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SALTWATER CONDITIONS IN SA POBLA AREA AND S'ALBUFERA NATURAL PARK, NE MALLORCA ISLAND, SPAIN

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ABSTRACT

Sa Pobla lies on a plain draining about 450 km^2 of the Mallorca island central depression. It is formed by complex Miocene coral reef deposits resting on marly sediments and topped by Plioquaternary calcarenites, coastal lagoon deposits, eolianites and some alluvium. The area is at the foot of the high Tramuntana range, dominated by carbonate formations, which form the northwestern boundary of the plain. The plain is open to the sea along a marshy low area, the S'Albufera Natural Park. It is separed from the sea by a dune belt, currently occupied by important touristic establishments. The rest of the area is dominantly rural, with irrigated agriculture. Until the seventies traditional shallow dug wells were used for irrigation around the lowlands, but afterwards large dry farming areas vere converted into irrigated land and numerous deep wells were drilled and put into operation. It seems that groundwater discharge around and below the marsh has decreased. The chemical characteristics of groundwater, and temperature and salinity logs in old environmental boreholes and in recently drilled point piezometers give clues about the changes and allow forecasting how new water abstraction plans for urban supply will affect local freshwater resources and the Natural Park.

1.– INTRODUCTION

Mallorca is the largest (3640 km^2) of the Balearic Islands (5000 km^2), an autonomous region of Spain, in the Western Mediterranean Sea (fig. 1). The total stable population of Mallorca is about 600.000 inhabitants, of which 350.000 live in Palma de Mallorca and its surroundings. An important source of income is tourism, that peak in summer and a smaller quantity the year round. Most of the touristic settlements are close to Palma and the nearby coastal resorts, and also in the opposite NE corner of the island, around Badia d'Alcudia (Alcudia Bay).

Urban and touristic resort supply, including some industrial settlements, needs large quanties of water, about 40 hm^3/a (million m^3 per year) for the Palma area, and about 3 hm^3/a for the Badia d'Alcudia area, with additional demands for the industrial towns of Inca and Manacor. Agriculture is an important freshwater consumer which demands up to 175 hm^3/a, of which 100 hm^3/a correspond to the Inca–Sa Pobla plain. Farmers and the small towns oppose the continuous expansion of well fields for urban and touristic resort supply, with increasing litigation and clash of interests. Complex deals have been settled to take and use the available water, mostly groundwater. Total abstraction approaches exploitable resources and consequently seawater intrusion is a common situation in many areas, and a concern for local water authorities [1][2].

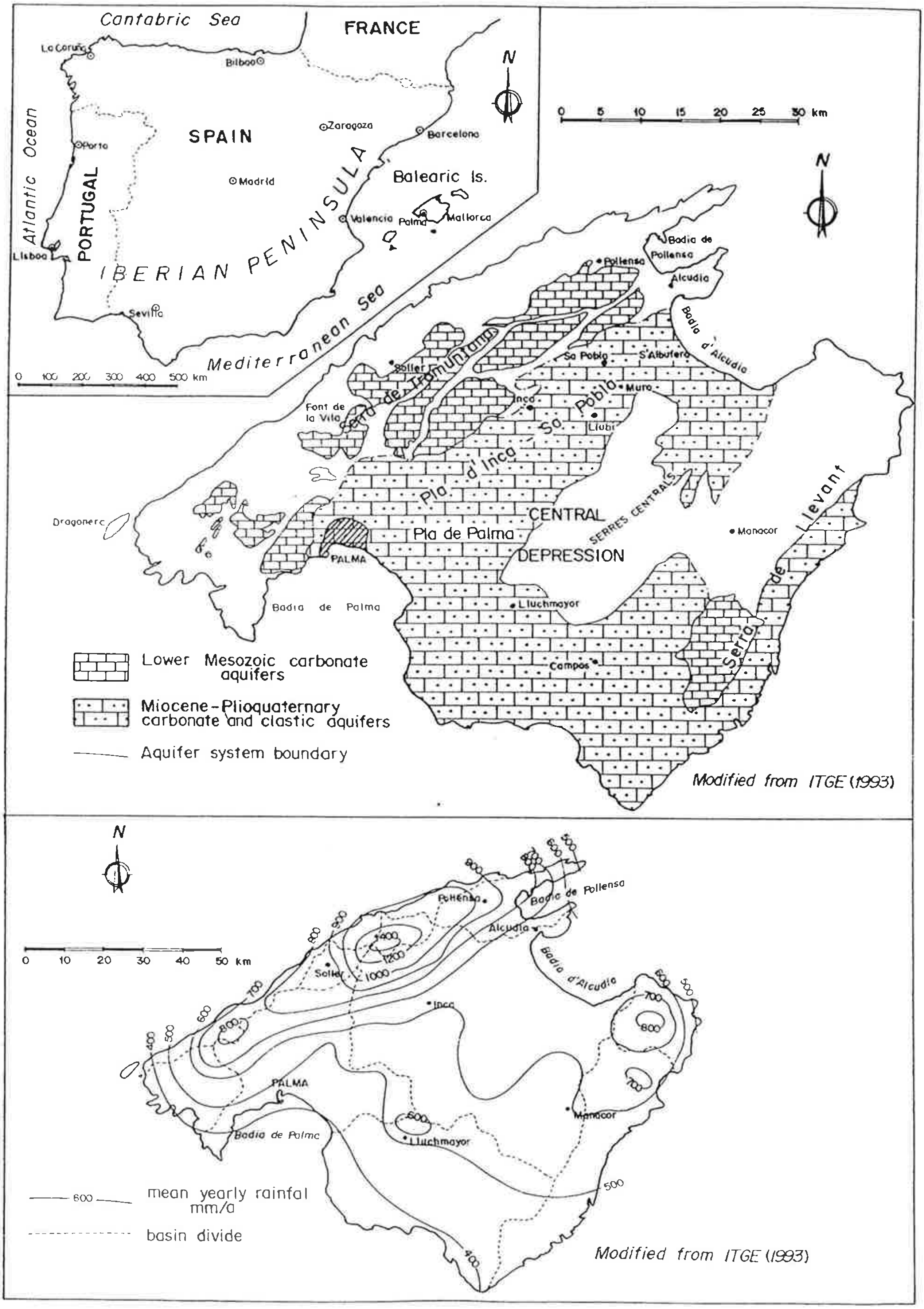

Fig. 1.– General situation map, mean yearly rainfall and sketch of the main physiographic units and aquifers of Mallorca Island (modified from [5]).

2.- HYDROGEOLOGICAL BACKGROUND

Mallorca is related to the Betic range formations of the Iberian Peninsula, which is part of the folded, faulted and thrusted belt fringing the northern boundary of the African Plate. The Alpine orogeny produced in Mallorca a series of thrusted Mesozoic and early Cenozoic, dominantly carbonated (dolostones and limestones) materials, forming the 90 km long Northern ridge (Serra de Tramontana), up to 1440 m altitude and occupying 900 km^2, with a complex structure [3], and the Southern ridge (Serra de Llevant), less than 500 m high. There is a pressure relief graven in between, filled up with upper Tertiary sediments, with some elevations up to 540 m, but mostly below 100 m altitude. Between Palma and Alcudia there is a low elevation corridor, the Inca–Sa Pobla Plain, less than 150 m high. Miocene (Tortonian) reef formations to recent quaternary calcarenites and coastal lagoon deposits close both ends of the corridor, around Palma Bay and around Alcudia Bay.

Mean rainfall varies from less than 500 mm/a near the SE coast to as high as 1400 mm/a in the central Serra de Tramontana. Interannual variations are 0.5 the local rainfall values. Most of the rains fall in early Autumn and in the late Winter period. Total usable mean water resources are reckoned 60 to 70 mm/a [2], or 22 to 25 hm^3/a.

No permanent rivers exist, except downstream some springs, but soon water infiltrates into the ground. Only after storms there is some ephemeral flow. There are only two small surface reservoirs for urban supply. A large part of groundwater recharge is produced along the Serra de Tramuntana. Part of it finds its way into the sea along the cliffs of the northern coast, forming some conspicuous springs and difficult–to–win diffuse and low discharge outflows. The rest collects along the inner boundary with the central corridor, where some highly transmissive formations occur, possibly the remnant of deeply karstified carbonates near old coastal lines [4]. This groundwater flows partly to Alcudia Bay and partly to Palma Bay. Here the discharge is produced by outflowing a buried permeability threshold at 90 m elevation [4][5], recharging the coastal plain's coral reef and calcarenite formations.

The water supply to the Palma area started by tapping a major spring in the limestones (Font de La Vila, 1 to 7 hm^3/a), followed by a series of wells in the Mio–Pliocene carbonate formations of the plain. Partly due to inadequate well siting, construction and operation, and partly due to excess abstraction, supply water got brackish (up to 5 g/l Cl^- in some instances), in spite of introducing 3 to 11 hm^3/a from the surface water reservoirs. New wells were constructed inland, behind the above mentioned hydrogeological threshold, in the so called S'Extremera unit, and later on in closely linked units. The system has a high transmissivity (up to 40.000 m^2/day) and is well bounded downstream. Exploitation has lowered the water table below the hydrogeological threshold most of the time, thus reducing the underground outflow towards the Palma Plain, and consequently worsening well salinization problems there. The intensive exploitation of the S'Estremera and related units is accompanied by a progressive groundwater depletion in summer and in dry years, but recovers in wet years, when there is increased recharge and less pumpage due to the use of other sources of water, including surface water in storage (fig. 2). Water supply problems to Palma has resulted in the drilling of additional wells in the system, thus producing a faster reserve depletion in high water demand periods and the need to resort to the already salinized wells in Palma Plain.

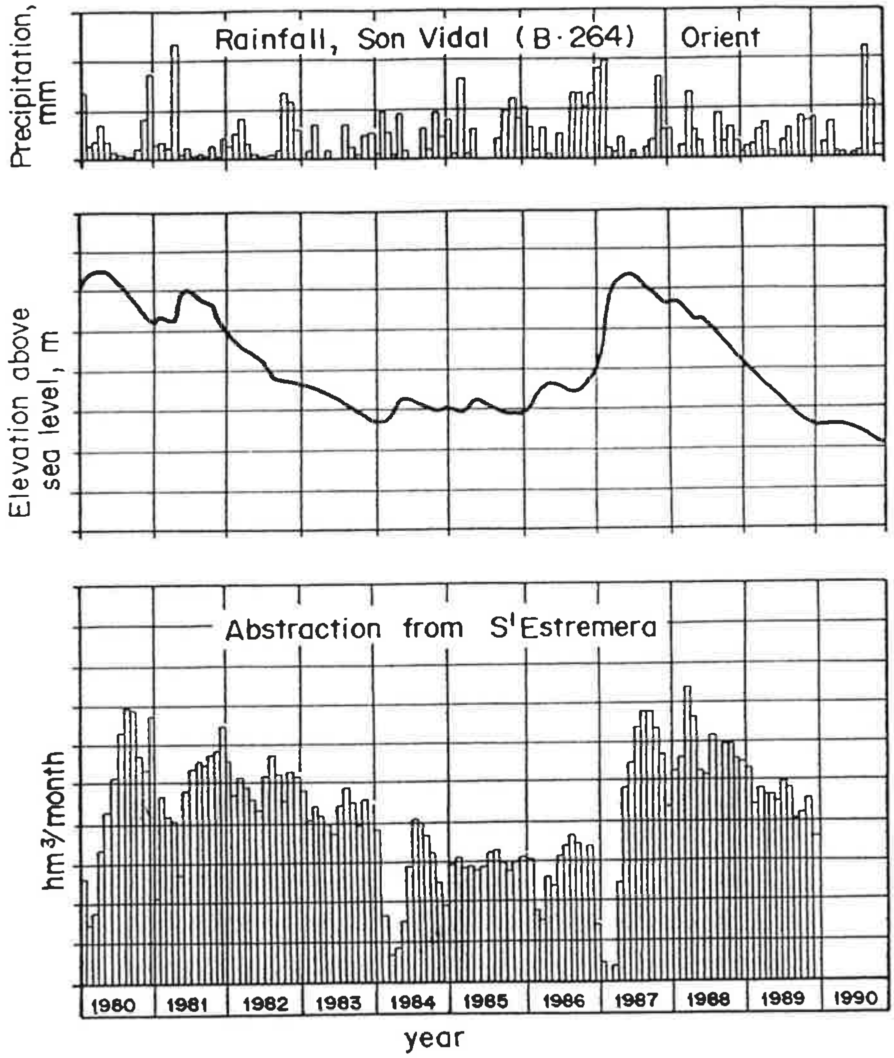

Fig. 2.– Rainfall, groundwater head and monthly abstraction for supply in the S'Estremera carbonate unit [4]. Other related units are not included. The head hydrograph in three observation wells in different places are practically coincident, due to the high hydraulic diffusivity of the aquifer. If the buried threshold at 90 m elevation is not attainned the system acts as a reservoir. It can be recharged with water from other sources to increase reserves. From the reservoir balance the storage is 0.2 to 0.4 hm^3/m of head change and natural monthly recharge is $R = \alpha(P - P_o)$, P = monthly rainfall, $\alpha = 0.2$ to 0.5 and $P_o = 0$ to 20 for P, P_o and R in mm/month [4].

The current high salinity of Palma sewage water does not allows reusing it for agriculture in exchange of fresh groundwater resources presently tapped by farmers.

Present pressure for additional supply water and for a drastic reduction of salinity has fostered new projects. One intends to tap a variable discharge spring at the foot of the high NE sea cliff, which need a long section of a submarine pipe and a large pumping station to carry the water to Palma. Other project aims at groundwater from the Sa Pobla area, in the plain limiting with the Alcudia Bay. This is the subject of this paper. Preliminary water withdrawals transported with a new pipeline already started in the spring of 1994, but were suppressed in June to avoid possible damages to other groundwater users.

3.– THE SA POBLA PLAIN AQUIFERS

The hydrogeological and seawater intrusion characteristics of the Sa Pobla Plain aquifers were the subject of the paper presented at the previous SWIM meeting [6] and will not be repeated here. The area receives local rainfall recharge and groundwater transfer from the central plains of the island as well as from the western part of the Serra de Tramuntana. The main natural discharge is through local outflows in swampy spring areas ("ullals") around the inner boundary of the wetland area, which currently is S'Albufera de Mallorca Natural Park. Coarse karstified calcarenites and coral reef deposits constitute highly permeable formations with intermediate aquitards in a complex setting that lies upon Miocene marls (fig. 3). Buried outcropings of the Mesozoic carbonate formations of the Serra de Tramuntana are possible, especially in the northern edge.

The coral reef formations and associate calcarenites are often highly permeable aquifers, generally bounded by poorly pervious marly formations. Near the inner boundary of the marsh they sub–outcrop and produce the major springs and seeps ("ullals"). The top Plioquaternary calcarenites, alluvium and eolian deposits are highly permeable as well and extend towards the sea below the marsh clayish sediments.

The mean discharge flow from the "ullals" is currently estimated about 25 hm^3/year, although it seems that in the past it was larger. Several years of occasional monitoring of the S'Albufera discharge canals, once deduced the saltwater component, yield values between 10 and 80 hm^3/year, without taking into account some temporary upstream springs. It is difficult to get an accurate figure since some "ullals" are out of the reach, in a swampy area with dense reed grows, and the artificial drainage channels in the marshland produce poor monitoring data due to admiting other waters and the tidal influence.

Total mean recharge to the Sa Pobla unit is reckoned at about 80 to 90 hm^3/a [2][7][8], but it is uncertain. Present intensive exploitation for irrigation of the old dry farming areas in the high parts of the Sa Pobla plain, by mean of deep wells, is reckoned at about 50 hm^3/a. This quantity equals the reduction in steady–state outflow. About 10 hm^3/a of groundwater are missing. They are the balance error or the outflow to the sea throughout other paths. The refinement of the groundwater balance is essential when new large abstractions are planned – just under way – to catch assumed surpluses, and when local supply and agricultural wells and the marsh supply of fresh water are in danger. Additional abstraction to be exported has

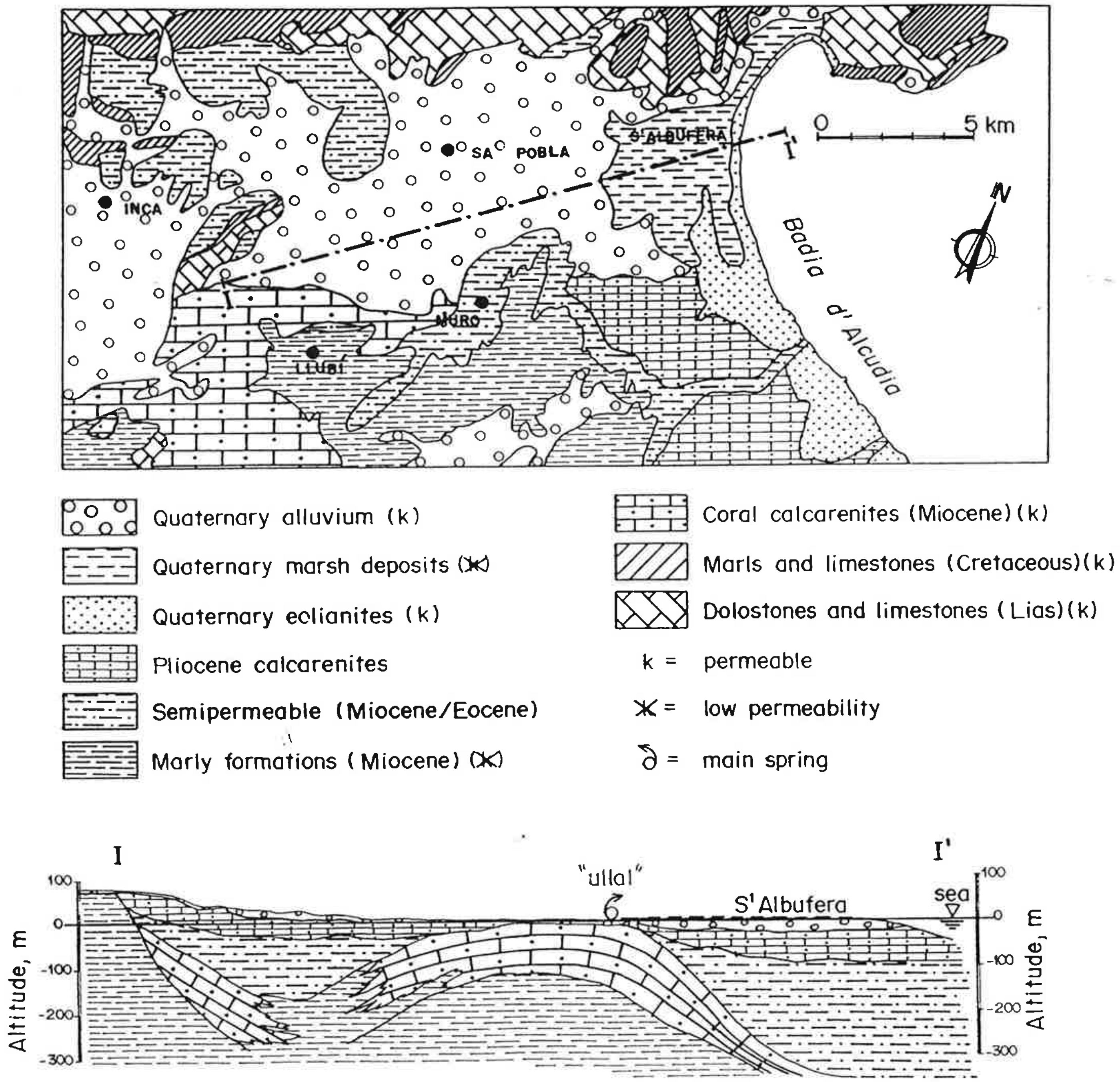

Fig. 3.– Simplified lithological map of the Sa Pobla basin (modified from [5]) and simplified longitudinal cross-section. The designation permeable and low permeable is true only for the formation as a whole, not in detail.

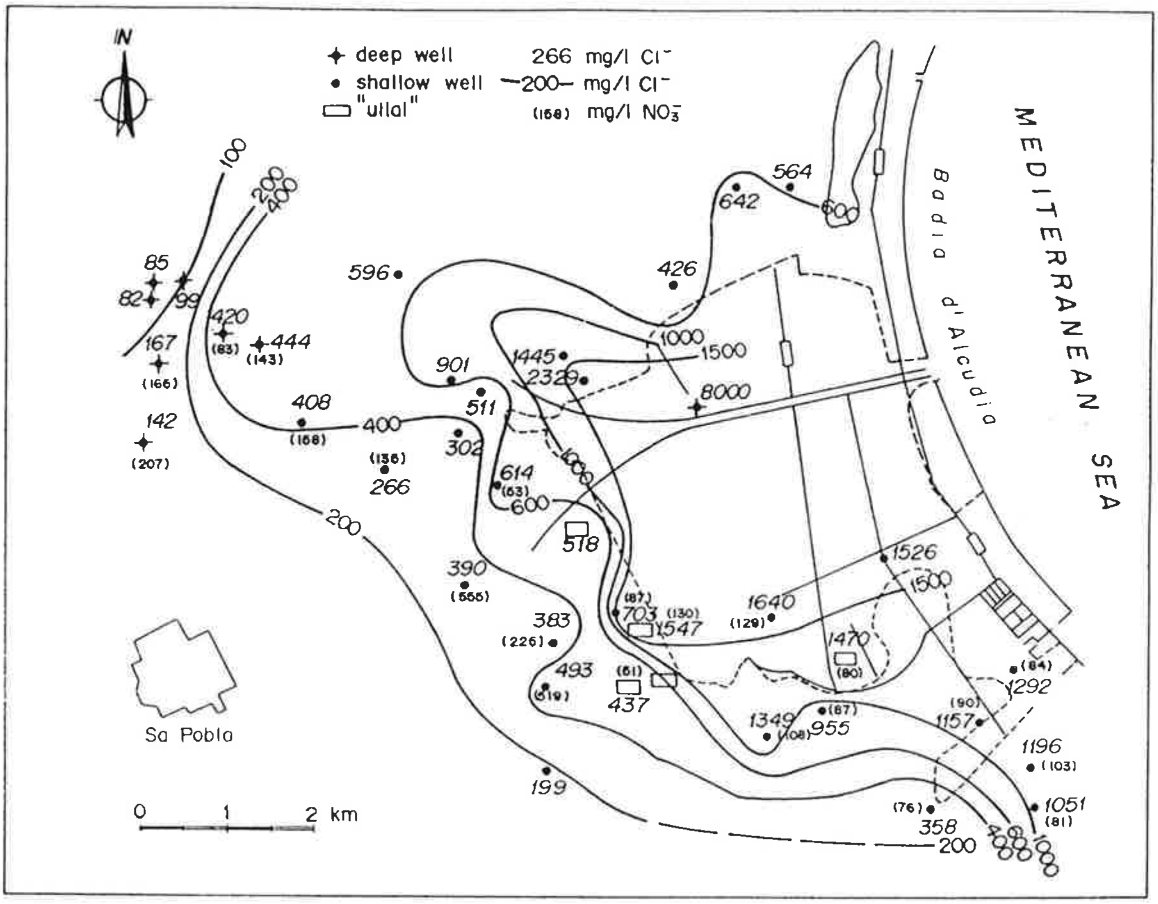

Fig. 4.– Chloride content in mg/l of shallow groundwater around the S'Albufera marsh and indication of nitrate concentration (modified from [8]).

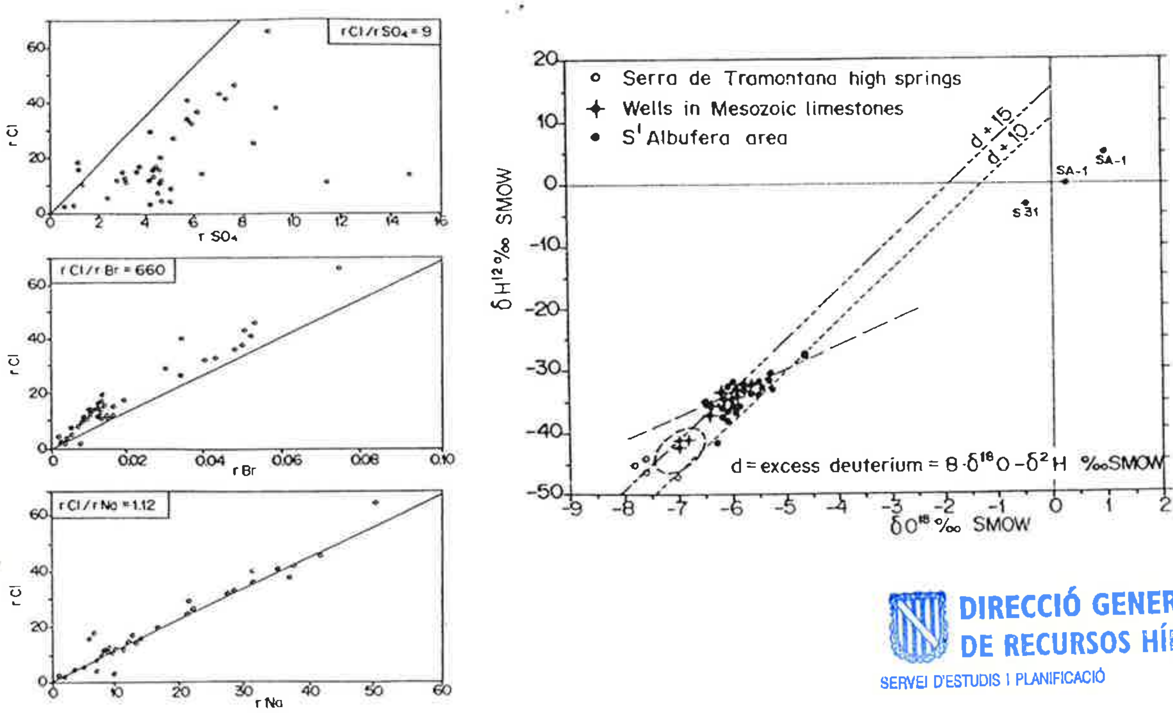

Fig. 5.– Chemical and environmental isotope relationships for local groundwater [6][7][8]. r = values in meq/l. The insets show the seawater value.

to be done without further disproportionate damage to local inhabitants, and economy, but any excess may be worth to be taken out. There is the possibility for winning some winter surplus of groundwater, to be stored in the way to Palma, in the surface reservoirs or better in the S'Estremera aquifer systems by means of artificial recharge, but this needs accurate studies and careful monitoring.

4.- HYDROGEOLOGICAL CHARACTERISTICS OF THE SA POBLA PLAIN AQUIFER

The water take elevation at the marsh inner boundary is about 0.75 to 1.0 m above mean sea level, increases up to 3 m between Muro and Sa Pobla, and attains 5 m near Llubí [6]. Since 1974 a monitoring borehole between Llubí and Inca shows a drawdown from 13 m to less than 7 m elevation, and east of the line Muro–Sa Pobla the decrease is from 3 to 2 m [5]. Other monitoring boreholes at the inner marsh boundary also show a downward trend [8] of about 15 to 30% of the elevation above mean sea level. In the southern part of the marsh the water table elevation is less than 0.5 m above mean sea level.

Shallow groundwater obtained from dug wells and some boreholes is relatively saline, as shown in figure 4, and also very high in nitrate content. Salinity is partly due to saline water diffusion from below and in part due to evaporation in the irrigated fields, where moreover large quanties of agrochemicals are added.

Figure 5 shows some chemical and isotope environmental ratios. There is no major deviation or Na respect to Cl except for a few samples, and also the Cl to Br relationship is close to that of the sea; the small deviation may indicate that part of the Cl is added (low in Br), but it can be simply some systematic analytical error. But most water samples show a large sulphate excess, even the more saline ones. This points to anthropogenic sources, the same that produce the large nitrate concentrations. Agricultural use of groundwater, further to enhance mixing with the underlaying saltwater (upconing of the mixing zone), produces evaporation and the consequent increase of salinity. This is shown by the decrease of the deuterium with the decrease in $\delta^{18}O$, as water is evapotranspirated, partly by transpiration (no isotope fractionation) and partly by evaporation (with isotope fractionation).

The data on tritium content of groundwater does not allow to attain sure conclusions, but they tend to show quite large turnover times [8], of several decades around the marshland boundary. This means a large volume aquifer, in agreement with the smooth changes in spring outflow and groundwater heads relative to recharge variability; most of the changes observed are related to the variable exploitation regime.

The "ullals" chemical characteristics look like that of shallow groundwater and salinity values are not essentially different. Only sulphate and nitrate content are lower, but still clearly indicating the anthropic influence. The stable isotopic analyses show that they do not discharge water from the Serra de Tramontana, but some intermediate elevation, non evaporated water component is present. Salinity from the main "ullal" (Son Sant Joan, U–3) varies between 300 and 700 mg/L Cl. Only a weak inverse relationship with water level elevation at the uptake structure exists. Probably the "ullals" are points where shallow and deep groundwater flow merge and the contributions changes according with the season, the year and the aquifer exploitation regime. This agrees with the fact that the tritum–derived turnover time may be larger than 50 years.

Deep saline groundwater from the marshland is chemically and isotopically seawater.

5.– THE COASTAL AQUIFER MONITORING NETWORK

As shown in [6], in the 70's a groundwater monitoring network was installed, when a large irrigated agricultural development was planned and the exploitation wells were drilled near Llubí and Muro. The plan did not come to an end and finaly was abandoned. Enviromental (fully or long–screened) cased boreholes were drilled and monitored, but systematic monitoring did not started until recently. As commented in [6] these boreholes presumably connect layers with different water heads, as shown by water temperature logs, and then the water salinity logs does not always represent the true salinity stratification in the ground [9]. The freshwater–saltwater mixing zone may appear thicker. This is especially true when groundwater abstraction increase the head difference between layers.

To get a better understanding of groundwater flow and salinity pattern new observation boreholes have been drilled in selected sites, to know salinity and temperature stratification, vertical head changes, and to complement the hydrogeological knowledge of the formations. In a few places two to five separated bores have been drilled, fitted with PCV pipes with a short screen at the desired depth, grouting the rest. To get the true local groundwater heads the pipe has to contain water of the same salinity of that in the screen, or a correction has to be made according with the salinity log converted into a density log (temperature changes have a minor effect). Salinity changes may develop when tube joints are not well sealed and there are large head diferences, or when the borehole water has been changed by injection or pumping.

Figure 6 shows the composite salinity and temperature logs of the different environmental boreholes and multipiezometer sites. In table 1 the main characteristics of the electrical conductivity and temperature logs are shown. Some features are (see [9] for explanations):

- slighly warm waters are found along the inner wetland boundary, probably related to ascending deep water. Warm water and low temperature gradients means moderate permeability. High temperature gradients means important upward flow along the bore with groundwater flow in upper permeable sediments
- relatively cool groundwaters exist near the coast and to the S. They are probably the result of the cooler seawater at one side and the warmer wetland at the other side, which produce nil to low vertical thermal gradients along the boundary
- common freshwater–saltwater relationships occur near the coast and to the S, but in the inner side of the wetland the observed salinity distribution may differ from that existing in the aquifer as a consequence of the environmental piezometer; upward flow apparently expands the mixing zone and rises the 0.5 mixing point.

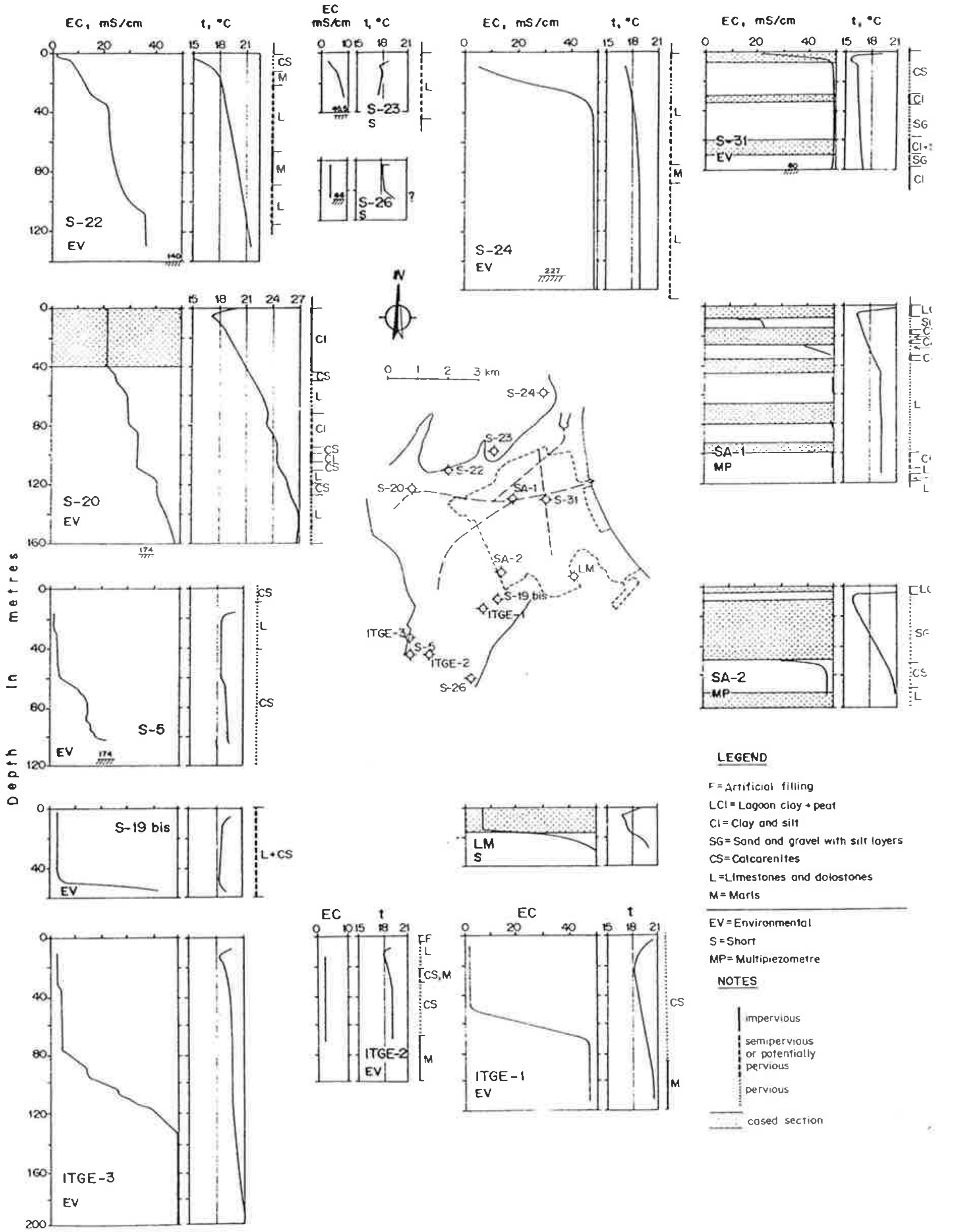

Fig. 6.– Composite salinity (electrical conductivity, EC) and temperature logs of the different environmental boreholes and multipiezometer sites. Only one log per site has been represented. Others practically coincide in the period 1992–94. The EC probe was not carefully calibrated, so EC values have some deviation (45 to 55 mS/cm for seawater).

Table 1.– Characteristics of the electrical conductivity and salinity logs. See figure 6.

			Salinity log		Temperature log			
					Temperature °C			
Place (1)	Design	Type (2)	Shape	Depth m (3)	25 m	100 m	Gradient	Observations
NE	S–24	EV	Interface	10	17.9	19.0	nil	sea effect ?
N	S–23	S	—	—	17.8	—	?	
N	S–22	EV	Steps	80 ?	18.3	20.6	normal	vertical mixing
NW	S–20	EV	Steps	50 ?	19.0	24.0	high	vertical mixing
SW	S–5	EV	Steps	>80	18.5	19.0	low	vertical mixing
SW	S–26	S	—	—	—	(18.5)	—	
S	ITGE–1			56	18.2	20.2	normal	
SW	ITGE–2				18.3	(18.7)	low	freshwater
SW	ITGE–3			115	18.8	19.0	low	
SW	SA–2	MP	—	10–50	17.2	(21)	high	
S	LM	S	Interface	20	17.5	—		
I	SA–1	MP	Interface	15–25	17.5	19.2	low/nil	
I	S–31	EV	—	<7	16.6	(17.0)	low	

(1) With respect to the wetland. I = inside

(2) Borehole type: EV = environmental, S = short, MP = multipiezometer

(3) Depth below sea level to the mid mixing zone.

The area is bounded to the north by pumped carbonate aquifers and to the south by calcarenites. The study of a vertical cross–section perpendicular to the sea may not be representative due to possible groundwater flow components parallel to the coastline, but it will assumed that it is true for preliminary calculations. Depth to the centre of the mixing zone show poor adaption to an interface, although it can be assumed it has two slopes:

Area	Wetland	Landward
Distance to the coast line (km)	2	6
Water depth to 0.5 seawater surface (m)	15	90
50% seawater mixing surface slope	0.007	0.03

Let us assume a homegeneous, thick water table coastal aquifer discharging q_o at the coast (flow per unit coastal length) and q_s at a spring line at a distance d from the coast, and be W the recharge. If saline water is assumed at steady state and hydrostatic, it can be written [10]:

$$q = h(1+\alpha)\, k\frac{dh}{dx}$$

q = fresh groundwater flow at distance x from the coast:

h = piezometric head above mean sea level
$\alpha = \rho_f/(\rho_s - \rho_f)$
ρ = water specific weight; f = fresh; s = saline
k = aquifer permeability (hydraulic conductivity)

At the coastline $q{=}q_o$ and at $x{=}d$; $q{=}q_o{-}Wd$
At $0{\leq}x{\leq}$d; $q{=}q_o{-}Wx$

At $x \geq d$; $q = q_o - Wd + q_o - W(x-d)$
At $x = d$ the h must be unique; $q = q_d$
At $x = 0$; $h = 0$

The solution is (z = equivalent freshwater thickness):

For $x \leq d$; $\quad z^2 = \frac{(1+\alpha)x}{k}[2q_o - Wx]$
For $x \geq d$; $\quad z^2 = \frac{(1+\alpha)x}{k}[2(q_o + q_d) - Wx] - \frac{2(1+\alpha)d}{k} q_d$

Near the coast, $W = 0$ as first approximation.

Below the wetland: $q_o/k = 0,00137$m.

Inland from the wetland (d=4 km): $3\frac{q_o}{k} + \frac{q_d}{k} = 0,0494$m. Then $q_d/k = 0.0453$m ($>> q_o/k$)

The possible values of k are poorly known. Below the wetland, a likely value for the Plioquaternary calcarenites is k=100 m/d. Then $q_o \simeq 0.14$ m^2/d or 0.05 hm^3/km/a. Landward from the wetland $k \simeq 300$ m/d. Then $q_d = 13.6$ m^2/d or 5 hm^3/km/a or a total discharge of 150 l/s from the "ullals" and diffuse. The figure seem quite low but not far from current values in a series of dry years. Environmental piezometres may show a too thin freshwater layer. The refinement of the observation network and some well done pumping tests will help in evaluating the balance of the area and the effect of new groundwater abstractions.

Fig 7 shows several months of continuous recording of water levels in three bores in the wetland. Borehole SA1–2 (screened between 9 and 17 m depth) shows tidal effects (3–5 m) for a local sea tide of 20–30 m, or a tidal efficiency of about 0.15. The delay has not been determined. The wetland loamy deposits act as a confining layer. For a confined aquifer in vertical contact with the sea along a lineal coast tidal eficiency [10][11] is:

$$ef = exp\left[-x\sqrt{\frac{\pi\, S}{t_o\, T}}\right]$$

For:

ef = tidal efficiency = 0.15.
x = effective distance to the coast = 2500 m
S = storage coefficient
T = aquifer transmissivity
t_o = tidal period = 0.5175 day

Then T/S = aquifer hydraulic diffusivity = $5{\cdot}10^7$ m^2/d, which is compatible with T = 2500 m^2/d and $S = 0.5{\cdot}10^{-5}$, common values for the area.

For boreholes A2 (deep and shallow) tidal effects are not seen but there is an exact diunal effect of 1.5 cm (shallow) to 2.0 cm (deep), with high stands short before noon and low stands

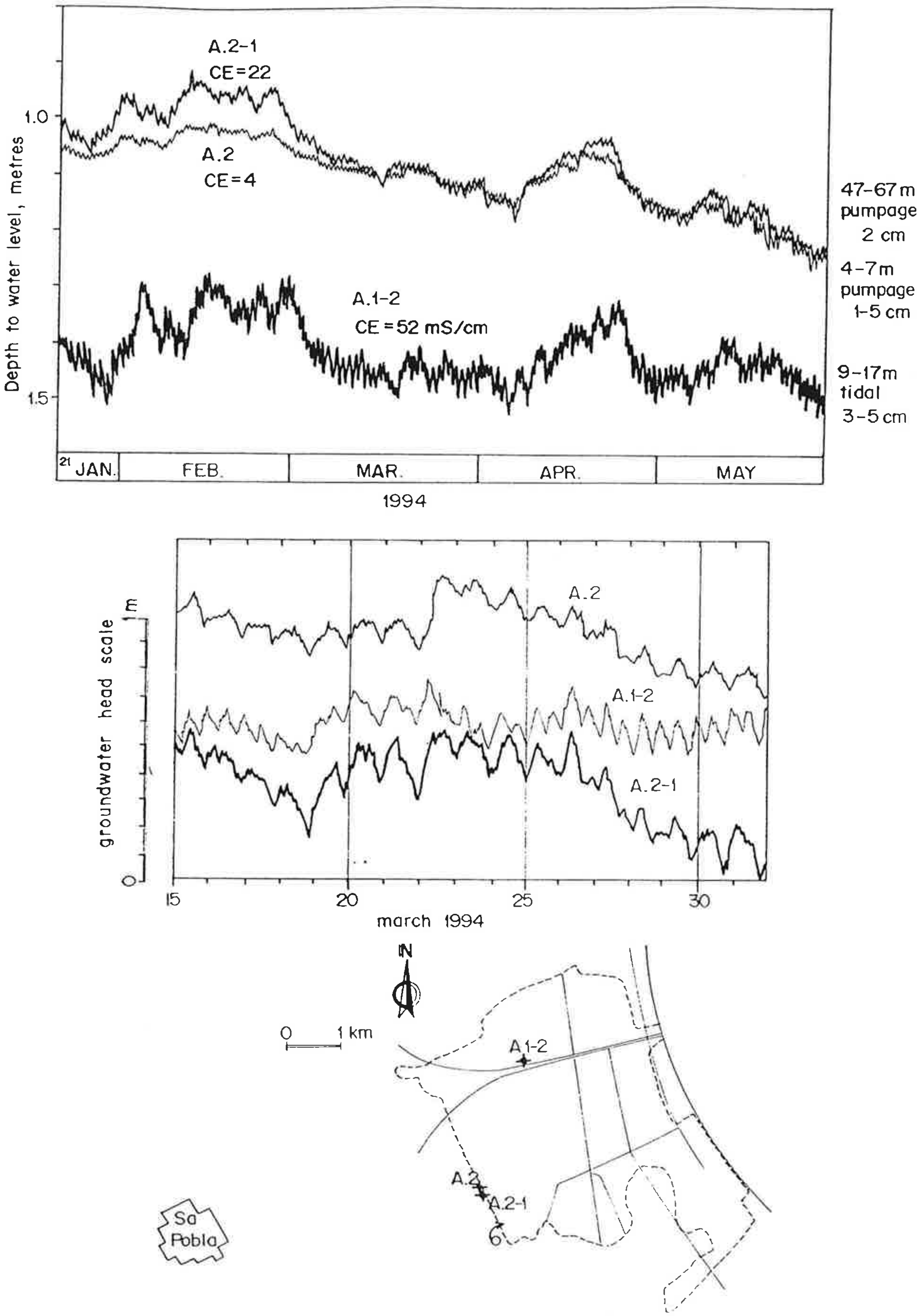

Fig. 7.– Water level records in three short–screened piezometers and detail of the dayly fluctuations.

short before midnight. Local time in April is about 2 hours in advance of solar time. Since the fluctuations increase with depth, local evapotranspiration induced fluctuations does not seem a likely explanation, although the absolute value is possible. Pumpage from nearly supply uptakes (Son Sant Joan) is a more likely cause since they do not show the week end rest periods expected from agricultural abstractions.

6.– CONCLUSIONS

The new areas to abstract groundwater to supply Palma de Mallorca may create salinity problems in already stressed coastal aquifers, although a careful use of groundwater resources in Winter and its storage in inland carbonate aquifers may produce a manageable alternative. This has to be carefully checked against present aquifer behaviour. In the Sa Pobla–Badia d'Alcudia area existing data and the monitoring network are still insufficient to understand present stituations and to produce likely scenarios under the new stresses. The old environmental monitoring boreholes are suspicious of producing a distorted vertical salinity distribution and new short–screened, nested boreholes are needed, some of them recently drilled or under way. Preliminary figures of groundwater flow are too low and need to be reconsidered, especially if aquifer water balance results are too inaccurate. Not only local supply wells and springs and agricultural needs have to be protected or substituted, but also the freshwater role in the S'Albufera de Mallorca has to be considered for maintaining the biodiversity that make valuable this site.

7.– ACKNOWLEDGEMENTS

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8.– REFERENCES

[1] Fúster, J. (1973). Estudio de los recursos hidráulicos totales de la Isla de Mallorca: informe de recopilación y síntesis. Memoria–Informe Com. Interministerial MOP–MIE–MA. Palma de Mallorca: 1–128 + annexes (3 vols).

[2] SH (1987). Hidrogeología de Mallorca. Servei Hidràulic de Balears. Palma de Mallorca: 1–83 + 12 charts.

[3] Gelabert, B., Sabat, F., Rodríguez–Perea, A. (1992). A structural outline of the Serra de Tramuntana of Mallorca (Balearic Islands). Tectonophysics, 203: 167–183.

[4] Custodio, E; Poncela, R.; Badiella, P.; Bayó, A. (1991). Hidrología subterránea del sector comprendido entre Palma y Alcudia, con énfasis en la explotación de agua subterránea para el abastecimiento de Palma, Mallorca. EMAYA. Curso Internacional de Hidrología Subterránea/Dep. Enginyeria del Terreny. Barcelona (internal).

[5] ITGE (1991). Palma de Mallorca, Cabrera. Mapa Hidrogeológico de España, Escala 1:200.000. 57/66. Synthesis and map.

[6] Custodio, E.; Barón, A.; Rodríguez–Morillo, H.; Poncela, R. and Bayó, A. (1992). Saline water in S'Albufera Natural Park aquifer system, Mallorca island (Spain): a preliminary study. Study and Modelling of Saltwater Intrusion into Aquifers (12th SWIM). CIMNE, Barcelona: 661–686.

[7] Rodríguez–Morillo, H. (1992). Estudio hidrogeológico de S'Albufera de Alcudia con énfasis hidrogeoquímico e isotópico ambiental (Isla de Mallorca). Master Thesis. on Groundwater Hydrology. Polytechnic University of Catalonia (unpublished).

[8] Calahorra, P.I. (1993). Estudio hidrogeológico del entorno del Parque Natural de S'Albufera de Alcudia (Mallorca): estudio hidrogeoquímico e isotópico ambiental. Master thesis on Groundwater. Polytechnic University of Catalonia. Barcelona: 1–238 (unpublished).

[9] Custodio, E. (1994). Effect of vertical flows inside monitoring boreholes in coastal areas. 13th Salt Water Intrusion Meeting. Cagliari (this volume).

[10] Custodio, E.; Llamas, M.R. (1976; 1983). Hidrología Subterránea. Ediciones Omega. Barcelona, 2 vols: 1–2150 (Ch. 9.18 and Ch. 13.3).

[11] Ferris, J. et al. (1962). Theory aquifer tests. U.S. Geological Survey, Water–Supply Paper 1536–E, Washington: 1–74.