MODELLING COASTAL SALTY SPRINGS: FIRST APROACH IN CARBONATE MEDIA (S'ALMADRAVA, MAYORCA, SPAIN)

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ABSTRACT

S'Almadrava spring (6 m.a.s.l.) is located in a karstified calcareous media, 2 km inland in the north-eastern coast of the Mayorca Island. Spring discharge has been monitored for flow rate, temperature, and electric conductivity (EC) discontinuously for more than 10 years. Yearly discharges fluctuate between 6 and 24 $Mm^3 a^{-1}$. Temperature and EC varies in response to variations in discharge rate, with values of 16-24ºC and 4-30 mS cm^{-1} respectively. Although the main observed feature is that EC tends to increase when flow rate decreases, the highest values of EC are associated to sharp increases in discharge after the first heavy rains following a dry period. Both karst and seasonal variations in recharge appear to control groundwater flow.

Mixture of sea and fresh water discharges above sea level, because the excess of elevation is balanced by the excess in density of seawater above that of the mixture. This explains why, up to a point, salinity increases with reducing discharge. However, compared to another karst salty springs at the Mediterranean, S'Almadrava displays two special features: near seawater concentration discharge after a long dry period (attributed to increased seawater intrusion caused by head drop during rainless periods) and a secondary salinity peak in the middle of the sharp drop in salinity after a rainfall event. The latter can reflect that a more complex scheme in groundwater flow must be taken into account.

INTRODUCTION

Brackish karstic springs are a relatively frequent phenomenon in coastal carbonate formations. Several cases are known in most Mediterranean countries but especially in the Adriatic and Aegean shores of the Balkan Peninsula. When fresh water is contaminated by seawater, the spring water discharge becomes useless. Thus, the study of karstic springs contaminated by seawater would be of social importance in areas where fresh water resources are scarce.

Systematic studies of karstic springs started in the late thirties (Kuscer, 1946/1947), being the hydraulic mechanism explained in the forties (Gjurasin, 1942,1943; Kuscer, 1950). To explain brackish discharges, Fouqué (1867), Wiebel (1874), Lehmann (1932), Gjurasin (1942,1943), Kuscer (1946, 1950), Mandel (1971) and Edelman (1966) propose that mixing of water occur in the conduit branching (Figure 1) and that seasonal changes of spring salinity are controlled by changes on fresh and seawater pressure in the branching. Note that conduit branching is considered here the place where the lower conduit filled with seawater, and the primary conduit, with fresh calcareous water, join to form the upper brackish water conduit leading to the spring.

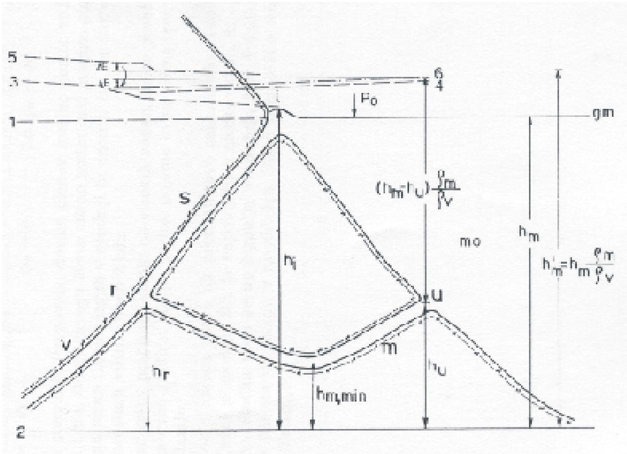


***Figure 1** Scheme of karstic conduits near the coast (Breznik, 1973).*

The most commonly proposed explanations for brackish springs development (Gjurasin, 1943; Kuscer, 1950; and Breznik, 1973) attribute the formation of lower conduits to carbonate dissolution with inland fresh water when rock was situated above sea level. In a second stage, either by tectonic subsidence of the massif (on early and late Miocene, in the case of Mayorca, Gelabert et al., 1992), or sea level rise (in Holocene, Herak, 1975), the elevation of sea level with respect to that of the massif could increase, and new conduits would be created by fresh water dissolution. Connection of both, old and new conduits would lead to a geometric scheme like the one shown in Figure 1.

In addition, it is well known that dissolution of calcareous rocks depends on several geochemical processes. Mixing waters equilibrated with calcite but with different salinities, can lead to both undersaturation or oversaturation with respect to carbonate phases, depending on temperature, pH, ionic strength, CO_2 partial pressure, etc. Thus, dissolution by water mixing must also be considered as an important factor controlling the formation of karstic conduits.

Breznik (1973) propose a classification of brackish karstic springs according to the cause of contamination. The three main groups are: a) springs contaminated due to the greater density of seawater, including submarine springs contaminated in their mouths and springs in karst aquifers, b) springs contaminated due to hydrodynamic effect and c) springs contaminated by a combination of both greater density and hydrodynamic effect.

Intensive investigations in the last 15 years have been carried out in several Mediterranean countries (Lebanon, Libya, Malta, France Italy and Spain), but the largest studies are located in Balkanic countries, Israel and Greece. Most recent studies focus on the characterization of Almyros spring in Greece (Breznik, 1989, Polydoropoulos et al., 1997, Lambrakis et al., 2000) and Blaz spring in Croatia (Bonacci et al., 1997).

S'Almadrava spring can be considered a good example of karstic spring affected by seawater, but displays some singularities that make it different from other Mediterranean springs. Several previous studies on the spring have been carried out to relate variations in the spring discharge flow and concentration with the hydraulic, geological and geometric features of the aquifer which the spring is the main point of discharge (MOPU-DGOH, 1973; SHB, 1987; Baron and Gonzalez, 1978; Cardoso, 1997). However, as in other places, the proposed hypotheses have not been demonstrated. Main problems appear in definition of dimension and geometry of karstic structures because the lack of information at depth. The main objectives of this study are to discuss the features of the spring and qualitatively model the spring discharge, in order to obtain a useful tool for prediction of its development.

THE AREA OF STUDY

Majorca, the largest of the Balearic Islands, is located in the Mediterranean Sea about 180 km southeast of Barcelona. The hydrological unit of Almadrava extends 50 km^2 in the northeastern part of the island, where extensive pumping has developed in recent years, especially during the summer. Low recharges, in addition to karstic caves have favoured the intrusion of seawater and the formation of a mixing water zone with calcareous fresh water. The main discharge point of the area is the S'Almadrava spring, which is located 2 km inland at an elevation of 6 m.a.s.l.

Geology

The geological structure of Mayorca is dominated by thrust imbricate systems. One of them, the Serra de Tramuntana, lies on the northwest border of the island, and it is aligned NE-SW having a NW tectonic transport direction. In the area of study, the structure is well known (Gelabert, 1997) and consists in three main thrust sheets and a few minor slivers. The main decollement levels of the system are evaporitic Keuper facies (Figure 2). Outcropping materials range from Upper Triassic to Quaternary in age and can be differentiate in four stratigraphic units (Gelabert et al., 1992) as follows:

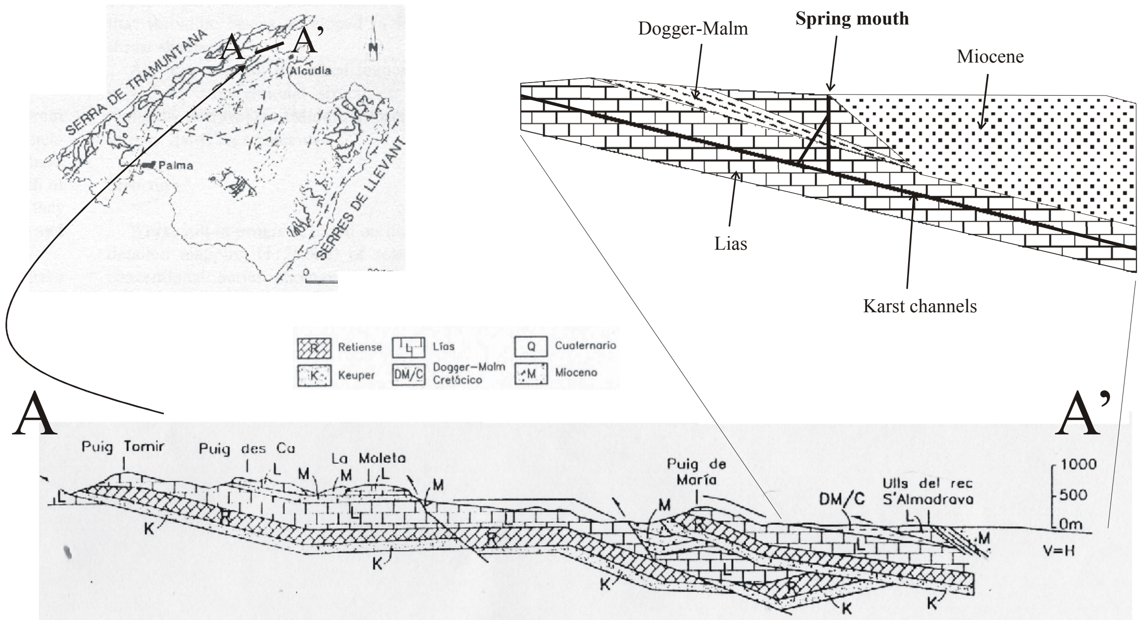


Figure 2 *General situation map (above left), geological cross section parallel to ground water flow (Gelabert, 1997) (bellow) and schematic cross-section focussing in the modelled area (above right)*

Late Triassic Keuper and Retian facies (metric rhythmic beddings of clays, marls and evaporites), Early Jurassic (Lias) (shallow marine laminated limestones, dolomites and breccias with several degrees of karstification and fractures), Jurassic Dogger-Malm Facies to Late Cretaceous (pelagic limestones and marls showing strong variations in thickness), and Lower and Middle Miocene rocks overlying the previously mentioned rocks (turbiditic series).

S'Almadrava hydrological unit

Definition of S'Almadrava hydrological boundaries is somehow complicated. By its highly imbricated structure, Keuper materials act as non-permeable bottom unit and individualize different minor hydrological units. Flow lines are also controlled by the geological structure, becoming parallel to striking thrust NE-SW (with direction to NE) and converging most of them in S'Almadrava spring.

The main body of the aquifer are the Liassic limestones that present both low permeability matrix rock and high hydraulic conductivity zones due to karstification and fracturation. Dogger-Malm facies with low permeability appear in the top of Liassic materials and isolate two aquifer levels in the area around the spring (see Figure 2). Miocene sediments also present very low values of hydraulic conductivity.

Groundwater flow and chemical characteristics

Several studies have been carried out in this area, but unfortunately only a few have been published. The earliest analyses of the spring behaviour are government reports defining water resources of the island (MOPU-DGOH, 1973; SHB, 1987). They suggest that spring behaviour is controlled by the high permeability zones in Liassic limestones. A systematic control of chloride ion concentration in spring discharge (Barón and González, 1978) estimates the contribution of seawater in total spring discharge 15 to 30% depending on seasonal variation. Limits and geometry of the hydrological unit were determined by Gelabert (1997), and finally Cardoso (1997) integrate the available data to proposing an explanation for the spring mechanism. However, some unresolved situations are left. We discuss these in the next section.

S'Almadrava's recharge takes place in the Serra de Tramuntana, over an area of 40 km^2 approximately. Rainfall average is 900 mm y^{-1} and displays important seasonal variations. It concentrates in sharp rainfall events once a month in winter season and once during summer.

Spring discharge is controlled by rainfall. The spectral correlation analysis of the spring discharge (Cardoso, 1997) shows that it fits the behaviour of a typical karst system, with fast responses to rainfall and short pulses. Yearly discharge flow for the 1976-1997 period varies from 6 to 24 $Mm^3\ y^{-1}$, and averages 12.3 $Mm^3 \cdot y^{-1}$.
Hydrochemistry of water discharging in S'Almadrava also displays an important temporal variation. Total concentrations are consistent with simple mixing of fresh calcareous water and seawater following the main flow line in the aquifer. Mixing water is usually undersatured with respect to gypsum and dolomite, and saturated or lightly oversaturated with respect to calcite (Cardoso, 1997). Chloride concentration fluctuate between 1.6 and 9.0 $g \cdot L^{-1}$, and EC normally present values in a well defined range of 5 to 22 $mS \cdot cm^{-1}$.
Temporal variation of flow discharge and EC are strongly dependent (Figure 3). After each rainfall event, salinity decreases suddenly, and gradually increases to about 20 $mS \cdot cm^{-1}$ when discharge rate ceases. However, this behaviour does not fit in rainfall events produced after long dry periods in which the spring dries up. In these cases, rainfall events cause concentrations increase and then decrease suddenly, reaching near sea values at the peak.

Notice that a secondary peak in salinity appears in the middle of the sharp decrease in salinity.

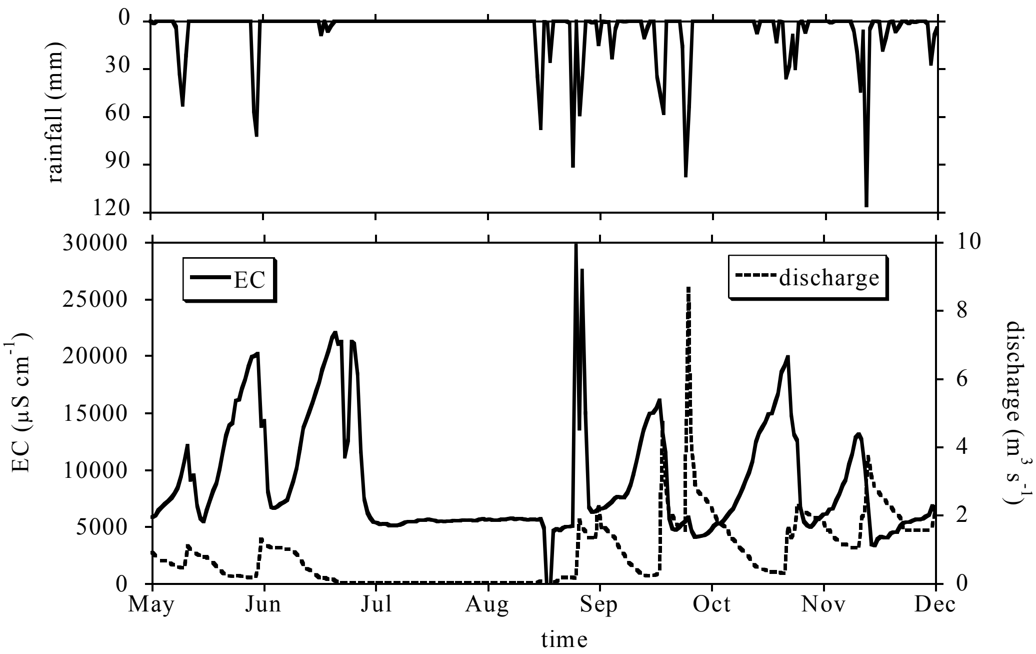


Figure 3 *Time dependent evolution of discharge and EC in the S'Almadrava spring in 1996. Rainfall in the recharge area during the same period is included.*

CONCEPTUAL MODEL OF THE SPRING

To really understand the conceptual model of the spring, two different situations have to be considered: dry and wet seasonal period. Both are described bellow.

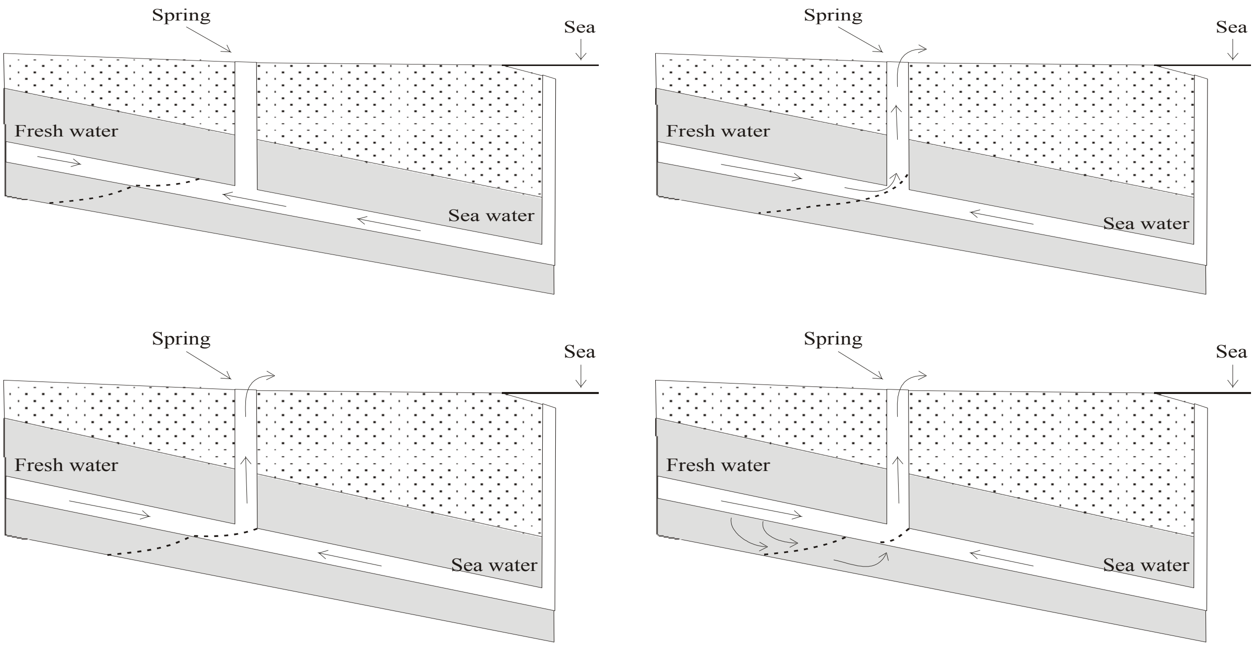


Figure 4 *Conceptual model proposed for S'Almadrava spring. a) Situation after a long dry period, b) Saltwater is discharged through the spring after the first heavy rainfall, c) A mixture discharges with an increasing proportion of seawater as freshwater head diminishes, and d) Heavy rains now cause a sudden decrease in the proportion of seawater, but a second day peak is caused by the slowly flowing seawater in the less permeable portion of the aquifer.*

Dry (summer) season

The summer season is characterized by long rainless periods in which the spring dries up. As a result, heads drop and the interface with seawater moves inland, salinizing the branch feeding the spring (Figure 4 a) and b)). When a new discharge event is produced, fresh water flow built up in the freshwater conduit is large enough to drag this high salinity water to the spring mouth. The result is a very high concentrated water discharge. Figure 5 a) focuses in a time period that illustrates this behaviour.

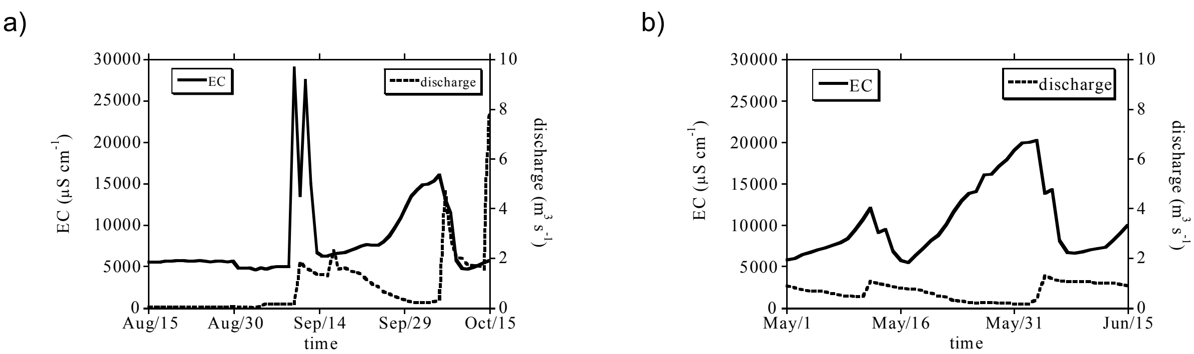


Figure 5 *Temporal variation of EC and discharge flow in a) dry season and b) wet season*

Wet (winter) season

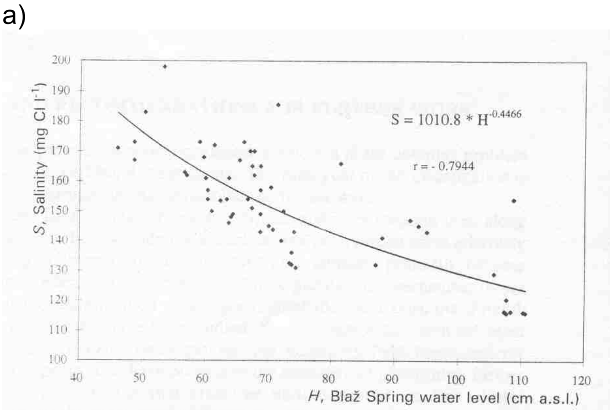
In this case, rainfall events are more frequent, and the spring does not dry up. Fresh water pressure is higher, the interface with seawater stays low and the primary conduit is filled with only fresh water. When a rainfall event is produced, fresh water flows through lower and upper conduit, and discharge in the spring (Figure 4 c)). Thus, the resulting discharge flow presents low concentration. As the fresh water inflow through the lower conduit decreases, the interface moves slightly inland, and the salinity of the upper brackish conduit increase. After, discharge salinity increase proportionally to the decrease in discharge flow, till a new precipitation event is produced and the whole process starts again (Figure 5 b)).

Notice also, the secondary salinity peaks following the initial drop after rainfall event, and prior to further reductions in salinity. These make the behaviour of the spring more complex, and cannot be attributed to any important change in discharge. It is proposed that a slow flow through less permeable media occur in the aquifer, in addition to the fast one in the karst channel system.

Other small variations could indicate the existence of several conduit-branching points at different depths that would produce minor changes in discharge flow and concentration.

In contrast to what have been reported in other brackish springs (Bonacci et al., 1997), S'Almadrava spring does not show a unique relationship between EC and flow discharge. Differences derive from the particularities of the spring previously discussed. Thus, after a long dry period, discharge present salinities higher than could be expected from the discharge flow value. Figure 6 allows comparing the relationship between of S'Almadrava and Blaz springs.

a)



b)

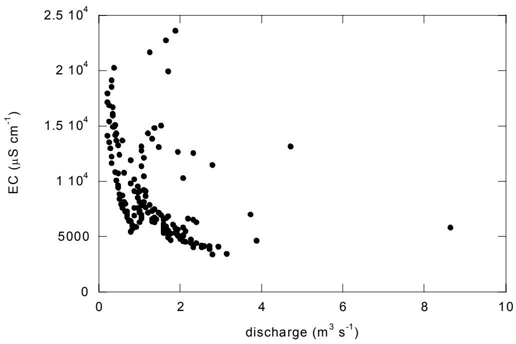


Figure 6 *Ratio between a) salinity and seawater level in Blaz spring (Bonacci et al. 1992) and b) Electric conductivity (EC) and discharge in S'Almadrava.*

NUMERICAL MODELLING

Aquifer flow and spring discharge is been modelled using SUTRA 2D code from the USGS (Voss, 1984). Modelled vertical cross section is assumed to be parallel to groundwater flow (i.e. perpendicular to shore line). Geometry and geological structure considered in modelling is shown in Figure 2.

Definition

Three main parameter zones have been defined taking into account the geometry and properties of materials. These zones correspond to a) Liassic materials (karstified and fractured carbonates that mainly control groundwater flow), b) Dogger-Malm and cretaceous sediments (that constitute the confining layer of aquifer at the vertical of the discharge point), and c) Miocene-Quaternary (in contact with seawater and covering most permeable materials in the near coast zone). In addition, a simple karst channel system has been defined in Liassic limestones according to the conceptual model explained above. The karst system consists of a conduit branching placed at 500m depth bellow the spring connecting it with lateral boundaries. A secondary conduit branching was defined to represent several possible pathways. Hydraulic conductivity at these channels shows a strong anisotropy parallel to the main channel direction.

Porosity and hydraulic conductivity values used in modelling are presented in Table 1.

	Hydraulic conductivity (m/d)	Porosity
Lias facies	1	0.01
Karst channels	1000 (max) 1 (min)	0.1
Dogger-malm	0.01	0.1
Miocene	0.01	0.2

***Table 1** Porosity and hydraulic conductivity values considered in the model*

The modelled domain was divided into 1300 irregularly quadrilateral elements of about 50m. No boundary conditions were defined at the bottom of the aquifer, which was defined in the contact with non-permeable Keuper materials. Vertical limit in sea side (right side), is assumed to represent a downwards karst channel and is treated as a specified constant pressure boundary. Concentration of seawater is set to 0.0357 in molar fraction. The left boundary presents a time dependent inflow boundary of fresh water. Subroutine BCTIME of SUTRA 2D code was modified to define inflow as a sinusoidal function with a four days period. The spring mouth was implemented by considering atmospheric constant pressure (0 bars) at the specific node.

Initial conditions

Initial steady state conditions were achieved by considering a constant freshwater inflow ($0.13 Mm^3y^{-1}$), allowing the intrusion of seawater in the aquifer. Longitudinal and transversal dispersivities were assigned values of 10 and 5 m respectively. The maximum tolerance criterion stands in $1 \cdot 10^{-7}$ for pressure and $1 \cdot 10^{-12}$ for concentration. Figure 7 displays the distribution of groundwater flow vectors and concentration for stable initial conditions.

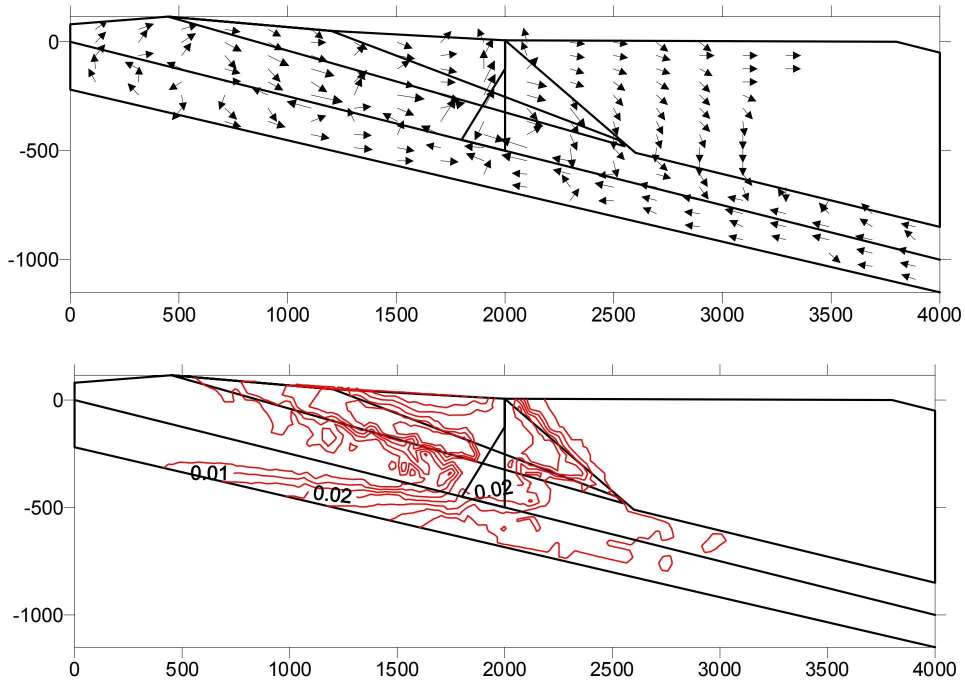


***Figure 7** Distribution of a) groundwater flow vectors and b) concentration (molar fraction) for steady state initial conditions.*

Groundwater flow appears to be controlled by high permeability channels. Minor instabilities in concentration can be observed but they are restricted to contacts between materials with a very large different hydraulic conductivity. The concentration distribution is consistent with flow and interface stands in the conduit-branching zone. Notice that concentration is the same in the whole upper brackish conduit.

Preliminary results

A preliminary simulation on time-dependent flow and transport was run out considering total yearly freshwater inflow equal to that in the steady state stage.

Obtained results at the spring mouth (Figure 8) reproduce the main features of both wet and dry season (recall Figure 3).

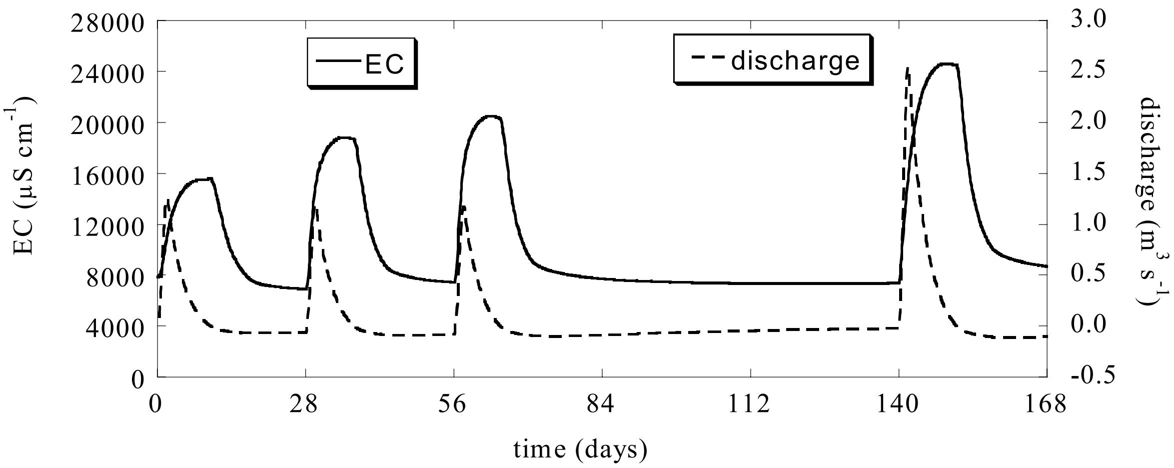


***Figure 8** Preliminary results for time-dependent flow and transport. EC and discharge variation in spring mouth.*

But problems appear when the spring dries up between consecutive rainfall events, and calculated concentrations decreases suddenly before the next rainfall event is produced. Thus, secondary salinity peaks are not reproduced by this model.

DISCUSSION AND CONCLUSIONS

A conceptual modelling of the behaviour of springs discharging a mixture with seawater above sea level has been proposed. Numerical modelling seawater discharge at these springs is possible by considering a karst channel system that connect the spring mouth with the seawater. Salinity of discharge depends on the freshwater inflow and the equilibrium in fresh and seawater pressure in the conduit branching.

In case of S'Almadrava, results reproduce coarsely the observed values of the spring concentration. However, the model fails to reproduce in fine scale response of EC to rainfall. Thus, a more detailed model has to be considered in order to properly understand the behaviour of the spring. We propose that a low flow through porous media occur in addition to the main controlling high flow in karst channels.

Minor instabilities in contact of different materials can be reduced by defining a finer mesh in karst channels and around the spring mouth.

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