Reach the hydraulic functioning of a coastal karstic aquifer with a conduit-matrix model

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Abstract: Coastal karstic aquifers are subject to saline intrusion by two ways: by the saltwater intruded wedge as usually observed in porous media, and by preferential flow in conduits characteristic of the karst systems. A conduit matrix model has been proposed recently to access the hydraulic functioning of the aquifer, using the observation and data (water level, conductivity, discharge) recorded at a brackish coastal karst spring. This new model, called SWIKAC (SaltWater Intrusion in KArst Conduits), based on a conceptual model of diffuse saltwater intrusion in the karst matrix and exchange with a main conduit discharging at the coastal spring, was first developed and validated using a case study: the Almyros of Heraklio in Crete. We propose in this presentation to apply the SWIKAC model to a new case study: the PortMiou submarine karstic spring (France). This application will meet two goals: a new insight in a coastal karst aquifer by measurements at the outlet, and a new validation for the use of the conduit matrix model in coastal area. The expected results are of outmost importance for the management of coastal freshwater resources. This kind of model gives clue to the depth and the location of the saline intrusion zone into the karst conduit. It's a useful tool to propose managing plan in accordance with the hydraulic functioning of the aquifer.
Keywords: coastal karst, brackish spring, saline intrusion, SWIKAC, hysteresis, Almyros, Port Miou.

I. INTRODUCTION

Karst aquifers are characterized by their drainage by springs at the base level. In coastal zone, these springs can be inland or sub-marine. Freshwater flows out, but for some cases brackish water flows due to the seawater intrusion within the aquifer. In these coastal karst aquifers, the saline intrusion occurs by two ways: by the saltwater intruded wedge as usually observed in porous media, and by preferential flow in conduits characteristic of the karst systems. The karst springs are a potential resource for the water supply in coastal regions. But they become unusable when they are brackish. However, the brackish springs are very useful to study the conditions for the mixing between the fresh water and the sea water at depth in the aquifer. Moreover, they can be fresh during high water event, and then constitute a real water resource.

In order to elaborate management plan to supply fresh water to coastal communities, we need to understand the hydraulic functioning of the coastal karst aquifer. Through this paper, we will try to show how to answer to two main questions:

- By which mechanism the salinity of the brackish spring varies?
- How is distributed the sea water intrusion within the karst aquifer?

II. CONCEPTUAL MODELS OF BRACKISH COASTAL SPRINGS IN KARST:

Brackish coastal springs presented here are composed of a fresh water and sea water mix, with variable proportions, giving a salinity inversely proportional to the discharge of the spring.Coastal karst springs are classically explained by a connection of karst conduits (Figure 1), (Breznik, 1998). A main conduit supplies the spring with the fresh water from the aquifer. It is connected to an annex conduit in direct relationship with the sea, within which the hydraulic head is proportional to the depth of the conduit below the sea water and to the density of the sea water.

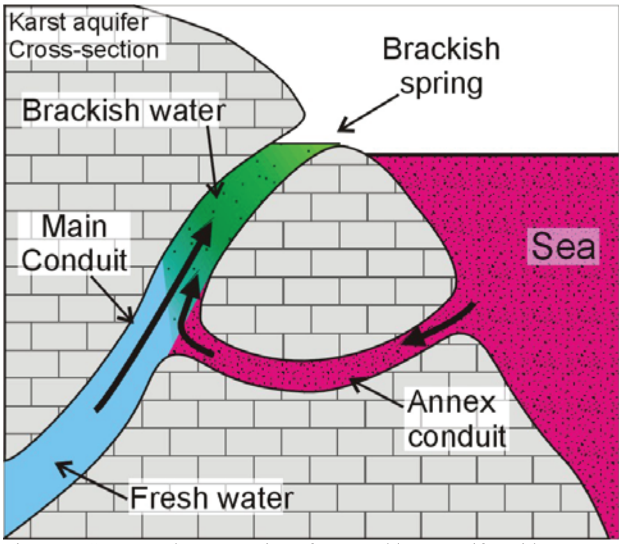

Figure 1: Conceptual cross section of a coastal karst aquifer with a connection of conduits to the sea.

A second conceptual model can explain the brackish springs. It takes into account the saline intrusion as a saltwater wedge in the porous or fractured matrix of the aquifer. When a karst conduit crosses this sea water invaded zone, the head difference between the karst conduit

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filled by fresh water, and the surrounding matrix filled of sea water, generates a flow of sea water from the matrix into the conduit (Arfib et de Marsily,2004)

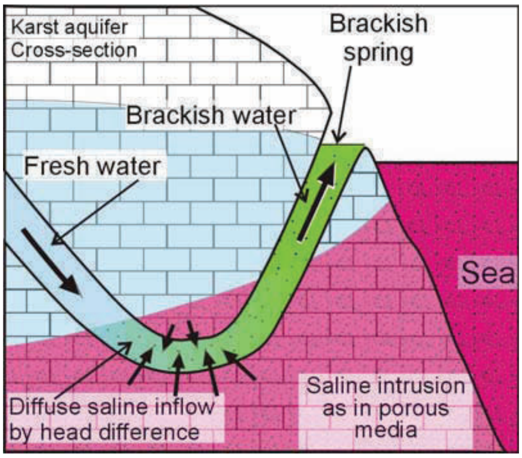

Figure 2: Conceptual cross section of a coastal karst aquifer with a diffuse saline intrusion

III. SWIKAC: A NUMERICAL MODEL TO SIMULATE THE SALINITY OF BRACKISH KARST SPRINGS

A. Equations (Arfib and de Marsily, 2004)

Using the conceptual model illustrated in figures 2 and 3, a numerical model has been developped to simulate the salinity of coastal karst springs. This model is called SWIKAC : SALT-WATER INTRUSION IN KARST CONDUITS (Arfib et de Marsily, 2004).

It's a 1D numerical model, which calculate the hydraulic head in a karst conduit, taking into account the head losses in turbulent flow (Darcy-Weisbach equation). The discharge rate of seawater from the matrix into the conduit is calculated with the analytical solution of Dupuit combined with the method of images, considering the conduit as an horizontal pumping well located at a distance from the sea (prescribed head boundary). Then, a mixing cell model (Bajracharya and Barry, 1994) is used to calculate the transport by advection in the conduit (upwind explicit finite difference scheme).

The salinity at the spring is calculated for each time step, for the discharge and hydraulic head measured at the spring. The results depend on the depth of the zone of conduit-matrix exchange (P: figure 3), the hydraulic conductivity of the matrix and the diameter of the conduit. These values are assumed homogenous in all the aquifer, and the mixing between freshwater and seawater within the conduit instantaneous.

The model can be applied, if the drop of salinity during high water level (C_{spring}):1- is due to a fall of the discharge of seawater inflowing into the karst conduit connected to the brackish spring (Q_{sea})2- is not only due to a dilution by raise of the fresh water discharge (Q_{fresh})

These two cases (fall of seawater discharge and dilution) are discriminated by drawing the hydrogram and chemogram at the spring, or with the hysteresis (Chanat and Hornberger 2002, Evans and Davies 1998, Valdes et al. 2005, Arfib et al. 2006) curve Q_{sea}-C_{spring} during high water level (discharge of seawater calculated at the spring with equation 1 and 2 versus the salinity at the spring).

The use of the Q_{sea}-C_{spring} hysteresis and the application of the SWIKAC model are illustrated below with two case studies.

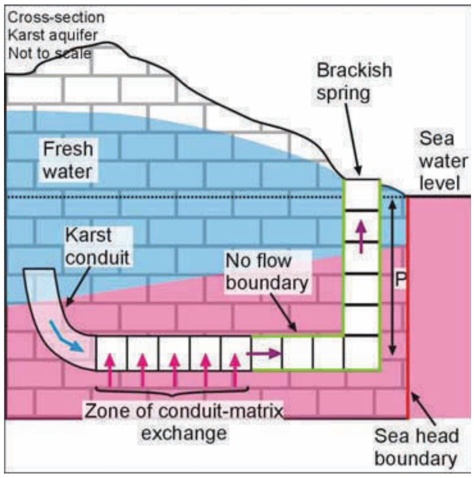

Figure 3: Conceptual model of the numerical SWIKAC model

IV. TWO CASE STUDIES

A. Conceptual models

Two sites were selected (Figure 4), each with a brackish spring with variable salinity function of the proportion of fresh water - sea water in the mixture inversely proportional to the discharge. The first site, the Almyros of Heraklio in Crete, was thoroughly researched (Arfib 2001, Arfib et al. 2002). It has a catchment area of 305 km², from the sea of Crete up to the Mount Psiloritis at 2456 m high. The spring is located inland at 3 meters above the sea level. Its salinity varies from 0 g/l during high water level (discharge > 15 m3/s), and 11 g/l during low water level in summer. Two years of measurements at 30-minute intervals at the inland brackish spring are available.

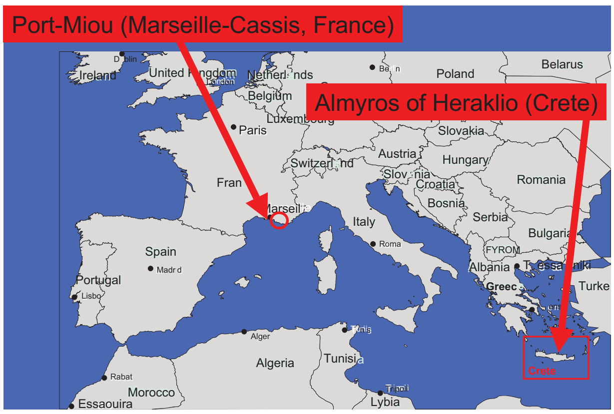

Figure 4: Location of the two case studies: Port-Miou (France) and Almyros of Heraklio (Crete)

The second site is Port Miou in France, near Cassis. It was described by Potié and Ricour (1974), Blavoux et al. (2004) and Cavalera et al. (2006). It has a catchment area of more than 500 km², from the sea to 1000 m of elevation. The salinity varies from 3 to 14 g/l. One year of measurements at 15-minute intervals is available. For a better legibility of the data, measurements were treated by a mobile average (24 hours), thus erasing any periodic influence of the marine level on the discharging water.

For the Almyros case, 18 high water level event were recorded and studied, and 4 for the Port-Miou case. All the high water level studied gave similar results for each case, but the two springs have a different hydraulic functioning.

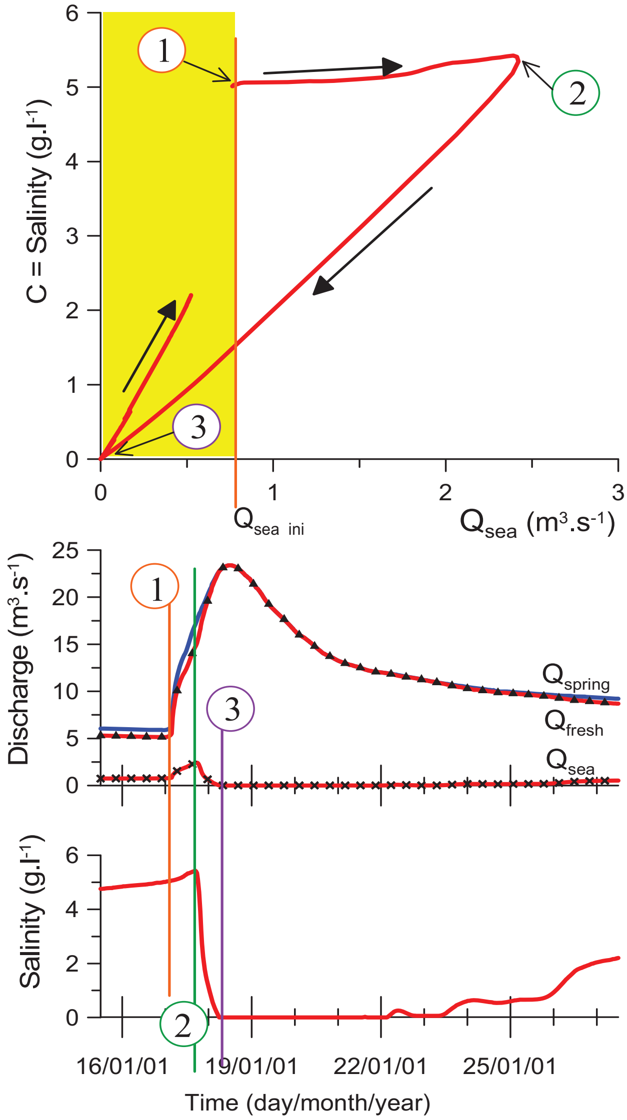

Figure 5: Hysteresis curve Qsea-C of a high water event from 16 January to 27 January 2001 at the Almyros of Heraklio spring, and evolution with time of the total discharge (Qspring), discharge of seawater (Qsea), discharge of freshwater (Qfresh) and salinity. [modified from Arfib et al. 2006]

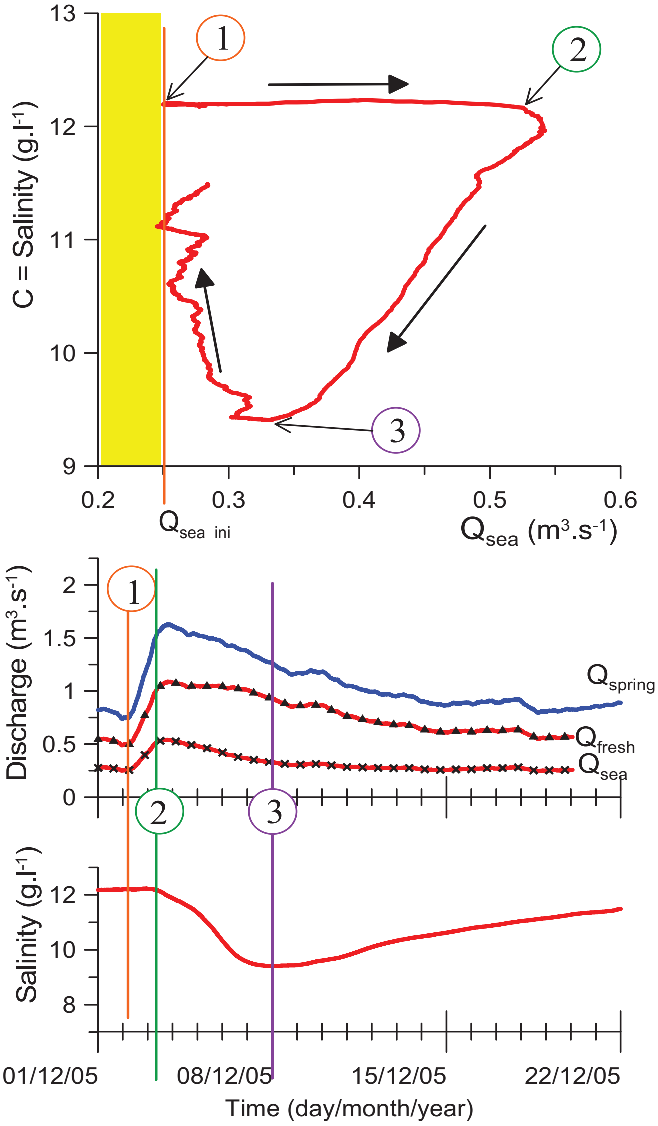

Figure 6: Hysteresis curve Qsea-C of a high water event from 01 December to 22 December 2005 at the Port-Miou spring, and evolution with time of the total discharge (Qspring), discharge of seawater (Qsea), discharge of freshwater (Qfresh) and salinity. [modified from Arfib et al. 2006]

By analysing the hysteresis curves Q_{sea}-C during high water events (Figures 5 and 6), we show that:

- for both case studies, the mixing between freshwater and seawater occurs far away the spring. This is highlighted by the temporal lag between the increase in flow and the decrease in salinity, and validated by the horizontal line between items 1 and 2 on the hysteresis curves Q_{sea}-C.
- for the Almyros of Heraklio spring, the sea water discharge taking part in the total flow decreases with a lower value (item 3 on the hysteresis curve, figure 5) than its initial value before the flood ($Q_{sea\ ini}$). The increase in head in the conduit during the flood limits the entrance of seawater from the matrix into the conduit.
- for the Port-Miou case, the drops in salinity observed during the floods recorded at the spring are only explained by a dilution, i.e. by the increase of freshwater discharge. The discharge of sea water did not decrease during these high water events to a value lower than $Q_{sea\ ini}$ (Figure 6).

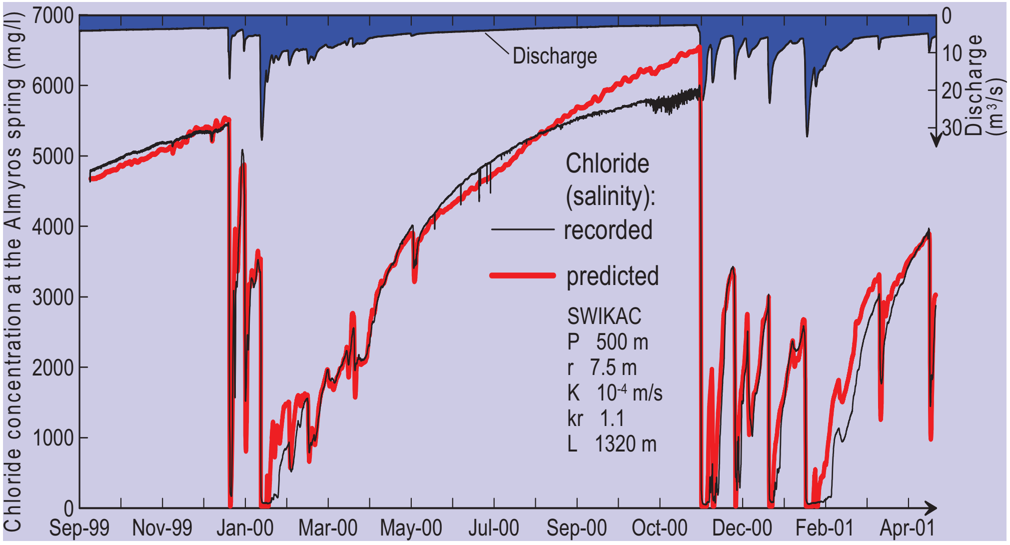

Figure 7: Recorded chloride concentration and that predicted with the SWIKAC model at the Almyros of Heraklio spring (Crete) (Arfib 2001)

B. Numerical modelling with SWIKAC for the Almyros case

Given the condition of application of the SWIKAC model, only the Almyros of Heraklio case is suitable and can be modelled. The Port-Miou spring, with a salinity which decreases only by dilution, is not in accordance with the conceptual model required for SWIKAC.

The model simulation of the salinity of the Almyros spring of Heraklio is given in Figure 7. The depth of the seawater intrusion into the conduit is found to be 500 m below the sea level, with a conduit diameter of 15 m, an hydraulic conductivity of the matrix of 10^{-4} m/s, a length of the seawater intrusion zone (zone of conduit-matrix exchange in figure 3) of 1,320 m starting 4,350 m away from the spring, and the relative roughness coefficient of the conduit is 1.1. The model reproduces remarkably well the general shape of the salinity curve and the succession of high water levels.

V. Conclusion

The SWIKAC model is suitable for karst systems where the seawater inflow into the conduit is regulated by the hydraulic head within the conduit. The good results produced by the model confirm the proposed conceptual functioning model for the Almyros spring. In this case, the brackish spring can be fresh for a high hydraulic head (e.g. Almyros), and not necessarily with a high discharge rate. The SWIKAC model calculates a height on the order of 15 m for obtaining freshwater at the Almyros of Heraklio spring throughout the year, but it does not take into account the possible losses of flow-rate or functional changes when there is continual overpressure in the system.

To the opposite, the Port-Miou spring shows that, for some cases, dilution can be the main mechanism for decreasing the salinity of the spring. The brackish spring can then be fresh with a high discharge rate of fresh water, but a high hydraulic head within the conduit is not sufficient. For this latter case, the building of a dam will not be efficient to decrease the salinity of the spring.

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