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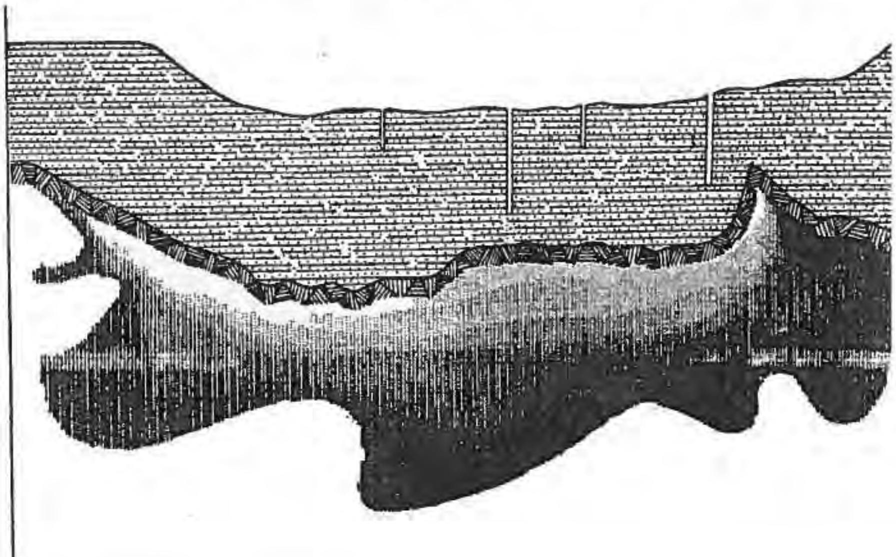
VINCENZO COTECCHIA
MODERN EXPERIMENTAL METHODS
FOR THE STUDY OF GROUNDWATER



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MODERN EXPERIMENTAL METHODS FOR THE STUDY OF GROUNDWATER

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SUMMARY

The use of special methodologies, for carrying out a fair underground water resources management accounts for an all-important factor

The objectives, unthinkable till a decade ago can be reached nowadays thanks to the accuracy of the equipment provided by modern technology.

Such a work is intended to be a report of the most advanced methodologies widely used at present in the hydrogeological field, taking also into account some moder applications by traditional methodologies.

The considerable advances of applied nuclear physics, electronics and science of information have allowed hydrogeology to resat to some instruments being sometimes easy to use and able to provide valuable data in a short stretch of time.

Traditional advanced techniques agree also upon the importance of the underground water resources pollution; for both the acquisition of data needed for the quantification and the definition of the state of pollution which is taking place, and for the development of methods of study concerning the territory and the hydrgeological environment. Such data turn out to be very useful to prevent and to determine the vulnerability of aquifers.

Modern technology makes available to the research worker increasingly more advanced equipment, enabling objectives to be attained that were quite out of reach a decade ago.

The rapid development of methodologies and scientific equipment directly or indirectly applicable to hydrogeological studies has paralleled to some extent the vertiginous growth in the importance of hydrogeology itself. This is a very good thing because hydrogeology is the discipline that can provide humankind with new water resources or protect existing ones from various forms of known pollution or even rehabilitate them when they have become contaminated.

Of the methodologies the mostly used ones will be taken into account, without excluding some new ways of applying long-established techniques.

The basic starting point for all hydrogeological investigations is a thorough intelligent understanding of the geological setting of the area concerned.

For instance, as regards methodologies that are particularly useful for hydrogeological investigations in fissured formations, fracture analysis is of prime importance. Information obtained by the statistical analysis of fractures (Fig.1) enables an assessment to be made of the distribution of permeability characteristics in a section through an anisotropic aquifer /32/. The results achieved in this manner can be very reliable, especially when they are arrived at in combination with the data acquired from other investigations.

In karst carbonate aquifers, recognition of the direction of preferential development of subterranean cavities may permit an initial forecast on the spatial trend of the levels where groundwater flow occurs (Fig. 2).

Equally valid are those methodologies which particularly concern absorption of water from the surface, and are designed to ascertain how the karst process is initiated and develops.

Where coastal karst aquifers are concerned, investigation of the palaeogeographic situation may well permit a forecast to be made of present hydrogeological conditions in a given area, provided that a careful study is also made of its tectonic history and of the relationships among the lithofacies more or less prone to karstification. Regarding the influence of the palaeogeography on the state of groundwaters, it is very important to recognize relative movements of sea level that have occurred in geological times.

By way of example mention should be made of the work done on the coasts of Southern Italy, where recognition of glacio eustatic changes in sea level in Tyrrhenian and Holocene times enabled us to forecast the present hydrogeological situation, especially as regards the existence of particular water-bearing levels that are highly permeable owing to karstification /12, 14, 15/.

Plotting of old shorelines in this case was based on palaeontological methods combined with absolute dating of fossils and palaeosols. Some of the main effects resulting from the rise in sea level (Fig. 3) from the minimum that occurred 14,000 years ago (100 metres below present m.s.l.) are reduction in the volume of the aquifer (Fig. 4), fossilization of pre-existing karst features and initiation of the karst cycle at new levels. Then, of course, there is the inevitable modification in the chemistry of the groundwaters caused by the more marked intrusion of the landmass by seawaters, and hence the greater possibility of the occurrence of molecular diffusion and mixing.

Similar palaeogeographic mapping of North Sea coastal environments, based not only on the methodologies mentioned but also on permafrost investigations, geophysical surveys and an analysis of molecular diffusion and dispersion, has revealed the relationship between past hydrogeological conditions and seawater intrusion phenomena (Fig.5) in some parts of Holland and Belgium /26, 55, 67/.

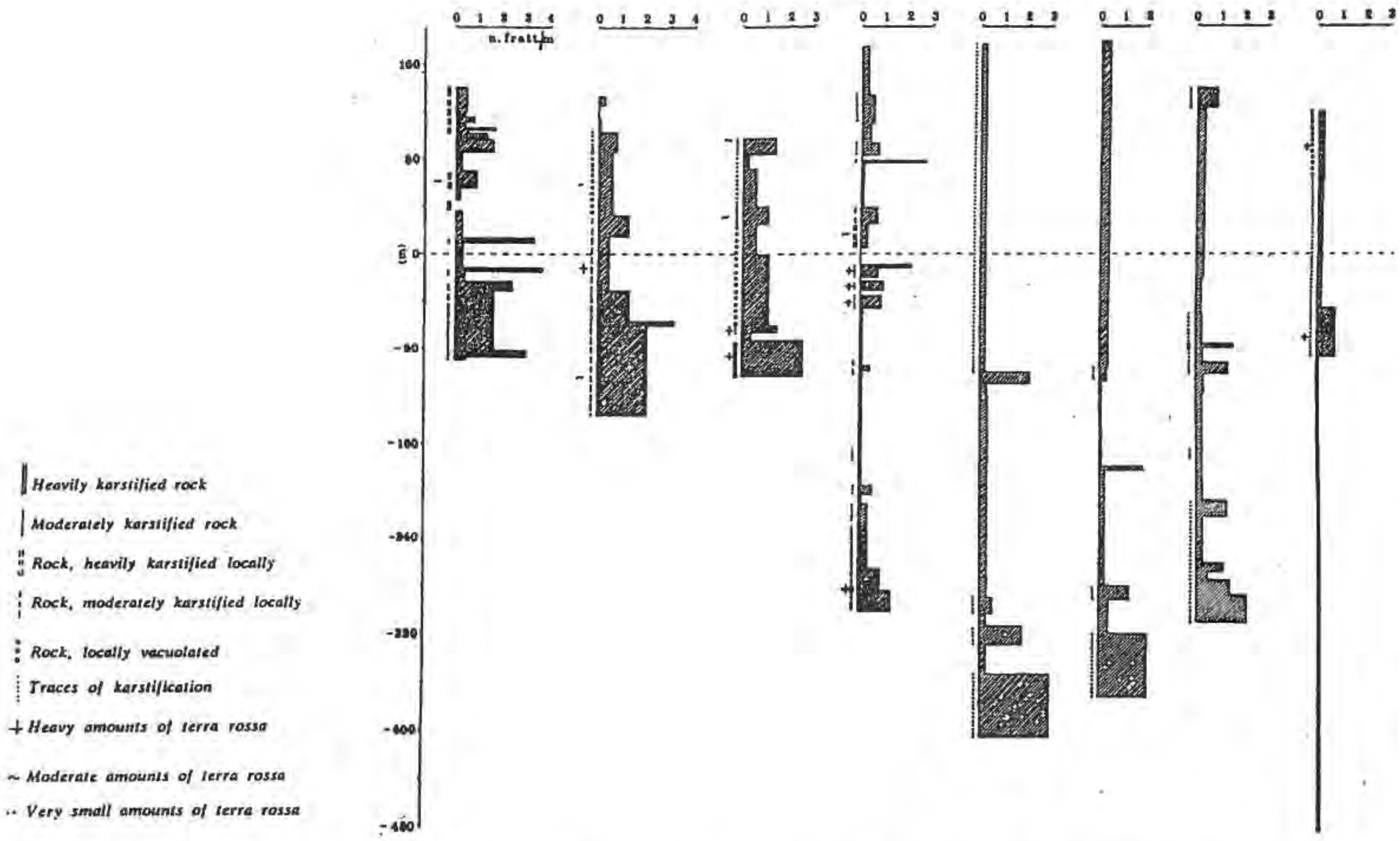

Fig. 1 - Histograms of fracture frequency calculated from cores taken from boreholes in the Murge Region (from Grassi et al., 1977)

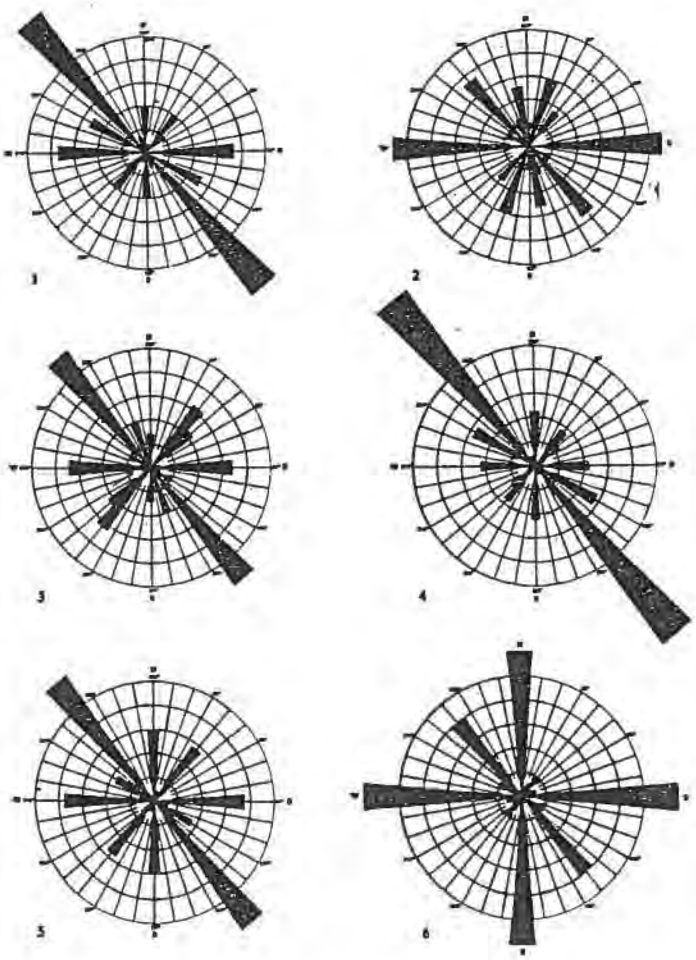

Fig. 2 -
Statistical analysis of direction of preferential development of subterranean karst cavities in the Murge Region (from Grassi, 1974)

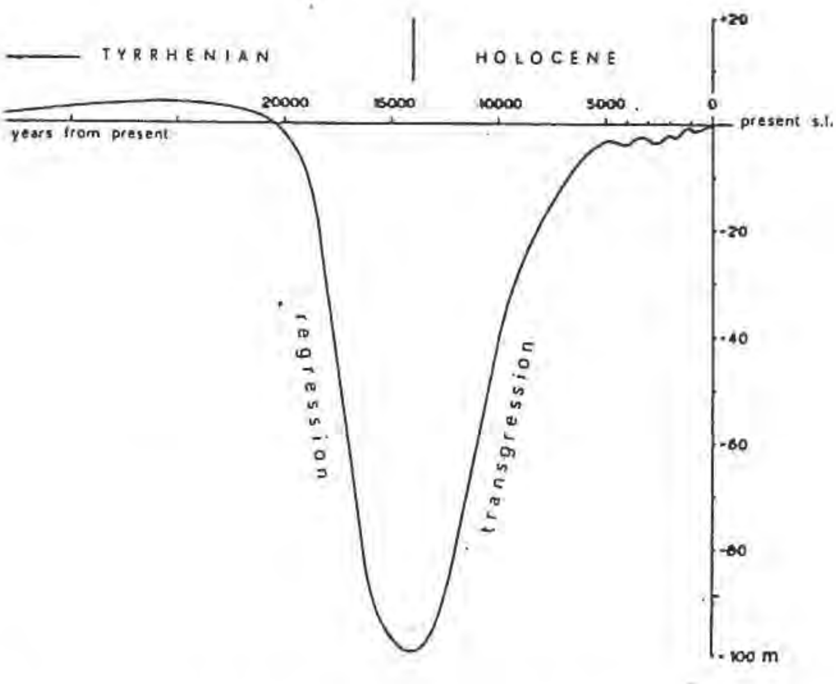

Fig. 3 - Glacio-eustatic changes in mean sea level in late tyrrhenian and holocene times (from Cotecchia et al., 1971a).

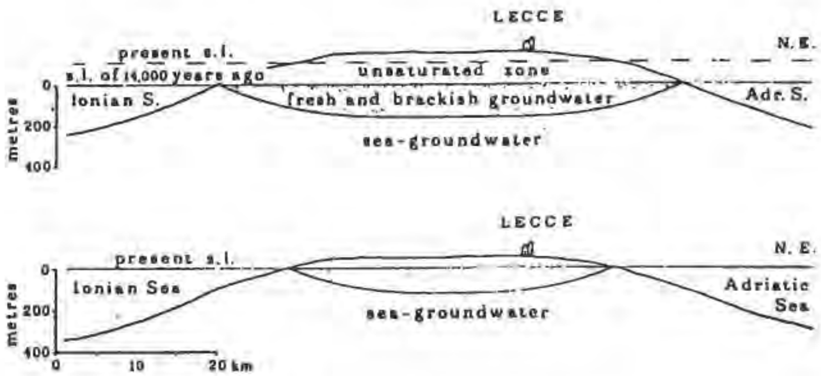

Fig. 4 - Schematic sections through the Salento Peninsula, showing thickness and extent of fresh and brackish groundwaters at the present time (bottom) and at the climax of the last retreat of the sea (top) (from Cotecchia et al., 1974a).

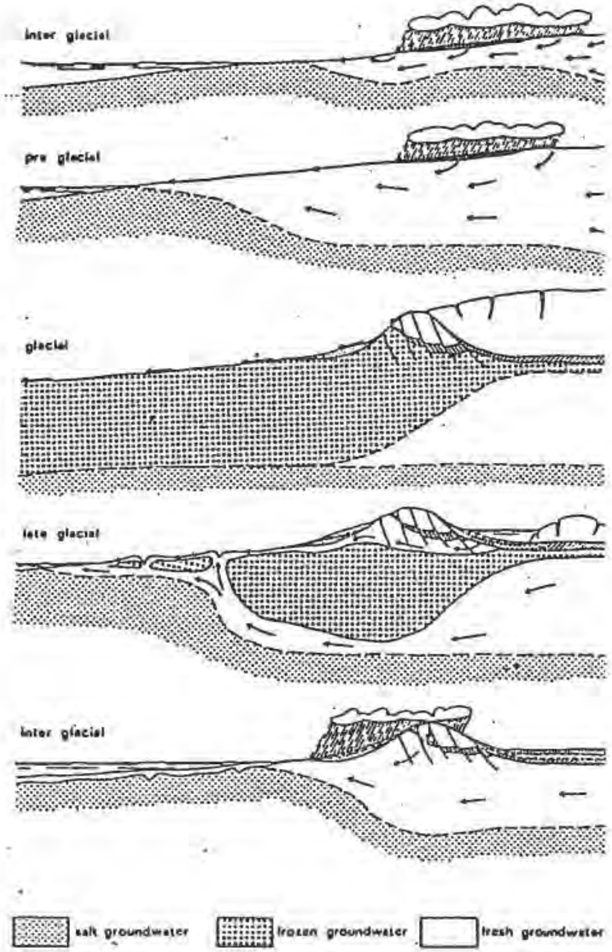

Fig. 5 - Relation between palaeohydrogeologica conditions and seawater intrusion phe mena in a dutch region (from Pomper,

Turning now to geophysical methods of investigation, applications concern the mapping of hydrogeological profiles, and, most importantly, the use of geoelectrical methods for ascertaining the extent of seawater contamination of coastal aquifers (Fig. 6), in relations to the freshwater-seawater equilibrium (Fig. 7) and the depth of the transition zone /27, 70, 87/.

Particularly worthy of mention are those seismic refraction methods which are used to ascertain the degree of fracturing of aquifers in general (Fig. 8) and which are especially useful for assessing the state of subterranean karst development /90/.

No less significant, however, for the location of subterranean cavities is the application of the vertical gravity gradient method. Recent trials with this method in the Grotte di Castellana area (Fig. 9) show it to have a higher standard of accuracy and better selectivity than the classical gravity method /57/.

Still on the subject of applied geophysics, the importance of instruments that record micro-and macro-tremors is anything but marginal. This is readily apparent when we consider the way tremors can modify aquifers either through variations in the state of fracturing or porosity of the medium, or by actually tilting the aquifer in one direction or another. A recent example of the effect of earth tremor is provided by the marked changes that occurred in aquifers in the part of the Southern Apennines affected by the earthquake of 23 November 1980 /11, 19/.

Fig. 10 shows Caposele spring example. The sill of the spring was lowered by 84 cm as a result of the earthquake, while other parts of the aquifer were uplifted by neotectonic action triggered off by the tremors. The diagram illustrates the very rapid variation in discharge as a result of the earthquake (from about 4 m^3/s to 7 m^3/s in less than a month). At the Cassano Irpino Springs the changes occurred a fortnight before the earthquake.

Pride of place among modern techniques available to the hydrogeologist must certainly go to remote sensing. As we all know, these techniques include any system of data acquisition by aerospace facilities (Fig. 11). The systems may be based on photographs taken by normal methods or supplemented by the use of emulsions and filters that broaden the visible spectrum band or they be based on imagery created by electromagnetic signals emitted or reflected from the earth's surface and picked up by multispectral scanners. The technique most commonly used in hydrogeology today is thermal infrared aerial prospecting, which finds wide application in all investigations concerning the inventory of seaward outflows from coastal aquifers (Fig. 12) /34/.

Of the various possible ways of processing signals recorded on different channels operating in various wavelength ranges, density slicing and DIGICOLOR are worthy of mention /73/.

The system is obviously applicable in all cases where a temperature difference on a given surface investigated can be tied in with hydrogeological factors. It is thus possible to make inventories of irrigated areas, to identify zones where the groundwaters are very close to the surface, and so on.

Everyone is acquainted with the purpose of the various programmes such as LANDSAT, SEASAT, EROS, etc. It is noteworthy the fact that a second-generation multispectral radiometer on board STEREOSAT in orbit 300 km above the earth will be capable of furnishing images with resolution of 15 m, which certainly means that the system will be useful for quite detailed hydrogeological investigations /50/.

While on the subject of detailed investigations, mention must be made of the importance of observation wells drilled specifically for the performance of a whole series of conventional and advanced investigations. If such boreholes are to provide data reflecting the real distribution of the hydraulic properties of an aquifer at depth, it is essential that they be completed in a way that provides maximum information on real conditions in the aquifer. It may thus be necessary to isolate stretches

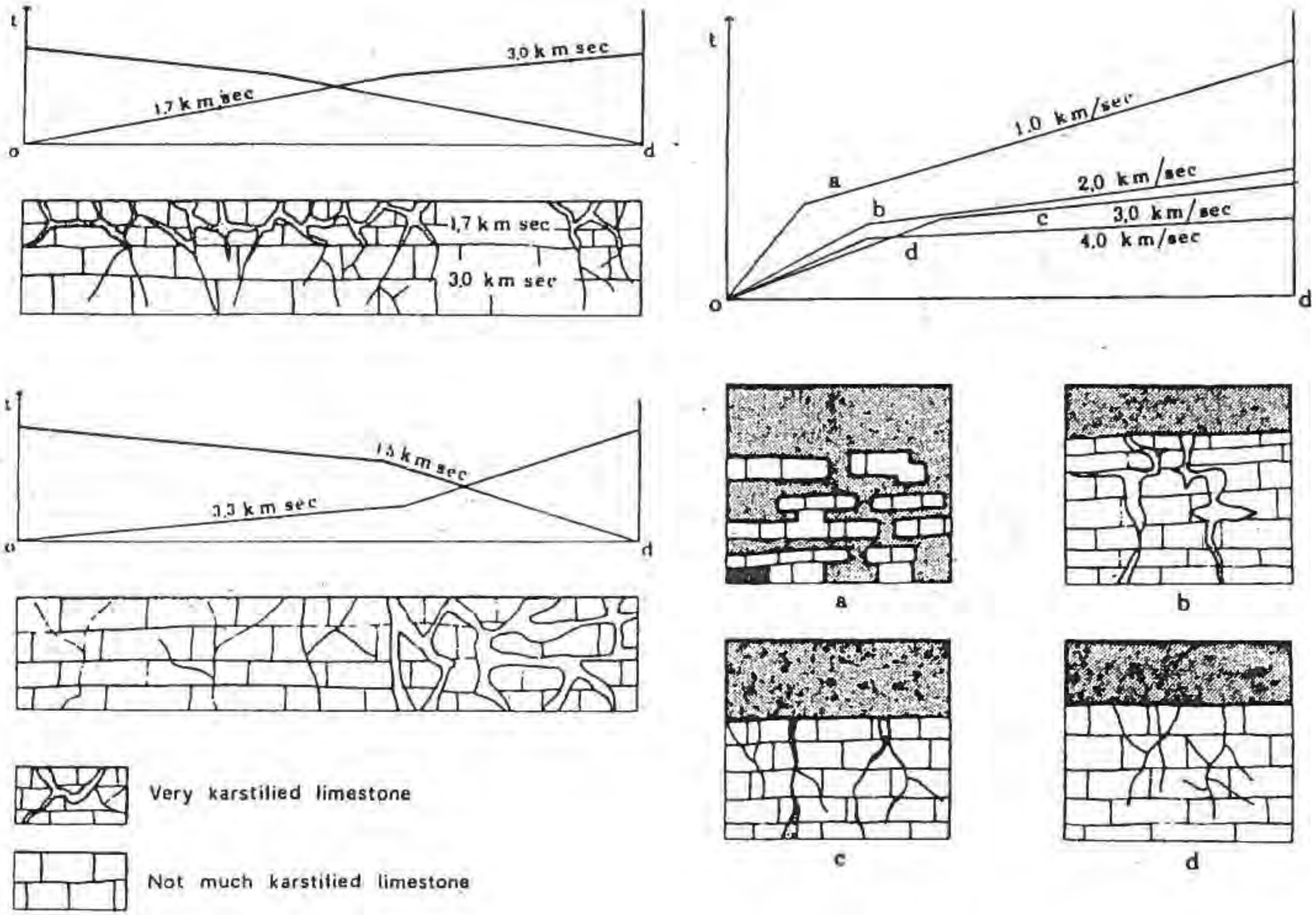

Fig. 8 - Travel-time curves relative to various states of karstification and the presence or absence of Terra Rossa (from Zezza, 1978).

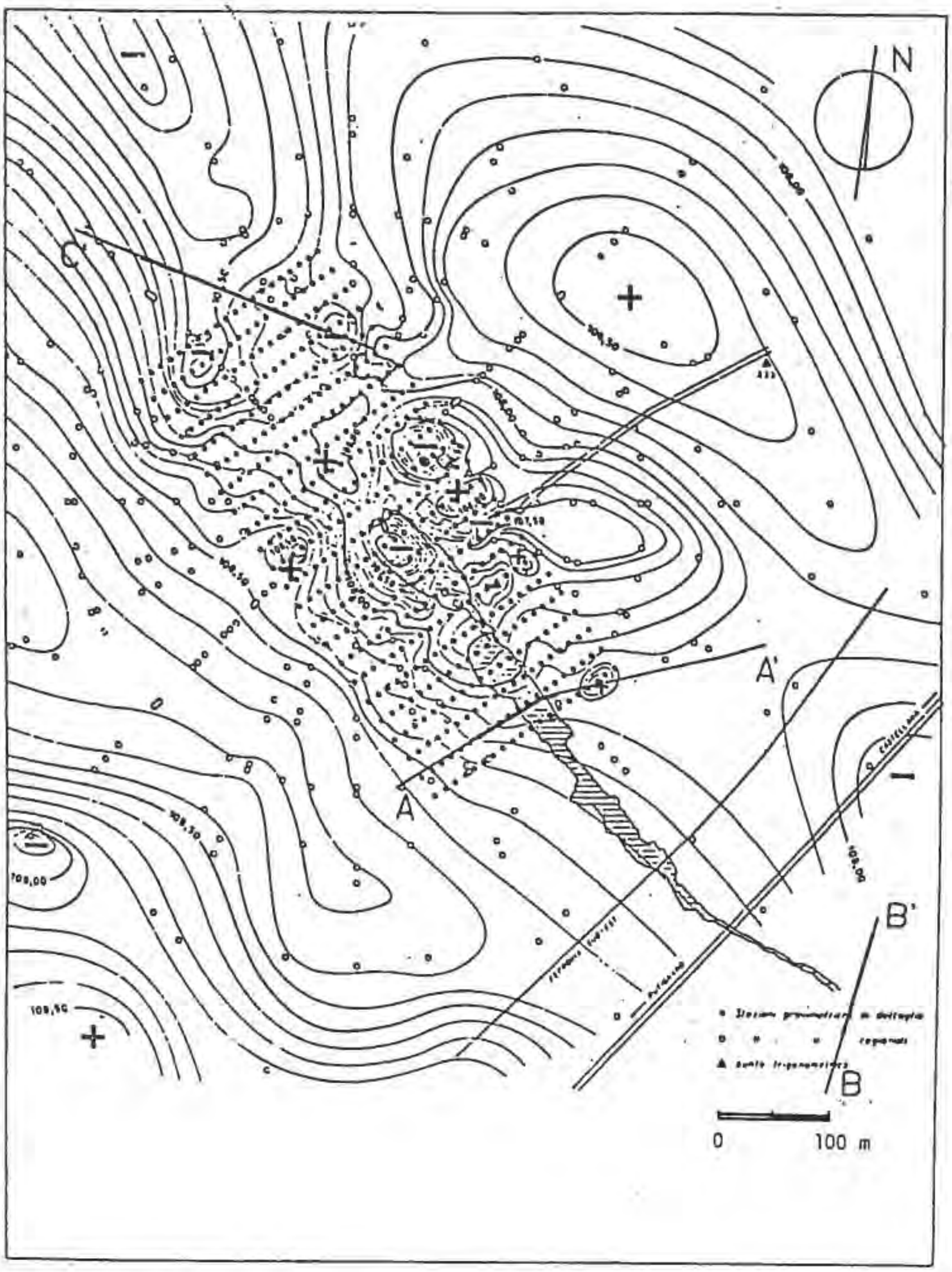

Fig. 9 - Gravity anomalies indicating the presence of subterranean karst cavities (from Mongelli and Ruina, 1982).

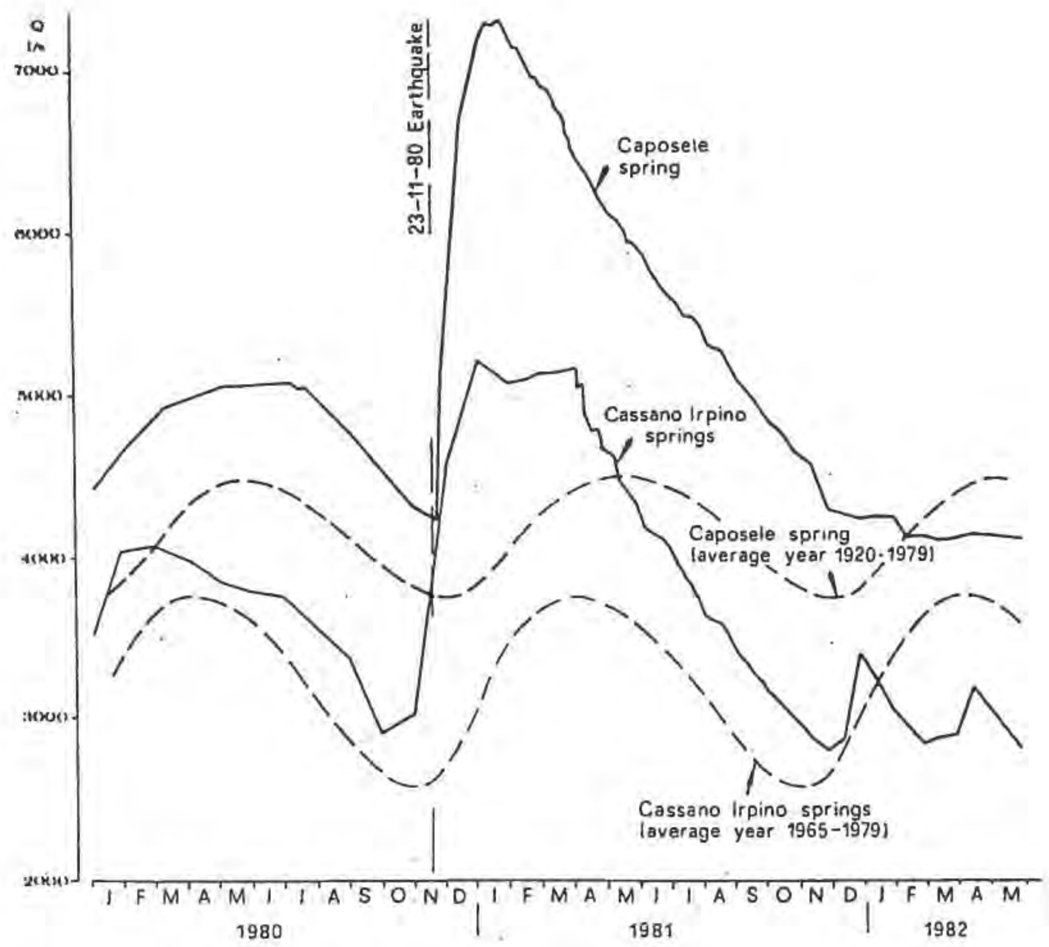

Fig. 10 - Discharge hydrographs of the Cassano Irpino group of springs and of the Sanità di Caposele spring before and after the earthquake in Campania and Basilicata on November 1980, comparison of these hydrographs with those for the average year reveals the big increase in discharge as a result of the quake (from Cotecchia and Salvemini, 1981).

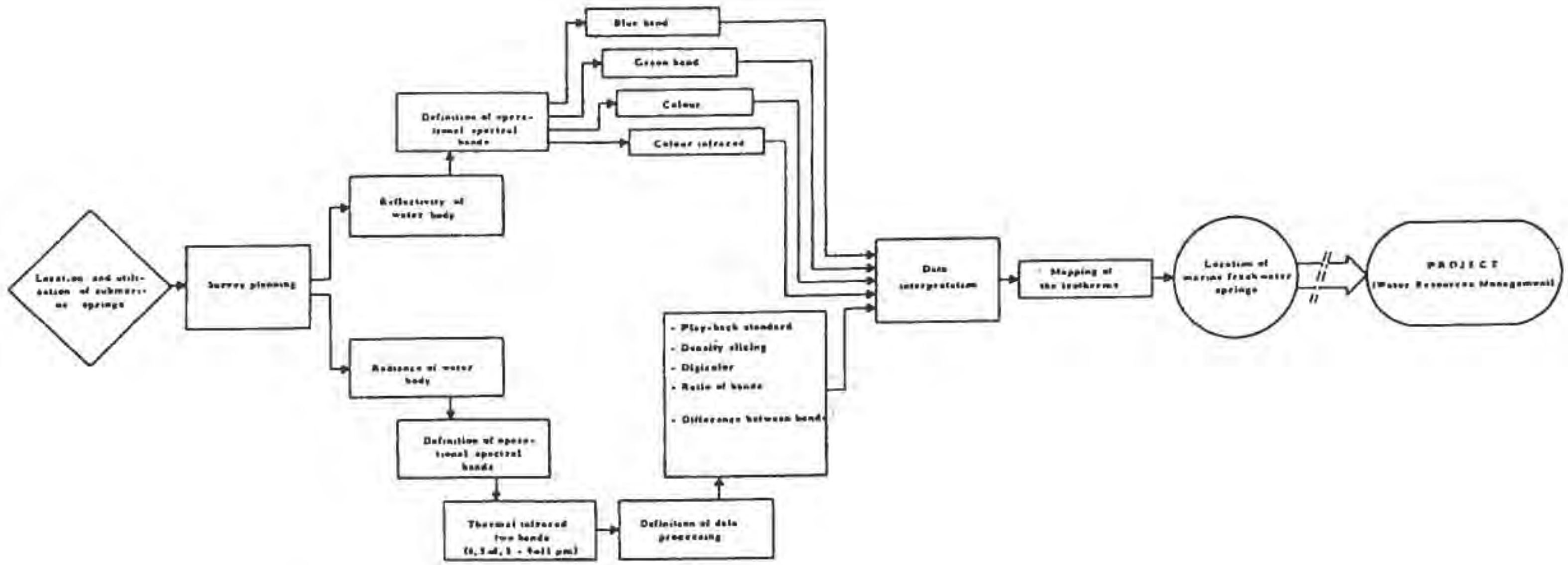

Fig. 11 - Operational scheme for remote sensing data acquisition system (from Guglielminetti et al., 1975).

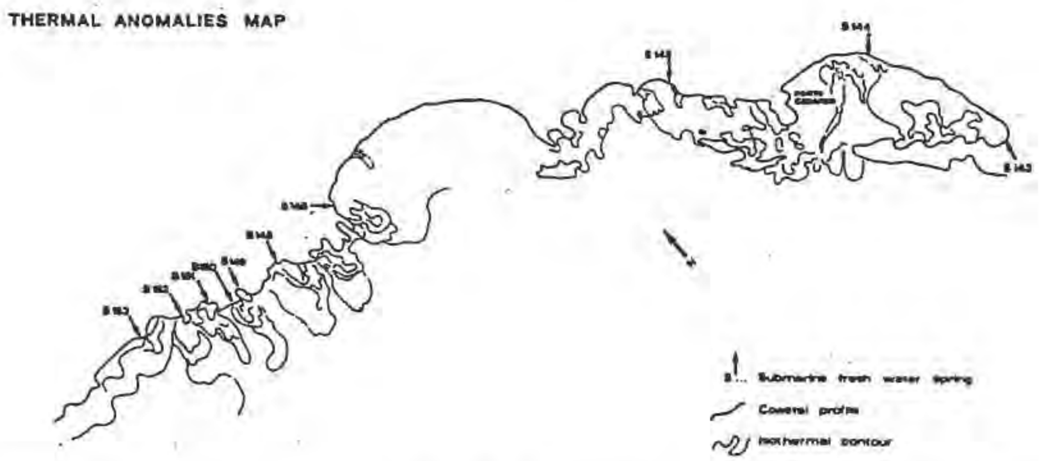

Fig. 12 - Thermal anomalies map of a portion of the Ionian coast of Apulia (from Guglielminetti et al., 1975).

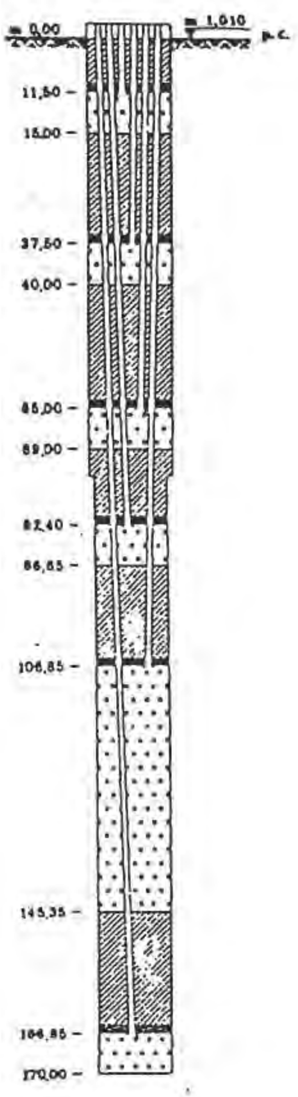

Fig.13 - Arrangement for isolating lenghts of borehole in fissured rock (from Cotecchia et al. 1973a)

of aquifer where preferential groundwater movement occurs. This can be done by installing PVC cells appropriately slotted to permit inflow of water from the aquifer. The cells are isolated from one another by cement plugs, but are connected to the surface by piezometers /5, 20/.

An example of this type of well completion (Fig. 13) is the 170 m borehole located at Chidro Spring on the Salento Peninsula.

The hydrogeologist has always obtained a mass of useful information by studying the water table or piezometric surface. In this field, progress has been made even in the case of this conventional approach, both as regards more correct methods of collecting the necessary water-level data (fig. 14), and as regards the possibility of acquiring new parameters for better characterization of the aquifer /81/. There is also the fact, of course, that new computer techniques enable us to plot equipotential maps more rapidly and to interpret the relevant data more confidently.

Some quite original thinking has been required to provide satisfactory interpretations of some causes of disturbance in groundwater levels. This is true in the whole range of studies concerning the transmission of fluctuations in receiving bodies - such as seas, lakes and rivers-to groundwaters, thus affecting their level. The way in which fluctuations are propagated from their source - generally the sea - towards the groundwaters (Fig. 15), where they cause attenuated fluctuations in level, depends largely on the hydrodynamic properties of the aquifer /2, 53/. It thus ensues that by determining the global attenuation values of stretches of aquifer between a single observation station and the coast we can ascertain the "diffusivity" values and plot lines of equal propagation or "communicability", known as isodiabases, between points in the aquifer and the sea.

The trend of these isodiabases in a coastal aquifer where the fresh groundwater floats on seawaters intruding the landmass has a similar significance to that of the equipotential lines of groundwaters overlying an impermeable basement. There are decided advantages in adopting this system for interpreting the groundwater situation /74/.

The application of this method to a stretch of coastal aquifer on the Salento Peninsula can be seen in fig. 16.

At this point mention should be made of ever-wider use being made of pneumatic piezometers (transducers), electro-pneumatic cells for measuring total pressures, strain gauges, arrangements for measuring compaction and for determining the ways in which the water drawing- especially from deep confined aquifers in unconsolidated formations - causes subsidence, a phenomenon that is occurring with increasing frequency in all parts of the world (Fig. 17).

Again looking at new ways of applying conventional methodologies, we might fruitfully dwell for a moment on the use of temperature data for obtaining information on the degree of mobility of groundwaters, for identifying the main recharge areas, for ascertaining the methods of groundwater movement in very anisotropic aquifers and for assessing the influence of the sea on coastal aquifers.

The interpretation of a temperature log of a borehole penetrating an aquifer certainly depends on one's basic knowledge of the aquifer, since there are various factors that can have an influence on the thermal stratification of groundwaters /4,10,24/.

The basic principle, however, is that water which infiltrates into the subsurface at a temperature that varies over a given range, depending on the air temperature, will tend to pick up heat, the longer it remains in the aquifer. Therefore, in general when one finds temperatures increasing with depth, it may well indicate that the groundwaters in the acquifer are not very mobile, on the whole, while a log reporting constant temperatures may signify that the permeability of the aquifer

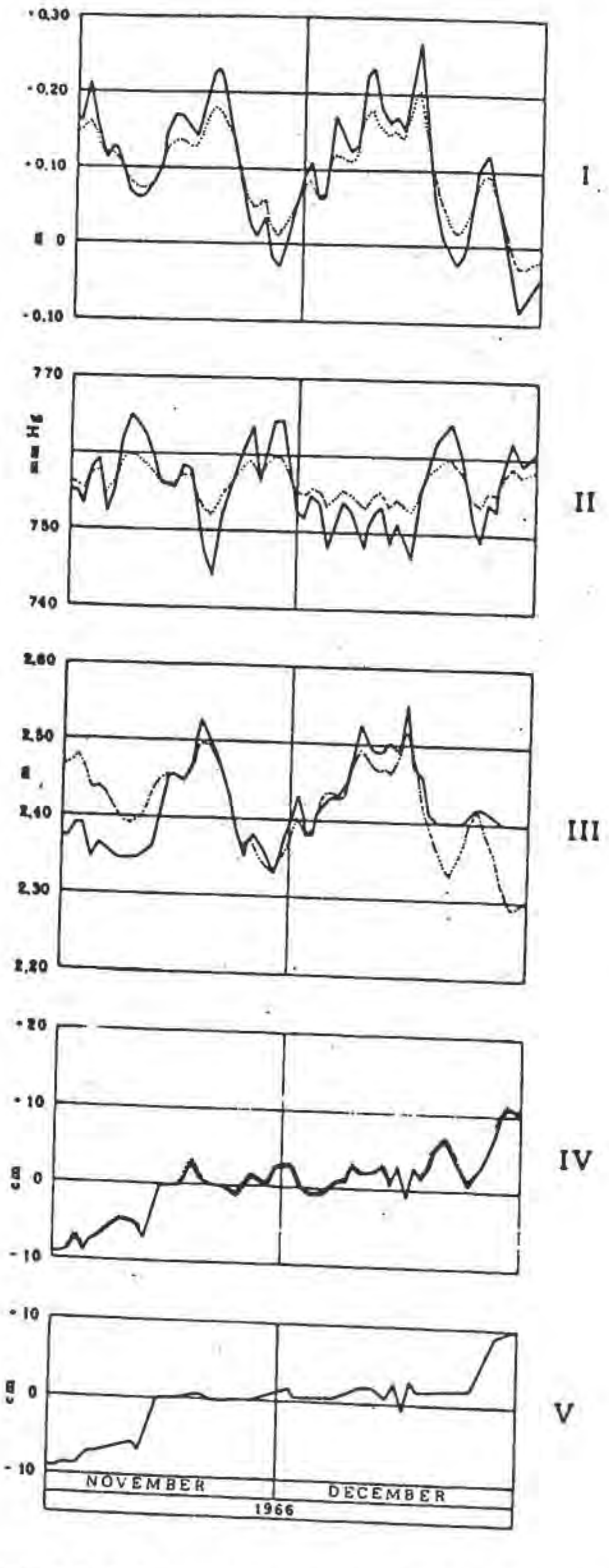

Fig. 14 - Groundwater stage records stripped of influence exerted by variations in sea level and barometric pressure (from Tadolini and Zanframundo, 1974).

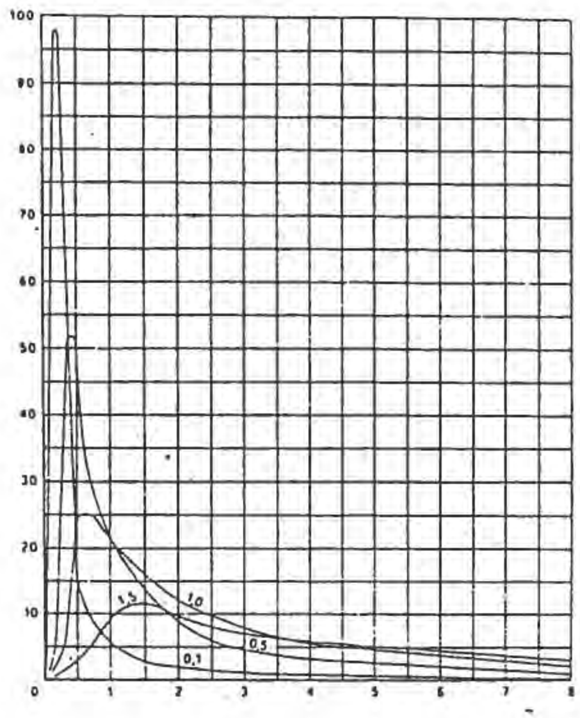

Fig. 15 -
Trend of pulsed response P(T) versus time T for some attenuation values (from Magri and Troisi, 1969)

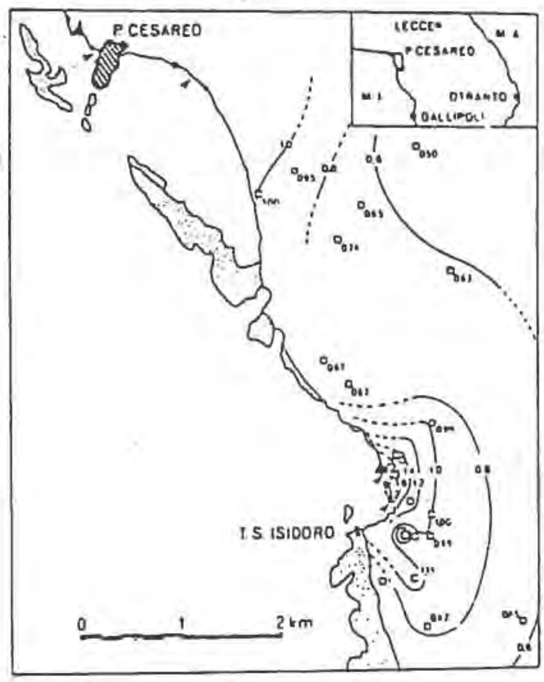

Fig. 16 -
Isodiabases plotted for a stretch of coastal aquifer on the Salento Peninsula (from Magri and Troisi, 1968).

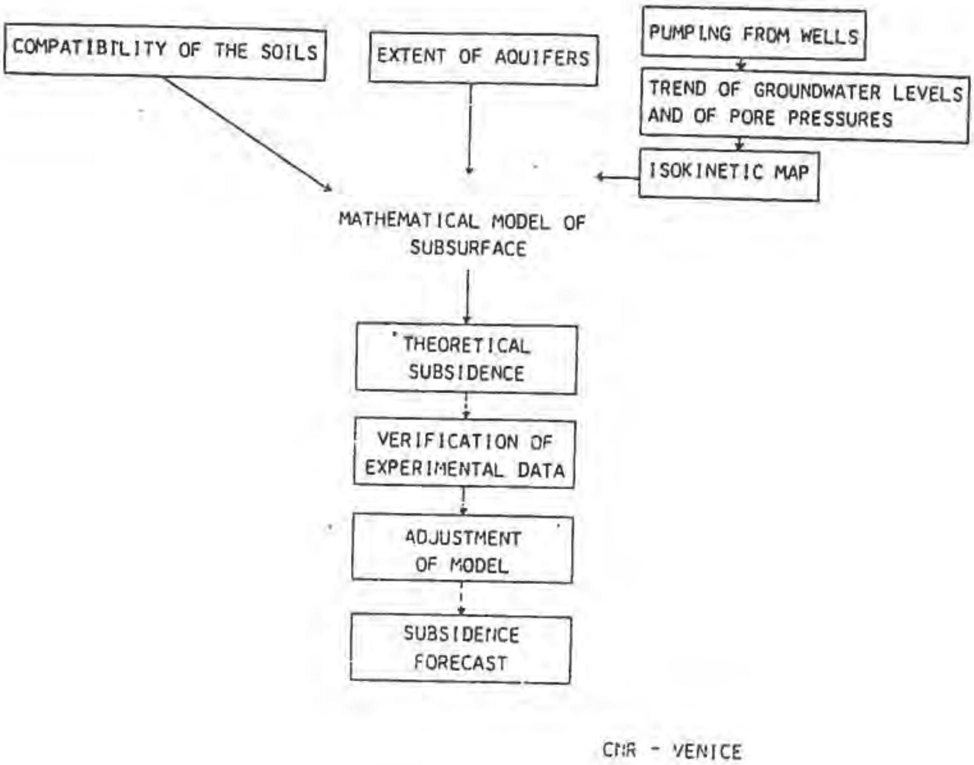

Fig. 17 - Block diagram of mathematical model of subsidence.

is good. Negative kinks in the temperature profile may well indicate preferential groundwater flow at given levels in anisotropic aquifers /24/.

In the fissured, karst Murge aquifer the interpretation of a whole series of temperature logs made in boreholes penetrating several hundred metres below sea level (Fig.18) have enabled the main lines of groundwater flow to be ascertained with certainty to the depths directly explored (fig.19).The results have also been extrapolated to even greater depths and it would appear that groundwater flow is still active even 2000 m below sea level (Fig. 20).

Though not of such general application as temperature, there are some hydrogeological situations, where the distribution of salinity and the way this varies with time provide useful information on the main phenomena influencing recharge and flow or possible exchanges between different aquifers /6, 7, 38, 39, 43, 44, 45, 46, 51/.

By way of example, this kind of measurement finds wide application in the study of salinization of the waters of coastal aquifers. Here it is, of course, necessary to have available observation wells which penetrate for several dozen metres into the seawater that intrudes the landmass and underlies the fresh groundwaters.

We shall not dwell on the many theories that have been propounded during years of investigations conducted by a great number of research workers in the most diverse hydrogeological situations. Over the last thirty years the Apulian aquifers have provided a rewarding field for studies and investigations in this regard /8,10,16, 20, 23, 74, 75, 77, 78/.

To follow the logical thread of the discussion, it would probably be better to say a few brief words on the type of information that can be obtained through the interpretation of salinity logs in observation wells and of the areal distribution of salinity. By systematically monitoring saline stratification in coastal aquifer, with particular regard to the position and thickness of the transition zone (or zone of diffusion), we can ascertain the real relations that exist at a given station between piezometric heads and elevation and thickness of the transition zone and also those that exist between variations in elevation and the thickness of the transition zone and variations in piezometric head /23/.

Fig. 21 shows the trend of saline stratification ascertained directly in situ by means of conductivity probes in a series of observation boreholes drilled on the Salento Peninsula.

By noting the geoghaphic location (fig. 22) it results that the transition zone is thickest in the areas farthest inland.

Turning now to the changes that occur in this zone, it is evident that it expands during dry periods and shrinks during rainy periods,of course with a lag of a few months - more marked inland and less so in the parts nearest the shore (Fig.23). The size of these vertical movements is decidedly greater than those recorded for the water table.

Salinity logging of observation wells also enables assessments to be made of how the equilibrium existing between fresh waters and salt waters is disturbed when the aquifer is overpumped - a subject that is very much to the fore these days. Indeed, by translating the salinity values into densities, a comparison can be made between the real height of the water table at a given point and the theoretical height corresponding to the position of the transition zone (Fig. 24). From this we can obtain an indication of the lack of equilibrium, which in a certain way quantifies the tendency of the transition zone to expand upwards /78/.

It is evident, for instance, how saline stratification in the well (MS) (Fig.25) with its marked lack of equilibrium, reflects a situation already classed as "dramatic" as regards the state of seawater contamination of the whole area where lized calcite /37/.

Analysis of the distribution of strontium in groundwaters also permits us to distinguish the more "active" parts of the hydrogeological system from the more "stagnant" parts.

Workers have also found significant correlations between strontium concentration and the values of the calcium-magnesium ratio (Fig. 30) in a coastal carbonate aquifer, with reference to the state of oversaturation or undersaturation of the groundwaters as regards calcite /80/.

Lithium, iodine, bromine and fluorine - like strontium - have also found useful application (Fig. 31), especially on problems concerning the mixing of waters of different origins /76/, even including inflows of juvenile waters in volcanic areas.

So far your attention has been drawn to modern aspects of traditional methodologies. Now we will pass on to applications of what may be classed as "advanced" methodologies, namely those that derive directly or indirectly from modern conquests in the fields of electronics, nuclear physics and most of the other disciplines.

The well-know developments in applied nuclear physics have provided the hydrogeologist with instruments that are, in some cases, extremely simple to use and which yield precious data with great rapidity. These methodologies can be grouped very schematically according to the kind of information they supply. Methodologies based on radioisotope probes or which can measure and classify environmental radioactivity by type, can be gathered in the first group, while the second embraces techniques based on the use of tracers, particularly of the radioactive variety, and the third takes in all the methods based on the measurement of environmental isotopes - radioactive or stable - present in nature and especially in groundwaters.

The study of the distribution of natural radioactivity in rocks (Fig. 32) is one of the best ways of determining porosity and particularly the degree of fracturing, as well as the presence of karstification and of terra rossa in carbonate rocks. As will be appreciated, these parameters are of immediate value in assessing the distribution of the degree of permeability of an aquifer /32, 42, 60/.

It is equally easy to obtain reliable profiles of the distribution of density of rocks penetrated by a borehole, by means of gamma-gamma logging (Fig. 33). The method most commonly used is that based on the principle of absorption and backscatter of a beam of gamma rays emitted from a source and received on their return by a detector. Source and detector can both be housed in the same probe, so measurements can be made by the single-well method /41, 42, 63/.

It is also possible to adopt a system based on the use of two separate probes one containing the source and the other the detector (Fig. 34), though in this case it is necessary to operate in two boreholes drilled very close together. As will be appreciated, the latter method can be used successfully only for shallow depths when for instance - it is necessary to ascertain the degree of compaction of beds close to the surface /58/.

Finally, on the subject of nuclear logging, mention must be made of the neutron-neutron-log (Fig.33-35) which can be used to ascertain the natural water content of soils. Thus we can ascertain porosity from the density obtained by means of the gamma-gamma log and the water content provided by the neutron-neutron log /17, 18, 42, 56, 62, 63/.

As you are aware, the neutron-neutron method is based on the thermalization and back-scattering of a beam of fast neutrons emitted from a source (such as Americium-Beryllium, for instance) and captured by a thermal neutron detector /52/. The energy of the neutrons emitted is attenuated by collision with hydrogen atoms. There are still some snags with this method or at least it involves making a series of corrections, for instance because of the variable presence of chlorine atoms or other

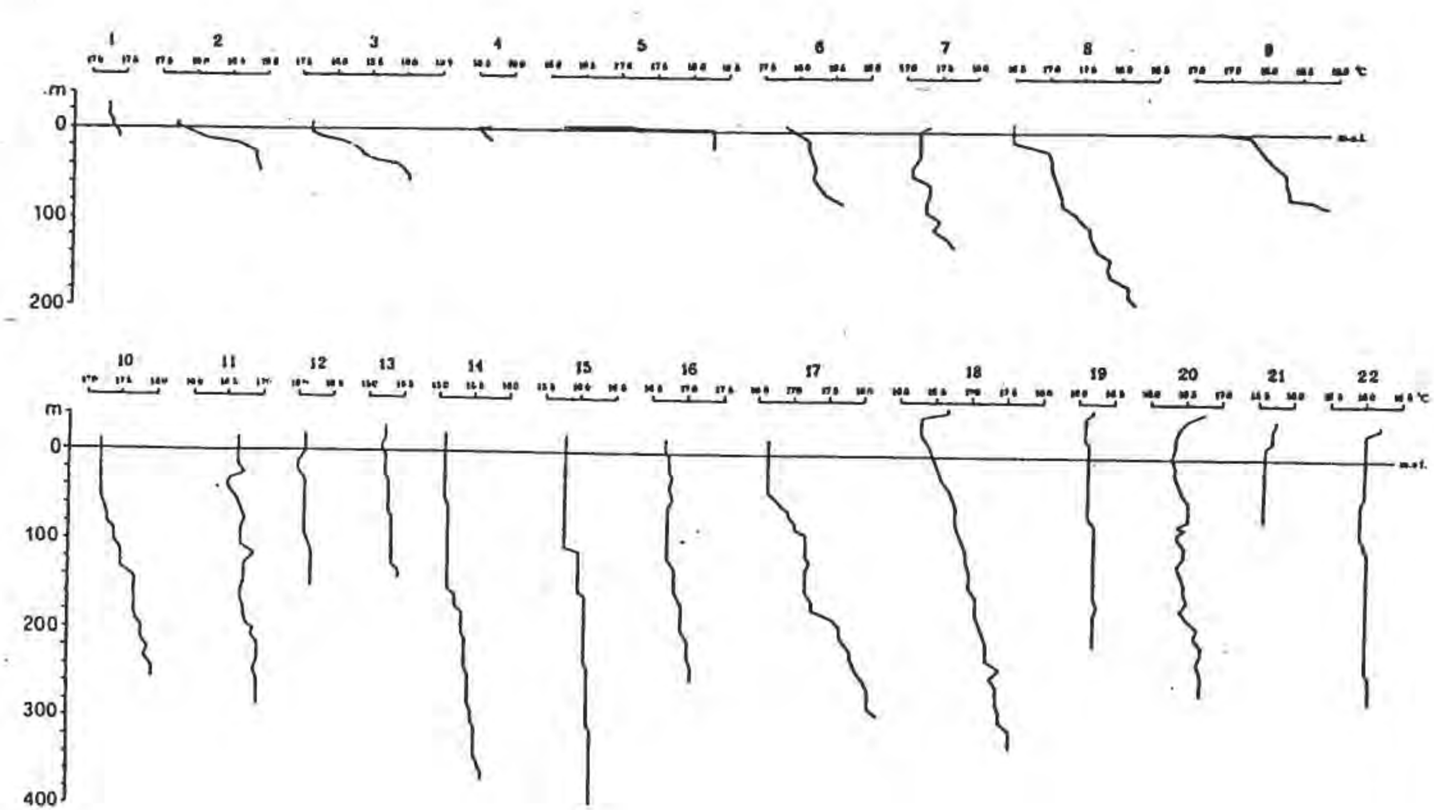

Fig. 18 - Water temperatures logged at various depths down boreholes located in the Murge Region (from Cotecchia et al., 1978).

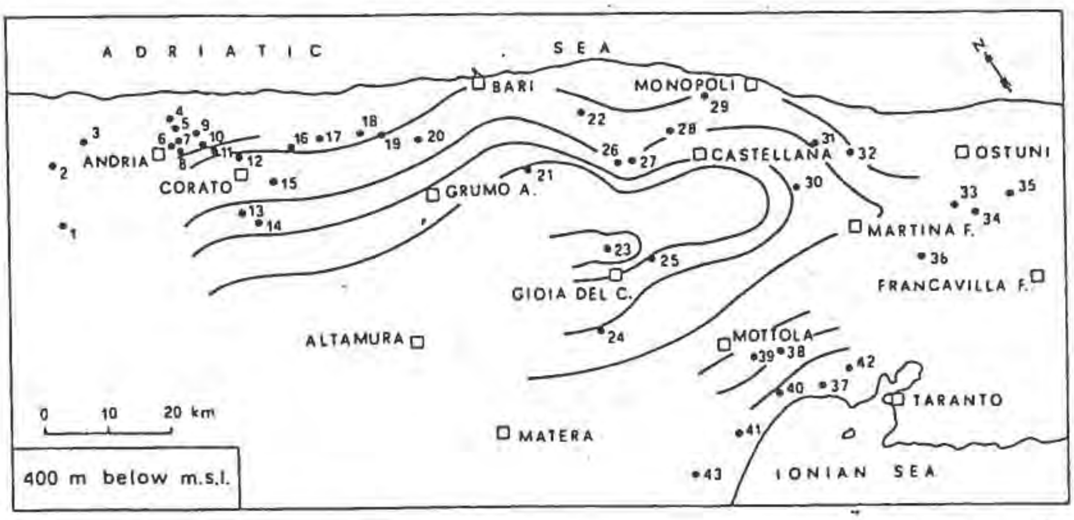

Fig. 19 - Horizontal distribution of water temperature 400 m below mean sea level (from Cotecchia et al., 1978).

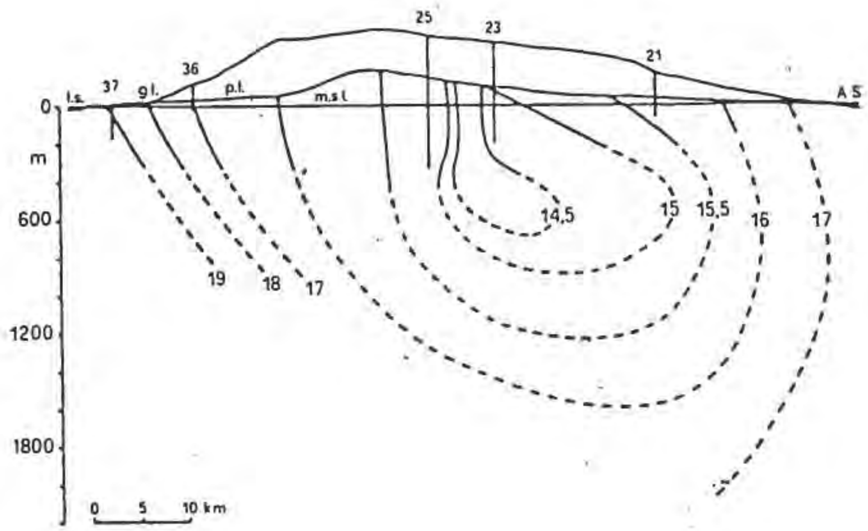

Fig. 20 - Trend of temperature with depth on significant vertical sections (from Cotecchia et al., 1978).

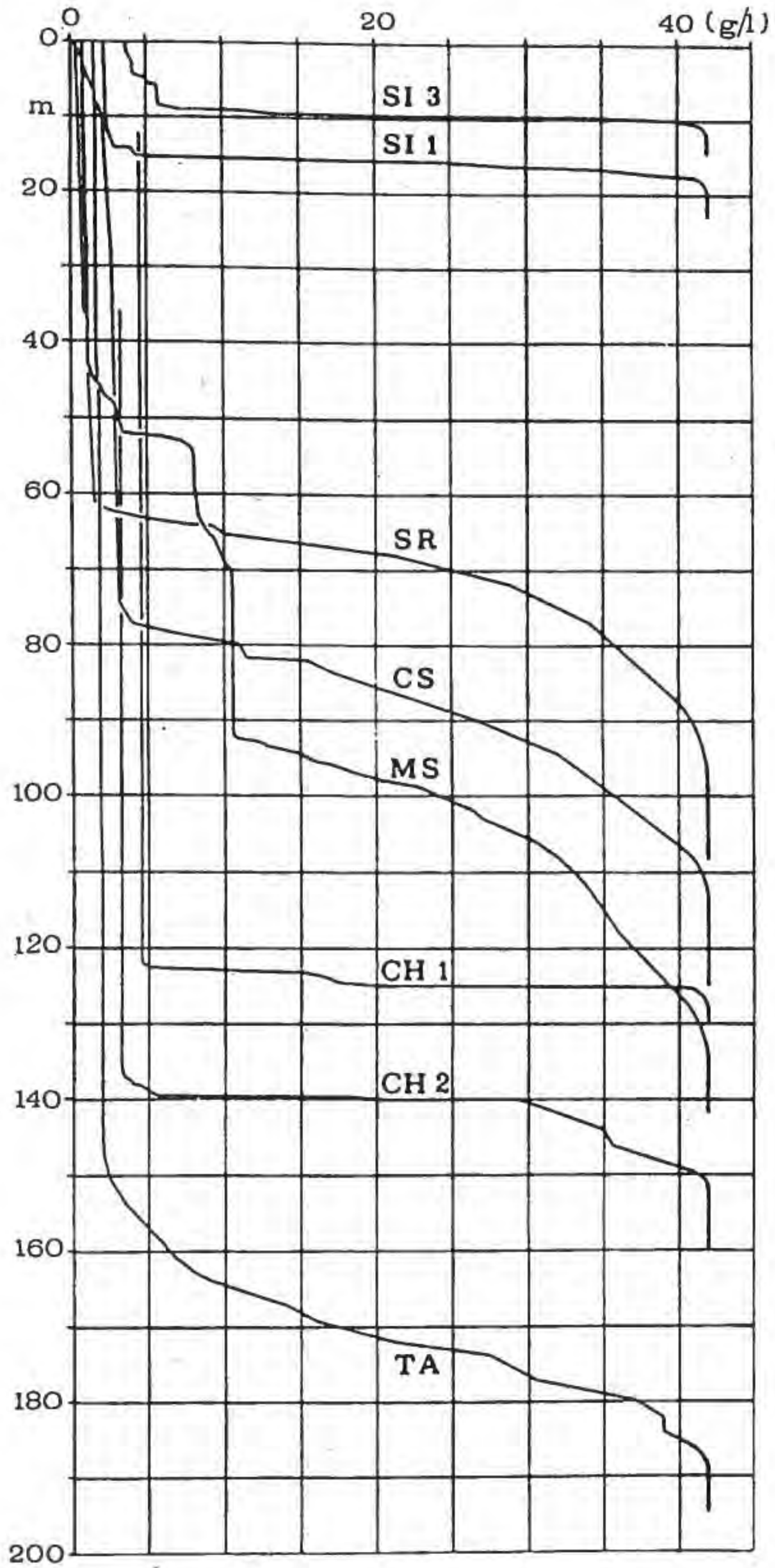

Fig. 21 - Trend of salinity with depth in observation wells drilled on the Salento Peninsula (from Cotecchia et al., 1974b).

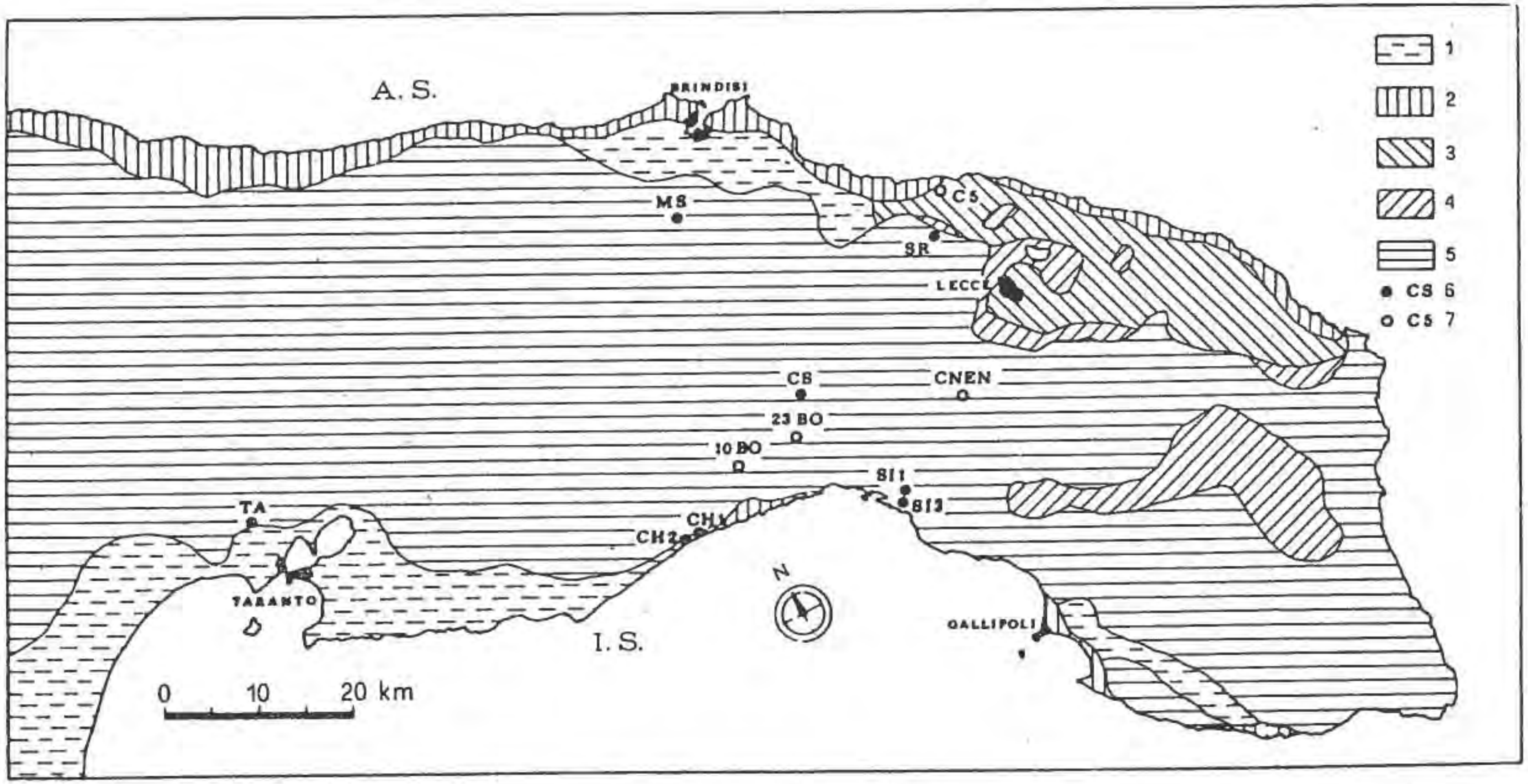

Fig. 22 - Horizontal geological section of the Salento Peninsula at sea level showing location of observation wells (from Cotecchia et al., 1974b).

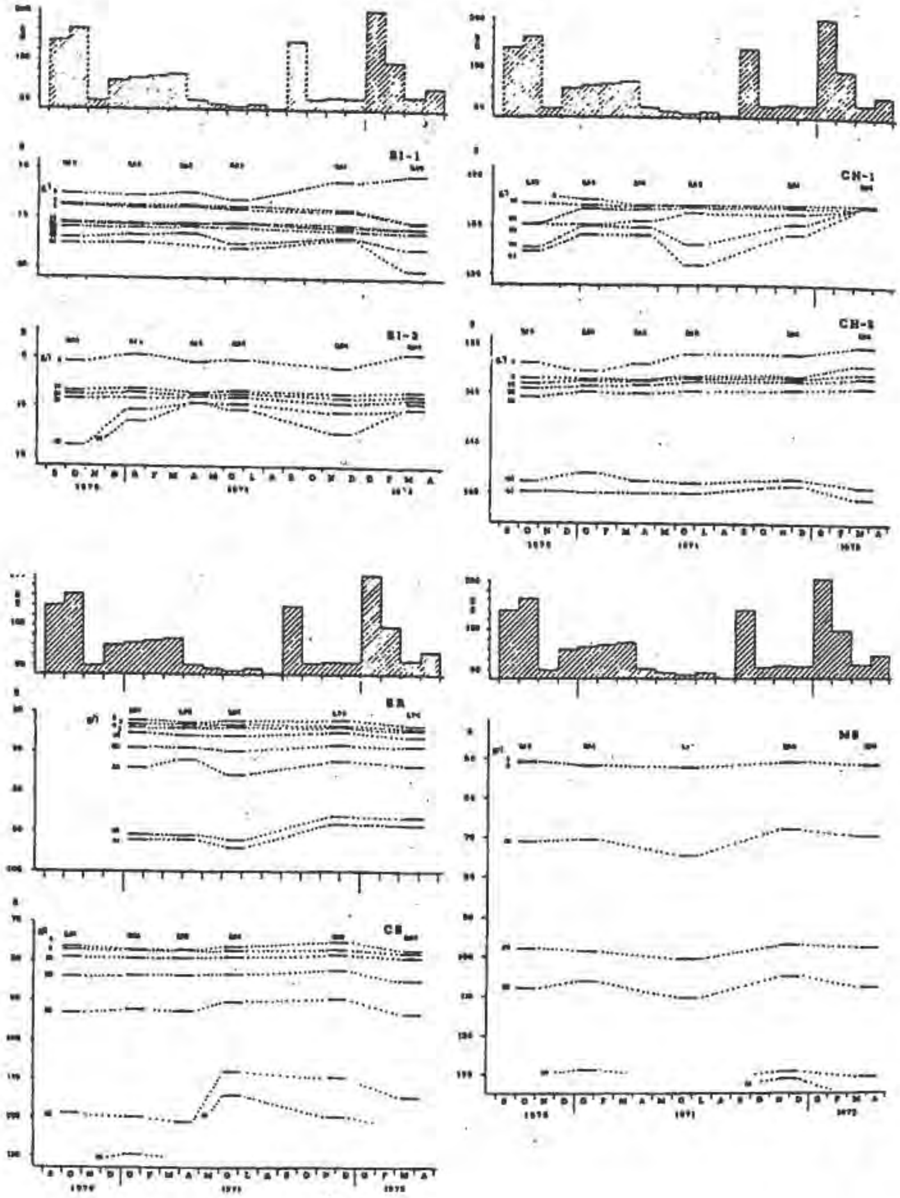

Fig. 23 - Variation of diffusion zone with time in a number of observation wells, total monthly rainfall indicated at top (from Cotecchia et al., 1974b).

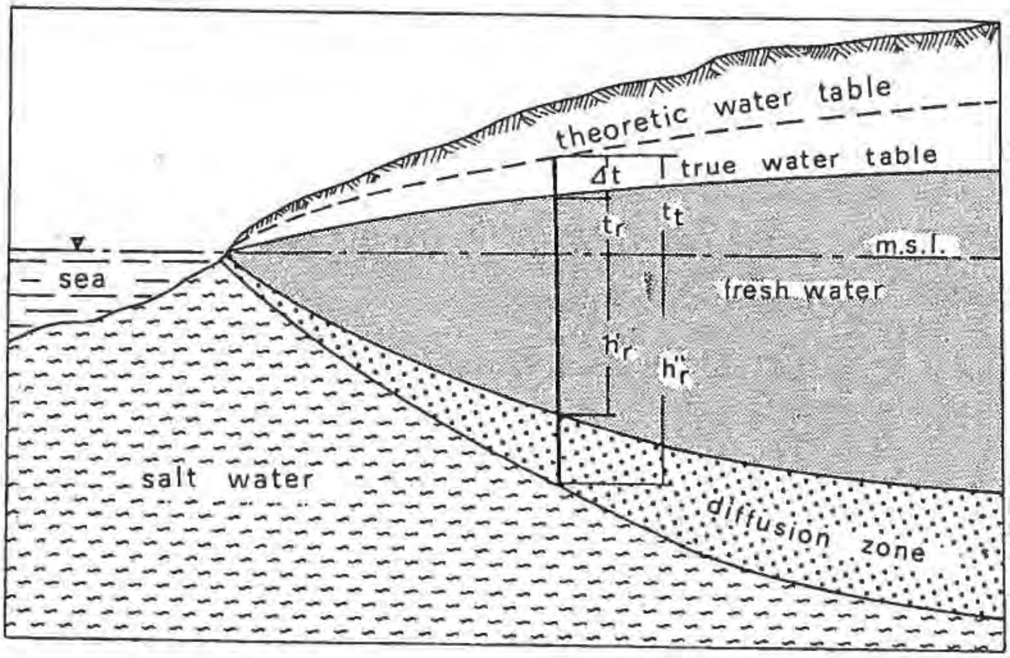

Fig. 24 - Schematic representation of the dynamic equilibrium of fresh ground water floating on encroaching seawater, compared with the theoretical state of static equilibrium (from Tadolini and Tulipano, 1977b).

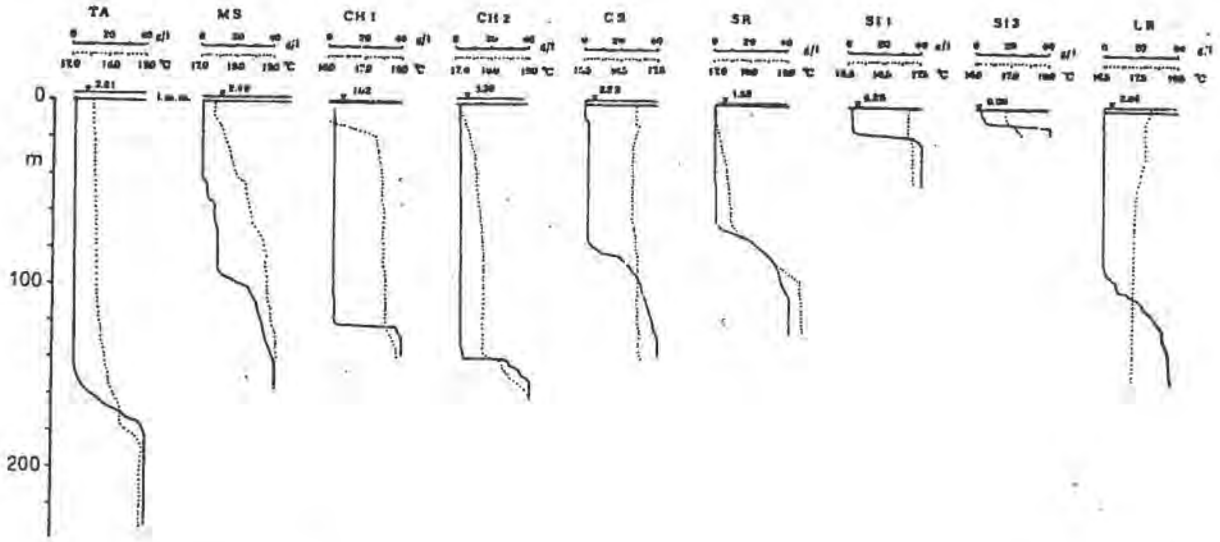

Fig. 25 - Salinity and water temperature trends in observation wells (from Tadolini and Tulipano, 1977b).

the borehole is located (Fig. 26).

Another method based on salinity measurements is that concerning the identification of referential vertical flowpaths in a fissured, karst aquifer. This can be used when making normal discharge tests in drilled wells, if we first ascertain the line stratification that exists in the unpumped well and compare this with the salinity trend of the waters extracted by pumping /77/.

The diagram in fig. 27 summarizes the method which can also be usefully employed to study how salinization occurs as a result of pumping.

The study of the chemical composition of waters is also of great help in understanding certain hydrogeological situations. Quite apart from providing information on water quality, this type of study can contribute significantly to our better comprehension of phenomena connected with such processes as recharge, groundwater flow, soil-water interaction, communication between lithologically dissimilar aquifers, etc.

Anyway we cannot really attempt to make a rapid survey that could be in any way representative of the cases where water chemistry has resolved difficult problems or at least been a great help in solving them.

Chemical methods have been very useful in clarifying problems concerning the quantification of annual recharge of the Apulian aquifer. The approach adopted was that of making detailed analysis of the temporal trend of concentrations of a number of key ions measured both in rainfall and in dry fallout, duly classified and considered according to their mainly marine or continental origin (Fig. 28).

Comparison of these data with the chemical profile obtained of the groundwaters provided a picture of the typical chemical composition for the recharge waters (Fig. 29), namely those which carry into the aquifer not only their own salts but also those deposited on the ground as a result of the evaporation of rains received during non-recharge periods and those deriving from dry fallout in general /22/.

Using this approach, combined with other investigations of a very decidedly hydrogeological nature performed on natural models selected precisely because they were so representative, it has been possible to establish that the Apulian coastal carbonate aquifer receives as annual recharge some 60% of the rain that falls in the six-month autumn-winter period /21/.

Studies of this kind can be profitably supported and improved by chemical analysis of dry fallout and by the study of the presence of minor constituents and trace elements in the groundwaters and recharge waters, which is the trend currently favoured. Even today these constituents are still considered especially from the aspect of values that are anomalous in comparison with natural levels, which are the result of a balance between geochemical presence in the rock and the various rock-water chemical interaction processes that control the equilibrium.

The possibility of using these constituents as natural tracers became apparent when it was found, for instance, that the strontium ion (Sr^{++}) and the fluorine ion (F^-) could be utilized as sensitive indicators for following the mineralization of groundwaters caused by the action of metal carbonates /28/. Other investigations have revealed that potassium (K^+) and strontium (Sr^{++}) are efficient natural tracers for quantifying recharge of aquifers in the Thames Valley from river waters /29/.

In particular, the study of strontium in groundwaters has found many applications in problems concerning the onset and development of karst phenomena in carbonate aquifers.

Here we can mention studies of the interaction between groundwaters and aragonitic carbonate sediments where it has been possible to estimate the efficiency of the dissolution and reprecipitation process by comparison of the strontium-calcium ratio of the groundwaters, of the aragonitic carbonates and of the recrystal-

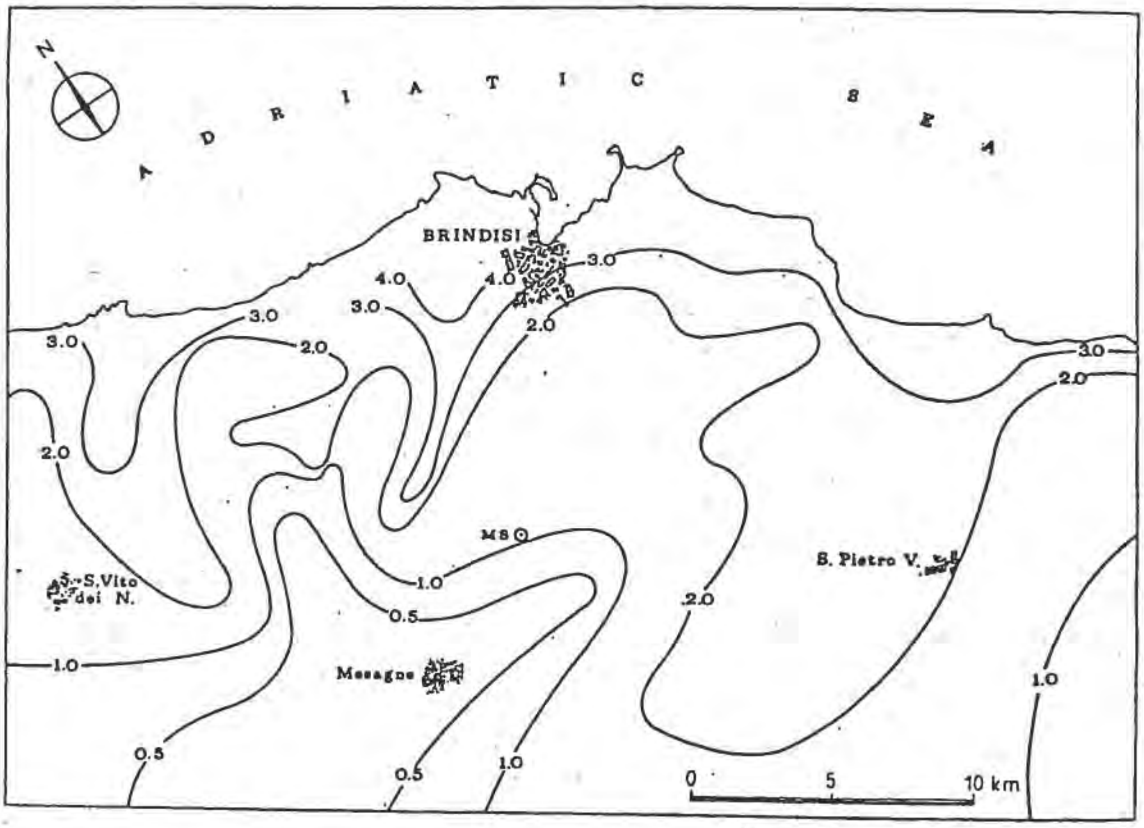

Fig. 26 - Salt content distribution on the water-table in the Brindisi area (from Tadolini and Tulipano, 1977b).

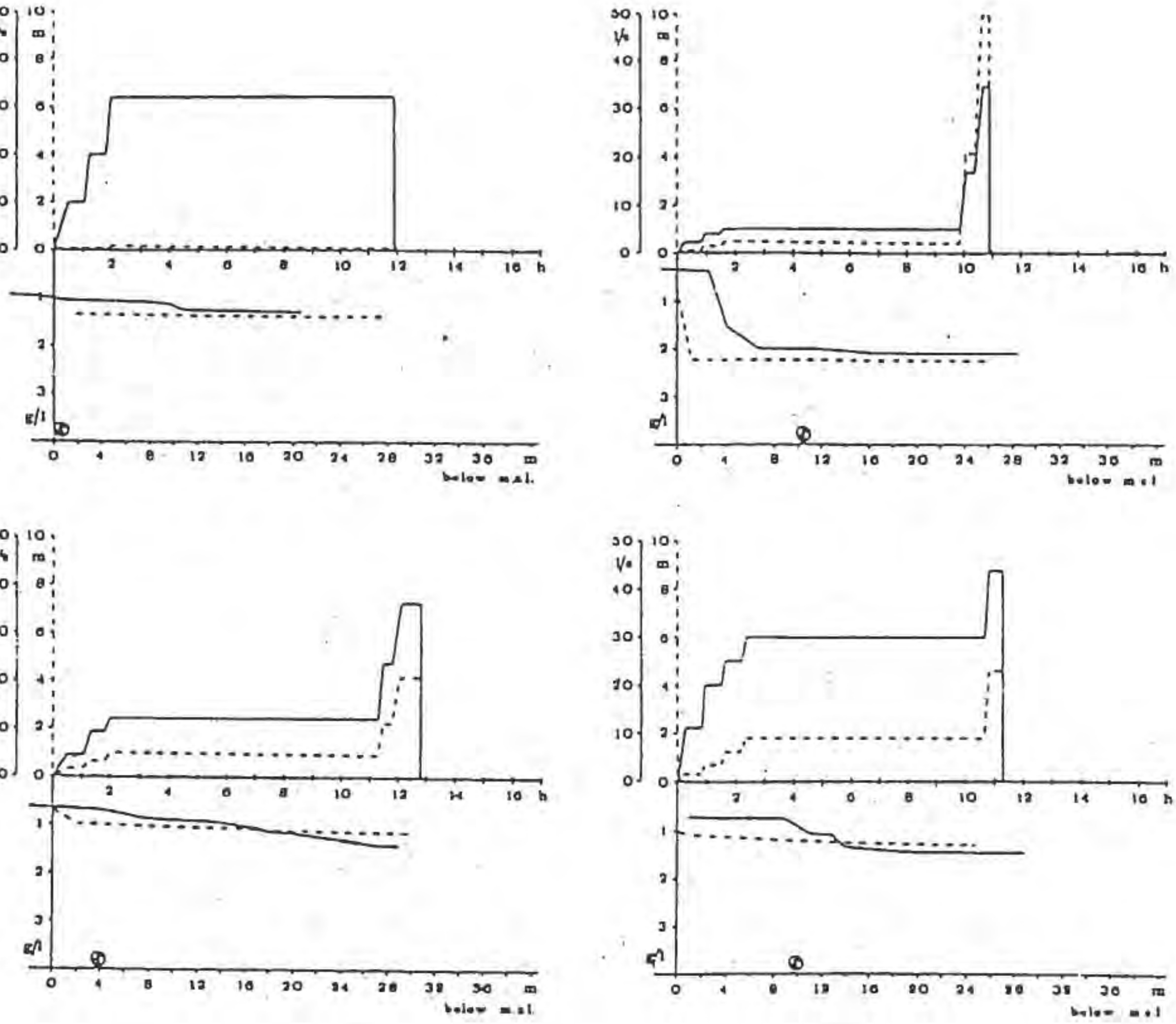

Fig. 27 - Discharge and drawdown vs. time (continuous line and broken line in the upper part of the diagrams); saline stratification (continuous line in the lower diagram plotted against the depth scale), and salinity trend of pumped waters (broken line in the lower diagram plotted against the time scale); suction level of pump is marked on the depth scale (from Tadolini and Tulipano, 1977a).

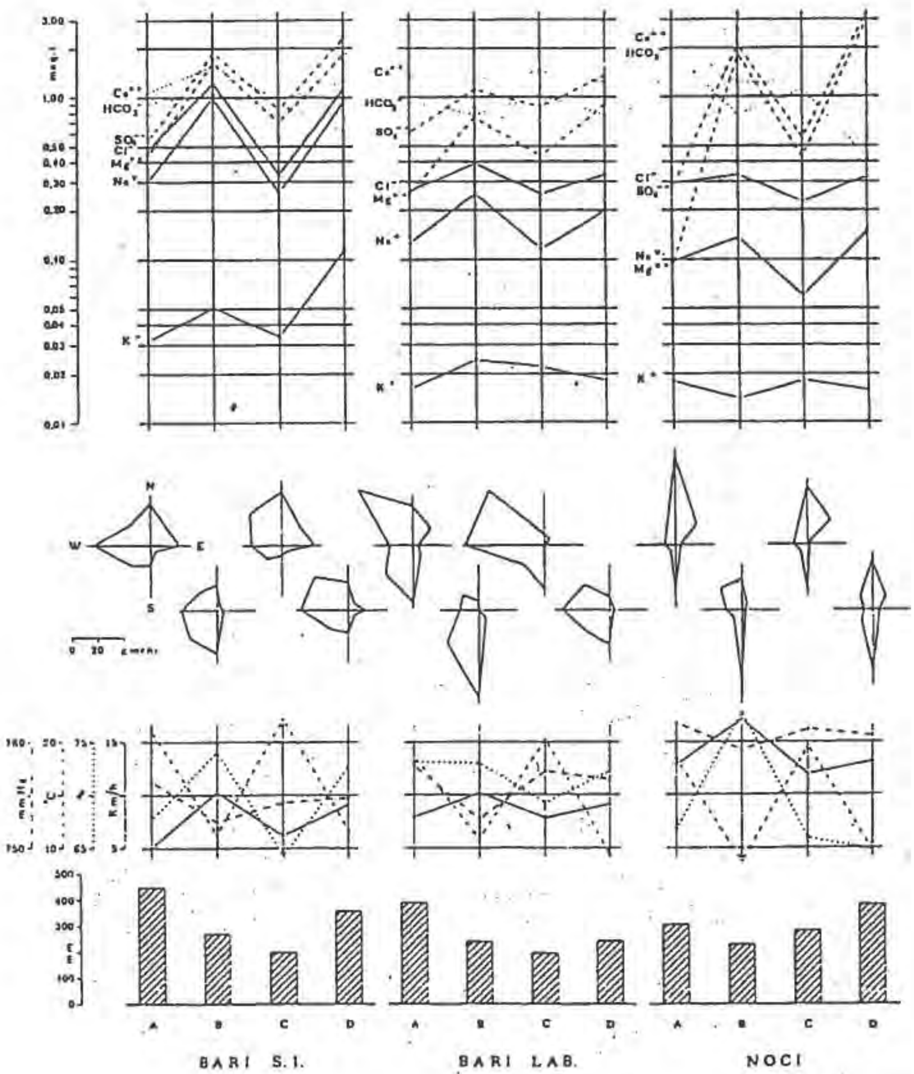

Fig. 28 - Diagrams showing relations between atmospheric parameters expressed as six-monthly averages and the average six-monthly ionic concentrations of dry fallout during the sampling period (from Cotecchia et al., 1973b).

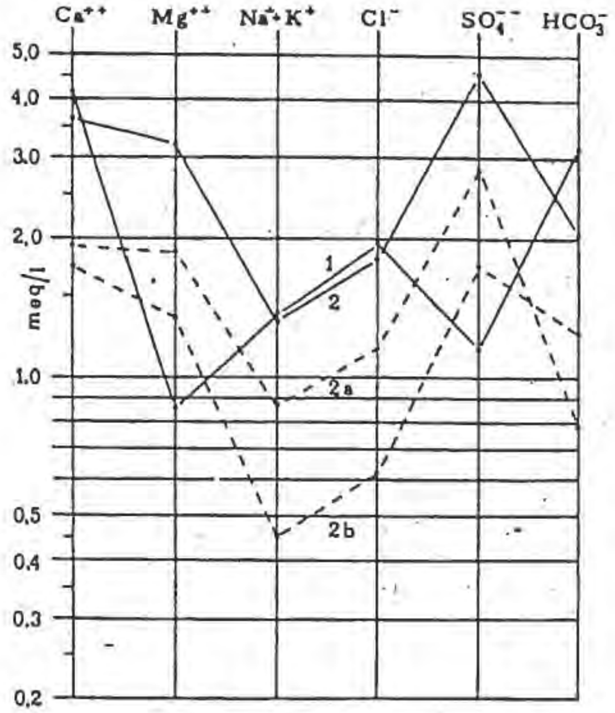

Fig. 29 - Semilog diagram showing average chemical composition of spring waters uncontaminated by intruding seawaters (1) and of recharge waters (2), obtained by summing rainfall (2a) and dry fallout (2b) contributions (from Cotecchia et al., 1973b).

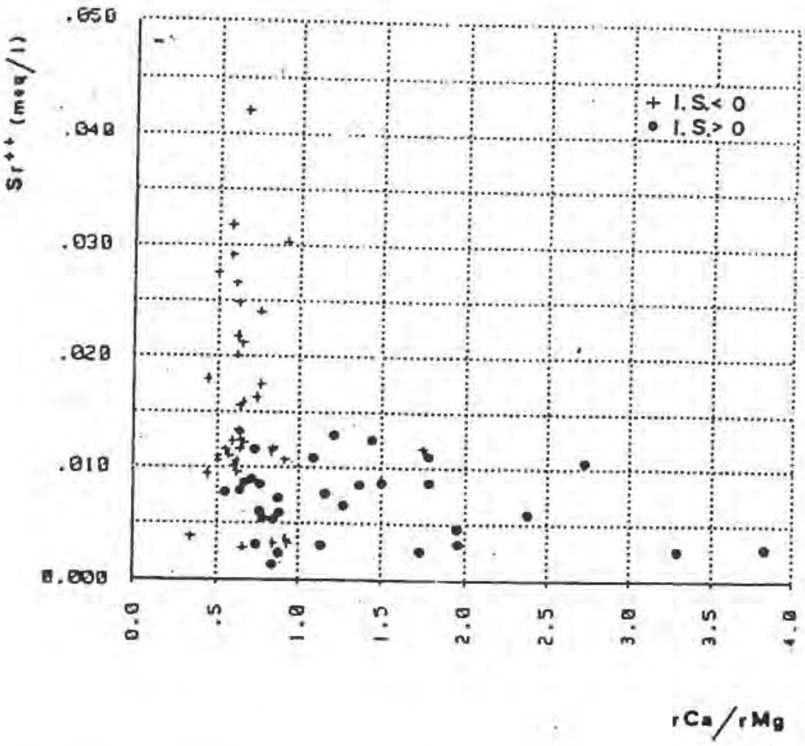

Fig. 30 - Relationship between Sr^{++} concentration and values of the Ca^{++}/Mg^{++} ratio in a coastal carbonate aquifer with reference to the classification of waters in terms of oversaturation or undersaturation as regards calcite (from Tadolini et al., 1982).

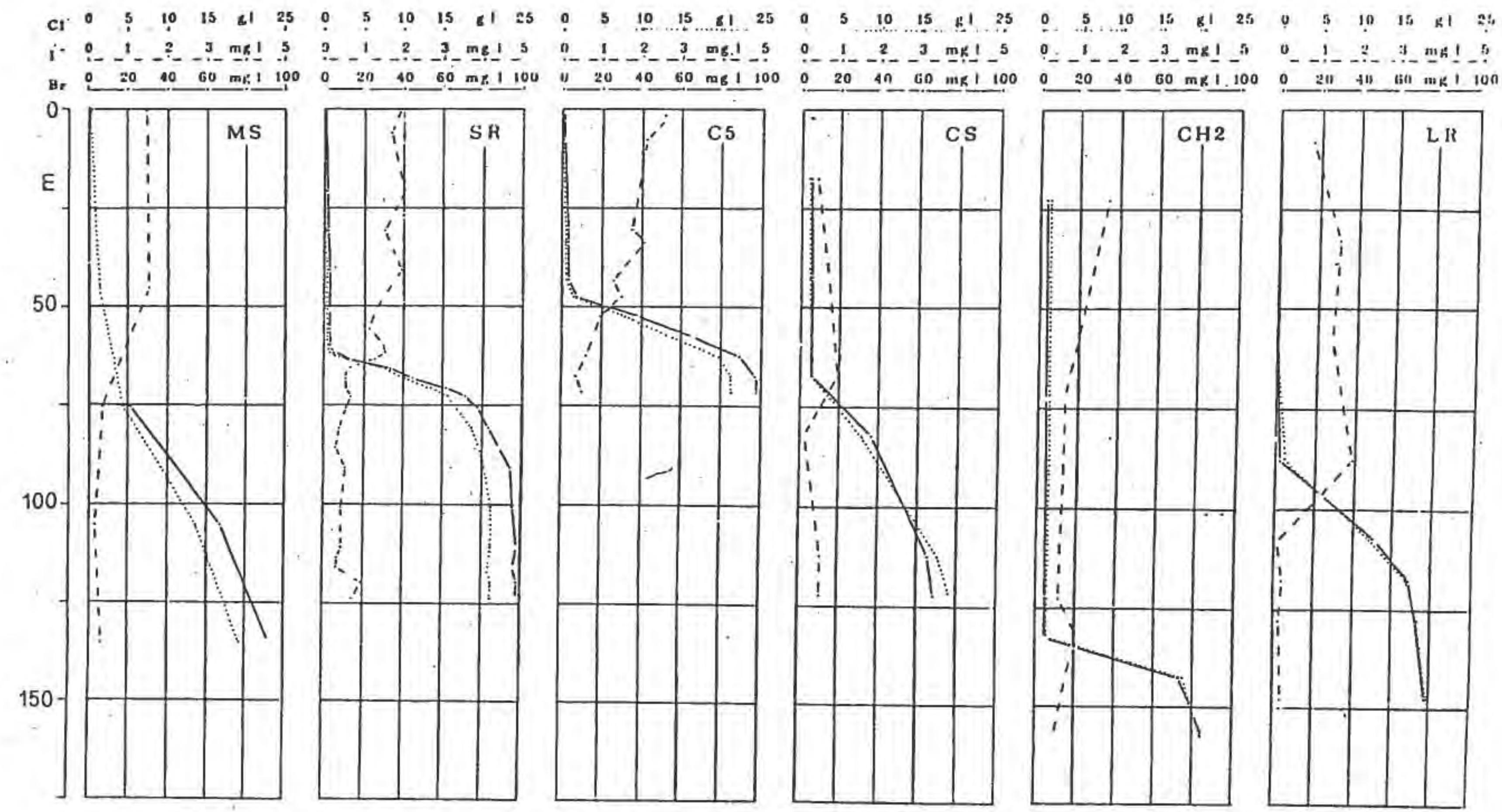

Fig. 31 - Distribution of chlorine, bromine and iodine contents at various depths in observation wells located in a coastal aquifer (from Tadolini and Tulipano, 1975).

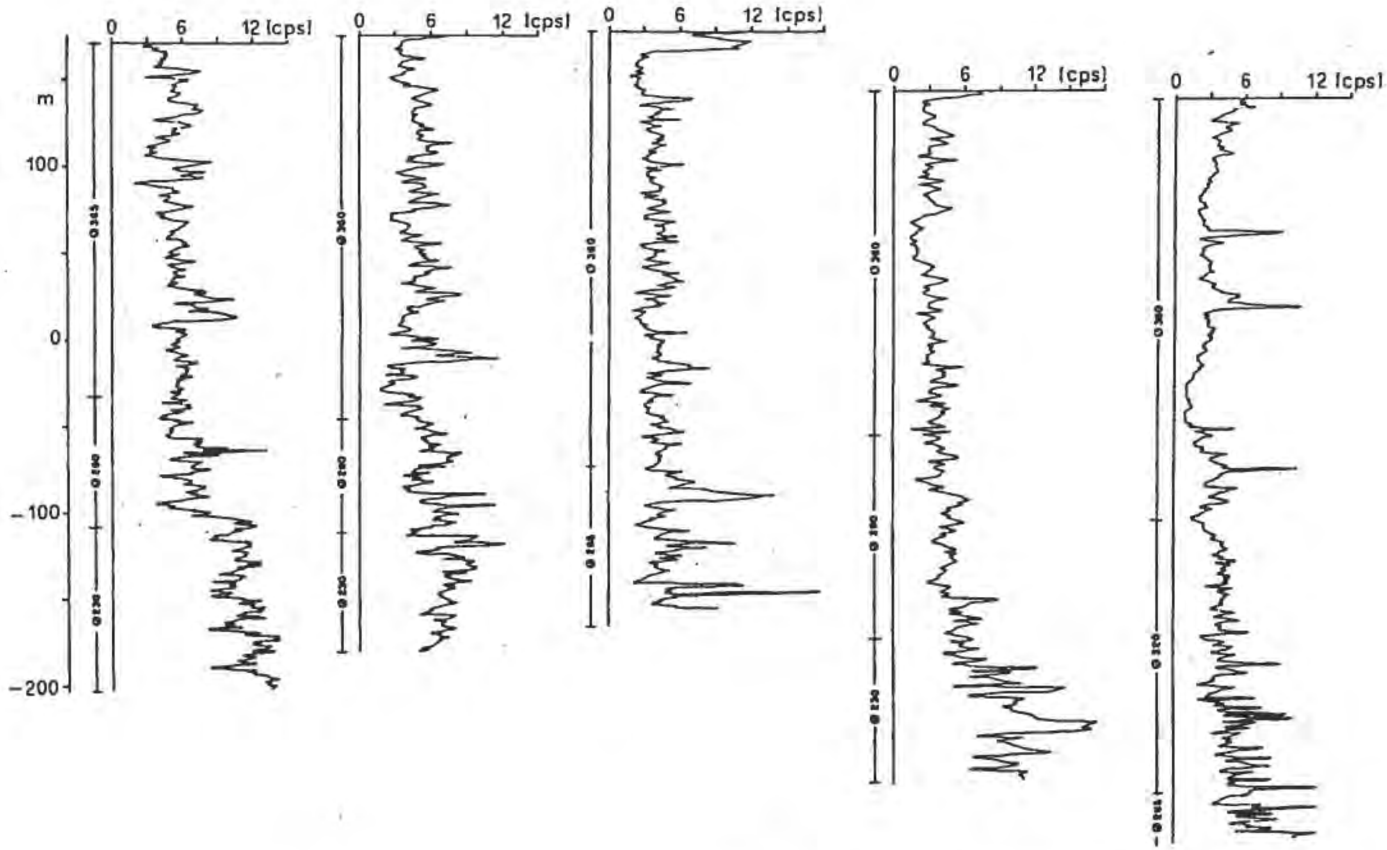

Fig. 32 - Natural gamma radioactivity logs of the carbonate rocks of the Murge (from Grassi et al., 1977).

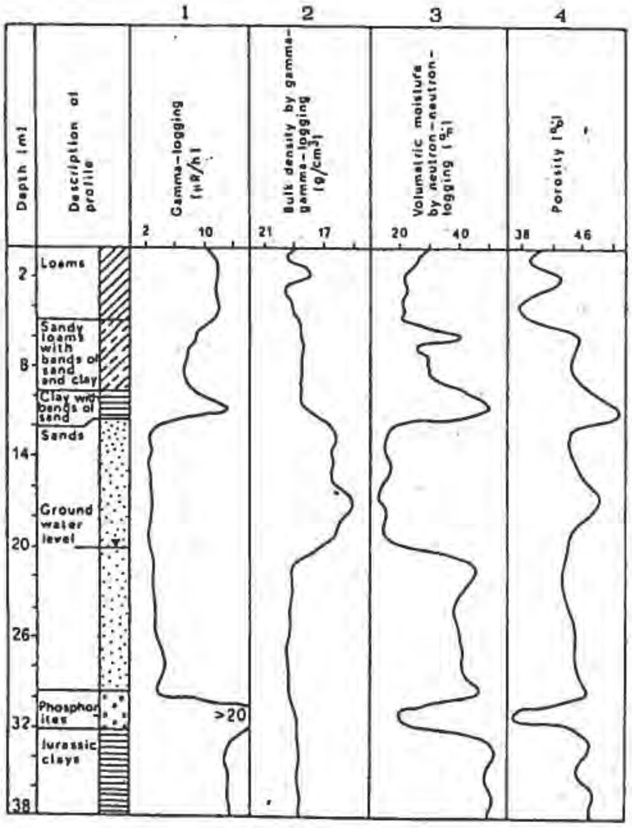

Fig. 33 – Nuclear logging (γ, γ-γ, neutron-neutron) of a well drilled in unconsolidated rocks and calculated porosity values (from IAEA, 1971).

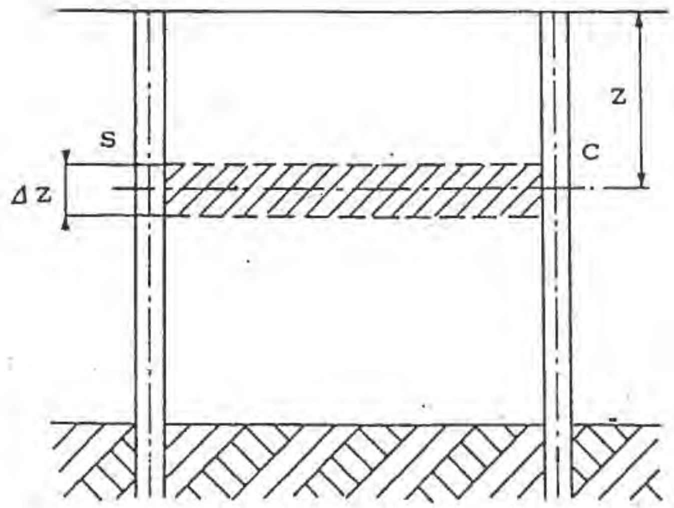

Fig. 34 – Density measurement by the double probe method (from Morel et al., 1974).

elements with a large capture cross-section that interact with the neutrons. Attemps have been made to improve the method, mostly based on the possibility of capturing only epithermal neutrons that can be detected by suitable helium or boron trifluoride counters.

A more direct hydrogeological application of techniques based on the use of radioisotope probes provides reliable information on evaporation and evapotranspiration. In some particular hydrogeological situations, it should be recalled that the equilibrium of an aquifer depends almost exclusively on recharge being balanced by evaporation and/or evapotranspiration, especially in arid climates where some aquifers lose their water solely through such processes. One of the main objectives that can be attained by the application of nuclear techniques in the determination of the depth beyond which losses no longer occur in this manner. The depth in question varies with climate, lithology of the soils, type of vegetal cover, permeability,etc.

Another application of nuclear techniques concerns the possibility of recognizing and quantifying particular constituent elements of rocks down boreholes by neutron activation probes (Fig. 36), /3/.

As far as artificial tracers are concerned, their application on hydrogeological problems involving knowledge of such parameters relating to flow paths and flow velocities are well known. The range of tracers available nowadays is quite vast, including chemical products, dyes, bacteria, spores and radioactive substances.

Every tracer has its advantages and disadvantages. Chemical tracers have the advantage of the large choice available. However, they may interact with the waters or with the rocks and they may possibly be toxic. Then again they are often difficult to detect in the field because, with the dilution involved, chemical analysis is needed to measure them /40/.

Easier to use, from this point of view, are the fluorescent dyes, the commonest of which are rhodamine WT, lyssamine FF, aminoacid G and fluorescein, which can be detected by portable fluorimeters at concentrations as low as $10^{-2} - 10^{-4}$ mg/l /30, 69/. Dyes have been extensively studied in an attempt to solve the problems of their absorption by suspended sediments and rocks, their interaction with water, their photo chemical and biological breakdown and their toxicity where man and aquatic organisms are concerned /71/. Nevertheless, the main complication involved in using dyes remains that of having to perform an intensive sampling campaign when working in wells.

Spores and bacteria are little used in hydrogeology, being suitable for only a few specific problems. Moreover they are not all that easy to detect /1, 54/.

Of the various tracers available, those which find greatest application and which are most widely used nowadays are the radioactive substances, which can be schematically divided into beta-emitting isotopes and gamma-emitting isotopes. Since they can be detected immediately, these tracers are extremely practical to use. Apart from this, it should be recalled that the indiscriminate use of tritium as the beta tracer - which was certainly preferred in the past since it is a constituent of the water molecule - has been found to be deleterious when tritium also has to be employed as an environmental tracer /72/.

With gamma tracers there exists a vast range of choice. One of the most important principles guiding the research worker in his choice of radioactive tracer is the half-life and the energy emitted, this being important as regards preventing contamination of the environment. The most commonly used are bromium-82, which has a half-life of 32.4 hours and is well suited to short experiments involving fast-flowing groundwaters, iodine-131 characterized by a half-life of 8 days and iodine-125 with a half-life of 60.2 days /88, 89/. By means of these tracers, flow velocity, flow direction and vertical currents can be measured in boreholes /35/.

The commonest way of measuring the velocity of groundwater flow is the single-

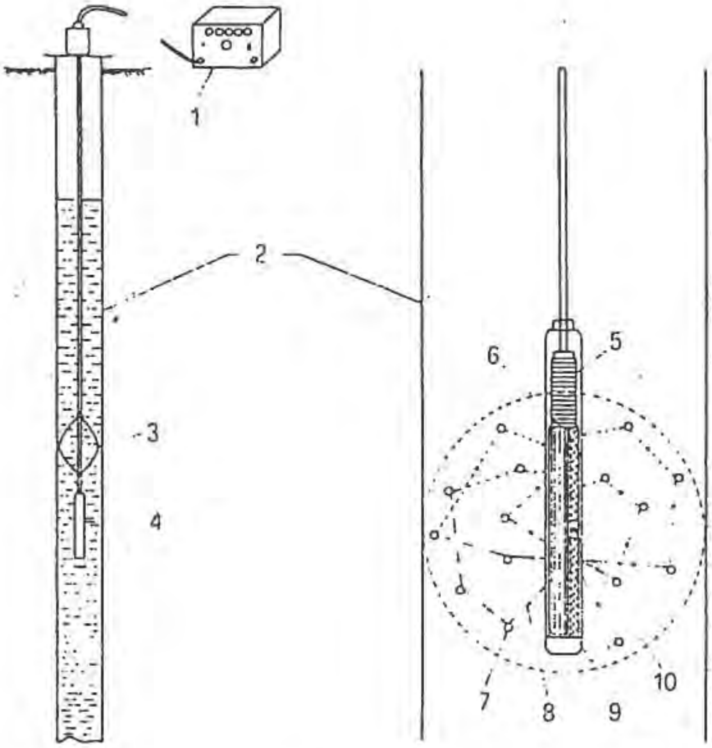

Fig. 35 - Arrangement of neutron-probe in borehole, diagram of neutron showdown and scatterring. (1: scaler; 2: perforated casing; 3: centring device; 4: probe; 5: pulse preamplifier; 6: counter; 7: atoms; 8: neutrons; 9: lead shield; 10: Am-Be source) (from Magri and Pirastru, 1968).

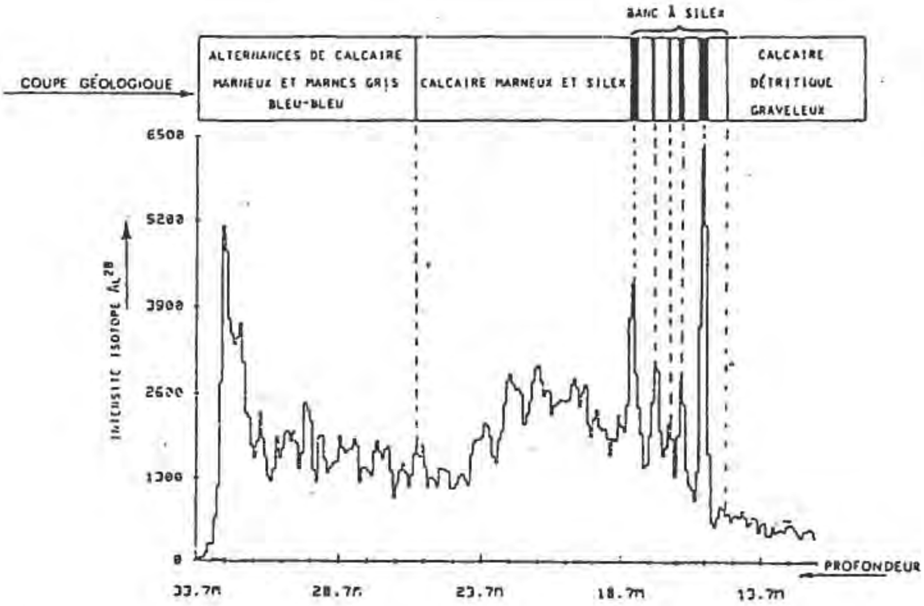

Fig. 36 - Identification of silicon at depth by neutron activation (from Baron, 1982).

well method, based on the measurement of the dilution of the tracer by the water passing through the treated section of the well (Fig. 37). /36/. These measurements, of course, also provide useful indications on aquifer permeabil ity and transmissivity /89/.

Measurement of flow direction can be performed in a single well by a variety of devices (Fig. 38) which all reveal the direction in which the tracer is drawn out of the treated section of the water well.

Measurement of vertical currents is significant in those cases where a borehole brings different aquifers or levels of preferential flow in one aquifer into communication with each other (Fig. 39). It is also suitable for quantifying the hydraulic head of one groundwater body or of one preferential water level compared with the others.

The measurement of flow velocities and vertical currents can also be performed using as tracers certain salts containing ions having a large capture-section for thermal neutrons, the concentrations of which can be determined in situ by means of neutron probes. Ideal for this purpose are cadmium chloride and sulphate and sodium metaborate.

There have been profound changes in the study of groundwaters in recent decades, especially with the introduction of new analytical techniques developed for environmental isotopes. However, these isotope techniques involve capital and running coasts that are far higher than those for conventional analytical techniques used in hydrogeology. They also call for highly qualified personnel. These factors have certainly retarded the introduction of such techniques in normal laboratory routines.

Fig. 40 shows a brief outline of the main fields of application of environmental isotopes. Some isotopes, such as tritium, carbon-14, oxygen-18, deuterium and carbon-13 have been used in numerous applications, so their advantages and disadvantages can be thoroughly assessed. Applications of the other isotopes are not so common, and some of them have been proposed only quite recently.

The measurement of tritium expanded enormously with the explosion of nuclear bombs which raised the level of tritium from its natural average value of 4-25 Tritium Units to as high as 6000 TU in 1963. Fig. 41 shows the trend of tritium concentrations in precipitation in the northern hemisphere, the tropics and the southern hemisphere /33/.

It is evident from the data available on tritium concentration in precipitation that the input at the earth's surface varies considerably in space and time. This accounts for the variability of the levels of tritium recharge in groundwaters. It should be noted that data on tritium may be difficult to interpret because of a series of phenomena which may intervene during the travels of the groundwaters: one major factor, for instance, is the effect of variability of percolation in the unsaturated zone, which may lead to the pulsed mixing of recharge attributable to various periods. As a result, unless recharge conditions are particularly favourable, tritium cannot furnish meaningful data on the exact age of the water and the route it has taken. The only thing certain is that concentrations in excess of 4 T.U. mark the contribution of recent recharge (post 1952), while the absence of tritium indicates water whose age is greater than 20 to 50 years. But even this limited information is important. The simple proof of the existence of recent recharge is essential for the evaluation of the real availability of groundwater resources, especially in regions where rainfall is low and seasonal rainfall does not markedly exceed evapotranspiration.

During the sixties, carbon-14 came to be used for dating waters. The majority of carbon-14 in groundwaters is of biogenic origin (Fig. 42). Numerous complicating factors have an influence on this method of dating, however. For instance, there is the carbon-14 released into the atmosphere from nuclear tests, and there is also isotope exchange between the rock matrix and the waters (in the quite frequent case of

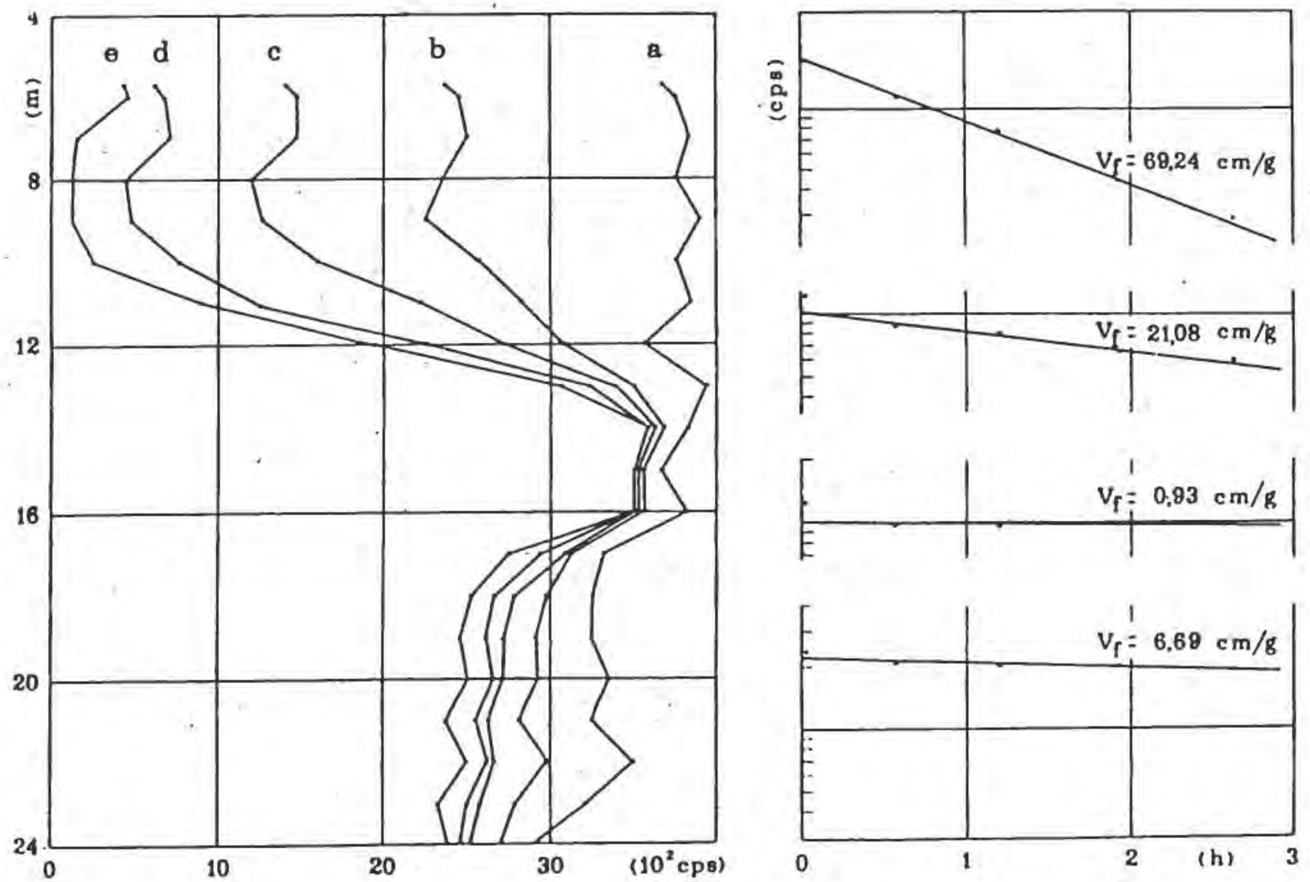

Fig. 37 - Measurement of velocity of groundwater flow by the single-well method (from Tazioli, 1973).

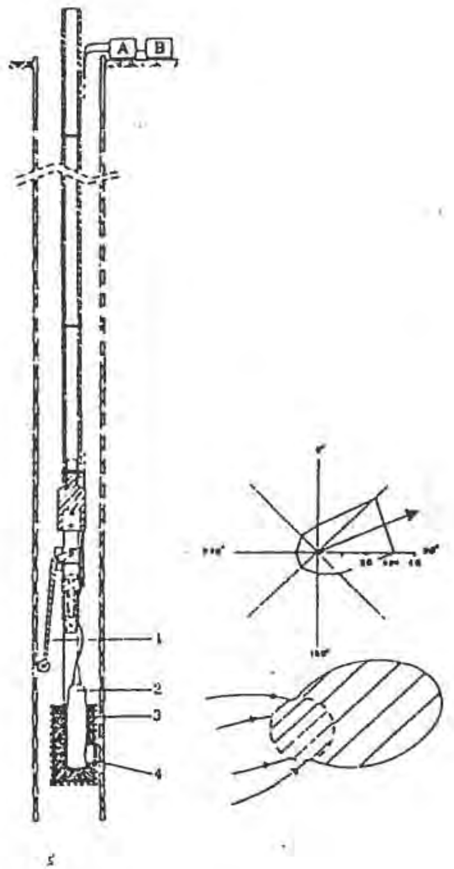

Fig. 38 - Arrangement for measuring direction of groundwater flow using collimated probe (from Tazioli, 1977).

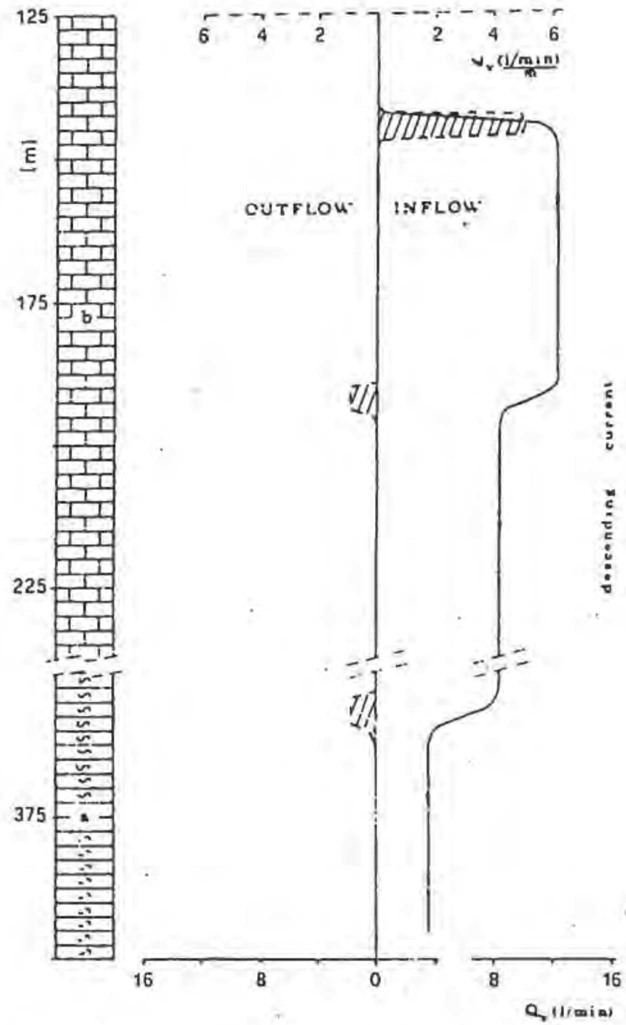

Fig. 39 - Descending vertical current in a borehole drilled in the Murge aquifer (from Tazioli, 1977).

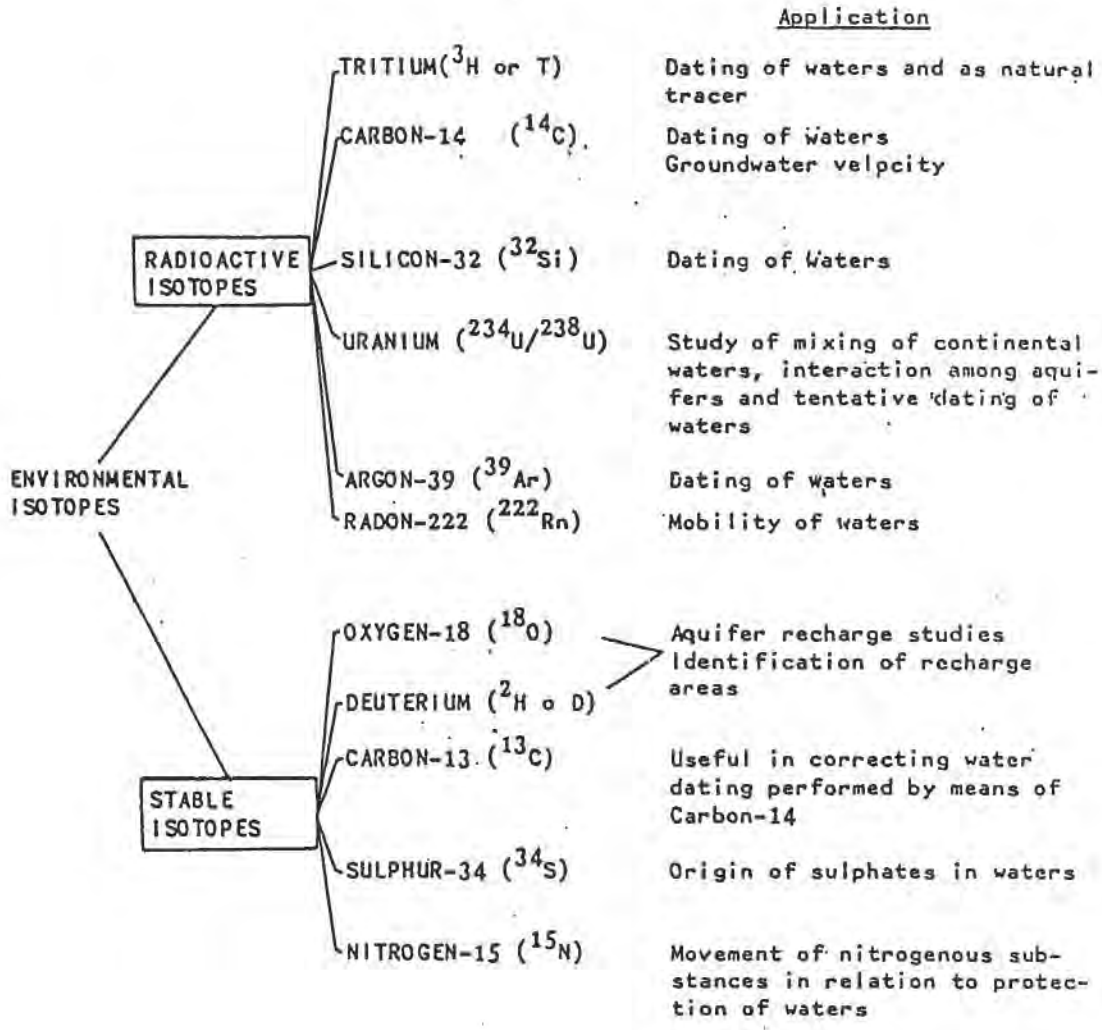

Fig. 40 - Application of environmental isotopes in hydrogeological investigations

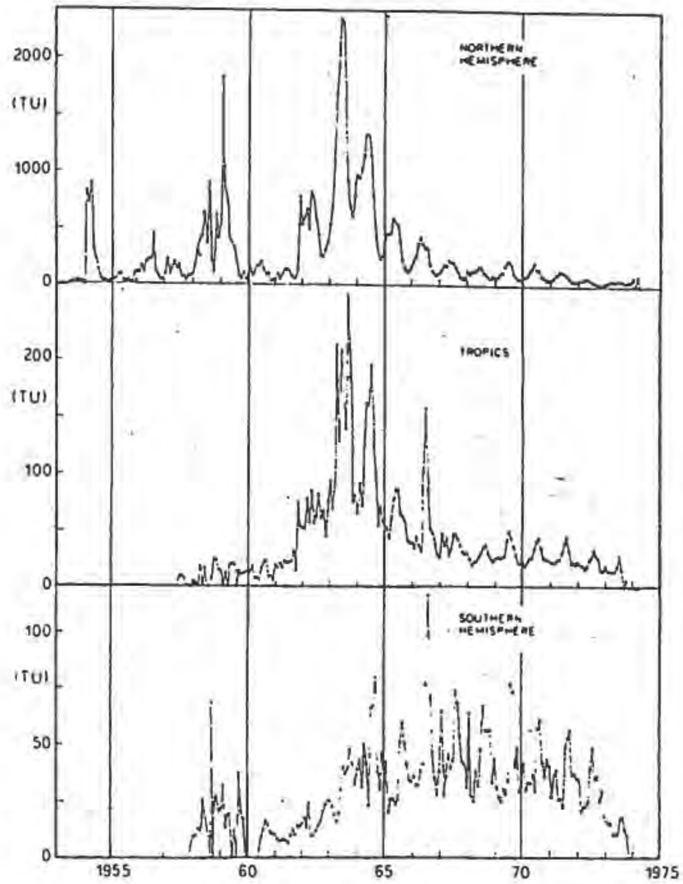

Fig. 41 -

Average tritium concentration in precipitation in the northern hemisphere, tropical stations and the southern hemisphere, based on records of the IAEA network (from Groenveld, 1977).

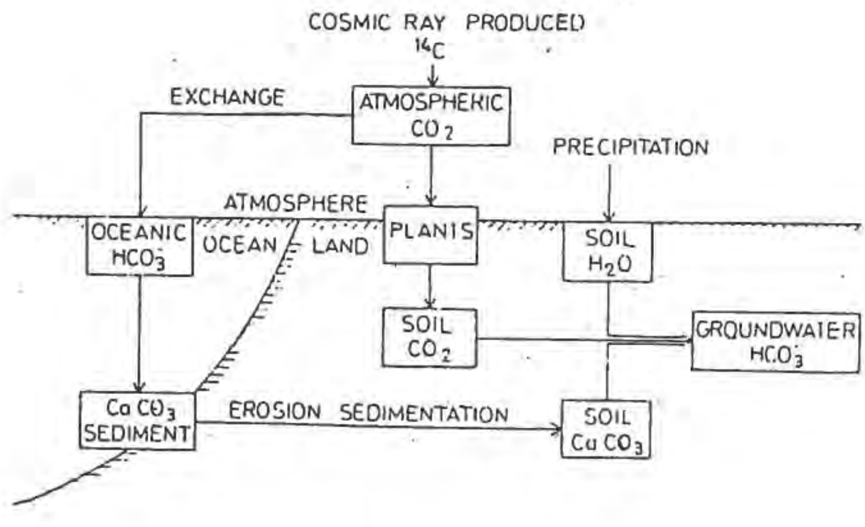

Fig. 42 - A part of the natural carbon cycle, as far as relevant to the origin of carbon-14 in groundwater

carbonate aquifers), and the presence of other nonmineral sources, which provide dissolved carbon of nonbiogenic origin.

If waters are not subject to complicated mixing, the total carbonate content and the carbon-13 values can be used to estimate the amount of diluting carbonates and to identify the source of these. But the methods proposed by various authors for correcting the results by reference to carbon-13 are not universally applicable.

Measurement of argon-39 offers a new possibility of dating waters /61/. This isotope has a half-life of 269 years and can be used to date waters in the 50 to 1000 year range, thus filling the gap between the times accessible with hydrogen-3 and carbon-14.

Being a noble gas, argon-39 exhibits very simple geochemical behaviour. During its average life of 390 years there exists only one well mixed reservoir, the atmosphere. Because argon-39 has a long half-life, compared with the atmospheric mixing times, it is uniformly mixed with atmospheric argon. The behaviour of argon-39 and argon in water is also simple, there being no interaction with the aquifer. Another factor is that no or virtually increase of argon-39 has been noted as a result of explosion of nuclear bombs or of nuclear reactors. As the artificial production of this element is so low, it is possible to assume a constant concentration as an input in computer models for argon-39 dating.

Figure 43 shows the calculated deviations of atmospheric argon-39 activity from the average level of activity over the last 1000 years. It is based on the variations in the carbon-14/carbon-12 ratio, due to the relative variations in the rate of production of carbon-14, considered to hold good for argon as well. As is evident, the deviations of the argon-39/argon ratio may reach 7% at most, which corresponds to a maximum dating error of about 30 years. This degree of approximation is not very significant when we consider the general uncertainties attaching to the dating of waters in the 50 to 1000 year range.

By and large, measurements of argon-39 permit determination of groundwater age in a way similar to those used for other isotopes. However, from the practical point of view it should be observed that with the existing technology, at least 20 tons of water have to be treated to extract the gas needed for the determination.

Silicon-32 behaves similarly. This permits the dating of waters in the 1000 to 2000 year range, thus filling the gap between tritium and carbon-14. Here again, however, the technique is not in common use because of the large quantity of water needed to concetrate the amount required for the determination.

In more recent years attention has been turned to the study of uranium isotopes. In the uranium-238 decay series, the first long-life isotope is U-234 (Fig. 44).

Application of uranium isotopes in hydrogeology involves a whole series of complex considerations of a physical and geochemical nature /65/. These are based on the preferential formation of hexavalent U-234 during the radioactive decay of U-238 and on the correlation between the total uranium content of water and the U-234/U-238 activity ratio (Fig. 45).

Use is made of the natural imbalance of this activity ratio when tackling problems concerning the mixing of waters of different origins, interaction between aquifers and the identification of water-rock interaction phenomena by recognition of the possible existence of reducing barriers. The activity ratio can also be used as a parameter for dating groundwaters on the basis of variations thereof dependent on the residence times in the aquifer and the possible presence of preferential flowpaths /64/.

The last noteworth radioactive element, that can be employed as a natural tracer is radon-222 originating from radium-226; it is always present in various proportions in rocks. Despite difficulties concerning the influence exerted on radon concentration

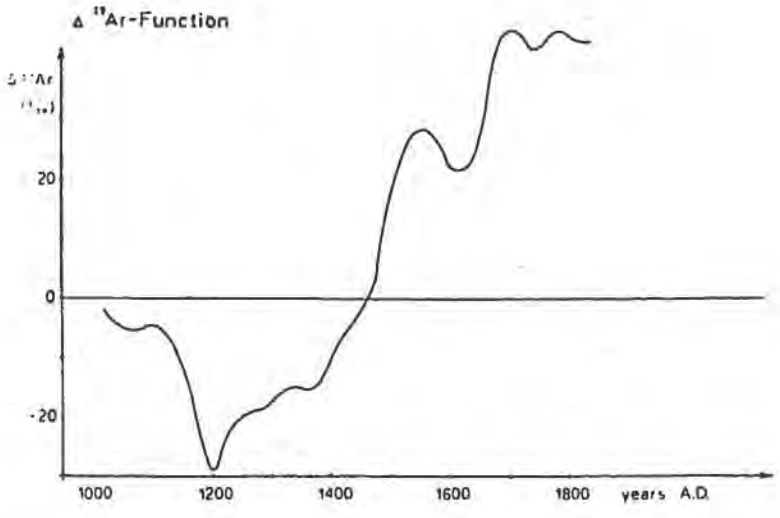

Fig. 43 - Calculated deviations of atmospheric argon-39 activity, relative deviation of argon-39 from the average argon-39 level in atmospheric argon plotted as a function of time (from Oeschger et al., 1974).

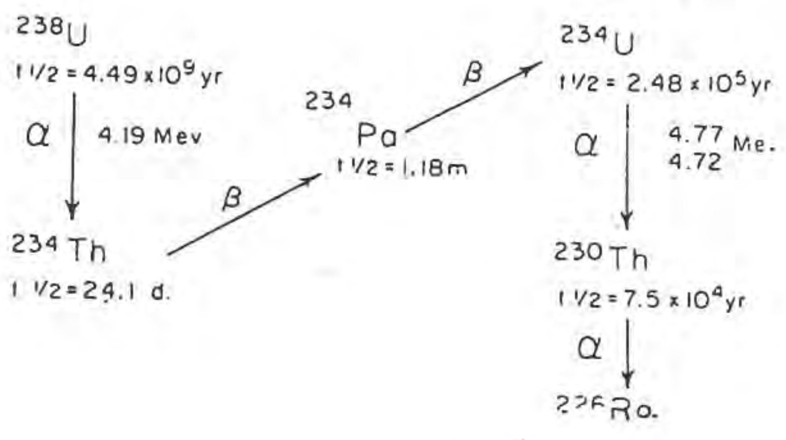

Fig. 44 - The uranium decay series

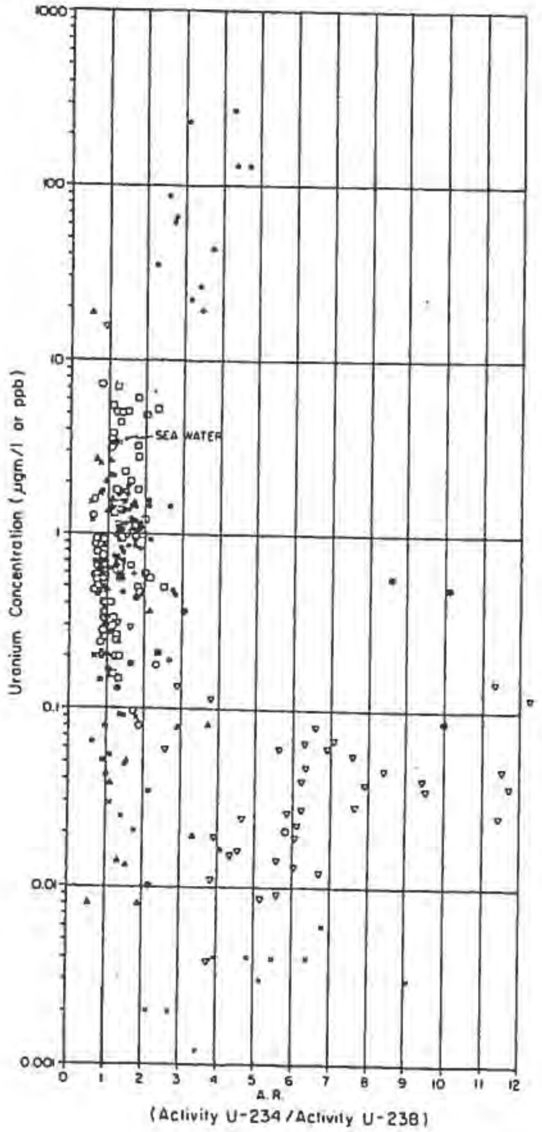

Fig. 45 - Scatter diagram showing the wide ranges of variation of uranium concentration and $^{234}U/^{238}U$ activity ratio (AR) in groundwaters (from Osmond and Cowart, 1976).

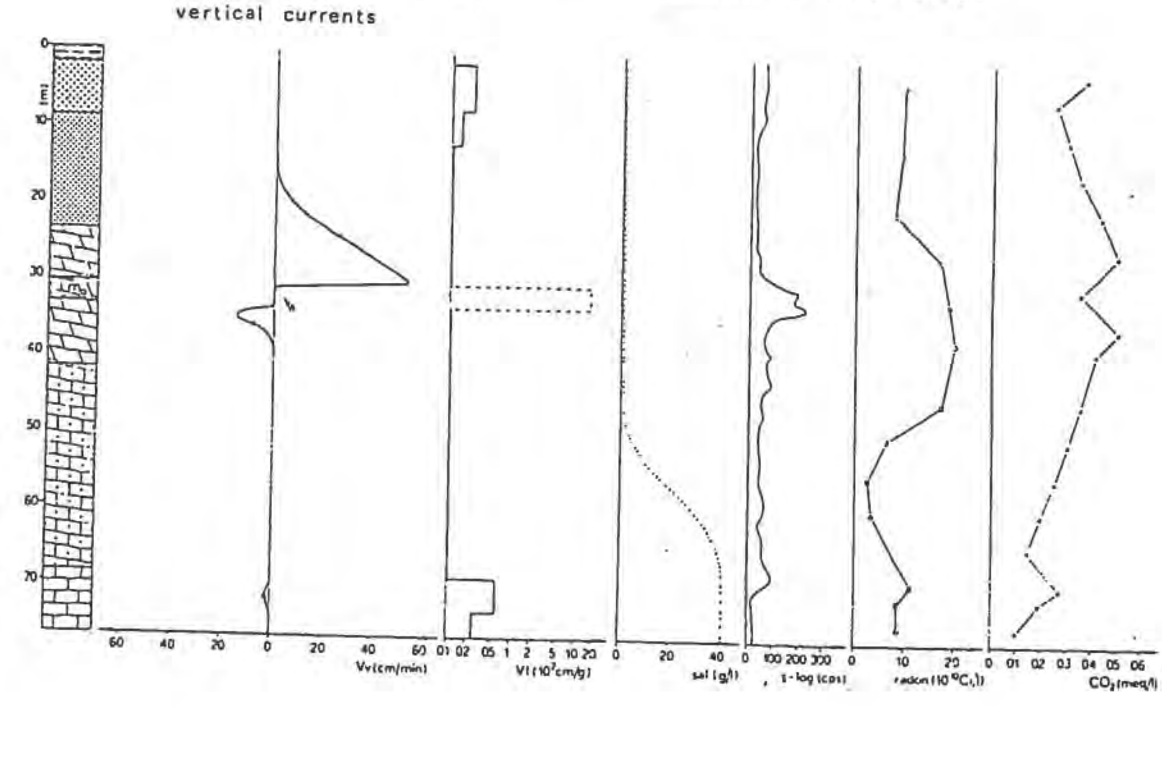

Fig. 46 - Radon content in relation to other parameters (stratigraphy, vertical currents, flow rates, salinity, natural radio-activity and CO_2 content) measured down a well drilled in a coastal aquifer (from Tadolini et al., 1971).

by tectonic conditions, atmospheric pressure and the temperature and salinity of waters, this element can be used as a natural tracer (Figg. 46, 47) to provide information on groundwater movement, especially in relation to the mobility of the waters /10, 74/.

There are very many applications covering a wide range of hydrogeological situations. The fact that the method is widely used is also attributable to the fact that it is easy and cheap to use, requiring only the filtration of the water on activated carbon and the determination of the radioactivity by means of counters, which can even be of the portable type.

Extremely useful new applications of the measurement of radon in groundwaters and the atmosphere concern studies of geothermal fields and active neotectonic situations. As regards the latter aspect, it would seem that it is possible to evolve methods for predicting earthquakes. It has been observed on several occasions that during the period preceding an earthquake there is a significant increase in the quantity of radon dissolved in the waters of deep wells. The two examples shown in fig. 48 illustrate measurements made before two earthquakes that took place near Tashkent (USSR) in 1966 and 1967 /68/.

These observation techniques are used extensively only in the USSR and China, at the present time, but they could well be widely extended, provided account is taken of the above mentioned difficulties involved in ascertaining and interpreting the concentration of radon in waters.

Deuterium and oxygen-18 are the stable environmental isotopes most widely used in recent years /25/. We know that deuterium occurs in seawaters as HDO at concentrations of about 320 ppm, while oxygen-18 is much more abundant and occurs as H_2O^{18} at concentrations of about 2000 ppm. During phase changes, the heavy isotopes tend to concentrate in the liquid phase. Isotope fractionation depends essentially on the temperature at which the phase change occurs, and to a lesser extent on pressure variations, too.

The effect of temperature on the isotopic composition of precipitation can be seen from figure 49 which illustrates a negative linear correlation between the O^{18} of precipitation and the temperature at the sampling station. In the hydrogeological interpretation, this temperature effect can be correlated with relief factors, amount of precipitation, distance from source of vapour, and seasonal and short-term variations.

Oxygen-18 in particular has been used successfully in studies for the identification of recharge areas, the identification of waters which infiltrated during times when the climate was different from what is now and studies in geothermal areas.

Deuterium has not been used widely on its own, but in conjunction with oxygen-18 it provides a way of identifying bodies of water that are subject to rapid evaporation. Deviations (δ) of precipitations from SMOW (Standard Mean Ocean Water), namely deviations from the average composition of the ocean as regards oxygen-18 and deuterium, exhibit linear correlation which, when plotted, permits each region to be characterized by the different value of the intercept. This linear relationship (Fig. 50), known as the "Meteoric Water Line" holds good for bodies of water when evaporation occurs under quasi-equilibrium conditions: if evaporation occurs, instead, under dynamic conditions (in other words, if there is a very pronounced temperature gradient at the air-water interface) the rainwaters fall on a flatter sloping Evaporation Line.

Here we have reported simple expressions to explain a phenomenon which is actually very difficult to interpret from the hydrogeological aspect.

Isotope fractionation during the formation of clouds and during precipitation is sometimes masked by collateral processes with isotopic exchanges between the

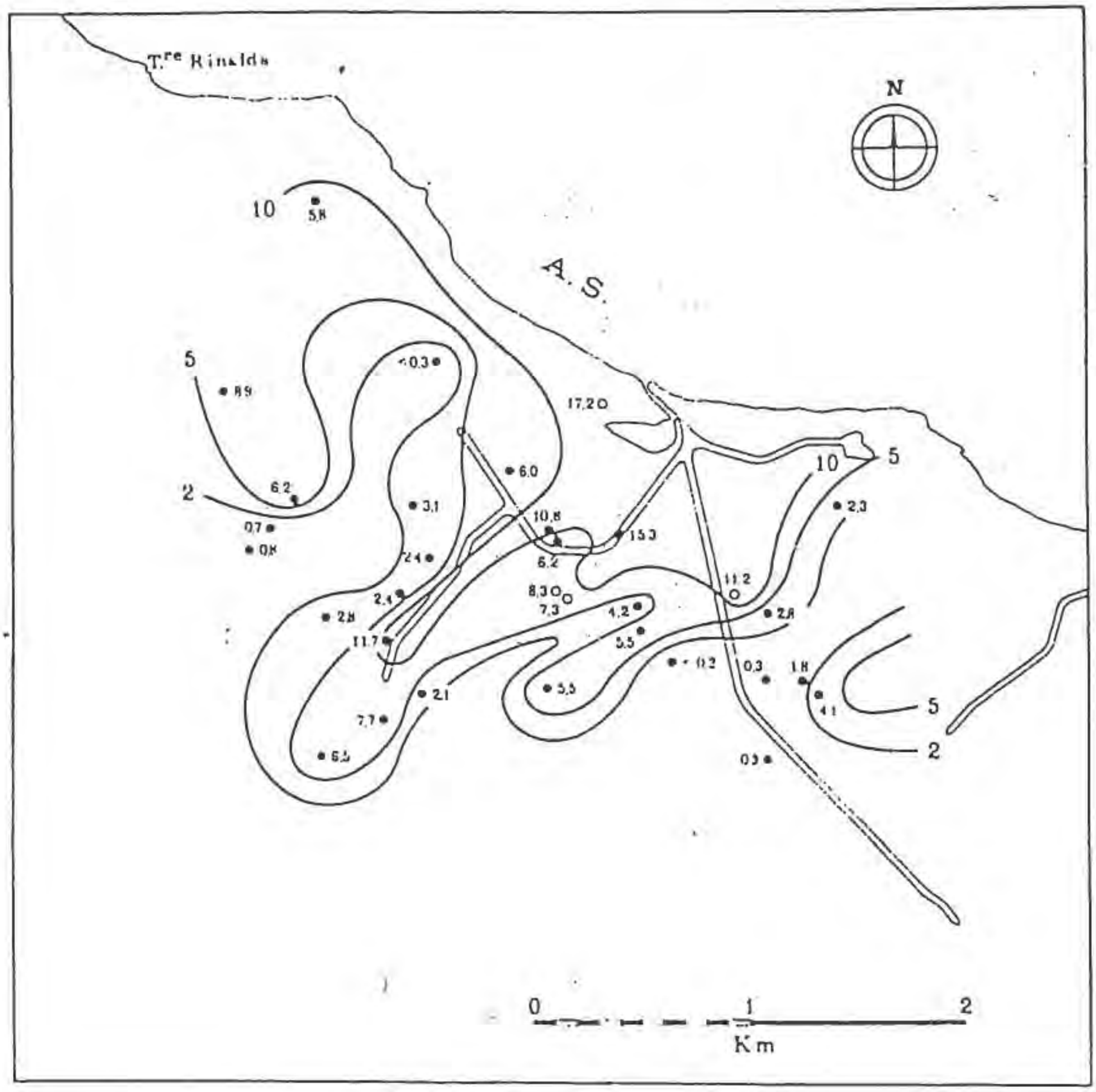

Fig. 47 - Distribution of radon content (10^{-10} Ci/l) of the waters of a shallow aquifer (from Cotecchia, 1977).

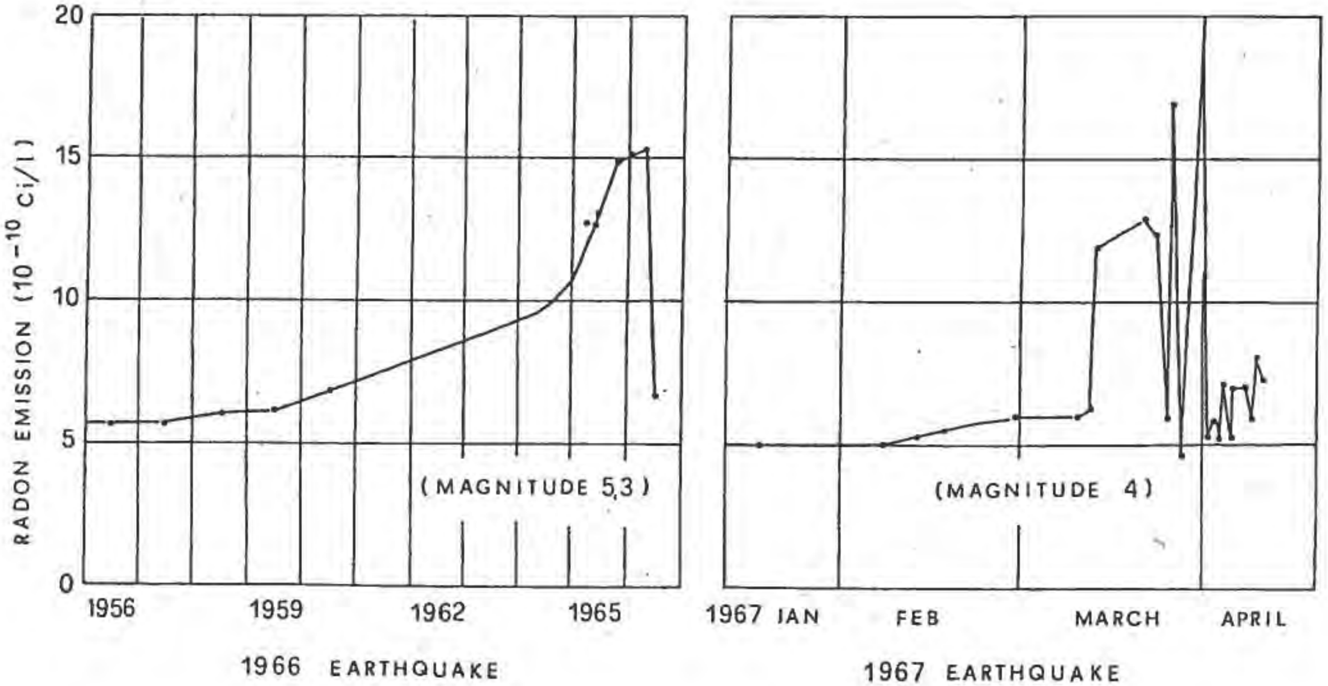

Fig. 48 - Radon emission measurements made before two earthquakes that took place near Tashkent, USSR in 1966 and 1967 (from Press, 1975).

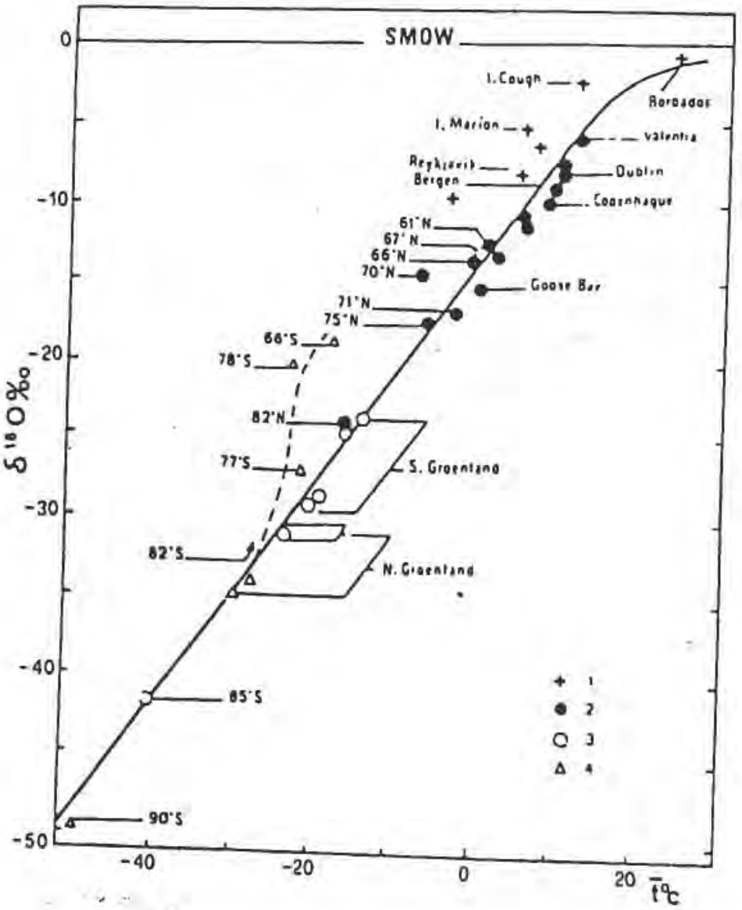

Fig. 49 -

Correlation between $\delta^{18}O$ of precipitation and temperature at the sampling station (from Daansgard, 1964).

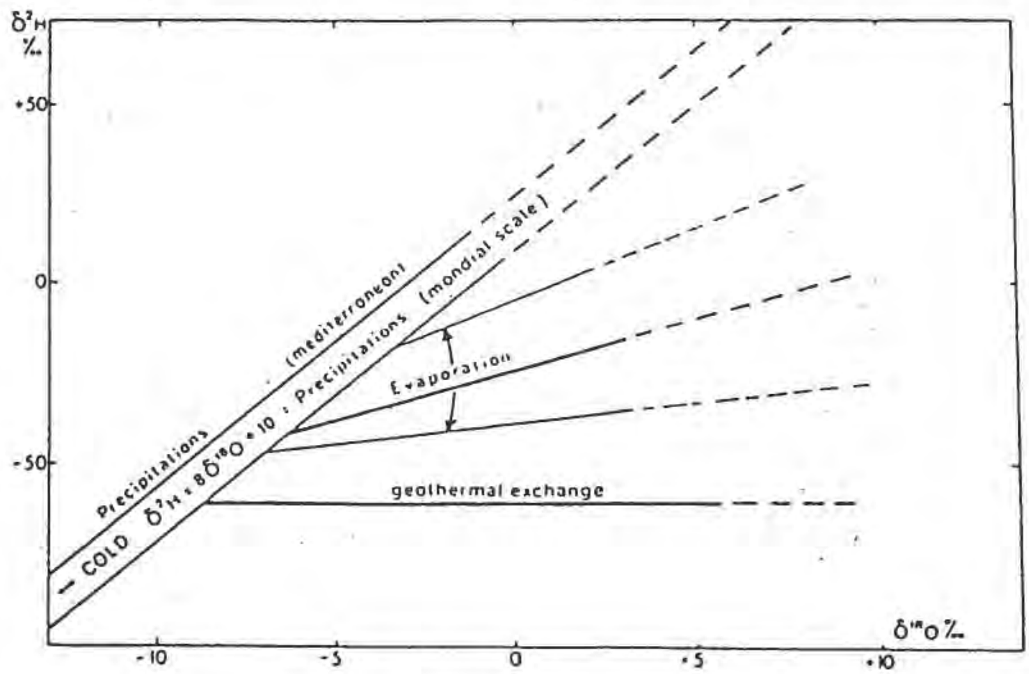

Fig. 50 - Linear correlation between δ D and $\delta^{18}O$ for rainwaters of the Mediterranean basin and world average

humidity of the air and raindrops and partial re-evaporation of raindrops before they reach the ground.

Nitrogen-15 is another stable isotope attracting the attention of hydrogeologists /48, 49/. By studying the concentrations of nitrogen-15 in nitrogenous compounds dissolved in water - mainly nitrates - it is sometimes possible to obtain information on their origin: for instance, it appears that nitrogen from chemical fertilizers can be distinguished from that present in compounds of natural origin.

An interesting technique involving a combination of geochemical and isotope methodologies is that which is based on the sulphur-34/sulphur-32 ratio, or rather the manner this deviates from an arbitrarily prefixed standard value thereof (Fig. 51) in studies designed to identify the possible origin of sulphur compounds dissolved in water /66/.

An important problem now receiving more attention from the hydrogeologist than it did in the past is the pollution of groundwater resources. The problem really hinges around the significance of "water quality" or rather, what we mean by "good quality water". Our reply today is certainly different from that we would have given only a few decades ago. Then we would have expected a "good-quality water" to be free from any substance extraneous to the natural "purity" of the water, the word "pure" signifying water with its full complement of "natural" dissolved salts.

Nowadays, after all the assaults there have been on groundwater resources and the damage that has certainly occurred in some cases, we tend to be less demanding in our standards; a water is considered to be of good quality when it is suitable for the use for which it is intended.

The attention of research workers is focused not only on the acquisition of data needed to quantify and define present pollution, but also on the development of methods of studying the land and hydrogeological environments that can be used to prevent pollution. For some years now we have been working on the plotting of thematic maps showing the vulnerability of aquifers to contamination. The whole question of vulnerability can be tackled in different ways depending on the objective concerned and the environmental data available. There are numerous examples of maps concerning the vulnerability of groundwaters. The map in figg. 52, 53 illustrate the possibility of polluting and the rate at which plluting bodies of a non specific nature penetrate and propagate: factors related to the hydrological properties of the soils and the hydrogeological characteristics of the groundwaters present /79/.

Maps of this kind are generally plotted on the basis of stratigraphic, geological, hydrogeological and chemical data acquired by the methodologies listed (preferential groundwater flowpaths, groundwater flow velocities, trace elèments present, etc.)/84/.

One of the main themes concerning the protection of groundwater resources these days is the impact of agriculture on water quality. Most of the studies relate particularly to the sensitivity of aquifers to nitrates, those essential components of fertilizers, which often affect groundwaters. Mention should be made of methods proposed for identifying areas that are the most vulnerable to the possible ingress and propagation of nitrogenous fertilizers in groundwater bodies /47/. In this case the final map which illustrates the probability of pollution by nitric nitrogen is plotted by superimposing two base maps, one concerned with land-use and the other distinguishing the cover soils according to their ability to prevent or allow vertical penetration of the pollutants.

The most widely known forms of pollution are caused by the activities of man, the discharge of industrial and urban effluents and farming.

Methods of ascertaining the level of pollution of groundwater differ from case to case, depending also on the "natural" state of the aquifer. For instance there are situations in coastal aquifers where seawater contamination masks the behaviour

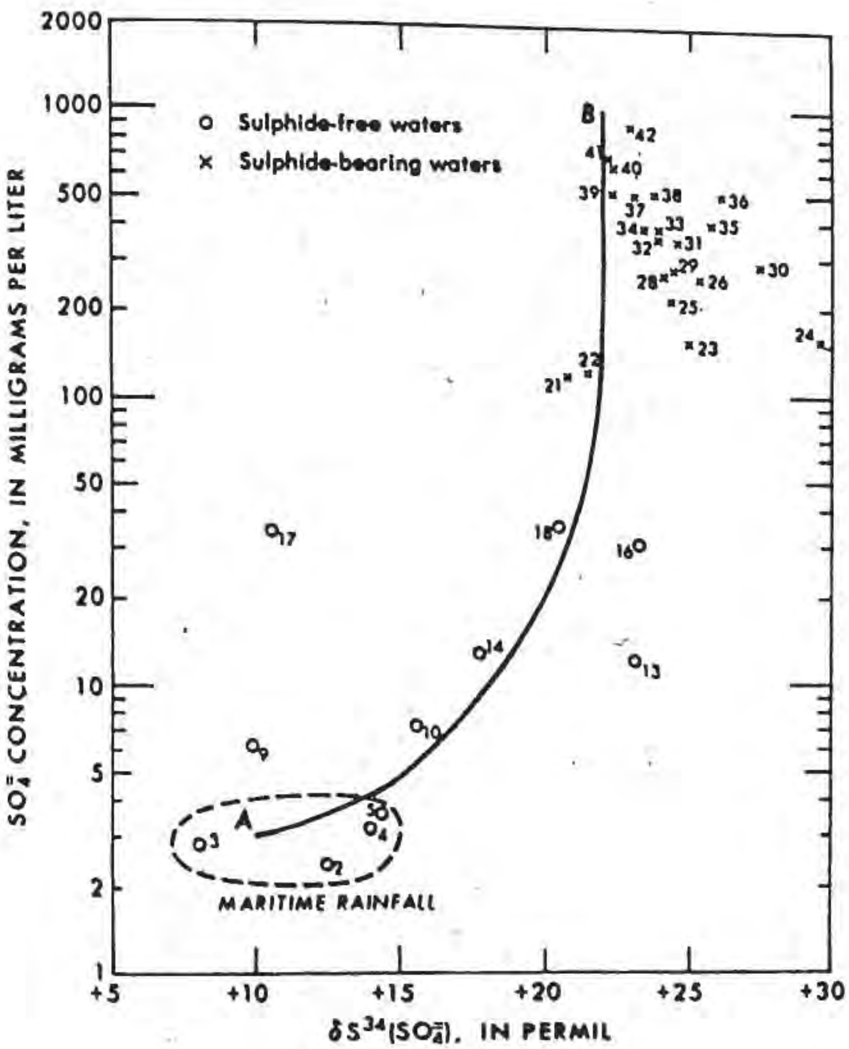

Fig. 51 - Graph of ^{34}S value and concentration of sulphate in a Florida aquifer (from Pearson and Rightimire, 1980)

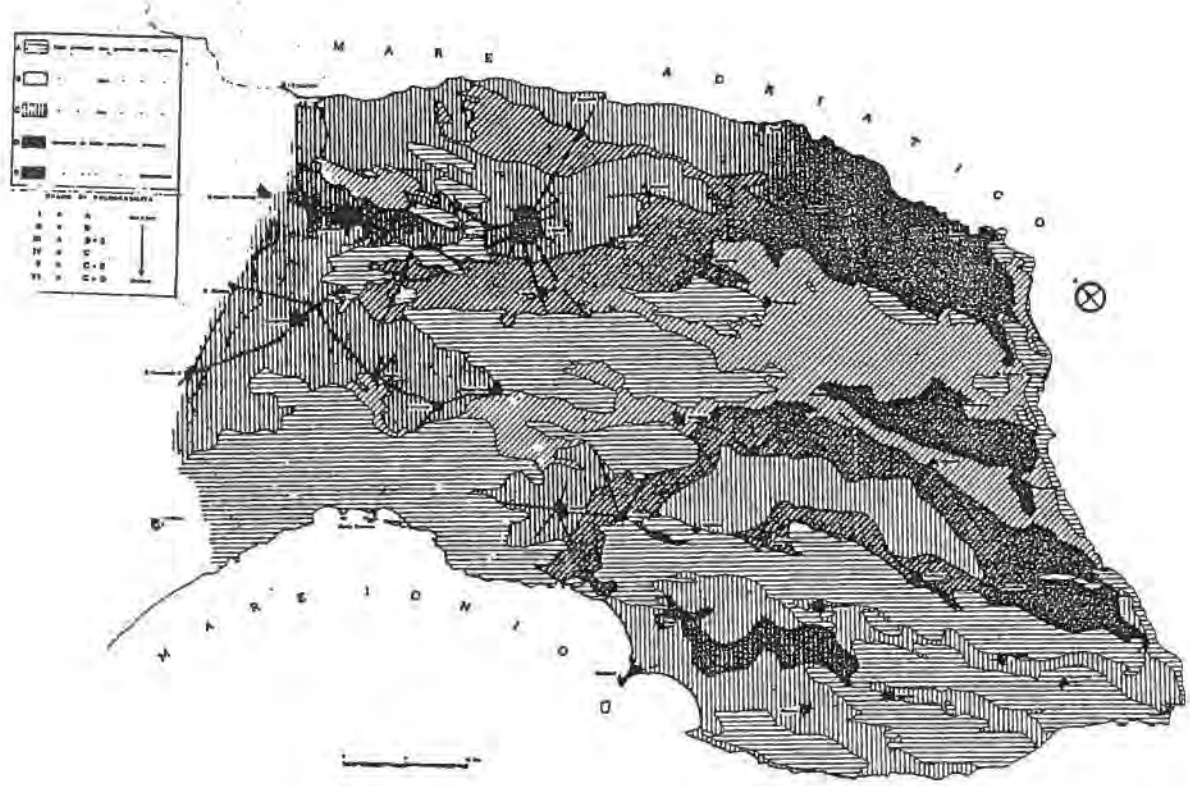

Fig. 52 - Map showing natural protection of deep aquifer from surface discharges of contaminating bodies (Salento Peninsula) (from Tadolini and Tulipano, 1980).

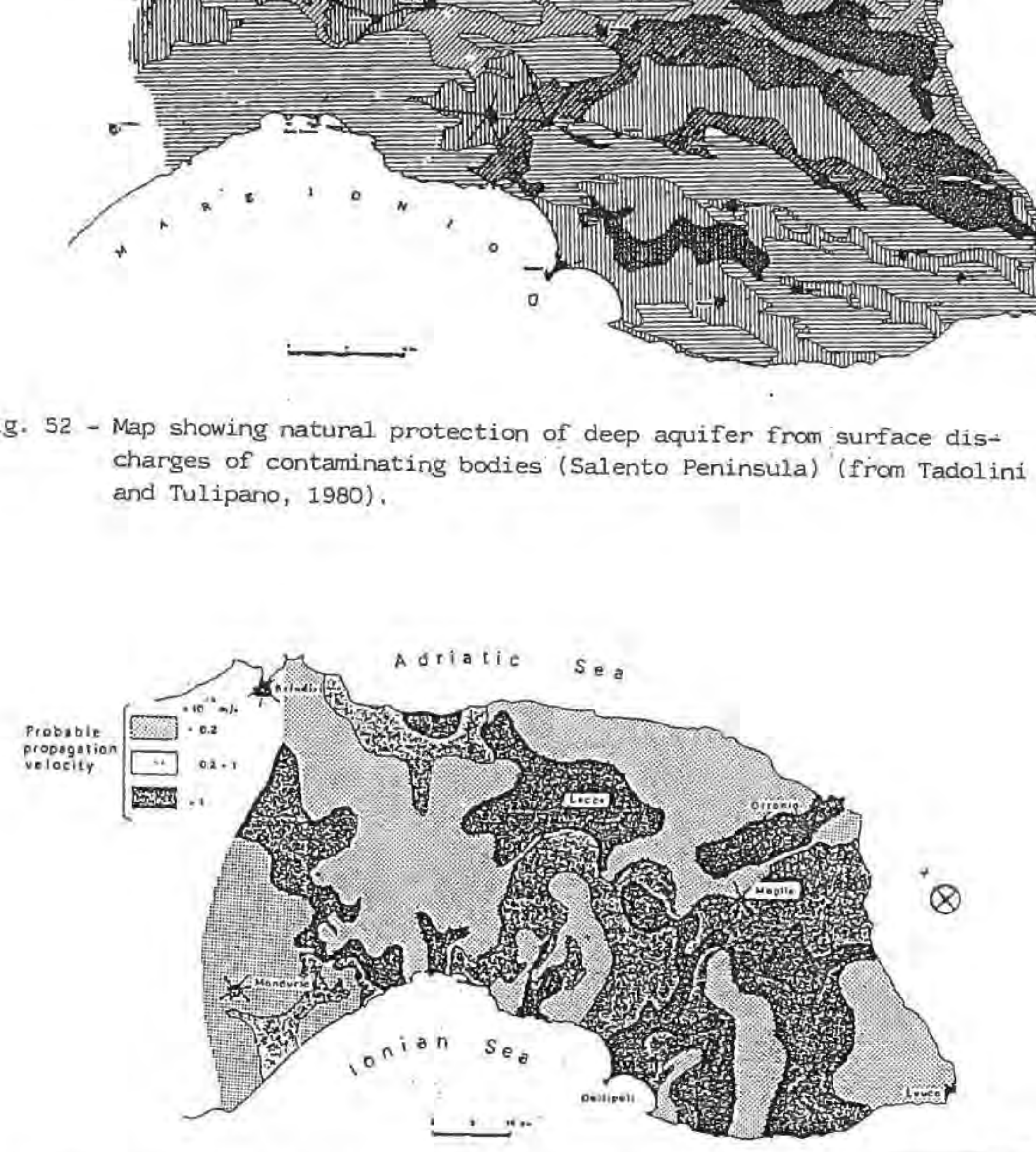

Fig. 53 - Map showing reaction of aquifer to propagation of a contaminating body in the groundwaters (from Tulipano and Tadolini, 1982)

of some ions which in other circumstances would act as good tracers for following anthropic pollution.

From the practical aspect, however, it is easier nowadays to ascertain the level of pollution, because of the improvement in sampling techniques and because numerous chemical and physicochemical parameters such as dissolved oxigen and pH can be measured directly in the well (Fig. 54).

But it is necessary to select from the numerous and well-known pollution indicators, those best suited to characterize each situation, paying particular attention to the relations existing between them.

In some particular hydrogeological situations the correlations between dissolved oxygen and the nitrate content (Fig. 55) have proved interesting, as have those existing between the value of the COD/O_2 ratio and dissolved oxygen (Fig. 56). These relations, taken together with other parameters have permitted valid classification of their quality and their self-cleansing capabilities /85/.

Again where coastal aquifers are concerned, the relationship between NO_3^- and the total dissolved salts content (Fig. 57) permits us to identify the waters where the nitrate content is not due to the mixing of fresh groundwaters and brackish groundwaters.

In the case of pollution, too, traditional and advanced technologies are all being brought to bear, because here, perhaps as in no other branch of hydrogeology, a multidisciplinary approach is needed, since the hydrogeologist alone cannot cope with the complex mass of factors that govern the environment and biological life which goes on there.

At this Conference, five papers have been presented on the treated theme. Bardlom, from India, discusses new geophysical applications based on the use of rotational seismic and electrical profiles, especially suitable for microstructural analysis. The author also referes to the advantages of gamma-gamma and neutron-neutron logging in wells where groundwater flow velocities are measured using the dilution methods and vertical currents with the double injection method. For both these measurements, the author proposes the use of stable tracers with neutron-capture properties and so can be obtained with the same neutron probes.

Hoehn, from Switzerland, uses experimental data obtained by means of uranium and lithium tracers to assess the efficiency of a model simulating advection and dispersion phenomena in an aquifer recharged from a polluted river. The experimental curves obtained in the field by measuring the variation in concentration of the two tracers in two observation wells downstream of a tracer-injection well show a reasonable tie-in with the calculated curves.

Malko, Oleinik and Shportuyit of the USSR stress the importance of tackling problems concerning the diffusion in groundwaters of pollutants coming from various anthropic activities. The authors have developed programms for an additive local one-dimensional scheme and an explicit three-layer Duport-Frankel scheme in Fortran language for the solutions of the problems of three-dimensional heat and mass transfer in groundwaters.

Troisi of Italy, in dealing with aspects concerning the simulation of an aquifer subject to pollution, makes several points on the problem of the "dispersivity" parameter, in the classical sense, understood as an intrinsic characteristic of the aquifer and thus independent of the flow regime. Experimental measurement of this parameters has, however, revealed several aspects that are not in line with the significance so far attributed to it, for example, an increase in dispersivity on moving away from the initial reference point. This and other considerations lead the author to support the proposal put forward by other authors, too, regarding the introduction of the "dispersion function" concept.

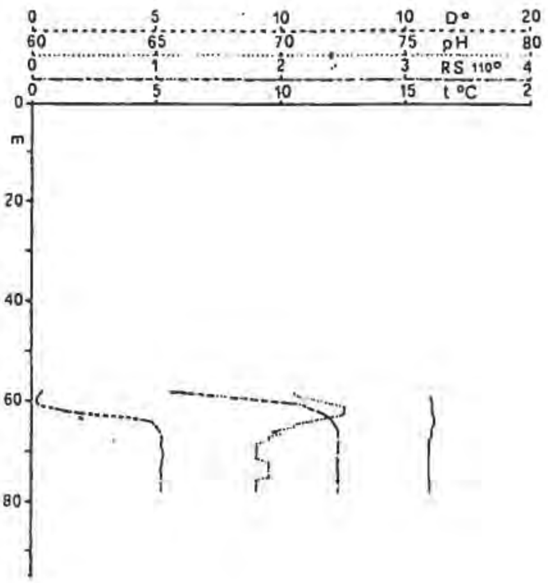

Fig. 54 - Trend of dissolved oxygen, pH, salinity and temperature down a drilled water-well (from Tulipano and Tadolini, 1982).

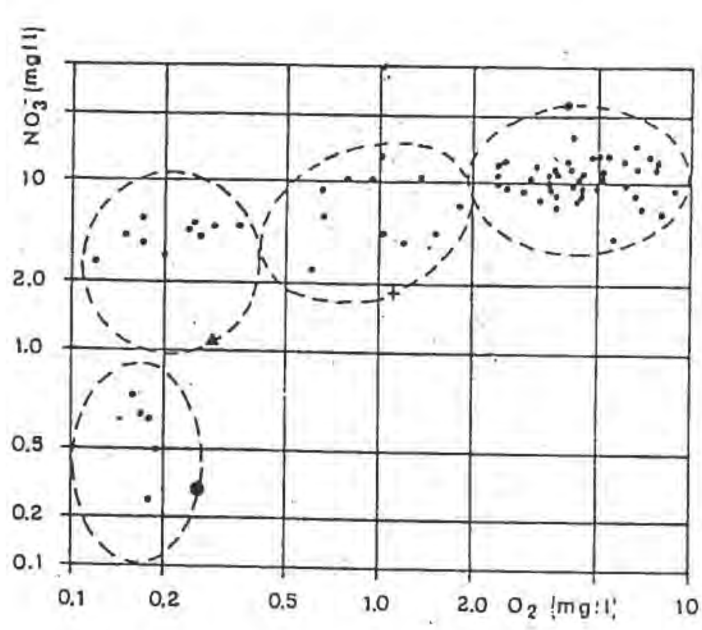

Fig. 55 - Relationship between NO_3^- and dissolved oxygen (from Tulipano et al., 1982).

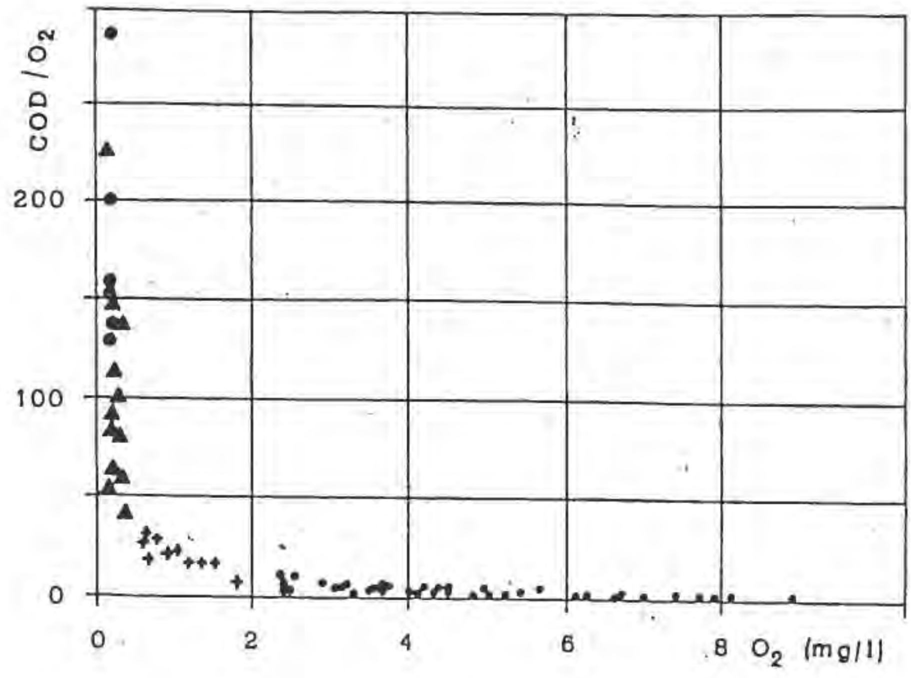

Fig. 56 - Relationship between dissolved oxygen content and COD/O_2 value (from Tulipano et al., 1982).

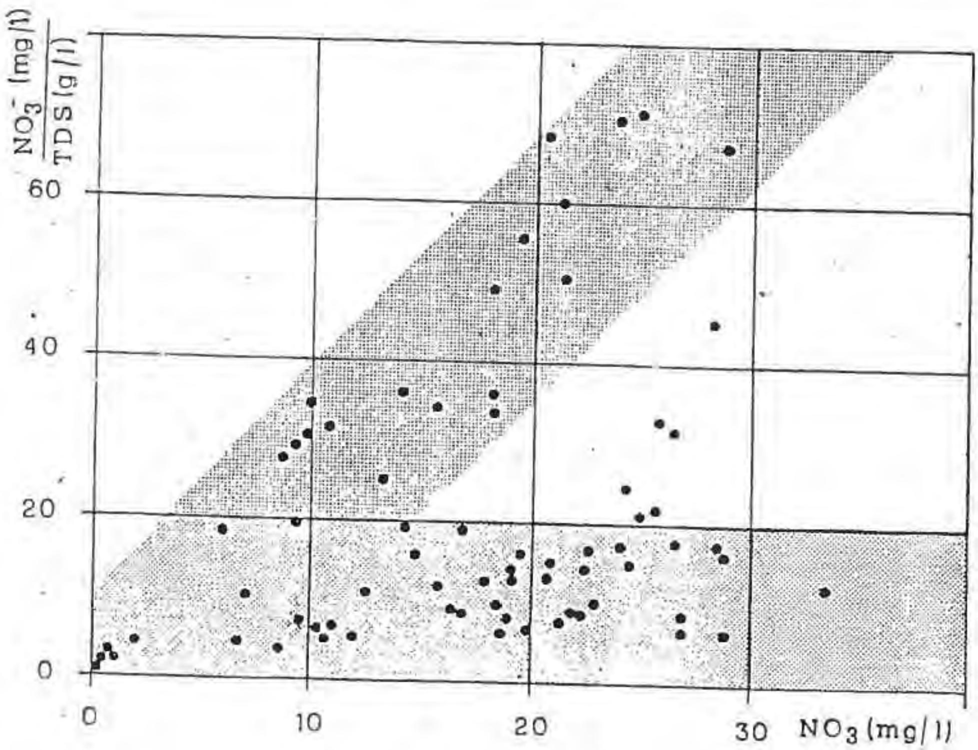

Fig. 57 - Relationship between NO_3 and NO_3/TDS values (from Tulipano et al., 1982).

Bonasountas, from the United States, refers to the possibility of predicting the behaviour of polluting bodies of various kinds run into or stored in the subsurfaces. The main advantage of the computer model proposed by the author is that it refers simultaneously to the interaction of the polluting body with the three subenvironments: the watershed (catchment basin), the unsaturated soil zone and the saturated zone. With this approach it is possible to predict the concentration of particularly harmful substances in these subenvironments ten years ahead.

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