Groundwater Quality Monitoring in a Coastal Mediterranean Aquifer Affected by Agricultural Contamination and Seawater Intrusion-Extrusion Processes (Vélez River, Andalusia, Spain)

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ABSTRACT

Water quality conditions have been assessed in the Río Vélez coastal aquifer (Andalusia, South Spain: an area of important agricultural and touristic development). This shallow fluvio-deltaic aquifer consists of coarse detrital deposits, of Quaternary age, that extend over about 20 km², being subdivided in two sectors –fluvial and deltaic- by a substratum elevation. The deltaic sector is highly vulnerable to seawater intrusion, but during periods of severe drought the substratum elevation prevents the advance of the salt water to the fluvial sector. Permeable and sandy deposits -that generally underlie the cropping areas of the inland sector- provide favorable conditions for vertical leaching of nitrate to the aquifer. Nitrate concentrations exceed the maximum contaminant level (MCL) for drinking water of 50 mg/l established by the European Community in almost all the wells sampled in the aquifer, with an average value of 85 mg/l and maximum up to 400 mg/l. In addition, the construction in the 1990s of a dam upstream has resulted in a decrease in aquifer recharge and in a significant advance of salt water intrusion during the 1991-1995 period. The 1996 to 1998 abnormally humid period has led to an effective flushing of the deltaic aquifer. At present, the main objective of hydrological policy is to use the reservoir to supply water for both irrigation and human consumption, and to stop pumping from the aquifer to prevent new episodes of marine intrusion. In addition, a careful management of agricultural practices is needed in order to improve water quality in the aquifer, which is considered as a freshwater reserve.

INTRODUCTION

The Río Vélez fluvio-deltaic aquifer is situated in the Mediterranean coast of Andalusia, S. Spain, some 40 km east of Málaga, and extends over the lowest sector of a 610 km² watershed (figure 1). The economy of this region is based on tourism and a profitable agriculture specialized in subtropical (mainly avocado trees) and out-of-season crops.

Two main consequences of the semi-arid Mediterranean climate of the area have to be emphasized due to their influence on groundwater quality: a) the seasonal scarcity of surface water resources when the water requirements are highest (normally from June to September), and b) the irregular year-to-year distribution of rainfall and runoff generation. Both circumstances –which are graphically shown in figure 2- recommend the regulation of water resources.

The first approach to fit the water demand with its availability was based on pumping the aquifer. This specially happened during the last 70s and 80s decades, and was made without appropriate control. At the same time, an alternative scheme based
on the regulation of the surface water resources was under study and construction (La Viñuela reservoir system).

La Viñuela reservoir system, located at the head of the Vélez river, is integrated by the La Viñuela dam and the diversions from the main rivers in the watershed. It currently regulates an area of 440 km², about 70% of the total surface. Since the La Viñuela reservoir started functioning in 1989, the downstream coastal aquifer has experienced a decrease in its water resources. This fact, together with the scarcity of rainfall in the first half of the 1990s and the increased groundwater extractions, led to a considerable decrease of the piezometric levels in the alluvial

Figure 1: General situation, major populations and main hydrological features of the Vélez River watershed.
aquifer. During the summer of 1995, a significant advance of the salt water wedge was registered and the water shortage due to severe drought was aggravated by a deterioration in the water quality, causing urban supply problems and losses in some crops.

The important rainfall recorded during the period 1996-1998 (figure 2) improved considerably this situation. The volume of water in the La Viñuela reservoir almost reached its maximum capacity in spring 1998. The piezometric levels quickly raised and the salt water wedge flushed considerably. During the last few years, the reservoir has supplied water for both irrigation and urban use, thus the pumping of freshwater from the aquifer has almost stopped.

![Figure 2: Graphical summary of precipitation distribution in the studied area: evolution of yearly values and long term average (left); monthly averages (right). Note the drought of the 1991-1995 period followed by three abnormally wet years. The data correspond to a station located in a central position of the watershed.](image)

At present, the aquifer has not significant marine intrusion evidences but an outflow from the dam sufficient to maintain a subterranean discharge to the sea is necessary in order to get a long-term control of this problem. In addition, the intensive agricultural practices over the extension which surrounds the aquifer involves the application of high doses of fertilizers, with a consequent deterioration of groundwater quality.

In this paper, the aquifer functioning and the modifications of groundwater quality as result of the current hydrological policy in the region are summarized.

**HYDROGEOLOGICAL SETTING**

The Río Vélez aquifer is made up of quaternary deposits (mainly gravel and sand) that extend over about 20 km². These sediments of fluvial origin have given rise to the development of a delta in recent times (at the end of the XVth century, there existed an estuary up to Vélez Málaga; the filling of this estuary was consequence of enhanced erosion in the watershed following the settlement of new farmers after the
expulsion of the Moors). In this coastal part of the aquifer, the presence of impervious silt and clay levels leads to distinguish two superposed units: an upper unconfined and a lower confined aquifers [CHSE, 1987].

The substratum and borders of the aquifer are metapelitic materials from the Internal Zones of the Betic Cordillera as well as Pliocene silts and silty clays, all having very low permeability.

A geometrical feature of the aquifer of hydrogeological importance is the existence of a very narrow section at around 4 km from the coast. This coincides with an elevation in the substratum which has an altitude close to sea level. As a result of this, two sectors of the aquifer can be easily distinguished: the fluvial sector and the coastal sector, which can become independent during times of severe drought due to general piezometric decrease. This situation is advantageous from a hydrogeological point of view as it makes it impossible for salt water wedge to intrude upstream from this area.

The average thickness of the permeable materials is around 30 m. The greatest thickness appears in the central sector, in the confluence of the rivers Vélez and Benamargosa, where it reaches 65 m, and in the delta sector, with a thickness of over 60 m, increasing significantly towards the sea. The average hydraulic conductivity is 70 m/day, ranging from 30 to 300 m/day [CHSE, 1997]. The storage coefficient values are comprised between $10^{-1}$ and $10^{-2}$.

The isopotentiometric lines included in figure 3 illustrate about the general trend of flow through the aquifer. Hydraulic gradients decrease towards the final sections of the fluvial part. In the deltaic sector, piezometric levels were slightly above or below the sea level during the period to which the measurements refer.

The average precipitation in the watershed is around 600 mm/year and the rainfall occurs mainly between November and April (figure 2). The metapelitic materials present a high run-off coefficient, meaning that a large part of the net rainwater which falls here contributes to feeding the surface drainage network.

The aquifer is mainly recharged by the stream flow of the rivers Vélez and Benamargosa. The water from irrigation returns also contributes, particularly in those areas in which the irrigation by gravity technique is still used. The main discharge from the system corresponds to groundwater withdrawal in over 400 wells, with an average of 30 hm$^3$/year, to which surface and groundwater discharges into the sea along the coastline must be added [CHSE, 1997].

**GROUNDWATER QUALITY**

The groundwater quality has been monitored mainly from a network of more than thirty wells and boreholes selected to provide information from both the fluvial and the deltaic sectors of the aquifer. During the 1993-1995 period, a monthly control of piezometric level and hydrochemical parameters has been carried out [García-Aróstegui, 1998].

Figure 3 shows the hydrochemical spatial variability of the aquifer registered in July 1994. Groundwater chemistry is illustrated by polygonal Stiff diagrams, and mineralisation is represented by electrical conductivity values. As a general trend, the mineralisation increases along the groundwater flow path. Local maximum values are registered in the central part of the alluvial aquifer due to a significant water
recirculation process (cycles of pumping-irrigation-infiltration), but the highest contents are located in the deltaic sector, which indicate saline intrusion affecting this part of the aquifer.

Figure 3: Spatial variations of the main hydrochemical features of the aquifer. Isopotentiometric lines are also shown (values in m a.s.l.). The situation depicted corresponds to July 1994.
Electrical conductivity ranges from 400 µS/cm to 2000 µS/cm in the fluvial sector. In contrast, in the deltaic sector, it remains mostly above 3000 µS/cm, with average values around 4000 µS/cm and maximum up to 29000 µS/cm. These maximum values are related to salt water intrusion in the vicinity of the shoreline and to the upconing of the interface caused by intensive pumping in the inland zone of the deltaic sector.

Piper plot of groundwater samples collected monthly during the 1993-1995 monitoring period is presented in figure 4 and complements the previous figure. This diagram clearly shows the significant geochemical differences between the fluvial sector and the deltaic sector. In the headwater part of the fluvial sector, groundwater of Ca-HCO₃ type is associated to the lowest mineralisation values. This reflects the dissolution of carbonate aquifers which made up most of the watershed boundaries, then drained by a number of springs that are the responsible of the Vélez river baseflow and impose their chemistry to the alluvial aquifer in its headwater sector. The flow along the fluvial aquifer is accompanied by a general increase in the Mg/Ca and SO₄/HCO₃ ratios, but bicarbonates and calcium maintain its prevalence.

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Figure 4: Piper plot of groundwater samples collected during the 1993-1995 period. Symbols refer to the location of samples in one of the two main sectors of the aquifer.
In the deltaic sector, the geochemical facies of ground waters varies widely from the Ca \text{SO}_4-HCO_3 type to Ca-Cl and Na-Cl types, with high salinities, especially in the western part of the confined aquifer, where marine intrusion has been more important. Figure 4 shows that in this sector water types are distributed following a mixing line between sea water and the most mineralized facies of the fluvial aquifer. Dispersion from the mixing line appears mainly related to the central area of the deltaic deposits and, as expected, most of the samples in this aquifer show a surplus of Ca$^{2+}$ that indicates seawater intrusion.

Among the factors contributing to the deterioration of groundwater quality, attention should be drawn to the anthropogenic pollution concerning mainly two groups of substances: nitrates and pesticides. Nitrates pollution is widespread through much of the aquifer and it is related to the massive presence of intensive agriculture and extensive use of inorganic fertilizers and manner and also with irrigation with wastewater.

Nitrogen application to improve crop production has been very high in the last decade, with rates of around 400 kg/ha/a of nitrogen, applied mainly from November to April [García-Aróstegui et al., 1996a].

During the first half of the 1990s, the average nitrate concentration for the aquifer was 85 mg/l, with nitrate contents above 50 mg/l in most of the wells. Nitrate pollution reached its highest levels (over 200 mg/l) in the central part of the fluvial sector, where the materials appear to be the most vulnerable, and in the deltaic sector, where land utilisation is the most intense.

Other factors that affect nitrate concentration are the rates of irrigation and infiltration. In fact, the maximum concentrations recorded during the 1990 decade appear connected to the humid period registered in 1996-98. The intensive precipitation favoured the lixiviation of the excess in nitrogen accumulated in the soil zone during the dry previous years, leading to local nitrate contents in groundwater above 400 mg/l and average contents in excess of 100 mg/l in the deltaic aquifer. At present, there is a background level throughout the aquifer that is frequently above the maximum contaminant level (MCL) for drinking water established by the European Community.

As regards pesticides, their presence has been revealed during the 1993-94 period, in coincidence with a more rigorous analytical testing [García-Aróstegui et al., 1996b]. The polluting substances derived from herbicides (simazine) and insecticides (metilparathion, metidathion and dimetoate). Although the concentrations were typically below the MCL (0,1 $\mu$g/l per individual substance), their presence is of concern because of the persistence of these kind of contaminants.

**SALT WATER WEDGE EVOLUTION**

As indicated above, the persistent drought during the first half of the 1990s and the increasing exploitation of groundwater reserves have produced a considerable decline in the potentiometric surface of the aquifer, accompanied by seawater intrusion in the deltaic sector [García-Aróstegui et al., 1998].

The reduced thickness of the deltaic unconfined aquifer avoids the development of a well-defined fresh water-salt water front and the conductivity logs indicated the existence of brackish water in the whole upper aquifer. Even in some
cases, electrical conductivity was higher in the shallowest water levels, as a consequence of lixiviation of solutes from agricultural practices, mainly nitrates and sulfates.

Before 1990 no evidences of saltwater intrusion were found in the deltaic confined aquifer [CHSE, 1987]. During the 1993-95 period, the fresh water-salt water interface has been registered in this aquifer at significant heights above the substratum, even in boreholes located at more than 1.5 km inland [García-Aróstegui, 1998]. This situation is illustrated in figure 5 by mean of the electrical conductivity values recorded in October 1993 and November 1994 in a fully-screened borehole drilled at 1 km from the shoreline.

In spite of the critical salinization reached in the summer of 1995, the rainy period beginning in 1996 produced important modifications in the interface position. The logs in figure 5 show clearly the change in the fresh water-salt water relationships in the confined aquifer. The conductivity profile in March 1996 shows the situation in a period of abundant groundwater recharge, with a significant improvement of the groundwater quality and a retreat of the salt water wedge.

This flushing process has continued and the salinity records in January 1997 showed conductivity values lower than 2000 µS/cm in all the inner part of the deltaic aquifer. Almost the same scenario still appears in January 2001 (figure 5). Figure 6 shows that this situation of groundwater quality improvement in the confined deltaic aquifer is clearly related to the rise of piezometric levels.
At present, the potentiometric surface in the confined aquifer is at its historical maximum and many boreholes present flowing artesianism. This is due to an important decrease in the extractions and an increase in irrigation return flow.

CONCLUSIONS

In the Mediterranean southern Spain, the first half of the 1990s decade has been characterized by a severe drought. Consequently, the groundwater extraction from the Vélez river aquifer has experienced a very important increase in order to satisfy the water demand for both irrigation and urban supply. Furthermore, the aquifer recharge has diminished during this dry period due to the starting of functioning of a reservoir system upstream, which has made practically nil the infiltration of stream water. This situation has favoured the salinization of most of the deltaic sector of the aquifer by seawater intrusion.

Apart of the above mentioned process, the groundwater quality deterioration during this period is also related to the intensive agricultural practices, with application of very high doses of fertilizers.

The abnormally humid period registered during 1996-1998 has considerably enhanced the aquifer recharge and, in addition, the pumping rates have been reduced. As regards salinization, the subsequent rise of the piezometric levels produced a very effective seawater extrusion process and the improvement of groundwater quality. However, nitrate content has reached its maximum values because the lixiviation of the excess accumulated in the unsaturated zone during the drought period. This situation continues at present.

References


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