THE COMBINED USE OF HYDROGEOLOGICAL AND HYDROCHEMICAL DATA TO EXPLAIN THE OBSERVED GROUNDWATER COMPOSITION UNDER IRRIGATED LAND IN THE CAMPINA DE FARO, ALGARVE

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ABSTRACT

In the Campina de Faro, Algarve, agricultural practices have a large impact on the groundwater composition. Nitrate concentrations have risen profoundly due to the extensive application of fertilisers. Excess water originating from irrigation practices returns to the aquifer and mixes with water from the regional groundwater system. This irrigation return flow is strongly concentrated due to high evapotranspiration and flushing of fertilisers. The concentration increase induces calcite precipitation and cation exchange, whereby Ca on the soil exchanger is replaced by Na. With a geochemical model this hydrochemical evolution can be simulated. The mixing in the aquifer allows application of a mixing cell model, that may then be used to calculate transmissivities and the change of the Cl concentration in time from the Cl mass balance. Results from the calculations appear to be in good agreement with hydrochemical observations. Near the coast, large drawdowns cause sea water intrusion, which increases Cl concentrations and induces cation exchange.

Keywords: hydrogeology, water balance, mass balance, evapotranspiration, calcite precipitation, cation exchange, mixing cell

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USO COMBINADO DE DADOS HIDROGEOLÓGICOS E HIDROQUÍMICOS PARA EXPLICAR A COMPOSIÇÃO DA ÁGUA SUBTERRÂNEA OBSERVADA NOS TERRENOS IRRIGADOS DA CAMPINA DE FARO, ALGARVE

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RESUMO

Na Campina de Faro, Algarve, práticas agrícolas têm grande influência na composição das águas subterrâneas. As concentrações de nitratos aumentaram fortemente devido à aplicação extensiva de fertilizantes. A água em excesso, proveniente das práticas de irrigação, volta ao aquífero e mistura-se com a água do sistema regional de água subterrânea. Esta água é fortemente concentrada devido à elevada evapotranspiração e à lavagem de fertilizantes. O aumento da concentração induz a precipitação de calcite e a troca catiónica, sendo o Ca substituído pelo Na no complexo de troca do solo. É possível simular esta evolução hidroquímica através de um modelo geoquímico. A mistura de águas no aquífero permite a aplicação de um modelo de 'mixing cell', que pode ser usado para calcular as transmissividades e a alteração da concentração de Cl no tempo, através do balanço de massa de Cl. Os resultados dos cálculos encontram-se aparentemente de acordo com as observações hidroquímicas. Perto da costa, a sobreexploração dos aquíferos provoca a intrusão da água do mar o que aumenta a concentração de Cl e induz a troca catiónica.

Palavras-chave: hidrogeologia, balanço de água, balanço de massa, evapotranspiração, precipitação de calcite, troca catiónica, mixing cell

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1 - INTRODUCTION

It is generally known that agricultural practices, defined by Sharma *et al.* (1985) as the sum of actions applied by the farmer to reach yield, can form a serious threat to the quality of groundwater. One of these practices, extraction of groundwater for irrigation, can have hazardous effects in coastal areas due to the danger of sea water intrusion. This is especially true for areas with a Mediterranean climate where the growing season, with its high water demand, coincides with the dry period (Calvache & Pulido-Bosch, 1994; Rozycki, 1996). A further widespread agricultural practice is the use of fertilisers, with a strongly polluting effect on groundwater. The use of nitrogen in particular as a fertiliser is well established throughout the world and increased use has led to extremely high nitrate concentrations in many groundwaters, which can cause serious health problems.

Although the influence of agricultural practices is well known, little is known about how these eventually affect groundwater quality. Various hydrochemical processes can take place and it is the combination of these processes that determines groundwater composition. Numerous studies have dealt with some of the processes separately (e.g. MAGARITZ & NADLER, 1993; MCCARTHY & ELLERY, 1994; COLLINS & JENKINS, 1996). This article discusses the combined effect of the hydrochemical processes in an agricultural area near Faro. An attempt is made to quantify this effect and determine the actual relative contribution of each process to the final groundwater composition. One of the more remarkable processes that is found to occur here is cation exchange due to evapotranspiration. The hydrochemical investigation is combined with a hydrogeological inventory to obtain additional information on the groundwater head distribution and groundwater flowpaths. Data from both studies are combined in a mixing cell approach that is used to calculate groundwater flow components, transmissivities and the change of Cl in time.

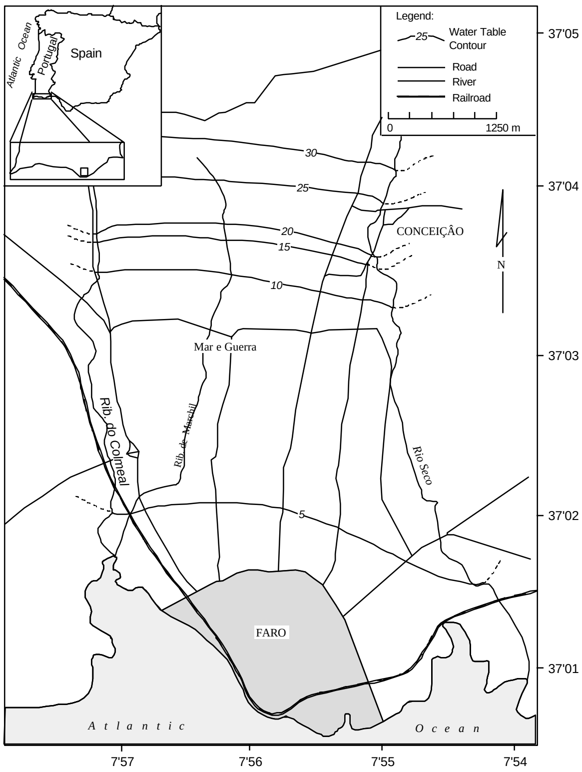

Figure 1: location of the study area; also shown are the groundwater level contours.

Figura 1: localização da área de estudo; também se mostram as isopiezas.

2 - STUDY AREA

2.1 - Characterisation

The study area, which is known as the Campina de Faro, is located directly north of the city of Faro in the Algarve (figure 1). It measures approximately four by six kilometres and is bordered by the Atlantic Ocean in the south, the river Ribeira de Colmeal in the west and the river Rio Seco in the east. The northern boundary marks the end of the area with intensive agricultural activities. Elevations increase from 2 meters above sea level in the south to 40 meters above sea level in the north. The topography is generally rather flat, an exception being the hill on which the city of Faro has been built, which is associated with diapiric activity (Silva *et al.*, 1986). The area has a warm Mediterranean climate with a mean annual air temperature of 16.3 °C and a mean annual precipitation of 531 mm (LOUREIRO & COUTINHO, 1995). A large part of the original vegetation (stone and cork oaks and Carob trees) has been replaced by olive and almond trees and irrigated agriculture (mainly citrus fruits, grapes and tomatoes). Pine trees are found on poor, calcite-free, soils along the coast.

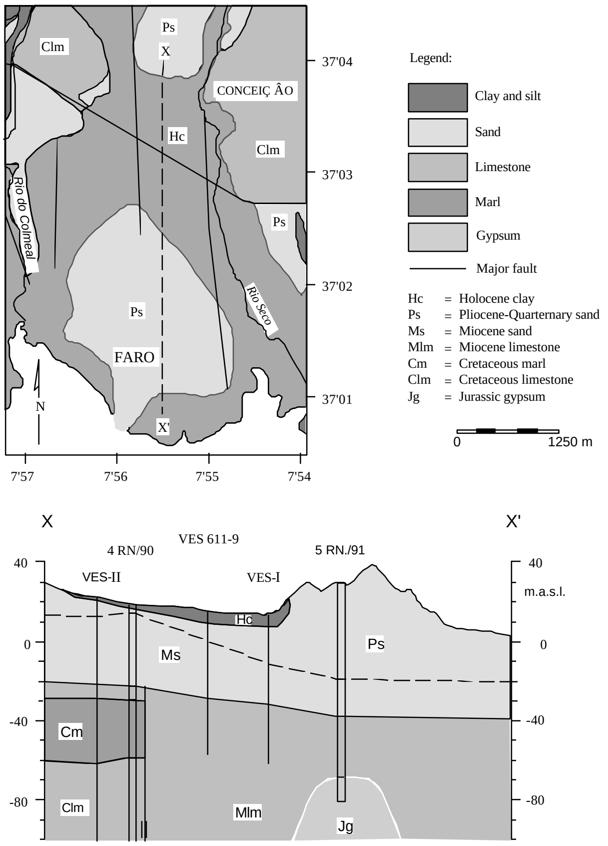

Figure 2: geological map and N-S cross section of the study area.

Figura 2: mapa e perfil geológico N-S da área de estudo.

2.2 - Geology and hydrogeology

A geological map and a representative N-S cross section are shown in figure 2. The oldest sediments in the study area are Cretaceous marls and limestones that dip to the south. They crop out in the north-western part of the area and the top of the sediments is found at a depth below 200 meters near the city of Faro. A graben-like structure formed at the end of the

Cretaceous in which Miocene limestones and, in a later stage, sands and marls were deposited (SILVA, 1988). The Miocene sediments dip to the east, but due to the presence of several N-S faults a stepwise structure is found (SILVA *et al.*, 1986; SILVA, 1988; ANTÃO, personal communication, 1996). The depth of the upper boundary varies between 3 and 25 m below surface; the presence of the marls appears to be very irregular (SILVA, 1988). Sands and gravels of Pliocene to Quaternary age cover the Miocene deposits and crop out in the Northwest and near the city of Faro. Their thickness varies between 8 and 50 meters but in some parts of the area the thickness is less due to fluvial and marine erosion that took place during the Holocene. In these eroded parts, the youngest sediments have been deposited. They consist of Holocene silts and clays of marine, fluvial and alluvial origin which can reach a thickness of up to 10 meters.

Three aquifers are discerned in the Campina de Faro. The first aquifer system is formed by Cretaceous limestone layers which are separated by marls. The transmissivity of this aquifer, as determined from a pumping test, amounts to 311 m2/d near the village of Mar e Guerra. Miocene limestones form the second aquifer, which increases in thickness from north to south (SILVA, 1988), and the Miocene, Pliocene and Quaternary sands make up the third. There is little information on the hydraulic characteristics of these last two aquifers; SILVA (1988) reports transmissivity values between 140 and 285 m2/d for the Miocene limestones. Although the sandy aquifer is partly overlain by Holocene clays and silts, it is still considered phreatic, because the thickness of these deposits is often too small to give the aquifer a confined character.

The general direction of groundwater flow is from north to south. Infiltration of rain water takes place in the Jurassic and Cretaceous limestones north of the Campina de Faro and provides abundant water for irrigation in cultivated areas near the coast. Solute concentrations increase from north to south due to strong evapotranspiration of irrigation water and irrigation return flow. The combined use of noras and furos causes comprehensive mixing in the aquifers.

3 - METHODS

During a field campaign in April and May of 1996, 71 domestic wells were sampled. Their location is shown in figure 3; 45 of these wells were so-called noras (shallow wells with a large diameter) and 26 wells were furos (deep drilled wells). Groundwater level, pH, EC and temperature were measured for each well and a qualitative estimate of NO_3 was made in the field. For most wells Cl, HCO_3, Ca and Mg were analysed locally. Thirty-six wells were sampled for a more detailed analysis at the laboratory of the Vrije Universiteit in Amsterdam. Thirty of the 36 wells were also sampled for isotope analysis of 18O and 2H at the Centre for Isotope Research in Groningen, The Netherlands. In September 1996, 16 additional samples were taken.

4 - RESULTS

A classification has been made into five different water types, based on the chemical data and well information such as location and depth. The most important chemical parameters used in this classification are Cl and NO_3 concentrations and Na/Cl and Ca/Mg ratios. The Na/Cl ratio is plotted against the Cl concentration in figure 4. Table 1 shows the means and standard deviations of all the chemical parameters per water type. Saturation Indices and CO_2 pressures are calculated using the program WATEQP (APPELO & POSTMA, 1993).

Table 1

statistical parameters per water type.

Quadro 1

parâmetros estatísticos por tipo de água

Water type	Sample Numbers		pH	EC	Na	K	Ca	Mg	Cl	HCO_3	NO_3
1A	24,28,49,50,65,68,73	Mean	7,29	929	2,07	0,04	6,16	2,13	2,45	6,60	0,65
		SD	0,17	83	0,29	0,01	0,58	0,32	0,36	0,32	0,34
1B	36,46	Mean	7,35	900	2,28	0,06	5,57	1,78	2,95	5,05	1,10
		SD	0,35	80	0,01	0,00	1,26	0,42	0,20	1,30	0,05
2	26,30,33,38,40,s15,s16	Mean	7,00	2371	5,44	0,16	16,92	3,21	10,17	4,52	5,63
		SD	0,09	355	1,09	0,20	2,93	0,75	2,87	0,44	0,98
3a	4,5,11,12,43,69,71,s1	Mean	7,12	1314	4,93	0,12	6,10	2,96	4,02	5,21	2,17
	s2,s3,s7,s13	SD	0,35	223	1,38	0,07	2,15	0,64	0,91	1,04	0,86
3b	66,s4,s5,s6,s9,s10,s11	Mean	6,93	1868	5,64	0,05	12,72	2,79	5,50	5,70	4,10
	s12,s14	SD	0,14	381	1,27	0,02	2,37	0,82	1,38	0,67	1,27
4	55,,60,61	Mean	7,53	4416	20,46	0,57	18,86	7,37	35,58	5,22	2,48
		SD	0,24	1427	7,42	0,59	6,63	3,01	16,33	0,63	1,21
5	10,14,15,16,29,37,51,52	Mean	7,22	1790	5,16	0,19	10,39	3,53	7,36	5,06	2,35
	58,63,s17	SD	0,35	406	1,80	0,15	3,13	0,90	2,24	1,24	1,14

Water type	Sample numbers		SO_4	Na/Cl	Ca/Mg	^{18}O	^{2}H	SI Calcite	SI Dolom.	SI Gyps.	PCO_2 (log)
1A	24,28,49,50,65,68,73	Mean	1,23	0,85	2,96	-4,31	-23,24	0,35	0,23	-1,70	-1,76
		SD	0,30	0,02	0,52	0,13	1,42	0,14	0,27	0,15	0,17
1B	36,46	Mean	1,01	0,.78	3.14	-4,20	-23,20	0,24	-0,01	-1,88	-1,95
		SD	0,59	0,06	0,03	0,19	1,50	0,52	1,04	0,34	0,25
2	26,30,33,38,40,s15,s16	Mean	4,92	0,56	5,48	-4,13	-23,40	0,20	-0,31	-0,88	-1,66
		SD	0,61	0,10	1,27	0,17	1,10	0,10	0,19	0,07	0,09
3a	4,5,11,12,43,69,71,s1	Mean	2,66	1,22	2,07	-4,32	-24,70	0,01	-0,27	-1,45	-1,71
	s2,s3,s7,s13	SD	0,95	0,17	0,62	0,12	0,97	0,50	0,91	0,22	0,30
3b	66,s4,s5,s6,s9,s10,s11	Mean	4,95	1,04	4,84	-4,33	-23,10	0,15	-0,35	-0,97	-1,48
	s12,s14	SD	1,70	0,12	1,16	0,00	0,00	0,16	0,33	0,17	0,13
4	55,,60,61	Mean	7,09	0,60	2,61	-3,64	-20,30	0,71	1,01	-0,83	-2,16
		SD	1,65	0,07	0,13	0,00	0,00	0,13	0,23	0,13	0,26
5	10,14,15,16,29,37,51,52	Mean	4,79	0,71	3,06	-4,18	-25,08	0,26	0,07	-1,08	-1,84
	58,63,s17	SD	2,10	0,14	0,88	0,22	2,36	0,54	0,95	0,26	0,26

EC in microS/cm; solutes in meq/l; isotopes in ‰ V-SMOW

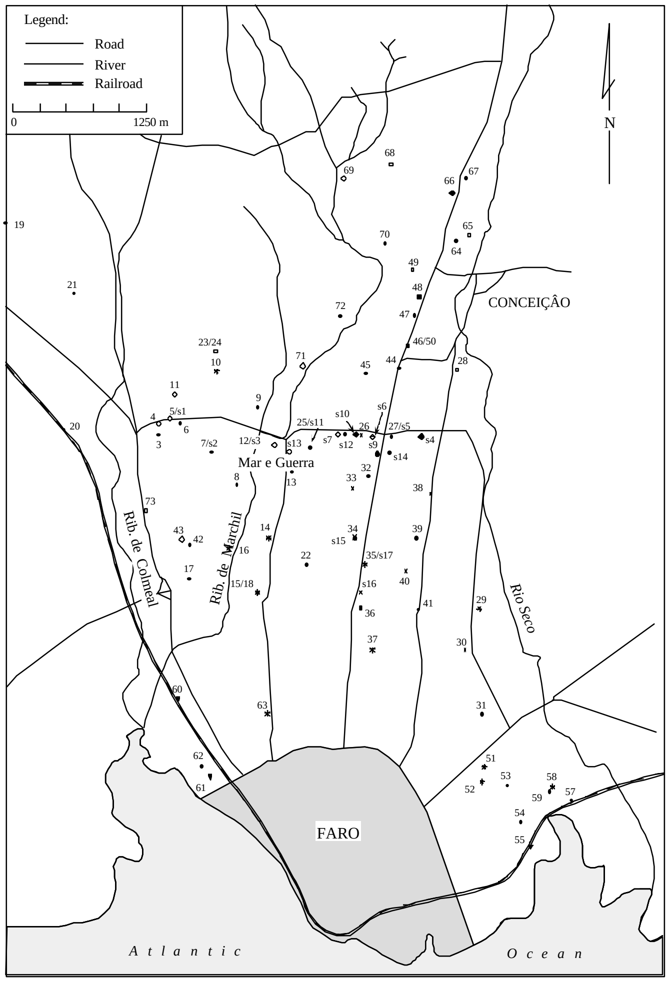

Figure 3: Location of the sampled wells; water types indicated by: □ 1a; ■ 1b; × 2; ◊ 3a; ◆ 3b; ▾ 4; ✳ 5; ● not classified.

Figura 3: Localização dos poços e furos amostrados; tipos de água indicados por: □ 1a; ■ 1b; × 2; ◊ 3a; ◆ 3b; ▾ 4; ✳ 5; ● não classificados.

Water type 1 is characterised by a relatively low Cl and a mean EC of about 920 µS/cm. Ca and HCO_3 are the dominant cation and anion respectively and the Na/Cl ratio is similar to the sea water ratio of 0.86. When considering the locations of the wells of water type 1 together with the geology of the area, it can be seen that some wells do not reach the Cretaceous aquifer. Therefore, water type 1 is subdivided in type 1a and type 1b. The samples of water type 1a are from wells that reach the Cretaceous aquifer. The samples of water type 1b were taken from wells in different aquifers and are believed to contain water from preferential flowpaths along faults.

Water type 2 has a high EC with especially high concentrations of Ca, NO_3 and SO_4. Na, Mg and HCO_3 are relatively low compared to Cl and Ca. The samples show a decreasing Na/Cl ratio with increasing Cl concentration; the Ca/Mg ratio is high. The wells reach the Miocene sands or limestones and are all located in the central part of the Campina de Faro.

Water type 3 is characterised by a high Na/Cl ratio and is subdivided into water type 3a, which has a Ca/Mg ratio <3.5 and type 3b, which has a Ca/Mg ratio >3.5. The Na/Cl ratio of water type 3a is slightly higher than that for type 3b, while the NO_3 and SO_4 concentrations are approximately two times higher in type 3b than in type 3a. All samples are from Miocene limestones or the Miocene and Pliocene sands; the wells of water type 3a are located in the northwest and those with type 3b in the northeast.

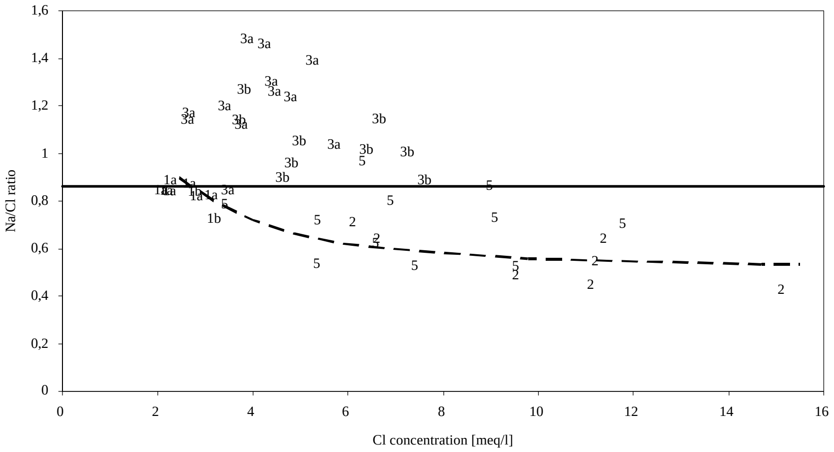

Figure 4: Relationship between Na/Cl ratio and Cl; numbers indicate the water type. Also shown is the line modelled by PHREEQC. Water type 4 is left out of the plot because of its high Cl concentration.

Figura 4: Relação da razão Na/Cl com Cl; os números indicam o tipo de água. Também se mostra a linha modelada por PHREEQC. O tipo de água 4 é suprimido do gráfico por possuir concentração elevada de Cl.

Water type 4 is characterised by its high mean EC of 3900 µS/cm. Cl is the main anion and Na and Ca are the main cations. Concentrations of Mg and SO_4 are also high, whereas alkalinity is relatively low; the Na/Cl ratio is below the sea water ratio. All wells withdraw water from the Pliocene sands and are located near the coast.

Most samples from water type 5 show characteristics of one of the other groups, though less pronounced. Mean EC is 1790 µS/cm and all ions show a large standard deviation. This water type is found in the Miocene limestones and sands and Pliocene sands.

5 - DISCUSSION

5.1 - Groundwater levels

From the groundwater level contour map (figure 1) it can be seen that in general the groundwater level decreases from approximately 30 m above sea level in the north to two meters above sea level in the southern part of the area. A steeper gradient is present near the village of Conceição, which can be explained by the large NW-SE trending fault (Silva *et al.*, 1986) which obstructs groundwater flow. Groundwater levels in the area were higher during the present study than in preceding years, as a result of unusually high rainfall: 1173 mm from October to May. After the summer extensive groundwater withdrawal for irrigation may result in groundwater levels below sea level, inducing the danger of sea water intrusion (Silva *et al.*, 1986).

5.2 - Hydrochemical processes

The different compositions of the groundwater types in the Campina de Faro are a result of several hydrochemical processes. These processes sometimes have a natural origin, but are often affected or even induced by agricultural activities. For each water type the main processes that occur are discussed in the following part.

5.2.1 - Water type 1: Cretaceous groundwater

The composition of this water type is determined by the evapotranspiration of infiltrating rainwater and the dissolution of calcite and dolomite. Gypsum is also present in the sediments (Costa *et al.*, 1985) and the increase of SO_4 is ascribed to this dissolution of this mineral. The evapotranspiration is considerably high in the study area and amounts to 85 % of the precipitation, as calculated from Cl concentrations.

5.2.2 - Water type 2: groundwater affected by agricultural activities

This water type is believed to originate from the mixing of Cretaceous groundwater (water type 1) coming from the north and rainwater infiltrating in the central part of the Campina de Faro. The composition of this locally infiltrated rainwater is determined by evapotranspiration and dissolution of minerals, similar to water type 1. The difference is that no dolomite has dissolved in this water, due to the absence of this mineral in the sediments in this part of the area (Antão, personal communication, 1997; Freitas, personal communication, 1997). Therefore the Mg concentration in the mixed groundwater is low compared to the Cretaceous groundwater. This is also indicated by the slightly negative SI for dolomite.

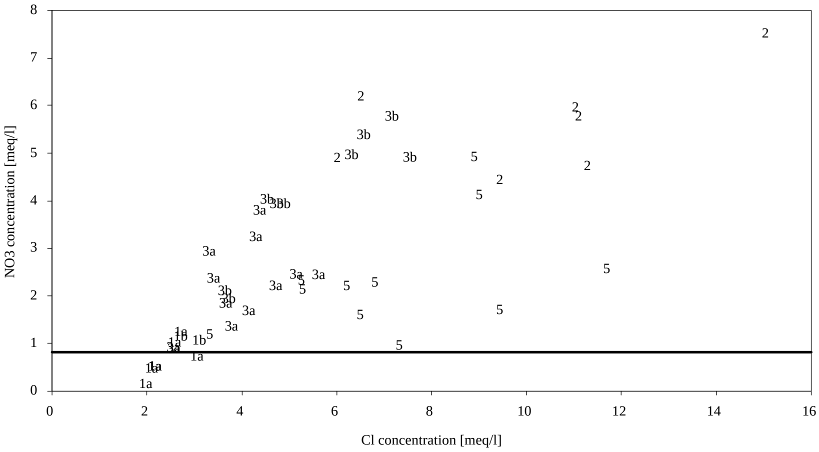

Figure 5: Relationship between NO_3 and Cl; numbers indicate the water type. Also shown is the line indicating the WHO concentration limit for consumption.

Figura 5: Relação do NO_3 com Cl; os números indicam o tipo de água. Também se mostra a linha indicadora do limite concentração para consumo da OMS.

The mixed groundwater is influenced by the application of fertilisers, causing high concentrations of NO_3, SO_4 and Ca. These high concentrations are already reported by Silva (1988). They further increase due to strong evapotranspiration induced by irrigation practices. In the plot of NO_3 against Cl (figure 5) it can be seen that nitrate concentrations in groundwater reach up to almost 8 mmol/l, which is 10 times the WHO drinking limit of 0.8 mmol/l. Irrigation practices further induce calcite precipitation and cation exchange.

The increase in concentration of Ca as well as HCO_3 due to the evapotranspiration of the groundwater initially in equilibrium with calcite, causes supersaturation with respect to this mineral, followed by precipitation. In this way the increase of Ca and HCO_3 is buffered and one would expect their concentration to stay at a constant level despite an increasing Cl concentration. However, figure 6 shows that this is not the case. This can be explained by the higher initial concentration of Ca with respect to HCO_3. During evapotranspiration the calcite equilibrium control causes the Ca concentration to rise further, while the HCO_3 concentration drops.

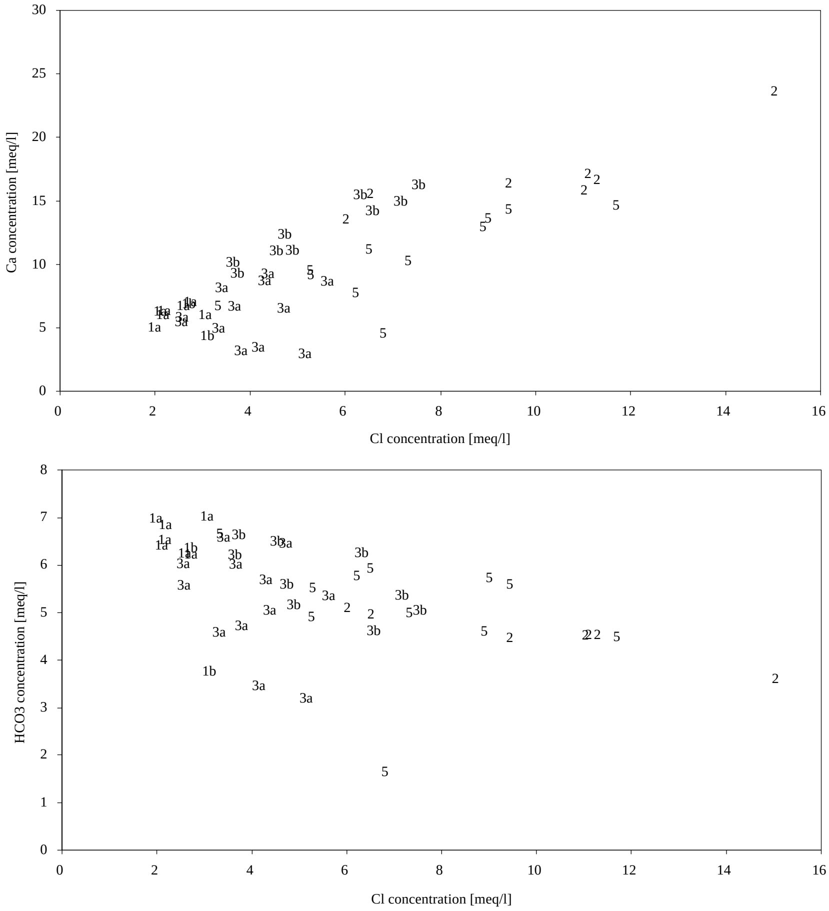

Figure 6: Relationship between Ca and Cl and between HCO_3 and Cl; numbers indicate the water type.
Figura 6: Relação do Ca com Cl e do HCO_3 com Cl; os números indicam o tipo de água.

The high Ca concentration is also partly caused by another particular process. Combined with a Na/Cl ratio well below the sea water ratio, this process can be recognised as cation exchange. Silva (1988) also reports cation exchange in this part of the Campina de Faro, but gives no explanation for it. Cation exchange is induced by the high evapotranspiration of the water that is used for irrigation. The process can be described as a reaction with an equilibrium constant (Appelo & Postma, 1993):

$$Na^{+} + 0.5Ca\text{-}X_2 \Leftrightarrow Na\text{-}X + 0.5Ca^{2+} \quad (1)$$

with:

$$K = \left([Na\text{-}X][Ca^{2+}]^{0.5}\right) / \left([Ca\text{-}X_2]^{0.5}[Na^{+}]\right) \quad (2)$$

The way of writing exchange reaction (1) conforms to the Gaines-Thomas convention, after Gaines and Thomas (1953). The X indicates the soil exchanger. It has a buffering function, due to the relatively large amount of cations on the complex, as compared to the concentration in the groundwater. Examining the equilibrium constant K in equation (2), it is evident that the exchange complex controls the relative increase of Na and Ca concentrations in the groundwater. When for instance the Ca concentration is concentrated 10 times, the Na concentration should increase $10^{0.5}$ (= 3.16) times. In the process of evapotranspiration however, Na and Ca increase both at the same rate. This induces uptake of Na by the complex, while Ca is released, resulting in a low Na/Cl ratio and high Ca concentration in water type 2 (figures 4 and 6).

To quantify the processes that occur in water type 2, the chemical evolution of this water type has been modelled using PHREEQC (Parkhurst, 1995). Table 2 shows the results of the model simulation; they correspond very well to the average values calculated for water type 2, the Ca concentration showing the largest deviation. The model is further used to simulate the change in Na/Cl ratios with an increasing effect of the evapotranspiration. The line representing this model simulation is shown in figure 4. A good fit is observed between this line and the sample points of water type 2 and a few of water type 5.

	pH	Na	K	Ca	Mg	Na/Cl	Ca/Mg	Cl	HCO_3	SO_4	NO_3
Observed	7,00	5,44	0,16	16,92	3,21	0,56	5,48	10,17	4,52	4,92	5,63
Calculated	6,97	5,27	0,09	15,48	3,18	0,52	4,83	10,17	4,79	4,92	5,63

Table 2: comparison of observed concentrations in water type 2 with those calculated with PHREEQC.

Quadro 2: comparação entre as concentrações observadas no tipo de água 2 e as calculadas pelo PHREEQC.

5.2.3 - Water type 3: groundwater affected by flushing

The high Na/Cl ratio in water type 3 indicates a second type of cation exchange where Na is removed from the complex and replaced by Ca. It is not certain what causes this type of cation exchange. The water composition from sample points west of the village of Mar e Guerra is possibly determined by flushing of a former sea inlet; those east and north of the village, however, have not been under the influence of sea water. Another explanation could be flushing of groundwater polluted by agricultural activities. In earlier times agricultural practices resulted in the uptake of Na by the exchange complex and a low Na/Cl ratio in groundwater, similar to what is now observed in water type 2. The high Na/Cl ratios observed in water types 3a and 3b are a result of the release of Na from the complex due to flushing by relatively unpolluted water. This means that the fraction of relatively unpolluted water has increased. There are two possible reasons for this. The first is the increased use of furos drilled into the Cretaceous aquifer in which the groundwater is relatively unpolluted (water type 1). The second reason may be that groundwater inflow from the north has increased, possibly caused by an increase in precipitation as reported by Loureiro and Coutinho (1995).

5.2.4. - Water type 4: groundwater influenced by sea water intrusion

This water type, with its typically high Cl concentration, is clearly contaminated with sea water, due to intensive pumping activities near the coast. The high nitrate concentrations also indicate the presence of agricultural influences. The low Na/Cl ratio and the high Ca concentration indicate cation exchange, where Ca on the complex is exchanged by Na from intruding sea water. Other characteristics showing the sea water influence are a high Mg and SO_4 concentration, and the high Saturation Indices for calcite and dolomite. The latter can be attributed to the inhibiting action of Mg on the precipitation of these minerals (Appelo & Postma, 1993).

5.2.5 - Water type 5: groundwater somewhat affected by agricultural activities

The high standard deviation of all the chemical parameters indicates that the samples within this group do not all show the same characteristics. Most samples in this group have some characteristics of water type 2, only less pronounced. This may be attributed to local variations in the type or amount of fertiliser used. However, it can also result from the influence of groundwater with a different composition, originating from greater depth or from the hill on which Faro has been built.

5.3 - Water balance

A water balance is calculated over a period of one year to determine groundwater inflow that is required to satisfy the water demand of the area. It is assumed that changes in storage can be neglected so the water balance becomes:

$$G_o - G_i = G_n = P - ET - I + IRF \quad (3)$$

In this equation G_o and G_i are the groundwater components into and out of the area respectively; G_n is the net groundwater flow. The average annual precipitation in the area amounts to P = 531 mm (Loureiro & Coutinho, 1995) of which 85 % is lost to evapotranspiration, which corresponds to ET = 450 mm, see below. The amount of groundwater that is used for irrigation is estimated at 1000 mm/yr for agricultural land in these climatic regions (Bos & Wolters, 1994). It is estimated that 50 % of the study area is used for agriculture, so I = 500 mm. The amount of irrigation return flow is estimated at 15 % of the groundwater withdrawals, which gives IRF = 75 mm. Inserting these values into equation (3) results in a net groundwater inflow of G_n = 344 mm.

5.4 - The chloride mass balance

When observing figure 2 and table 1 simultaneously, it can be seen that the Cl concentration generally increases from north to south. Not regarding water type 4, this increase can be attributed to evapotranspiration as a result of intensive irrigation. Because of the use of both noras and furos in the area, mixing in the aquifer is intense and thus variation of water quality with depth is small. This allows a mixing cell model to be applied to calculate the unknown groundwater flow components such as transmissivities (T) as well as the change of Cl in time (dM/dt). Table 3 shows the results of these model calculations. A subdivision of the area into 9 cells is made, each having a length of 500 m and a variable width depending on the width of the study area (figure 7). The most downstream cell is located north of the hill on which Faro has been built, because more to the south the flow system is complicated by this hill. The negative values for dM/dt in cells 4, 5 and 6 indicate that Cl concentrations are decreasing, which means that polluted groundwater is being replaced by fresher water. This supports the hypothesis that the high Na/Cl ratio for this water type is caused by flushing, since the samples from water type 3a and 3b are taken from wells that are mainly located in cells 4 and 5.

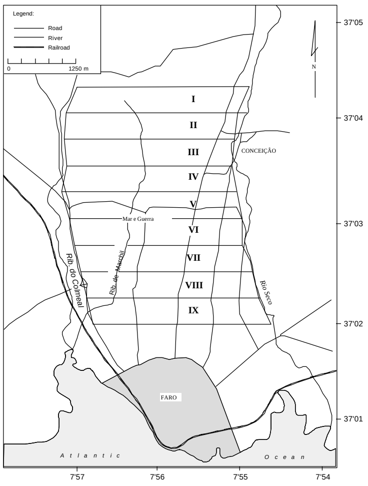

Figure 7: subdivision of the area into 9 cells
Figura 7: subdivisão da área em 9 células

Cell	Area [m^2]	T [m^2/d]	dM/dt [mmol.m/yr]
I	2031250	290	0,391
II	1843750	274	0,943
III	1687500	282	0,943
IV	1625000	182	-0,731
V	1625000	1045	-1,602
VI	1625000	1854	-1,377
VII	1625000	2558	1,736
VIII	1625000	1046	3,317
IX	1625000	147	2,952

Table 3: results from the mixing cell model.
Quadro 3: resultados do modelo de 'mixing cell'.

6 - CONCLUSIONS

In the present study, both hydrochemical and hydrogeological data are used to obtain an idea of the impact of agriculture on the groundwater in the Campina de Faro. In this area three aquifers are present: the Cretaceous limestones, the Miocene limestones and the Miocene, Pliocene and Quaternary sands. A water balance shows that groundwater inflow from the north must amount to 344 mm/yr to satisfy the water demand of the area.

Five different water types are discerned, based on various chemical parameters and well characteristics. The composition of the groundwater is influenced by natural and human activities. Evapotranspiration of rainwater and dissolution of minerals like calcite, dolomite and gypsum are the two main processes that determine the basic composition of the groundwater. In the central part of the Campina de Faro, where the agricultural activities are most intense, addition of fertilisers and irrigation further influence the water composition. Evapotranspiration of irrigation water induces calcite precipitation and cation exchange. It was possible to quantify these processes using the geochemical model PHREEQC. Near the coast, intrusion of sea water causes a second type of cation exchange to occur. A third type of exchange takes place where a former sea inlet is being flushed or where groundwater polluted by agricultural activities is replaced by relatively unpolluted water. Hydrochemical observations are confirmed by results from a mixing cell method that was successfully applied, using the Cl mass balance, to calculate transmissivities and the change of Cl in time. The model calculations confirm that there is a decrease of Cl concentration in time in the area where flushing of polluted groundwater is thought to occur. The method serves as a useful tool to explain chemical evolution of the groundwater flow system.

SYMBOLOGY

ET	Evapotranspiration
G_i	Groundwater inflow
G_n	Net groundwater flow
G_o	Groundwater outflow
I	Irrigation
IRF	Irrigation return flow
K	Equilibrium constant
P	Precipitation
X	Soil exchanger

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