

Understanding and management of water resources in karstic environments: report on a panel discussion

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Abstract Karstic aquifers have special properties which complicate assessment of water resources in karst environments. For karst aquifers in particular, it is very important to incorporate understanding gained from monitoring and research programmes into management strategies. This paper gives a summary of the panel discussion on Karst and the Environment which took place on 19 November 1996 at the International Symposium on Hydrology in the Humid Tropic Environment, in Kingston, Jamaica. Speakers brought their expertise from Jamaica, USA, Cuba, England and Mexico to bear on both quantity and quality issues of water resources in karst environments. For both understanding and modelling the resources, karst solubilities and variable transmissivities were the most important features. For management strategies, continuing incorporation of new understanding about the aquifers offered the most potential for maintaining quantity and quality of the karst water resources.

Conocimiento y manejo de los recursos de agua en ambientes kársticos: informe de una discusión de panel

Resumen Los acuíferos kársticos tienen propiedades particulares que complican la evaluación de recursos de agua en ambientes kársticos. Para los acuíferos kársticos en particular, es muy importante el incorporar los conocimientos adquiridos durante programas de monitoreo e investigación a estrategias de manejo de los recursos. Este informe es un resumen de la discusión de panel en Karso y el Ambiente que tuvo lugar el 19 de noviembre del 1996 durante el Simposio Internacional de Hidrología en Ambientes Húmedos Tropicales en Kingston, Jamaica. Los participantes del panel compartieron sus conocimientos y experiencias en Jamaica, los Estados Unidos de América, Cuba, Inglaterra y México con relación a problemas cualitativos y cuantitativos en ambientes kársticos. Los participantes estuvieron de acuerdo que para desarrollar modelos de los recursos, la solubilidad del karso y la variabilidad en transmisividad son los factores más importantes. Los participantes también concluyeron que, para mantener tanto la cantidad como la calidad de los recursos de agua en ambientes kársticos, se debe continuar incorporando nuevos conocimientos en las estrategias de manejo.

INTRODUCTION

This symposium sought to bring together expertise in karst environments to highlight issues facing scientists and managers. A handful of themes surfaced throughout the symposium and were important for both understanding and managing the resource. Karstic environments are of particular concern in the management of water resources

due to the moderate solubility of limestone and dolomite geologies and the high percentage of population residing in karstic regions. Water quality in karstic regions is of particular concern because of the potentially low residence time in the subsurface and the potential of contaminated waters to alter karstic dissolution rates (Stednick). The high variability of sedimentologic and diagenetic conditions of karstic aquifers generally leads to a wide range of surface and subsurface hydro-physical conditions. Movement of waters in karstic regions can be classified as intergranular (micropore) flow and conduit (macropore) flow (Stednick). These dual transmissivities, associated with matrix and pipe flow, control many aspects of understanding, simulating, and managing the resource.

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SPECIAL FEATURES OF KARST SYSTEMS

Similar features unique to karst systems were found in disparate areas ranging from Jamaica to the USA and Spain.

Karstic systems in Jamaica exhibit high infiltration rates and up to 40% of average annual precipitation ultimately resides in karstic groundwater systems. Using closed basins, previous studies have indicated that conduit flow is primarily responsible for the movement of solutes through karstic systems in Jamaica. Conduit flow rates have been measured, using tracer studies, to be approximately 1.5–3 km day⁻¹ in karstic regions of Jamaica. Conversely, diffuse flow is responsible for the storage capacity of karstic aquifers in this region, but is generally inaccessible due to low permeability. High flow rate results in minimal attenuation of contaminants that may be introduced into conduit flow. Contaminants that find their way to diffuse flow regions remain there for long periods (White).

Limestone aquifers in South Florida, USA, are used for public drinking water supply, irrigation water supply and for disposal of municipal wastewater treatment plant effluent. The geostatigraphy in South Florida consists of up to 6 m of surficial soils (typically organic) and marl deposits underlain by the Biscayne Aquifer and the Floridan Aquifer both of which are confined karstic limestones and interbedded

clays. The Biscayne Aquifer provides a significant drinking water supply for South Florida (786 million gallons per day (mgd) in 1985). The Biscayne Aquifer is bounded by low permeability clay deposits and is not considered to be at significant risk from surface contamination. The Floridan Aquifer is a thick sequence of limestones containing a zone of fractured dolomite within the lower portion of the strata commonly referred to as the boulder zone. The boulder zone is a high permeability karstic feature within the Floridan Aquifer that is thought to be hydrologically connected to the Atlantic Ocean, resulting in typically saline waters found in this strata. The boulder zone is overlain by up to 300 m of low permeability limestone that allows for the confinement of municipal wastes (secondary effluent) from the cities of Miami and Fort Lauderdale which are injected to the Boulder Zone at the rate of approximately 300 mgd (Wedderburn).

The island of Cuba is approximately 114 000 km² of which approximately 65% is karstic. Up to 90% of the groundwater reserves lie within karstic regions and 70% of the total water supply is derived from karstic aquifers (Molerio-Leon).

Karstic features that influence the mobility of contaminants within the saturated zone and dictate the frequency of monitoring include (Chilton):

- (a) high permeability, low gradient systems which are easily influenced by groundwater withdrawals including directional changes; and
- (b) little attenuation of contaminants observed in many karstic systems related to high transmissivities.

Tracing experiments are frequently difficult because of low gradient diffusion of the tracer or existence of multiple outflows (Chilton).

Modelling of the saturated zone in karstic regions must include a range of effective porosities, which will result in dampened contaminant transport response. An example from Barbados, was the response of down-gradient wells to pesticide application (Chilton). With higher effective porosity, contaminant peaks were delayed and attenuated (Fig. 1).

These high transmissivities and the potential for rapid contaminant transport in karstic systems require that groundwater monitoring programmes take into account the behaviour indicated in Fig. 1. Differences in seasonal groundwater flow regime can also result in differences in contaminant transport that must be accounted for in the development of a monitoring programme. For example, during high flow periods flow consists of conduit flow that is very responsive to precipitation events and discharges to sinkholes. During low flow periods however, matrix flow may dominate resulting in a very different response and contaminant transport characteristics (Chilton). A solution to this concern includes development of a wellhead protection zone based on a conservative approach.

MODELLING

Modelling of karstic systems is therefore somewhat difficult due to highly variable conductivities and preferential flow. In addition, commonly used rainfall-runoff models are difficult to apply to karstic regions because of the presence of nonuniform conduit flow to the subsurface. For these reasons tracer studies are generally required to determine flow paths and flow rates (Stednick).

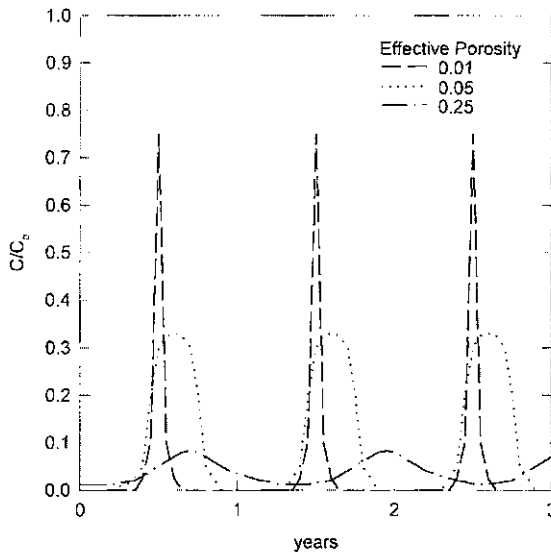


Fig. 1 Delayed and attenuated contaminant peaks with lower effective porosity.

A time series with both stochastic and deterministic components was used to model karst groundwater movement from the Ixtina karst formation in northern Spain. The formation of about 6 km² area is intensely karstified with high infiltration rates and rapid transfer of water within the formation. The system is an isolated unit due to its high relief and an almost continuous border of surrounding mountains. The formation has defined input and outlet locations, but due to heterogeneity of the material and complexity of internal flow paths the overall response is nonlinear. Instead of attempting to recreate detailed flow paths, the Ixtina formation was treated as a black box (Garfias).

Different statistical methods were applied to model the hydrographs. Modelling of hydrographs was based on flow from the Aldabide outlet, the principal outlet from Ixtina, and was broken into deterministic and stochastic components. This was a relatively simple model with one deterministic and one stochastic component. The deterministic component was represented with precipitation inputs and discharge outputs. Time series of discharge were used to determine the stochastic component of the model. Linear regression analysis provided the initial model which was then calibrated with discharge measurements. Model validation was performed using precipitation inputs to model outlet discharge. Use of days 2, 3 and 4, from the time series, improved model predictive ability. Results obtained with this model were highly satisfactory and supported the model selection. In the future this model may help with decision making in regard to subterranean water resources of the Ixtina karst aquifer (Garfias).

REGULATION AND MANAGEMENT

Based on current understanding of hydrologic processes in karstic environments, the management approach recommended is to minimize discharges to karstic aquifers

and improve permit systems for water abstractions and effluent releases. This approach is illustrated in examples from Jamaica, Florida, and Cuba.

The geological map of Jamaica indicates the major regions of interest to discussion of karstic hydrology in Jamaica. Limestone aquifer overlies a volcanic base lithology on the majority of the island, excluding the Blue Mountains. Along the northern coast a limestone aquiclude serves as a barrier to infiltration. Along the southern coast are areas of alluvial aquifers (White).

There are currently considered to be four major types of pollution risk to the karstic aquifers in Jamaica (White):

- (a) saline intrusion—related to pumping of irrigation wells in the southern region of Jamaica;
- (b) discharge of wastewaters associated with processing of sugar cane—generally discharged directly into sinkholes;
- (c) discharges of mining wastes associated with bauxite mining—generally high in Na/NaCl; and
- (d) high nitrate surface waters (of unknown origin) discharged to reef areas on the northern coast—potentially causing the eutrophication of offshore ecosystems.

Recent regulatory changes have led to a watershed approach to water resources regulation in Jamaica. Most new development will require a discharge permit (beginning January 1997) and the permitting programme is designed to include industrial dischargers as well as municipal discharges. The Natural Resource Conservation Authority will administer the programme which will also include air quality regulation. An inventory of groundwater pollution in Jamaica was presented and a summary of those data is given here (Table 1).

Table 1 Summary data on pollution of groundwater resources, Jamaica.

	Aquifer area polluted (km ²)	Polluted production abandoned (Mm ³ year ⁻¹)	Polluted existing production (Mm ³ year ⁻¹)	Unpolluted production at risk (Mm ³ year ⁻¹)	Groundwater reserve polluted (or at risk) (Mm ³ year ⁻¹)
Saline upconing	> 288	87.0	183.5	nil	nil
Industrial effluents	> 58	3.5	29.1	182.4	427
Domestic effluents	85	1.7	9.9	nil	nil
Total	> 431	92.2	222.5	182.4	427

Potential solutions to existing and future contamination concerns in Jamaica have been developed including (White):

- (a) use of evapotranspiration beds to minimize industrial and municipal discharges to karstic systems;
- (b) waste minimization from bauxite mining including recycling and closed system disposal;
- (c) effluent reuse from sugar processing; and
- (d) development of a solid waste management plan for Jamaica.

Given the reliance of the region on groundwater systems, South Florida has taken several steps to protect karstic aquifers (Wedderburn). The Water Resources Act of 1972 established a permitting programme and monitoring associated with the issuance of permits. Legislation in the 1980s included the Underground Injection

Rule, wetlands protection legislation, and groundwater monitoring requirements. The 1990s have seen a new mapping programme to determine contamination potential of the subsurface waters and a surface water quality monitoring requirement to minimize potential for contamination of subsurface waters.

The management of karstic groundwater systems in Cuba began in 1963 with the promulgation of the Inland Waters Act and establishment of the Ministry of Hydraulic Resources. In that same year a groundwater monitoring system was established including (Molerio-Leon):

- 2597 wells for monthly water level monitoring;
- 527 seawater intrusion wells for biannual monitoring;
- 2167 water quality daily control monitoring locations;
- 29 rain gauge stations including precipitation water quality monitoring;
- 10 rain gauge stations for isotopic analysis of precipitation;
- development of a database for data collected associated with the programme; and
- the Ministry of Environmental Protection, established in the 1970s.

A hydrogeological map of Cuba has been developed and should be available in 1997 along with a corresponding geographic information system (GIS) database. Groundwater models have been developed for real-time evaluation and decision support. Due to recent economic hardship in Cuba, the government has used monitoring data and simulation models to reduce total groundwater sampling locations and frequencies in order to optimize data collection (Molerio-Leon).

In addition to extraction rates that exceed recharge in some areas, karstic groundwater systems in Cuba have water quality problems including (Molerio-Leon):

- (a) saltwater intrusion;
- (b) cultural impacts in domestic areas;
- (c) fertilizers and agricultural chemicals;
- (d) industrial and hydrocarbon contamination; and
- (e) mining and radioactive wastes.

A decrease in nitrate contamination of karstic aquifers has been noted over the past seven years which is believed to be related to economic conditions in Cuba. Decreases in groundwater pumping combined with decreased fertilizer application rates are believed to be the main factors influencing the decrease in nitrates observed. Other factors that may be influencing the decreases include: increased flushing due to several successive wet years combined with low retention times associated with the karstic aquifers in the region and nitrification/denitrification processes. Decreases from 60 to 15 mg l⁻¹ NO₃ have been noted in some aquifers, and decreases from 160 to 32 mg l⁻¹ NO₃ in others, have been noted in the period 1988–1996. The area south of Havana has reported NO₃ decreases from 55 to 5 mg l⁻¹ over the same period.

Programmes have been initiated to restore aquifers influenced by saltwater intrusion. A new fertilizer production facility is expected to be operational in 1997 and has been designed to operate within the existing regulatory framework (Molerio-Leon).

CONCLUSION

Understanding hydrologic processes in karstic environments is critical to the development of sound regulatory framework and management alternatives. Several

examples of research in karstic systems have led to regulatory approaches for water resource protection in karstic environments that are many times different from those taken in non-karstic environments. The information made available through research and modelling has led to a more effective management of these resources.