An oceanographic survey for the detection of a possible Submarine Groundwater Discharge in the coastal zone of Campo de Dalias, SE Spain

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Abstract The Campo de Dalías, in south-eastern Spain, is an area of important economic activity linked to agriculture and tourism, both of which have exacted fierce exploitation of aquifer water. The recovery of one of these aquifers in recent years has even triggered fresh water discharges into the sea. An oceanographic survey was undertaken along the coastline in order to detect possible Submarine Groundwater Discharge (SGD). Salinity and temperature data were collected on the seasurface, as well as in 51 vertical profiles. These results suggest the existence of a thermohaline anomaly in the area of the port of Aguadulce possibly due to submarine groundwater discharges.

1 Introduction

Submarine Groundwater Discharge (SGD) can be defined as the flow of water through continental margins from the seabed into the ocean, independent of the flow mechanism or chemical composition (Burnett et al. 2003; Moore 2010; Johannesson et al. 2011). In this context, SGD can derive both from fresh water originated from meteoric recharge to terrestrial aquifers (due to differences in hydraulic head), and from salt water derived from recirculation of seawater in coastal aquifers (due to tides, ocean swell, density and geothermal gradients (Taniguchi et al. 2002; Kim and Swarzenski 2010).

The main methods for detecting SGD are infiltration counters, hydrogeological models, natural tracers (Ra, Rn, CH_4 and salinity), numerical models and airborne or satellite thermal imaging (Burnett et al. 2006; Charette et al. 2001; Kim and Hwang 2002) and marine remote sensing techniques (Christodoulou et al 1993, Karageorgis et al 2011). Additionally, recent studies have demonstrated that the spatial distribution of SGD can also be studied using sediment resistivity profiles

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(Viso et al. 2010; Henderson et al. 2010). Each of the above mentioned methods has its advantages and disadvantages. Thermal imaging, resistivity profiles and marine remote sensing techniques can not quantify the discharge, but they do identify it and provide information for its spatial distribution.

The specific hydrological situation of the Southern Basin in Spain, with its unfavourable water balance, makes it necessary to understand all water resources of the area in detail, including SGD. For this reason, since the 1970s, numerous studies have been carried out to develop techniques for locating and quantifying upwelling of groundwater water through the seabed (Espejo et al. 1988). In 1988, the Confederación Hidrográfica del Sur de España, in collaboration with Empresa Nacional Adaro de Investigaciones Mineras, S.A., used infrared remote sensing of electromagnetic radiation to determine surface thermal anomalies that could be attributable to SGD along the coast of the Southern Basin. Moreover, this survey was complemented by meteorological, oceanographic and hydrogeological data. This multidisciplinary survey showed the existence of a thermal and salinity anomaly in the marine environment of Aguadulce which is probably related to a SGD.

This aquifer has been subject to fierce exploitation, with the consequent decline in piezometric levels. The visible springs close to Aguadulce port dried up and the wells in the area began to be affected by what seemed to be marine intrusion (Molina et al. 2002, Morell et al. 2008). Water levels in the aquifer are now recovering as a result of the abandonment of some salinized wells, and the decrease in the groundwater abstractions in this sector due to deteriorating water quality, and improved regulation of these water resources.

Although in the study area has been a previous study (Espejo et al. 1988), this was carried out at the regional scale and mainly using remote sensing techniques. This paper focuses on a particular sector of the Andalusian coast using data from an oceanographic survey and it aims to verify possible SGD in the Aguadulce sector, by means of a survey of temperature and conductivity of coastal waters.

2 Hydrogeological framework

The Campo de Dalías coastal plain is situated in the extreme south-east of Spain, to the west of the bay of Almería. It covers an area of about 330 km^2 and traces the coastline for about 50 km. Its northern limit is in the foothills of the Sierra de Gádor, whilst the other borders are coastal (Fig. 1). The importance of intense agriculture practised in this area is fundamental for the local economy. Campo de Dalías includes about 20,000 ha of cultivated ground. In addition, the population has grown from 8,000 inhabitants in 1950 to more than 120,000 at present. Tourism also plays an important role in the local economy. Together, these factors have lead to an alarming growth in the water demand in this part of Almería.

Three hydrogeological units are distinguished: Balerma-Las Marinas, Balanegra and Aguadulce (Fig. 1). The Aguadulce aquifer unit has a complex geometry as a consequence of the lithological diversity and structure of the area (Pulido et al. 2000). The carbonate strata of the Felix nappe are highly developed and overlie the thicker Gádor nappe. A layer of phyllites separates the two units, making two distinct aquifer layers. Miocene calcarenites overlie the carbonate layers of both nappes and are in hydraulic connection with these; Pliocene calcarenites and other more recent detritic sediments can also be found, which also behave as aquifers.

Thus, three aquifers occur in the area: an upper aquifer consisting of Pliocene calcarenites together with Plioquaternary detritic materials and two carbonate aquifers: one corresponding to the Felix carbonate strata and the other comprising the Gádor carbonate rocks, which extend to depth. Overall, there is a sequence of formations separated by layers of low permeability. The intense fracturing favours hydraulic connection between the various aquifer levels, which, under a natural regime, would show the same piezometric level. However, overexploitation of the unit has given rise to a difference in levels, depending on the cross-section.

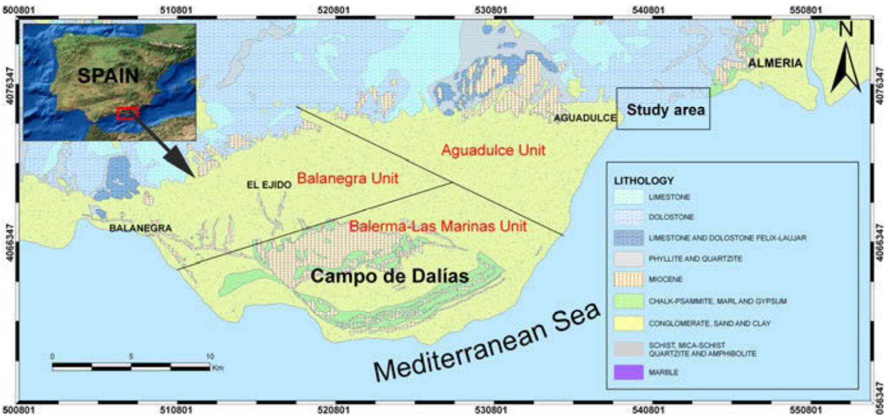

Fig. 1. Hydrogeological map of the study area.

3 Methods

In December 2010, an oceanographic survey was undertaken by the company CITECAM and the Water Resources and Environmental Geology Research Group of the University of Almería. The survey was designed to measure physical characteristics of the seawater in order to map the thermohaline structure of a zone from the port of Aguadulce to a point that is 5.6 Km eastward to the port (Fig. 2). Surface measurements were made using a SBE 45 Thermosalinograph, while conductivity, temperature and pressure measurements through the water column were made using a SBE 25 Sealogger CTD.

The survey transects have a total length of 23 km, and the surface thermoaline data was collected at a constant depth of 20-30 cm every 10 seconds with a velocity of 4 knots. Fifty-one (51) vertical profiles of temperature and conductivity from the water surface to the sea bed were carried out using CTD.

Data treatment was consisted of an initial calculation of statistical parameters in order to check goodness of fit and confidence intervals. Then the data were analysed using the Ocean Data View (Schlitzer 2007) and Arcgis 9.3 software. Furthermore, the data was treated statistically by cluster analysis.

Additionally, we used other derived variables, such as potential temperature and potential density. Potential temperature is used to compare waters taken from different depths or when vertical movements during the measurement procedure have to be taken into account, so avoiding the influence of compressibility of the water. Potential density allows a better estimate of the density difference between two water types. Using the Ocean Data View software, vertical temperature and salinity profiles were produced for all the sampling points, as well as T-S diagrams.

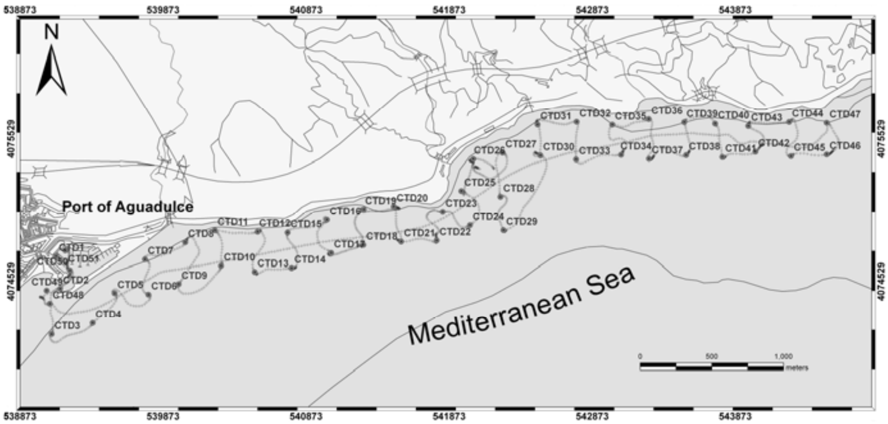

Fig. 2. Map showing the location of sampling stations.

4 Results and Discussion

Surface water analysis

The cluster analysis based on seawater temperature and salinity values showed that five seawater classes can be defined in the study area (Table 1).

Table 1. Statistics of each seawater class identified by cluster analysis of thermohaline data.

Class	Code	Nº of cells	Average Temperature	Average Salinity	Covariance
1		11	16.04	36.11	0.00628
2		57	15.68	37.01	-0.00045
3		64	15.89	37.02	0.00024
4		60	16.04	37.00	0.00010
5		32	16.19	36.99	0.00022

Class 1 is characterised by much lower values of salinity than the other groups, and correspond to the water inside the port of Aguadulce (Fig. 3). Classes 2 to 5 differ from each other mainly on the basis of temperature; a clear and continual increase of temperature was observed from the port of Aguadulce to the east (Fig. 3). The relationship between the variables is more significant in Class 1. In the other classes, the two variables are statistically independent, which allow us to suggest that the temperature changes were not linked to salinity changes, but rather to the diurnal pattern of insolation.

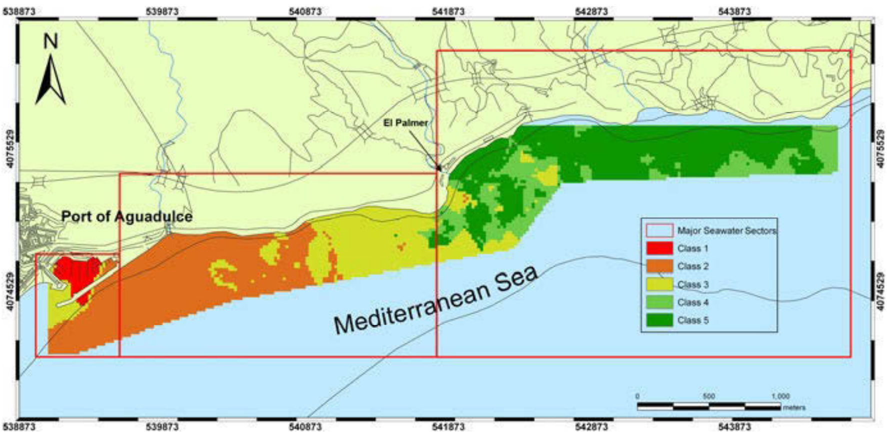

Fig. 3. Map showing the five (5) seawater classes produced by the cluster analysis on the basis of temperature and salinity values.

This interpretation leads to a simplified classification scheme consisting of three major seawater sectors in the survey area (Fig. 3). The first sector corresponds to Aguadulce port and is dominated by water belonging to class 1, whose salinity is lower than at the remaining sites. Class 1 salinity does not correspond to typical values for seawater in the Mediterranean at this time of year, and this suggests that there is an input of continental water within the confines of the port. The second sector extends from outside the port to El Palmer and is dominated by water classified in classes 2 and 3. The third sector is dominated by classes 4 and 5 and corresponds to the easternmost zone of the survey area. In this sector, only isolated anomalies were detected at certain points, which could be due to some continental inflows, possibly from urban wastewater discharges along the coast (Fig. 3).

The data exhibited a thermosaline anomaly in the area of Aguadulce port. This accords with the presence of a SGD, since the date of the survey (December 2010), the seawater temperature was around 15.5 ºC, which was below the 21.5 ºC measured in springs and boreholes in the aquifer. The salinity measurements also showed an anomaly.

Water column analysis (CTD)

The interpretation of the CTD data was done taking into account the three major sectors defined by the cluster analysis. CTD data showed that the stations located outside from the port exhibit almost similar temperature and salinity profiles. In these stations the seawater was significantly colder and more saline than the stations inside the port. This can be also observed in spatial distribution of salinity at the seasurface (Fig. 4d).

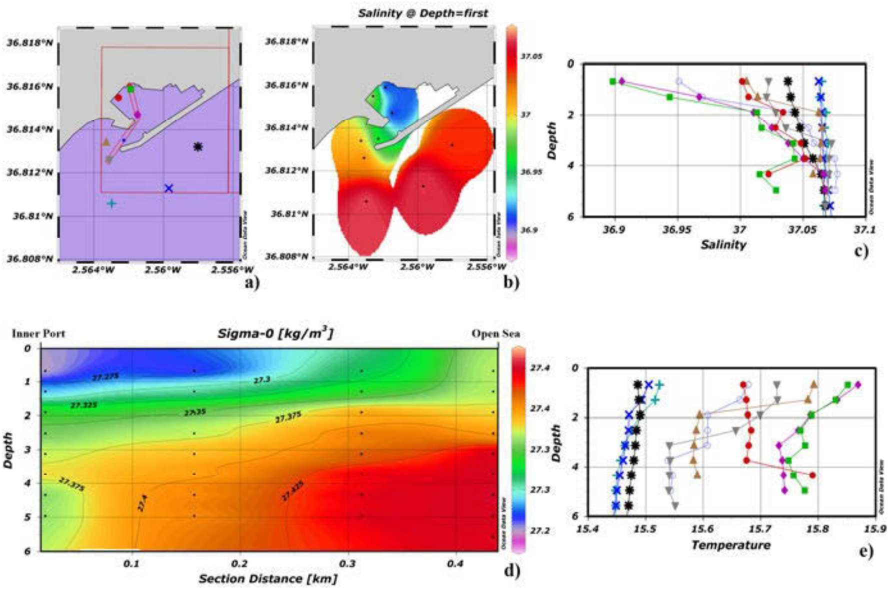

Fig. 4. Graphs resulting from CTD data. a) location of sampling stations; b) temperature and salinity profiles c); d) surface salinity map; e) potential density cross-section.

The potential density profile along a transect from the inner part of the port to the open sea clearly shows a band of lower density inside the port with the lowest values at the sea surface (1m) (Fig. 4e). This band of lower density is typical of seawater that is receiving inflows of continental fresh water (Stewart 2009).

The sectors 2 and 3, identified on Fig. 3, show values in-keeping with what is expected in the Mediterranean Sea at this time of year. There are only small anomalies at depth, which may be attributable to anthropogenic inputs as uncontrolled water waste discharges from the land, although submarine freshwater discharges cannot be ruled out.

5 Conclusions

The oceanographic survey undertaken over the 5.6 km between Aguadulce port and the city of Almería deduced a thermohaline anomaly in the vicinity of Aguadulce port, consisting of markedly lower salinity and higher temperature than for seawater. The temperature and salinity values obtained are typical of coastal waters that receive inflows of continental water. This discharge also appears in 1988, but during the nineties and early 2000, the entry of seawater, cooler and more saline waters into the aquifer were clearly detected by means of groundwater temperature and electrical conductivity logs.

The thermohaline anomaly occurred the last years may have been established due to the recent recovery of water levels in the aquifer, following a decline in the quantity of pumped abstractions as a result of worsening water quality, and because a new desalination plant now covers part of the water demand for the Campo de Dalias.

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