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SEAWARD OUTFLOW COASTAL AQUIFERS: INVESTIGATIONS AND STUDY METHODOLOGIES

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SEAWARO OUTFLOW FROM COASTAL AQUIFERS: INVESTIGATIONS AND STUDY METHODOLOGIES

Dear friends and colleagues

the theme proposed by our friend Aureli provides us with the possibility of making a panorama of some extremely interesting facets of one particular aspect of coastal aquifer hydrogeology, namely seaward outflow of groundwaters.

As these flows are lost unused to the sea, the subject is of great importance from the water resources point of view. Seaward discharge is the last act of a cycle that starts with aquifer recharge. The story is quite complex, its evolution being controlled by an infinite variety of factors many of which are still unknown or difficult to identify. Even the influence on the hydrological,physicochemical and isotopic characteristics of seaward outflows, of such known factors as sea-action, mixing-effect and water-rock interaction makes it difficult to be certain of the form and nature of the groundwater circuit connecting such outflows to the hydrogeological system.

Of course, exact interpretation of the phenomena controlling seaward outflow from a coastal aquifer wherein freshwater and seawater coexist can only be attempted within a framework of general hydrogeological knowledge, particularly regarding exact identification of geological and structural lineaments and aquifer permeability characteristics.

Study methodologies differ quite markedly in some aspects, depending on the type of aquifer involved /5,6/. The differences stem from

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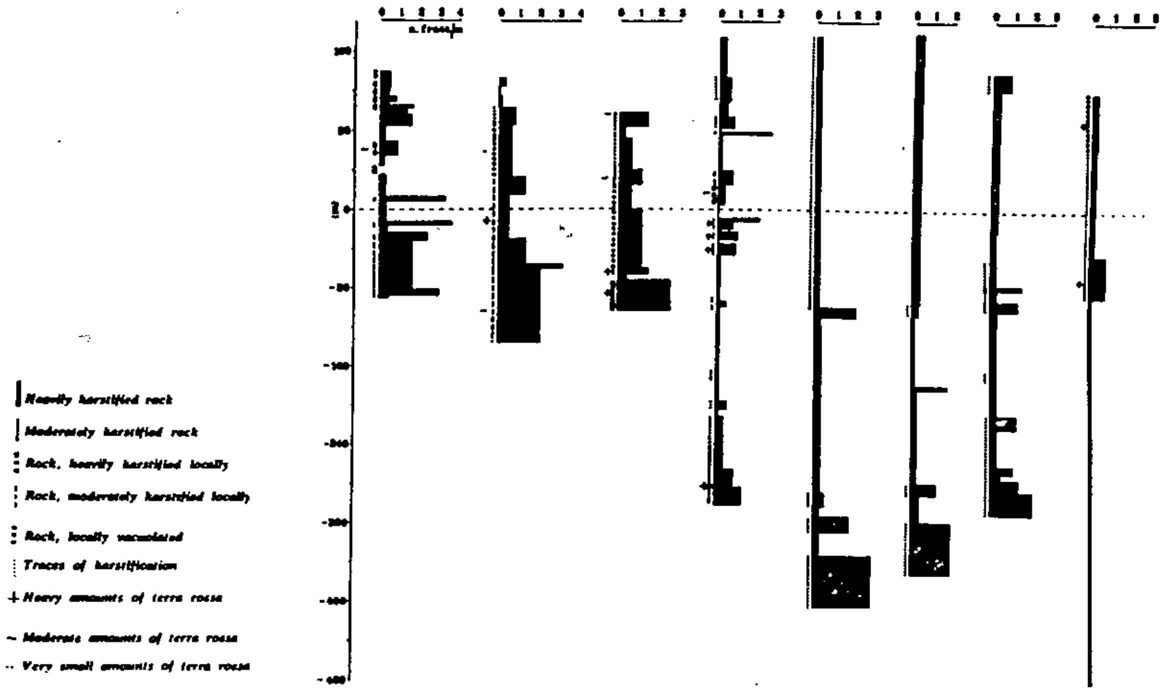


Fig.1- An example of the fracturing distribution along the vertical boreholes drilled through the carbonate and Karstic aquifer of Murgia, Southern Italy (by Grassi et al. 1977)

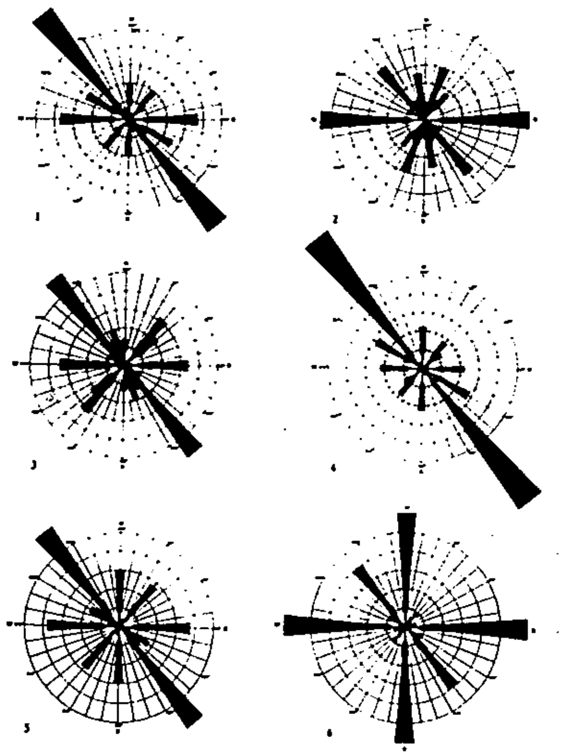


Fig.2-Statistical analysis of direction of preferential development of subterranean karst cavities in the Murgia region.(by Grassi, 1974)

the need to take account of the diverse degree of anisotropy that occurs in aquifers with primary permeability on the one hand and secondary permeability on the other, or the hydrogeological role of tectonic dislocations which can result in the creation of preferential flowpaths, intercommunication between aquifer systems and the prevision of easy routes for seawaters to intrude far into the landmass.

Evaluation of seaward outflows is particularly complex when the aquifer is karstic. It is well known that the hydrodynamic characteristics and the chemical nature of groundwaters - especially when viewed in terms of their relationship with intruding seawaters - can be quite dissimilar and often decidly singular even in places quite close together in the same karst region /7/. Such differences in characteristics may be attributable to:

- variations in the degree of fracturing of the carbonate formation (Fig.1) /18/;
- marked anisotropy which controls the orientation and spatial distribution of the karst conduits owing to the processes which caused the phenomenon (Fig.2) /17/;
- the important role played by terra rossa in the evolution of groundwater flow lines;
- palaeogeographic events that may have affected different parts of the region in diverse ways.

This latter aspect is very important because of the information it can provide on the history of relationships between aquifer and sea, and hence on the mechanisms of seaward flow of the groundwaters. Specific study of this question, particularly in the case of carbonate aquifers, is especially important when repeated, rhythmic variations in the base level of subterranean groundwater flow in geological times, as a result of changes in sea level (Fig.3), have characterized the evolution of karstification /7/. The result as seen today is often a succession of very permeable water levels separated at times by quite thick levels where permeability is extremely low /40/. In such circumstances, groundwaters reach the sea sometimes via conduit flow and sometimes

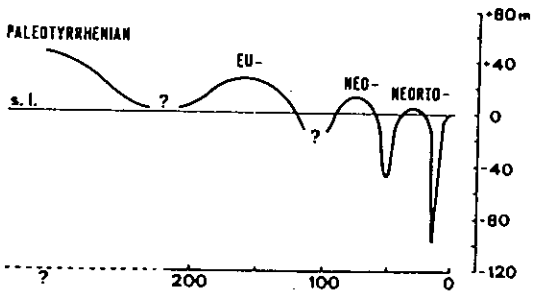


Fig.3-Variation of sea level as to the the continent during the Tyrrhenian estimated in relation to the present mean sea level (by Cotecchia et al. 1969)

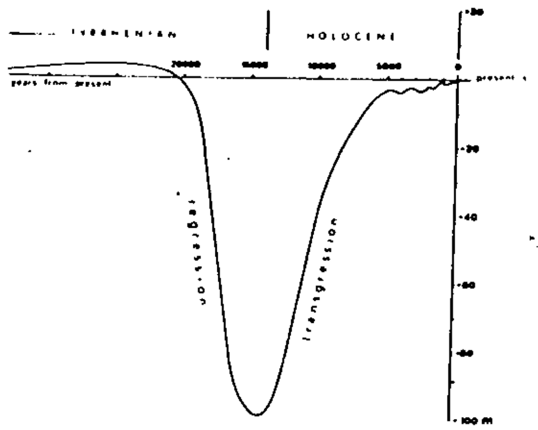


Fig.4-Glacio eustatic changes in mean sea level in late Tyrr enian and Holocene times (by Cotecchia et al., (1971).

via diffuse flow, but in any case under hydrogeological conditions that are very diverse even on the same vertical section through the aquifer.

It comes as no surprise, therefore, to find stretches of coast where springs are located in the immediate vicinity of the littoral and others where they occur on the seabed quite a distance offshore.

Studies on this matter made in Apulia show that since the last maximum retreat of the sea (which occurred some 14 000 years ago) its mean level has risen by a good 100 m or so, owing to the ongoing Flandrian trasgression (Fig.4) /8/. This rise in sea level has reduced the distance between the Ionian and Adriatic seas to about one third, thus decreasing the thickness of the body of fresh an brackish groundwaters proportionally /9/. Consequently, during the Flandrian, there has been a big reduction in the volume of groundwater, a rise in the level of the underlyng intruding seawaters and progressive encroachment of saltwaters.

Repeated changes in mean sea levels, that can be postulated on the basis of old shorelines (Fig.5) /7/, have each resulted in rejuvenation of the karst cycle, the zone of brackish water which is so aggressive vis-a-vis aquifer materials moving upwards or downwards accordingly /12/.

Then, too, there are the effects of hypogeal deposits of terra rossa which have caused exceptionally premature "fossilization" of parts of the karst drainage system. However, on the Salento Peninsula, which is more exposed to seawater intrusion, the effect most directly bound

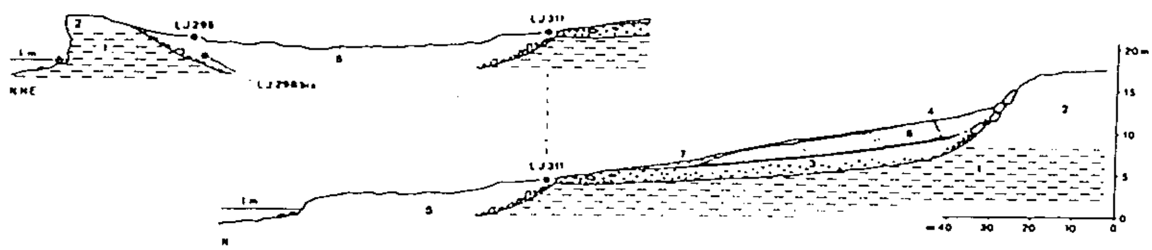


Fig.5-Identification of ancient coast-lines carried out also by means of paleontological method in a coast area of the Salento Peninsula (by Cotecchia et al, 1969)

up with the way groundwaters discharge to the sea has been the formation of a network of subhorizontal karst conduits.

Throughout the region, a rise in mean sea level has resulted in the pressurization of groundwaters in many karst conduits, leading to the creation of the numerous seabed springs found around the whole area.

It is also of interest in this regard to mention a palaeogeographic study -made for different reasons - of the Netherlands region as it was during the last glacial cycle. There, where the main aquifers are formed of alluvial sediments, the creation of polders with their associated dykes and canals, had a very marked influence on hydrogeological conditions modifying the original characteristics of groundwater outflow. At the start of the last glacial period, the outflow of groundwaters floating on intruding seawaters occurred partly on the surface, where marshes were formed, and partly in the subsurface (Fig.6). As the sea level dropped so, too, did the interface. The build-up of glaciers on terra firma and the consequent formation of permafrost to a considerable depth blocked much of the groundwater flow, this being restricted to a thin lens of brackish water floating on the seawater.

During the subsequent interglacial period the level of the sea rose again and part of the region was inundated. Flow of fresh groundwaters restarted and the interface began to advance inland. It has still not reached a definitive position and so the nature of groundwater outflows

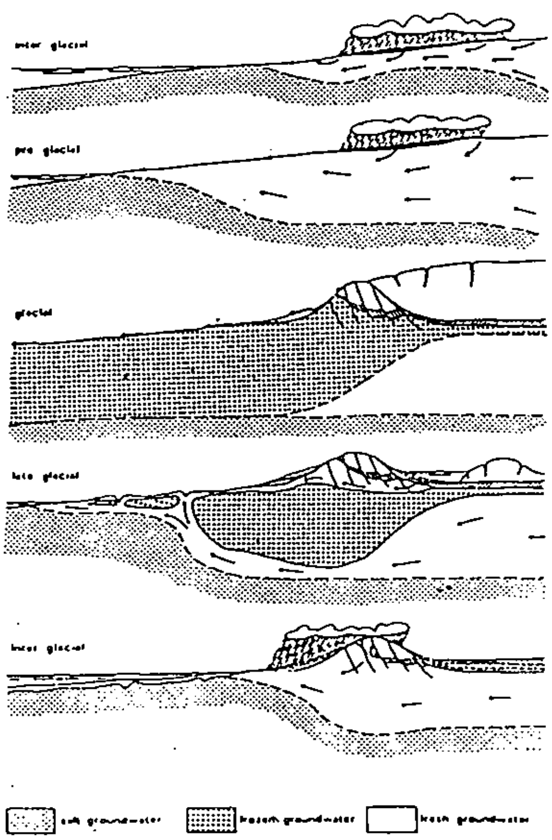


Fig. 6 - Relation between paleo-hydrogeological and seawater intrusion phenomena in a Dutch region (by Pomper, 1977)

is still changing slowly /32/.

Seawater intrusion is one of the phenomena most directly affecting seaward outflow from coastal aquifers. Since the intruding seawater forms the surface on which the groundwater flows occur, it is evident that outflows are influenced by the vertical mobility of seawaters intruded beneath the landmass. This mobility is induced in the short term by periodic and aperiodic oscillations in sea level and in the long term by variations in piezometric head as a result of alternation of periods of heavy rainfall and relative drought /11, 39/.

Study of the inland propagation of sea-level oscillations (Fig.7) influencing not only the position of the transition zone between the fresh and the salt waters, but also the groundwater levels themselves /42/, is one simple way of ascertaining the hydrodynamic characteristics of an aquifer close to where seaward outflows occur.

Determination of global attenuation values (Fig.8) for stretches of aquifer between a given observation point and the coast enables "diffusivity" values to be obtained, thus permitting the plotting of lines of equal propagation or "communicability", known as isodiabases, which reveal much about aquifer-sea relationships /29/.

The trend of these isodiabases in coastal aquifers has a similar significance to that of the equipotential lines of groundwaters overlying an impermeable basement, as is evident from Fig.9 which illustrates an application of the method to a stretch of coastal aquifer on the Salento Peninsula.

This is not the place to dwell on every natural and man-made cause of variations in elevation and thickness of the transition zone and more generally the whole range of phenomena connected with the freshwater-saltwater hydrodynamic relationships, which are all factors that have a more or less direct influence on the amount of seaward outflow /5,41/.

Suffice it to mention in this respect, therefore, the importance of the role played by the cyclic flow of seawaters into and out of the landmass, a phenomenon which result in complete renewal of the saltwaters underlyng the fresh groundwaters in a relatively short space of time /24/. It is because of this cyclic flow that the intruded saltwaters are returned to the sea in a mixture with coastal springwaters. The main factor regulating such flow is the variation in hydraulic head of the groundwaters in relation to oscillations in sea level. Submarine springs, too, play an important role sometimes when, for example, the head of seawater is greater than that of the groundwater, so the spring becomes an estavelle, providing an easy way for saltwaters to penetrate inland. This phenomenon is generally sufficient alone to explain why the waters of coastal springs are brackish. Sometimes, however, this fact does not depend solely on the existence of cyclic flow: for instance, Kohout, on the subject of seaward outflow in Florida, explains the existence of brackish springs (Fig.10) by postulating thermalization and rise in the aquifer of waters of marine origin in areas where the

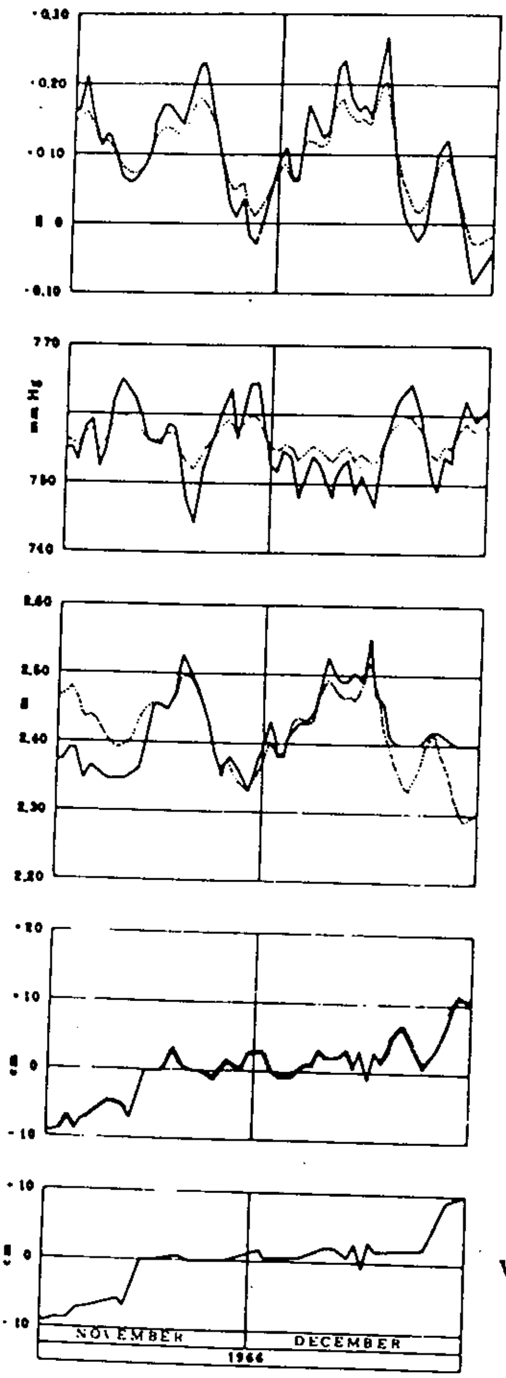


Fig. 7-Groundwater stage records stripped of influence exerted by variations in sea level and barometric pressure (by Tadolini and Zanframundo, 1974)

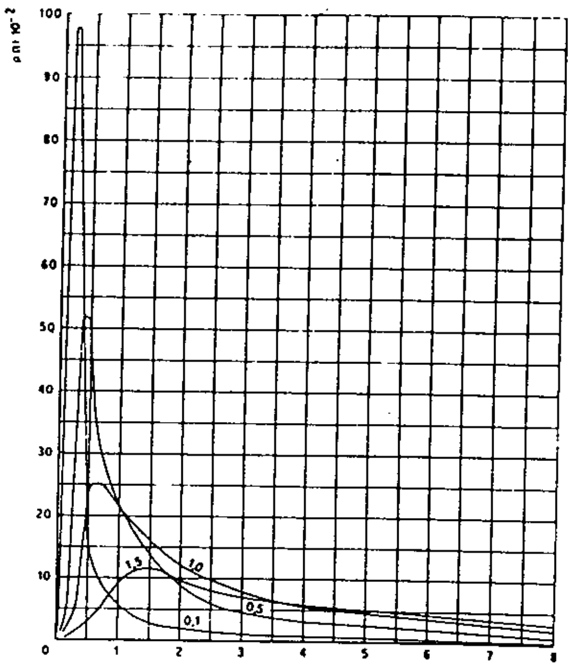


Fig. 8- Trend of pulses respose P (T) versus time T for some attenuation values (by Magri and Troisi, 1969)

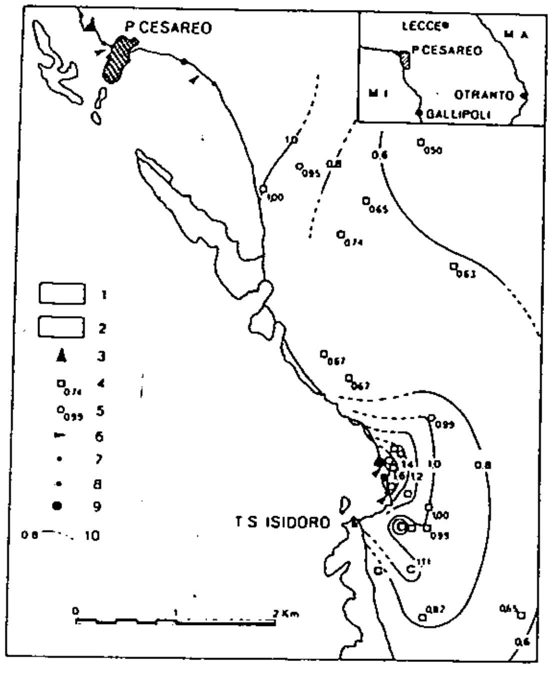


Fig. 9-Isodiabases plotted for a stretch of coastal aquifer on the Salento Peninsula (by Magri and Troisi, 1969)

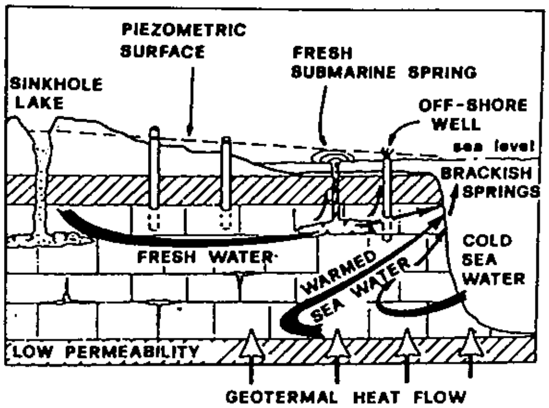


Fig.10-Idealized diagram depicting the hydrologic conditions involved in the occurrence of submarine springs in a thick artesian aquifer far away from active volcanism (by Kohout, 1966)

piezometric head is such as to permit the resurgence only of freshwater, which in actual fact occurs much closer to the shore /25/.

For some time now the modelling approach has been adopted to try to acquire a better understanding of freshwater-seawater relationships.

The matter has received ample coverage from those who have preceded me here, so I shall dwell only on a few general points.

Even when modelling the co-existence of freshwaters and seawaters, and seaward outflows from coastal aquifers, the physical problem has to be mathematically schematized; this is achieved by defining the hydrogeological system, boundary conditions and system regime.

The system is formed by various aquifers and the aquitards and aquicludes that bound these, as well as by the waters of various densities flowing therein.

Boundary conditions are generally established by reference to piezometric head, salt concentration, existence of diffuse or concentrated flows, and the location of all other elements that define system.The regime can be steady-state or transient. In general, various factors such as, for istance, rainfall, tides and abstractions, mean that it must be considered transient.

A model is defined, of course, by a set of equations, the main ones being that for flow in porous media, that for continuity, and others which consider and identify the interface. Application of these equations, however, normally necessitates adoption of several simplifyng assumptions, the commonest being constancy of hydrogeological parameters, monodimensional flow, thin interface and steady-state regime.

Constancy of hydrogeological parameters involves the assumption the system is completely homogeneous and isotropic, which never actually occurs in nature, while the assumption of monodimensional flow ceases to hold good when there are concentrated coastal outflows. Then again the interface is generally fairly thick, so density variations throughout the diffusion zone cannot really be considered negligible. Steadystate conditions thus occur, in fact, only for very brief periods, because variations in head and the resulting fluctuations of the interface actually result in transient conditions.

These few points summarize the hydrogeologist's recommendation to the model builder to pay great care to the simplifications adopted, especially when analytical methods are employed rather than numerical methods which, though less rigorous, are more flexible in adapting to the complexities of the various situations.

For the study of diffuse outflows in the presence of a fluctuating transition zone sometimes of considerable thickness, it may be useful to adopt the scheme proposed by Henry /21/ for an aquifer bounded by aquicludes with a constant flow of freshwater and a constant head of saltwater (Fig.11). This scheme has been modified by Pinder & Cooper who imposed appropriate boundary conditions and then resolved it by an iterative finite difference procedure which indicates the temporal

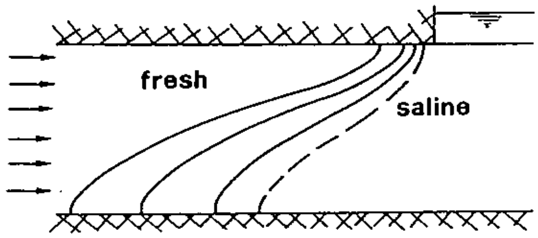


Fig.11-Sketch by Henry: continuous lines stand for the following position of 0.5 g/l isoaline until regimen conditions are satisfied (dashes) (by Van Geer, 1979)

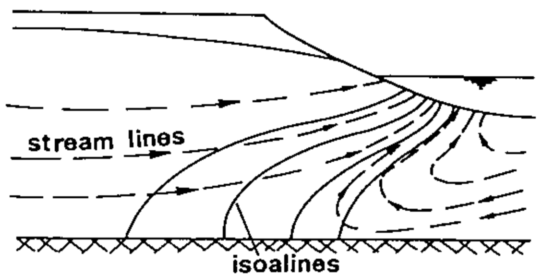


Fig.12-Sketch of the cross section of the Biscayne aquifer (by Van Geer, 1979)

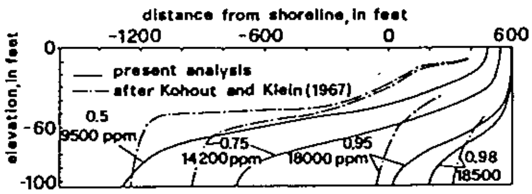
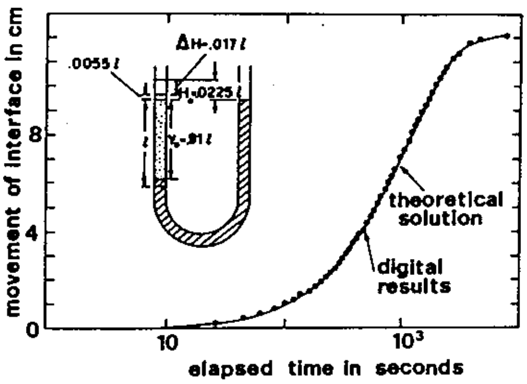


Fig.13-Comparison between the estimated isochlorinity lines (continuous line) and those (dashes) obtained from field data (by Segol & Pinder, 1976)

and spatial evolution of the isoaline contours and hence of the interface. This model (Fig.12),which in this latter form is suitable for solving the same problem for an unconfined aquifer, was used by Segol & Pinder to study the Biscayne aquifer in Florida, the calculated isochlorinity lines being found to be in good agreement with field data produced by Kohout & Klein (Fig.13).

The problem of the movement of the transition zone in the presence of concentrated submarine outflows can be tackled by likening the system to a U-tube, one arm of which is filled with seawater while the other represents the aquifer (Fig.14). In this manner Pinder & Cooper have been able to find a numeric representation of the temporal movement

Fig.14-Comparison between the numerical solution and the analytical one pertaining to the vertical shifting of the interface depending on water level variation according to a U pipe scheme (by Pinder & Cooper, 1970)



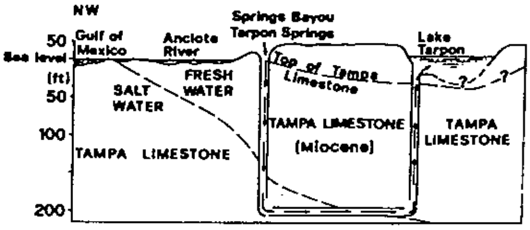


Fig.15-An example of equilibrium in springs, according to a natural U scheme Tarpon Springs, Miami, Florida (by Stringfield & Le Grand, 1969)

of the interface as equilibrium conditions vary, starting from the Henry /19/ analitycal approach.

This schematization provides a very good approximation of conditions at Tarpon Springs (Florida) which are hydrogeologically connected to Lake Tarpon (Fig.15). Here equilibrium is controlled by tidal oscillations in the Gulf of Mexico, so flow can either be from the lake to the springs or vice versa, thus producing cyclic oscillation in lake level too.

Among the other study methodologies likely to be most successful for understanding seawater-groundwater relationships, as well as an entire series of other phenomena connected with outflows, are those based on interpretation of hydrogeochemical and isotope data, of course /6/.

Taken as a whole, chemical data on natural waters are of basic importance not only for the study of mixing, but also in relation to a great variety of other processes bound up with type of aquifer, and age of the waters and hence their origin, for instance.

One such example of the use of chemical data is Howard & Lloyd's study of a coastal carbonate aquifer in eastern England. Here dilution diagrams revealed significant differences in the local character of the main constituents;these could be tied in with the various origins of the intrusion and diverse mixing processes involving different kinds of fresh groundwaters and seawaters. One of the conclusions reached was that in this specific hydrogeological situation, the seawaters intruded more recently differ from those intruded in time past. By way of example it suffices solely to report the diagram indicating the concentration of the Ca^{++} ion in relation to that of the Cl^- ion (Fig.16). It is evident from comparison of experimental values obtained and the theoretical mixing curves that there are meaningful deviations, enrichment being attributed to reverse ion exchange affecting seawaters near the intrusion

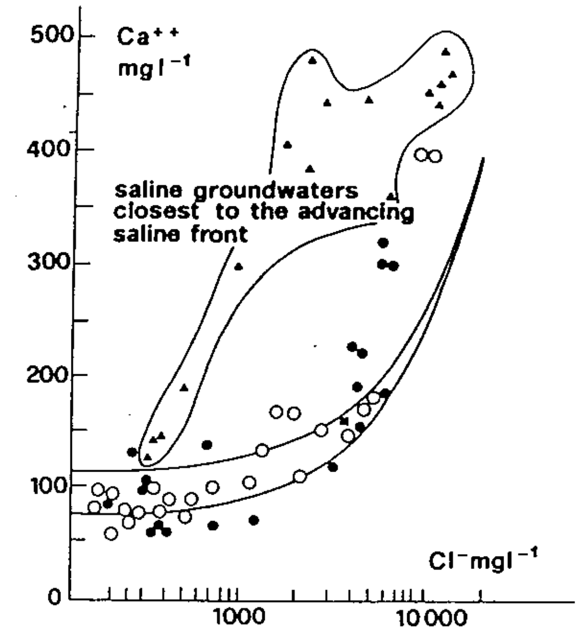


Fig.16 — Ca^{++} Concentrations of saline groundwaters from the Chalk limestone of eastern central England plotted against respective chloride ion concentrations for comparison with sea water dilution curves representing chemically inert mixing between sea water and fresh groundwaters. (by Howard & Lloyd, 1983, modified)

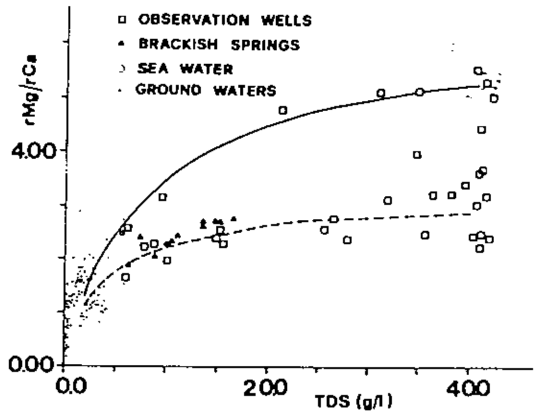


Fig.17 — rMg/rCa vs.TDS relationship for fresh and saline groundwaters and coastal springs water in Apulia, Southern Italy, and curves of theoretical mixing of fresh water with two types of salt waters (by Tulipano & Fidelibus, 1984)

front on contact with the clay minerals present in system fissures /23/.

A similar approach was also adopted by Tulipano & Fidelibus when studying the main Apulian springs which drain groundwaters flowing through a karstified carbonate coastal aquifer. The intrusion age indicator adopted in this case was the rMg/rCa ratio which tends to decrease more markedly in intruded seawaters than in present-day seawaters. This is because as residence time increases there is increasingly more replacement in solution of the Mg^{++} by Ca^{++} owing to dolomitization of the carbonate rock.

It is evident from Fig. 17 that the ratio in the case of the intruding seawater which is continually renewed is 4.5, while that for seawater intruded in time past is 3.5. By plotting theoretical curves for mixtures of fresh groundwaters and young and old intruded seawaters, it is possible to classify in terms of age of the intruded seawaters in outflows of mixture from springs or which are intercepted by observation wells /45/.

The situation described by J.F.Mink in a study on differences between intruded seawaters and ocean waters in the case of a basalt coastal aquifer on a Hawaian island is somewhat diverse. Here marked enrichment in calcium and magnesium (Fig.18) is accompanied by a decrease in sodium and potassium in intruded seawaters compared with values for ocean waters well offshore. The enrichment is found in groundwaters influenced by seawater intrusion compared with the values obtained when the mixture is made with ocean water proper. The differences here are due to ion exchange reactions that occur as the ocean waters make their way through a thick layer of sediments-partly calcareous and partly argillaceous-covering the basalts /30/.

The study of minor costituents has also found interesting applications in this context. For instance examination of the B-Li ratio of coastal springs drainign the Apulian aquifer (Fig.19) has revealed

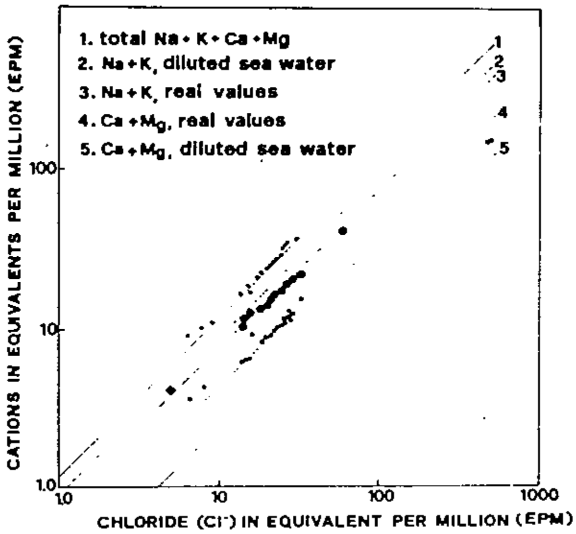


Fig.18-Comparison of the total major cation content of well water from the basaltic aquifer of Pearl Harbour region, as a function of chloride content with that of sea water diluted to the chloride of the well water. The total major cation content of the well water at various chloride concentrations is equivalent to the total major cation content of sea water at comparable chloride concentration. (by Mink,1960)

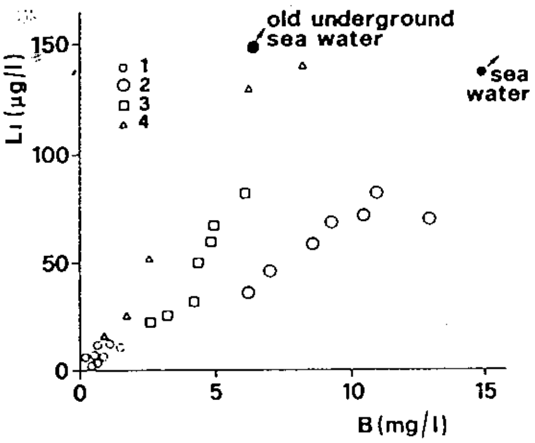


Fig.19- Cl Li/B relationship related to the main costal springs of Apulia region, Southern Italy (by Brondi et al. 1983)

differences among the various resurgences even when hydrogeological conditions are the same. These differences are the result of diverse concentrations of the minor elements intruded seawaters discharged in the springwater mixtures owing to differences in residence time /1/.

LLoyd et al have found that iodide is a reliable natural tracer in a great number of hydrogeological environments.

It is evident from Fig.20 that the methodology adopted permits classification of intruded seawaters on the basis of residence time by reference to the iodide enrichment that occurs due to exchange between the mother rock and the waters themselves /22/. In another hydrogeological situation where the authors could demonstrate in other ways that the seawater intrusion was recent, iodide-enrichment compared with the theoretical dilution curve (Fig.21) excluded any continuous exchange of seawater due to cyclic flow, thus leading to some interesting ideas being postulated to explain the landward intrusion mechanism /28/.

The same workers have also found that, in the case of an alluvial aquifer in the Lima basin whose waters drain into the Pacific, the ratio of I^- and Sr^{++} concentrations (Fig.22) permits recognition of the fact that recharge occurs in areas with diverse lithological conditions, and enables these to be identified /28/.

In the study of springs it is important also to identify the

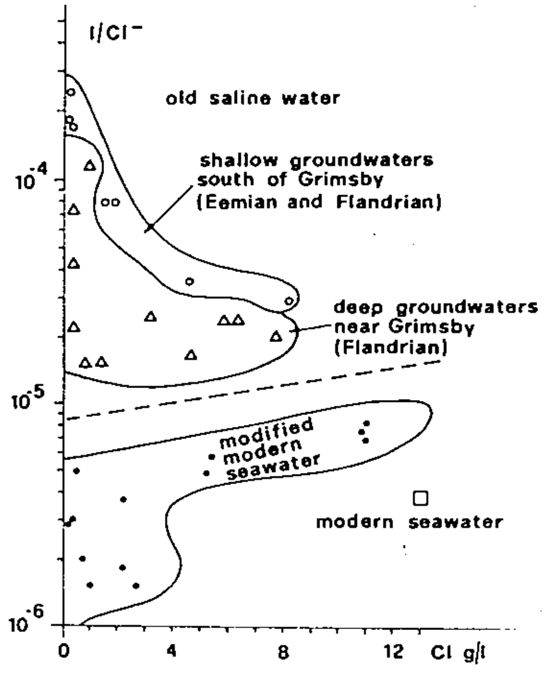


Fig.20-Identification of different saline groundwaters in the Lincolnshire Chalk aquifer using iodide and chloride concentrations (Howard & Lloyd, 1978)

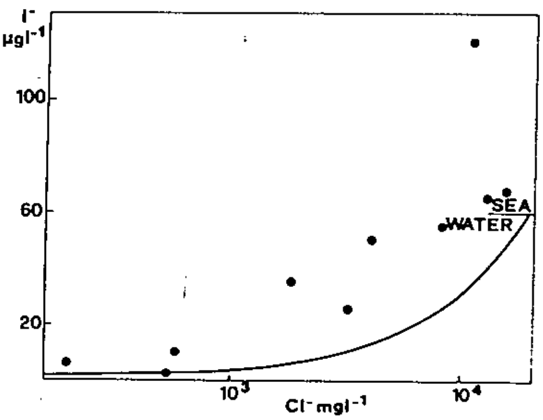


Fig.21- Iodide-chloride relationship for groundwaters from the Sussex Coastal Chalk aquifer, England, compared with seawater-freshwater-dilution relationship (by Lloyd and al.,1982)

characteristics of the freshwater component of the mixture discharged again because these are bound up with those of the recharge waters. In the study by Tulipano & Fidelibus already referred to, the rSr/rLi ratio (Fig.23) would appear to depend on the residence time of the fresh groundwaters in the aquifer /45/.

Hydrogeochemistry certainly does not resolve all the problems surrounding the origin of waters and the relationships between seaward outflow and recharge areas, or even the mechanisms of groundwater flow in the aquifer.

Environmental isotopes can, however, make a big contribution in this respect. The most commonly used stable isotopes, deuterium and oxygen-18, of course, characterize groundwaters in relation to the recharge period and the relief of the recharge areas.

In the stable isotope composition of groundwaters were the same as that of rainfall, there would be absolutely no difficulty in recognizing the pattern of subterranean water flows between recharge and outflow points. However, the original stable isotope composition of recharge waters is altered by a variety of mechanisms, the main ones being isotope fractionation during infiltration, isotope exchanges in geothermal zone during infiltration.. isotope exchanges in geothermal zones, relationships with surface waters, and mixing with intruded seawaters or with waters which infiltrated in times when the climate was different (Fig.24) /16/.

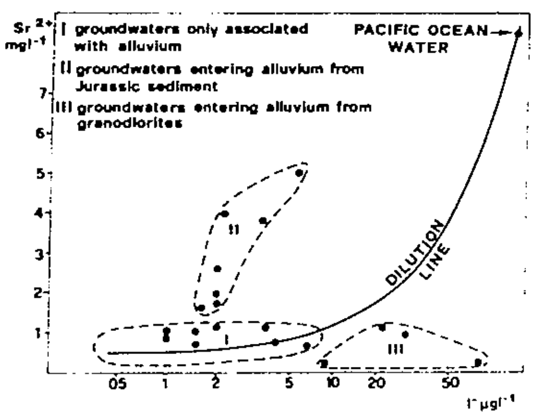


Fig.22 - Strontium - iodide relationship for groundwaters from the Lima Basin alluvial aquifer, Perù, with respect to the seawater dilution curve (by Lloyd and al.,1982)

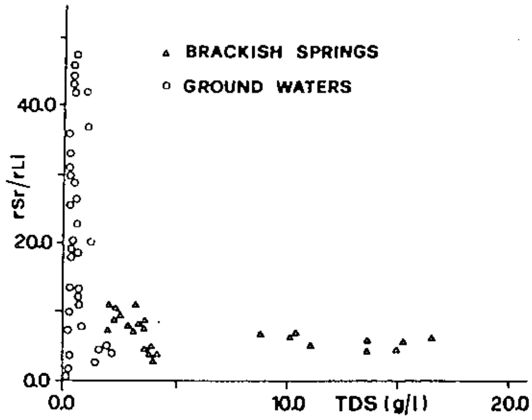


Fig.23 - rSr/rLi vs. TDS relationship for groundwaters and for the three main groups of coastal springs of the Apulia region, Southern Italy (by Tulipano & Fidelibus, 1984)

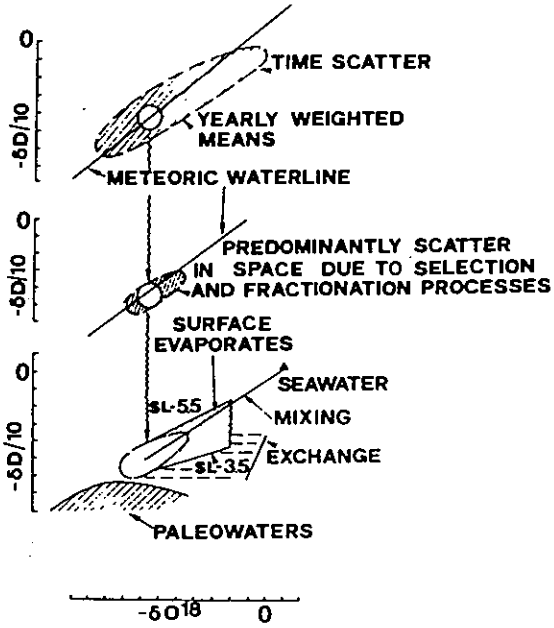


Fig.24-Schematic representation of changes is isotope composition that accompany the transition from (a) precipitation to (b) infiltration to (c) groundwater. The scale is arbitrary (by Gat, 1971)

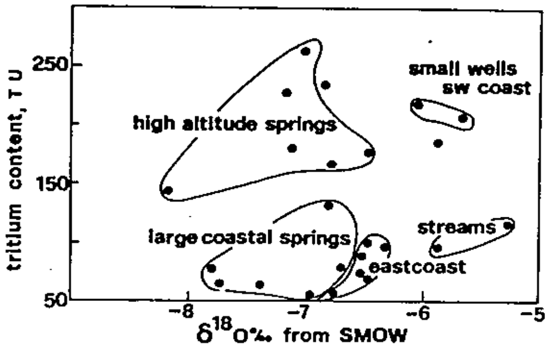


Fig.25-Tritium versus oxygen-18 content of groundwater sampled in springs (by Davis et al. 1979, modified)

Basically the actual method of study involves identifyng these mechanisms and in evaluating their relative effects on final isotope composition of the waters concerned. Only in this manner, namely by extrapolating the original characteristics, to the isotopic presence become environmental tracer.

In addition to stable isotopes which provide indications on the environmental nature there are, of course radioactive isotopes whose decay properties permit determination of the absolute age of the groundwaters, generally from the time they infiltrated into the subsoil.

It is difficult to give a succint overview of the progress made in this field in recent years because so much praiseworthy research has been carried out on the use of stable and radioactive environmental tracers in the study of coastal outflow. Very interesting, because of the simplicity of the approach adopted, is the work done by Davis et al. on an island close to Korea. In perfect accord with the permeability characteristics of the basalt coastal aquifer, the ingenious correlation of tritium content and $\delta^{18}O$ values (Fig.25) reveals the pulsed nature of recharge, which is not evened-out in the aquifer. The authors use this information to identify the various water conveyance systems which, starting from diverse recharge areas, lead, in different times, to the outflow /13/.

Dinçer & Payne, starting from the assumption of recharge which eventually becomes well evened-out in a karst aquifer in SW Turkey, obtained theoretical estimates of tritium contents at the coastal resurgences, postulating various possible residence times. The actual residence time in the aquifer of the spring waters was then calculated by comparing real and estimated values (Fig.26).

The values thus calculated then became the basic parameter which was used together with data on average spring discharge to estimate the volume of groundwaters stored in individual portions of the aquifer drained by the coastal resurgences /14/.

Like tritium, carbon-14 can be a very useful investigatory tool for studying coastal outflows, since it can be utilized to date the waters over considerably longer time intervals. However, its use is complicated by the particular complexity of the phenomena affecting the presence of this radioisotope in groundwaters, especially those in carbonate aquifers.

The natural C-14 contents has been used for decades to obtain meaningful estimates of water age. However, a series of corrective factors must be employed especially to take account of the evolution of the whole chemistry of the carbonates in the waters. The main approach adopted to this end is evaluation of the C-13/C-12 ratio.

It is perhaps worthwhile in this respect to mention some applications of the methodology involving only "apparent age", derived from the C-14 figure uncorrected for the effect of the various fractionations. This approach enables the relative chronology of the waters to be ascertained. Hanshaw ed al., for instance used this method for the study of artesian groundwaters in a carbonate aquifer in central Florida. In this case, measurement of only C-14 on samples from wells along the groundwater flow line (estimated by plotting the piezometric gradient) permitted calculation of flow velocity on the basis of the differences in apparent age and the distance between the sampling points. The data thus obtained compare well with those derived from the usual hydraulic laws, especially over long distances /19/.

Looking more closely at seaward outflow and the influence of salt waters on fresh waters, Hanshaw et al. made comparisons based only on the C-14 content measured in the brackish seaward discharge, as well as in the fresh waters, ocean waters and intruding seawaters, to identify the origin of the salt waters forming part of the outflow mixture. This approach was possible since the C-14 values of the ocean waters is very high compared with that of the intruding seawaters /20/.

It is thus evident that despite the well-known limitations of C-14, it permits verification of the amount of exchange between seawaters and intruded seawaters in many cases.

Fig.27 concerning data obtained in the Salento Peninsula (Southern Italy) illustrates the decrease in the C-14 content of intruding

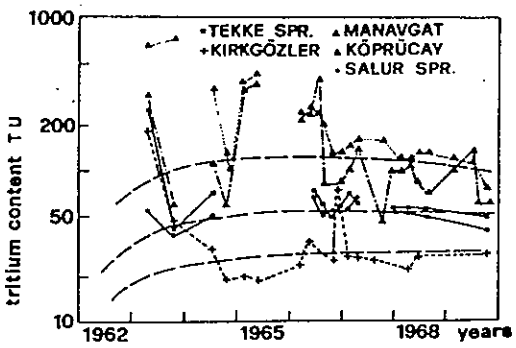


Fig.26-Comparison of the theoretical tritium output curves with the tritium content of the major springs (by Dinçer & Payne 1971)

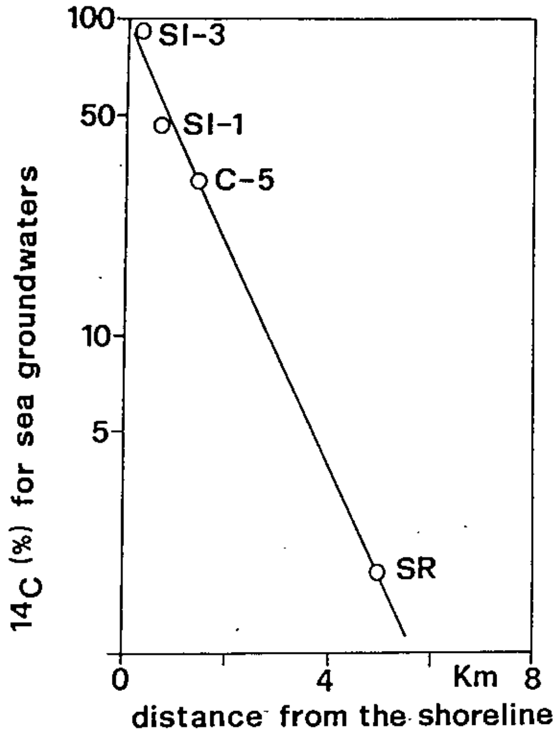


Fig.27-^{14}C contents of sea-groundwaters sampled in observation-wells as a function of the distance from the shoreline (by Cotecchia et al, 1974)

seawaters with increase in the distance inland. This, of course, reflects the amount of recycling of the intruded seawaters /9/.

The studies and methodologies outlined so far are designed of course, to frame coastal springs in a hydrogeological setting. It now remains to be seen what problems are encountered in the practical study of such springs, particularly when they are being seriously considered as possible sources of water supply. For instance, great attention is now being paid to the possibility of tapping submarine springs discharging large quantities of groundwater often of a quality such as to permit direct use, i.e. without having to be blended with better-quality waters.

Submarine outflows can be diffuse or concentraded, of course. The former generally come from porous aquifers and are more likely to escape direct observation. In this regard, Kohout has suggested a methodology based on analysis of the flow lines and salinity variations of groundwaters and seawaters, correlated with biological zoning (Fig.28). This latter parameter considers the presence of brackish-water species close to the shore and the manner these gradually give way to typically marine species as the natural consequence of the discharge of relatively fresh waters into the sea near the shore /26/. With seaward outflows of this kind the only way of tapping the waters is by intercepting them on terra

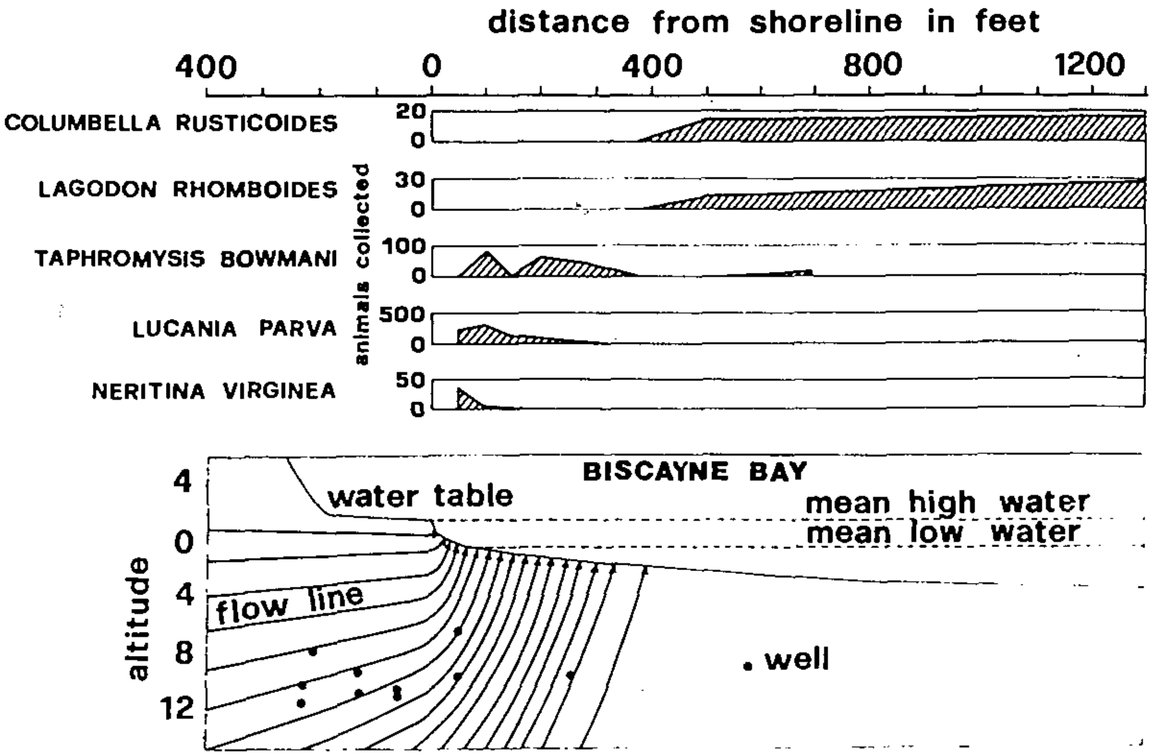


Fig.28-Cross-section showing groundwater flow pattern underlyng Biscayne Bay at Miami, Florida, related to distribution of selected animals (by Kohout & KolipinsKi 1967)

firma before they are discharged into the sea.

Concentrated submarine outflows, generally coming from fissured or fissured and karstic aquifer are certainly of greater practical interest. However, it is by no means unusual to find that submarine springs may act cyclically, either draining groundwaters to the sea or drawing in seawaters to the aquifer, depending on tidal and groundwater levels /2/. Such cases are of no interest, of course, from the use aspect.

The presence of a submarine spring is generally evident from the typical patch that appears on the surface of the sea: the larger the patch the bigger the discharge. The fresh water rises from the vent towards the surface, of course, because its density is lower than that of the salt-water, and the area concerned appears opalescent /36/. Stefanon has provided wide coverage of the relevant visual phenomena in documentation detailing years of investigations on submarine springs. Fig.29 illustrates just one of the many examples.

Concentrated submarine outflows occur in many forms, all connected with stratigraphic and/or tectocnic situation. Resurgences in hard rock are usually found either along a fracture or a discontinuity between one stratum and another. The vent is often sculpted, too, by solution

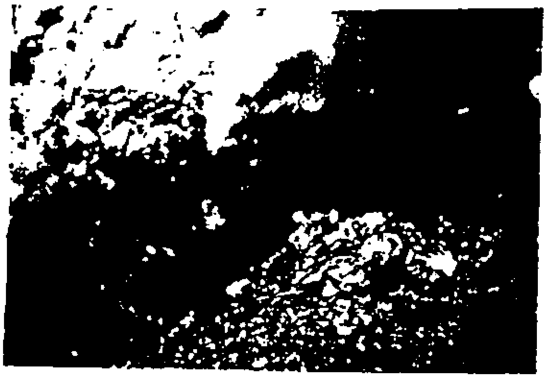


Fig.29-Optical effect of opalescence, brought about by fresh water flowing into the sea (photograph kindly offered by Dr. Stefanon)

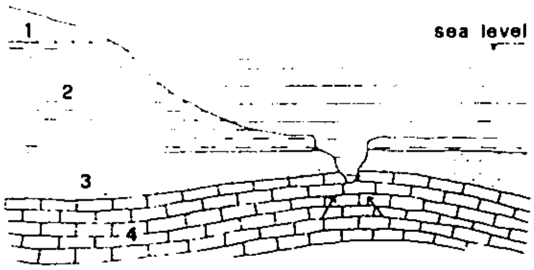


Fig.30- Schematic geologic section relative to the emergence of the "citri" in the Mar Piccolo of Taranto, Apulia, Southern Italy (by Cotecchia, 1977)

or erosion phenomena. Examples of springs of this kind are found at Port-Miou in France /33/ and at Citrello and Galeso in the Mar Piccolo at Taranto in ltaly (Fig.30) /36/.

The shape and size of the resurgences at the contact between a bed of hard rock overlyng loose sediments varies depending on the quantity of detritus that can be kept clear by the pressure of the upwelling waters which is, of course, variable in many cases.

The study of seaward outflows starts with an inventory of springs along the coast. Before the advent of remote sensing techniques the best method involved identification and measurement of temperature and salinity anomalies resulting from the resurgence of much less saline waters whose temperature differs from that of the seawaters. A complete inventory of seaward outflows on very long stretches of shore is much simpler since modern technology has made available airborne equipment for electromagnetic remote sensing and television (Fig.31).

The techniques differ from one another only as regards the type of equipment used and the methods of performing the survey.

It is also very useful to take aerial photographs which permit the exploration of objectives in the near infrared field at a wavelength of 0.9 um, namely just beyond the visible domain; this is generally done.

An appropriate combination of photosensitive emulsions and filters permits penetration of the seawater cover, allowing photographs to be taken directly of the sea bed up to certain depths.

To obtain quantitative as well as qualitative information, however, it is necessary to use multispectral scanners or infrared telecameras which provide information in the thermal infrared domain more directly connected with the temperature of the relevant objectives. The thermographs (Fig.32) obtained by special eletronic processing techniques directly reveal the presence of resurgences /3/ and permit the plotting of isotherms

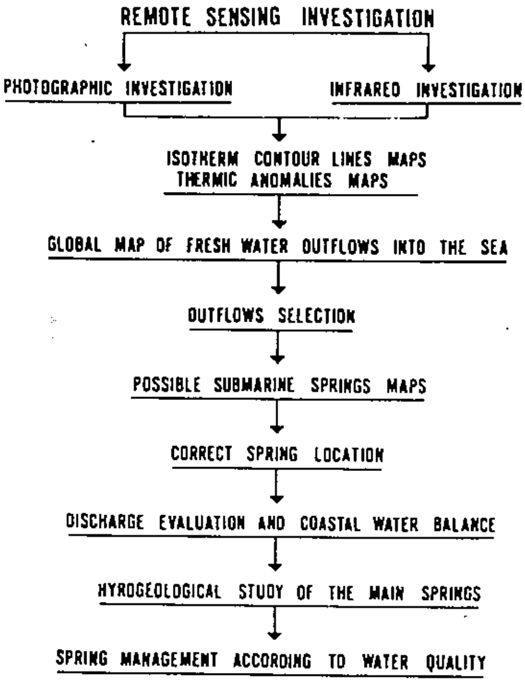


Fig.31-Analysis procedure for the inventory of the submarine springs by remote sensing.

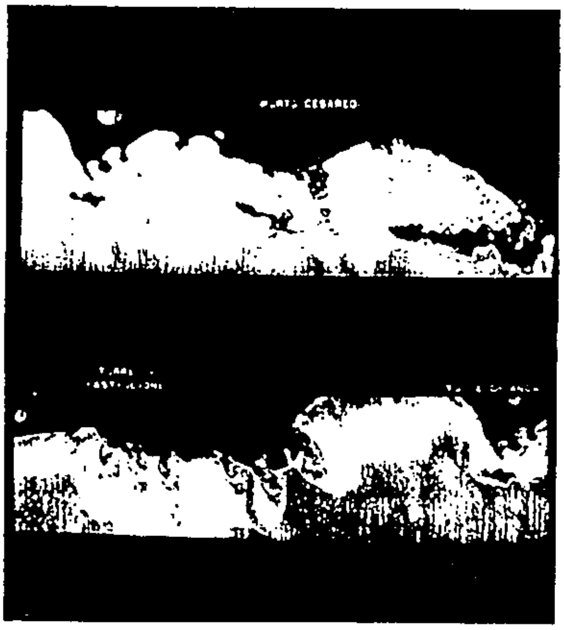


Fig.32- Example of surveys of outflows into the sea by means of multispectral, airborne scanner: the return, here reproduced in black and white was effected by DIGICOLOR techniques (by Cassa del Mezzogiorno)

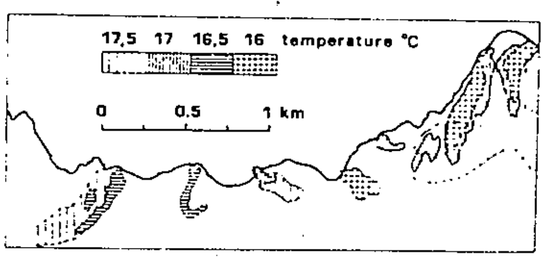


Fig.33-Example of isothermal map: the contouring includes isothermal areas with 0.5° interval (by Gandino & Tonelli, 1983)

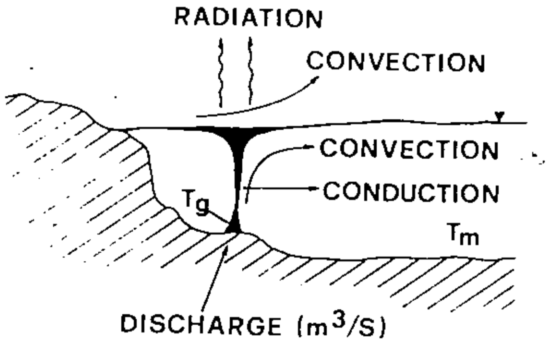


Fig.34-Sketch of a submarine spring showing the different ways of heat exchange with the outside (by Tonelli, 1983)

for the temperature anomaly produced in the sea, corresponding to isoradiant intervals (Fig.33).

There is a wealth of literature on this subject. Suffice it here to cite Gàndino & Tonelli whose paper on a survey of coastal springs in southern Italy explains the various processing and modelling techniques suitable not only for locating resurgences but also for obtaining a approximate estimate of discharge /15/. The quantitative evaluation is based on the balance between quantities of heat emitted by the undersea spring in a given length of time and the heat exchange between freshwater, saltwater and the atmosphere as a result of conduction, convection and radiation. Thermography, in particular, reveals the quantity of heat exchanged with the atmosphere by radiation (Fig.34).

If conduction and convection are ignored, the spring discharge is underestimated. In the heat equation where the only unknown is the discharge, it is necessary to include a coefficient of proportionality; this depends, among other things, on the special conditions under which the survey is made, and has to be calibrated to provide the absolute discharge value. Such calibration is not needed, however, when it is wiched to ascertain the seaward discharges along a whole stretch of coast, provided the survey is done quickly enough to enable conditions to be considered constant during the whole period involved /44/.

Mention must now be made of problems connected with the harnessing of coastal springs. Considerable difficulties are generally encountered and these differ, of course, depending on the type of spring to be tapped, especially in relation to whether it is subaerial or submarine.

One of the most delicate matters in the case of submarine springs is that of designing and building headworks which cause the least possible interference to hydraulic conditions at the spring, in relation to the head of the groundwaters feeding it and that of the seawaters over it.

Submarine springs almost always provide a mixture of groundwaters and waters of marine origin. The contamination cannot be attibuted solely

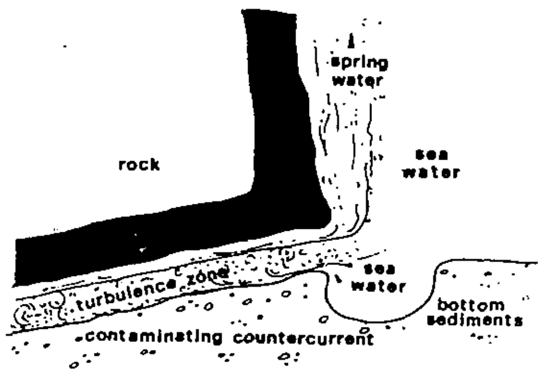


Fig.35-General view of a fairly common situation in a submarine spring mouth: the spring water exists through the upper part of the conduit leaving space for the sea water to enter the mouth and to descend to the lowest part. Some of the sea water is dragged out mixed with the spring water and it is replaced by some other which enters the conduit in form of a very thin layer of a contaminating counter current. (by Stefanon, 1973)

to the intrusion of seawaters into the aquifer where it mixes with the originally fresh groundwaters in the zone of diffusion. Indeed, it is often the result of hydrodynamic mechanisms which control the seaward outflow of springwater and the ingress of seawater via the same conduit, resulting in the creation of what some authors refer to as a "salt-water cone" (Fig.35) /36,33/. There can be no doubt that poorly conceived headworks can exacerbate this phenomenon, in which case the quality of the tapped waters deteriorates.

There are many tapping methods, since these must be designed to suit the seabed conformation and seawater depth, as well as the shape and size of conduits, their dispersion over the seabed and, especially, the hydrogeological conditions of the whole system.

Systems may range from simple flexible plastic frames /27/ to gather the spring waters to those allowing an initial stage of data collection and a subsequent one when the waters are actually tapped and led ashore. As indicated, choice of the most suitable system depends also on conduit shape. For instance, in the case of a spring with quite a large conduit at Port Miou (France) Potiè designed a system calling for construction of two barriers (Fig.36) one directly on the bottom and the other keyed into the vault of the conduit, the aim being to permit the outflow of freshwaters while at the same time preventing countercurrent flow of saltwater.

At the construction stage, however, the suspended barrier was found to be unnecessary, since the same result could be obtained by sealing the karst openings in the top of the conduit at a point where the vault had a natural-barrier configuration (Fig.37) /33/.

While Potiè's proposed solution is certainly feasible in the case of large conduit-flow springs, the system installed on a submarine resurgence in the Mar Piccolo at Taranto during an initial phase of

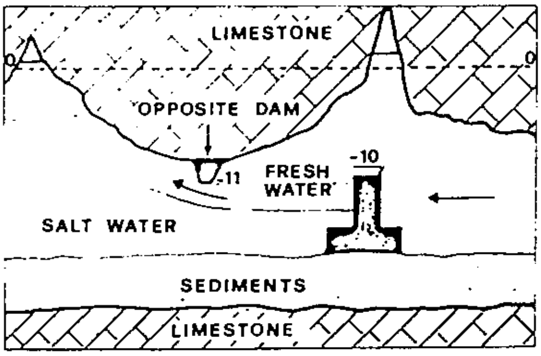


Fig.36-Example of placing of a Karst conduit feeding the submarine spring of Port Miou (France) with artificial thicknesses (by Potié, 1973)

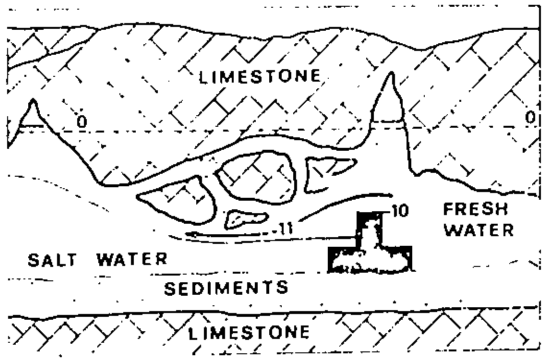


Fig.38- Sketch of the capping device on the bottom at the "Citrello" mouth in Taranto (Southern Italy) (by Stefanon 1972)

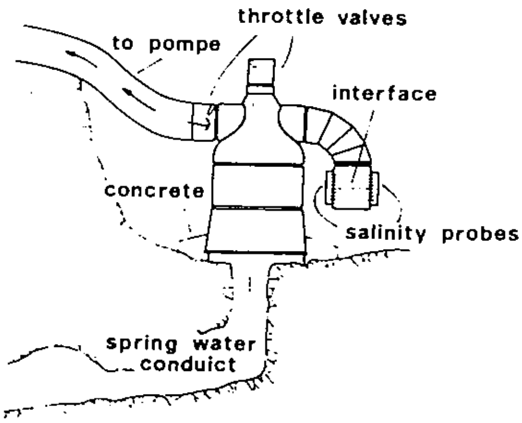


Fig.37- Sketch of works foreseen to use, as inverterd barrier, the shape of the karst conduit feeding the Port Miou spring in France (by Potié, 1973)

experimentation and data collection is suitable for more general applications /35/. Indeed, this system, with appropriate modifications, will be used for actually tapping the waters from this spring and conveying them onshore. The essential feature of the system is a fibreglass bell structure anchored to the seabed around the resurgence. The bell has three openings (Fig.38), the top one, which permits the outflow of spring waters, is connected to a pipeline for landward conveyance. The quantity of water tapped off can be varied by means of a butterfly valve; the piping system is complete with flow meters and flow control devices.

There is another opening in the side of the bell. This also has a control valve to permit the discharge of that portion of the flows that is not led onshore. The third opening is connected by means of a device with a transparent port for viewing the position of the interface between the freshwaters flowing from the spring and the surrounding seawaters. It is planned to install salinity probes in this line to actuate servocontrols for opening and closing the valves mentioned above. Regulation of discharges tapped and the pressure inside the bell will thus be altered automatically to suit the hydrologic equilibrium at any given moment between groundwaters and seawaters. The project is designed to tap and lead onshore around 700 l/s for irrigation.

There are also other problems regarding the tapping of submarine springs which are generally located close to the shoreline and do not usually occur in isolation but as a resurgence area with numerous upwellings, generally at an elevation very close to mean sea level. These springs can be classified by reference to the type of drainage channel which may or may not be tidal, depending on the elevation of the free surface of the flowing waters compared with minimum sea level. Tidal springs have some quite singular characteristics, /43/ of course, owing to the marked influence exerted on water quality by the periodic and aperiodic oscillations in sea level and by wave action. Such springs are very common in Apulia /15/.

It has emerged quite clearly from studies that have now being going on for a considerable number of years that knowledge of dynamics of such springs is best acquired by observation of the main hydraulic, chemical and physical characteristics for a reasonable length of time (Figs.39 and 40).

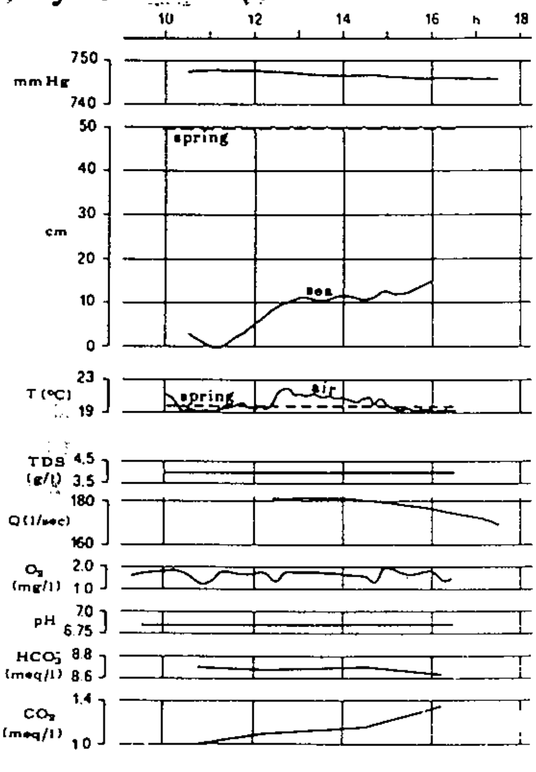


Fig.39-Daily surveys of hydraulic, physic and chemical parameters carried out in Vasca di Trani spring waters, Apulia, Southern Italy (by Tadolini et al., 1983)

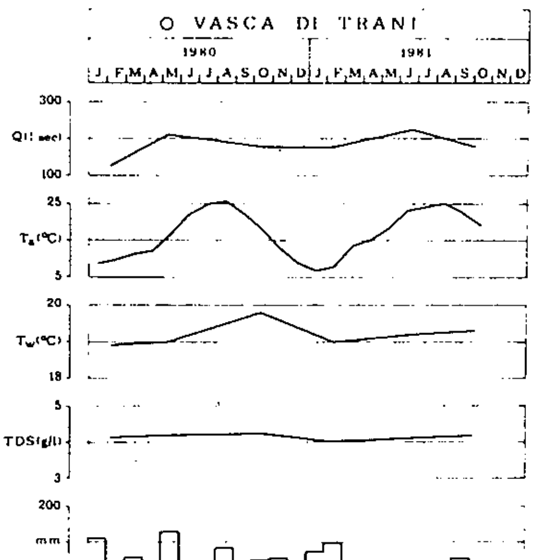


Fig.40-Chronological diagrams of discharge (Q), temperature and salinity of waters (TW and TDS), of air temperature (Ta) and histograms of rainfalls relative to Trani springs (by Tadolini et al.,1983)

Projects to tap springs such as these will only be really successful when there is a good understandig of the mechanisms that regulate outflow in relation to the immediate and longterm hydrologic equilibria between groundwater and seawater /38/. A very complete example of such a situation is provided bi the studies performed on the largest Apulian spring with a tidal channel, namely the Chidro.Lengthy studies on this spring culminated in the design and construction of headworks for harnessing its waters which issue forth via a great nember of subaerial and submarine vents and flow into a large funnel-shaped depression lying a few dozen metres from the shore (Fig.41).The average discharge is around 2400 l/s and the salinity about 3.4 g/l, so the wateras are quite acceptable for irrigation after being mixed with fresh waters from various surces, particularly in a region where water resources are stretched to the limit. Geological conditions in the springs area are schematized in Fig.42. The Mesozoic limestones that comprise the geological setting for the whole of Apulia are permeable due to fissuring and karstification, thus forming a huge aquifer which supplies the whole complex od springs.The clays which onlap the carbonate basement create a hydrogeological barrier, but in the spring area the cover thins locally owing to a combination of geological and geomorphological factors. The high pressure

Fig.41-Overall view of Chidro spring (Apulia, southern Italy)

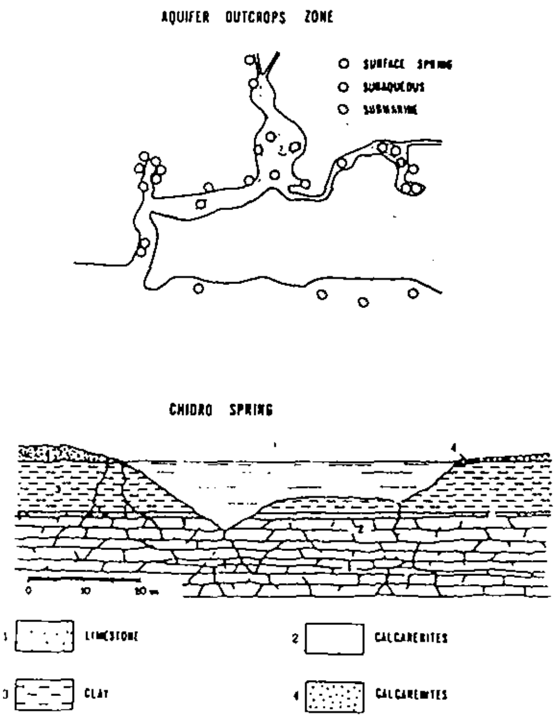


Fig.42-Plan and schematic geologic section of Chidro spring, Apulia, Southern Italy (by Cotecchia F.et al, 1973)

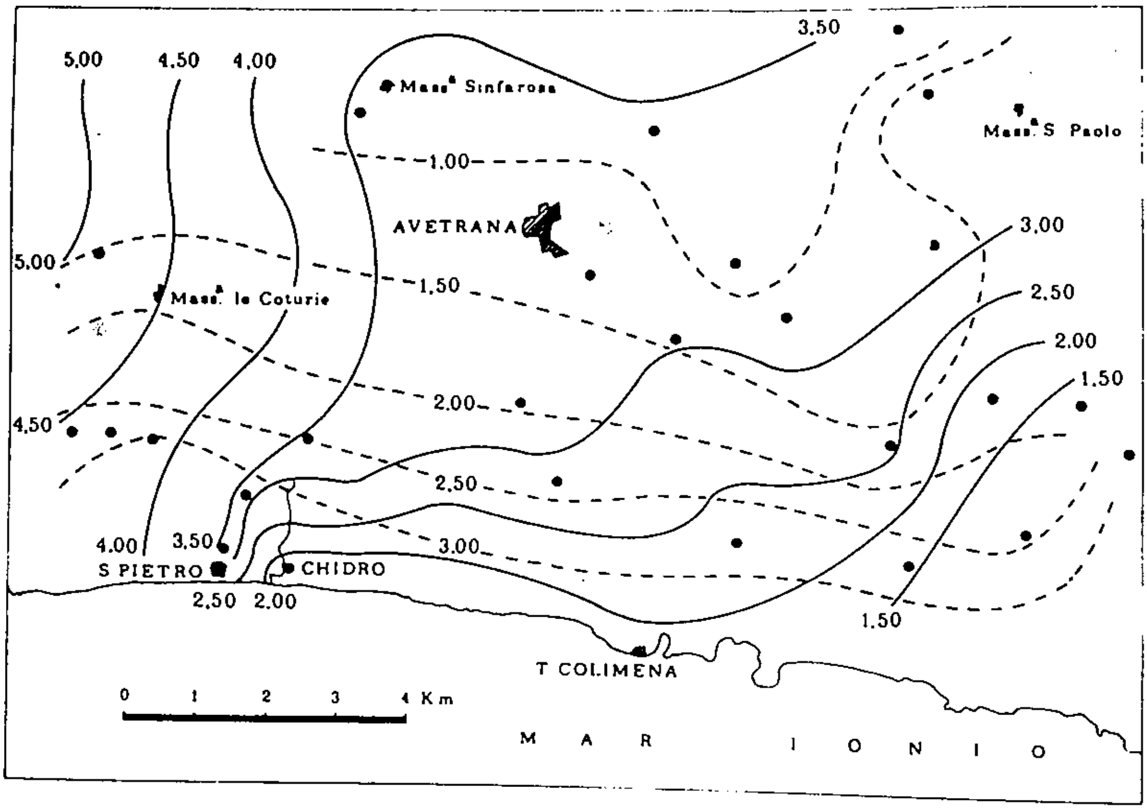


Fig.43-Average trend of the piezometric surface (continuous line)and of salt distribution (dashes) at the roof of the deep aquifer, Chidro spring, Apulia, Southern Italy (by Cotecchia et al.,1973)

groundwaters were thus able to perforate and erode the cover and to carve out the funnel-shaped depression now occupied by the spring.

It is evident from the plot of the piezometric surface (Fig.43) that the spring provides one of the few resurgences in this area through which equilibrium is maintained between deep aquifer recharge and discharge, since the impervious clay cover stretches for many kilometres along the coast, hence preventing unrestricted outflow of groundwaters /10/.

Owing to the peculiar shape of the spring careful precaution had to be taken to prevent influx of seawater as a result of headworks construction, because the level of the groundwater in the natural basin is only a few decimetres above that of the sea. The springs headworks thus include sliding gates on the natural outflow channel and a diversion canal which starts from upstream of that point (Fig.4). The gates open vertically thus permitting the spring waters to flow through a variable sized opening on the bottom on the channel. This solution was necessary to keep a head between the basin and the sea so as to stop direct intrusion of the latter and, more generally, prevent any change in the equilibrium of the hydrogeological system. The works are designed to abstract no

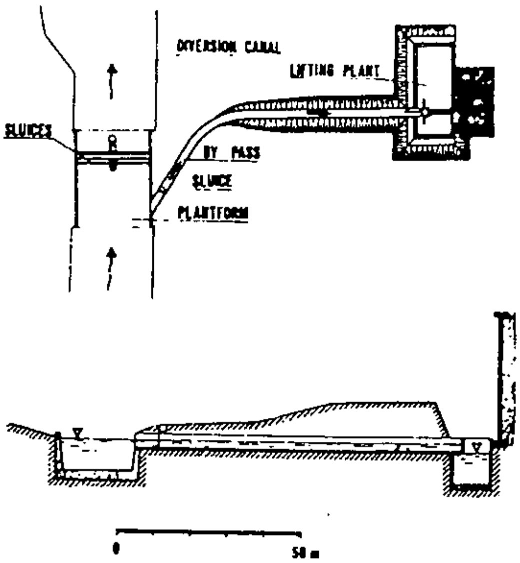


Fig.44-Plan and section of the Chidro spring capture works, southern Italy (by Cotecchia et al.,1975)

more than one third (800 l/s) of the total discharge. As a further guaranteed that this offtake is not exceeded, the bed of the diversion canal is set a certain height above the bottom of the seaward outflow channel /4/.

The examples given here certainly do not exhaust the subject of seaward outflow from coastal aquifers. Other papers on the same theme are being presented at this meeting but in my opinion much more scientific research remains to be done, especially as regards study, design and construction of works to tap submarine springs.

The demand for water, so vital for some of the world's developing regions, can perhaps be satisfied to some extent by tapping these still considerable unconventional resources which are at present lost to the sea.

It is in the hope that we shall soon be able to meet again to exchange further more fully-matured experiences that I conclude my paper.

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