



Universitat d'Alacant
Universidad de Alicante

Departamento de
Ingeniería Química



TEMA 3

**Ejemplos de modelización
de sistemas ácido-base,
precipitación / disolución e
intercambio iónico**

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**Este tema ha sido elaborado a partir
de las siguientes fuentes:**

- **“Geochemistry, Groundwater and Pollution”. Appelo and Postma, 1993 (1ª ed.) y 2005 (2ª ed.) Balkema.**
- **Tesis de Licenciatura: ESTADO ACTUAL DEL ACUÍFERO DEL CUATERNARIO DE JÁVEA. Celia Sempere Pérez. 1996. Universidad de Alicante.**
- **Proyecto “Red de calidad química de las aguas continentales subterráneas y superficiales de la provincia de Alicante”. Departamento de Ingeniería Química de la Universidad de Alicante y Excma. Diputación Provincial de Alicante.**
- **“Hydrogeochemical transport modeling of 24 years of Rhine water infiltration in the dunes of the Amsterdam Water Supply”. B.M. van Breukelena, C.A.J. Appelo, T.N. Olsthoorn. Journal of Hydrology 209 (1998) 281–296.**

3.1 Sistema bicarbonato/ carbonato/ dióxido de carbono/ calcita

3.1.1 Especies de CO₂ en agua

3.1.2 Sistemas abiertos y cerrados al intercambio de CO₂

3.1.3 Precipitación/disolución de calcita en sistemas abiertos y cerrados

3.1 Sistema bicarbonato/ carbonato/ dióxido de carbono/ calcita

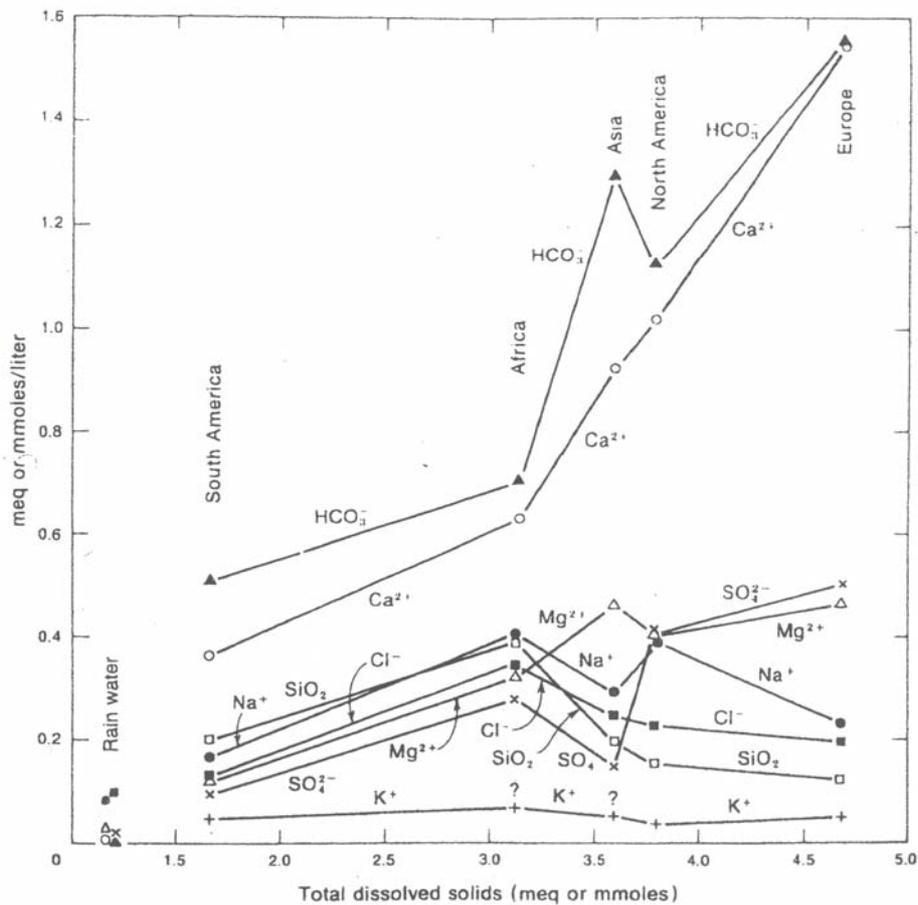


Figure 4.1. The relation between total dissolved solids and concentrations of individual ions in average river water compositions from different continents (adapted from Garrels and Mackenzie, 1971).

Relación TDS con la concentración de iones disueltos en agua de ríos de diferentes continentes

3.1 Sistema bicarbonato/ carbonato/ dióxido de carbono/ calcita

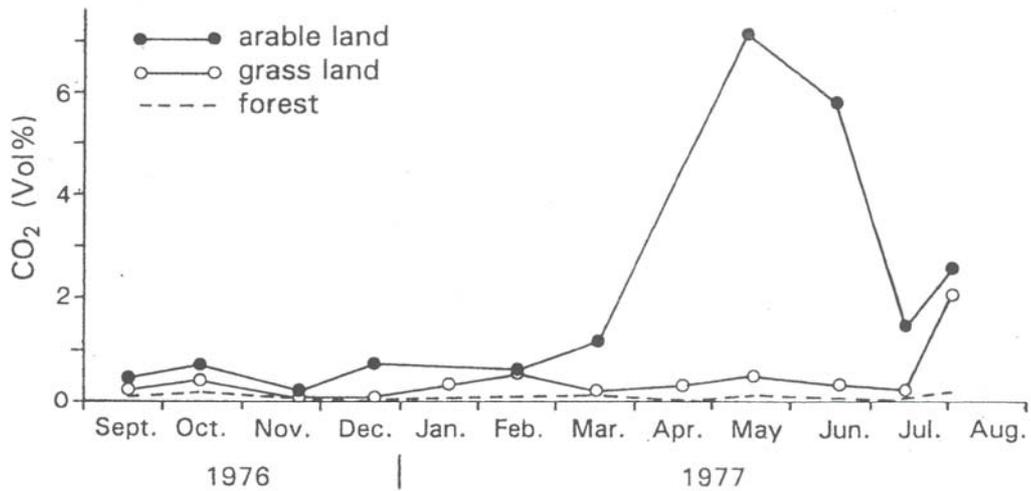


Figure 4.9. Soil CO₂ pressures under different vegetation (from Albertsen, 1977).

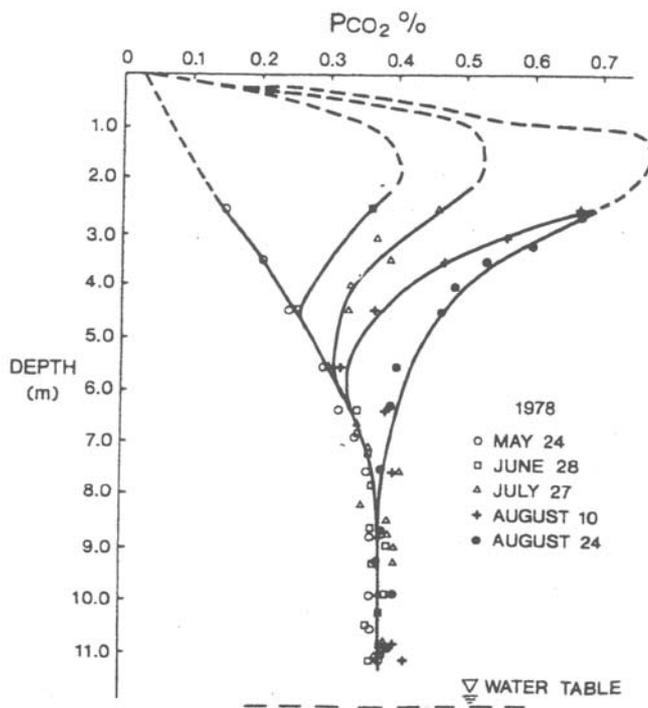
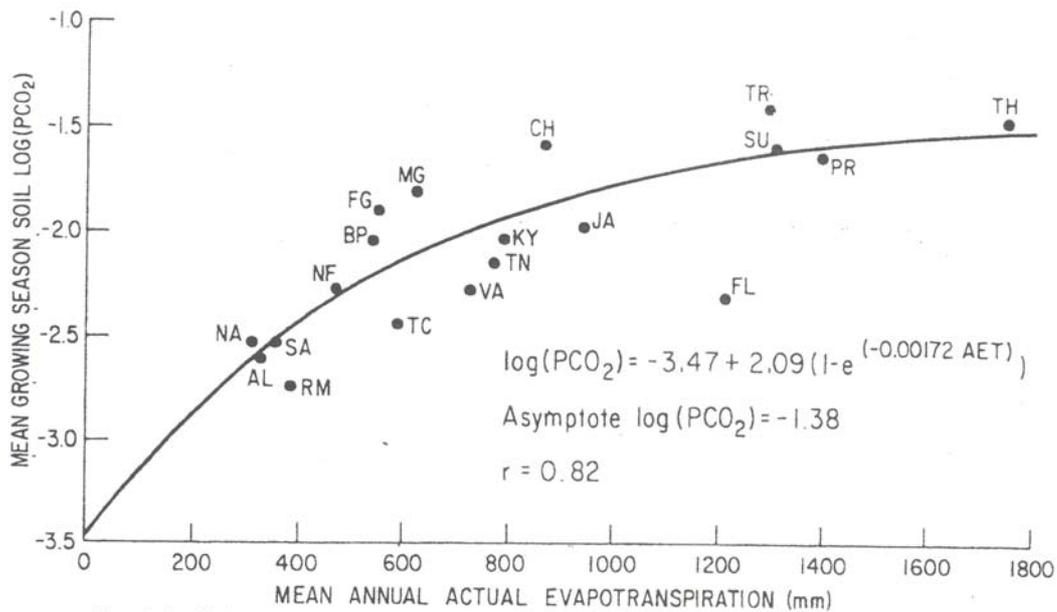


Figure 4.10. Seasonal fluctuations of soil CO₂ pressures in the unsaturated zone (Reardon et al., 1979).

3.1 Sistema bicarbonato/ carbonato/ dióxido de carbono/ calcita



The relationship between mean growing-season soil log(PCO₂) and mean annual actual evapotranspiration predicted by equation (7). NA = Nahanni, Canada; SA = Saskatchewan, Canada; RM = Rocky Mountains, Canada; NF = Newfoundland, Canada; BP = Bruce Peninsula, Canada; TC = Trout Creek, Ontario, Canada; AL = Alaska, USA; VA = Reston, Virginia, USA; TN = Sinking Cove, Tennessee, USA; KY = Mammoth Cave, Kentucky, USA; FL = south Florida, USA; FG = Frankfurt-Main, W. Germany; MG = Müllenbach, W. Germany; JA = Jamaica; TR = Trinidad; PR = Puerto Rico; CH = Yunan, China; SU = Sulawesi; TH = Phangnga, Thailand

Figure 4.11. Relationship between soil CO₂ pressure and evapotranspiration (Brook et al., 1983. Reprinted by permission of John Wiley & Sons, Ltd).

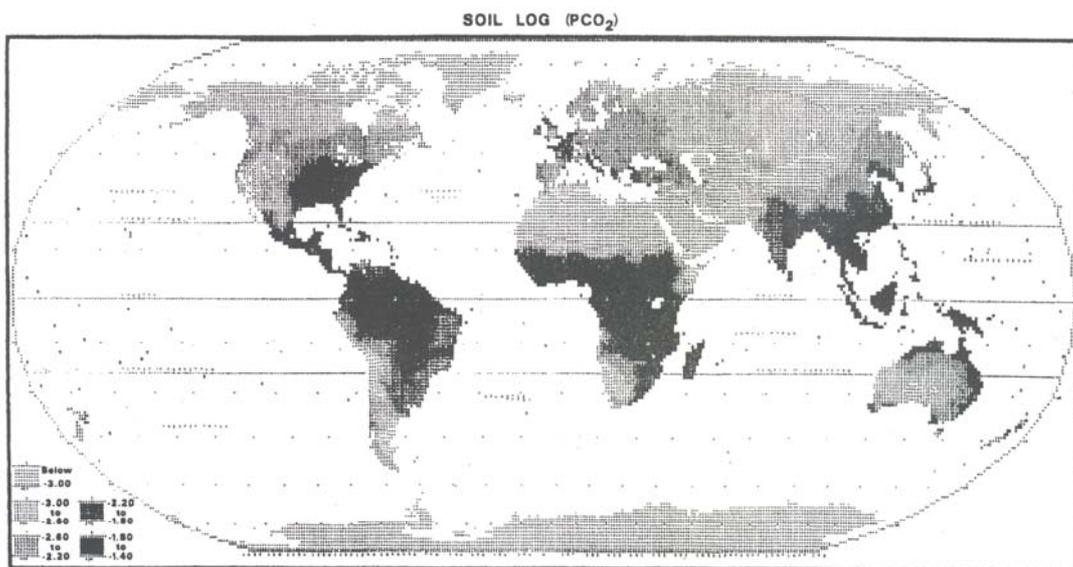


Figure 4.12. Map of soil CO₂ pressure produced with the relationship shown in Figure 4.11

3.1 Sistema bicarbonato/ carbonato/ dióxido de carbono/ calcita

Productos de solubilidad de minerales carbonatados

Table 4.1. Mineralogy and solubility of some carbonates (thermodynamic data from Nordstrom et al., 1990).

Trigonal	Formula	$-\log K$	Orthorhombic	Formula	$-\log K$
Calcite	CaCO_3	8.48	Aragonite	CaCO_3	8.34
Magnesite	MgCO_3	8.24	Strontianite	SrCO_3	9.27
Siderite	FeCO_3	10.89	Cerussite	PbCO_3	13.1
Rhodochrosite	MnCO_3	11.13			
Dolomite	$\text{CaMg}(\text{CO}_3)_2$	17.09			

Especies de CO_2 en agua

Table 4.2. Approximate equilibrium constants for dissolved CO_2 species at 25°C . (Precise values and temperature dependance are provided in Appendix B).

$\text{H}_2\text{O} \leftrightarrow \text{H}^+ + \text{OH}^-$	$K_w = [\text{H}^+][\text{OH}^-]$	$K_w = 10^{-14.0}$	(4.1)
$\text{CO}_{2(\text{g})} + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3^*$	$K_H = [\text{H}_2\text{CO}_3^*]/P_{\text{CO}_2}$	$K_H = 10^{-1.5}$	(4.2)
$\text{H}_2\text{CO}_3^* \leftrightarrow \text{H}^+ + \text{HCO}_3^-$	$K_1 = [\text{H}^+][\text{HCO}_3^-]/[\text{H}_2\text{CO}_3^*]$	$K_1 = 10^{-6.3}$	(4.3)
$\text{HCO}_3^- \leftrightarrow \text{H}^+ + \text{CO}_3^{2-}$	$K_2 = [\text{H}^+][\text{CO}_3^{2-}]/[\text{HCO}_3^-]$	$K_2 = 10^{-10.3}$	(4.4)

Sistema abierto al intercambio de CO_2

EXAMPLE 4.1. Calculate TIC at $\text{pH} = 7$ and $\text{pH} = 10$, when the CO_2 pressure is 0.01 atm.

ANSWER.

We calculate the concentrations of individual species, and add them up:

	$\text{pH} = 7$	$\text{pH} = 10$
$[\text{H}_2\text{CO}_3^*] = 10^{-1.5} P_{\text{CO}_2}$	$10^{-3.5}$	$10^{-3.5}$
$[\text{HCO}_3^-] = 10^{-6.3} [\text{H}_2\text{CO}_3^*]/[\text{H}^+]$	$10^{-2.8}$	$10^{0.2}$
$[\text{CO}_3^{2-}] = 10^{-10.3} [\text{HCO}_3^-]/[\text{H}^+]$	$10^{-6.1}$	$10^{-0.1}$
$\Sigma\text{CO}_2 =$	$10^{-2.72}$	$10^{0.38} \text{ mol/l}$

3.1 Sistema bicarbonato/ carbonato/ dióxido de carbono/ calcita

Sistema abierto al intercambio de CO₂

Table 4.3. Calculated CO₂ species in soilwater and rainwater. Values in mol/l and atm.

P_{CO_2}	$10^{-1.5}$	$10^{-3.5}$
H ⁺	$10^{-4.6}$	$10^{-5.6}$
pH	4.6	5.6
HCO ₃ ⁻	$10^{-4.6}$	$10^{-5.6}$
CO ₃ ²⁻	$10^{-10.3}$	$10^{-10.3}$
OH ⁻	$10^{-9.4}$	$10^{-8.4}$

Sistema abierto e interacción con calcita

Table 4.4. Calculated CO₂ species and Ca²⁺ in soil water in contact with CO₂ and calcite, in an open system. Values in mol/l and atm.

P_{CO_2}	$10^{-1.5}$	$10^{-3.5}$
Ca ²⁺	$10^{-2.6}$	$10^{-3.3}$
CO ₃ ²⁻	$10^{-5.6}$	$10^{-5.0}$
HCO ₃ ⁻	$10^{-2.3}$	$10^{-3.0}$
H ⁺	$10^{-7.0}$	$10^{-8.3}$
OH ⁻	$10^{-7.0}$	$10^{-5.7}$
pH	7.0	8.3

Sistema cerrado al intercambio de CO₂

Table 4.5. Calculated CO₂ species and Ca²⁺ in soilwater in contact with CO₂ and calcite, in a closed system. Values in mol/l and atm.

$P_{\text{CO}_2(\text{initial})}$	$10^{-1.5}$	$10^{-3.5}$
HCO ₃ ⁻	$10^{-2.7}$	$10^{-3.5}$
Ca ²⁺	$10^{-3.0}$	$10^{-4.2}$
CO ₃ ²⁻	$10^{-5.3}$	$10^{-4.1}$
H ⁺	$10^{-7.7}$	$10^{-10.8}$
H ₂ CO ₃	$10^{-4.1}$	$10^{-9.4}$
OH ⁻	$10^{-6.3}$	$10^{-3.2}$
pH	7.7	10.8
$P_{\text{CO}_2(\text{final})}$	$10^{-2.6}$	$10^{-7.9}$

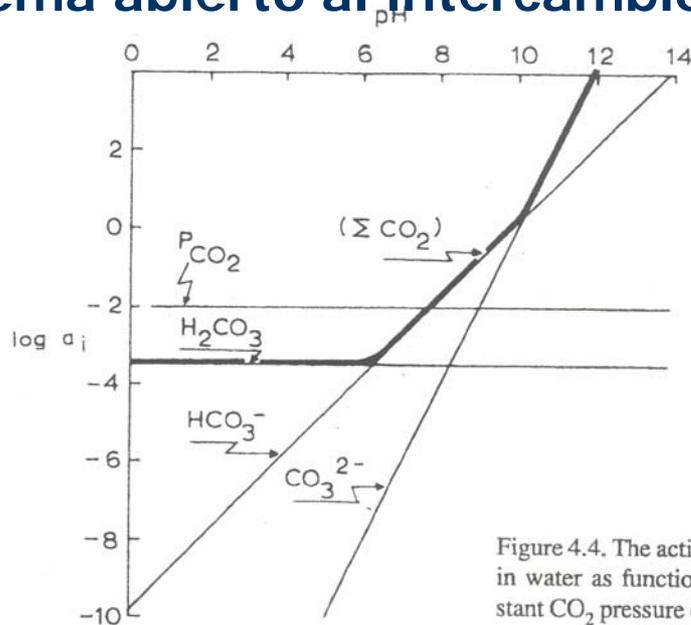
Simulaciones con PHREEQ A 15 °C

Table 4.6. Summary of concentrations in water in which calcite dissolves at 15°C (PHREEQE calculations, which include complexes and activity corrections).

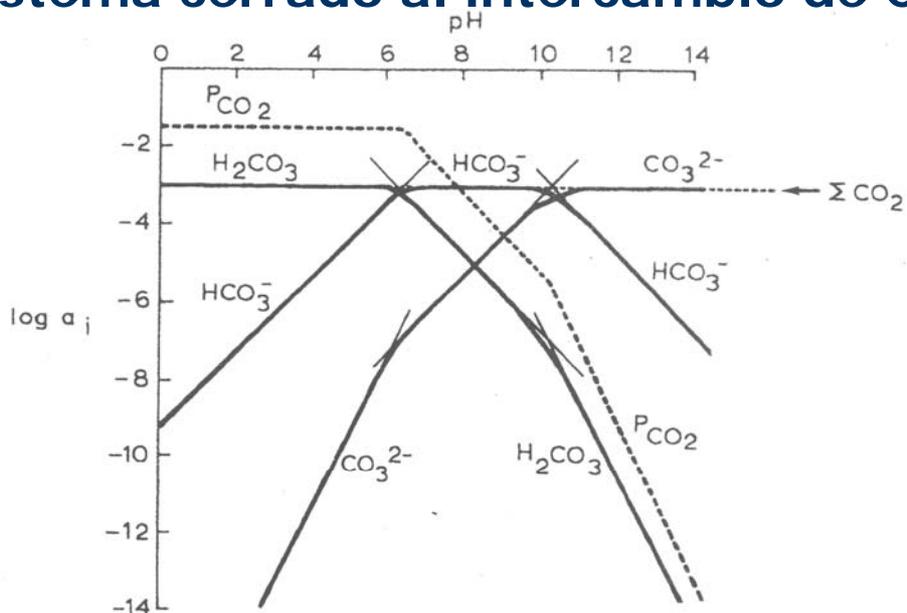
	Open system with constant P_{CO_2} (Section 4.2.2)		Open system with constant P_{CO_2} and calcite (Section 4.2.3)		Closed system with known initial P_{CO_2} and calcite (Section 4.2.4)		
P_{CO_2} initial	$10^{-1.5}$	$10^{-3.5}$	$10^{-1.5}$	$10^{-3.5}$	$10^{-1.5}$	$10^{-3.5}$	atm
P_{CO_2} final	$10^{-1.5}$	$10^{-3.5}$	$10^{-1.5}$	$10^{-3.5}$	$10^{-2.5}$	$10^{-6.4}$	atm
pH	4.63	5.63	6.98	8.29	7.62	10.06	
Ca ²⁺	—	—	2.98	0.58	1.32	0.12	mmol/l
Alk	0.02	0.002	5.96	1.16	2.65	0.24	mmol/l
EC	2	1	600	120	265	25	μS/cm

3.1 Sistema bicarbonato/ carbonato/ dióxido de carbono/ calcita

Sistema abierto al intercambio de CO₂



Sistema cerrado al intercambio de CO₂



3.2 Intercambio catiónico en intrusión agua salada - agua dulce

3.2.1 Procesos de intrusión marina. Estudio de la hidrogeoquímica

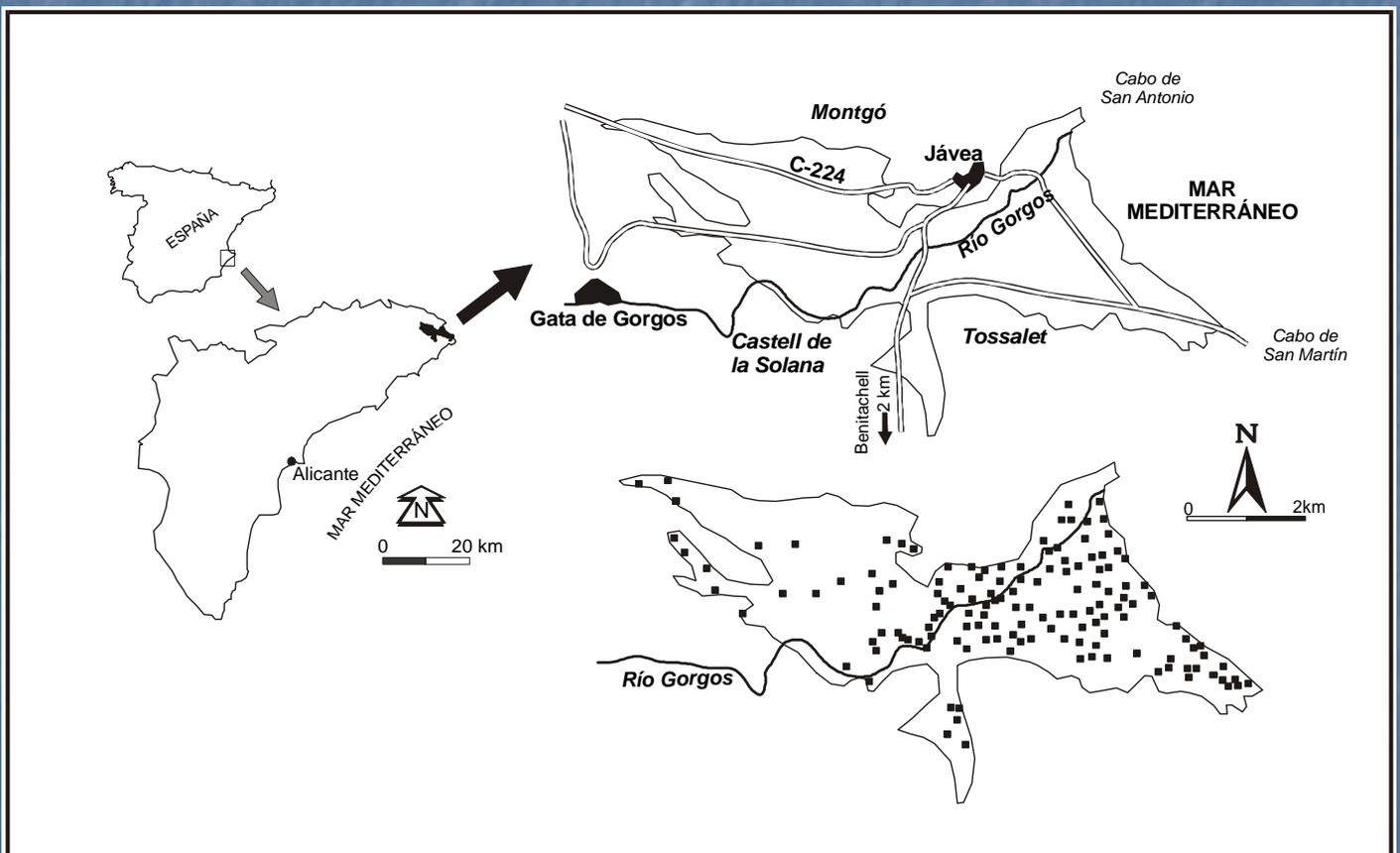
3.2.2 Equilibrios de intercambio catiónico: valores para coeficientes y cálculo de la composición de intercambio

3.2.3 Cromatografía de intercambio catiónico

3.2 Intercambio catiónico en intrusión agua salada - agua dulce

Procesos de intrusión marina.
Estudio de la hidrogeoquímica

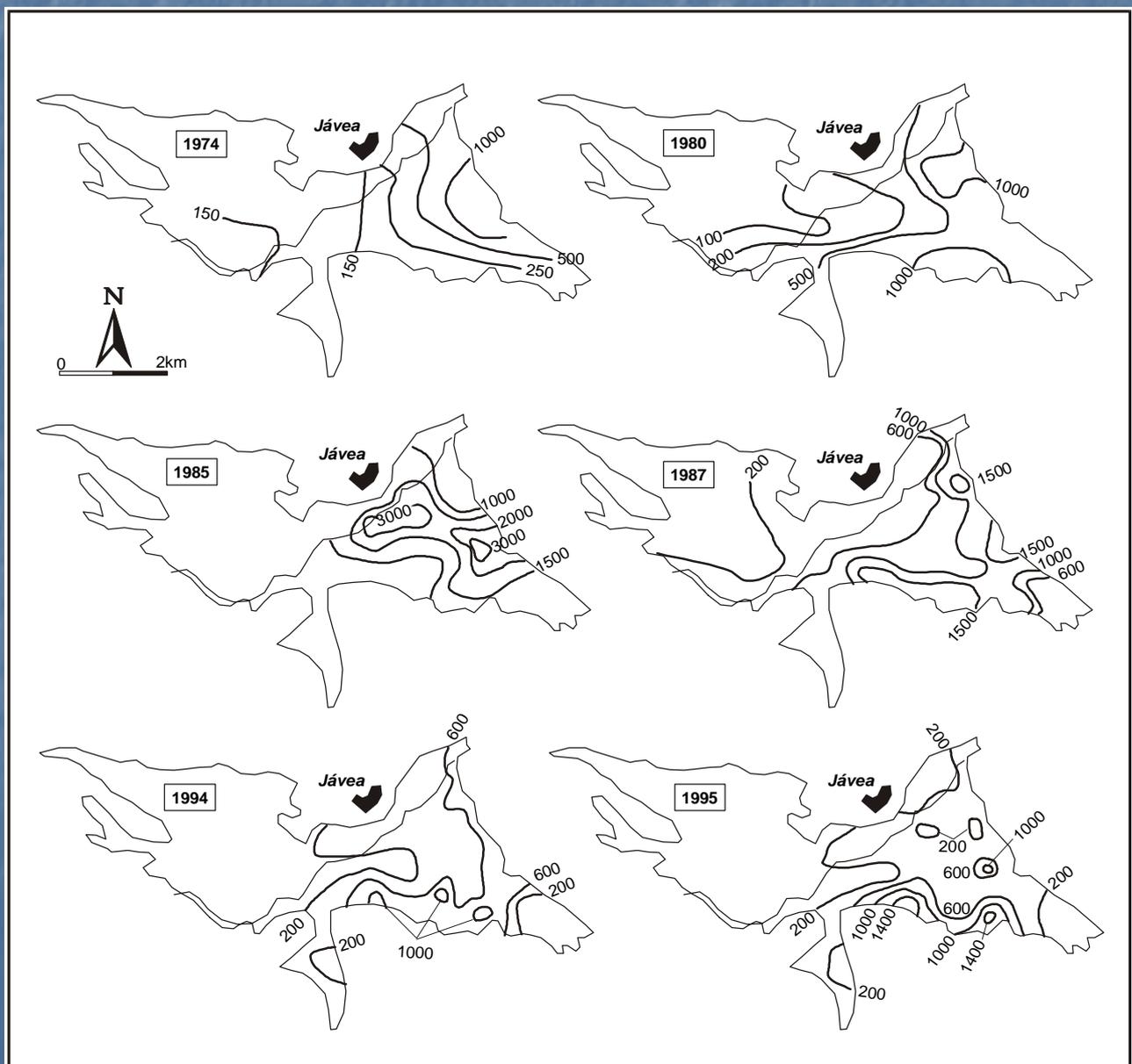
Acuífero Cuaternario de Jávea



3.2 Intercambio catiónico en intrusión agua salada - agua dulce

Procesos de intrusión marina.
Estudio de la hidrogeoquímica

Acuífero Cuaternario de Jávea. Evolución [Cl⁻]



3.2 Intercambio catiónico en intrusión agua salada - agua dulce

Procesos de intrusión marina.
Estudio de la hidrogeoquímica

Cálculo del exceso de ión i una muestra de agua

Cálculo del % agua marina en una muestra de agua

$$C_{Cl^-} = 19620 \cdot X + 95 \cdot (1-X)$$

$$C_{Cl^-} = [Cl^-] \text{ (mg/L)}$$

X = fracción másica de agua marina

$$X = \frac{C_{Cl^-} - 95}{19620 - 95}$$

Composición de un ión i (C_{isr})
por mezcla agua dulce – agua de mar

$$C_{isr} = C_{im} \cdot X + C_{ia} \cdot (1-X)$$

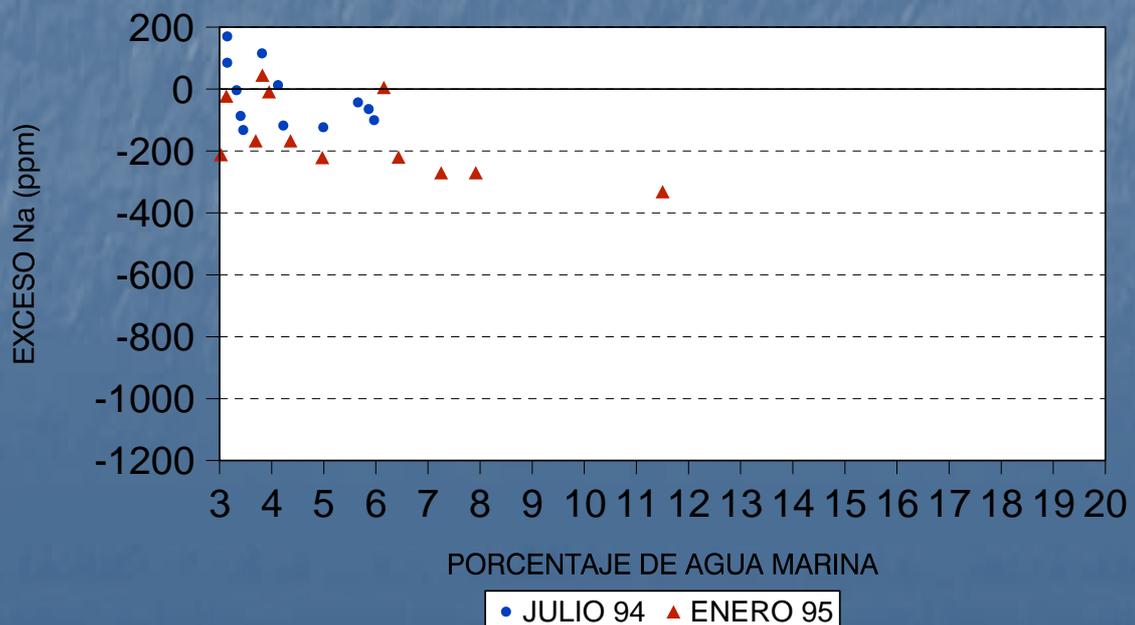
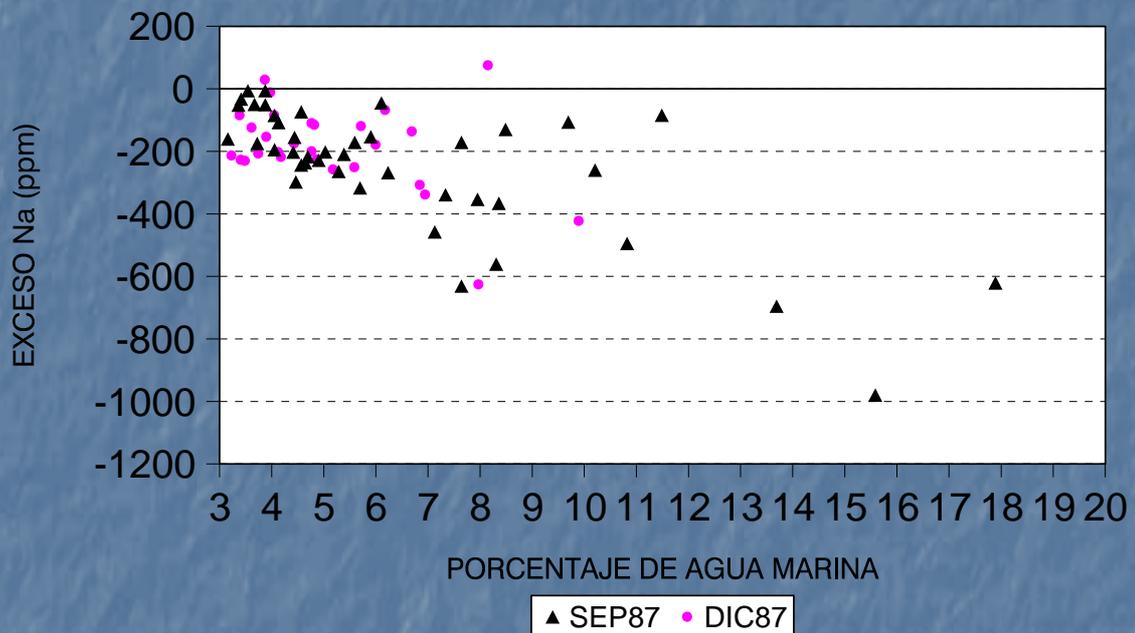
$$\text{Exceso de ión i} = C_i - C_{isr}$$

C_i = conc. de ion i en la muestra

3.2 Intercambio catiónico en intrusión agua salada - agua dulce

Procesos de intrusión marina.
Estudio de la hidrogeoquímica

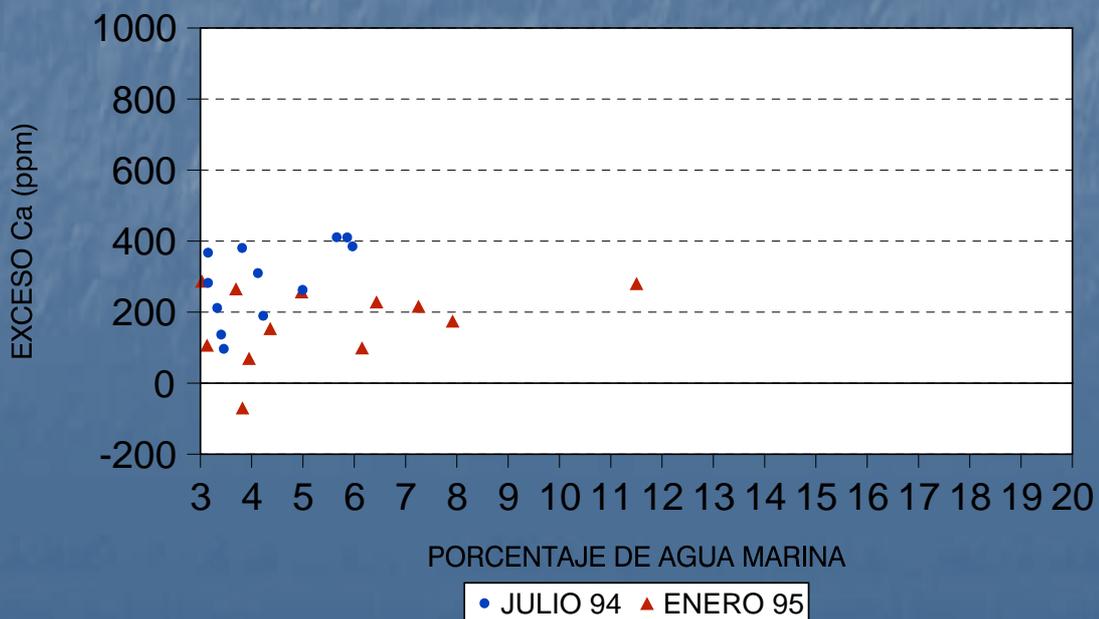
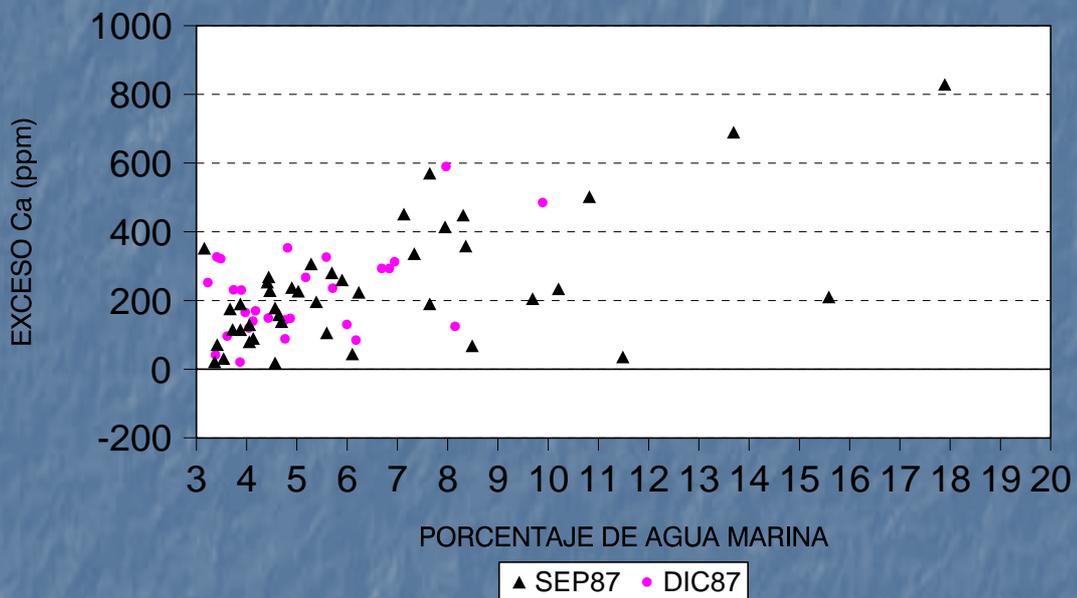
Acuífero Cuaternario de Jávea. Evolución [Na⁺]



3.2 Intercambio catiónico en intrusión agua salada - agua dulce

Procesos de intrusión marina.
Estudio de la hidrogeoquímica

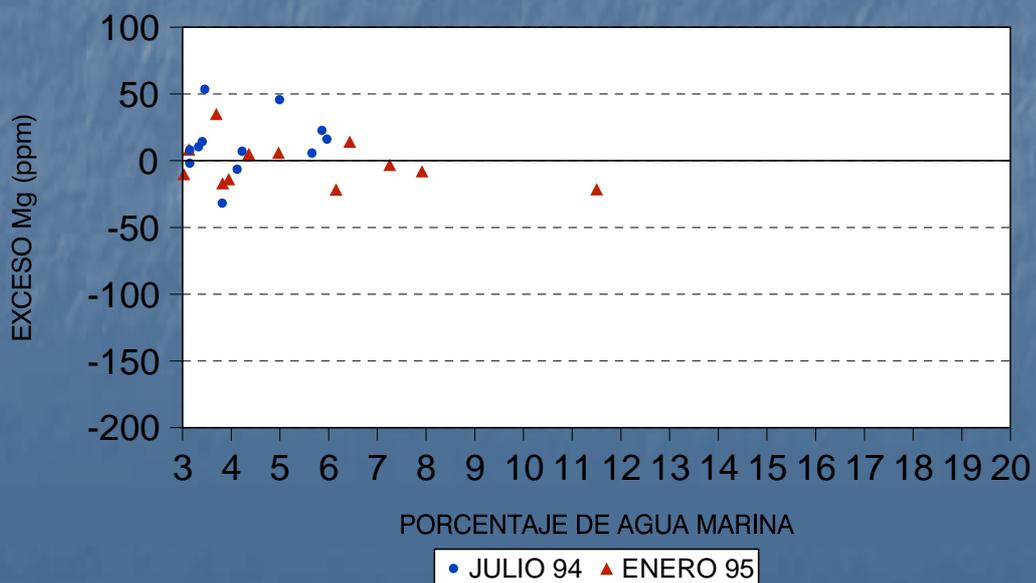
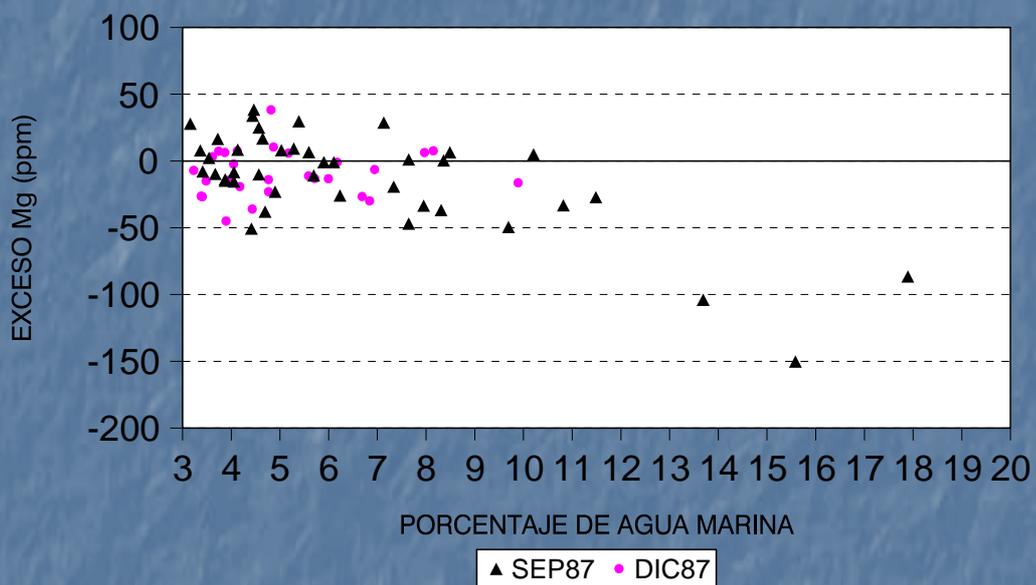
Acuífero Cuaternario de Jávea. Evolución $[Ca^{2+}]$



3.2 Intercambio catiónico en intrusión agua salada - agua dulce

Procesos de intrusión marina.
Estudio de la hidrogeoquímica

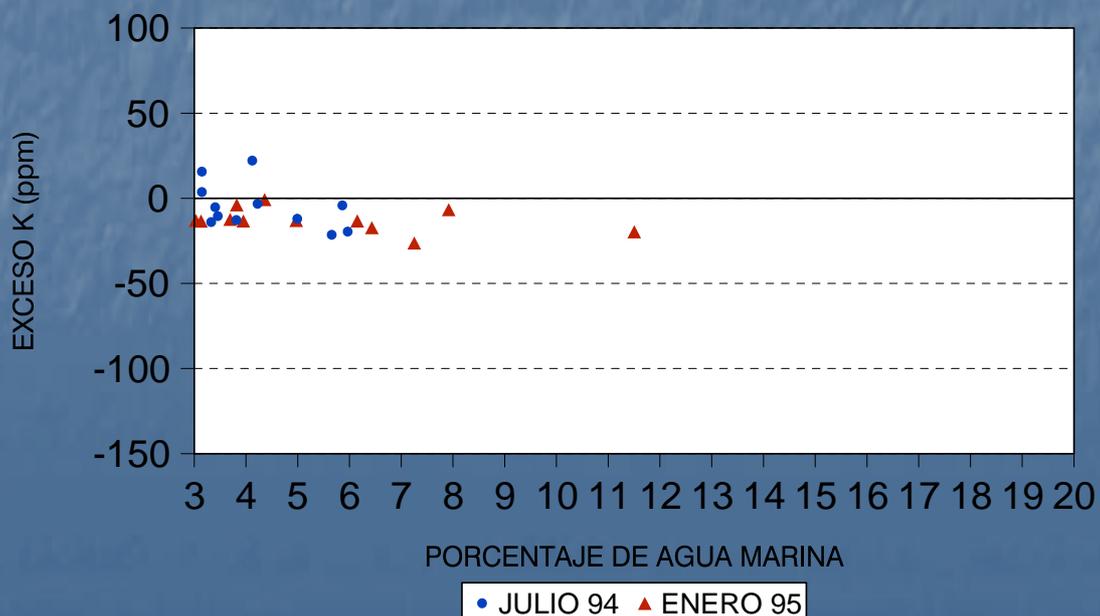
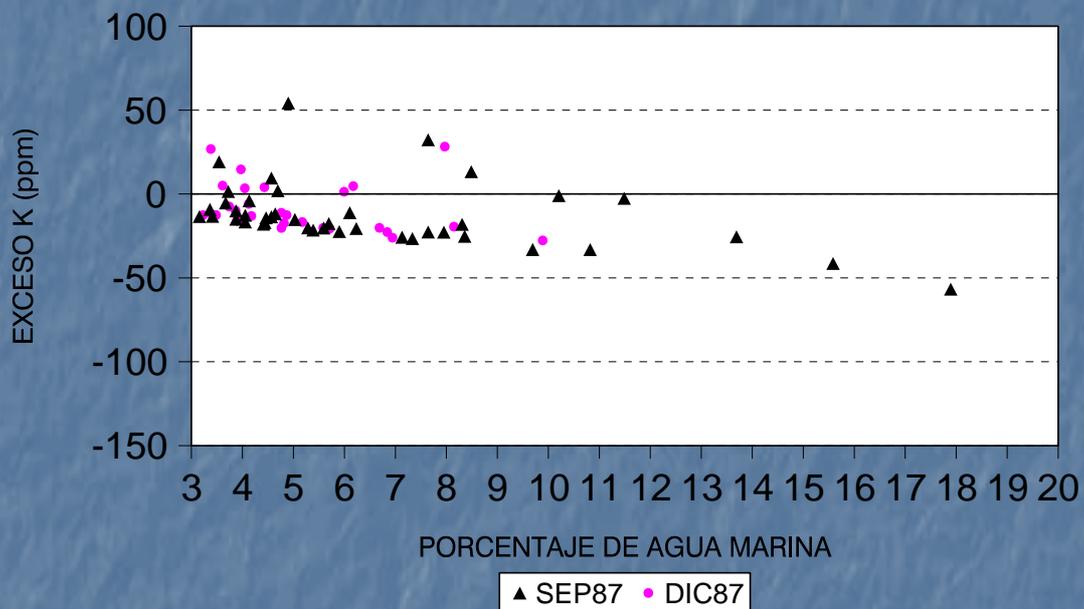
Acuífero Cuaternario de Jávea. Evolución [Mg²⁺]



3.2 Intercambio catiónico en intrusión agua salada - agua dulce

Procesos de intrusión marina.
Estudio de la hidrogeoquímica

Acuífero Cuaternario de Jávea. Evolución [K⁺]



3.2 Intercambio catiónico en intrusión agua salada - agua dulce

Procesos de intrusión marina. Estudio de la hidrogeoquímica

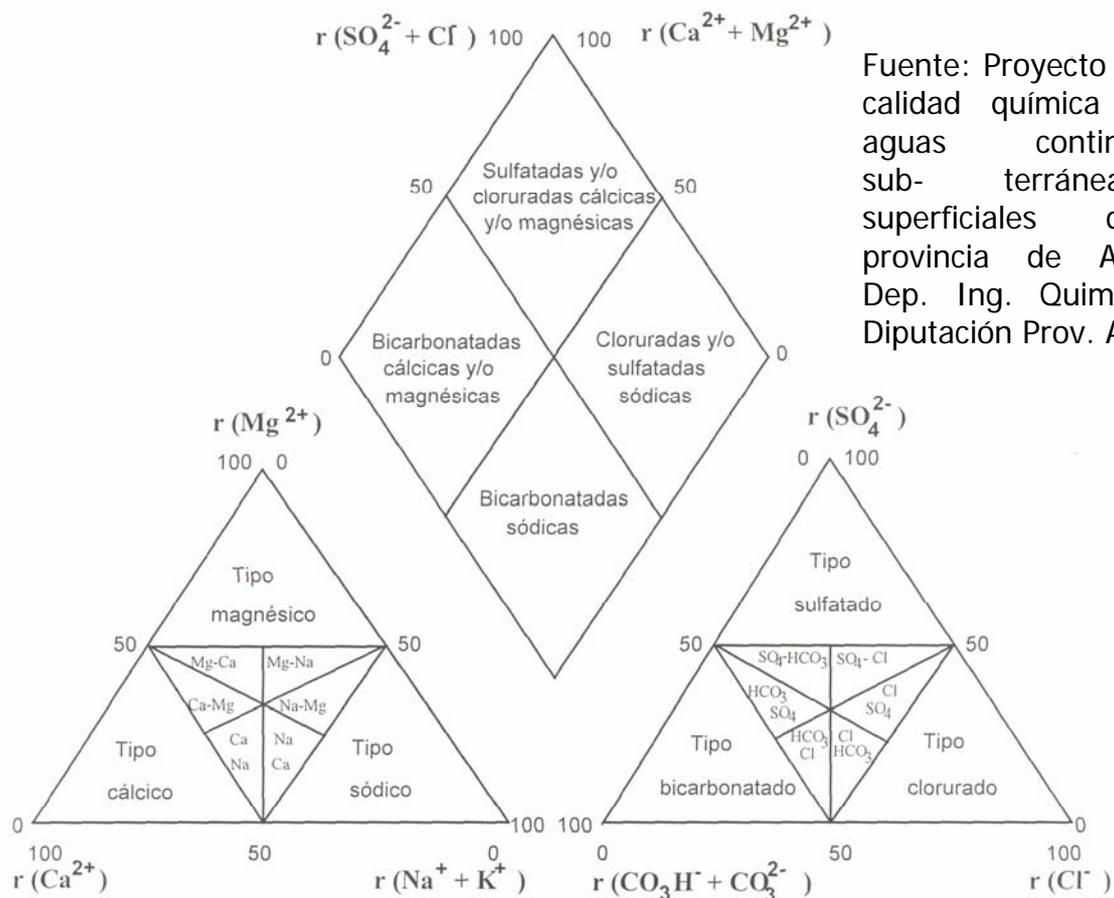
2.1. CLASIFICACIÓN GEOQUÍMICA DEL AGUA.

Diagramas de Piper: dos zonas triangulares que representan, por separado, aniones y cationes y, otra romboidal, donde se refleja un tercer punto deducido de los anteriores.

En el triángulo de cationes se representan los porcentajes de equivalentes de calcio, de magnesio y de sodio más potasio respecto al total de equivalentes de cationes.

En el triángulo de aniones, los porcentajes de equivalentes de sulfatos, de cloruros y de bicarbonatos más carbonatos respecto al total de aniones.

Clasificar las aguas mediante diversas combinaciones, definida los iones mayoritarios.



Fuente: Proyecto "Red de calidad química de las aguas continentales, sub-terráneas y superficiales de la provincia de Alicante". Dep. Ing. Quim. UA y Diputación Prov. Alicante.

Figura A.2.1. Facies química del agua según el diagrama de Piper-Hill-Langelier

3.2 Intercambio catiónico en intrusión agua salada - agua dulce

Procesos de intrusión marina. Estudio de la hidrogeoquímica

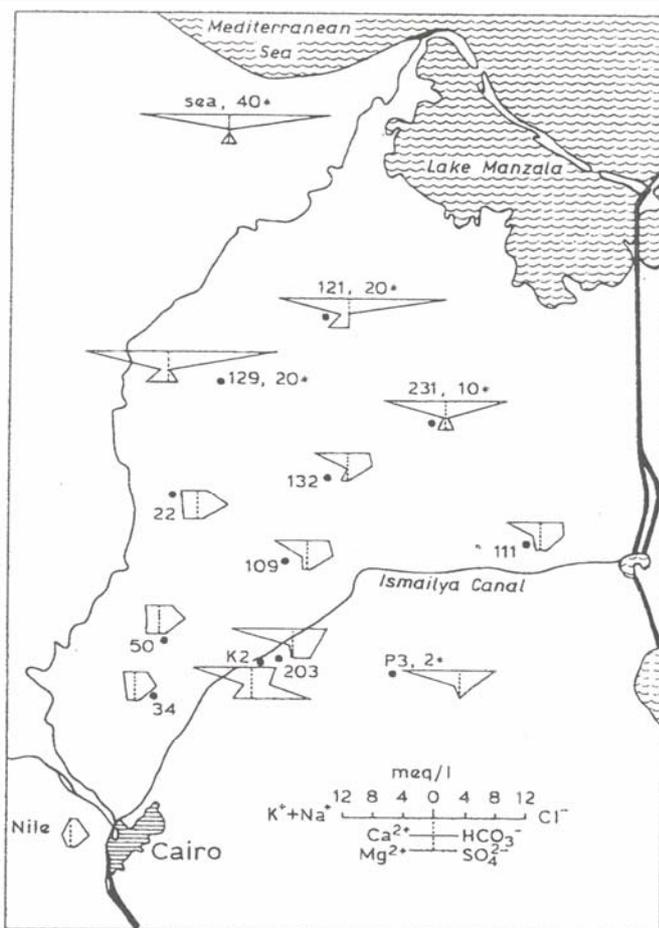


Figure 5.3. Stiff diagrams of groundwater in the Nile delta, Egypt, indicating salt water upconing in borehole 121 and 129, and Ca²⁺/Na⁺ exchange near the Ismailya canal.

3.2 Intercambio catiónico en intrusión agua salada - agua dulce

Procesos de intrusión marina. Estudio de la hidrogeoquímica

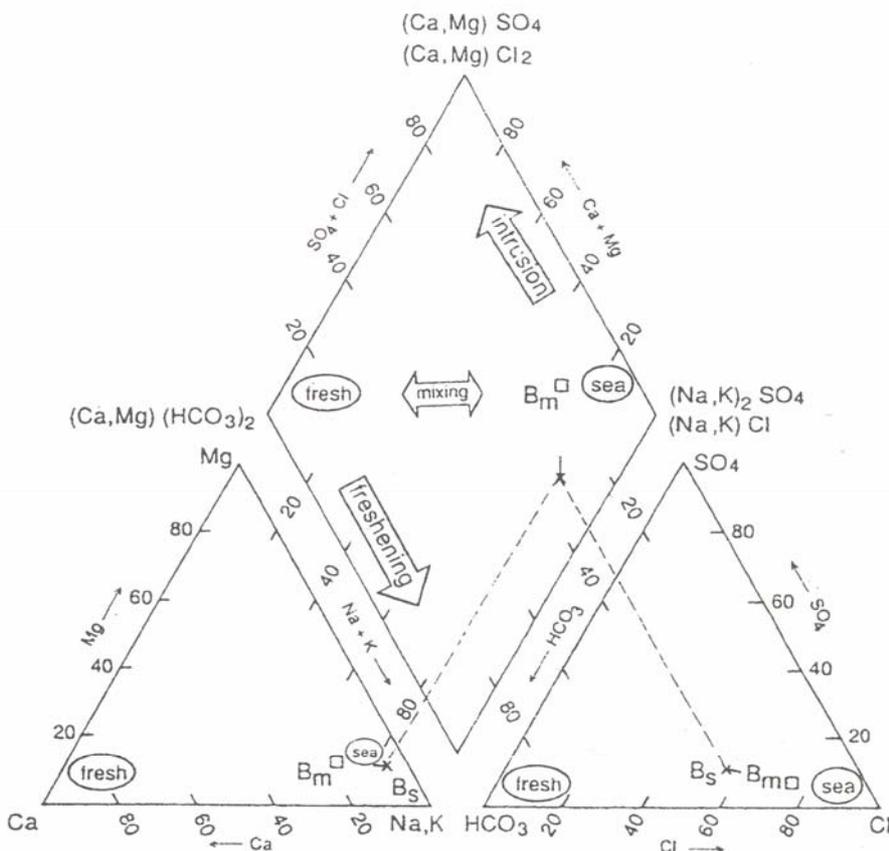


Figure 5.4. Piper plot showing 'average' compositions of fresh water and seawater, and NaHCO₃-sample (B_s) from Table 5.2. The tail at B_s points to the calculated composition of a conservative mixture B_m'.

3.2 Intercambio catiónico en intrusión agua salada - agua dulce

Procesos de intrusión marina. Estudio de la hidrogeoquímica

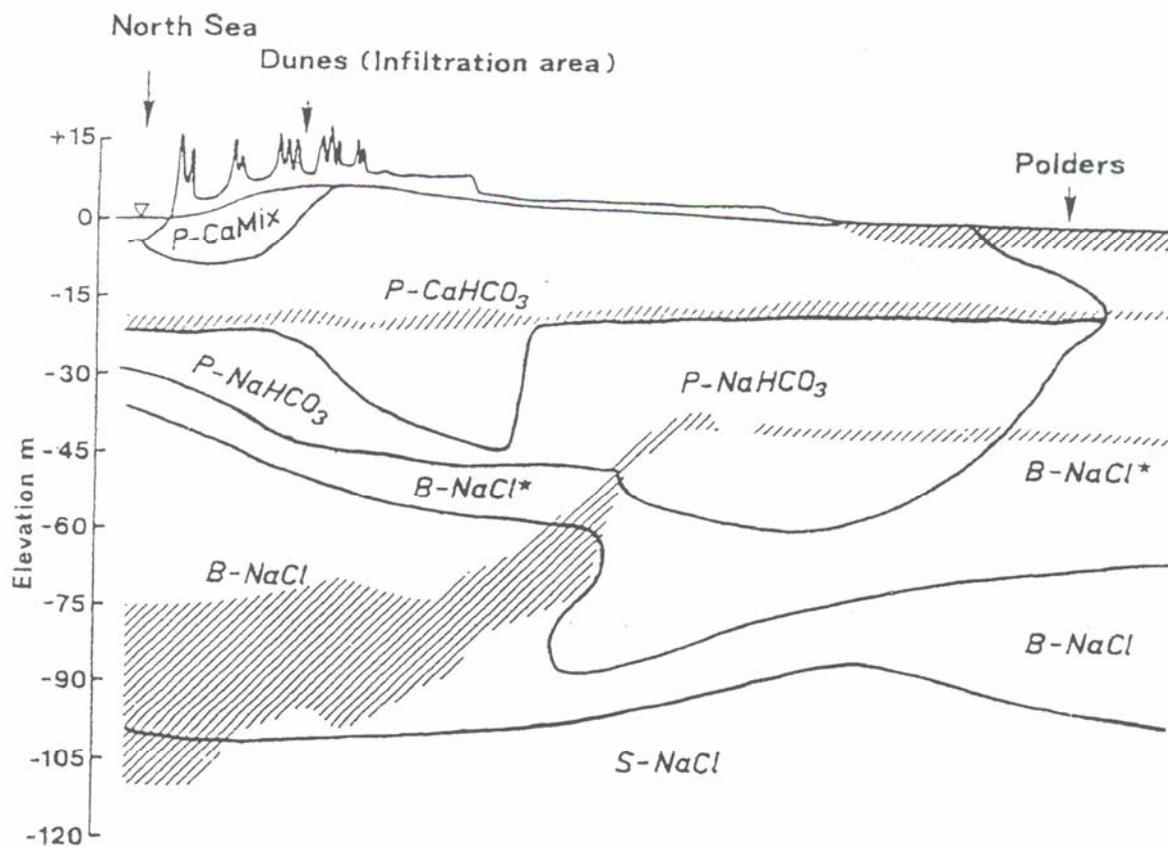


Figure 5.2. Section through the Dutch coastal dunes near Castricum, showing refreshing of a brackish water aquifer. The prefixes P, B and S before the water types indicate fresh, brackish and salt water. Low permeability layers (clays) are shown hatched. (Modified from Stuyfzand, 1985).

3.2 Intercambio catiónico en intrusión agua salada - agua dulce

Equilibrios de intercambio catiónico

Capacidad de intercambio catiónico (CEC)

Cation exchange capacities of common soil and sediment materials.

	<i>CEC</i> , meq/100g
Kaolinite	3 – 15
Halloysite	5 – 10
Montmorillonite	80 – 120
Vermiculite	100 – 200
Glauconite	5 – 40
Illite	20 – 50
Chlorite	10 – 40
Allophane	up to 100
Goethite & Hematite:	up to 100
Organic matter (C)	150 – 400 (at pH = 8)
or, accounting for pH-dependence:	$51 \cdot \text{pH} - 59$ (= <i>CEC</i> per 100 g organic carbon), (Scheffer and Schachtschabel, 1970)

Solids with a large specific surface reside in the clay fraction ($< 2 \mu\text{m}$), and the coarser grains in a sediment are often coated with organic matter and with oxyhydroxides of iron. Adsorption capacity is therefore linked to clay content (fraction $< 2 \mu\text{m}$), clay minerals, organic matter (% C), and oxide or hydroxide content. Usually the *CEC*, or Cation Exchange Capacity of a soil, is given in meq/100 g. An empirical formula which relates *CEC* to percentage clay ($< 2 \mu\text{m}$) and organic carbon is (e.g. Breeuwsma et al. 1986):

$$CEC \text{ (meq/100 g)} = 0.7 \cdot (\% \text{ clay}) + 3.5 \cdot (\% \text{ C})$$

3.2 Intercambio catiónico en intrusión agua salada - agua dulce

Equilibrios de intercambio catiónico

EXCHANGE EQUATIONS

Ion exchange can be described as a reaction with an equilibrium constant. The exchange of Na^+ for K^+ is for example:



with the equilibrium constant:

$$K_{\text{Na}\backslash\text{K}} = \frac{[\text{Na-X}] [\text{K}^+]}{[\text{K-X}] [\text{Na}^+]}$$

Note that we write the elements in subscript form below the equilibrium constant in the order in which they appear as solute ions in the reaction.

Square brackets in the equations denote activities. The Debye-Hückel theory offers a straightforward model to relate concentrations and activities in water (Chapter 3). For the adsorbed cations the matter is more complicated, and different conventions are in common use.

Activities of exchangeable ions are sometimes calculated as

An equivalent fraction β_I for ion I^{+} is calculated as:

$$\beta_I = \frac{\text{meq } I\text{-X}_i \text{ per 100 g sediment}}{CEC} = \frac{\text{meq}_{I\text{-X}_i}}{\sum_{I,J,K,\dots} \text{meq}_{I\text{-X}_i}}$$

where I, J, K, \dots are the exchangeable cations, with charges i, j, k , and $\text{meq}_{I\text{-X}_i}$ indicate $\text{meq } I\text{-X}_i$ per 100 g.

A molar fraction β_I^M is likewise obtained from:

$$\beta_I^M = \frac{\text{mmol } I\text{-X}_i \text{ per 100 g sediment}}{TEC} = \frac{(\text{meq}_{I\text{-X}_i})/i}{\sum_{I,J,K,\dots} (\text{meq}_{I\text{-X}_i})/i}$$

where TEC are total exchangeable cations, in $\text{mmol}/100 \text{ g}$ sediment. Use of fractions gives $\sum \beta = 1$.

3.2 Intercambio catiónico en intrusión agua salada - agua dulce

Equilibrios de intercambio catiónico

For homovalent exchange it makes no difference what convention is used, but for heterovalent exchange the effect is quite notable. A heterovalent exchange is, for example, the exchange of Ca^{2+} for Na^+ such as occurs with seawater intrusion:



The way of writing of Reaction (5.19) conforms to the *Gaines-Thomas* convention, after Gaines and Thomas (1953) who were among the first to give a rigorous definition of a thermodynamic standard state of exchangeable cations. It uses the equivalent fraction of the exchangeable cations for the activity of the adsorbed ions.

$$K_{\text{Na}\backslash\text{Ca}} = \frac{[\text{Na-X}] [\text{Ca}^{2+}]^{0.5}}{[\text{Ca-X}_2]^{0.5} [\text{Na}^+]} = \frac{\beta_{\text{Na}} [\text{Ca}^{2+}]^{0.5}}{\beta_{\text{Ca}}^{0.5} [\text{Na}^+]}$$

Use of molar fractions in Equation (5.20), would follow the *Vanselow* convention

If, on the other hand, the activities of the adsorbed ions are assumed proportional to the number of exchange sites (X^-) which are occupied by the ion, Reaction (5.19) is written as:



Reaction (5.19a) agrees with the *Gapon* convention

$$K_{\text{Na}\backslash\text{Ca}}^G = \frac{[\text{Na-X}] [\text{Ca}^{2+}]^{0.5}}{[\text{Ca}_{0.5}\text{-X}] [\text{Na}^+]} = \frac{\beta_{\text{Na}} [\text{Ca}^{2+}]^{0.5}}{\beta_{\text{Ca}} [\text{Na}^+]}$$

The molar and equivalent fraction are identical in the Gapon convention: both are based on a single exchanger-site with charge -1 .

3.2 Intercambio catiónico en intrusión agua salada - agua dulce

Equilibrios de intercambio catiónico: valores para coeficientes y cálculo de la composición de intercambio

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Table 5.5. Values for exchange coefficients with respect to Na⁺ (Gaines-Thomas convention, i.e. equivalent fractions are used for exchangeable cations). Based partly on a compilation by Bruggenwert and Kamphorst, 1982.

Equation: $\text{Na}^+ + 1/i I-X_i \leftrightarrow \text{Na-X} + 1/i I^{i+}$ with $K_{\text{Na}\setminus I} = \frac{[\text{Na-X}] [I^{i+}]^{1/i}}{[I-X_i]^{1/i} [\text{Na}^+]} = \frac{\beta_{\text{Na}} [I^{i+}]^{1/i}}{\beta_i^{1/i} [\text{Na}^+]}$

Ion I ⁺	K _{Na\I}	Ion I ²⁺	K _{Na\I}	Ion I ³⁺	K _{Na\I}
Li ⁺	1.2 (0.95-1.2)	Mg ²⁺	0.50 (0.4-0.6)	Al ³⁺	0.6 (0.5-0.9)
K ⁺	0.20 (0.15-0.25)	Ca ²⁺	0.40 (0.3-0.6)	Fe ³⁺	?
NH ₄ ⁺	0.25 (0.2-0.3)	Sr ²⁺	0.35 (0.3-0.6)		
Rb ⁺	0.10	Ba ²⁺	0.35 (0.2-0.5)		
Cs ⁺	0.08	Mn ²⁺	0.55		
		Fe ²⁺	0.6		
		Co ²⁺	0.6		
		Ni ²⁺	0.5		
		Cu ²⁺	0.5		
		Zn ²⁺	0.4 (0.3-0.6)		
		Cd ²⁺	0.4 (0.3-0.6)		
		Pb ²⁺	0.3		

3.2 Intercambio catiónico en intrusión agua salada - agua dulce

Equilibrios de intercambio catiónico: valores para coeficientes y cálculo de la composición de intercambio

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Table 4

Values for exchange coefficients with respect to Na⁺ (Gaines–Thomas convention); exchanger composition in equilibrium with model-input values

Ion 1	Selectivity coefficients (K_{Na1})		Exchanger composition, equilibrated with ^a :	
	Appelo and Postma (1993)	Model input	Dune water (model input)	Mean composition infiltration water
Na ⁺	1.0	1.0	0.86%	3.21%
K ⁺	0.20 (0.15–0.25)	0.08	0.53%	1.87%
Mg ²⁺	0.50 (0.4–0.6)	0.50	4.24%	12.29%
Ca ²⁺	0.40 (0.3–0.6)	0.40	94.36%	82.63%

^a Model input selectivity coefficients are used in the calculation.

Fuente: "Hydrogeochemical transport modeling of 24 years of Rhine water infiltration in the dunes of the Amsterdam Water Supply". B.M. van Breukelena, C.A.J. Appelo, T.N. Olsthoornb. *Journal of Hydrology* 209 (1998) 281–296.

3.2 Intercambio catiónico en intrusión agua salada - agua dulce

Cromatografía de intercambio catiónico

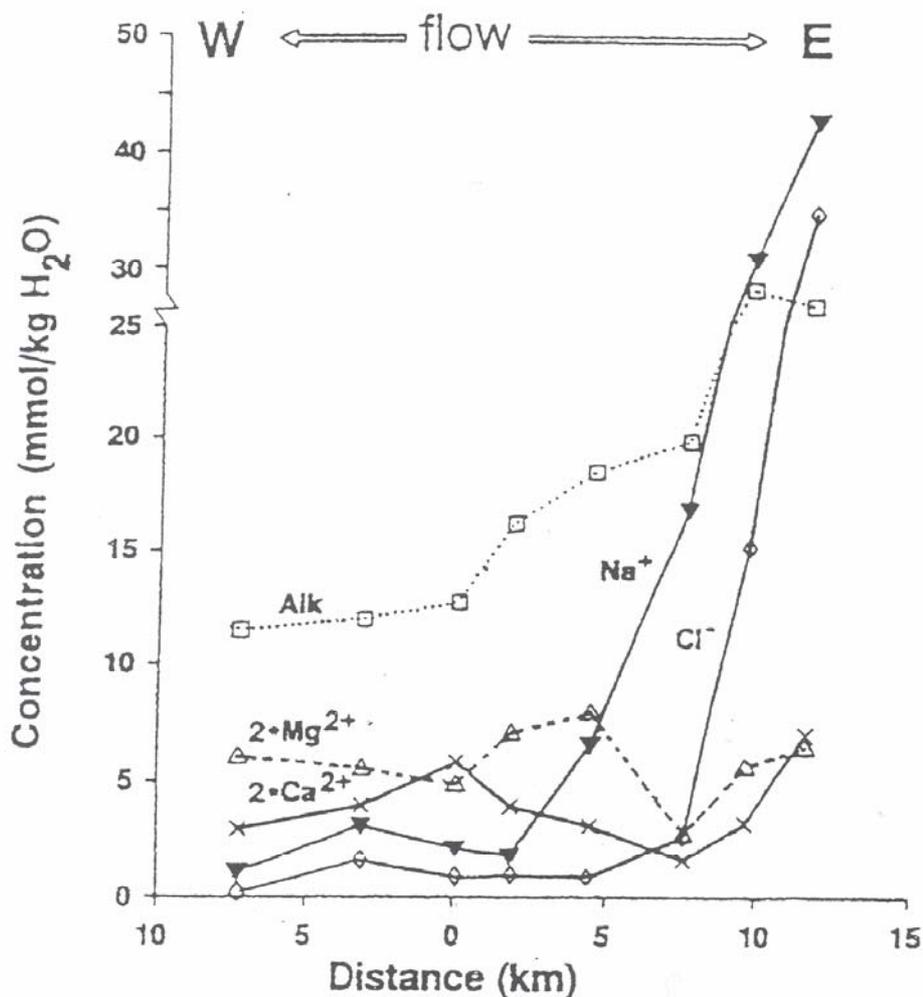


Figure 5.16. Chromatographic pattern along a flowline in a W-E transect through the subsoil of Hoor, The Netherlands. Water infiltrates at point 0, and CaHCO₃ changes successively into MgHCO₃ and NaHCO₃ water quality types (Beekman, 1991).

3.2 Intercambio catiónico en intrusión agua salada - agua dulce

Cromatografía de intercambio catiónico

6.4.3 *Quality patterns with salinization*

The development of a chromatographic pattern depends on the ratio of exchangeable and solute concentration, which gives the velocity of a front (Equation 6.27). When the ratio is small, because the *CEC* of the aquifer is low or the solute concentrations are high, the succession of the fronts will be rapid. In case of seawater intrusion, the high concentrations accelerate the transitions of the water types and reduce their lateral extent in the aquifer. This may be the reason why a chromatographic sequence of salinization has not been observed at the field scale, even though CaCl_2 -water type is an ubiquitous indicator of salt water upconing in coastal areas (Section 6.1). Information on the sequence of compositions with salt water intrusions must therefore be obtained from column or small-scale field experiments (Appelo et al., 1990; Beekman, 1991; Bjerg et al., 1993; Van Breukelen et al., 1998; Gomis-Yagnes et al., 2000; Andersen, 2001), or from models as discussed in the next section.

Beekman and Appelo (1990) performed column experiments, displacing fresh water with seawater diluted 1:1 with distilled water (Figure 6.20). When about 75 mL had been leached from the column, the brackish water had displaced the fresh water and both Ca^{2+} and Mg^{2+} increased because of the exchange with injected Na^+ and the salinity effect, where cations must balance the increased Cl^- . The amount of adsorbed Ca^{2+} was small and therefore Ca^{2+} rapidly dropped again towards the Ca^{2+} concentration in the brackish water. The Mg^{2+} concentration showed a small decrease after the initial salinity jump and then an increase towards the brackish water Mg^{2+} content. The high Ca^{2+} concentrations resulting from the salinity jump, may, in combination with high SO_4^{2-} concentrations, lead to gypsum precipitation (Gomis et al., 2000).

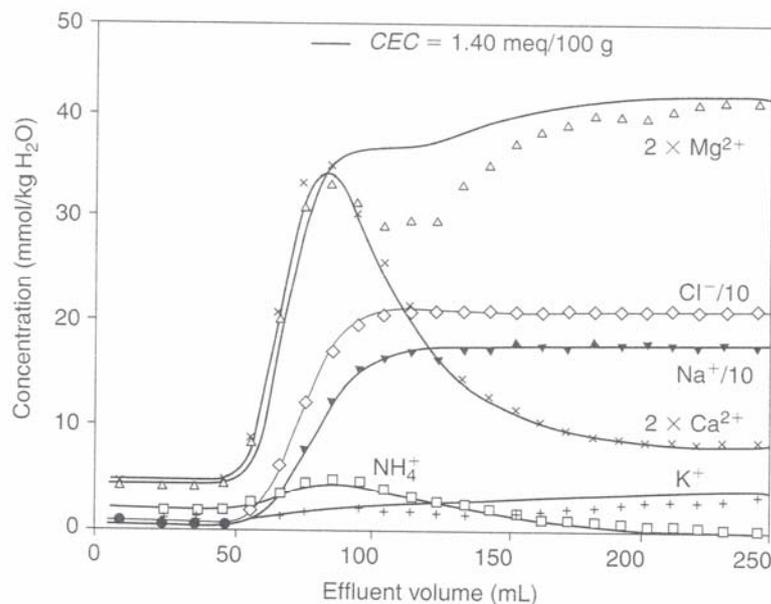


Figure 6.20. Column experiment with once diluted seawater displacing fresh water (Beekman and Appelo, 1990).

3.2 Intercambio catiónico en intrusión agua salada - agua dulce

Difícil interpretación de resultados de campo:

- Complejidad hidrogeológica
- Variabilidad en extracciones y recarga
- Presencia de contaminación
- Procesos de mezcla agua dulce-salada-roca

Desplazamiento cromatográfico en laboratorio:

- Ensayos en columnas con variables controladas
- Aplicación de modelos de transporte reactivo