Isotopic evidence of the overexploitation of karst aquifers

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Abstract Tritium behaviour has been successfully used as evidence to forecast aquifer overexploitation before it becomes a management problem and creates a water use conflict. The most important evidence is the onset of serial but not consecutive recharge events, the variation in ^3H activity at the same measuring points during the year and, especially, the presence of groundwater with no ^3H activity, or at least none related with known or measured ^3H inputs.

Key words karst; overexploitation; tritium; aquifer; Cuba; tracer; isotopes; safe yield; recharge

INTRODUCTION

The most common, simple and intuitive definition of overexploitation of an aquifer is a continuous disequilibrium between the groundwater abstraction and groundwater replenishment. It is supposed that when more water than that entering the aquifer is extracted, the available resources become systematically exhausted or its quality deteriorates, but the concept is incomplete because it is known that overexploitation can occur, even when recharge is greater than abstraction, due to bad management practices. A more general agreement states that overexploitation of groundwater takes place when a limit in volume, yield or water quality is surpassed. Therefore beyond those limits, some side effects—usually ambiguously defined as *undesirable effects*—due to over-exploitation appear, e.g. systematic groundwater level decline that in turn causes the exhaustion of springs and the abandonment of water wells, loss of water quality and, in turn, contamination of the productive aquifer, and subsidence.

For water supply purposes, this limit is often called the “safe yield” or “groundwater resource”. Conventionally, overexploitation should take place when this boundary is exceeded, but experience show that sometimes water is abstracted beyond this limit and no undesirable side effects become apparent. Therefore the concept of overexploitation, which is important to know given the kind of problem managers are dealing with, falls into a category of ambiguous definitions: (a) the limit established by the “safe yield” and the safe yield itself; (b) the limit established by the management practices; and (c) the limit established by the water quality that is particularly required.

Therefore, a scarcity in water quantity and a loss of water quality commonly come together as a consequence of aquifer overexploitation. Because of the socio-economic impact caused by the high costs of aquifer remediation (increasing groundwater reserves and improving water quality) Young (1992) defined aquifer overexploitation as a failure to achieve maximum economic returns to the resource. Overexploitation can also allow a loss of groundwater quality when waters of undesired chemical composition are drained into a productive formation. Sea water intrusion is the most common but not the only source of water quality deterioration due to overexploitation. Acid mine drainage, oily waters or even untreated domestic waste waters could enter the aquifer when flow lines are altered by pumping. Another important side effect of aquifer overexploitation is subsidence.

But, as Adams & MacDonald (1995) have pointed out, “*certain aquifers are more susceptible to overexploitation than others—equally certain managing practices are conducive to over-exploitation*”. Karst aquifers, particularly those of the Humid Tropics, fall into this category because of the particular way in which groundwater flow is organized within them.

In a regional karst aquifer system, groundwaters converging from different local and sub-regional flow systems do not necessarily contribute continuously to groundwater resources (Fig. 1). This singularity means that different parts of the aquifer behave differently in time and space. In fact, according to the degree of karst development, its distribution within the aquifer, its relation to local erosion base levels and the way they modulate the recharge inputs, karst aquifers show very complex hydrodynamic responses. Under certain boundary conditions some of the local flow

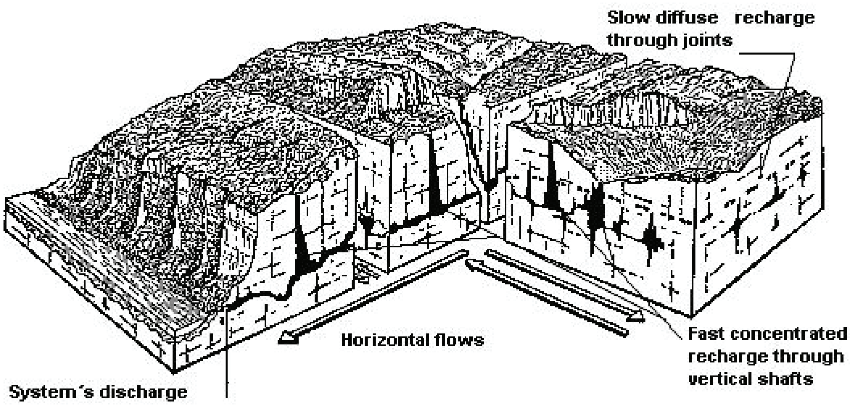

Fig. 1 Recharge patterns of a karst aquifer (modified after Mangin).

systems and even its associated epikarst could seasonally or inter-annually become saturated by water or be completely dry. This changing behaviour is not necessarily reflected in the yield of springs or in the water level decline. The generally big fluctuations recorded in groundwater levels —sometimes associated with the effect of hurricanes or heavy rains—of large, regional karst flow systems masks the actual behaviour of the aquifer. Some cave levels or local flow systems become hydrologically active for several months or years leading to an erroneous assessment of groundwater reserves and, therefore, to the establishment of an abstraction plan based on an erroneous safe yield estimation that eventually could lead to overexploitation.

On the other hand, groundwater abstraction can isolate local flow systems interrupting their contribution to major systems and reducing the reserve therein. Sometimes an active epikarst can be completely drained producing a local and sometimes abrupt lack of water supply. River runoff can be shortened and even interrupted if fed by karst springs (concentrated or diffuse) that become dry when their own local flow systems are drained. The inverse is also true and some episodic rivers flow only when their local flow systems become hydrological active.

It is very common that evidence of overexploitation appears suddenly. That is why Adams & McDonald (1995) remarked that "*overexploitation is normally diagnosed a posteriori because hydrogeological assessment can often only be achieved when an aquifer has been stressed*". But, in fact, different types of evidence that appear during the overexploitation process are commonly not well interpreted because they are not integrated with groundwater monitoring and used for adequate prevention. Induced local pollution, isolated episodes of local subsidence, fluctuations in the yield of springs, or in the particular case of karst aquifers, desiccation of water filled caves, changes in the hydrological behaviour of the epikarst, variations in the drainage stratification (or in the hydrology of cave levels) among others, appear during the whole historic process of over-exploitation and can be used as evidence of it.

It would be highly profitable if overexploitation could be detected before its undesirable side effects (groundwater level decline, recharge of poor quality waters and subsidence) become apparent. Considering that time is already involved in the concept of safe yield and that side effects become apparent according to the degree of mixing of waters from different sources, which is also a time dependent variable, a good approximation for the identification of overexploitation hazard has been obtained by the author using radioisotope techniques involving tritium and radon-222 modelling in Cuban karst aquifers. This paper focuses on the constraint that time, and more precisely, groundwater residence time, introduces in safe yield and how, in the case of karst aquifers, aquifer exploitation management practices should take it into account.

SAFE YIELD AND AQUIFER OVEREXPLOITATION

The safe yield of an aquifer is defined as the quantity of water that can be extracted annually from an aquifer without producing undesirable effects (Todd, 1970). As Todd points out, this intuitive definition is more complex than it seems at first sight, since "*there can be more than an undesired* *result effect … the safe may be limited to an amount less than the net amount of water supplied to the basin and that the safe yield can vary as the conditions governing it vary*" (Todd, 1970, p.201). The concept is completed when he points out that "*the safe yield cannot exceed the long time mean annual water supply to the basin…Extractions exceeding this supply must come from storage within the aquifer*". And continues "*… in any one year the draft can exceed the recharge without causing permanent depletion. But on a long-term basis, when series of wet and dry years would tend to average out, the draft becomes an overdraft if the mean supply is exceeded*" (Todd, 1970, p.201).

THE CONCEPT OF RESIDENCE TIME (TW)

The residence time of waters (that is used as a synonym for turnover time, transit time, mean residence time of waters, age of the waters, kinematic age, hydraulic age, among others) is the relationship between the mobile water volume (V_m) and the volumetric flow rate (Q) in the system: $t_w = V_m/Q$. For vertical flow in the recharge area, especially in the unsaturated area, Q is equal to the infiltration rate or the recharge (I): $t_w = V_m/I$. If the system can approach a pattern of one-dimensional flow, this definition yields (Maloszewski & Zuber, 2004) $t_w = x/v_w$, where x is the length for which t_w is determined, and v_w it is the mean velocity of water that equals the relationship between the flow velocity (v_f) and the effective porosity (n_e). As tritium is a tracer, it is convenient to introduce the concept of mean tracer age (t_t) that can be defined as $t_t = \frac{\int_0^\infty t' C_I(t')dt'}{\int_0^\infty C_I(t')dt'}$, where C_I is the concentration of tracer observed at the measuring site (the outlet of the system) as a result of an instantaneous injection at the system's entrance.

Mean tracer age is only similar to the half-life of waters if immobile, static areas do not exist (stagnant zones) in the aquifer and the tracer is injected and measured in the flux. When the radioisotope age of an atmospheric radioisotope does not have sources or sinks other than radioactive disintegration, it can be identified by the age of the water (Maloszewski, 1992; Maloszewski *et al.*, 1983, 2004). In this way, the radioisotope age (t_a) is defined exclusively for the radioactive disintegration as $C(t_a)/C(0) = \exp(-\lambda t_a)$, where $C(t_a)$ and $C(0)$ are the current and initial radioisotope concentrations, respectively, and λ, the disintegration constant. Regrettably, as Maloszewski & Zuber (2004) pointed out, few radioisotope tracers are available for dating groundwater when in motion and immobile. Obviously, as these authors point out, the ages of immobile systems or of systems that can be partially immobile for certain periods of time cannot be interpreted, directly, in terms of the hydraulic parameters.

THE SINGULARITY OF KARST AQUIFERS

The typical heterogeneity of the system of collectors and conducts of groundwaters and the differences in the natural recharge patterns in karst systems (Fig. 1) is the main cause of the differentiated space and time distribution of the replenishment of groundwater resources. In fact, two extreme recharge patterns are recognized in karst systems: a rapid, fast concentrated recharge along vertical shafts and open cracks in bare karst areas; and a slow, diffuse, recharge through joints and soil cover in buried karst systems. This means that different recharge rates exist for the same recharge event. Even more, different arrival times to the outlet are then recognized depending on the degree of water mixing. In turn, this allows for different isotopic behaviour. This difference is the reason why, in particular flow domains, water with different age coexists.

The sustained extraction of groundwaters belonging to the current hydrological cycle causes, inexorably, the exhaustion of the available resources and this relationship could be rigorously determined with the use of the proper isotopic tracers. In general, the variable "residence time" is not taken into account in the water balance and in the assessment of groundwater resources. But the abstraction of "old" ground waters or the exploitation of water of very slow replenishment leads to the, sometimes very fast, exhaustion of the resources, particularly in karst aquifers. Remediation works like artificial recharge, protection against the contamination of the water supply wells and springs or the deep injection of waste liquids, are other aspects in which the residence time is fundamental and yet, regrettably, it is not usually considered in either. As a basic principle it is strongly recommended that waters not participating in the current hydrological cycle should not be exploited in any way, to guarantee its replenishment. However, the term "current hydrological cycle" is ambiguous by nature and has to be more precisely defined. Anyway, isotopic techniques provide appropriate resources to determine the residence time of groundwater. Quantifying this variable provides criteria for adopting appropriate management practices without damaging the aquifer by the exhaustion of its resources or the artificial recharge of contaminated waters (Maloszewski & Zuber, 1990, 1992, 2004).

RESULTS AND DISCUSSION

The sustained application of environmental stable (^{18}O, ^{2}H) and radioactive (^{3}H, ^{222}Rn) isotope techniques has allowed the identification of the recharge patterns in some karst aquifers of Western Cuba (Arellano *et al.*, 1992; Molerio, 1994, 2004, 2005; Molerio *et al.*, 1993, 2000, 2002a,b). Until now the most profitable approach has been based on that of Maloszewski (Herrman *et al.*, 1990; Maloszewski, 1992; Maloszewski & Zuber, 1990, 1992, 2004; Maloszewski *et al.*, 1983, 2004), but the Exponential Model for Input Function (Clark & Fritz, 1997) was also successfully applied. Research carried out by the author and his colleagues following that approach (Molerio, 1994, 2004, 2005; Molerio & Pin, 2002; Molerio *et al.*, 1993, 2002a,b) in two important karst aquifers showed that the corresponding tritium based isotopic balance for the different flow systems indicated the overexploitation of the groundwater. As a consequence, those results provided the appropriate managerial tools to redistribute the groundwater exploitation abstraction well system and for the design of proper locations for artificial recharge wells and to improve the protection against the contamination. The most important results obtained were the following:

(a) The isotopic balance of the groundwater showed that in the discharge area and in some points of the aquifer, waters with different residence times converge, indicating a stratification of the aquifer system associated with the development of different cave levels.

(b) During the dry season, certain boreholes and the system's outlet convey waters with no tritium activity. It is highly probable that these waters are not linked with the natural replenishment associated with the current hydrological cycle or at least that which took place in the last fifty years. Modelling shows the best fit for waters of 100 years residence time (Fig. 2). During the dry season the exploitation of the volumes that might eventually be recharged associated with the "cold front" rains does not reach the aquifer, limiting or impeding its natural regulation and, in turn, contributing to the exhaustion of the aquifer because of the systematic lack of replenishment.

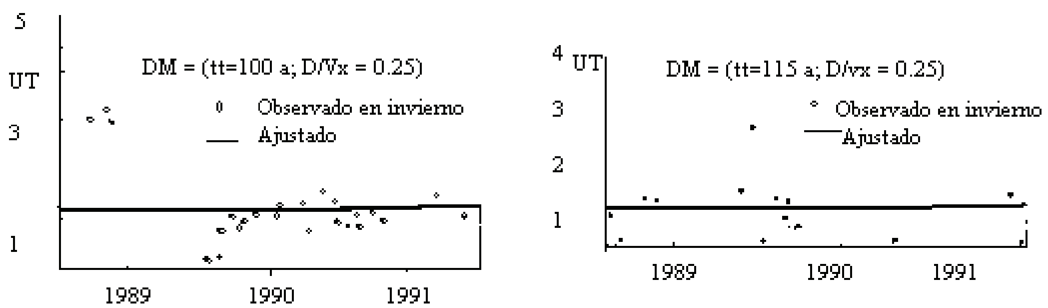

Fig. 2 Best fits for the tracer transit time.

(c) In some cases, the difference between transit times varies from three months in the upper part of the flow system to 100 years in the lowest levels. The exploitation of these waters during the dry season represents a constant reduction of water resources.
(d) Because of the nature of the integration of the cave system, a good mixing of waters exists. The fact that successive recharge events are not consecutively identified is good evidence of this; i.e. recharge waters arrive at the outlet and at other sampling points in a differentiated way, some earlier than others, but without following a strict chronological order, in what seems to be a typical feature of the Cuban karst systems.
(e) Most recharge events that can be identified with a well-known tritium input in the rainwater basically take place during the rainy period (May–October). This fact confirms that these karst system receive some fresh recharge annually but not across the whole extent of the aquifer.
(f) The isotopic results show that, at least for a part of the year, losses by evaporation take place in several parts of the aquifer, mainly close to the outlet or in karst depressions where groundwater outcrops. Therefore, some of these karst features behave as points of groundwater loss, and not recharge, as anticipated intuitively.

FINAL REMARKS

Isotope techniques, mainly those based on the ^{3}H balance, are valuable tools for detecting over-exploitation of karst aquifers. Because ^{3}H is part of the water molecule and hence travels with it, its use as a tracer reduces the uncertainty in the determination of water residence time. The strong seasonal effect on recharge in the Humid Tropics is a useful tool for the application of isotope techniques in water balance studies. Evidence derived from the seasonal behaviour of isotopes like ^{3}H are enough to detect overexploitation trends before they become apparent. Among these types of evidence the most important are the onset of serial but not consecutive recharge events, the variations in ^{3}H activity at the same measuring points during the year and, especially, the presence of groundwater with no tritium activity or at least not related with known or measured ^{3}H inputs.

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