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Hydrogeological Prospecting With Geomathematical Tools In Karstic And Fissured Non-Karstic Aquifers

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A group of geomathematical tools have been succesfully tested in different fractured media in order to: a/ **Reduce** the costs of hydrogeological prospecting, after the identification of perspective areas for a given water quality and quantity demand; b/ **Increase** the effectiveness of water well drilling in low permeability rocks; c/ **Optimise** the groundwater monitoring network in terms of the minimun number of stations and minimun frequency of measurements allowing equal or greater informativity and d/ **Simulate** the development of cave conduits to locate water supply sources or identify the main flow paths for groundwaters in karstic terrains.

According to the kind of problem to be solved, tools applied includes techniques from Multivaried Digital Image Processing and Authomatic Mapping; Multivaried Statistical Analysis, particularly dealing with Factor Analysis, Clustering and Pattern Recognition; some principles from the Theory of Authomatic Command of Feed-Back Open Systems under Random Inputs; Non-Formalized (Boolean) Combinatory and Polivalent Logics; Non-Equilibrium Thermodynamics and Fractal Mathematics.

After a general development of the theoretical principles, two case studies are presented.

A **first** case study deals with a ***karstic coastal region*** in Western Cuba, where the main problem was to identify an adequate area for water supply avoiding sea water intrusion and contamination from oil fields. Lowest acceptable design yield was 50 lps. Data processing allowed to identify: a/ the length, orientation and type of the water-bearing fractures; b/ the width of the water-bearing fractured zone along the main aquifer fissures; c/ the optimum distance to the coast of the proposed water wells and d/ the topographical (geomorphological) surface were the karstic aquifer lies, satisfying the design yield. Thus the prospecting area was reduced from 125 km^2 to only 35 km^2 with a sustainable reduction in time and costs.

The **second** case study deals with a ***non-karstic fissured*** territory, built mainly by intrusive low-permeability rocks of Eastern Cuba. The main problem was to identify the tectonic structures acting as aquifers in order to reduce **ineffective water well drilling**. Data processing allowed to identify those factors controlling aquosity concerning to: a/ the geological framework; b/ the water well design; c/ the basic hydrogeological parameters that has to be measured during drilling and d/ the expected yields of the proposed wells for a given probability. After applying these techniques, effectivity of water-well drilling has been increased from an average of 40% to 85%.

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INTRODUCTION

Hydrogeological prospecting 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 prospecting and evaluation, as well as the aquifer and the hydrogeological system ehwere they belong are thereafter sistematically monitored in order to prevent their exhaustion or contamination.

Therefore, prospecting and monitoring are strongly linked. Their cost should warranty the maximum efficiency of the information derived from those works. Priority is almost improve the cost-benefit ratio in research and management of groundwater resources.

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

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

* **Optimization** of the groundwater monitoring network of Cuba in terms of account for the minimun number of stations and the lowest frequency of measurements and observations allowing the same or higher informativity [1,6,20,27,28].

* **Reduction** of the costs of hydrogeological prospecting, my means of the identification of the most perspective or favourable areas for a certain demand of groundwater quantity and quality [3,4,19,21,22,25,26].

* **Increasing** the effectivity of water-well drilling for agricultural and husbandry supplies in low permeability rocks where, historically, the risk of uneffective drilling and unsatisfied demand is as high as 60% of drilling works [7,8,10,11,13,14,25-28].

* **Mathematical simulation** of the spatial developent of caves networks to allow the location of water supply sources in zones of difficult access and high hydrogeological complexity, as is the case of the karstic mountains of Cuba [5,9,12,15-17,23,24].

TECHNIQUES APPLIED

To meet the above mentioned objectives the main author and his colleagues have introduced and conjugated, in the national hydrogeological practice, a set of mathematical processing techniques of the existent raw data allowing a substantial reduction of the costs of acquisition of new information. Those techniques meet the following properties:

1. They are invariant with respect to time and space scales.

2. Allow an increase of informativity without a necessary increase in the number, kind and frequency of observations or measurements.

3. The reduce researcher subjetivity while numerical methods of information filtering and classification are used.

4. Allow an adequate discrimination of variables and objects to be investigated, incorporating a measurement of information and, therefore, of certainty.

5. They favour the discovery of the regularities of the processess, contributing to the establishment of the driven laws and mechanisms.

The main techniques applied are the following:

1. Digital and Cartographical Processing and Interpretaion of Aerospatial Imagery and Topographical Maps.

2. Statistical Uni- and Multivaried Analysis and Pattern Reonnaissance.

3. Theoretical tools from the Authomatic Command of Feed-Back Open Systems under Random Inputs.

4. Non-equilibrium (Irreversible) Thermodynamics

5. Techniques from the Information Theory, Combinatory Non-Formalized (Boolean) Logics, Error Theory and Uncertainty Evaluation and from the Polivalent Logics.

6. Authomatic Mapping techniques reducing the spatial uncertainty in inter-extrapolation (kriging, co-kriging y fuzzy sets).

7. Fractal Geometry.

Until now these tools have been succesfully applied by the authors in the solution of a high number of case studies comprising groundwater prospecting, artificial tracers 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.

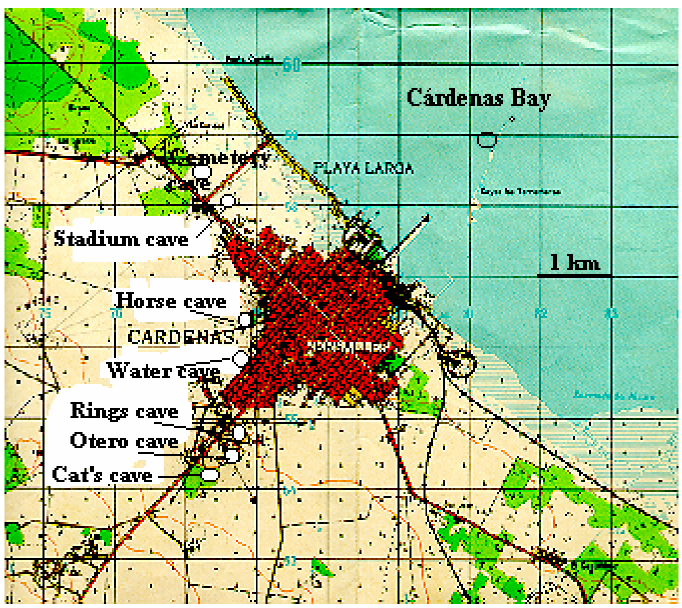
STUDY CASES

1. Groundwater prospecting in a karstic coastal aquifer: Water Supply to the Cárdenas City, Matanzas, Cuba..

Identification of the problem:

The intention is to identify the factibility of increase in 250 lps, the present supply to the city of Cárdenas (fig. 1). One of the possibilities is to define if the present water supply system (Water cave) has any feasibility to increase its yield. Other is to identify if other near sources (caves) could allow the yield and quality of the water required. the third possibility is the assessment of a more extensive territory but close to the city preventing sea water intrusion or source exhaustion.

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



Discussion of Results

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

- The **most aquifer fractures** that could deliver yields equal or over 50 lps, resulting those oriented **90-270°, 115(295)-135(315)° y 5(185)-10(190)°,** while the last ones reduces the potential down to 30 lps.

- The **width of the most perspective fractured zone**, ranging between **150-200 m.**

- The **optimum distance to the coastal shoreline** that could minimize the effects of increasing mineralization, estimating the **shortest in 3 km and the longest around 7-8 km**.

- The **better topographic surface (=erosion surface)** for develop groundwater prospecting, was enclosed between altitudes of **15 to 25 m a.s.l.**

Figure 2 shows the radar image of the territory, at 1:500 000 scale and, enclosed, the results of the digital processing of the whole fracture system of part of the territory. The upper part of fig. 3 shows a detail of the interaction of the fracture system at an approximate scale 1:62 500 and, in the lower part the selected most favourable hydrogeological fractures.

The **reduction of the prospecting area is remarkable** and approaches **50%** with a certainty of **92%.** Field validation was developed in three days with and effectiveness of **85%** and **90%**, respectively, for the forecasted aquosity and mineralization of the system.

2. Reduction of Innefective 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 prospecting in low permeability rocks (RBP) is an universal problem. RBP occupies close to the 20% (fig. 4) of the emerged lands of the Earth and, in particular, the main part of the population from the Third World lives in these territories. As is well known by the hydrogeologists, grondwaters in low permeability rocks lies in fractures or in the meterorization crust while the main limitations for a succesful prospecting and developing of groundwater resources are the following:

1. Not all the fractures of the same tectonic episode has the same potential yield.

2. Fractures of the same or different tectonic generation or with similar geological or geomorphological evolution do not show comparable yields.

3. Wells and galleries distributed more or less closely do not necessarily intersect the same number of aquifer fractures.

These facts has limited worldwide the effectivity of well drilling for water supply. At world scale, the **effectivity index**, defined as the rate between **drilled/effective wells yielding more than zero liters per second is around 45%.**

In Cuba, RBP outcrops through almost 30% of the country and are associated to zones of husbandry development of the Central Basin. The **effectivity index for the 1984-1991 period averaged 60% but in certain places is as low as 40%. In terms of unsatisfied demand it represents not only a social or economic problem while it needs alternative supplies that not always could be satisfied with surface water.**

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

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

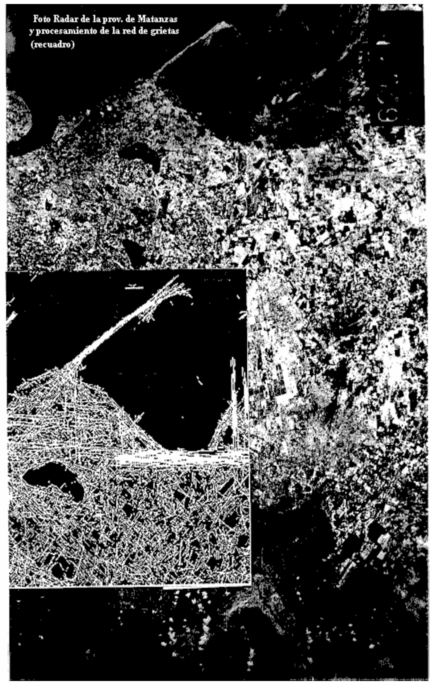


Fig. 3. Details of the fracture system (upper part) digitally processed and map of the potential groundwater zones in Varadero-Cárdenas

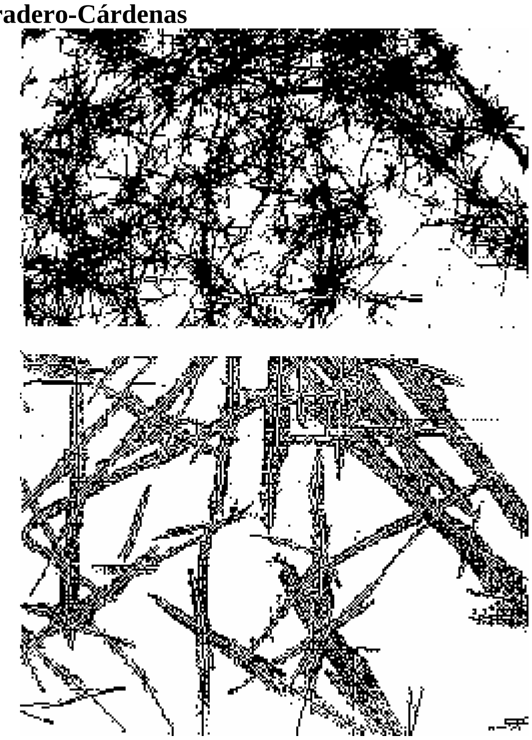


Fig. 4. Distribution of Precambrian shield areas in the Northern and Southern Hemispheres where most hard low permeability rocks are found (after Dijon)

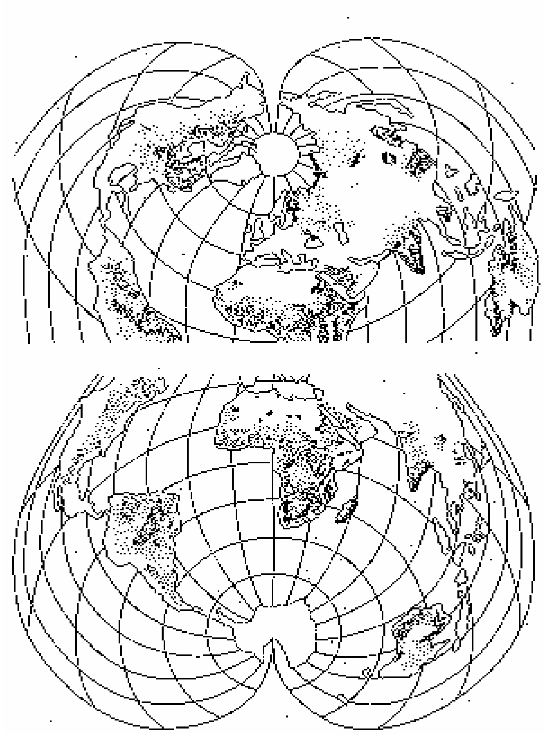


Fig. 5. Selected area for groundwater prospecting in central Camagüey

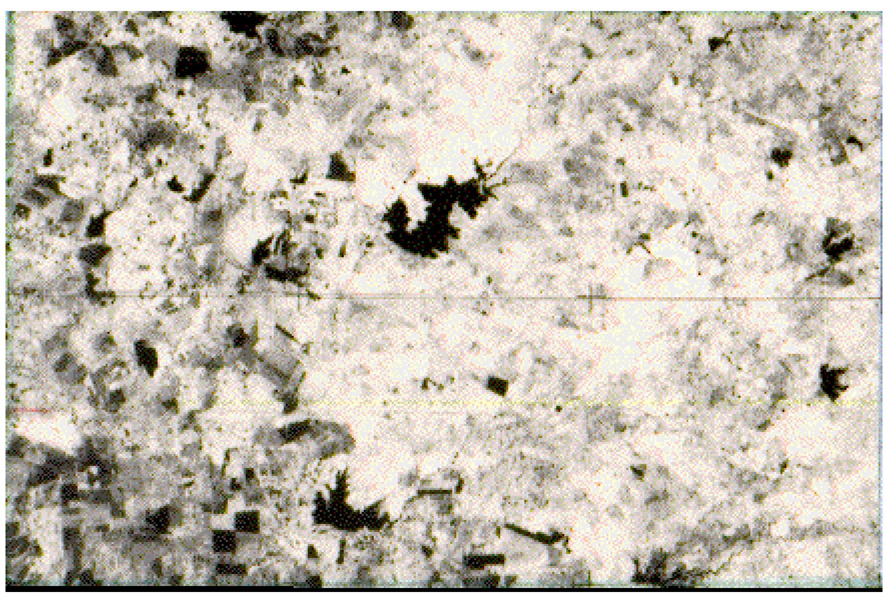


Fig. 6 Tectonic alignments derived from digital processing

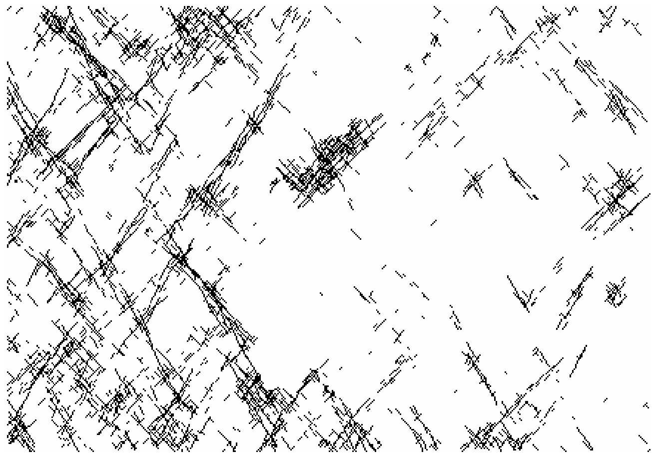


Fig. 7. Paleovalleys defined by digital processing

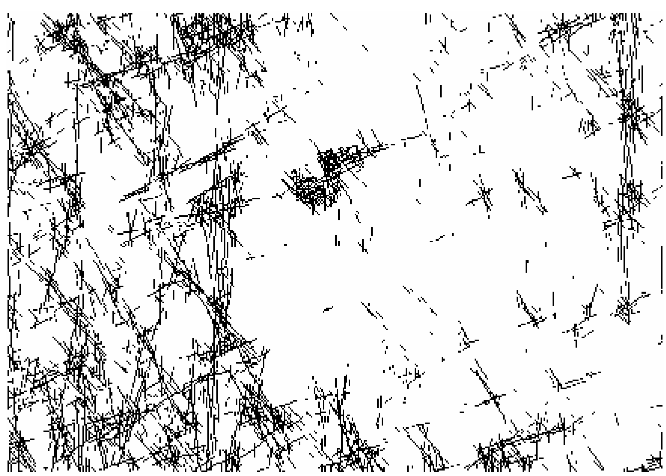
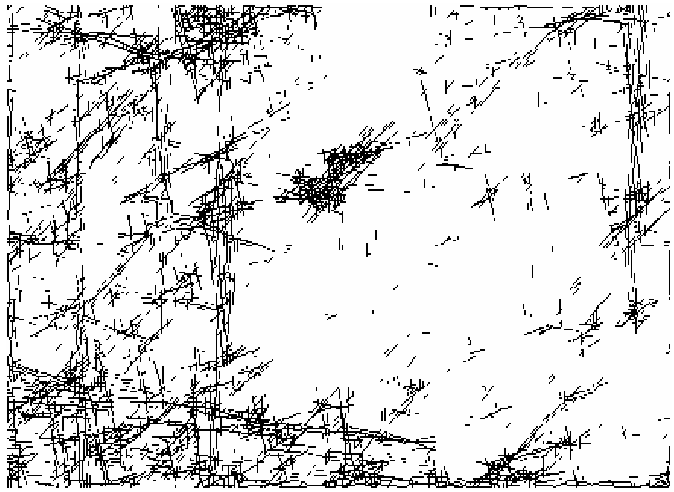


Fig. 8. Erosive and tectonic cliffs and scarpments defined by digital processing



Discussion of Results

The methodology applied allowed the identification of:

1. The **factors of design and construction** influencing in the more or less yield capacity of the water wells, particularly: *total depth, depth of appearance of groundwaters, the distance to the perspective tectonic structures and the optimum drawdown for specific yields.*

2. The **geological and tectonic factors** controlling the acuosity of RBP in these zones, in terms of identifying its genetic type and geometric parameters (figs. 6-8) like *minimum and maximum length, width of the influence zone, distance to fracture axis and fracture orientation in terms of the expected yields.*

3. The **indexes of the physical properties** most important for the characterization of RBP's acuosity and as a second order result the definition of a very simple methodological principles for drillers to identify the optimum depth of the water well.

Results of the methodology were sistematically validated in the field by drilling, geophysical prospecting and mathematical modelling of the inverse problem leading to **an increase in the effectivity index up to 85%.**

CONCLUSIONS

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

Some limitations are now trying to be reduced. The most important are the following:

*** The innaplicability of the formal mathematical logics to the description and identification of rocks types. This problem remains unsolved in the international literature and in our methodology the solution is approached by Boolean aproximations 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 the Irreversible Thermodynamics, particularly, those concerning the application of the 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.**

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