CENTENAIRE DE LA SOCIÉTÉ GÉOLOGIQUE DE BELGIQUE
COLLOQUE *GÉOLOGIE DE L'INGÉNIEUR*, LIÈGE, 1974, 291-312

THE HUGE AQUIFER AND THE MARINE INTRUSION INTO THE FISSURED AND KARST MESOZOIC LIMESTONES OF APULIA (SOUTHERN ITALY) : RECENT STUDIES AND INVESTIGATIONS BY EMPLOYING MODERN METHODOLOGIES

V. COTECCHIA (*)

ABSTRACT

Cretaceous calcareous and dolomitic rocks, bedded, jointed and karstified, and hence generally very permeable, form the basement of Apulia (Southern Italy). These rocks constitute a huge aquifer with fresh and brackish groundwaters which float on groundwaters of marine origin. Sea level constitutes the base level of the groundwaters.

In this paper an outline is first given of the geological features having a special bearing on groundwater investigations. Then the techniques used are sketched in very briefly—listed almost—, after which a succinct description is given of the results of investigations on the groundwaters of the Salentine Peninsula (south-eastern Apulia) and, in conclusion, the information available on the paleohydrogeology of the peninsula is set forth.

1. INTRODUCTION

The great economic importance of groundwaters contained in fissured carbonate rocks needs no emphasis. From this aspect, the hydrogeology of limestone and dolomite masses outcropping in coastal areas, where seawater intrusion occurs, is of particular interest. It is not the purpose of this paper—which in fact deals with the hydrogeology of the carbonate formations along the coasts of Apulia—to describe the results achieved, but rather to outline the concepts, methods and techniques used in the investigations.

In the light of experience, the author wishes to draw attention to the importance attaching to geological research. This must always precede the hydrogeological investigations *sensu stricto* and range over a much broader area than that selected

(*) Prof. Ing. Vincenzo Cotecchia, Director of Geotechnics and Engineering Geology Institute, Bari University.

for investigation. The other point to which attention is drawn is the advantage offered by the techniques which serve to clarify particular geological problems. However, it is in no way wished to minimize the utility of the time-honoured and newer isotope techniques for studying the behaviour of groundwater.

Thus appropriate geological studies constitute the fundamental basis for profitable investigation of subsurface waters, though, as will be apparent from some examples given ahead, isotope techniques offer the most striking and surprising results.

In the following pages the writer refers to studies he could develop in a district of Southern Italy where, only twenty years ago, the first knowledge of the existence in said area of remarkable main aquifer reservoir was got (Cotecchia, 1955) and the methods of drawing from wells partially penetrating fresh water floating on brackish water were considered (Cotecchia, Orabona, 1959). In particular in the last years a wide, organic research study on the subject was made by the writer for Consiglio Nazionale delle Ricerche (Istituto di Ricerche sulle Acque). The most important papers published on this subject are listed in the bibliography. In the light of the concepts mentioned, an outline is first given of the geological features of Apulia which have a special bearing on groundwater investigations. Then the techniques used are sketched in very briefly—listed almost—, after which a succinct description is given of the results of researches on the groundwaters of the Salentine Peninsula (south-eastern Apulia) and, in conclusion, the information available on the paleo-hydrogeology of the peninsula is set forth.

2. OUTLINE OF GEOLOGY AND PALEOGEOGRAPHY

A limestone-dolomite series some 9 000 metres thick, ranging from Mesozoic to Lower Tertiary in age, forms the framework of Apulia's hills (Murge and Salentine Serre) and mountains (Gargano). Neogene and Quaternary sediments, mainly detrital-organogenic, outcrop in the lower-lying areas between the hills and mountains. The basal part of the limestone-dolomite series consists of Triassic evaporites and black limestones.

Carbonate sedimentation during the Mesozoic occurred in a reef environment, in what is now the Gargano area, and in a platform environment, in the Murge and Salentine areas. Indeed, the distribution of facies in the Gargano clearly indicates that during Lower Jurassic times there existed a typical reef environment which, in the Upper Jurassic evolved to fore-reef and back-reef environment. These two environments continue to be separate in the Lower Cretaceous.

In the Murge and Salentine areas, during the same period, carbonate sedimentation was occurring on a platform which was sometimes above sea level and sometimes below. This included a number of small lagoons and was subject to continuous, general subsidence (Zezza, 1973).

At the end of the Cenomanian a large part of the carbonate deposits was emergent for a long period. This led to the development of karst phenomena and the formation of terra rossa residues, which were subsequently laterized and bauxitized, as demonstrated, for instance, by the attitude of the bauxite mineralization in the San Giovanni Rotondo Mine (Gargano).

Sedimentary episodes, with stratigraphic breaks, occurred in the Lower Tertiary, and at the present time Paleogene formations are found in the Adriatic coastal strip of the Gargano and Salentine areas.

During this long period of emergence, which preceded the Miocene marine invasion, there was ample time for the calcareous masses to be affected by karst phenomena. The landform was gradually shaped into extensive plateaux and dolines, especially in the Gargano (Cotecchia, Magri, 1966) and the Murge. Very probably, too, most of the west central part of the Gargano and the south central part of the Murge, where rocks very susceptible to karstification occur, were subject to peneplanation.

In the Miocene there was a neritic-littoral environment—lagoonal in places—around the emergent parts of the Gargano, the Murge and the Salento. Here originated the calcarenites whose typical facies is represented by Pietra Leccese (Lecce Stone).

Denudation of the plateaux and dolines commenced with the Late Miocene uplifts, which were concomitant with the tectonic dislocations that, starting from the Bradano Trough, separated the Gargano from the Apennines and the Murge. This destruction of the highlands started from the steep sides of faults, where erosion caused by runoff was decidedly more marked than erosion by dissolution, especially in the Gargano. At the same time the progress of surface karst processes slowed down, but was not halted, while groundwaters started to circulate at greater depth, thus initiating the development of deep karst phenomena.

There was a new cycle of sedimentation in the Pliocene and Pleistocene, which brought the configuration of Apulia gradually closer to that of the present day. The marine invasion in the Pliocene and Pleistocene (fig. 1) re-established a neritic environment that lasted, with brief interruptions, to the end of the latter epoch. This resulted in carbonate sedimentation which, however, often gave way to the deposition of terrigenous sediments that now occur as extensive clay deposits in south-central Apulia and conglomerates in the Tavoliere region. Then towards the end of the Pleistocene, when the sea was gradually retreating and the sedimentation areas were partially filled, the Gargano joined up with the Murge and the latter with the Salentine Serre (fig. 1).

It is apparent from the paleogeographic outline sketched in above that intensification and attenuation of karstification over the ages depended closely on the variation of the karst base level and hence on the phases of sinking or uplift of the carbonate basement or on variation in sea level.

Karst phenomena are most marked when dissolution has affected the main system of joints having a NE-SW Apennine trend. The close relationship existing between structural features and karstification is always particularly evident in hypogene karst conduits (e.g. the famous Castellana Caves) where both the line of major development and the secondary branches clearly follow fractures (fig. 2).

This enlargement of joints by rock solution over the ages has given rise to a network of cavities of different shapes and sizes. Sometimes the cavities are in the fossil state, in other words they are filled with materials transported mechanically by surface runoff waters (terra rossa or calcareous breccia with a terra rossa matrix) or with materials that were in solution but were subsequently deposited chemically from the infiltrating waters (calcitic incrustations) or even with materials deriving from the collapse of large cavities (collapse breccia).

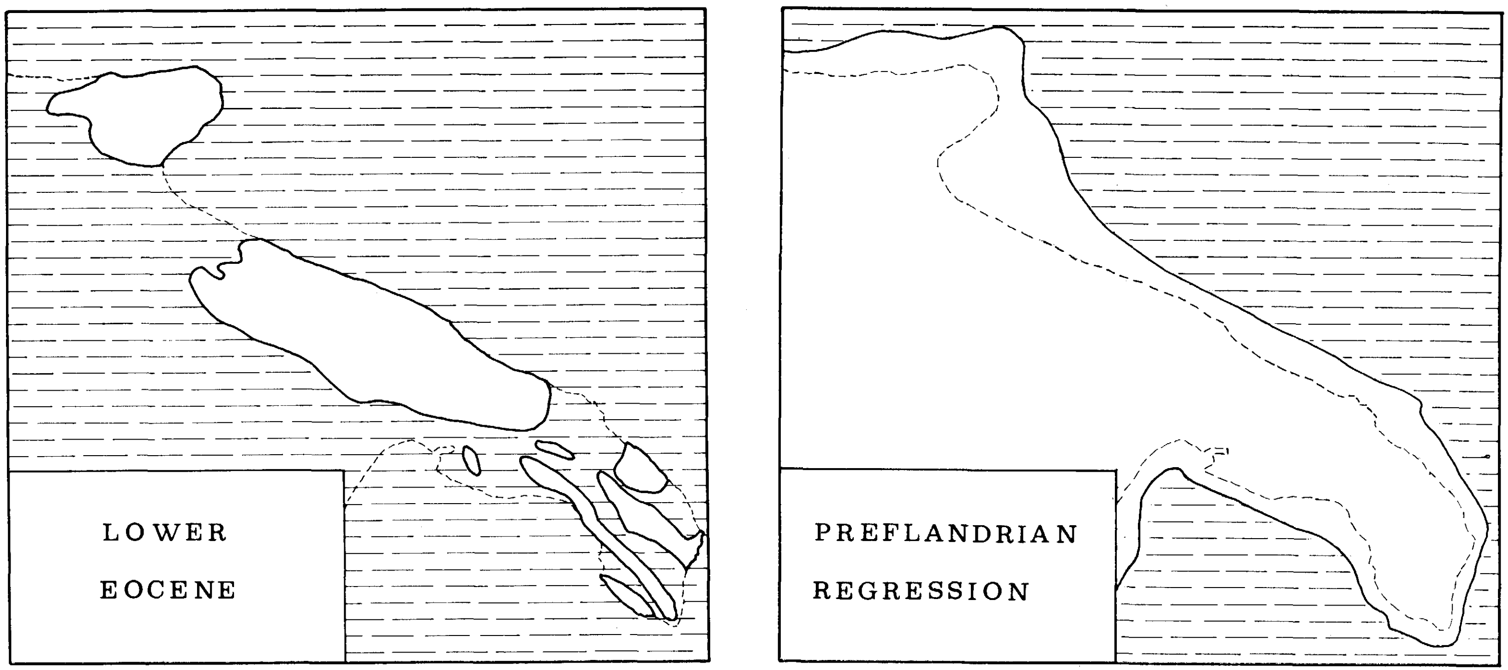


FIG. 1. — *Paleogeological scheme of Apulian region during the Lower Eocene and the Pre-Flandrian regression.*

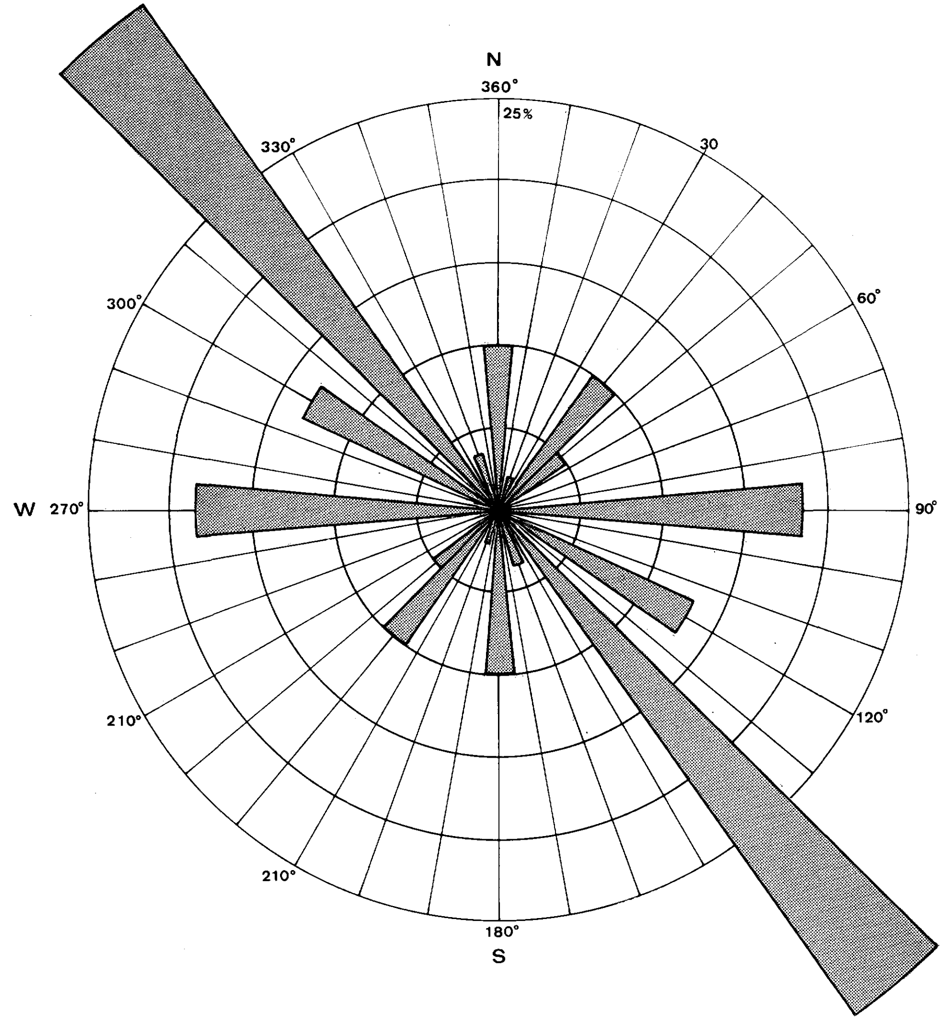
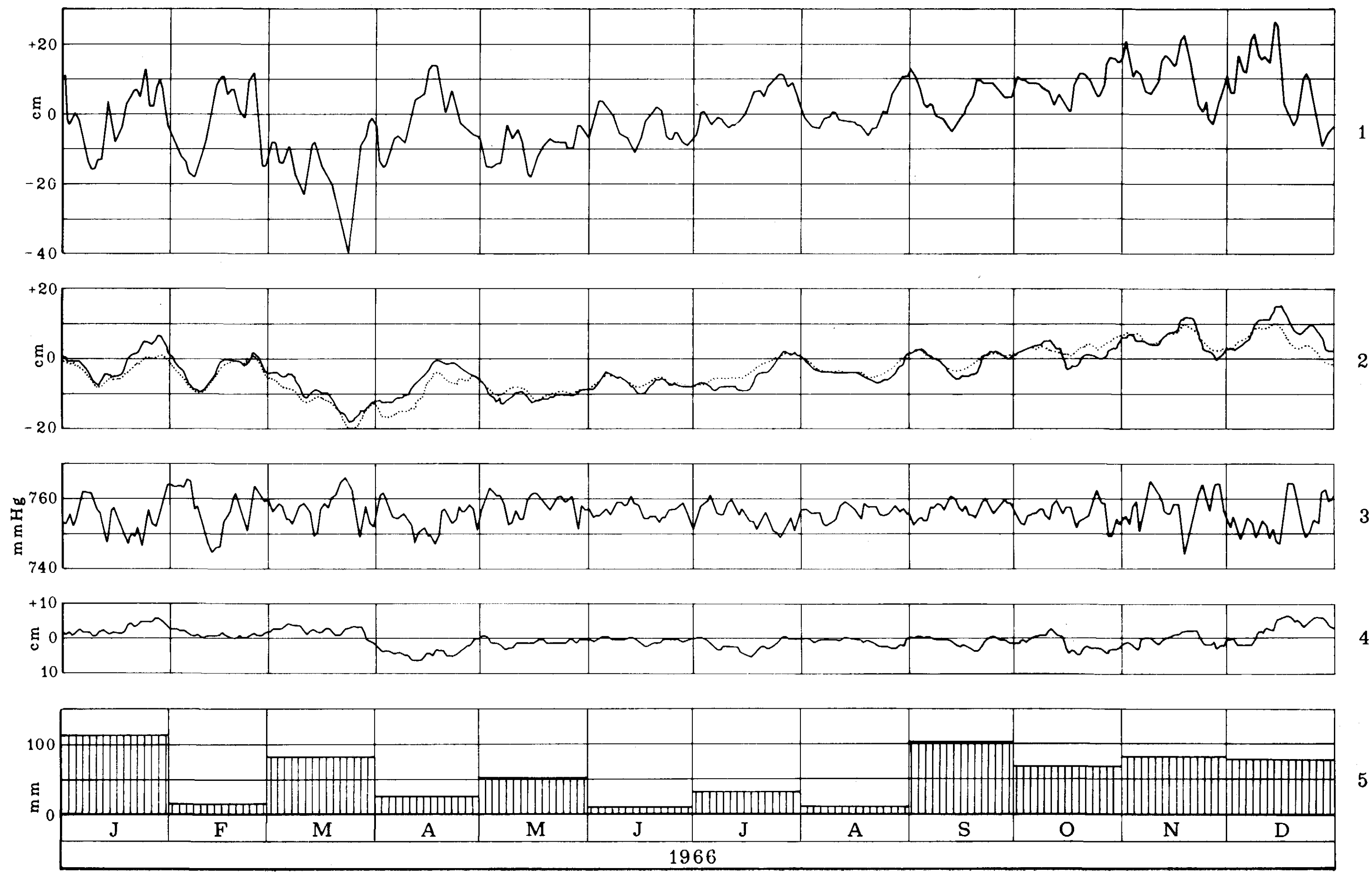


FIG. 2. — *Trend of longest axes of the main karst caverns known in the Murgia area (Apulia); this is the same as that of the principal structural features.*

3. METHODOLOGIES AND TECHNIQUES

The linchpin of the hydrogeological studies has been the investigation run to determine the regional trend of the water table or piezometric surface of the groundwaters.

The selection of a suitable network of groundwater observation and measuring points was preceded by a detailed inventory of all the water points available in the region. Then the network was set up and equipped with automatic water-level recorders which provide a continuous record of level variations on monthly charts.


+20
cm 0
-20
-40
1
+20
cm 0
-20
2
760
mmHg
740
3
+10
cm 0
10
4
100
mm 0
5
J
F
M
A
M
J
J
A
S
O
N
D
1966

The necessity of carefully screening the data thus obtained before they are interpreted and processed must be emphasized. In this regard, attention is drawn to the importance attaching to the correlations existing between changes in the levels of groundwaters floating on seawater that has intruded the land-mass and those of the interface at the salt water-fresh water contact, in relation to both the alternations of the periods of aquifer recharge and discharge, and to withdrawals.

In hydrogeological situations such as this, the data do not really provide a direct indication of the variations in thickness of the aquifer over the course of time as a result of inflow, outflow and abstraction, since they are influenced to a greater or lesser extent by periodic and aperiodic fluctuations of the sea level and by variations in atmospheric pressure acting directly and indirectly, through the sea, on groundwater levels (Magri, Tadoline, 1969). Thus the first thing to do is to purge the water-level data of the effects of these influences. This can only be done when apposite and accurate tide-gauge and barometric readings are available.

By way of example, figure 3 illustrates the relationship existing between aperiodic fluctuations in sea level, atmospheric pressure, mean monthly rainfall and changes in groundwater levels. The influence of the sea-level fluctuations on groundwater levels is very apparent. The direct influence of atmospheric pressure as such is practically nil, while the effects of inflows from rainfall in the six-month autumn-winter period, of seaward outflows and of abstraction during the summer months are not apparently appreciable. Thus it is obvious what serious errors can be made in interprepation when the water level data are used as the basis for investigation without first purging them of interfering elements.

To obtain the effective variation in the time of the thickness of the fresh water, it is necessary moreover to follow the vertical displacement of the top of diffusion zone.

In this regard, it has been found very useful to drill "observation wells" which penetrate into the intruding seawaters. In these wells it is possible to monitor changes in the top and the bottom of the zone of diffusion, as well as variations in the salinity of the groundwaters as a result of rainwater inflows.

Salinity logging performed every three months by means of conductimetric salinometers has revealed the relationship that exists between the thickness of the zone of diffusion and distance inland from the coast. In observation wells drilled near the shore the transition from groundwater to sea water is abrupt, the intermediate zone of diffusion being no more than a few metres thick, while in wells

FIG. 3. — *Relation between aperiodic fluctuations of the sea (Diagram 1), atmospheric pressure (Diagram 3), mean monthly rainfall (Diagram 5) and changes in groundwater level (unbroken line in Diagram 2) at Well 4 II S (located as shown in fig. 14). The dotted line in Diagram 2 shows the calculated curve that most closely approximates to the changes in groundwater levels in the well (A = 1.4 days 1/2). Comparison of the two curves in Diagram 2 clearly illustrates the influence of sea level fluctuations on groundwater levels. The differences between the two curves in Diagram 2 are shown in Diagram 4 which represents the changes in groundwater level that are "not influenced" by sea level fluctuations. It is apparent from comparison of Diagrams 3 and 4 that atmospheric pressure has virtually no direct influence on water table levels, while comparison of Diagrams 4 and 5 similarly indicates that inflows from autumn-winter rainfall, outflows to the sea and abstraction during the summer have no appreciable influence. The relationship between atmospheric pressure and nonperiodic fluctuations of the sea emerges clearly from a comparison of Diagrams 1 and 3.*

drilled farther inland the zone of diffusion may be as much as several dozen metres thick (figs. 4 and 5) (Tadolini, Tulipano, 1970).

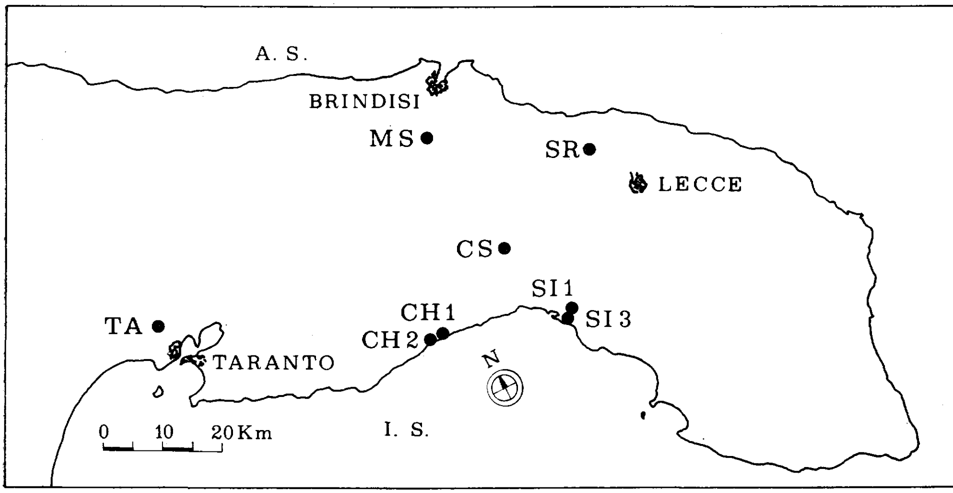


FIG. 4. — *Location of observation wells of Salentine Peninsula.*

Salinity logging has also shown that the oscillation that occur at the top of the zone of diffusion during the alternating periods of aquifer recharge and discharge are far greater than those which occur in phreatic or piezometric levels. In other words, the effect of these events is felt in the aquifer mainly as variations of the elevation of the zone of diffusion itself, which, in its turn, contracts and expands as the hydraulic head of the aquifer varies. As the elevation of the water table or piezometric surface decreases, the zone of diffusion expands (figs. 6 and 7), while as it increases it contracts (Cotecchia, Tadolini, Tulipano, 1974).

The fluctuations in levels also constitute an important means of investigation for acquiring basic indications on "communicability" between groundwaters and the sea. Indeed, in favourable hydrogeological situations it has been possible to calculate the oscillations induced in the aquifer from fluctuations in sea level, starting from the differential equation of the non-permanent motion of the percolating waters (Magri, Troisi, 1969).

In figure 8, which gives an application of the method in an area where there are many springs, the existence of corridors formed by areas where communicability is poor is quite evident. In practice, these coincide (fig. 9) with the areas of preferential groundwater flow (Tadolini, Tazioli, Tulipano, 1971).

Good results have also been obtained by systematic measurements of groundwater temperatures made with nickel resistance thermometers (100 ohm at 0 °C), since for given chemical composition and environmental isotope content, temperature is a valid "tracer" which can be applied to the study of the problem of the supply and circulation of groundwater (Carlin, Magri, Mongelli, 1973).

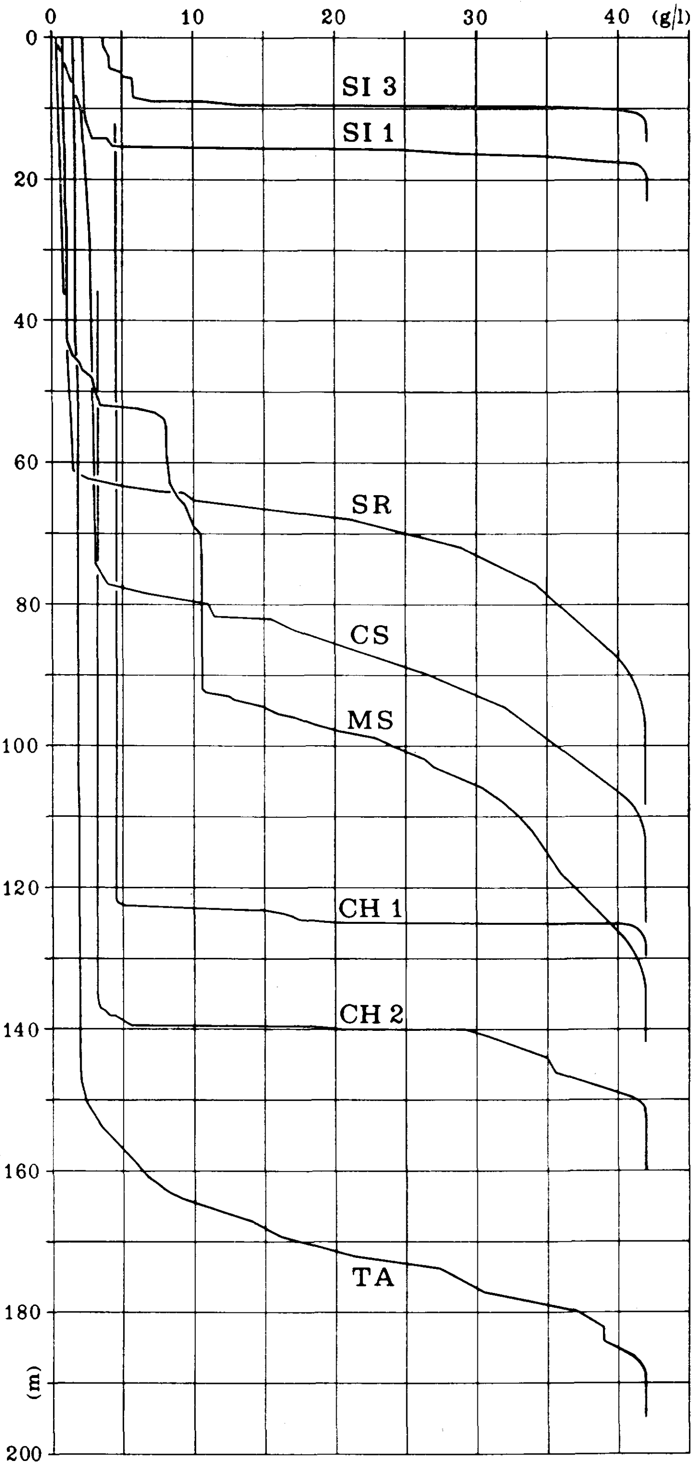


FIG. 5. — *Mean behaviour of the salinity (g/l) against depth (m) referred to the phreatic or piezometric surface, in the observation wells shown in figure 3.*

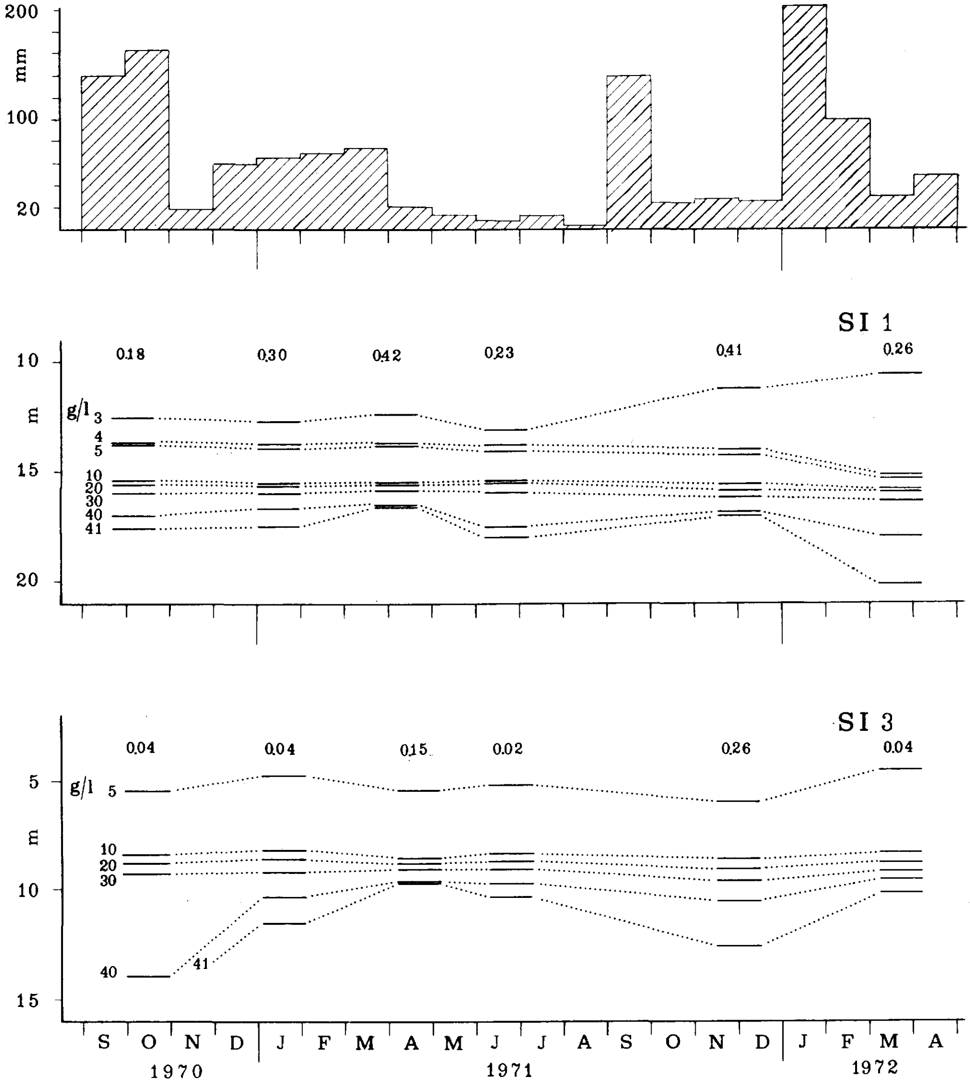


FIG. 6. — *Variations in the time of the trend of salinity stratification inside the diffusion zone of SI-1 and SI-3 wells; depths are referred to the water table whose elevation is marked over each salinity stratification.*

The studies of the chemical composition of precipitations (liquid and dry) and of groundwaters have also made a major contribution to understanding of the problem.

Among other things, these studies have shown that in Apulia the chemical composition of the rainwaters and of the dry precipitations is markedly influenced by the distance from the sea and by seasonal climatic variations (Cotecchia, Tadolini, Tittozzi, 1971).

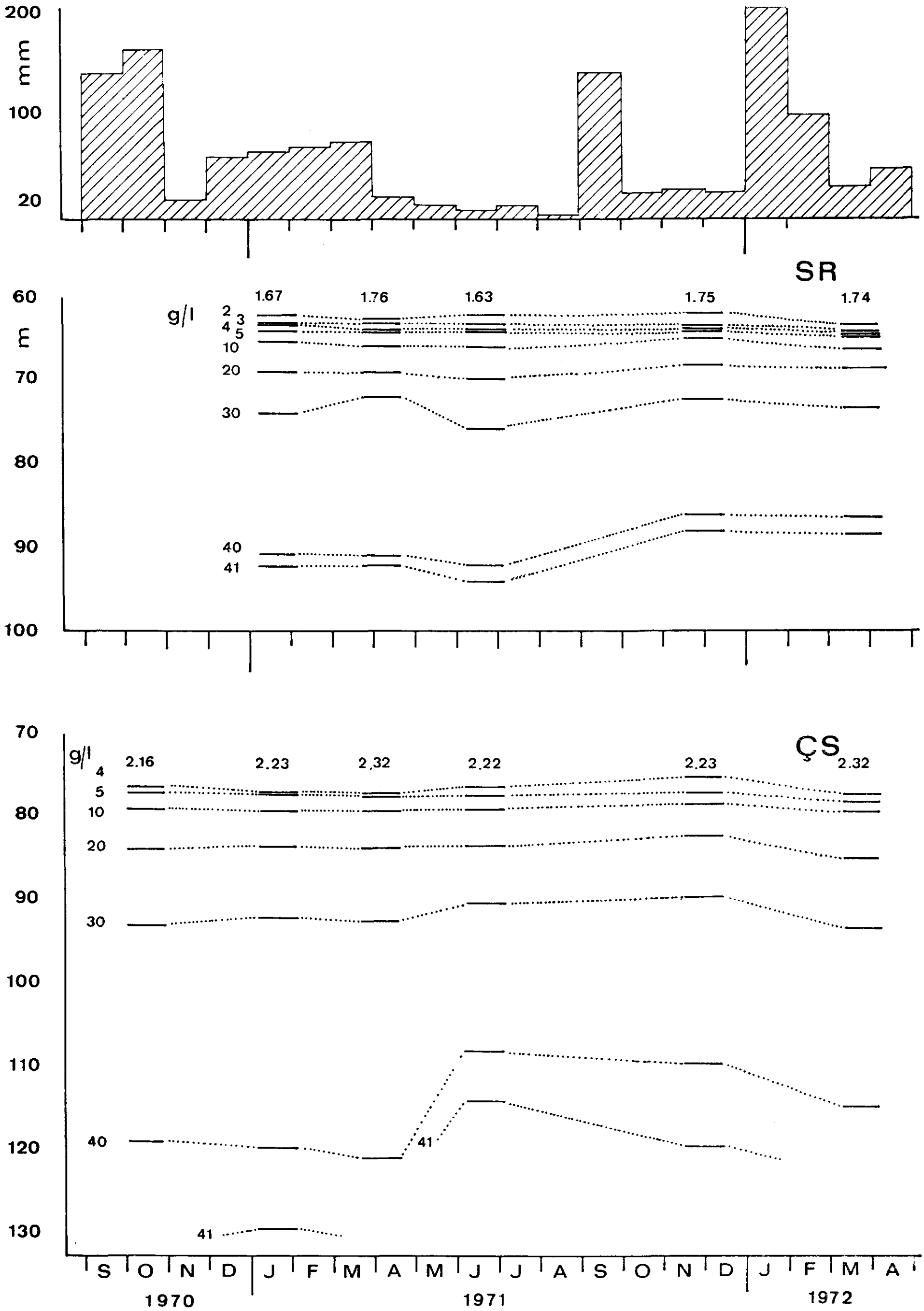


FIG. 7. — *Variations in the time of the trend of salinity stratification inside the diffusion zone of SR and CS wells; depths are referred to the water-table whose elevation is marked over each salinity stratification.*

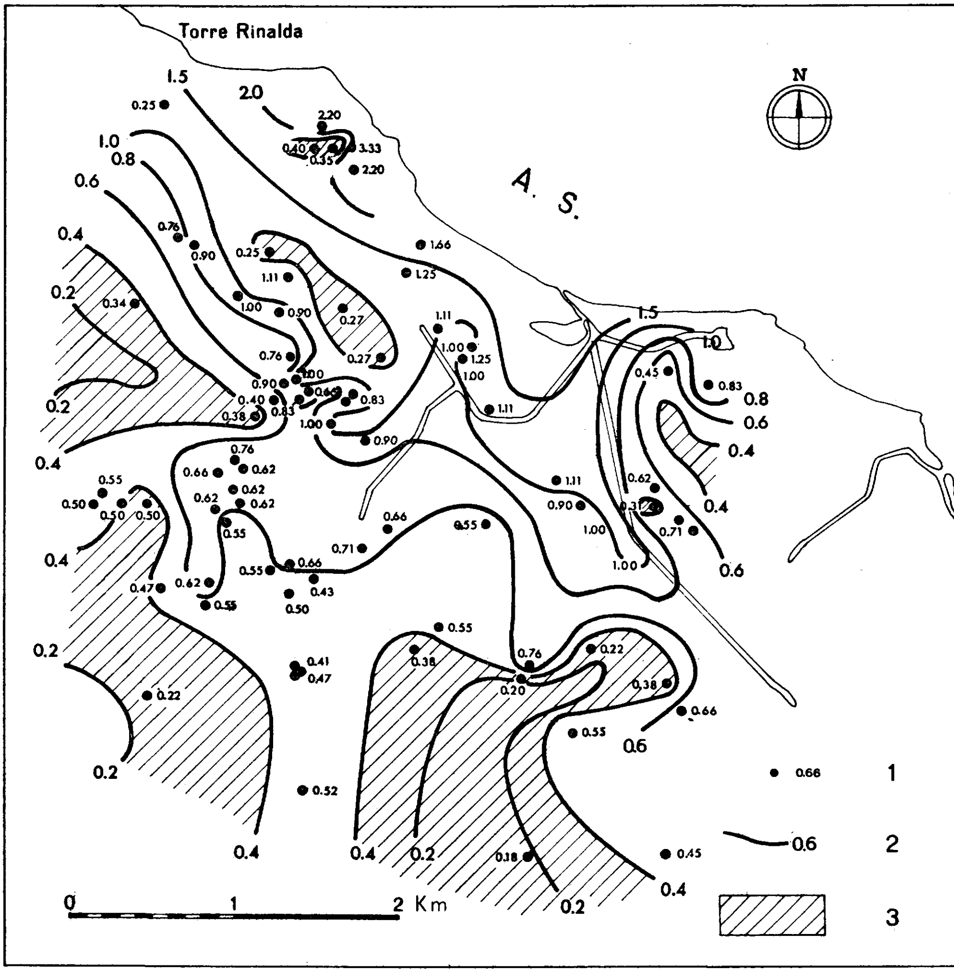


FIG. 8. — *Isodiabasic lines referred to Idume springs area. A.S., Adriatic sea; 1, location of well with the value of "communication"; 2, isodiabase; 3, low communication area (< 0.4).*

By comparing the data on the chemical composition of liquid and dry precipitations with those on groundwaters that are not polluted by intruding salt waters, it has been possible to establish that only a part of the groundwater recharge (about 60 %) derives from infiltration of the autumn-winter rainwaters (Cotecchia, Tadolini, Tittozzi, 1973).

Radio-isotope probes (neutron-thermal neutron probe; gamma-gamma probe) have found wide application in *in situ* measurements of primary and secondary permeability of rocks; parameters of great importance for estimating—albeit roughly—the storage capacity of the aquifers.

By logging the natural radioactivity of the carbonate aquifers it is possible to recognize the presence of terra rossa or marly limestone levels, which are indicated

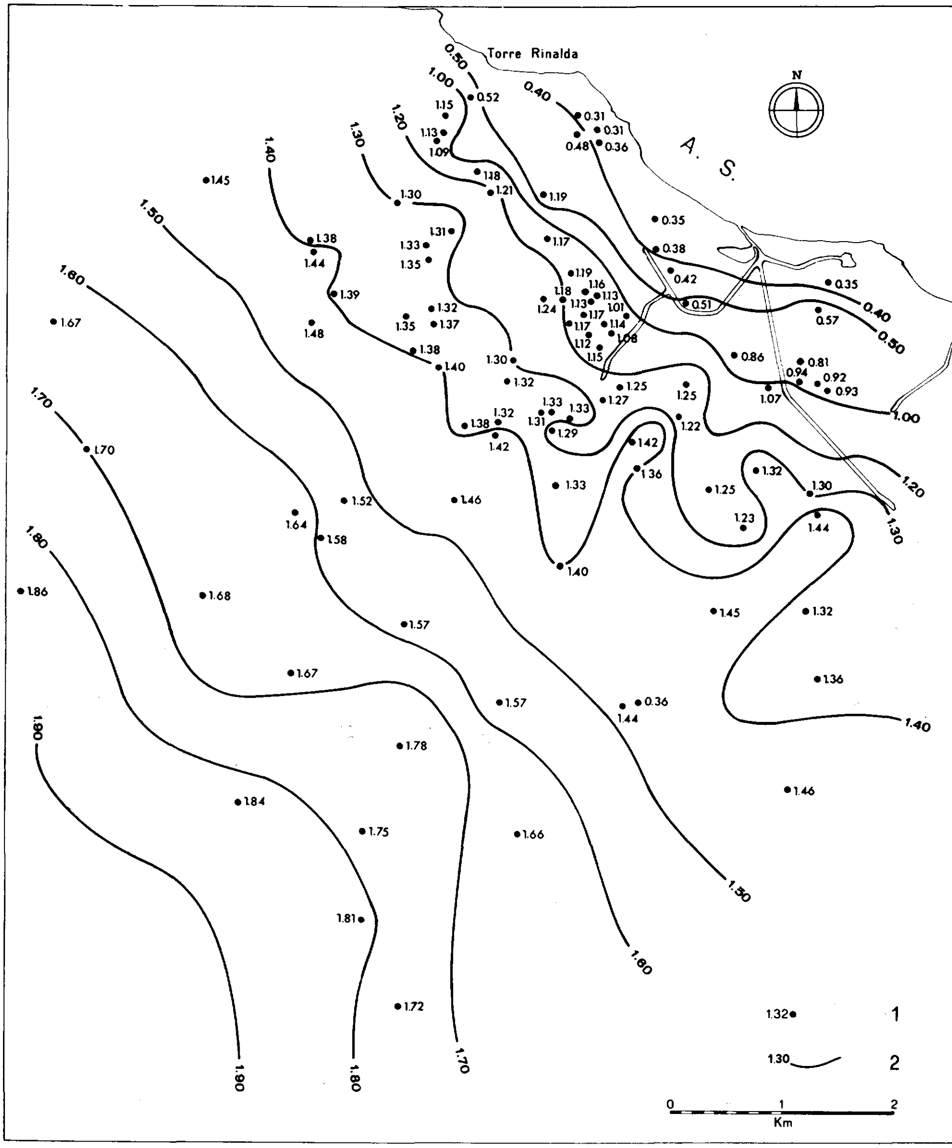


FIG. 9. — *Configuration of water table in April 1969 referred to Idume springs area. A.S., Adriatic sea; 1, location of well and altitude (m) of water-table; 2, trend of water-table contours.*

by an increase in radioactivity. In fissured rocks where the distribution of gamma radioactivity is homogeneous, reliable indications have been obtained on the degree of fissuring of the rock.

Methodologies based on artificial radioactive tracers have been used by us for many years, especially for measuring filtration velocities, vertical currents and the direction of groundwater flows (Cotecchia, 1969; Tazioli, 1973).

As is generally known, measurement of the dilution of a tracer in a single well provides data on the velocity of groundwater flow. In carbonate rocks where groundwater circulation often occurs along enlarged solution joints, it is apparent that only a broad indication is gained at to flow velocity, but this is none the less useful. In particular, in the Apulia region, measurement of the filtration velocity of "sea groundwaters" has provided invaluable information on the exchange between these and the sea in stretches of coast where very permeable formations are in outcrop.

For the correct interpretation of hydrogeological data obtained by measurements in wells, great importance attaches to the determination of ascending and descending currents therein—and this not only in the case of fissured carbonate formations. It is absolutely necessary to ascertain whether there are vertical currents when logging temperature or salinity or sampling water for chemical analysis, isotope determinations and so on. When wells are found to have vertical currents, temporary (Cotecchia, 1969; Tazioli, 1973) or permanent (Carlin, Tadolini, 1969) "cells" must be installed if correct data are to be obtained.

The measurement of vertical currents in wells also makes it possible to determine the distribution of hydraulic heads with depth, and to recognize possible interchanges between different aquifers, as well as to identify the most productive water levels.

By way of example, figures 10 and 11 show the trend of vertical currents at various depths in two wells drilled in Miocene calcarenites overlying Cretaceous dolomitic limestones. In both cases differences in the hydraulic head and the most productive levels are highlighted.

Measurement of the direction of groundwater flows using the single well method has proved particularly useful in aquifers with water levels at different piezometric heads, i.e. when the direction of flow in a well varies with depth. This phenomenon has often been observed in coastal wells where the movement of sea groundwater is influenced in various ways by the tides and by variations in atmospheric pressure.

Figure 12 indicates the data on two measurements in a well drilled 1 400 m inland from the Adriatic coast north of Lecce. In this case both the groundwater and the sea-groundwater flow towards a large spring (Tadolini, Tazioli, Tulipano, 1971).

Apart from artificial tracers, environmental isotopes have also been used, both radioactive (^{3}H, ^{14}C, ^{222}Rn) and stable (^{18}O, D, ^{13}C).

Among other things, by means of environmental tracers it has been possible to clear up certain aspects of intrusion of the carbonate aquifer by sea-waters, and to introduce the time factor in relationships linking the sea and groundwaters.

The CO_2 naturally present in groundwaters has been used in parallel with isotope investigations to clarify certain aspects of hydrogeological phenomena. Indeed, the CO_2 content of the groundwaters has often been measured along with the radon content, since it ensues that radon and CO_2 are more concentrated where the groundwaters are the most mobile (Magri, Tazioli, 1970). The importance of this fact in relation to the hydrogeology of carbonate rocks is very evident.

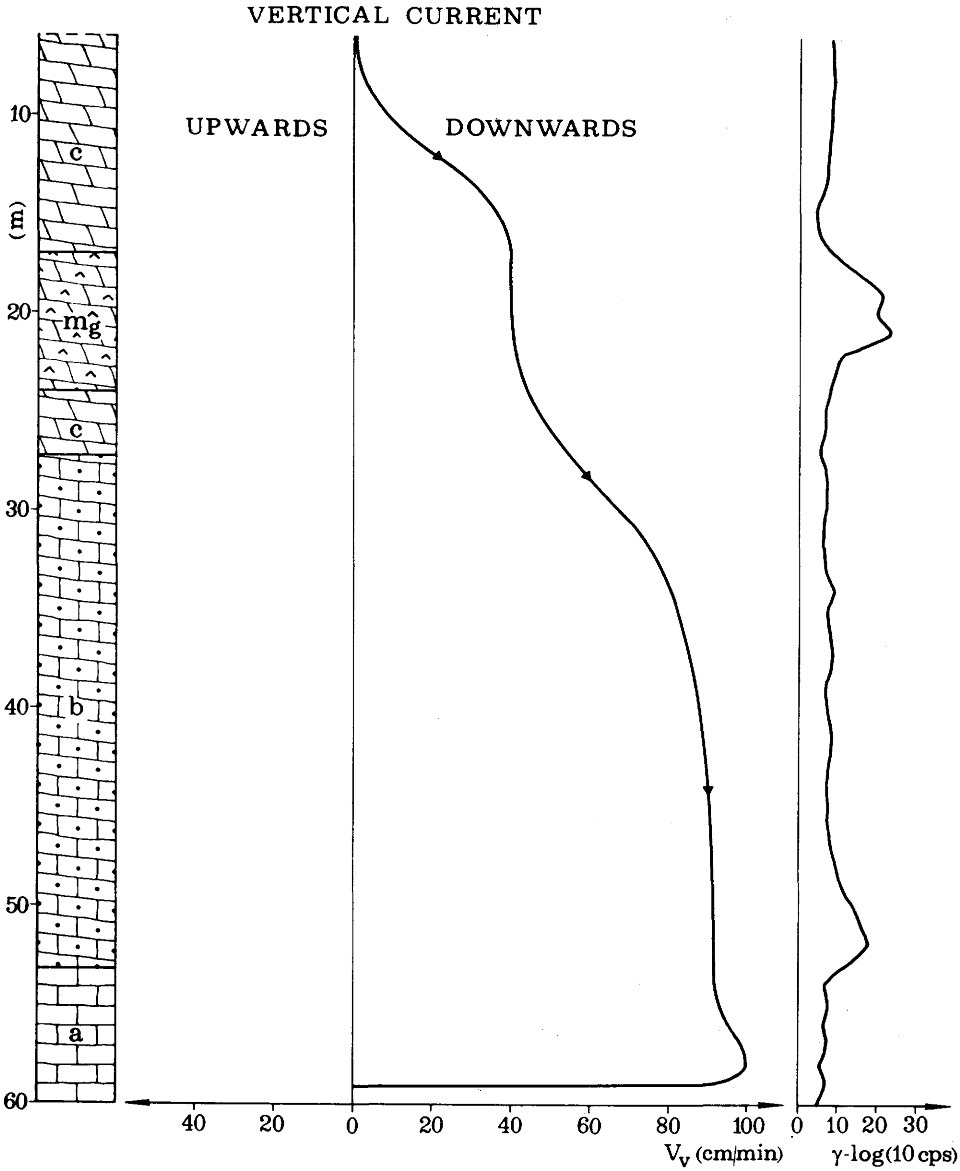


FIG. 10. — *Vertical current in the water and natural radioactivity of the aquifer, measured in a well, drilled at 3 km from the sea. In this situation the head of the shallow aquifer is obviously larger than the head of the deep aquifer. a, limestones and dolomitic limestones — Upper Cretaceous; b, marly calcarenites — Miocene; c, limestones and dolomitic limestones, calcarenites and calcirudites — Miocene;* m_g, *glauconitic-phosphatic calcarenites-guide horizon — Miocene.*

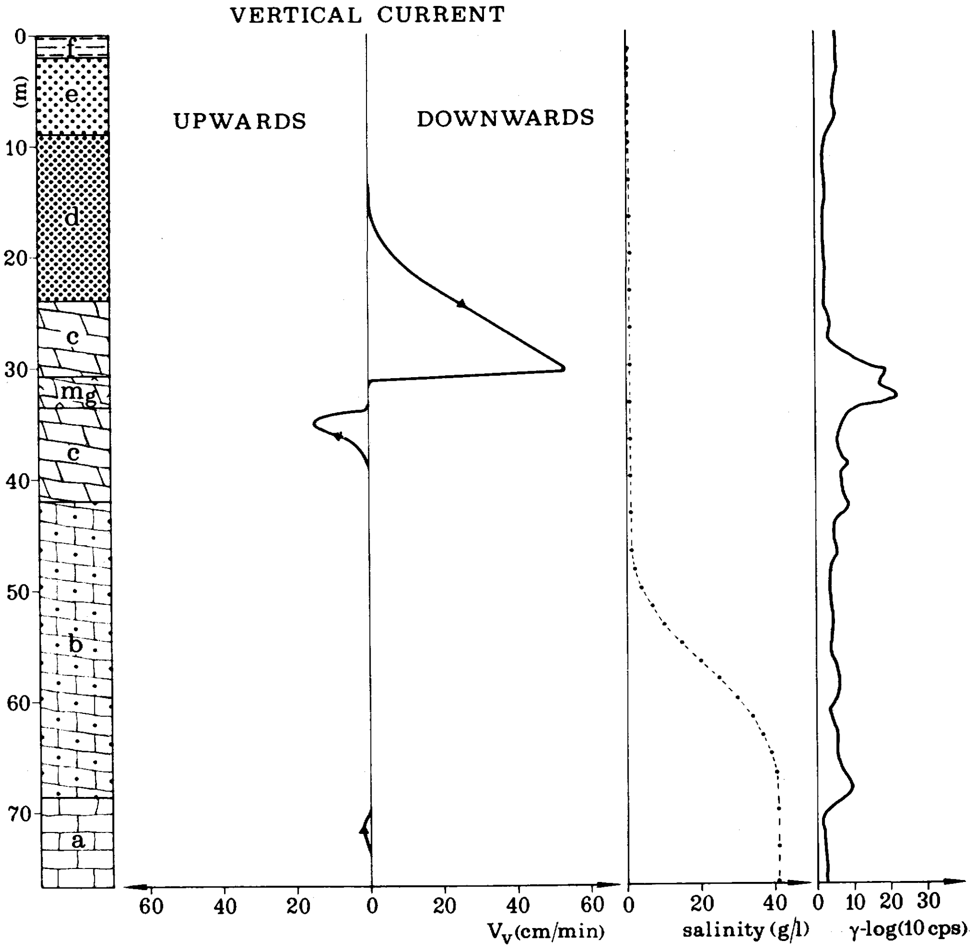


FIG. 11. — *Vertical currents, salt content and natural radioactivity measured in a well drilled at 1 400 meters from the sea. a, limestones and dolomitic limestones — Upper Cretaceous; b, marly calcarenites — Miocene; c, limestones and dolomitic limestones, calcarenites and calcirudites — Miocene; d, calcarenites and calcirudites — Miocene; e, very fossiliferous calcarenites and calcirudites — Pliocene; f, very fossiliferous calcareous "tufa" — Pleistocene.*

4. HYDROGEOLOGICAL OUTLINE OF SALENTINE PENINSULA

To demonstrate the results obtained with the techniques indicated above, a description is given of the most salient hydrological data of the central part of the Salentine Peninsula (south-eastern Apulia), by way of example.

Cretaceous calcareous and dolomitic rocks, bedded, fractured and karstified, and hence generally very permeable, form the basement of the Salentine Peninsula. Here a lot, continuous fresh and brackish groundwater floats on salt groundwater

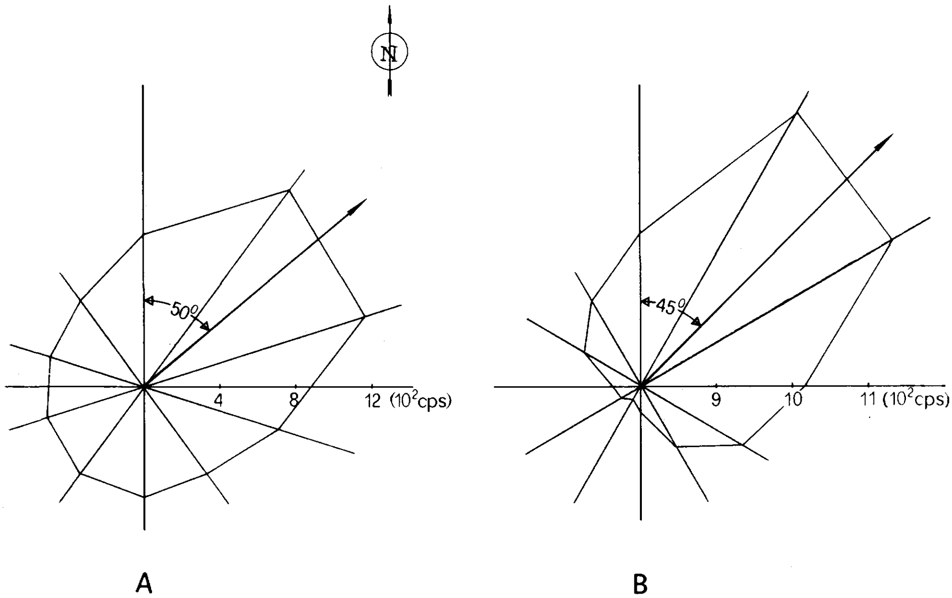


FIG. 12. — *Groundwater direction diagrams obtained in a well at the depth of 33 (A) and 75 (B) meters. The diagram A was obtained using iodine-131 and a gauge consisting of an annular array of tubes filled with activated carbon in granular form; the diagram B using bromine-82, detected by a collimate probe 12 hours after the injection.*

because of intrusion of the sea into the peninsula (fig. 13). The sea level thus constitutes the base level of the fresh and brackish groundwaters. The gradient of the water table is always less than 1 ‰ and locally may be as low as 0.1 ‰.

Mean annual rainfall is 620 mm, 26.6 % of which (165 mm) is received in spring and summer (from April to September) and 73.4 % (455 mm) in autumn and winter (from October to March). As evapotranspiration is much more marked in the spring-summer period (when the mean air temperature is 21.6 °C, against 11.9 °C in the autumn-winter period), it ensues that the groundwaters are recharged almost exclusively during the months of October to March inclusive.

The temperature of the main coastal springs ranges between 17.5 and 18.5 °C, seasonal variations being less than 0.3 °C. This shows that the springs are not fed directly by infiltrating waters but that they drain aquifer waters, as confirmed by the relatively constant discharges, notwithstanding the very considerable seasonal variation in rainfall.

The groundwaters are not recharged solely by the infiltration of rain on the outcrops of the permeable Cretaceous limestones and dolomites. Indeed, in the south-western part of the area shown in figure 14, recharge occurs also by concentrated infiltration in terrain that is not very permeable or which is practically impervious: runoff gathers in natural channels and reaches the aquifer via swallow holes.

In the north-eastern part of the area shown in figure 14, instead, recharge is mainly by subsurface flows that arrive from the extensive outcrop of limestone and dolomite, which receives good rainfall, located to the north-west of Mesagne.

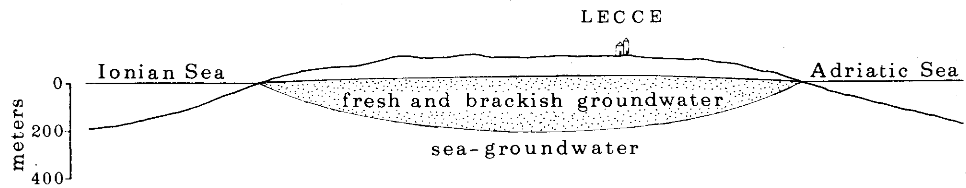


FIG. 13. — *Schematic hydrogeological section of Salentine Peninsula from Ionian Sea (I.S.) to Adriatic Sea (A.S.).*

Concerning connection between the groundwaters and the sea, along the Adriatic coast a strip of silty clay, sandy silt and calcarenite, irregularly permeable or practically impervious, overlying permeable limestone and dolomites lying beneath sea level, impedes outflow of the groundwaters to the sea. Indeed, outflow occurs mainly via a number of springs, the largest of which is the Idume Spring [ID. spring in the figures; discharge 1 000 l/s (Tadolini, Tazioli, Tulipano, 1971)]. The same situation is encountered along the Ionian coast starting from a point 5 km north-west of Porto Cesareo, where almost the whole seaward flow occurs through the Chidro (CH.) Spring [discharge 2 500 l/s (Cotecchia, Tadolini, Tazioli, Tulipano, 1973)]. In the Porto Cesareo area, however, where the limestones and dolomites outcrop right down to the sea, outflow occurs in diffused form or through numerous springs.

The outflow of groundwater occurs more readily and more abundantly towards the Ionian Sea, as is shown by the fact that though the aquifer is recharged most heavily in the south-westerly part, the underground watershed lies decidedly closer to the Adriatic Sea. However, the combined action of outflows towards the Ionian and Adriatic Seas is such as to attract underground flows both from the north-western and south-eastern areas of the peninsula, as shown by the trend of the water table contours and hence the direction of groundwater flows (fig. 14).

The waters of the coastal springs draining the aquifer, all brackish (rarely containing less than 2 g/l of salts and sometimes over 8 g/l), carry to the sea large quantities of water of marine origin, mixed with fresh groundwaters, because of the molecular diffusion and dispersion which occurs at the sea-groundwater/fresh-groundwater interface. A similar quantity of salt water, of course, then flows inland from the sea. In addition there is the sea water which moves to and from the land-mass because of seasonal fluctuations of the interface. The phenomenon is rendered apparent by the existence of marine estavelles in the Porto Cesareo-San Isidoro area, where the limestones and dolomites are in outcrop down to the sea (Carlin, Dai Pra, Magri, 1968).

The isotope data collected in the coastal strip of these areas confirm the existence of a very considerable interchange between the sea and the sea groundwaters, as attested to by the data obtained with oxygen-18, deuterium, carbon-13 and carbon-14 measurements (fig. 15).

Examination of the temperatures of the groundwaters in relation to recharge and groundwater circulation shows that the thermal regime is stationary (Carlin, Magri, Mongelli, 1973); this fact indicates that at present the hydrological regime is stationary, too. So on the whole, the same quantity of water flows seawards each year as infiltrates into the subsurface.

The chemical composition of the perched groundwaters, which have no connection with the sea or with the groundwaters of marine origin, is similar to that of the fresher waters floating on the groundwaters of marine origin (henceforth

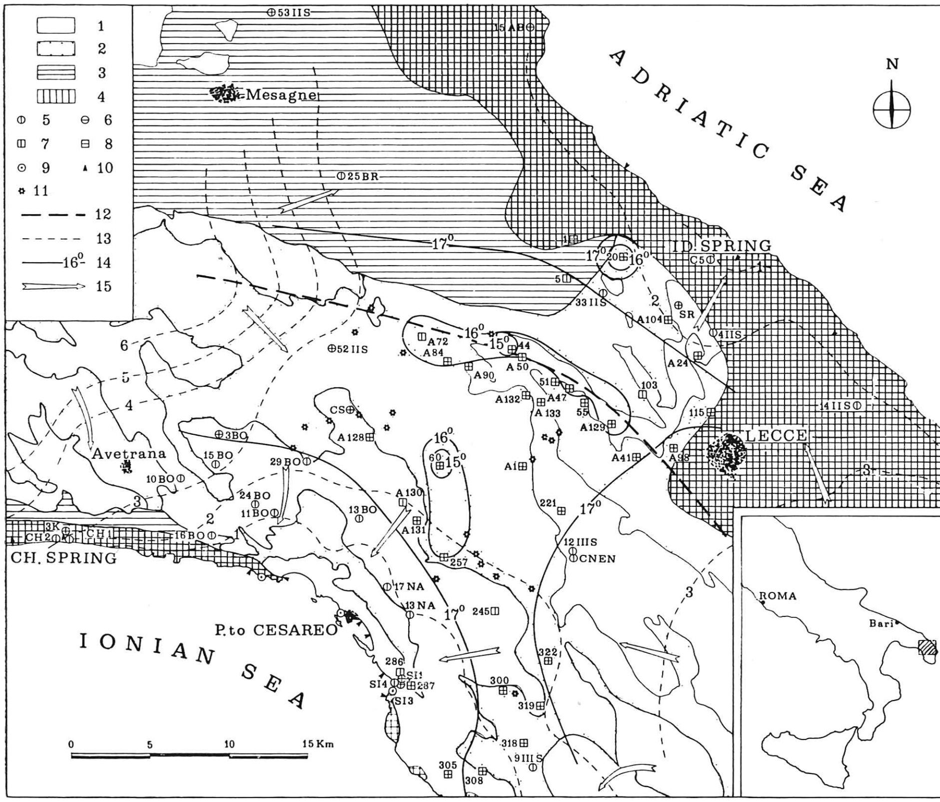


FIG. 14. — *Hydrological map of the central area of the Salentine Peninsula. 1, Cretaceous limestones and dolomites permeable because of fissuring and karstification; 2, Mio-Plio-Quaternary formations, slightly permeable through porosity (calcarenites), or practically impermeable (silt and clays), but permeable as far as the recharge of the deep aquifer is concerned since runoff is conveyed to the aquifer via swallow holes or via Cretaceous outcrops; 3, Mio-Plio-Quaternary formations slightly permeable through porosity, or practically impermeable, but completely impermeable to the effects of aquifer recharge. When permeable they contain small perched aquifers; 4, Mio-Plio-Quaternary formations slightly permeable, or practically impermeable, but entirely impermeable to aquifer recharge, covering Cretaceous limestones and dolomites lying below sea level and hence impeding outflow to the sea; 5, drilled wells in which temperature and environmental isotope measurements have been made; 6, drilled wells in which temperature measurements have been taken in air; 7, dug wells in which temperature measurement have been taken in water; 8, dug wells in which temperature measurements have been taken in air; 9, marine estavelles or groups of marine estavelles; 10, spring or groups of springs; 11, swallow holes conveying surface runoff to the aquifer; 12, outline of the underground watershed of the fresh and brackish groundwaters; 13, trend of water-table contours (in metres above sea level); 14, behaviour of the isotherms (in °C) of waters at water-table; 15, prevailing directions of ground flows.*

referred to simply as "sea-groundwaters"). Likewise, the chemical composition of the sea-groundwaters is more or less the same as that of the sea.

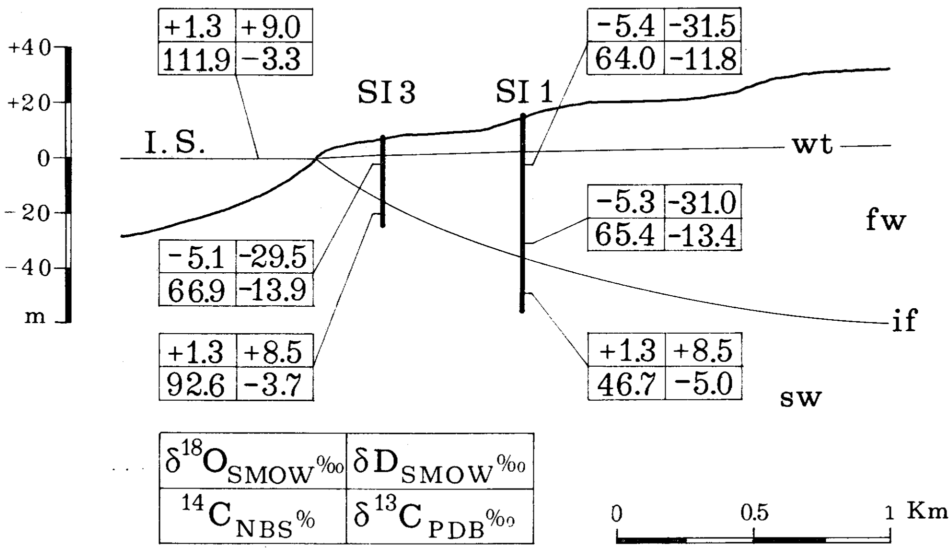


FIG. 15. — *Schematic section and isotope data of S. Isidoro area. I.S., Ionian Sea; wt, water-table; fw, fresh and brackish groundwater; if, interface; sw, sea-groundwater.*

5. INFORMATION ON THE PALEOHYDROGEOLOGY OF SALENTINE PENINSULA

It is known that in the Late Pleistocene important variations occurred in the sea level because of glacial eustasy, and locally because of tectonic movement. A fair amount is known about relative movements between sea and land in the Salentine Peninsula during the Tyrrhenian and Holocene (Cotecchia, Dai Pra, Magri, 1969-1971; Dai Pra, Magri, 1973). In particular, during the time of the last maximum regression, some 14 000 years ago, the sea was about 100 metres below its present level (fig. 1). Then commenced the Flandrian transgression, which brought the sea to its present level. This rise in sea level reduced the distance between the Ionian and Adriatic Seas by about one third and hence also reduced by the same amount the thickness of the fresh and brackish groundwater lens, which is a direct function of the distance from the coastline—naturally, for given values of discharge and permeability. So as the level of the sea rose during the Flandrian, the volume of fresh and brackish groundwater was reduced to less than half. Consequently, while on the one hand the seaward outflow was generally greater than the corresponding recharge, on the other, to compensate for the big reduction in volume of fresh and brackish groundwaters, the level of the underlying sea-groundwater rose, and inflow of sea water occurred (Cotecchia, Tazioli, Magri, 1974).

Let us consider now the isotope data (Cotecchia, Tazioli, Magri, 1974). In the central part of the peninsula and the Chidro Spring area the ^{14}C content of the sea-groundwaters is 5.5 % or lower. Even in the very unlikely case that only 50 % of the total carbon present in the water samples is of biogenic origin, this means that the age of the sea-groundwaters is 17 730 years or more. So the water predate the beginning of the Flandrian transgression. The sea groundwater of the Adriatic side instead shows a Flandrian age (C-5 Well; older than 3 500 years).

In the coastal area of the Chidro Spring and in the central parts of the peninsula, the sea-groundwaters have a higher heavy isotope content than present-day sea water. So these sea-groundwaters derive from old waters an ingressive sea when climatic conditions were different from those now prevailing.

References

CARLIN, F., DAI PRA, G. and MAGRI, G. (1968). — Segnalazione di polle inghiottitoi marini lungo la costa ionica della Penisola Salentina. *Quad. de la Ricerca scientifica,* Vol. XLIX.

CARLIN, F., MAGRI, G. and MONGELLI, F. (1973). — Temperatura delle acque sotterranee della Penisola Salentina. *Geol. appl. e Idrogeol.,* Vol. VIII, parte II.

CARLIN, F. and TADOLINI, T. (1969). — Soluzione tecnica adottata per la sistemazione di un pozzo perforato per studi idrogeologici. *Geol. appl. e Idrogeol.,* Vol. IV.

COTECCHIA, V. (1955). — Influenza dell'acqua marina sulle falde acquifere in zone costiere, con particolare riferimento alle ricerche d'acqua sotterranea in Puglia. *Geotecnica,* n. 3.

COTECCHIA, V. and ORABONA, O. (1959). — La stratificazione alina nelle falde con superfici di fondo rappresentate dall'acqua marina e precisazioni sul comportamento idraulico dei pozzi relativi a siffatte falde. *Ingegneria sanitaria,* n. 1.

COTECCHIA, V. and MAGRI, G. (1966). — Idrogeologia del Gargano. *Geol. appl. e Idrogeol.,* Vol. I.

COTECCHIA, V. (1969). — Metodologie e primi risultati delle ricerche sulle acque sotterranee della Puglia. *Quad. de la Ricerca scientifica,* Vol. LVIII.

COTECCHIA, V., DAI PRA, G. and MAGRI, G. (1969). — Oscillazioni tirreniane e oloceniche del livello mare nel golfo di Taranto, corredate da datazioni col metodo del radiocarbonio. *Geol. appl. e Idrogeol.,* Vol. IV.

COTECCHIA, V., DAI PRA, G. and MAGRI, G. (1971). — Sul Tirreniano della costa ionica salentina (Puglia). Datazione di un campione di coralli col metodo del $^{230}Th/^{234}U$. *Geol. appl. e Idrogeol.,* Vol. VI.

COTECCHIA, V., TADOLINI, T. and TITTOZZI, P. (1971). — Influenza del chimismo delle piogge sulle acque sotterranee della Puglia. *Geol. appl. e Idrogeol.,* Vol. VI.

COTECCHIA, V., TADOLINI, T., TAZIOLI, G. S. and TULIPANO, L. (1973). — Studio idrogeologico della zona della sorgente Chidro (Taranto). *2° Conv. int. sulle acque sotterranee,* Palermo.

COTECCHIA, V., TADOLINI, T. and TITTOZZI, P. (1973). — Precipitazioni secche in Puglia e loro influenza sul chimismo delle acque alimentanti la falda sotterranea. *Geol. appl. e Idrogeol.,* Vol. VIII, parte II.

COTECCHIA, V., TADOLINI, T. and TULIPANO, L. (1974). — The results of researches carried out on diffusion zone between fresh water and sea water intruding the land mass of Salentine Peninsula (Southern Italy). *Symp. on Hydrol. of Volcanic Rocks,* Lanzarote, Canary Islands, Spain.

COTECCHIA, V., TAZIOLI, G. S. and MAGRI, G. (1974). — Isotopic measurements in researches on sea water ingression in carbonate aquifer of Salentine Peninsula (Southern Italy). *Proc. Symp.,* Vienna, 1974, IAEA, Vienna.

DAI PRA, G. and MAGRI, G. — Spostamento verticale massimo del livello mare nella zona di Taranto durante gli ultimi 125 000 anni nella prospettiva della destinazione geologica di rifiuti contenenti transuranici. Comit. Naz. En. Nucl. RT/PROT (73) 24.

MAGRI, G. and TADOLINI, T. (1969). — Influenza della pressione atmosferica sui livelli della falda profonda della Penisola Salentina. *Quad. de la Ricerca scientifica*, Vol. LVIII.

MAGRI, G. and TROISI, S. (1969). — Sulla influenza delle fluttuazioni di specchi d'acqua sui livelli delle falde costiere. Applicazione allo studio della circolazione idrica sotterranea, nella Penisola Salentina. *Geol. appl. e Idrogeol.*

MAGRI, G. and TAZIOLI, G. S. (1970). — Radon in groundwater of dolomitic and calcareous aquifer in Apulia (Southern Italy). *Isotope Hydrology* (Proc. Symp. Vienna, 1970), IAEA, Vienna.

TADOLINI, T. and TULIPANO, L. (1970). — Primi risultati delle ricerche sulla zona di diffusione della falda profonda della Penisola Salentina (Puglia). *Conv. int. sulle acque sotterranee*, Palermo.

TADOLINI, T., TAZIOLI, G. S. and TULIPANO, L. (1971). — Idrogeologia della zona delle sorgenti Idume (Lecce). *Geol. appl. e Idrogeol.*, Vol. VI.

TAZIOLI, G. S. (1973). — Metodologie e tecniche radioisotopiche in Idrogeologia. *Geol. appl. e Idrogeol.*, Vol. VIII, parte II.

ZEZZA, F. (1973). — Su talune facies d'ambiente cotidale-lagunare della piattaforma carbonatica murgiana. *Boll. Soc. geol. it.*, Vol. XCII.