DEVELOPMENT OF A EUROPEAN TEST SITE IN A COASTAL REEFAL LIMESTONE AQUIFER AT CAMPOS (MALLORCA, SPAIN)

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Abstract

A test site is developed for studying saltwater intrusion processes in a multi-scalar sedimentary rock aquifer. The aquifer consists of karstified reefal limestone and is situated near Campos (Mallorca), where saltwater pollution is present. It is highly heterogeneous with channeling in the reef and high porosity but lower permeability in the slope deposits. Several cored drillings were made. Cores are described and thin sections taken for a thorough geological interpretation of the site. Hydraulic characterization consisted of a number of geophysical logging like impeller flowmeter logging, optical televiewer, acoustic televiewer, natural gamma, formation conductivity, and salinity-temperature logging. The latter also allowed the identification of the saltwater intrusion extent.

Keywords: karstification, preferential flowpaths, reef, carbonates, saltwater intrusion

Introduction

The presented paper offers a test-site set-up protocol for an aquifer with saltwater intrusion problems as part of the ongoing EU-funded project ALIANCE. The main objective of this project is to develop a strategy for the quantative description of fluid flow and storage in a shallow aquifer contaminated with saltwater. Or, in other words, it identifies the data needed for an effective quantification of a saltwater intrusion problem in a hard rock aquifer.

To achieve this goal a test-site has been set up in a sedimentary karstified limestone aquifer, situated near the town of Campos, Mallorca (Spain). Saltwater intrusion was identified as one the main problems in the

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European Fifth Framework Program under which ALIANCE is sponsored. Saline pollution of coastal aquifers becomes a problem everywhere where population growth pressures the mostly scarce freshwater reserves. Example of these problems in the Mediterranean region are ample (Custodio et al., 1989; Fidelibus and Tulipano, 1991; Jemai et al., 1998; Petalas and Diamantis, 1999; Yechieli, 2000). Several modeling tools for density-dependent groundwater flow are already available and increasingly take into account heterogeneity (Oude Essink, 1998; Paniconi et al., 2001; Voss and Souza, 1987). However, the first step in a saltwater investigation study is still understanding the field data. From the above-mentioned articles it is clear that this is not always straightforward, especially in a heterogeneous aquifer.

The choice for Mallorca was based on several criteria of the project's objectives not least of all the socio-economic relevance of the aquifer in Campos. Campos is a region for agricultural use where water levels are only slightly above sea-level (Barón Periz and González-Casasnovas, 1987). As a consequence, a large part of the aquifer, that has a surface area of about 420 km^2, is already polluted with seawater. An average of 49 Mm^3/year were extracted for irrigation and urban use in 1987, with a definite increasing trend in the following years. On the other hand, the aquifer, consisting of karstified reefal limestone deposits, also poses an interesting multi-scalar (hydro)geological problem besides the challenge of saltwater intrusion.

The Campos test site, the property is called Ses-Sitjoles, can thus be used to test new research tools as well as possible hypotheses for saltwater intrusion. Several cored drilling were made. Cores are investigated for porosity and permeability, as well as depositional characteristics. The open boreholes were then investigated by a suite of geophysical logging tools and some preliminary hydraulic testing was carried out, water samples were also taken. After an introduction into the regional setting of the test site, the geology of the test site is described in more detail. The hydrogeological characterization by geophysical logging, testing and monitoring is given next.

Test site location and regional setting

The Ses Sitjoles test site lies on the upper Miocene Llucmajor platform in the south- western part of Mallorca (Figure 1). The flat lying and through tectonic flexure slightly emerged reef complex is about 20 km wide and 200 m thick. Steep sea cliffs that display the facies architecture of the reefal unit in exquisite detail form the western and southern margins of the platform. It has been extensively described in numerous papers (Pomar, 1993; Pomar and Ward, 1995 and 1999; Pomar *et al*., 1996). The eastern border of the platform is built by the Campos basin, which seems to have subsided only during Pleistocene time (Jenkyns et al., 1990). The northern border is the Mesozoic basement of the Serra de Levante, to which the platform onlaps.

The platform prograded on a gentle depositional profile towards the south and south-west. It shows all characteristic features of a prograding reefal complex with aggradation and progradation, without backstepping. The latter is missing, because the rate of carbonate production could keep up with the rate of creation of accommodation space (Pomar and Ward, 1995). The upper Miocene was a time of tectonic stability and low terrigeneous influx. Consequently, the reefal architecture and the distribution of lithofacies were mainly controlled by sea level fluctuations of 4^{th} to 7^{th} order. Subsidence during deposition is thought to have been minor, and most of this flat-lying platform has been buried no more than several

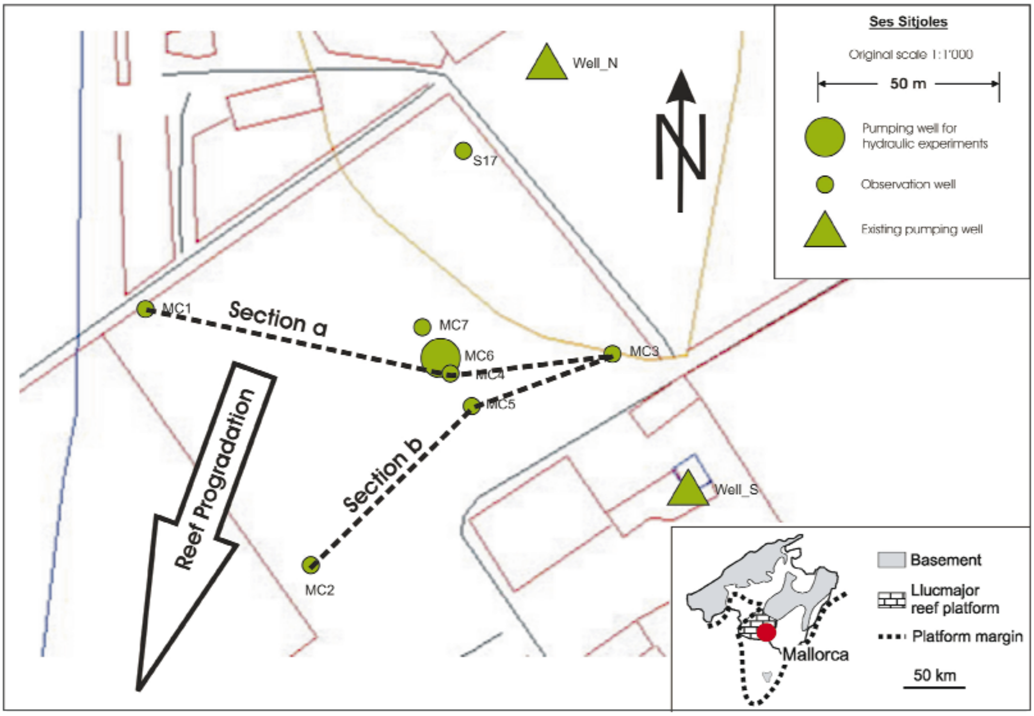

Figure 1. Ses-Sitjoles test site, location and drilling distribution.

tens of meters. That is why much of the primary porosity has been preserved. Dissolution of aragonitic constituents leads to a high amount of moldic porosity. This process, in combination with extensive karstic channeling in some lithofacies types, makes the Llucmajor platform an excellent aquifer. Over-exploitation lead to the current situation, where saltwater intrusion is probably present in most of the Campos basin.

Test site development

Six observation boreholes (MC1-MC5 and MC7) with a depth of 100 m and a diameter of 101 mm were drilled on the site (Figure 1), five of which have been cored (Table 1). One more existing borehole is available on site; it has a slotted PVC screen to a depth of 100 m and a diameter 56 mm (Figure 1). One large diameter (MC6, 300 mm) well is drilled in the middle of the test cluster (MC4-MC5-MC7) and serves as a pumping well for hydraulic testing. It is drilled to a depth of 59 m, about 2 m above the beginning of the freshwater-saltwater interface. Distances of 5-15 m between boreholes as well as distances of 50-100 m are thus present to represent a multi-scalar test-site.

Exploratory geophysics consisted of optical borehole televiewer, acoustic televiewer, natural gamma, long and short normal resistivity measurements, temperature-conductivity logging and pH-oxygen logging. In a next phase, induction formation conductivity was recorded and impeller flow-meter logging carried out

Table 1. Borehole characteristics and labelling.

Borehole	Diameter upper/lower	Full PVC	Screened	DN PVC (mm)
MC1	150 101	0-38 m	38-54.8 m	100
MC2	101 101	n.a.	n.a.	n.a.
MC3	130 116	0-39 m	39-68 m	115
MC4	130 101	0-39 m	39-68 m	100
MC5	150 116	0-36 m	36-60 m	115
MC6	380 300	0-38 mm 58-59	38-58 m	200
MC7	130 101	0-37 m	37-60 m	100

Table 2. Geophysical logs carried out in the test site boreholes. X means once, 1 or 2 indicates 1 or 2 logs. TCGS = temperature conductivity natural gamma log, BHTV = borehole televiewer, FAC40 = acoustic televiewer, LN/SN = long normal/ short normal, IFM = impeller flowmeter, DIL = dual induction log, SAMPLE = water samples taken.

BH	TCGS	BHTV	FAC40	PH	LN/SN	IFM	DIL	SAMPLE
MC1	2	X	X	X	X	X	X	3 depths
MC2	2	X	X	X	X	X	X	3 depths
MC3	2	X	X	X	-	X	X	3 depths
MC4	3	X	-	X	-	X	X	3 depths
MC5	2	X	X	X	-	X	X	3 depths
MC7	1	X	X	X	-	X	X	3 depths

(Table 2). In addition, borehole-to-borehole seismic profiles were shot and single borehole and borehole-to-borehole electrical tomography were recorded;, these investigations are the subject of another paper (Friedel et al., in press; Maurer et al., in press) and will not be reported here. Most of the geophysical logs require that boreholes remain open. For most hydraulic testing boreholes should only be selectively open to prevent hydraulic short-circuiting. The initial idea was to seal boreholes with temporary packers, stopping possible vertical flow, but allowing for geophysical logging at all times after removal of the packer. Borehole instability in the upper part of the reefal aquifer, however, lead to the installation of a PVC tube to a depth below the instable zone. This PVC tube is screened from the top of the watertable down (Table 1).

Test site geology

The architectural concepts derived from and illustrated with the splendid outcrops at the cliff coast around Cap Blanc by Pomar (1996), and Pomar and Ward (1999) can act to a certain degree as an analogue model for the Ses Sitjoles site. Most of the lithofacies types reported by the mentioned authors have been recognized on core material. From top to bottom, five main lithofacies types, namely inner lagoon, outer lagoon, reef core, proximal and distal slope, have been encountered at Ses Sitjoles (see figures 2 and 3). They have been recognized in all cored boreholes with varying thickness and depth. The observed lithofacies types are as follows.

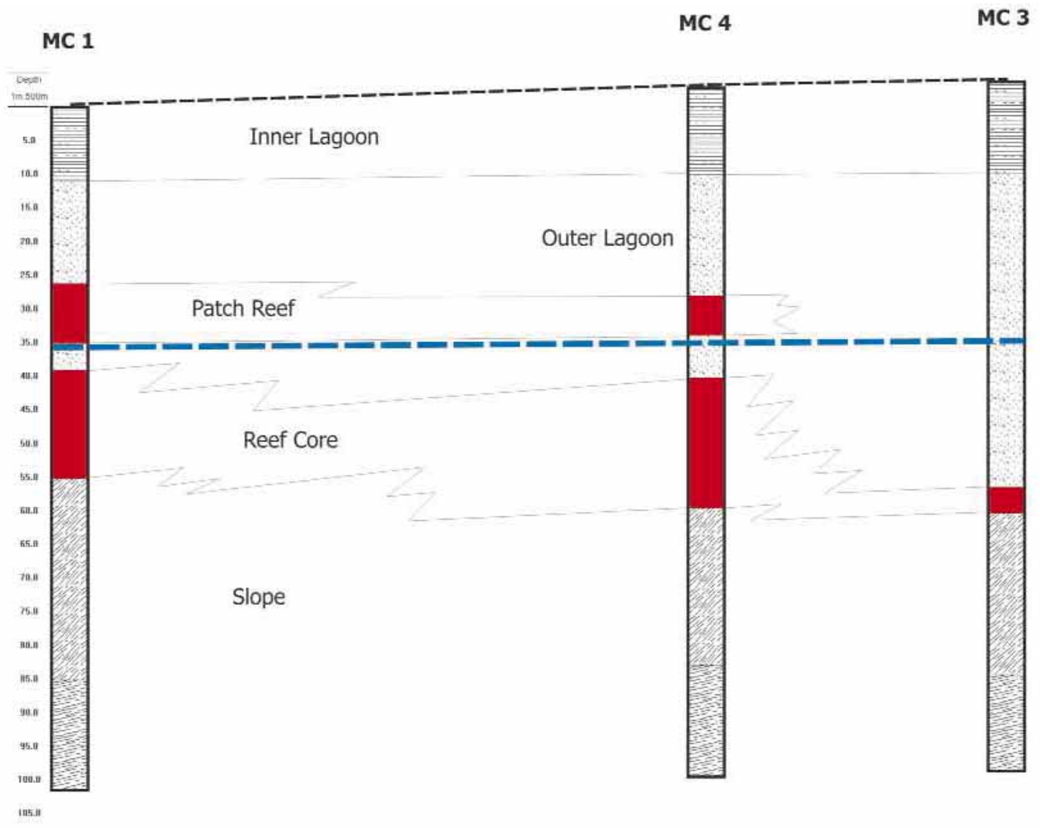

Figure 2. Cross-section a

Marly-clayey sediments of *inner lagoon* lie entirely in the vadose zone and are not considered. *Outer lagoon* only partly lies in the saturated zone. Within the saturated zone, the rock consists of skeletal grainstones and packstones with very high moldic and intergrain porosity (35-50 %), but presumably moderate permeability. The *reef core,* with thickness of 4-19 m, consists of framestones but also red algal bindstones occur. Increased moldic porosity is typical. Especially the lower part of the reef core is usually karstified and well connected through channels. The karstified host rock is dense and re-crystallized with low matrix porosity, but high permeabilities due to extensive channeling. Typical total matrix porosity for reefal framestones varies between 1 and 20 %. Open porosity at dm- and cm-scale can be small. Blocky calcite cements occlude most of the growth-framework porosity within re-crystallized and preserved corals.

Proximal slope deposits with a thickness of 20-30 m consist of white, bioclastic, extensively bioturbated, poorly cemented skeletal rudstones to packstones, with high intergrain and moldic porosity (35-50 %) that are steeply bedded (10-30°). Lenticular layers of coral rubble and skeletal debris-flow rudstones are common. Fractures occur, especially towards the overlying reef core. This unit is slightly anisotropic due to steeply dipping beds and coarse- grained layers in between.

Distal slope deposits build the lowermost unit encountered at Ses Sitjoles and consist of white, well-cemented, strongly bioturbated, gently dipping (less than 10°) and fine-grained packstones and grainstones. The rock is dolomitized in the lower part and it exhibits a high intergrain porosity, but low connectivity and, therefore, presumably low permeability.

The 5-cored drillings at Ses Sitjoles revealed the same lithofacies units as described by Pomar (1996). A complex architectural pattern has been encountered, which is strongly controlled by ancient sea level fluctuations. Depth and thickness of the lithofacies units vary considerably. Due to sequence-stratigraphical concepts direct interpolation between boreholes is not possible. Therefore, exact analysis of erosional surfaces and comparison to outcrop analogues is crucial for a complete understanding of 3D-structure. Based on these concepts, two geological sections have been drawn (figures 2 and 3).

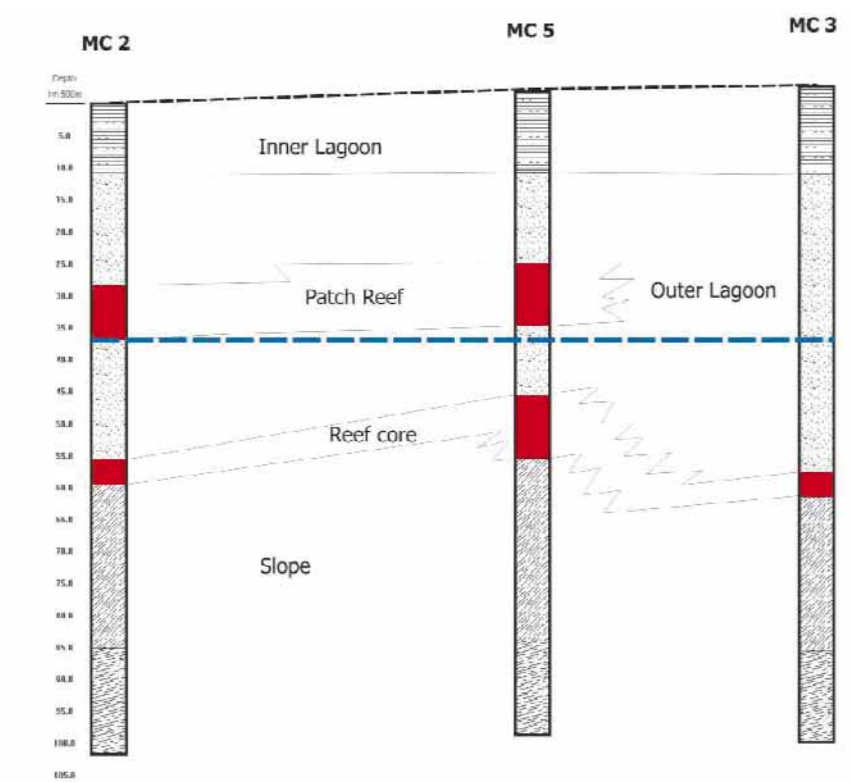

Figure 3. Cross-section b.

Thick or high lying reef core was encountered in boreholes MC1, MC4 and MC5 which is typical for aggradation or a high stand phase in reef history. MC2 and MC3 show a thin, low-lying reef core, covered by thick outer lagoon sediments. These features could be explained by the offlapping or lowstand phase. A thick outer lagoon is typical for aggrading tract systems and indicates the presence of an aggrading bundle in direction of reef progradation. Based on the work carried out by Pomar and Ward (1995) and Pomar (1996), we conclude that reef progradation at Ses Sitjoles took place in south or southwest direction (Figure 1). For our test site a top of a 7th order reef crest curve which trends in NW-SE-direction and encompasses MC1, MC4 and MC5 is postulated. MC2 and MC3 lie already in a low stand position, covered with thick aggradational outer lagoon sediments. At MC3 no patch reef has been encountered. The explanation for patch reefs in the outer lagoon observed at all other boreholes could be the presence of an overall lower order (6th?) sea level rise with its aggradational reef core stack further towards the sea.

Test site hydrogeology

The water table is about 40 m below ground surface, and only just above the mean sea level. On site scale the hydraulic gradient is not measurable.

Two existing private pumping wells adjacent to the test-site and labeled Well_N (for north) and Well_S (for south) are equipped with a downhole sensor that records head, conductivity, temperature and pH continuously (see Figure 1 for location). This has a double goal, on the one hand it records pumping sessions by the well owners, on the other hand they give background information on groundwater level variability throughout the year. A pumping session always discharges the same amount of water. However, head changes due to pumping activities can only be interpreted approximately as the wells have a rectangular form and depth of the well is uncertain.

Most of the observation wells (MC1-MC7) are equipped with a temporary packer system, behind which there is a string of pressure sensors. These pressure sensors need to measure very small changes in head, and have an accuracy of 1 mm. Three to five sensors hang on 1 string in one borehole. All sensor strings from all observation boreholes are then connected to one data logger that continuously records with a user-defined interval. Sensor-depths depend on inflow zone encountered during impeller flow-meter logging. There is at least one sensor in freshwater, one in saltwater and one in the transition zone. The temporary packer should seal off any vertical flow caused by the presence of the borehole. But, as the upper part of the borehole has a filter screen, this is not true for the freshwater zone. To correct for air pressure changes, air pressure and air temperature are also measured by two independent systems on site.

Monitoring, so far, revealed that groundwater levels vary by 50 cm during the 7-year monitoring data of different observation wells in the surrounding of the Ses Sitjoles site within the regional aquifer (km-scale). The time series show similar patterns of minima and maxima; however the amplitudes are different. During the past year groundwater levels in several existing and newly developed observation wells at the Ses Sitjoles site have been monitored in more detail and show variations of 35 cm (figures 4 and 5).

The Ses Sitjoles site is characterized by a high degree of geological heterogeneity as described in the previous paragraph. A hydraulic characterization will, therefore, by definition, need different methods. Preferential pathways are identified by impeller flow-meter runs in all boreholes. A marked contrast between reef complex and proximal slope deposits is seen from the impeller flow-meter. Other tools are needed for proximal slope deposit characterization. With temperature anomalies, caused by drilling fluid injection, pathways are derived in the upper part of the proximal slope. For the lower part of the proximal slope, the formation conductivity logs show porosity variability.

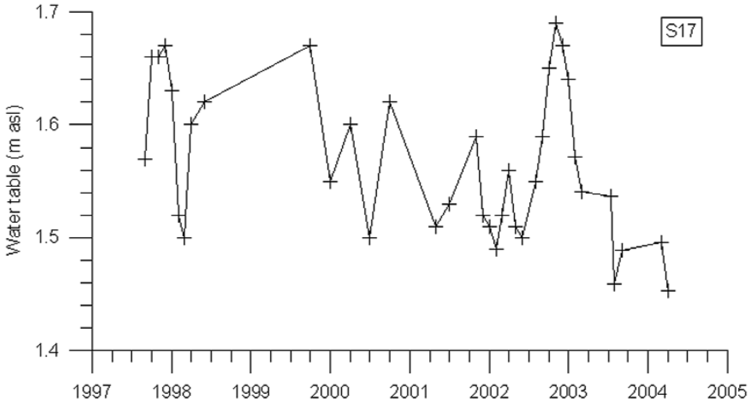

Figure 4. 7-year period water table variations in S17.

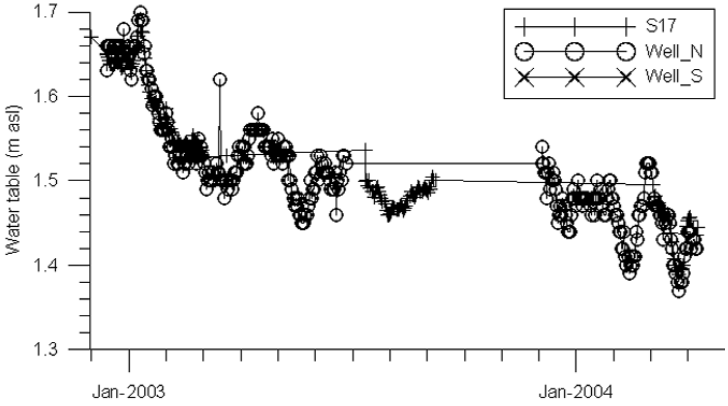

Figure 5. Water table variations on site.

Based on the regional water balance and first hydraulic tests at the Ses Sitjoles site, transmissivity values in the order of $10^{-1}m^2s^{-1}$ could be derived for the reef deposits. The annual extraction rate (49 Mm^3/yr) is in the order of the groundwater recharge (precipitation 190 Mm^3/yr) and points towards possible overexploitation of the aquifer

Preferential pathways in the reef deposits

The impeller flow-meter is run in all boreholes. With this tool it is possible to identify preferential pathways by stimulating vertical upward flow within the borehole (Molz et al., 1989). The objective in the Ses Sitjoles test-site is to characterize the hydraulic difference between the slope and reef deposits and to identify (if any) major inflow regions. These inflow regions would serve as monitoring points during larger scale pumping tests. In the case where sufficient drawdown is measured while logging the vertical flow component, transmissivity values for the major flowing feature can be derived (Paillet, 2000). In our case, however, transmissivities are too large (or drawdowns too small), and only inflow rates are calculated. An example is presented for borehole MC5, but the same procedure is followed and the same pattern is observed in all boreholes (figures 6 and 7).

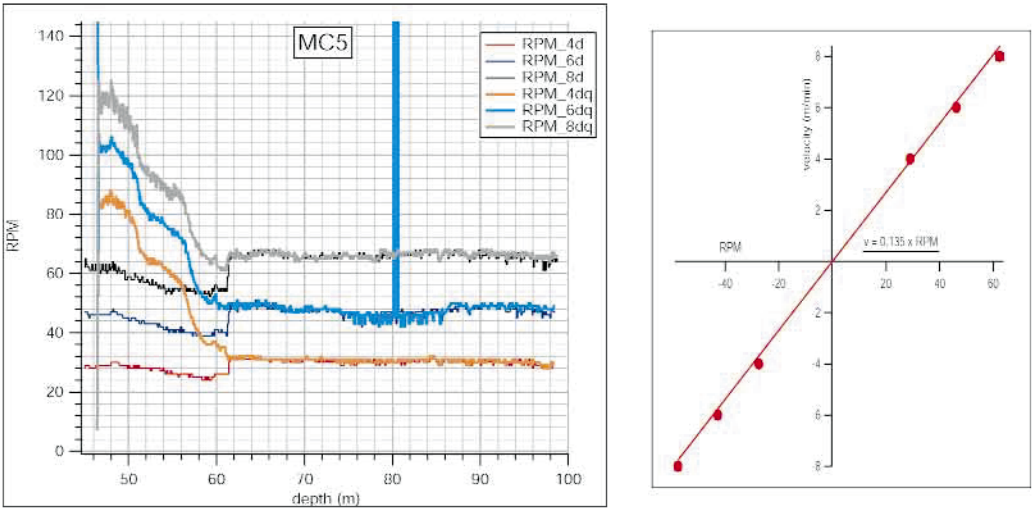

Figure 6. Impeller flow-meter recording for different cable speed runs down without and with pumping (q) and calibration of RPM with velocity.

The impeller flow-meter is run up and down the borehole at three different cable speeds to measure the ambient flow within the borehole (Figure 6), the same logs are then recorded while pumping at a constant discharge rate. The measured drawdown is in the order of several mm. After calibration of the logs for velocity and correcting for cross-sectional area, the inflow rate at three different zones is derived. No caliper logs are available for the time of the impeller flow-meter logs. Acoustic televiewer data were recorded but before over-drilling of the boreholes, and may, therefore, only be seen as indicative of outbreak zones.

The lower, stable, part of the borehole is used for calibrating the recorded rounds per minute for velocity (Figure 7). A constant diameter (PVC tube) is then assumed for the calculation of the inflow rates. Although the total discharge rate fits well with the discharge rate of the pump, this needs clarification. The drill bit size used was larger than the casing diameter. Taking the average drill bit size for cross-sectional area gives a total inflow rate higher than discharged by the pump. This could indicate that water is lost between the last IFM measurement and the inlet of the pump. When the inflow points are plotted along with the optical televiewer, the first inflow points coincides nicely with a sequence boundary above the reef-slope boundary and implies a change in hydraulic conductivity. The other inflow zones can be linked to outbreak zones in the reefal part.

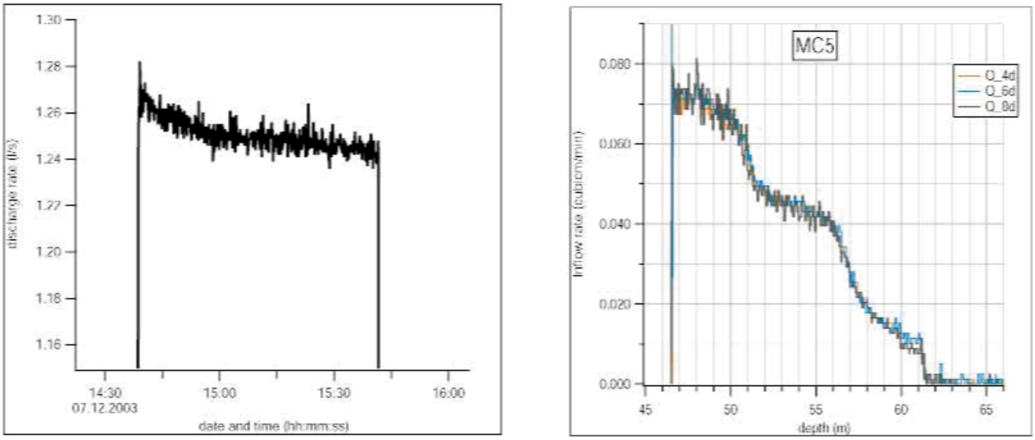

Figure 7. Calculated inflow rates for MC5 and recorded discharge rate during testing (left).

Flowpaths and porosity variability in the proximal slope deposits

Flowpaths are identified from temperature anomalies caused by the injection of drilling fluid (Hearst et al., 2000). The temperature log for MC3 shows most variation, followed by MC1, with less variation in MC4, and almost no variation in MC2 (Figure 8). Theoretically, a temperature log should reflect the geothermal gradient with depth, but most logs will deviate from this gradient because of external influences, the temperature conductivity for different rocks can be different, and drilling may have injected colder or warmer water. As long as steady state is not yet reached, these temperature anomalies may indicate outflow or inflow points, i.e. more permeable parts of the borehole. At Ses Sitjoles, drilling activities would inject warmer water than groundwater in summer and colder water in winter. This injected water penetrates the surrounding aquifer.

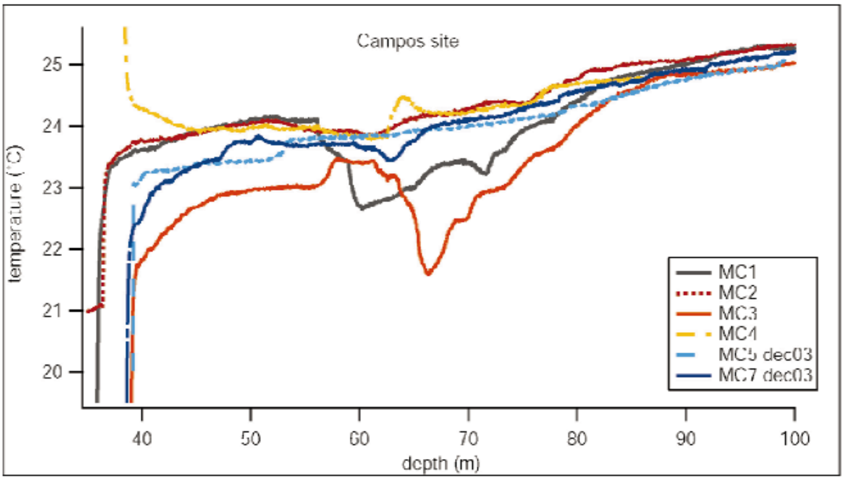

Figure 8. Temperature profile for all boreholes in Campos; MC3 has the largest anomaly at 65 m depth.

As it can be seen from the temperature log for MC3, the temperature anomalies are all negative and overall temperature is lower than temperature logs taken in the surrounding area at the same time (e.g. MC2). As drilling of MC3 was done in winter, the drilling fluid was colder than groundwater. Drilling water is progressively injected into the formation with drilling, with no recovery at surface. It is lost into the formation where it will cool the formation water. As drilling progresses some water would always try and flow upward out from the drill-stem. Water will then enter the first permeable structure it encounters, partly or entirely. In the case of MC3, most drilling water was captured at a depth of 65 m, although some water also entered at lower inflow points. It is only partly captured by the higher more permeable reef deposits because most is lost at 65 m depth. This explains the positive temperature anomaly at 56-63 m, temperature is still lower there than in MC2, but higher than at 65 m depth. Colder water is still escaping, but the water is already heated more than the water in the 65 m permeable feature. The temperature logs, therefore, indicate that the lower slope deposits exhibit changes in permeability that may be of some hydraulic consequence.

For the lower part of the proximal slope we see very little inflow paths, but porosity changes become clear from the formation conductivity logs. Instead of formation resistivity, formation conductivity is recorded because of the high water conductivities at this depth (up to 42,000 μS/cm). This tool records the inverse from the LN (Long Normal) and SN (Short Normal) resistivity. The tool used, has two different coil spacings (see e.g. Hearst et al., 2000 for an explanation on the induction theory) that may compare to a long spaced (81 cm) and short spaced (51 cm) formation conductivity recording. The formation conductivity relates the formation water conductivity and the connectivity of the rock, represented macroscopically by the formation factor. Hence, changes in electrical conductivity may indicate either fluid salinity changes and/or geological changes. Using the ratio of water conductivity and formation conductivity the apparent formation factor is derived, when neglecting the surface conductivity. The double-spaced induction-logging tool (called DIL38) shows that porosity and possibly permeability changes are also strong in the proximal slope deposits (Figure 9).

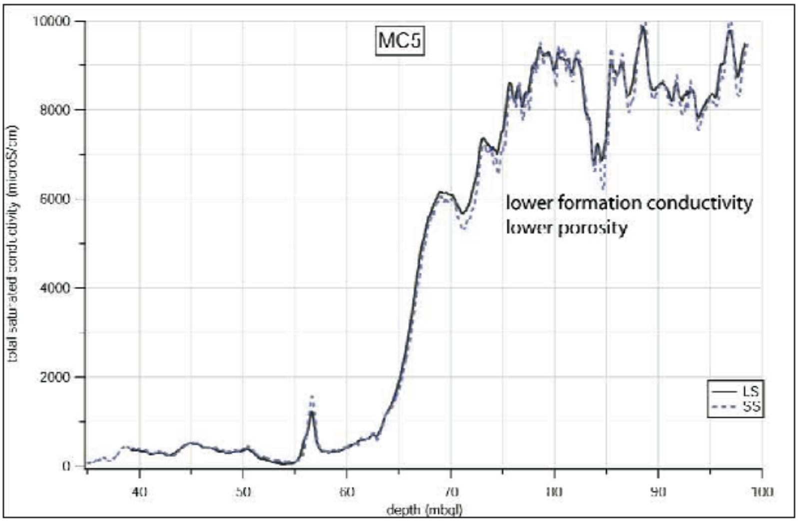

Figure 9. The formation conductivity recorded in borehole MC5, all other boreholes have similar shapes and peaks.

Salinity distribution

Conductivity profiles were taken in every hole at least once (Table 2). More or less the same concentration values and shape is encountered in all the boreholes. Values below 4,000 µS/cm are encountered in the upper reef part of the aquifer from the water table on. Around a depth of 62 m, conductivity values increase towards a maximum value of 42,000 µS/cm at a depth of 75 m (Figure 10). Empirically calibrating the probe for TDS values, the maximum conductivity corresponds to the typical Mediterranean seawater of 35,000 mg/L (Figure 10). Analyses of groundwater samples also confirm the seawater nature of the saltwater. The large interface zone indicates ongoing dispersion of saltwater into fresher water. The fact that the freshest water recorded has a TDS value of around 3,300 mg/L, also points in the direction of ongoing overexploitation. In the regional hydrogeological report (Barón Periz and González-Casasnovas, 1987), the authors claim that the aquifer is already affected by saltwater intrusion and that the main recharge of the aquifer comes from rainwater. Although Mediterranean rainwater has a higher salt content it does not explain values of 3,300 mg/L TDS. The interface starts around the reef-slope boundary, although it does not always coincide, and is sometimes governed by e.g. a sequence-boundary.

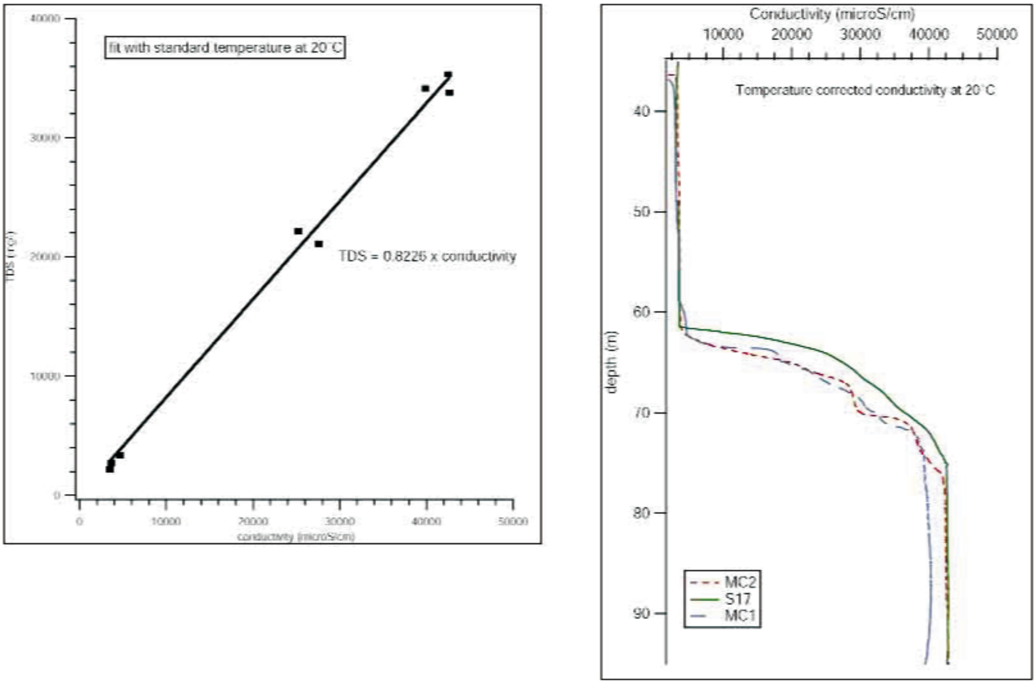

Figure 10. Conductivity profile for a selection of boreholes and the empirically derived relationship between measured conductivity and TDS.

Results and Discussion

The Ses Sitjoles test site is situated in the Llucmajor-Campos hydrogeological unit. The aquifer consists entirely of reefal talus and reef core sediments. This unit is well defined in that it has clear boundaries in all directions, but little is known about its hydraulic properties. Piezometric data are scarce and not continuous. The reef core and talus sediments display a complex architecture as their deposition is controlled by ancient sea-level fluctuations. Four different facies build up the saturated part of the aquifer, (1) outer lagoon, (2) reef core, (3) proximal slope and (4) distal slope deposits. The reef propagated in the south to southwestern direction.

A test site with a total of seven observation boreholes and one pumping well is set up. Boreholes are located at different distances from each other to achieve a multi-scalar test site. A temporary packer system seals off hydraulic short- circuiting, although, in the part of the PVC tubing, this is only partly true. Pressure is monitored in all boreholes at different levels in all boreholes, as well as in two pumping wells on site to give an idea on background groundwater level changes. Core description, thin section studies, and a suite of preliminary geophysical logging (borehole televiewer, acoustic logging) served to build a largely qualitative database and describe differences in porosity (formation conductivity logging).

The impeller flow-meter shows a marked contrast in hydraulic properties between reef core and proximal slope deposits, where the reef core has a much higher transmissivity. Temperature logging indicates preferential pathways in mostly the upper part of the proximal slope deposits, but of a much lower hydraulic conductivity than the reef core. The lower part of the proximal slope deposits has marked porosity changes that are recorded by the formation conductivity. The lowest salinity water has a TDS content of 3,300 mg/L, around the reef-core-slope deposits' boundary salinity increases to 35,000 mg/L, Mediterranean seawater. From a hydrogeological point of view, the reef core forms the most important part of the aquifer.

The Llucmajor-Campos aquifer properties were not well-known, and although we have gained more insight into it, some questions remain that should be addressed. The reef core is responsible for most of the aquifer's transmissivity, even when the slope deposits are also highly transmissive. In such an environment (transmissivity around 0.1 m^2/s), most ordinary hydraulic testing methods fail. No transmissivity, for example, could be derived from the impeller flow-meter logging, because drawdown was too small. This leaves us with only an approximate idea on transmissivity.

Another question refers to the high salinity values in the reef part. A steady increase in salinity has been noticed in the past twenty years, indicating saltwater intrusion, but it is not clear how saltwater enters in the reef core six km inland. Groundwater level monitoring has revealed a monthly cycle sympathetic with sea level tides, indicating that the phreatic aquifer at Ses-Sitjoles may be confined or semi-confined closer to the sea. Another explanation is that sea level tides enter through a karstic pipe. To further investigate the issue of tidal movement and salinity increases, a more regional approach is needed. A rigorous analysis of water level measurements with respect to sea tides is currently worked on. Current research on hydraulic properties focuses on small scale first, from thin sections to borehole scale, before moving upward to site and regional scale.

Conclusion

From the discussion above, some general conclusions can be drawn. Saltwater intrusion has already affected the aquifer at six kilometres distance inland from the sea. Our current observations indicate that saltwater intrusion entered through the reef core, rather than the talus sediments. Therefore, delineation of the reef core on a regional scale is the major challenge for understanding saltwater intrusion in the Campos-Llucmajor aquifer unit. Characterizing this aquifer is not easy, because of its extreme transmissivity. Most known aquifer-testing methods, for example, pumping tests, packer testing etc, fail. Therefore, research into new testing procedures becomes important for understanding the regional transport in this aquifer.

In the near future, a rigorous analysis of the water level measurements so far (one and a half years of data) with respect to sea tides and barometric changes is carried out. Besides this, recorded formation conductivity changes will be linked to changes of porosity, derived from thin sections or permeability changes measured on core plugs in the laboratory. In our opinion, the Ses Sitjoles Site offers a long-term perspective for studying the hydraulic characteristics of and saltwater intrusion processes in a high transmissivity reefal limestone aquifer commonly found in the Mediterranean area.

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References

BARÓN PERIZ, A. and GONZÁLEZ- CASASNOVAS, C., (1987). Hidrogeología de la Isla de Mallorca, *IV Simposio de Hidrogeología*. Servicio Hidráulico de Baleares, Palma de Mallorca (Spain): 83.

CUSTODIO, E., MANZANO, M. and JONES, B.F., (1989). Saline water in the Llobregat Delta aquifers, Barcelona, Spain, *28th International Geological Congress*; abstracts. International Geological Congress, Abstracts: 1355.

FIDELIBUS, M.D. and TULIPANO, J., (1991). Mixing phenomena due to sea-water intrusion for the interpretation of chemical and isotopic data of discharge waters in the Apulian coastal carbonate aquifer (southern Italy). In: G.A. BRUGGEMAN (Editor), *Hydrogeology of Salt Water Intrusion; a Selection of SWIM Papers. International Contributions to Hydrogeology*. Verlag Heinz Heise, Hanover, Germany: 317-327.

FRIEDEL, S., MAURER, H.R., HERFORT, M. and VAN MEIR, N., (In press). Application of geoelectrical single-hole tomography to characterise a coastal aquifer, *SEG meeting*, Denver, Colorado, USA.

HEARST, J.R., NELSON, P.H. and PAILLET, F.L., (2000). *Well logging for physical properties. A handbook for geophysicists, geologists and engineers*. John Wiley & Sons, England, 483 pp.

JEMAI, S., TARHOUNI, J., WALRAEVENS, K. and REKAYA, M., (1998). Historical evolution of the piezometry and salinization of the Korba Aquifer. In: W. DE BREUCK and L. WALSCHOT (Editors), SWIM 15; *Abstracts of papers* *presented at the 15th Salt-water intrusion meeting*. Natuurwetenschappelijk Tijdschrift. Natuur-en Geneeskundige Venootschap, Gent, Belgium: 89–90.

JENKYNS, H.C., SELLWOOD, B.W. and POMAR, L., (1990). *A field excursion guide to the island of Mallorca*. Geologist's Association Guide. London, 93 pp.MAURER, H.R., FRIEDEL, S., JAEGGI, D. and LOEW, S., (In press). Geophysical characterization of a coastal aquifer-initial results, *Annual Near-Surface EAGE Meeting*, Utrecht, The Netherlands.

MOLZ, F.J., MORIN, R.H., HESS, A.E., MELVILLE, J.G. and GÜVEN, O., (1989). The impeller meter for measuring aquifer permeability variations: evaluation and comparison with other tests. *Water Resources Research*, 25(7): 1677-1683.

OUDE ESSINK, G., H., P., (1998). MOC3D adapted to simulate 3D density-dependent groundwater flow., *Modflow'98 Conference*, Golden, Colorado: 291–303.

PAILLET, F.L., (2000). A field technique for estimating aquifer parameters using flow log data. *Ground Water*, 38(4): 510–521.

PANICONI, C., KHLAIFI, I., LECCA, G., GIACOMELLI, A. and TARHOUNI, J., (2001). A modelling study of seawater intrusion in the Korba coastal plain, Tunisia. In: M. KOCH (Editor), *Characterization and Modelling of Variable Density Flow in Groundwater*. Pergamon. Oxford, United Kingdom: 345–351.

PETALAS, C.P. and DIAMANTIS, I.B., (1999). Origin and distribution of saline groundwaters in the upper Miocene aquifer system, coastal Rhodope area, northeastern Greece. *Hydrogeology Journal*, 7(3): 305-316.

POMAR, L.,(1993). High-resolution sequence stratigraphy in prograding Miocene carbonates; application to seismic interpretation. *AAPG Memoir,* 57: 389-407.

POMAR, L. and WARD, W.C., (1995). Sea-Level Changes, Carbonate Production and Platform Architecture: The Lluchmajor Platform, Mallorca, Spain. *Sequence Stratigraphy and Depositional Response to Eustatic, Tectonic and Climatic Forcing*: 87-112.

POMAR, L. and WARD, W.C., (1999). Reservoir-scale heterogeneity in depositional packages and diagenetic patterns on a reef-rimmed platform, Upper Miocene, Mallorca, Spain. *AAPG Bulletin*, 83(11): 1759-1773.

POMAR, L., WARD, W.C. and GREEN, D.G., (1996). Upper Miocene reef complex of the Llucmajor area, Mallorca, Spain. *Concepts in Sedimentology and Paleontology*, 5: 191-225.

VOSS, C., I. and SOUZA, W., R., (1987). Variable density flow and solute transport simulation of regional aquifers containing a narrow freshwater-saltwater transition zone. *Water Resources Research*, 23(10): 1851–1866.

YECHIELI, Y., (2000). Fresh-saline ground water interface in the western Dead Sea area. *Ground Water*, 38(4): 615–623.