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SOME ASPECTS OF SEA WATER INTRUSION IN CATALONIA (SPAIN)

SUMMARY

Along the coast of Catalonia, problems of salt water encroachment into the aquifers are common, both under natural conditions or under heavy groundwater abstractions. Some of the situations have already being presented and discussed in other meetings, but some aspects are not yet well understood or evolve differently from foreseen. Several situations are considered, including coastal unconsolidated formations, semiconsolidated alluvial fans and limestone aquifers. The fast evolution of some coastal areas may explain some of the encountered problems. The areas of Lleria (small semiconsolidated alluvial fan), Montroig (coastal plain), Tarragona (limestones and calcarenites with an alluvial formation), Sitges (sediments overlying limestones), Garraf (limestones), Maresme (coastal sands and arcoses), Baix Ter (small delta) and Empordà (recent coastal plain) are considered and compared briefly with the results obtained in the Llobregat and Besós delta areas, and presented elsewhere.

1. INTRODUCTION

Most of the densely populated and industrialized catalan coast in Spain has comparatively small water resources. River basins are small, specially in the Southern part, where the water shortage is enhanced by the low annual

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SGOP = Geological Service of Public Works. CAPO = Eastern Pyrenees Water Authority. UPB = Polytechnical University of Barcelona. CIHS = International Ground Water Hydrology Course.

rainfall rate (about 450 mm/year against more than 700 mm/year in the Northern part). Both surface and groundwater are intensively exploited and overdraft becomes the normal situation. As a consequence sea water encroachment is a widespread and increasing problem. Fresh-salt water mixing presents many different aspects, the local aquifer structure playing a decisive role. Some of the best known situations are briefly discussed, in a descriptive form, putting more emphasis on the hydrogeology than on calculation methods.

Reviews of problems were prepared in 1970 [19], 1976 [10] and 1981 [6]. The well known sea water intrusion in the Llobregat and Besós deltas, near Barcelona, were presented in the previous SWIM meeting in Uppsala [7]. In them sea water penetration is produced through the offshore part of the deep confined aquifer. Although trapped salt water can be found in the low permeability intermediate layer of the Llobregat delta, it is almost stagnant in the short term.

Extensive salt water bodies are found in the most recent upper formations. To explain fast salinizations of wells in some other areas, residual sea water in recent formations has been suggested, instead of a direct sea water encroachment. This aspects are discussed later on. Fig. 1 is a situation map and shows the localities that will be mentioned in the paper.

In the references some of the published papers are mentioned, but most of the information is taken from unpublished reports and papers from the organizations in which the authors work.

2. SMALL SEMICONSOLIDATED ALLUVIAL FANS

Between the rugged coastal carbonate limestones and the sea, small flat areas are frequent. They are alluvial fans of dominantly coarse materials that contain highly pervious layers between less pervious ones. These small flats, sometimes of less than 1 km^2 surface, are interesting sites for human, touristic or industrial settlements, and the only places where wells of reasonable depth can be sunk.

There is a thick transition zone between fresh and salt water with a very thin fresh water layer on the top, so that it is extremely difficult to get fresh water, but for isolated household applications.

The Lleria and Mataset alluvial fans have been studied during the civil works of units I and II of the Vandellós Nuclear Site [5]. Up to 150 m of half indurated sediments pile up on fractured limestones, presenting a transmissivity in excess of 40,000 m^2/day, most of the permeability being concentrated in thin layers inside the well cemented conglomerate slabs, up to 2000 m/day.

Fresh water from the carbonate belt flows through these alluvial fan materials, where it mixes with salt water, as shown in Figure 2. Studies by means of radioactive tracers [1, 4, 15] show the lack of significant vertical circula-

tion along the bore-holes, both in fresh and mixed water. Darcy velocity attains 2 m/day in the slighly brackish upper part. Total fresh water flow is about 0.5 to 1.10^6 m^3/year/ km of coast, in close agreement to that expected from water balances in the limestone massif.

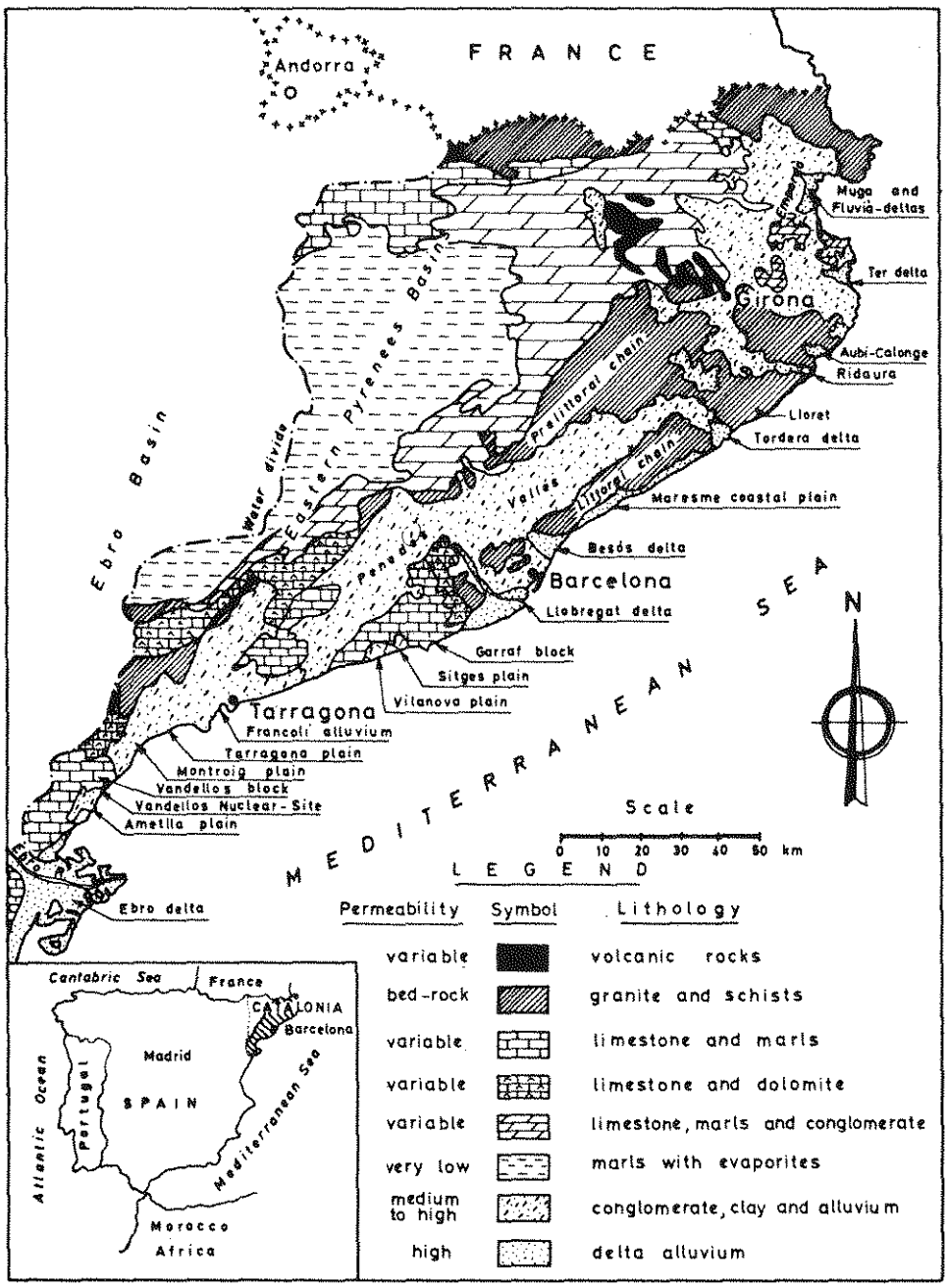

Fig. 1 – Situation and lithology map.

The sharp vertical changes in permeability are clearly reflected in the borehole salinity logs. Permeability is higher near the coast, presenting a major component in that direction, as deduced from data of a detailed pumping test. Water temperature decreases downwards. It can be explained as the cooling effect of the sea. The upper part reflects the heating effect of flowing fresh water (Fig. 2).

3. SMALL COASTAL PLAINS

Most of the small coastal plains present a permeable cover (alluvium, sand beaches, alluvial fans) resting on almost impervious formations (marine or continental clays, granite). Natural salt water wedge penetration is in close agreement with the direct influence of permeability and permeable saturated thickness to the square and it is inversely related with fresh water flow discharge into the sea. In most instances a well-defined interface exists, the thickness of the mixing zone being a fraction of total aquifer thickness.

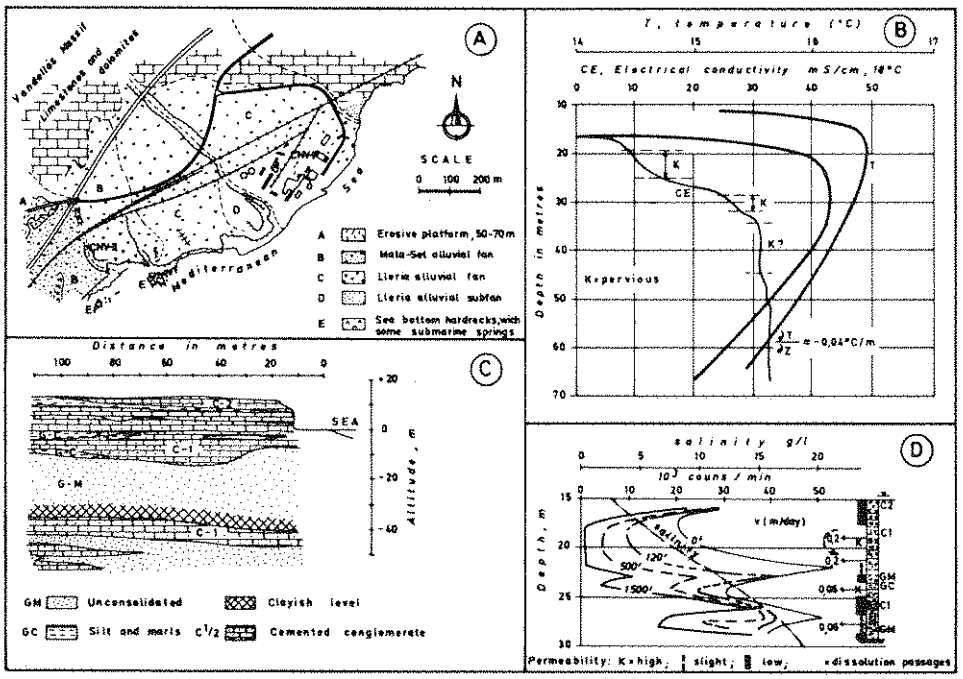

Fig. 2 – Small unconsolidated alluvial fans. The Lleria-Mata Set fans at the Vandellós Nuclear site. A - Morphological map. B - Simplified cross section. C - Typical salinity and temperature bore-hole logs showing the heterogeneity effects and the sea cooling effect. D - Typical radioactive tracer dilution curves for a bore-hole, showing the vertical heterogeneity; the flow concentrates around the conglomerate layer presenting dissolution passages.

The evolution under exploitation depends greatly on the presence of shallow low permeability layers extending until the shore or further on. In many instances they provide a protective cover that greatly reduces sea water intrusion if wells near the coast don't disturb them.

Figure 3 shows two typical extreme situations in the Southern part of the Tarragona plain [3, 8, 14]. Frequent changes in lithology, depth and basin area of the different alluvial fans and the littoral deposits explain the continuous changes in the salt water penetration along the coast. Where thick coarse cones derived from carbonate areas intersect the coastal line, the salt water wedge may penetrate a few km under natural conditions. Pumping wells increase the encroachment lenght and wells get easily problems of salt or brackish water upconing. Conversely, when the cones present a low permeability and thickness along the coast, sea water intrusion generally only reach some wells near the coast, even when exploitation is close to mean fresh water recharge. In the Maresme strip, where granite-derived sands and altered granite constitute the aquifers, despite an intense exploitation and frequent water table elevations below sea level, sea water intrusion is limited to the areas close to the coast and inside the villages (Fig. 4). Most wells in this area are dug ones more than a hundred years old, and those near the coast probably do not reach the clay and silt layers that protect the inland part of the aquifer, which thus is half-isolated from the near-shore sands. Some abnormal deep penetrations of salt water in areas not shown in figure 4 can be explained by the local effect of thick pervious alluvium deposits along some ravines.

4. CONSOLIDATED CARBONATE FORMATIONS

Consolidated carbonate formations are frequent along the coast. A lot of wells tray to get fresh water resources from them in areas close to the shore or near the bottom of deeply incised ravines, the only places where the rough topography allows well sitting.

Fresh water flow proceeds mainly through fissures and joints, many of them related to techtonic disturbances. The pervious areas are irregularly distributed and salt water penetration greatly increases when the fissures are deep and orientated normal to the coast.

In the Vandellós massif, near the nuclear site, only a few wells yield enough fresh water. They are those presenting only a fissure zone a few metres below the water table (Fig. 5). Other wells with a thicker and more pervious water bearing zone yield brackish to salty water. A clear salinity stratification exists. Under exploitation conditions, fresh water wells get some lateral inflow of brackish water, that slowly impairs the abstracted water quality. Near Tarragona pervious miocene coral-reef calcarenites and cretaceous limestones are found. They present a deep natural sea water penetration, enhanced by an intensive exploitation in some areas [2, 18]. Most wells get salt water by upconing processes. The salinity situation depends largely on the annual

recharge, wet years being followed by a sharp decrease, and then a slow return to the initial conditions, according to the delayed drainage of the less pervious formations inland (Fig. 5). In the eastern area, the calcarenites and limestones become confined under the plain tertiary and quaternary sedi-

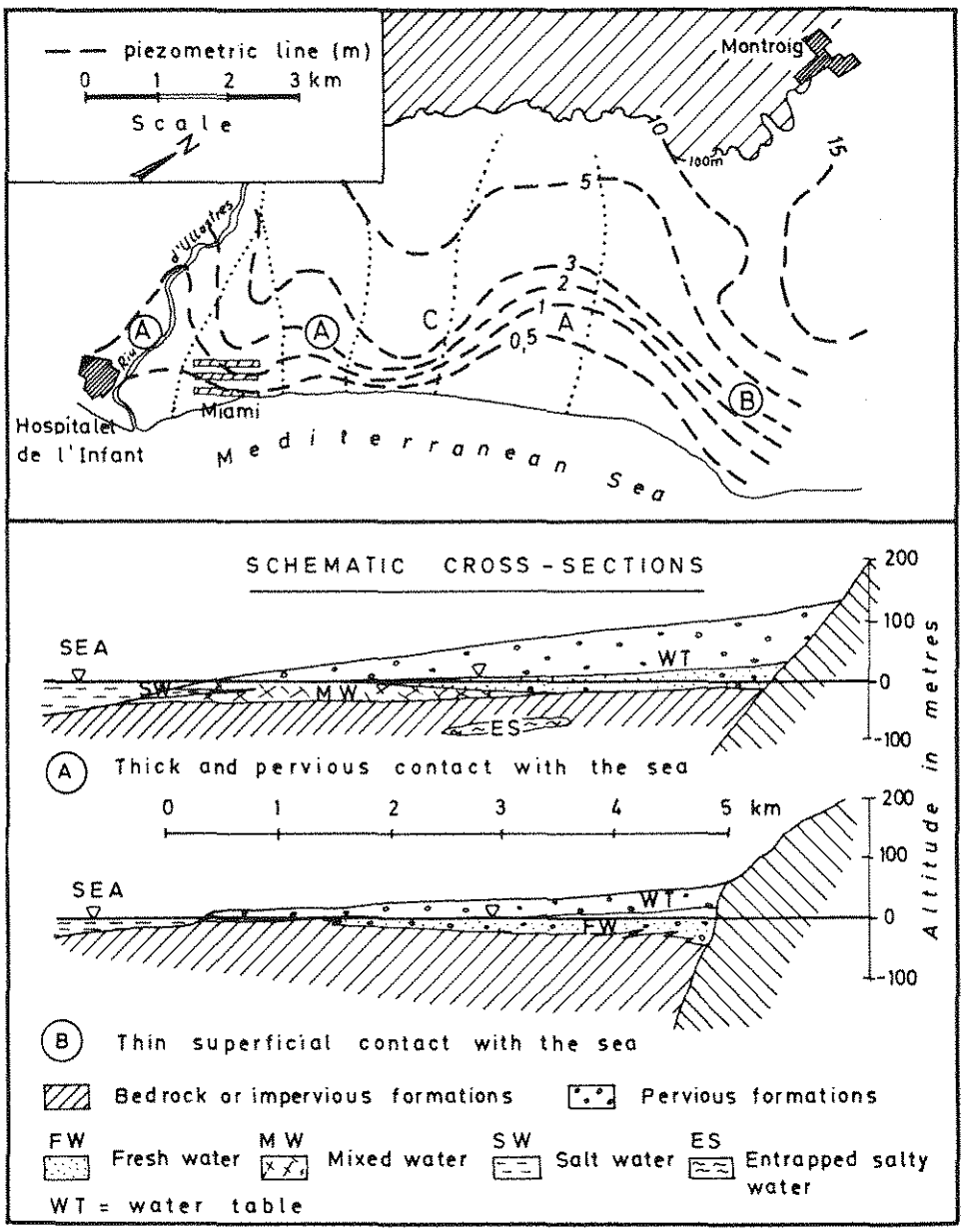

Fig. 3 - Sea water intrusion in the alluvial fans of the Southern Tarragona Plain. Situation A contains a deeply penetrant salt water wedge, while situation B is free from saltt water and even when heavily exploited, sea water encroachment is very slow. C indicates inter-fan areas. The debris source area has a great influence in permeability.

ments, forming a closed pocket. The intense exploitation of fresh water in such a formation steadily produces its replacement by salt water.

In the Garraf massif the only saturated pervious areas are deep cavities along karstified horizontal faults and the associated scort of fissures and broken areas. Mixing with salt water inside the main submarine spring duct (about 500 l/s) starts far away [9]. It is produced through sea water flow toward the deep-seated duct, in which the salt water potential is decreased by the final vertical outlet (Fig. 6). It includes fresh water to be obtained near the coast. Some fresh water can be tapped by shallow wells in the nearby ravine bottoms and small coastal plattforms.

5. UNCONSOLIDATED SEDIMENTS RESTING ON CARBONATE ROCK FORMATIONS

Unconsolidated sediments are mainly continental miocene and quaternary gravels, sands, silts and clays, resting on pervious, mainly karstified, carbonate rock formations. Under exploitation conditions, water salinity behaviour depend on the situation in depth. Deep highly pervious formations generally contain salty water. Wells just tapping up to the water table yield small quantities of fresh water [17], but more penetrant wells and specially those close to or attaining the underlaying limestones are very prone to sea water pollution by upconing. Would exploitation be intense, the upconing increases according to the progressive salt water encroachment through the limestones. The Sitges-Vilanova plain [11] is a good example (Fig. 7).

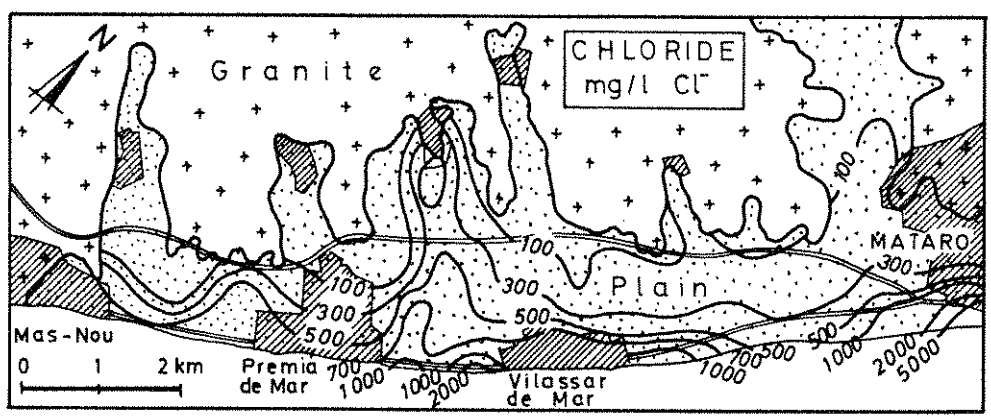

Fig. 4 – Chloride content in groundwater in the Southern Maresme area. It is a plain of alluvial and dilluvial granite-derived sands resting on arcose and granite. Despite a long-time soustained overpumping, sea water intrusion is not intense.

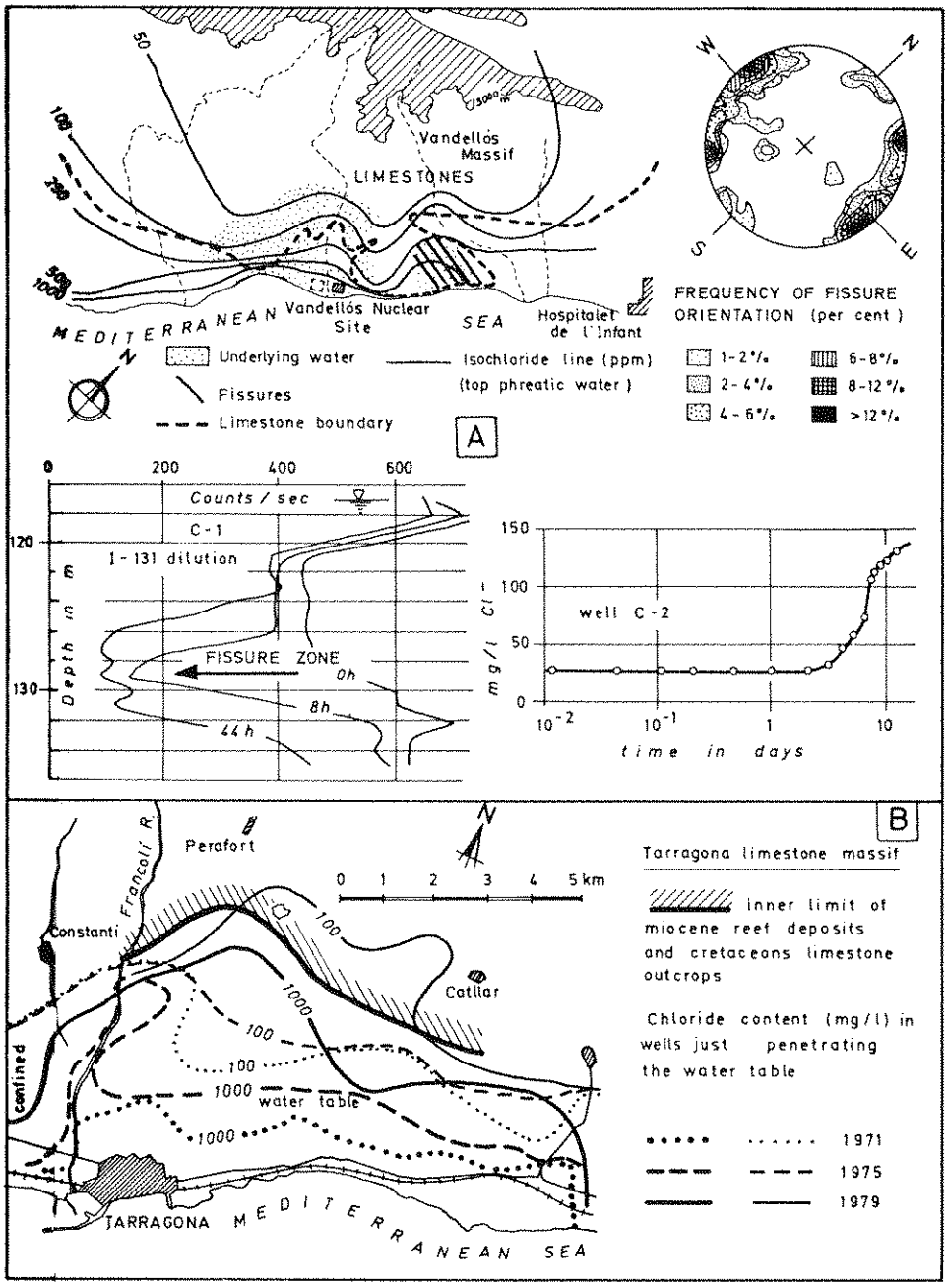

Fig. 5 – Sea water encroachment in limestone formations in the Tarragona area. A - Vandellós massif, affected by a fissure set intersecting the coast line, which allow for a deeper penetration of sea water; in one of the wells the fissure zone is localized by means of a radioactive tracer; in other well the pumped water salinity increases after some time due to brackish water movement in the fissures. B - Progressive salt water pollution of coral-reef and massive limestones during the recession period following a very wet year (1971).

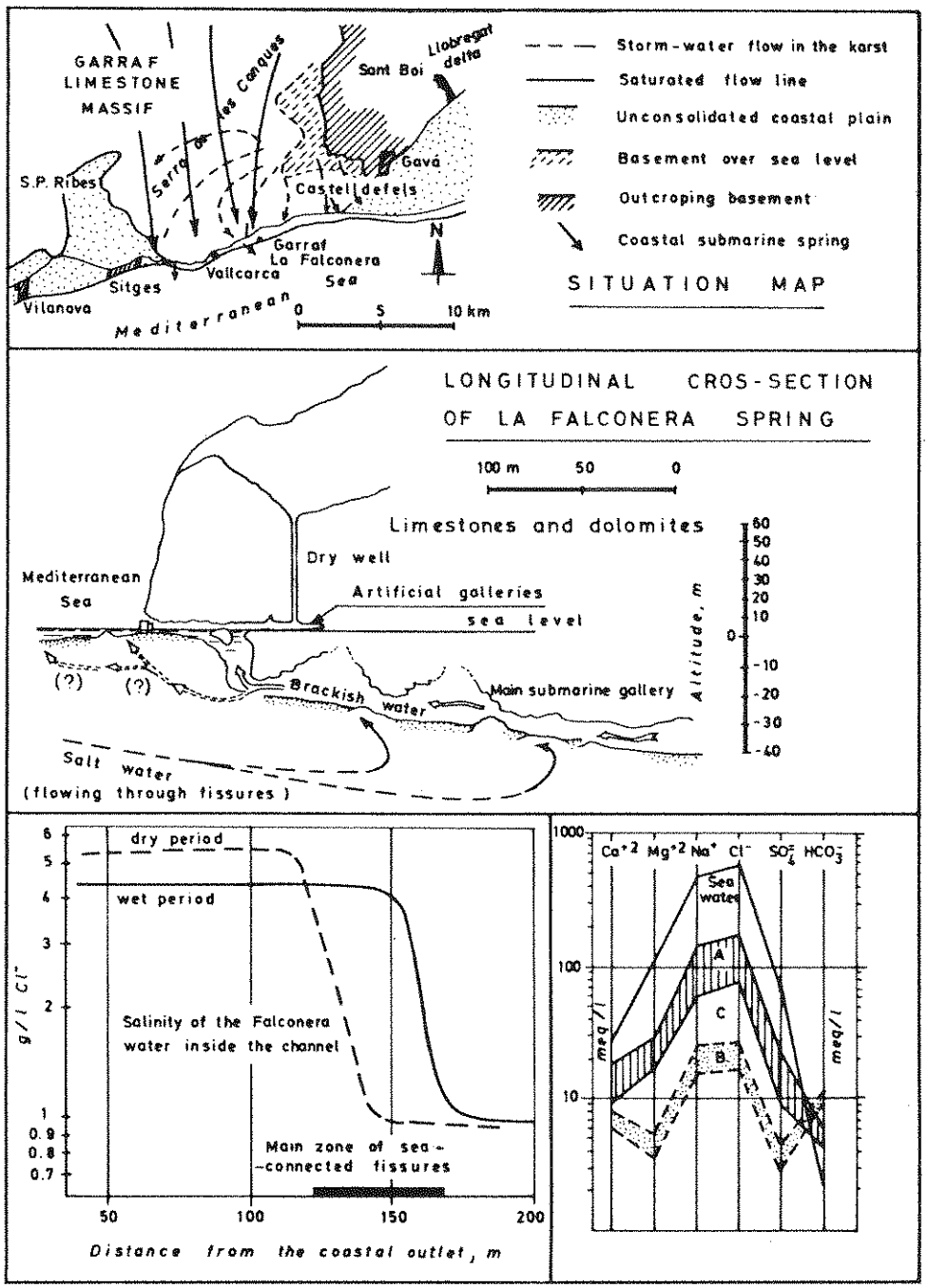

Fig. 6 – Salt water penetration in the Falconera submarine coastal spring, in the Garraf Limestone Massif, near Barcelona. The higher density of sea water allow their continous slow penetration into the main channel. Chemical analyses plot in two main separated areas, before and after the main zone of sea connected fissures.

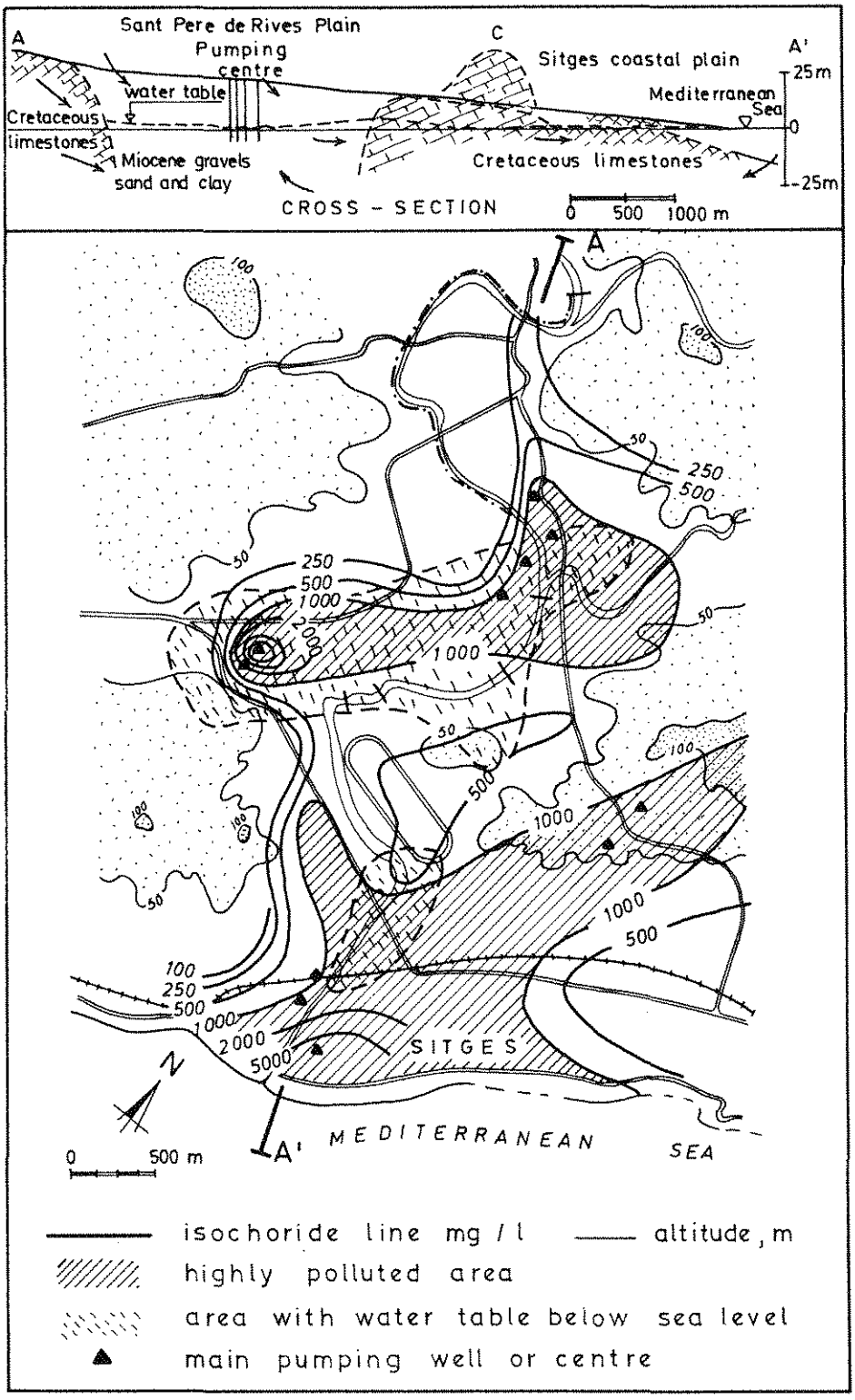

Fig. 7 – Sea water pollution by upconing in the Sant Pere de Rives plain. The differences in the form of the most polluted area and the area having a water table below sea level is due to uncertainties in the data.

6. RECENT ALLUVIAL AND DELTAIC COASTAL FORMATIONS

Recent alluvial and deltaic coastal formations have in common:

- Generally a two aquifer system exists near the coast, with a fine sand, silt and clay semipervious lens between them. Large lateral variations can be expected (Fig. 8). This is a consequence of recent eustatic level changes.

- The slope of the land surface permits to build up enough fresh water hydraulic head to maintain the flow in the deep formations. Thus salt water originally in the coarse sediments is flushed out in most of the aquifer. The main exception is the big flat Ebro delta, in which the deep aquifer only contains salty water, although in the Llobregat and perhaps in the Empordà deltas, some marginal areas with deep salt water still exist due to insufficient local water head.

- The small tides do not produce periodically sea flooded areas. River outlets are protected during low water situations by a sand bar. Only man's intervention by deedging it out for recreational navigation or flood control favors the penetration of a salt water wedge along the river channel, as in the mouth of the Muga river.

Pore water in the intermediate semipervious lens in generally fresh water, since original salt or brackish water has been flushed out by the upward flow under natural conditions, but salt water may be held in the less pervious thick formations of some areas, such as the Llobregat delta [7].

In the Ter delta [12] flushing is not complete (Fig. 8) due to small vertical gradients. The recent exploitation of the deep aquifer has reversed the flow, creating real salinization risks. Thus some fresh water pollution by salty water shows up after some time.

A more complex situation exists in the Fluvià-Muga deltas (Empordà) due to the very recent origin of that area (some centuries) and the existence of wetlands and coastal lagoons. The coastal area still has salt water and most of the fresh water discharges by upward flow into the marshes [16].

After starting operation of some large supply wells, salt water is slowly penetrating (Fig. 9), but the salinization process of the wells presents some appealling diverse aspects [13]. Figure 10 shows a case in which the salinity decreases with the pumping time, following a logarithmic trend. In that case, brackish water slowly infiltrates in the deep aquifer from the upper one is being diluted by fresh water from other areas of the deep aquifer. The start of a nearby well may still aid in the reduction of the salinity of the abstracted water, specially if it is in the more saline area, or produce the opposite effect. The quantitative description of these evolutions is under way.

In other areas, in spite of intensive overdrafts in the summer period, a full recovery is attained during the winter rest period, and coastal alluvial aquifers (Ridaura and Tordera) can be used as coastal reservoirs for seasonal water regulation. Most of the upstream runoff infiltrates into the ground. The semipermeable layer plays a significant role. When it is not developed enough, sea

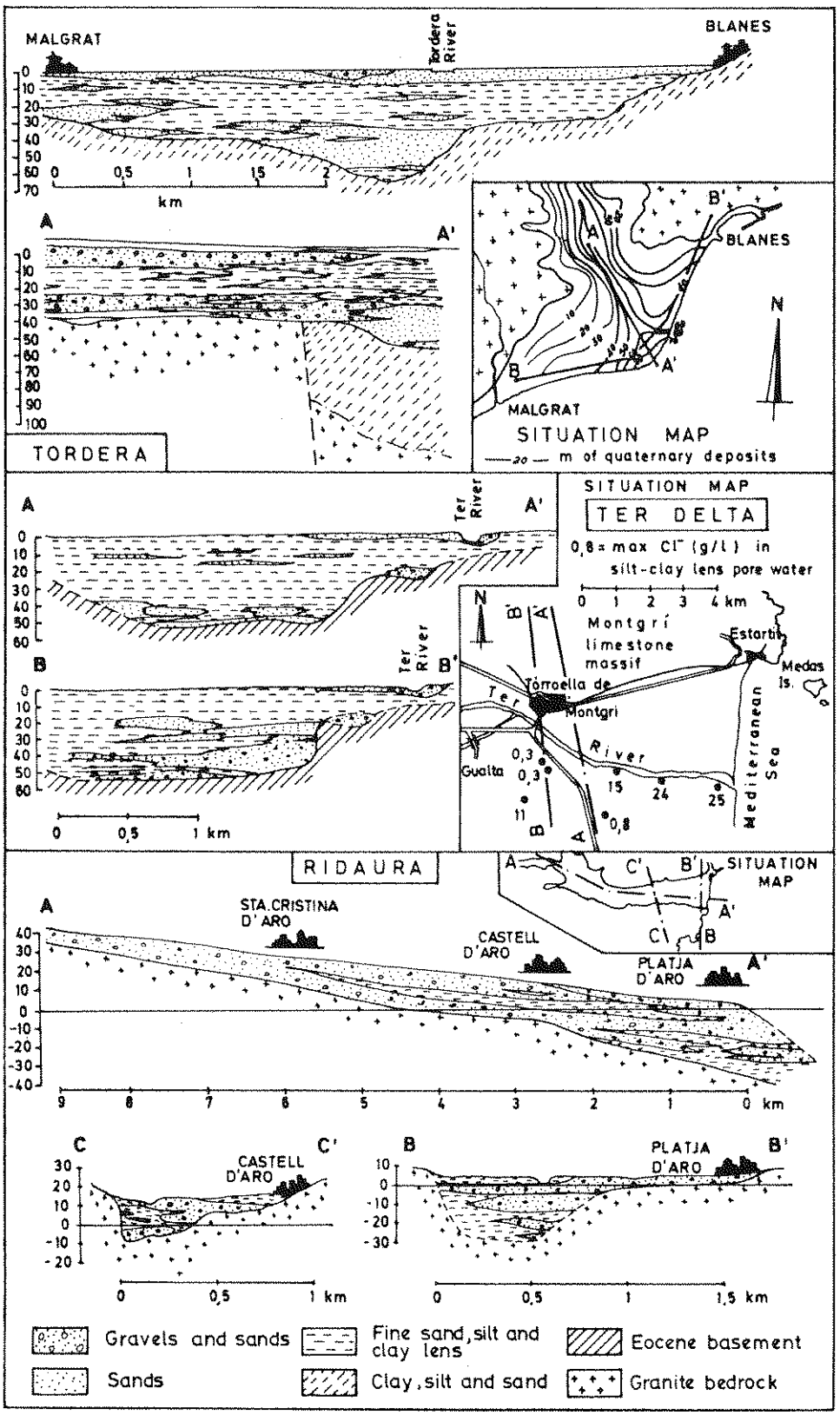

Fig. 8 – Cross-sections of three coastal alluvial formations in Northern Catalonia, showing a generally poorly defined two-layer aquifer when compared to the more well structured Llobregat, Besós and Ebro deltas. For the Ter it is given the maximum salinity found in pore water from the intermediate semipervious lens.

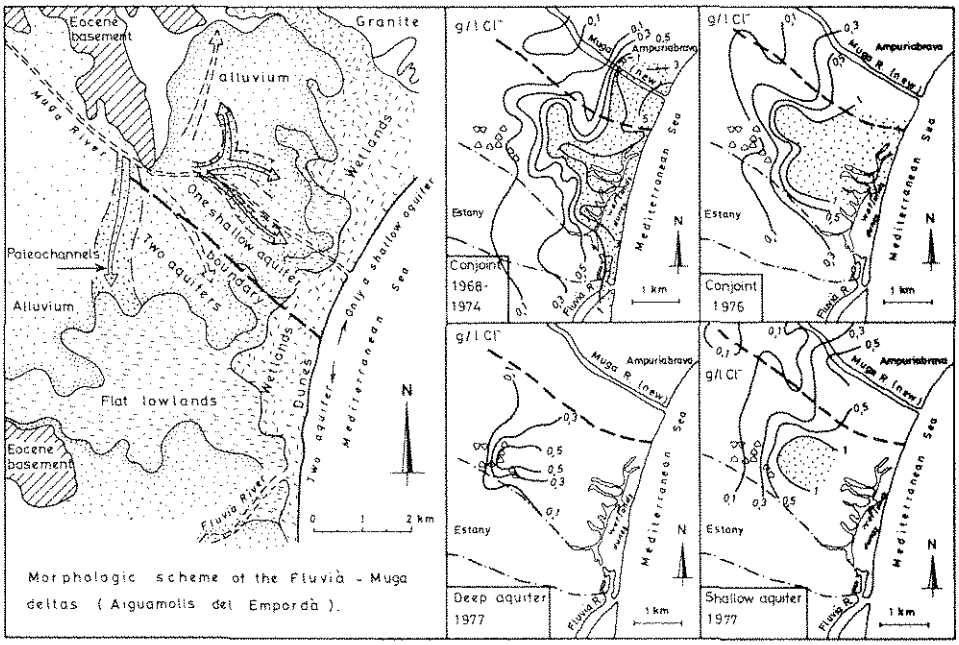

Fig. 9 – The Fluvià-Muga deltaic area. Salt water moves toward the main pumping centres, following a complicate pathway due to the existence of salty water lagoons and two aquifers connected by a semipervious layer. Airborne salt play also its role (after E. Vinyals, personnal communication).

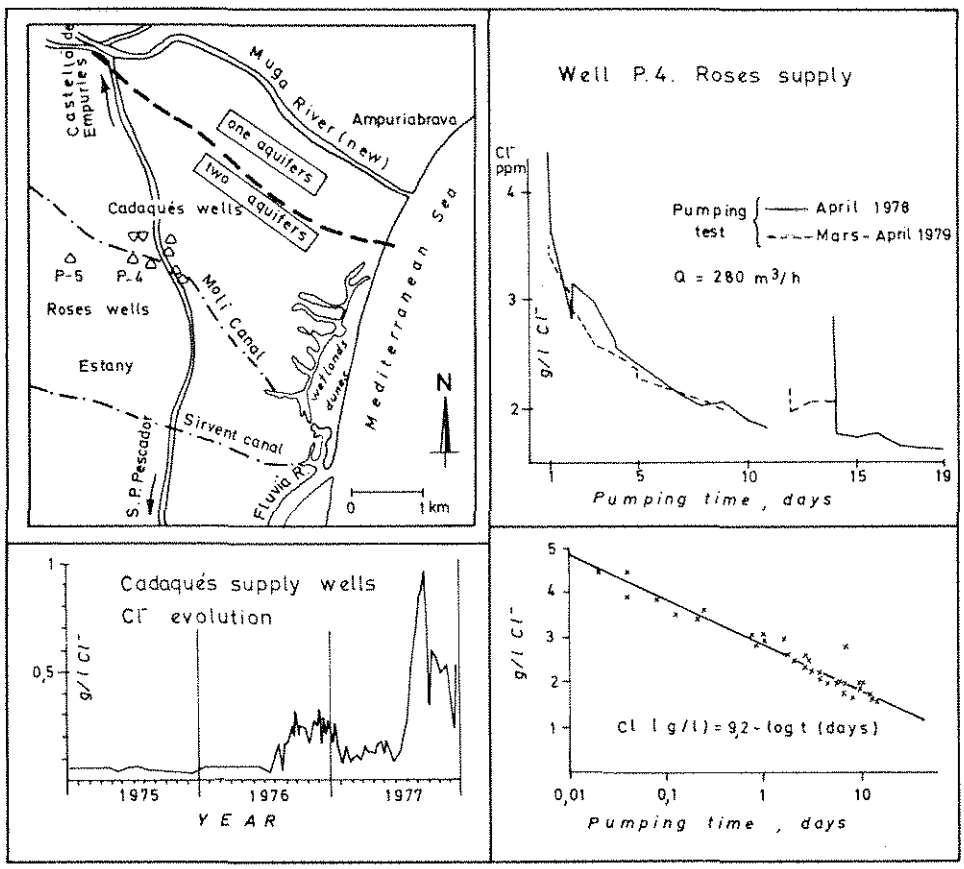

Fig. 10 – Salinity changes in supply wells in the Empordà lowlands. Interferences between wells and interaquifer flow influence the abstracted water salinity.

water intrusion can be felt before the summer season is over, as in other Costa Brava areas (Lloret, Calonge, Aubì-Palamós).

7. CONCLUSIONS

Local circumstances play a dominant role in sea water encroachment, both under natural and under conditions of man's influence. They deserve a carefull study before trying to understand a given situation of formulating recommendations. Semipermeable or low permeability interlayerings are of uttermost importance and must be clearly determined, and respected when sinking wells and bore-holes. They must be considered in detail when designing a sea water intrusion observation network.

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