MECHANISMS OF GROUNDWATER SALINIZATION IN A COASTAL KARSTIC AQUIFER SUBJECT TO OVER-EXPLOITATION

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ABSTRACT

Within the studies on seawater intrusion in coastal aquifers, the acquisition of data directly from observation-wells reaching the underground salt water allow the recognition of real vertical pattern of salinity throughout the aquifer and the calculation of a few parameters useful for describing the equilibrium condition between fresh and salt water and its trend. The experience developed in Salento Peninsula during several years of researches allow outlining the behaviour of a typical fractured and karstic aquifer subjected to a strong overexploitation, brought about by the unavailability of other local water resources in the region. Continuous over-exploitation causes the progressive groundwater salinization and an ascertainable reduction of the amount of fresh water in the aquifer. The measured and calculated parameters obtained from thermal-conductivity logs performed in a network of observation wells, allow the evaluation of the equilibrium state between fresh and salt water, the assessment of the real hydraulic head of groundwater respect to the sea level and the amount of the fresh water loss. The evolution in the time of these parameters consents to formulate hypotheses about the mechanism controlling the salinization process in a coastal aquifer subject to continuous over-exploitation.

INTRODUCTION

Researches carried out on seawater intrusion in the Salento Peninsula (Puglia – Southern Italy) during the last 30 years allowed establishing some methodologies apt to describe and quantify the salinization of karstic coastal aquifers subject to over-exploitation.

In Puglia region, in particular in the Salento Peninsula, mainly due to the progressive development of agricultural practices, starting from the sixties of past century water demand has continuously increased. During the following period, many projects aimed at the transfer of water resources from bordering regions were never accomplished: as a consequence, groundwater, which remains the only local available water resource, has been subject to heavy exploitation.

Only for drinking purposes, the withdrawal from the Salento Aquifer is actually estimated in more than 4 m^3/s. The withdrawal for irrigation and industrial use cannot be exactly known owing to the presence on the territory of thousands of abusive wells: it can be roughly estimated in more than 30 m^3/s. On the base of the climatic series from 1930 to 1980 (therefore, not taking into account the present decrease of total precipitation and the increase of the mean atmospheric temperature) the mean annual recharge to the aquifer was established in about $900 * 10^6$ m^3, corresponding to a continuous discharge lower than 30 m^3/s. This value, compared with the estimated value of the total withdrawal, indicates that the Salento Aquifer is actually subject to over-exploitation: this over-exploitation in the time favoured seawater intrusion and, consequently, progressive salinization of groundwater.

The first research project dealing with seawater intrusion in the Salento Aquifer was financed by the Italian National Council of Researches and started in the sixties. The project was aimed at the drilling of a net of totally screened observation wells reaching underground salt water (Tadolini & Tulipano, 1970, Cotecchia et al., 1974). Periodic thermal–conductivity logs were performed regularly till 1976. After the end of the project, the measurements were only sporadic. Last logs belong to the period 1995–96 and relate to a number of observation-wells of the previous net restored in the framework of a project aimed at creating a groundwater monitoring net at regional scale. The project failed owing to competence problems among the numerous different Water Authorities involved in the management of groundwater resources in the Puglia region.

GENERAL GEOLOGICAL AND HYDROGEOLOGICAL FEATURES

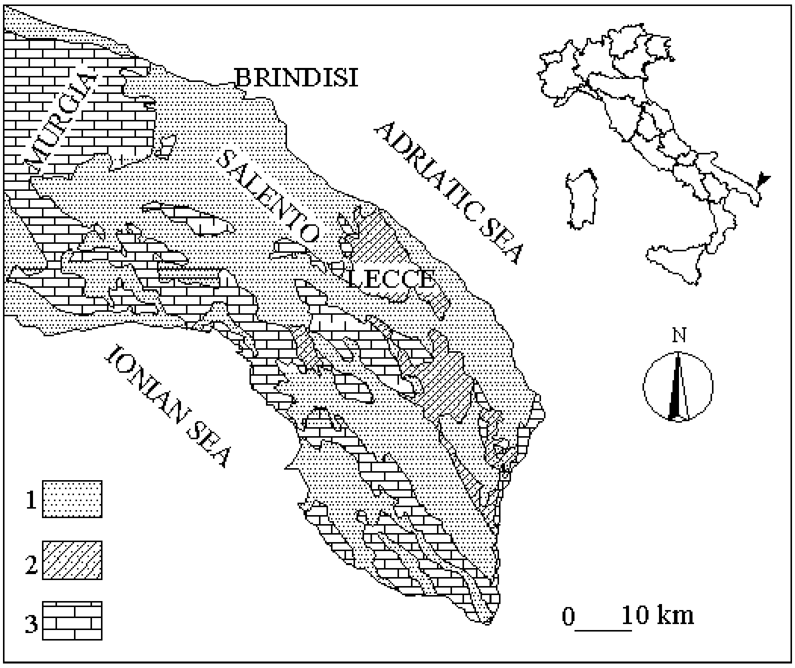


Figure 1 *Geological map of Salento Peninsula – 1) Calcarenites, sands and clays (Plio-Quaternary), 2) Calcarenites, marly calcarenites (Miocene), 3) Limestones, dolomitic limestones (Cretaceous)*

The Salento Peninsula represents the SE part of the Apulian carbonate platform. Limestones and dolomitic limestones of Cretaceous make up the geological basement; transgressive deposits (calcarenites, sands and clays), which age ranges from Miocene to Quaternary, cover partially the basement (Figure 1). Nevertheless, Cretaceous formation is almost everywhere present at sea level. Clay levels interposed between the Cretaceous formation and the permeable post Cretaceous sediments make feasible the presence of shallow aquifers. Limestones and dolomitic limestones, constituting the main aquifer (Salento Aquifer), are fractured and karstified.

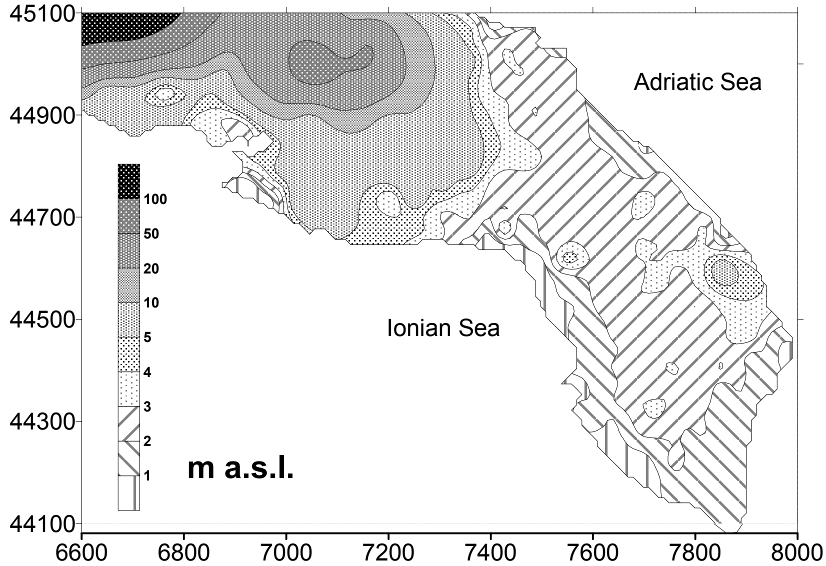


Figure 2 *Water table elevation (m a.s.l.) for the Salento Aquifer*

Water table elevations reach max values of 4 m a.s.l. in the innermost part of the peninsula. The hydraulic heads decrease toward the coast with a mean gradient of 0.02 $^{0}/_{00}$ (Figure 2). The aquifer discharge along the coasts through diffuse and concentrated springs draining water having salinity ranging between 3,5 and 10 g/l. The most relevant spring is the Chidro spring, with mean discharge of 2,500 l/s. Figure 3 shows groundwater T.D.S. contour lines. The reconstruction is based on chemical analyses of numerous samples drawn from irrigation wells and outlines clearly the effects of the exploitation.

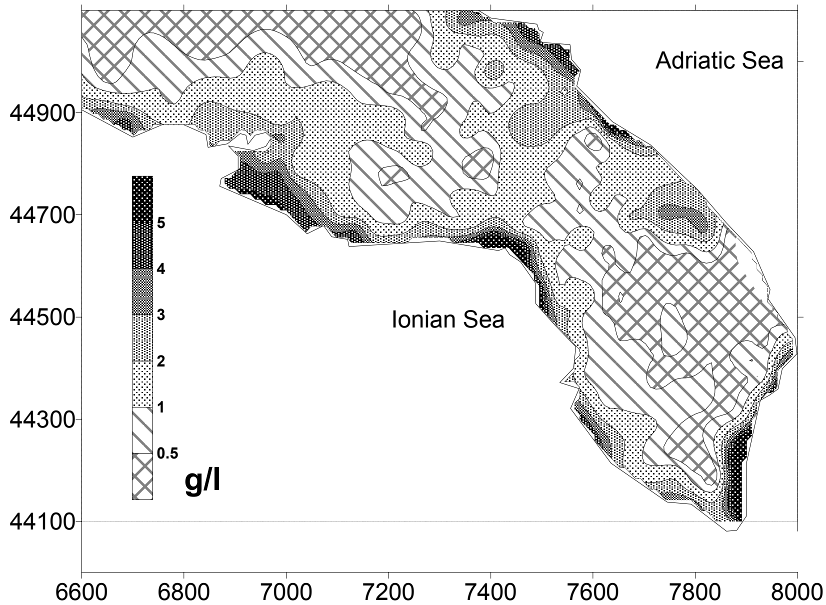


Figure 3 *T.D.S. (g/l) contour lines for Salento Aquifer*

TEMPERATURE AND CONDUCTIVITY LOGS

Temperature and conductivity profiles allow the recognition of the salinity vertical distribution along the well column that is screened in order to intercept the fresh, brackish and salt-water bodies present in the aquifer. Through the laboratory calibration of the thermal–conductivity probe, the field profiles can be converted in salinity and density profiles at a fixed reference temperature. As an example, Figure 4 shows the first and the last salinity profile available for the observation wells LR and SR.

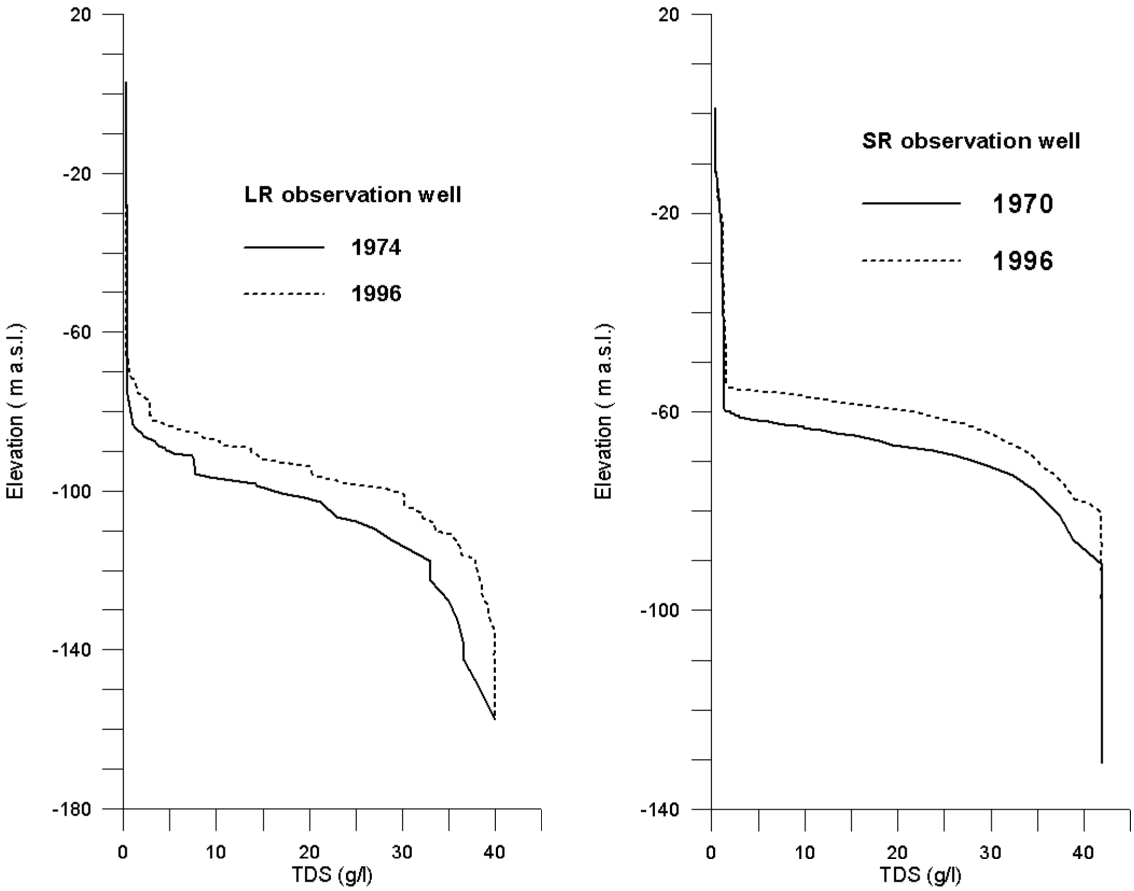
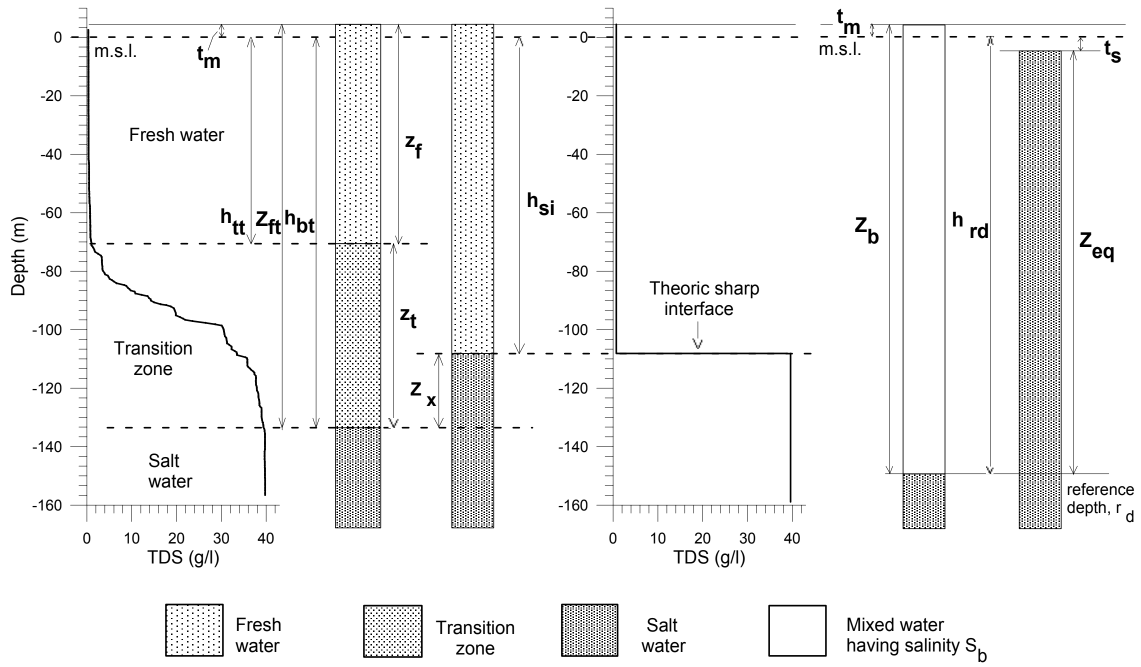


Figure 4 *Salinity profiles related to first and the last field survey respectively for the observation wells LR and SR.*

The trend of profiles visualises the rise of the transition zone occurred in the considered period. The profiles for the other observation-wells not considered here outline for the transition zone the same general rising trend. The elaboration of the salinity profiles allows the calculation of parameters able to quantify the real state of the equilibrium between fresh and salt water and to describe the evolution of salinization induced by the over-exploitation. Moreover, the interpretation of the above parameters allows outlining the mechanism governing the salinization processes.

PARAMETERS FOR QUANTIFYING THE FRESHWATER-SALTWATER EQUILIBRIUM

Figure 5 illustrates schematically the measured and calculated parameters which following paragraphs will deal with. The term groundwater indicates the fresh water and brackish water of transition zone on the whole.



MEASURED PARAMETERS

t_m = measured hydraulic head
h_{tt} = elevation of the top of transition zone
Z_{ft} = thickness of the water column overlying the top of salt water
h_{bt} = elevation of the bottom of transition zone
z_f = thickness of fresh water
z_t = thickness of transition zone
h_{rd} = elevation of the reference depth (r_d, defined within salt water body)
Z_b = thickness of the water column overlying r_d

CALCULATED PARAMETERS

Z_x = $Z_{ft} * (\delta_{ft} - \delta_f) / (\delta_s - \delta_f)$
h_{si} = elevation of theoric sharp interface = $t_m - (Z_{ft} - Z_x)$
Z_{eq} = $(Z_b * \delta_b) / (\delta_s)$ = thickness of Z_b expressed as salt water
t_s = equivalent groundwater head = $h_{rd} + Z_{eq}$,
being:
δ_{ft} = average weighted density of Z_{ft} related to S_{ft} (average weighted salt content of Z_{ft})
δ_f = density of freshest water found in the well (related to S_f, salt content of fresh water)
δ_s = density of salt water (corresponding to S_s, salt content of salt water)
δ_b = average weighted density of Z_b (related to S_b, average weighted salt content of Z_b)

Figure 5 *Scheme of the the parameters obtainable from the salinity profiles derived form thermo-caonductivity logs carried out in observation-wells reaching salt water beneath groundwater in a coastal aquifer*

Disequilibrium index

The salinity and temperature profiles related to the whole water column (fresh, brackish and salt waters) allow calculating both, the weighted mean density of the groundwater till the bottom of the transition zone, and the density of salt water present beneath it. This way one obtains the real Ghyben – Herzberg coefficient, K_r, and, knowing the elevation of the bottom of transition zone (h_{bt}), the theoric hydraulic head (t_t) (Figure 6): this is the hydraulic head, which should act to maintain the salt water at the measured depth (Tadolini & Tulipano, 1977, Tadolini & Tulipano, 1979, Cotecchia et al., 1986, Tulipano & Fidelibus, 1999). The t_t value can be compared with the value of the hydraulic head measured in the well (t_m). Owing to the fact that the observation well is completely screened, t_m corresponds to the "environmental head" defined by Lusczynsky (1961). The difference $\Delta t = t_t - t_m$ can be positive or negative. Positive values indicate the tendency of groundwater to increase its weight and it normally, as first step, is obtained through the increase of salinity of the groundwater. Negative values indicate that the condition of equilibrium between fresh and salt water has been already reached.

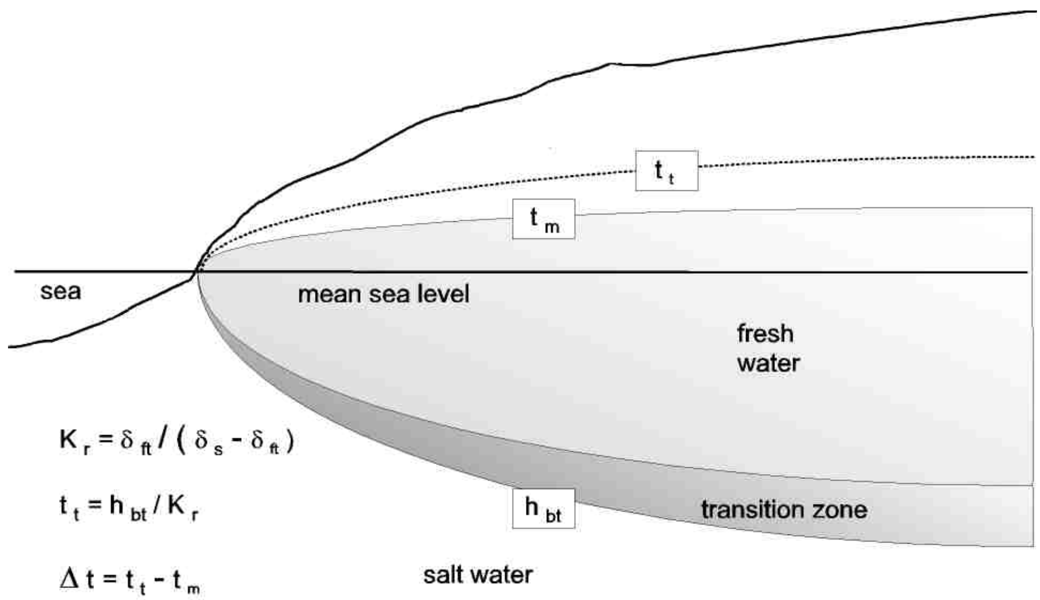


Figure 6 *Schematic vertical section of a coastal aquifer with indication of the parameters used for the calculation of the disequilibrium index*

Theoretical sharp interface

The elevation of a theoretical sharp interface can be calculated separating the whole water column above the bottom of the transition zone (z_{ft}) in two components: one column of fresh water, with salinity of 0.5 g/l (max salinity of fresh waters not influenced by salinization in the concerned aquifer), and one salt water column, having the same salinity measured below the bottom of the transition zone. In practice, this is equivalent to consider that freshwater and saltwater are non-miscible fluids: a rise of the sharp interface causes the reduction of the thickness of the fresh water column. This way, the reduction (or the increase) in the time of the fresh water thickness can trace salinization progress (or the recovering of the aquifer).

Equivalent groundwater head

The water column of thickness z_b, measured from a reference depth (r_d) located below the bottom of the transition zone, can be converted in a column of salt water having the same weight. This last column will have obviously a thickness lower than previous. The value of the elevation (t_s) of the top of the equivalent saltwater column represents the real hydraulic head of groundwater that can be compared with the sea level (Tulipano & Fidelibus, 1999). The t_s value depends on the environmental head and on the salinity of the water column above the bottom of transition zone; this means in practice that t_s depends mainly from the thickness of the transition zone. Initial undisturbed conditions (no exploitation) should be marked by positive values of t_s: groundwater flows toward the sea and discharge takes place through coastal subaerial or submarine springs. If, afterwards, the aquifer is over-exploited, the first effect is the groundwater pressure drop: this step is marked by negative values of $t_{s.}$

DISCUSSION

The number of available observation wells in the Salento Peninsula is not enough for outlining at a regional scale the state of equilibrium between fresh and salt waters. Nevertheless, the results obtained by analysing the single wells (local scale) are sufficient for underlining the dramatic situation induced by the uncontrolled exploitation.

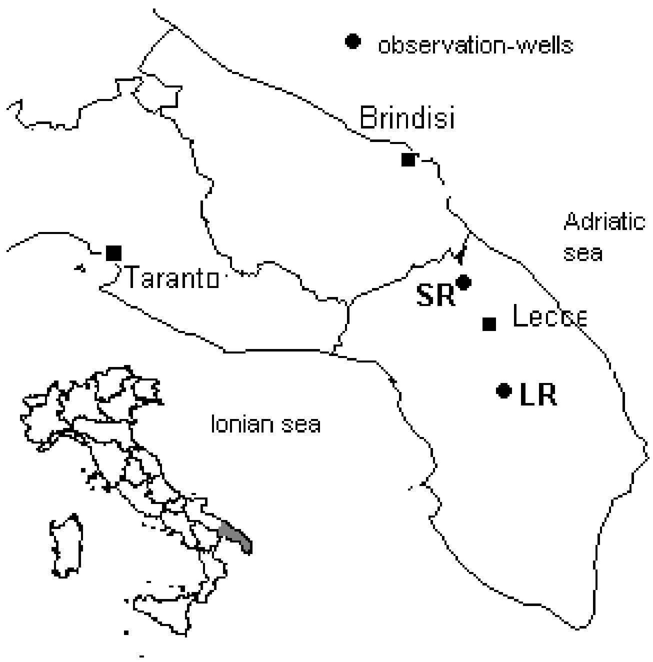


Figure 7 *Location of observation wells*

The following discussion will deal only with the results obtained interpreting, through the above-mentioned methodology, the trends of the measured and calculated parameters in two observation wells, LR and SR (location in Figure 7)

Observation well LR

Figure 8 shows the rise of the transition zone and of the theoric sharp interface occurred between the first (1973) and the last survey (1996). For the entire considered period the environmental head (t_m) is higher than the theoric head (t_t): consequently, Δt maintains negative values, while the equivalent groundwater head t_s is always positive. Apparently this seems a good situation (equilibrium condition). However, looking at the thickness of the transition zone, having a mean value of about 65 m, it is possible to hypothesise that this equilibrium has been reached owing to a serious salinization of groundwater. The natural thickness of the transition zone in undisturbed conditions for this zone, in fact, should be no more than 30 m because of the variation of t_m less than 0.5 m. The above hypothesis is supported by the trends of the other parameters shown in Figure 9. The figure shows the trend of total precipitation related to the recharge period (October–March) in the nearest pluviometric station for the period 1970-1997 that can be so compared with the evolution of the environmental head (t_m), the variation of the fresh water thickness (ΔH_{si}, calculated as difference of each H_{si} from the first datum) and the equivalent groundwater head (t_s). It is worthy to note, in 24 years, the loss of about 15 m of fresh water. This lost thickness of fresh water is evidently replaced by an equal thickness of salt water: in the real case this means that groundwater salinity is increased. This increased salinity justifies the increase of the equivalent groundwater head.

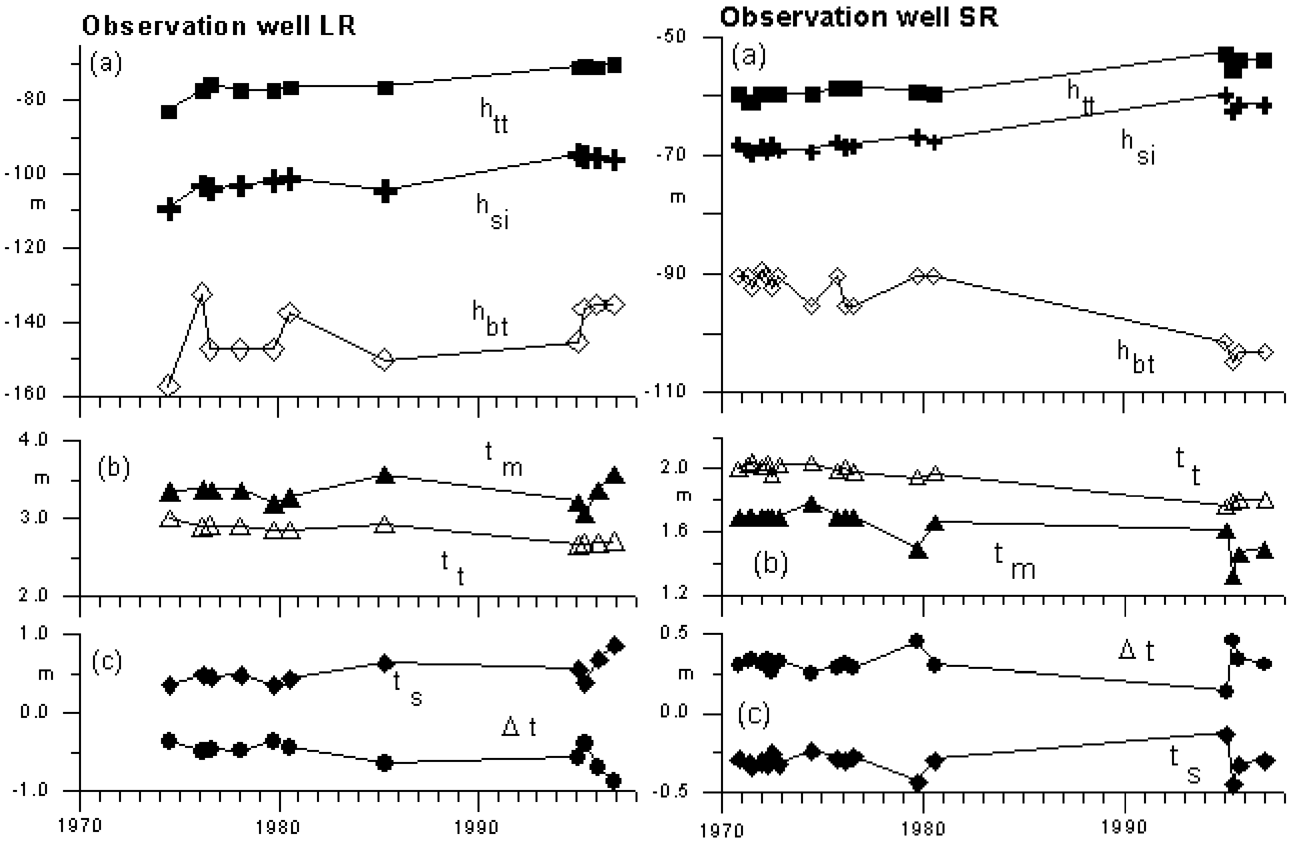


Figure 8 *Evolution in the time, respectively for observation well LR and SR, of (a) elevation of the top of transition zone, elevation of the theoric sharp interface, elevation of the bottom of transition zone, (b) measured hydraulic head (environmental head), theoric hydraulic head, (c) equivalent groundwater head and disequilibrium index*

Observation well SR

For the observation-well SR (Figure 8), the rise of the theoric sharp interface is accompanied by an important expansion of the transition zone, especially due to the deepening of its bottom. The t_m values are always lower than the t_t ones; consequently the Δt is always positive. The equivalent groundwater head maintains negative values: this represents a condition of depression of groundwater with respect to the sea. Also in the case of well SR, the decrease of the fresh water thickness is evident. The trend of the all parameters (Figure 9) indicates that the aquifer surrounding the observation well is under strong overexploitation; salinization is in progress. The recovery of a positive t_s value will be obtained only with the increase of the weight (salinization) of groundwater.

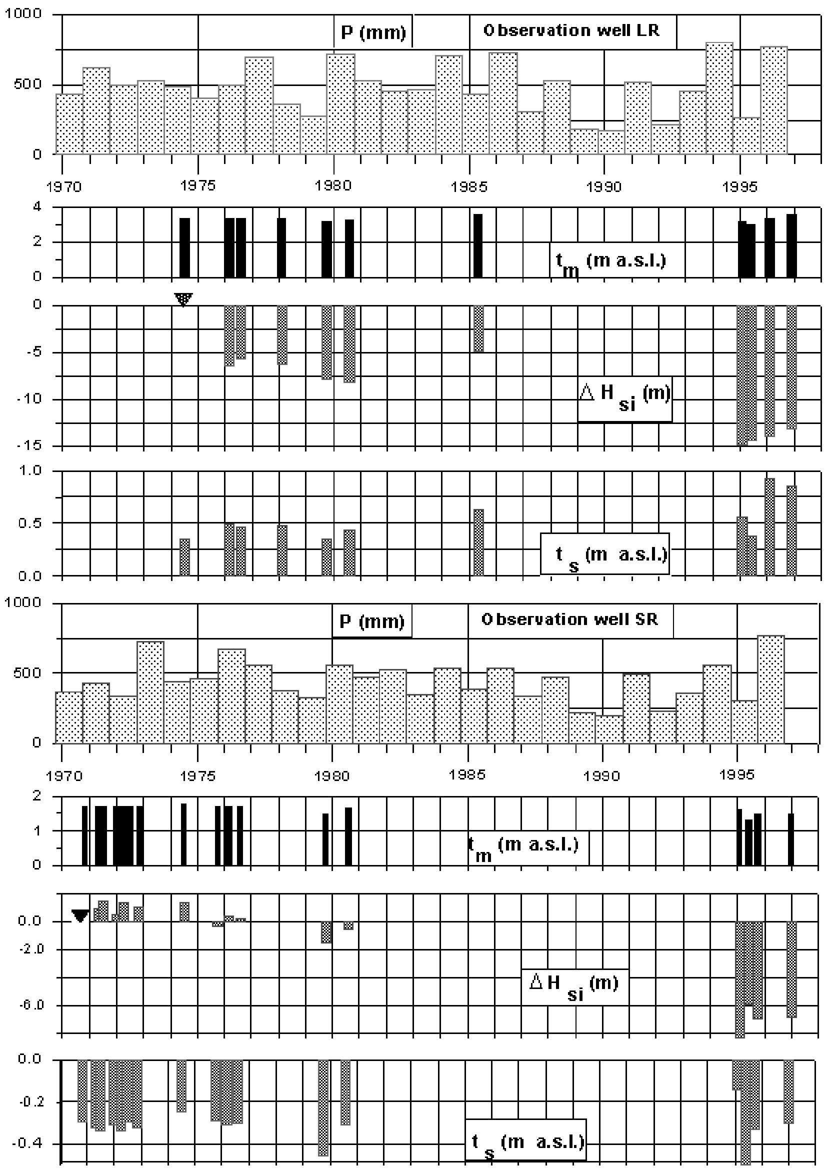


Figure 9 *Variation in the time, respectively for observation wells LR and SR, of total precipitation of the recharge period (October-March), environmental head, variation of the thickness of freshwater calculated from the first datum, equivalent groundwater head.*

EFFECTS OF NEGATIVE T_S VALUE ON COASTAL DISCHARGE

Thanks to the co-operation with the Italian Navy, in September 1999 an aerial infrared survey was carried out along a stretch of the Ionian coast of Salento Peninsula. The IR-images obtained in the 9 – 12 μm band (far infrared) were compared with IR-images taken in September 1972. Figure 10 clearly shows the strong decrease of groundwater discharge into the sea. Field recognition confirmed the disappearance of many coastal springs. It means that in the concerned coastal zone interested by the loss of equivalent groundwater head (negative values of t_s), the discharge of groundwater is replaced by seawater intruding inland through the same karstic channels that before were feeding the springs.

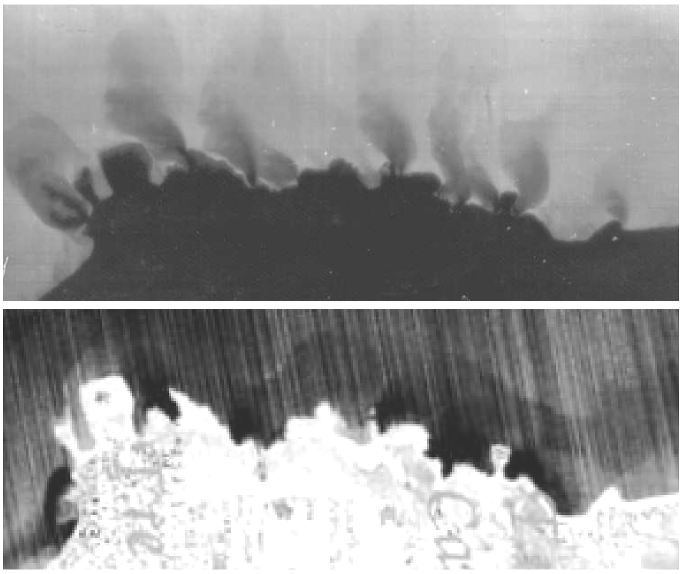


Figure 10 *Far-infrared images (density slicing) of Torre di Castiglione coast (Ionian Sea side – Salento Peninsula) respectively of September 1972 and September 1999.*

CONCLUSIONS

Previous considerations and the evaluation of data belonging to the other observation wells not considered here, allow outlining the salinization mechanism consequent to progressive over-exploitation. According to the scheme of Figure 11, initial not-disturbed conditions of the aquifer (Step 1) should be marked by negative values of Δt and positive values of t_s: transition zone has the thickness due to natural water table fluctuations and groundwater can flow regularly toward the coast. When over-exploitation comes about, initial conditions of positive Δt values and negative t_s values occur. Salinization of groundwater takes place owing to the upward migration of underground salt water (salt transport); in the meantime the groundwater flow toward the coast is prevented in that part of the aquifer (Step 2, example of SR). When the weight of the fresh water column reaches a value able to balance the salt water pressure, the system reaches new equilibrium conditions: Δt becomes negative and t_s positive and groundwater starts again flowing towards the coast (Step 3, example of LR). The last two steps should happen by turns under continuous overexploitation conditions. Obviously, maintaining conditions of over-exploitation, groundwater will become completely salinized.

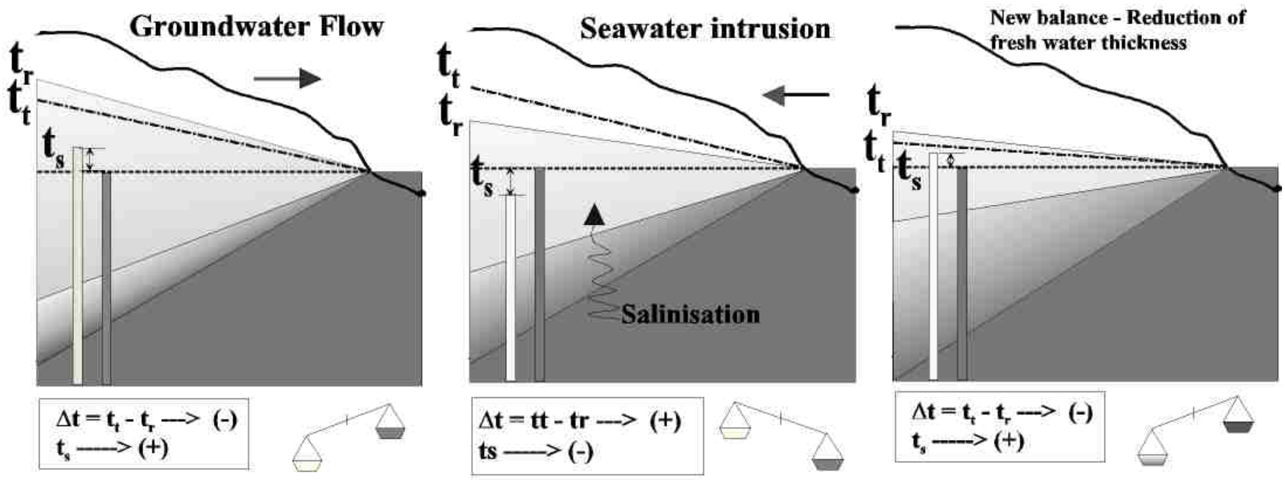


Figure 11 *Sketch of the salinization mechanism in a coastal aquifer*

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