b) The width of the most prominent fractured zone ranges between 150 and 200 m.
- (c) The optimum distance to the coastal shoreline that could minimize the effects of increasing mineralization: estimating the shortest at 3 km and the longest at 7–8 km.

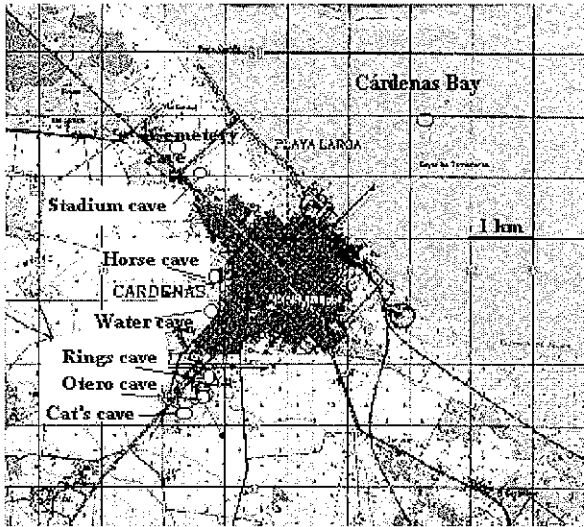


Fig. 1 General location map of the studied area (Cárdenas city and its surroundings) showing the explored caves.

(d) The best topographic surface (i.e. erosion surface) for developing groundwater exploration, was between altitudes of 15 and 25 m a.s.l.

Figure 2 shows the radar image of the territory, at a scale of 1:500 000 and, within the figure, the results of the digital processing of the whole fracture system of part of the territory. Figure 3(a) shows a detail of the interaction of the fracture system at an approximate scale of 1:62 500 and, Fig. 3(b) shows the selected most favourable hydrogeological fractures.

The reduction of the exploration area is remarkable and approaches 50% with a certainty of 92%. Field validation was developed in three days with an effectiveness of 85 and 90%, respectively, for the forecast water resource and mineralization of the system.

### Reduction of ineffective water well drilling in low permeability rocks

**Identification of the problem** This is one of the most important tasks developed with the geomathematical tools described above. Groundwater exploration in low permeability rocks is a universal problem. Low permeability rocks occupy close to 20% of the emerged lands of the Earth (Fig. 4) and, in particular, the majority of the population of the Third World lives in these territories. As is well known among hydrogeologists, groundwater in low permeability rocks lies in fractures or in the meteorization crust while the main limitations for successful exploration and development of groundwater resources are as follows: (a) not all the fractures of the same tectonic episode have the same potential yield; (b) fractures of the same or different tectonic generation, or with similar geological or geomorphological evolution, do not show comparable yields; and (c) wells and galleries distributed more or less closely do not necessarily intersect the same number of aquifer fractures.

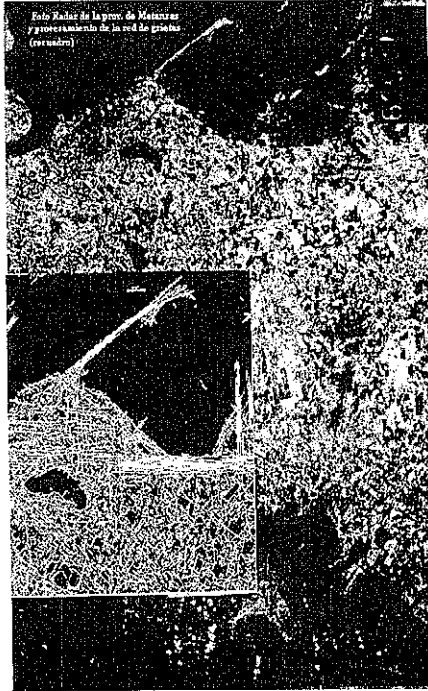
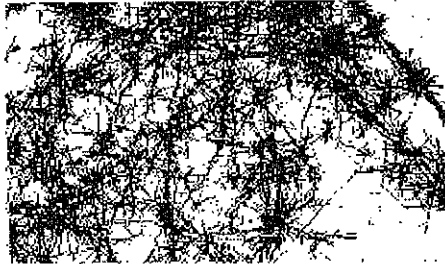
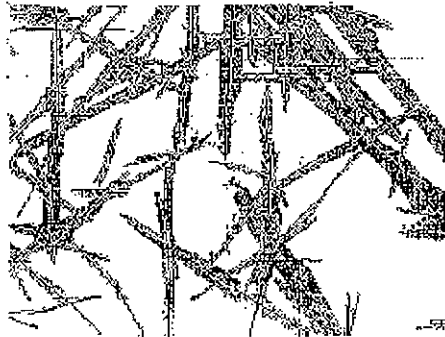


Fig. 2 Radar image and fractal digital processing of the Varadero-Cárdenas area.



(a)



(b)

Fig. 3 (a) Details of the fracture system, digitally processed, and (b) map of the potential groundwater zones in Varadero-Cárdenas.

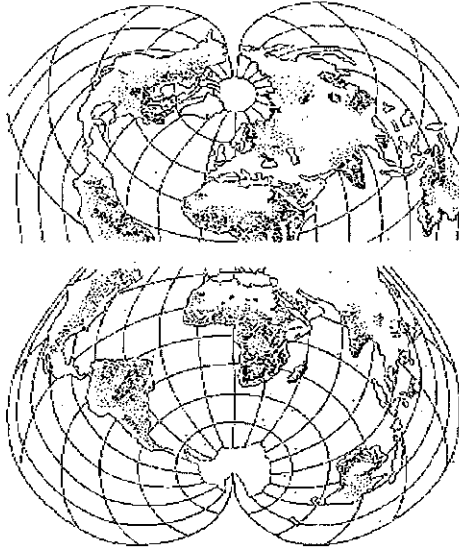


Fig. 4 Distribution of Precambrian shield areas in the Northern and Southern Hemispheres where most hard low permeability rocks are found (after Dijon).

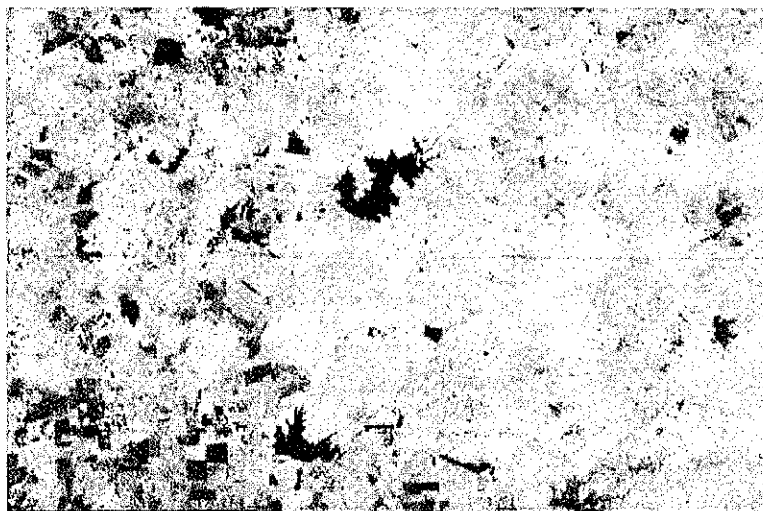
These facts have limited worldwide the effectiveness of well drilling for water supply. On a world scale, the effectiveness index—defined as the rate between drilled/effective wells yielding more than zero  $l\ s^{-1}$ —is around 45%.

In Cuba, low permeability rock outcrops through almost 30% of the country and is associated with zones of agricultural development of the Central Basin. The effectiveness index for the 1984–1991 period averaged 60%, but in certain places was as low as 40%. In terms of unsatisfied demand it represents not only a social or economic problem but also alternative supply needs that could not always be satisfied with surface water.

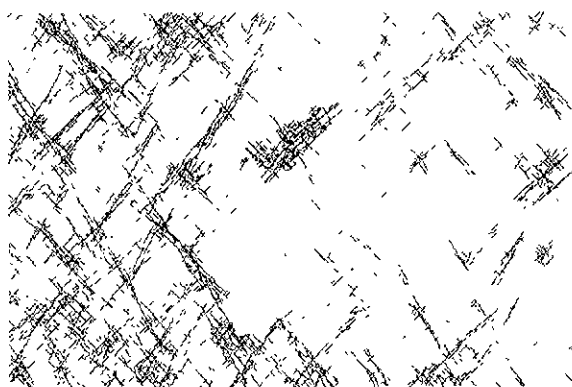
Geomathematical tools were applied to the central Camagüey province in order to define the regularities of fracture water yields (Fig. 5).

**Discussion of results** The methodology applied allowed the identification of:

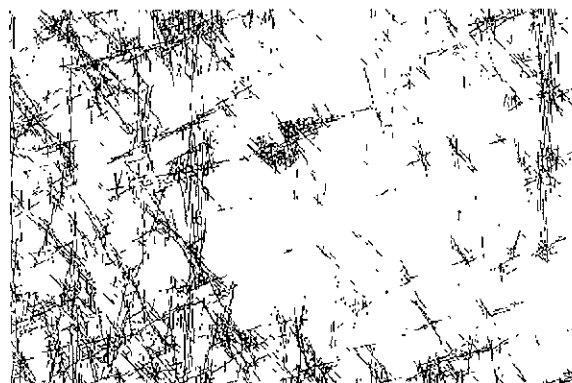
- (a) The factors of design and construction influencing the yield capacity of the water wells, particularly: total depth, depth of appearance of groundwaters, the distance to the prospected tectonic structures and the optimum drawdown for specific yields.
- (b) The geological and tectonic factors controlling the water resources of low-permeability rocks in these zones, in terms of identifying the genetic type and geometric parameters such as minimum and maximum length, width of the influence zone, distance to fracture axis and fracture orientation in terms of the expected yields (Figs 6–8).
- (c) The indexes of the physical properties most important for the characterization of the water resources of low-permeability rock and, as a second order result, the definition of very simple methodological principles for drillers to identify the optimum depth of the water well.



**Fig. 5** Selected area for groundwater exploration in central Camagüey.



**Fig. 6** Tectonic alignments derived from digital processing.



**Fig. 7** Paleovalleys defined by digital processing.

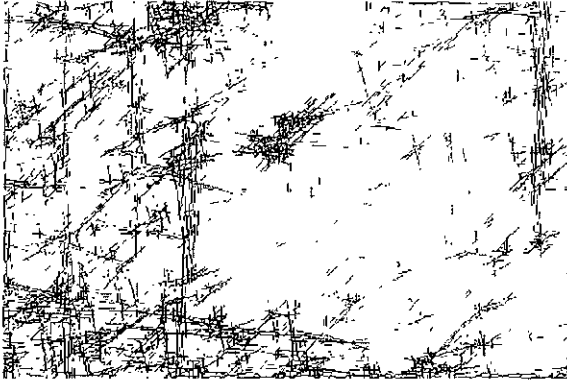


Fig. 8 Erosive and tectonic cliffs and escarpments defined by digital processing.

The results of the methodology were systematically validated in the field by drilling, geophysical exploration and mathematical modelling of the inverse problem leading to an increase in the effectiveness index up to 85%.

## CONCLUSIONS

The application of these group of advanced mathematical and physical techniques needs improvement in the near future. Its validity has been successfully demonstrated in a wide range of applications as was previously referred to.

Some limitations are now being reduced. Among the most important is the inapplicability of formal mathematical logic to the description and identification of rock types. This problem remains unsolved in the international literature and in our methodology the solution is approached by Boolean approximations but more precise solutions should be gathered in the near future accounting for the eventual importance of the lithology itself.

A similar problem is faced with some principles of Irreversible Thermodynamics, particularly, those concerning the application of Onsager's Reciprocal Relations to macrosystems, the onset of the triggering mechanisms of saturated flow in karstic zones and the relations among forces and hydrodynamic fluxes.

**Acknowledgements** Invaluable support has been received from several persons and institutions for the development of these studies. The authors are specially grateful to D. M. Arellano, Director of CENHICA-INRH and to J. M. Morejón, Director of the National Enterprise of Well Drilling and Construction of Cuba (ENPC) for their sustained moral and financial support. Thanks are also extended to our speleological colleagues who validated our results by means of direct exploration techniques, especially to: Vladimir Otero, Lázaro Fiallo, Roberto Gutiérrez, Gabriel García, Hermógenes Rodríguez, Carlos Aldana, Alfredo García, Abel Pérez, Enrique Dalmau and Roberto Sánchez. To their colleagues from CENHICA and from ENPC: Joaquín

Gutiérrez, Osvaldo Barros, Yamilé Bustamante, José F. Santiago, Juan C. Batista, Ambar Menéndez, Ibrahim Plaza, Ernesto Varela and Jorge L. Gelabert. Special thanks are expressed to Pedro J. Astraín and Carlos M. Guilarte. The senior author wishes to express his acknowledgement to his wife, Ana, for her continuous support.

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