VINCENZO COTECCHIA

Geohydrological aspects of the cretaceous limestone aquifer in Apulia, and their bearing on the practical avoidance of sea water contamination in extraction from wells and springs

Estratto dai
"Quaderni di geofisica applicata"
Vol. XXIV - 1963

Editi dalla FONDAZIONE ING. C. M. LERICI e dall'ISTITUTO DI GEOFISICA APPLICATA DEL POLITECNICO DI MILANO

MILANO - VIA BONARDI 15

Stampato dalla
EDITRICE POLITECNICA TAMBURINI - MILANO - 1963

VINCENZO COTECCHIA *

Geohydrological aspects of the cretaceous limestone aquifer in Apulia, and their bearing on the practical avoidance of sea water contamination in extraction from wells and springs**

SUMMARY

A general geohydrological outline of the region, with particular reference to the partially karst limestones of the Cretaceous, is followed by a discussion of the problems of sea-water intrusion in relation to groundwater behaviour in the limestone aquifer. An analysis is made of the Ghyben-Herzberg equilibrium as applying to aquifer discharge and to water table fluctuations; the modifying effects of sea-water intrusion on the G. H. relation are examined.
In view of the saline stratification of the aquifer, certain practical methods have been adopted in the region to reduce the salinity of water drawn from wells or springs. The basic principles tested in this connection are summarized, as well as the methods of checking the interface position. In conclusion, it is stressed that extraction from deep aquifers such as that in Apulia should be planned and operated collectively.

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

(**) Report presented to the Panel of groundwater geologists' on Mediterranean karst hydrogeology. FAO-UNSF. Athens, March 1963.

GLI ASPETTI IDROGEOLOGICI DELLA FALDA ACQUIFERA CONTENUTA NEI CALCARI CRETACICI DELLA PUGLIA E GLI ACCORGIMENTI PRATICI CHE NE DERIVANO AL FINE DI EVITARE NEI POZZI E NELLE CAPTAZIONI DI SORGENTI L'INFLUENZA DELL'ACQUA MARINA

SOMMARIO

Premessi nella parte I i caratteri geoidrologici generali della regione pugliese, con particolare riferimento ai calcari del Cretacico (in genere fortemente permeabili per fessurazione, solo localmente carsici), nella parte II del lavoro si illustra il comportamento idrogeologico della falda acquifera che nei calcari ha sede, in relazione alla invasione marina del continente. Vengono quindi esposti interessanti sviluppi e conseguenze dell'equilibrio di GHYBEN-HERZBERG, *in relazione a talune fondamentali modalità di deflusso della falda e ai caratteri di permeabilità dei calcari. In particolare, sulla base di semplici riferimenti analitici e di convincenti osservazioni pratiche svolte per un sufficiente numero di anni sui pozzi e sulle sorgenti della regione, si giunge a conclusioni che, a parte i riferimenti alla Puglia, presentano alcuni aspetti di validità generale in merito al regime idraulico di falde acquifere nelle condizioni descritte.*

Nella parte III del lavoro vengono trattati i limiti di validità e i criteri di correzione della relazione di G. H., sulla scorta di esperienze dirette svolte in merito alla effettiva stratificazione alina della falda e alla zona di diffusione *fra quest'ultima e l'acqua marina. Vengono così illustrate le apparenti anomalie nelle altezze idrauliche della acqua dolce, derivanti particolarmente dalla presenza e dai caratteri specifici della* zona di diffusione.

In conseguenza della stratificazione alina della falda acquifera e degli effetti che detta stratificazione ha sul pompaggio da pozzi, particolari accorgimenti pratici sono in uso in Puglia per ridurre il contenuto salino delle acque estratte dalla falda. Questo argomento è trattato nella parte IV del lavoro, laddove, premesse la inidoneità di taluni accorgimenti noti, la ampia diffusione di pozzi trivellati, le modalità di uso di questi nella regione, si espongono gli orientamenti pratici per evitare l'eccessiva influenza salina sulle acque pompate da pozzi, nonchè si descrivono le opere di captazione alle sorgenti e quelle della falda con cunicoli drenanti. Infine si illustra la accertata possibilità di controllare la posizione della interfaccia *con la geofisica.*

Nelle conclusioni viene richiamata l'attenzione sulla opportunità che le opere di captazione, in casi di falde acquifere del tipo della falda profonda della Puglia, si eseguano e si usino in forma collettiva.

Part I

GENERAL GEOHYDROLOGICAL OUTLINE OF THE REGION

1.1 Geological features.

This paper is concerned especially with the area known as the « heel » of Italy, namely, the long narrow section of Apulia running NW-SE following the axis of the Apennines, from the right bank of the River Ofanto to Cape S. Maria at Leuca (Fig. 1). With a length of 250 km and a width varying from

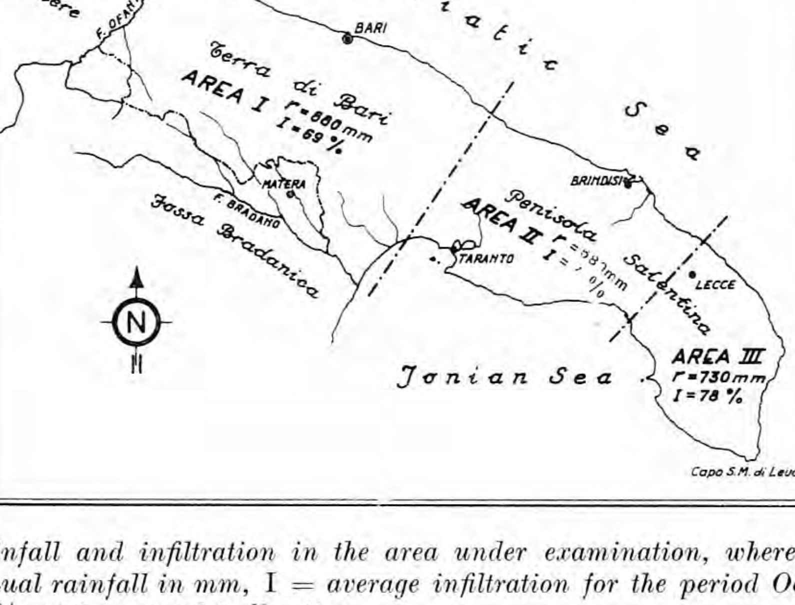


Fig. 1 - Rainfall and infiltration in the area under examination, where r = *average annual rainfall in mm,* I = *average infiltration for the period October-March, in* $^{0}/_{0}$ *of the annual infiltration.*

35 to 50 km, it has a coastline of almost 500 km washed by the Adriatic and Ionian Seas. This region comprises the *Bari district*, the *Salento Peninsula*

and the *Taranto Coast*, and its physical relief consist of low, flattish hills. In the *Murge* hills (Bari area) only a few peaks exceed an elevation of 680 m, while the highest point of the *Serre* hills in the Salento Peninsula is no more than 200 m (Serra dei Cianci).

The Murge and Serre are formed basically by a slight continental folding of Cretaceous limestones — and to a limited extent of Eocene-Oligocene limestones — extending from the Apennines to the Dalmatian-Albanian region. This limestone platform — defined as the foreland of the Apennines — is characterized by tectonic Alpine folding, of which the anticlines form the Murge and Serre. The limestones drop between the Murge and the Apennines, through a system of faults producing a horst and graben structure running in the direction of the Apennines, roughly parallel to the River Bradano on the southwest border of Apulia. This structure underlies the predominantly clayey formations of the Mio-Pliocene and Calabrian which fill the so called *Fossa Bradanica.* The limestones of the Murge also dip, on the left of the Ofanto, through a system of secondary faults normal to the previous ones, and continue under the mainly Pliocene and Quaternary sandy-clayey formations of the *Tavoliere di Foggia.*

The Cretaceous outcrops in Apulia include more or less consolidated limestones sometimes slightly dolomitic, having a microcrystalline and cryptocrystalline structure. Dolomitic limestones and dolomites are less frequent. The beds are broadly folded, sub-horizontal or inclined not more than 20° to 25°, and intensely fractured. The small outcrops of Eocene and Oligocene coralline limestones are mostly restricted to the coast between Otranto and Leuca. Lithologically speaking, these limestones closely resemble the cliff limestones of the Cretaceous. In the Province of Lecce, these Cretaceous limestones are directly overlain by soft fine-grained arenaceous limestone of the Miocene. This is slightly marly and very little fissured, and its outcrops almost invariably occur in level or gently sloping areas. Locally it goes under the name of *pietra Leccese.*

Scattered here and there among the Murge, but much more frequently in the Serre, there are numerous Pliocene and Pleistocene formations which represent all that is left of a once extensive mantle of rock waste deriving from calcareous tufas and sandy clays, deposited following the well-known marine transgression which began in Apulia at the commencement of the Pliocene.

1.2 Precipitation.

The rainfall pattern falls into three areas, as follows: *a*) the Murge (Area I); *b*) between a line from Brindisi to Taranto and a line from Gallipoli to Otranto (Area II); *c*) the South of the Salento peninsula (Area III) (See Fig. 1).

In the first area the rainfall ranges from over 750 mm in the center to 600 and 500 mm proceeding towards the Adriatic and Ionian coasts. In the Salento plain (Area II) it is more uniform, with an annual rainfall of little more than 600 mm. In the South of the peninsula there is a zone of higher rainfall which exceeds 800 mm in certain points.

Most of the rain during the year falls between October and March. These months account on average for 70 % of the annual total, and it is only this rainfall which is of interest in connection with recharge of the deep aquifer of the area.

1.3 Permeability and infiltration of the Apulian limestones.

The geological formations with which this paper is mainly concerned are Cretaceous limestones and dolomitic limestones, together with the small Eocene-Oligocene limestone outcrops which are lithologically similar that they can virtually be taken as identical. These limestones mostly contain deep tectonic fractures which combine with the bedding joints to make up a complete and fairly uniform network of fissures through which groundwater movement takes place.

The dimensions, frequency and orientation of these fractures vary according to different factors. The tectonic fractures go down to considerable depths (as it has been demonstrated by test drillings recently carried out for oil exploration), whereas the occurence of karst phenomena is mainly restricted to the top 100-200 m of the limestone. Isolated vertical openings, dissolved out into rifts of varying sizes and large sinks, are found in the Murge. The presence of large and extensive horizontal cavities in any number can, however, be ruled out, apart from a few isolated cases such as the Castellana Caves. Naturally, these openings have developed from already existing tectonic fractures, and it is in these areas where most of the recharge to the deep aquifer takes place.

A thick deposit of red soil, which is generally impermeable, is often found filling these fissures.

Groundwater exploration recently carried out in Apulia has borne out the belief, aquired for some time by certain scholars, that the fissures in the Cretaceous limestones in the Salento and Bari areas are mostly interlinked. In this way they are entirely saturated with water at the bottom, forming a large groundwater reservoir, which has been named the *deep aquifer* to distinguish it from the aquifers not very extensive and important in the Tertiary and Quaternary formations above.

Now, while it is true that the Murge limestones contain large open fissures and cavities, there are good reasons for believing that the flow of groundwater through the fissured limestones is in most cases laminar. This is because the flow mainly takes place along the bedding plains, which are usually sub-horizontal.
We refer to the vertical diaclases and specially to the most frequent diaclases

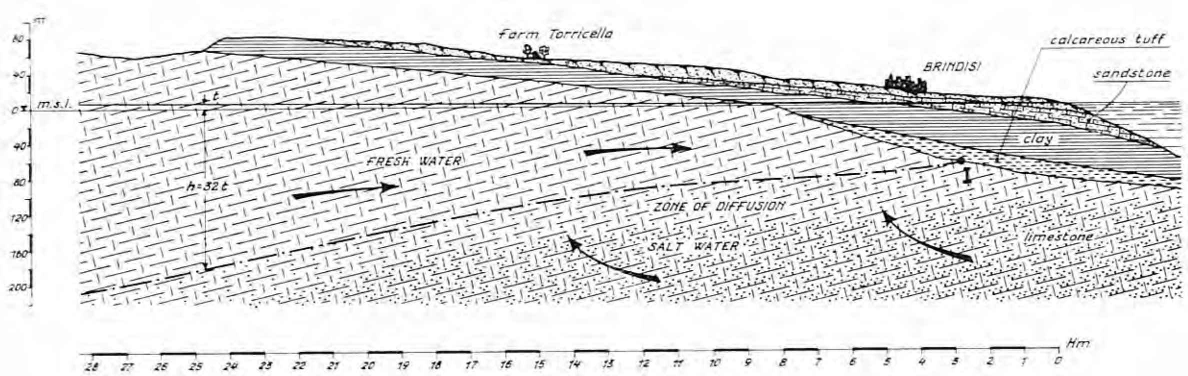


Fig. 2 - Geo-hydrological section near Brindisi.

limited to the layer thickness forming, with the latter, a group of parallelepipeda. We do not consider the wide discontinuities in the lithoid mass.

The aforesaid diaclases contribute very little to the movement of the underground water towards the shore but influence sensibly the water movement in the working wells.

With the exception of the phenomena concerning the big diaclases, in most cases the natural movement of the aquifer takes place along the bedding plains, where there are incoherent deposits of different kinds (small lithoid fragments, red soil, etc), therefore owing to the low hydraulic gradient (around $0.3 \div 0.5\ ^{0}/_{00}$) and the effects of the G-H equilibrium (to be discussed later), the valid movement law will be Darcy's law. In most cases, the rate of infiltration is of the order of a few meters per day.

With regard to recharge of the deep aquifer in the Cretaceous limestones, it must first be stated that the only permeable rocks of post-Cretaceous age to be taken into consideration are those directly in contact with the limestone base, i.e. those constituting a potential source of recharge for the deep aquifer in the limestones. The sandy and gravelly Pleistocene formations stretching over a wide area inland from Brindisi (Fig. 2) are a case in point. These porous deposits are more or less highly permeable, but they are always divided from the fissured Cretaceous limestone base by grey-blue sandy clays of the Pleistocene. The effect of these clays is to trap rainfall recharge in aquifers near the surface, and prevent percolation to the deep aquifer in question.

The same considerations apply to the large number of outcrops of permeable calcareous tufas occurring in the Murge, whereas the reverse is true of the organogenic limestones (Plio-Pleistocene) outcropping right in the center of Area III (Salento peninsula — see Fig. 1). These limestones are porous and permeable in some places and compact in others, but they are often directly in contact with the Cretaceous limestones. In most cases they contain fractures and karst phenomena and thus can be considered as sources of recharge for the deep aquifer.

The *pietra leccese*, which is only slightly permeable (through fissures), is likewise in direct contact with the Cretaceous limestones. To sum up, in the light of the knowledge gained by groundwater investigations to date, the only source of replenishment to the deep aquifer in the first two of the areas indicated above is rainfall recharge coming through the Cretaceous limestones. With regard to the Lecce area, on the contrary, the permeable formations include not only the fissured Cretaceous limestones but also the Plio-Pleistocene organogenic limestones and calcareous sandstones, as well as the *pietra leccese*. The coefficients of infiltration of these formations have not yet been ascertained with any certainty. For the Cretaceous limestones in the Murge many researchers have agreed on an average annual coefficient of infiltration of the order of 50%, and even 60%.

Considering prudently that the direct penetration of water to the aquifer is restricted to the period from October to March, with an infiltration through the limestones equal to 50% in Area I and 45% in Areas II and III, and assuming infiltration coefficients of 50% for the organogenic arenacious limestones in the Lecce area, and 10% for *pietra leccese*, the average annual recharge of the deep aquifer in the region is not less than 1,600-1,700 $\times 10^6$ cu. m.

Part II

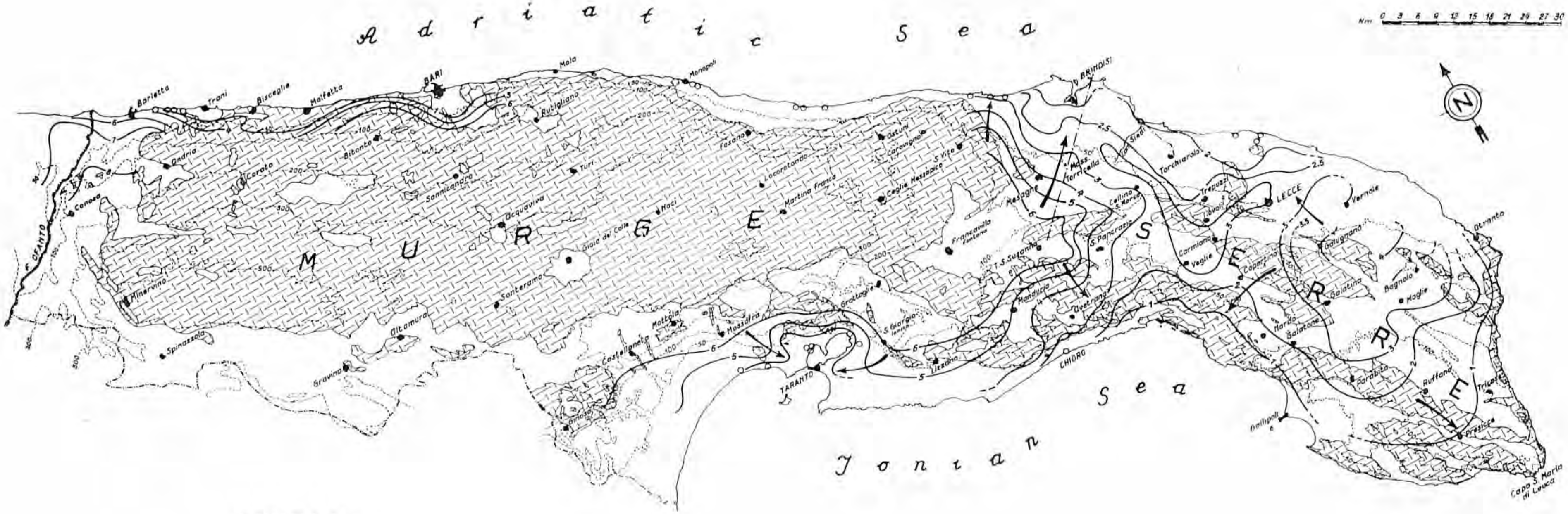
BEHAVIOUR OF THE LIMESTONE AQUIFER

2.1 The deep aquifer and sea water intrusion.

Generally speaking, the outlets of this aquifer are where the limestone outcrops reach the sea. Hence, the water table surface rises very gradually inland (with a hydraulic gradient of around $0.3 \div 0{,}5\ ^{0}/_{00}$) due to the high permeability of the waterbearing formation. To the latter factor is also due the almost total absence of surface water courses. The gradual slope of the aquifer, in relation to the surface relief, accounts for the complete absence of springs in the areas away from the coast. The sea level represents the hydrographic datum in Apulia, and the water table, or the piezometric surface of the *deep aquifer*, which often coincides with the water table, tends towards this level.

This aquifer floats on the encroaching sea water, roughly in accordance with the differing densities of sea water and fresh water [4]. Investigations over the last ten years have thrown much light on the intrusion of sea water into the fractured limestones of which Apulia consists. It has been ascertained that the Ionian Sea communicates with the Adriatic beneath the Salento peninsula. Sea water has also been found in the limestone at a depth of over 1,000 m below the impermeable formations of the *Tavoliere di Foggia* at a considerable distance from the sea. Sea water has even been found in the waterbearing stratum at a depth of over 2,000 m in the oil test drilling sunk by AGIP Mineraria at Gaudiano in the Ofanto Valley, in the Northeast corner of the area studied in this report; this drilling lies about 45 km from the sea.

The way in which the Cretaceous limestones disappear below younger impermeable deposits in the vicinity of the coast, generally halts the normal seawards flow of the aquifer. The fresh water is therefore almost invariably compelled to skirt round the impermeable barriers and discharge directly into the sea around their edges, more or less at sea level (see Fig. 3). Only when the impermeable overburden along the coast is a little above sea level (by a few meters or fractions of a meter) the groundwater spills over the underground barrier, outflowing as tipical *overflow springs for stratigraphic damming*, or else penetrates through it in the form of artesian springs.



LEGEND:

Outcrops of Cretaceous and subordinately Eo-Oligocene limestones
Piezometric contour lines
o Springs
Traces of the explained sections in the text.

Fig. 3 - Piezometric contour lines

The GHYBEN-HERZBERG relation (*G-H* for short) assumes, for the sake of simplicity, a density of 1 for the fresh groundwater, giving $(h + t) \times 1 = h \times \rho_s$. Since $\rho_s = 1.0299$ kg/l and 1.0307 kg/l for the Adriatic and the Ionian Sea respectively, this works out at theoretically $h = 32\text{-}33\ t$. This, however, disregards the fact that the groundwater in Apulia has a fairly appreciably saline content, with the density increasing with depth. This salt contains a high percentage of NaCl, which is to be attributed primarly to *saline transmission* from sea water, as far as the upper levels of the aquifer are concerned.

The transmission of salt from saline water to static fresh water may proceed very slowly, but eventually reaches a high level. In aquifers such as that in Apulia a certain saline equilibrium is eventually reached, as the result of the continual replenishment of fresh water by percolation, and depending on the rate of this inflow. In this connection, areas have been traced in Apulia where particular geological conditions slow down groundwater flow, for example inland from Barletta, where the saline concentrations at various depths of the aquifer are higher than elsewhere. This argument is not entered into more deeply here in view of the general nature of this study.

2.2 INFLUENCE OF THE GHYBEN-HERZBERG EQUILIBRIUM ON THE HYDRAULIC REGIME OF THE AQUIFER.

The lack of some of the essential hydrological data, particularly as concerns the fluctuations in level of the interface, prevents an exhaustive discussion of the present hydraulic behaviour of the aquifer in question (the average annual variation in the water table, or piezometric surface, is apparently around 40 cm, apart from a few peaks).

Considering the average percentage of voids throughout the limestone aquifer as of the order of 5-10 % (which is a fairly high average), the aforesaid rise in the aquifer surface, limited to the area where it is unconfined, constitutes an increase in groundwater storage of 150-300 $\times 10^6$ cu. m at the most. In order to make a comparison between this volume and the annual subsurface inflow of at least 1700 $\times 10^6$ cu. m, it would be necessary to make hydraulic calculation for which we dispose of a few hydrologic data. However, in view of the great discrepancy between these two volumes of water, it seems clear that the variation of the interface level (governed at least partly by the static equilibrium expressed in the *G-H* relation) is of considerable importance with regard to the annual groundwater inventory between recharge, outflow and extraction (the latter being of relatively minor importance).

If two aquifers of equal permeability are taken, the first with a *definite and fixed bottom* (impermeable horizontal substratum) ([1]) and the second, as in the case of the deep aquifer in Apulia, with a *definite and variable bottom*, represented by the *G-H interface* (Fig. 4), it is obvious that in the first case (case *a*) an inflow will simply cause a rise in the hydraulic gradient, while in the second case (case *b*) the level of the bottom will fall. Groundwater inflow thus causes a smaller rise of the piezometric slope in the second case than in the first.

With regard to the theoretical application of the *G-H* relation, it is interesting to note that, conditions being equal, a given subsurface inflow through a cross section of the aquifer at a distance *L* from the coast, will cause a piezometric slope in an aquifer resting on salt water equal to about 1/6th of that caused in an aquifer resting on an impermeable floor (all at sea level).

Assuming that the Dupuit — Forchheimer theory concerning groundwater movement is broadly acceptable, i.e. assuming that the vertical compo-

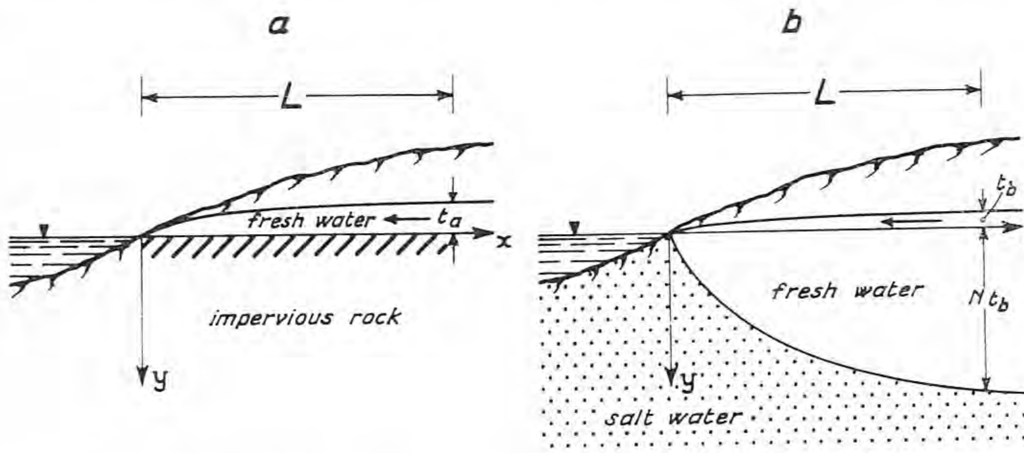


Fig. 4 - Comparison between aquifer with horizontal, fixed and definite bottom surface and aquifer with unstable, definite bottom surface according to Ghyben-Herzberg relation.

$$\left(For\ N = \frac{\rho_s}{\rho_s - 1} = \frac{1.03}{1.03-1},\ the\ result\ is\ t_b \simeq \frac{1}{6} t_a \right).$$

nent of the velocity of filtration is always negligible, and the horizontal component constant in all points of the same vertical (which is, in fact, true in areas distant from the aquifer outlet to the sea), the two cases (*a*) and (*b*)

(1) It represents one of the most frequent conditions, specially in the case of aquifers in coastal alluvial strata, when the impermeable substrata are either subhorizontal or slightly sloped in the direction of the aquifer movement.

in Fig. 4([2]) in accordance with Darcy's law, give rise to these equations:

Case (*a*)

$$q = f\, t_a\, i_a = f\, t_a \frac{dt_a}{dx} = \frac{1}{2} f \frac{dt_a{}^2}{dx} \text{ hence } t_a{}^2 = \frac{2\,q}{f}\, x \tag{1}$$

Case (*b*)

$$q = f\, N\, t_b\, i_b = f\, N\, t_b \frac{dt_b}{dx} = \frac{1}{2} f\, N \frac{dt_b{}^2}{dx} \text{ hence } t_b{}^2 = \frac{2\,q}{f} \cdot \frac{1}{N}\, x \tag{2}$$

indicating by f the coefficient of permeability, q discharge through strips of equal width in each case, $N = \dfrac{\rho_s}{\rho_s - 1}$ where ρ_s is the density of sea water and 1 the fresh water density, and t_a, t_b and i_a and i_b the elevations of the water table above sea level and the hydraulic gradients in the points considered.

From the above expressions:

$$\frac{dt_a}{dx} = i_a = \frac{q}{f}\,\frac{1}{t_a}; \qquad \frac{dt_b}{dx} = i_b = \frac{q}{f}\,\frac{1}{N}\,\frac{1}{t_b};$$

from which, equivalating q/f, we get:

$$i_b = \frac{1}{N}\,\frac{t_a}{t_b}\, i_a \,.$$

From (1) and (2) it follows that $t_a/t_b = \sqrt{N}$, and hence, substituting (3), we get:

$$i_b = \frac{1}{\sqrt{N}}\, i_a \quad \text{that is, for} \quad \rho_s = 1.03 \text{ g/cm}^3, \quad i_b \simeq \frac{1}{6}\, i_a.$$

To complicate the matter, however, when sea water is present below the fresh water aquifer, there occurs the well-known *delay* in the movement of the interface to conform with the *G-H* relation. Thus, if the water mass in the fresh water aquifer, resting in perfect static equilibrium on the sea water, receives some recharge, it will take a certain time before equilibrium is re-

([2]) The two extreme flow lines in Fig. 4 are two parabolas with their horizontal axes coinciding with sea level [2].

established between the new elevation t of the water table and the depth h of the interface ($h = 32\,t$). This is due to the time needed for the enormous mass of sea water underlying the aquifer to move out and make way for the increased volume and weight of fresh water (Fig. 5).

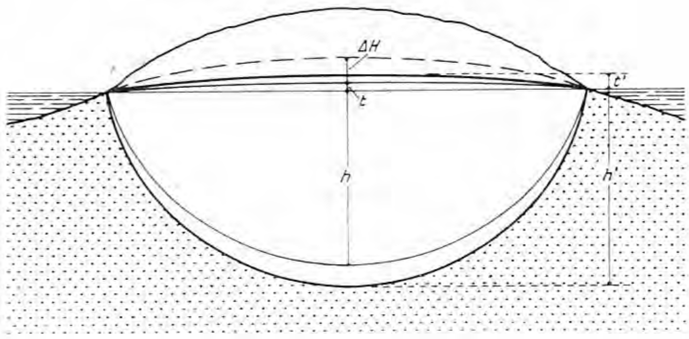


Fig. 5 - Not considering the « delay » phenomenon, there would be a new arrangement of the underground fresh water given by:

$$t' = t + \frac{1}{33}\,\Delta H \qquad h' = 32\,t + \frac{32}{33}\,\Delta H$$

as a consequence of a rain infiltration which increases the aquifer by Δ H.
Actually later on only, when the new equilibrium has been reached, it will be:

$$h' = 32\,t', \quad \textit{where} \quad (t' + h') < (t + h + \Delta H)$$

In the Salento peninsula, where the sea water has encroached from coast to coast, the delay with which the sea water in the limestone responds to changes in water table elevation according to *G-H* relation, is naturally governed by the permeability of the limestone and, apparently, by the distance from the coast. In other words, the *delay* increases in proportion to the distance from the coast, where the mass of sea water is more free to move.

The type of anisotropy of the rock in regard to the permeability is also an important factor. When the permeability of the limestone is mostly along the semi-horizontal bedding planes, the *delay* is greater than when there are many fissures cutting through the strata and enabling the groundwater to flow vertically ([3]).

([3]) Bearing in mind the theoretical framing of the problem, we have spoken so far abont the change of the equilibrium state according to the G-H relation.

Needless to observe that instead it is actually an uninterrupted displacement. In some cases it is more evident or less, in others almost negligible, according to the mentioned hydrological conditions, compared with a position of the interface average equilibrium. This position specially at a remarkable distance from the coast does not suffer much the piezometric changes of the aquifer.

The initial studies now being carried out indicate that delays in the li-limestones of Apulia, some km far from the coast, are much less than in permeable and porous sands or gravels in other places. Disregarding the areas near the coast, and considering only the more interesting areas inland, where permeability is often mainly a result of horizontal bedding planes, the delays encountered for fresh water aquifer thicknesses of around 100 m, at a distance of about 8-10 km from the coast, were of the order of a few weeks or some months. Where the rocks contained numerous vertical fissures, it is considered that the delay could be exceptionally of only a few days.

In this connection, it is recalled that in the Miami aquifer in Florida [1], where the sea water intrusion takes place through porous and partially fissured limestones (Pleistocene oolitic limestones, Miocene tufaceous limestone and coralline limestones), a delay of some few months was recorded at a distance of only 3-4 km from the coast.

One of the main problems connected with the different peculiarities in achieving the *G-H* equilibrium, concerns the distribution of inflow to the aquifer above and below sea level. Thus, if we take the general case indicated in Fig. 5, with a static level of t above m.s.l. at point P, and the interface at a depth $h = 32\,t$, and assume a rainfall recharge which immediately raises this level by ΔH (where $H = h + t$), the fresh water mass in the aquifer should theoretically sink forcing also the sea water at base to the displacement by $32/33\ \Delta H$ according to the *G-H* principle, in order to reach a new equilibrium, characterized by

$$t' = t + \frac{1}{33}\,\Delta H$$

$$h' = 32\,t' = h + \frac{32}{33}\,\Delta H\,.$$

However, in view of the delay necessary for achieving this now position of equilibrium, the groundwater will flow towards the sea at a hydraulic gradient i, since the water table is not in equilibrium with the sea. The hydraulic gradient will tend to drop, due both to normal discharge of fresh water into the sea in the absence of new recharge, and to the re-establishing of static equilibrium by the entire aquifer mass resting on the sea water. When this new equilibrium is finally established, the values for t' and h' will certainly respond to the *G-H* law, ($h' = 32\,t'$), but in such a way that $(h' + t') <$ $< (h + t + \Delta H)$.

The foregoing considerations account for several interesting features observed in connection with groundwater circulation through the deep aquifer in the karst limestones of Apulia. In effect, if we disregard the delay described above, the inflow of meteoric water to the aquifer, and hence the increased flow through a given section of the aquifer, causes considerably smaller increases in gradient than is normal in the case of aquifers having a sub-horizontal, fixed and definite impermeable bottom. This feature, in conjunction with the varying effects of the *delay* itself, is reflected in the normal hydraulic gradients of the Apulian equifer, the discharge variations in springs, and in other hydraulic phenomena.

2.3 Groundwater outflow.

The wells drilled along the Adriatic coast, in the region under study, are mainly located between Barletta and Ostuni. Those along the Ionian coast, in the Taranto area, lie a little further inland. In the Salento peninsula, on the contrary, they occur almost everywhere, and some are well away from the coast. The position of the existing wells is, for economic reasons, mostly governed by topography; thus, there exist no wells in the higher areas of the Murge from which to obtain data for mapping water table contours (or piezometric contours).

The general pattern of the latter, in the present conditions of the groundwater flow, are shown in Fig. 3. In view of the slight variations in water table level, the general trend of the piezometric contours shown gives a reasonably adequate picture of gradients and direction of flow.

The gradients vary on average from 0.3 to $0.5^{0}/_{00}$ [4], with a few exceptions in the case of fairly impermeable rocks, such as exist in the hills behind Bari (between Bitonto, Casamassima, Sannicandro and other villages in the surroundings, where groundwater investigations have recently begun). These decidedly low variations are linked with what has already been said concerning hydraulic regime in *G-H* equilibrium conditions.

Investigations in the Murge have shown that the direction of groundwater flow is at right angles to the coast between Barletta and Ostuni. It veers Northwest at the point where the limestone platform, on reaching the River Ofanto, dips beneath the impermeable formations of the *Tavoliere di Foggia*.

---

(4) Taking into account the general increase in the aquifer discharge towards the shore line and considering the character of permeability along the way almost uniform, the piezometric gradient starts from a maximum value near the coast and decreases to zero towards the inland. The average value of the mentioned gradient is found, with the same downflow, in distances from 8 to 5 km from the coast.

In the Southern spurs of the Murge, the direction of flow is towards Brindisi and Taranto. At the top of the Salento isthmus, where the convergence of inflow causes a rise in the water table, there is a sharp division between the Southern Salento aquifer (Lecce area) and the Murge aquifer.

Groundwater discharge into the sea takes place to only a small extent through visible springs. Given the karst topography of parts of the area it is no cause for surprise that some springs, for example the one at Chidro, have a discharge of the order of 2,000 l/sec. This demonstrates that in certain points the groundwater outflow tends to follow the karst phenomena, as seems particularly the case in the South of the Salento peninsula.

The size of these spring discharges are largely governed by the presence of impermeable rock barriers along the coast. These frequently impede the outflow of groundwater towards the sea for a number of km, and divert it around the ends of the barrier, where the largest outflows are normally encountered (Fig. 3).

The springs recorded and measured by the State Hydrographic Service are, however, only the largest and most evident ones. In addition to these there is a large number of coastal springs, mostly underwater, of which the individual discharges are small. These represent the continuous outflow from long stretches of water-bearing limestones which dip directly into the sea.

A typical example of this is the Adriatic coast, where the springs recorded by the Hydrographic Service account, on average, for a total discharge of scarcely 2 cu. m/sec, whereas the discharge from the aquifer into the sea has been computed at not less than 20 cu. m/sec.

Moreover we often notice, also along some coastal stretches without manifest springs, salt contents in the sea (at a short distance from the coast) considerably inferior to about $40 \div 42$ g/l got off-shore. According to the data got from the analyses of sea water samples drawn in several spots about 10 m far from the coast at most, Cl^- contents often reach $8 \div 10$ g/l in comparison with 21.5 g/l representing the average contents of Cl^- in the Adriatic and Ionian sea. All this confirms there are fresh water springs also where they are not manifest; many of them are submarine.

2.4 Variations in static level of the water table.

Without giving the detailed records and measurements carried out to date in the local wells, it is worth noting that the periodical fluctuations in the water table are related not only to the amount of rainfall recharge, but also to the distance from the coast. Thus, the greatest variations are found at points lying inland on limestone outcrops which are permeable at the surface. Nevertheless, variations of the order of a meter or more are very rarely met with. The rapidity with which water infiltrating in coastal areas discharges to the sea means that, where limestone aquifers dip directly into the sea, the fluctuations in wells near the coast rarely exceed 30 cm. With regard to the delay between water table fluctuations and rainfall recharge, these seem to be negligible where highly permeable rocks outcrop, and particularly where the rock is very fractured and contains karst caverns and vertical openings. On occasions, the effect of natural fissures is supplemented by infiltration wells, which causes rises of up to 40-50 cm in the static level in the space of a few days. On the Lecce coast, on the contrary, where the permeable outcrops of Cretaceous limestones are 10 km distant, there is a delay max of 2 to 3 months between rainfall and rise in the water table.

With regard to the effects of the tide upon the water table, maximum variations of 2-10 cm occur at distances of about 2 km from the sea, when the intervening rock is fairly permeable. At greater distances from the coast, the effects of the tide upon the water table rapidly disappear.

2.5 Variations in spring discharges.

In the first place it must be stressed that most of the springs concerned occur in limestones that dip directly into the sea, without any impermeable overburden, and hence there is no clearly defined line of outflow, such as is normally the case with springs. Furthermore, from what is known of the theory of aquifers discharging to the sea, the hydrodinamic net is such that most of the groundwater discharges through bands of rock immediately below sea level [2, 4, 7]. In such circumstances, the periodical discharge measurements carried out by the responsible authorities are not very reliable, apart from special cases of artesian springs outflowing at a certain distance from the shore-line [5].

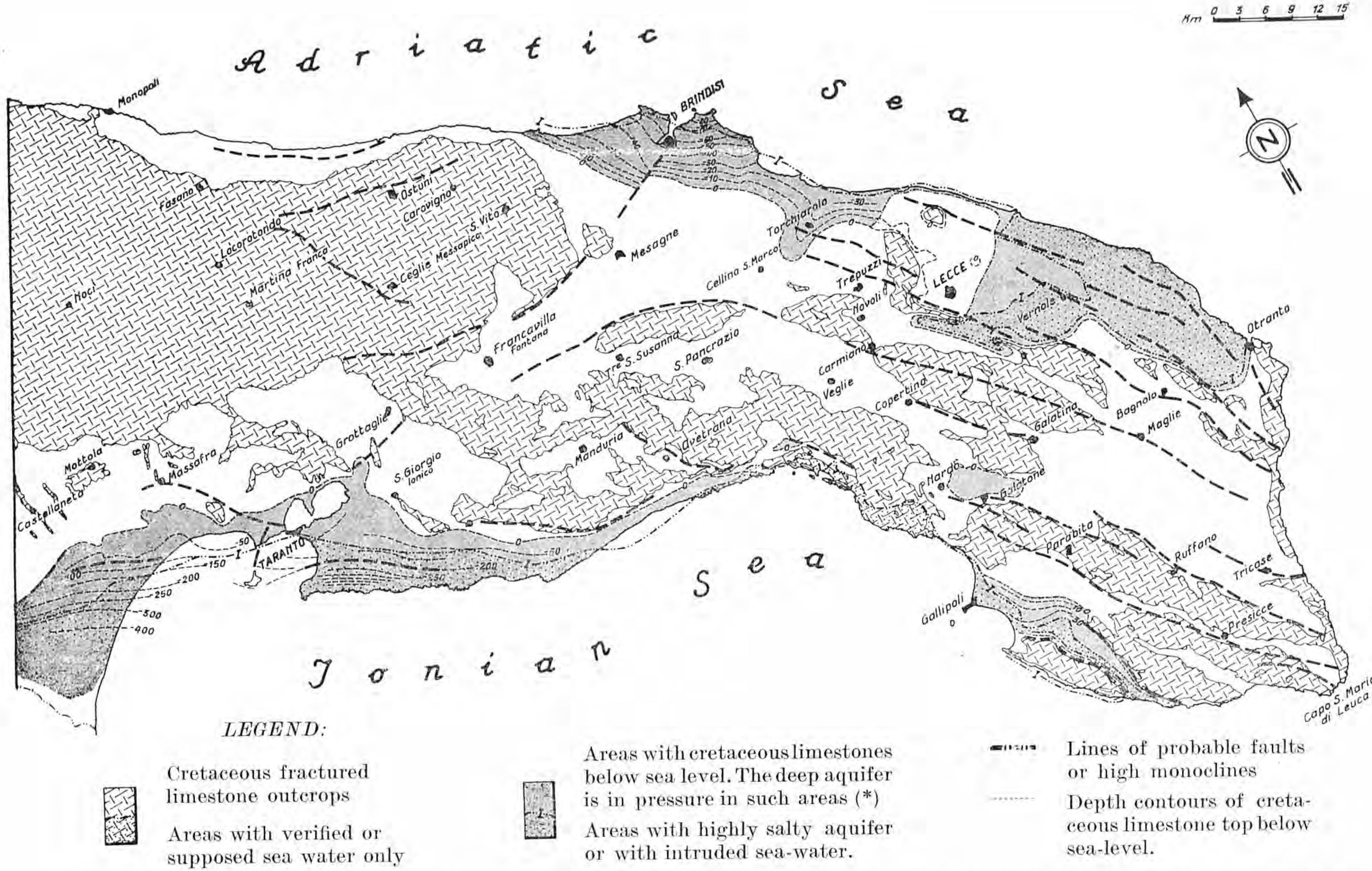
Bearing this in mind, it is still worth noting that a few of the springs for which the discharge measurements seem more realiable have variations which do not completely correspond to the rainfall variations. At the artesian spring at Chidro, on the Ionian coast (Avetrana), in particular, the total average discharge of about 2,400 l/sec showed an annual variation of the order of 10%, which is totally different from the considerable variations recorded for many springs in the karst areas of the Apennines. This fact, too, might be accounted for by drops in the interface level following increases in aquifer thickness. In view of this, it may be stated that the increases in hydraulic gradient landwards from springs fed by aquifers resting on salt water are generally much more restricted than in the case of aquifers having an almost horizontal, fixed, definite impermeable floor.

2.6 Sea water intrusion in the Salento peninsula.

With regard to the investigations of the theoretical interface, stress is placed on the importance assumed by Line I in Fig. 6, which is intended to denote the position of the extreme points I of the interface (Fig. 2), on the seaward side.

This line (shown in Fig. 6 in the present conditions of the aquifer) becomes of outstanding significance when the limestones lie below sea level, i.e. where it represents the points at which the *interface* intersects the surface of the permeable formation containing the confined deep aquifer. Line I can thus lie on either side of the coastline; i.e. on land or offshore. In the first case the strip of land between Line I and the coastline consists of rocks saturated with sea water or highly brackish water. In the second case, the result is that wells drilled offshore in the strip between Line I and the coastline, would encounter fresh water, or at any rate water with a much lower salt content than sea water.

In the coastal areas, where fissured limestones lie above sea level, and the water table flows unconfined towards the sea, Line I practically coincides with the *actual shore-line.* The latter, in its turn, only rarely coincides with the coastline. As it has been stated already, when the permeable limestones outcrop at the coast, the *actual shore-line* often recedes inland. In such a case, the strip of land between the actual shore-line and the coastline is almost completely penetrated by sea water, and there is no possibility of finding a fresh water aquifer here.



(*) In the area between Lecce and the sea the deep aquifer exceptionally takes place also in the «pietra leccese» of Miocene, whose fissures are connected with the cretaceous limestone ones. Therefore where the latter are below sea-level, the deep aquifer may not be in pressure.

Fig. 6 - Sea water intrusion into Penisola Salentina

Part III

LIMITS ON THE VALIDITY OF THE GHYBEN-HERZBERG RELATION

3.1 Adjustment of the Ghyben-Herzberg relation.

The *G-H* theory starts from the assumption that the position of the *interface* is determined by the hydrostatic equilibrium between fresh water and salt water, due to their different densities. In 1940 Hubbert [7] succeeded in demonstrating that the flow of fresh groundwater towards the sea would create a dynamic equilibrium between fresh water and salt water. Later research supported this conclusion [2, 9]. In particular, the *G-H* relation does not correspond with the true state of affairs along the shore-line, due to the formation there of the line of outflow of the fresh water towards the sea. This last feature is clearly evidenced in the way in which the Apulian springs discharge and by the variation in saline concentration, a question which will be discussed later.

It is also known (see in this connection the investigations carried out on the aquifer in the Bay of Biscayne, Florida), that the sea water immediately below the interface is not stationary, but flows perpetually in a cycle from the floor of the sea into the zone of diffusion and back to the sea, and this cyclic flow tends to lessen the extent to which the sea water occupies the aquifer [8].

The hydrogeological conditions in the Bay of Biscayne are comparable to those along the Apulian coasts. At Biscayne the investigations were carried out in areas where the thickness of the aquifer, under *G-H* conditions, varies around 30-40 m, in fissured limestones with a permeability of 3-4 cm/sec.

Apart from a few localized impermeable occurrences, the Apulian limestones generally have a permeability in the range of 0.5-5 cm/sec. (a wide extension of scarcely permeable limestone appears landward some km. from Bari).

Finally, it must be taken into consideration that, due to saline diffusion, the average density of the fresh water in the aquifer is appreciably above unity, though the salinity decreases rapidly upwards from the interface and is frequently negligible near the aquifer surface. In the case of the deep aquifer in Apulia, this modifies the *G-H* relation from $h = 32\, t$ to $h = 40\, t$, as it has been checked in practice in many cases, sometimes in areas far from the shore-line.

3.2 Zone of diffusion between salt-water and fresh-water.

The assumptions on which are based the elementary hydrodynamic theories establishing the form of the interface are well known. According to these assumptions flow takes place in the lowest layer of fresh groundwater, while the underlying salt water is static [2, 7]. In Apulia, however, as it has also been found elsewhere, there exists a diffusion of salinity between fresh water and salt water, so that at last we can distinguish above sea water two zones with a thickness that does not change much from case to case, a superior one (whose thickness is sometimes so little to be negligible) where the salt contents are low and almost constant and an inferior one where salinity increases gradually, going downwards, till reaching the salinity of the sea.

The phenomenon of *saline diffusion* arises from various causes, one of which is molecular diffusion, which acts with extreme slowness; the slower the rate of recharge, and hence the slower the flow of groundwater inside the aquifer, the higher towards the surface of the aquifer will the effects of molecular diffusion extend. The large amount of information obtained from wells drilled in Apulia also goes to show that the thickness of the aquifer, and the predominantly horizontal permeablity, combine to considerably cut down saline diffusion towards the surface. A number of wells in the center of the Salento peninsula, where the aquifer thickness reaches 100 m, have demonstrated that the salinity at the surface of the aquifer consists of negligible chlorine-ion concentrations.

Investigations by Palmer [10] and Wentworth [14], and more recently by Cooper [3] and Kohout [8], (in the aquifers at Pearl Harbor (Hawai) and in the Bay of Biscayne respectively) have shown that, apart from *molecular diffusion*, there is a veritable cycle of flow caused by vertical fluctuations of the interface. Near to the coast these fluctuations are produced basically by the tides, while inland they are caused mainly by seasonal variations in the piezometric surface. In both cases, the variations in saline concentrations in the *zone of diffusion* (5) cause differences in piezometric gradient; these, in turn, give rise to movement of convection, such as is caused in the atmosphere by temperature variations, and in the sea by the combination of temperature and density variations from one point to another.

Even where the thickness of the fresh water aquifer in the Apulian Cre-

(5) As there are not only phenomena of molecolar diffusion but also phenomena of mixing among waters with different salt contents, it would be better to speak simply of *transition zone* even if the latter has sometimes a remarkable thickness in the fresh water bearing stratum. Yet in scientific works it is used the improper term *diffusion zone* that, to simplify, we too shall use.

taceous limestones exceeds 100 m, saline diffusion has been found to produce saline concentrations of the order of 1.5-2 g/l near the aquifer surface. The cases in question are obviously due to intense fissuring and dissolving out of the limestone, particularly in a vertical direction (in other cases, where groundwater circulation mainly takes place through horizontal bedding plains, the saline concentration in the upper layers of the aquifer is often below 0.3 g/l, with Cl^- concentrations below 0.02 g/l, denoting that saline diffusion from below is completely absent).

TABLE I – Cl^- *contents found at different depths in Copertino well* (*water table* t = + 2.25 *m a.s.l.*)

Depth of drawings of sample, in m referred to sea level	Corresponding to	Cl^- contents in g/l
+ 0.75	+ 0.34 t	0.07
— 3.25	— 1.45 t	0.14
— 7.25	— 3.20 t	0.12
— 11.00	— 4.90 t	0.10
— 15.25	— 6.75 t	0.10
— 19.25	— 8.55 t	0.10
— 23.25	— 10.05 t	0.10
— 27.25	— 12.10 t	0.10
— 30.25	— 13.45 t	0.10
— 35.25	— 15.65 t	0.10
— 39.25	— 17.50 t	0.10
— 43.25	— 19.20 t	0.10
— 47.25	— 21.00 t	0.12
— 59.75	— 26.50 t	1.80
— 71.75	— 31.80 t	2.33
— 74.75	— 33.20 t	2.60
— 77.75	— 34.50 t	3.20
— 80.25	— 35.65 t	4.30
— 84.75	— 37.65 t	6.40

There are many factors which affect the variations in the salinity of the Apulian aquifer between the surface and the *theoretical interface* (lying at a depth $H = 33\,t$ below the water table). Account must be taken of the degree and anisotropic character of permeability of the rock, the aquifer thickness, the rate of infiltration, water table fluctuations and distance from the coast. In a region as broad and varied as Apulia, the part played by these factors differs from one point to another, giving rise to corresponding variations in the zone of saline diffusion.

A statistical analyses of the investigations carried out indicates that, with the exception of a few areas very near the coast (where the thickness of the fresh water aquifer decreases to a score or so of meters, and the tidal influene is considerable), the saline stratification in the aquifer is characterized by a constant, modest salt concentration, beginning from the water table as far as the depth of $20 \div 22\, t$ below sea level (where t represents the height of the piezometric surface above sea level); then the gradual increasing of salinity begins and when the depth is about $32\, t$ we have a concentration of about 5 g/l; at last when the depth is $40\, t$ below sea level we reach sea salt concentration.

For example table I shows the Cl^- contents obtained at different depths in a well drilled in a highly fractured limestone near Copertino. These Cl^- contents are more important as to the effects of sea influence on fresh water. The obtained data refer to a period of low water, characterized by $t = 2.25$ m a.s.l. Between $33.22\, t$ and $34.55\, t$ it has been noticed the variation from a Cl^- concentration of 2.60 g/l (salt contents 4.75 g/l) to a Cl^- concentration of 3.20 g/l (salt contents 5.85 g/l). The salt contents of 5 g/l has been found therefore at a depth a little over the $32\, t$ aforesaid. But this is within the limits of displacement between the height fluctuations of water table and theoretical interface.

3.3 Hydraulic heads caused by diffusion.

Sea water and fresh water thus mingle intimately in the *zone of diffusion*, due to the manner in which the latter originates.

On the other hand, while the zone of diffusion remains substantially unchanged by the large quantity of salts transmitted to the fresh water and discharged to the sea, a much stronger mechanism than simple molecular diffusion acts hydraulically and transfers sea water into the fresh water aquifer (Fig. 7). The experiments carried out by Cooper [3] serve to demonstrate that the hydraulic effect outweighs the chemical effect of the salt concentration gradients; these are normally slight, especially in areas away from the coast, and cannot set up that saline transmission to the aquifer which is encountered predominantly in the zone of diffusion ([6]).

([6]) It is worth mentioning that experiments made by Kohout [8] in Florida, show that the flow of sea water towards the fresh water in the area studied is equal to a discharge of about 10% compared with the fresh water discharge, which is partially brackish due to sea water, and flows towards the sea. But the hydraulic study of the problem presents remarkable difficulties of practical fulfilment.

Exhaustive data, with regard to the Apulian aquifer about the pressure gradients depending both on the head losses, due to the movement, and on the density variations, due to salt losses have hitherto not been collected. There is strong evidence, however, that this phenomenon is wide-spread, though the experiments carried out have not made it possible to trace the current lines in the most important areas, for the purpose of determining the cycle of flow in the zone of diffusion.

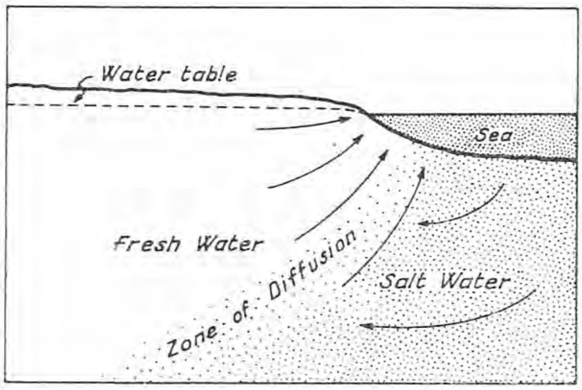


Fig. 7 - Movement of salt water from the sea to fresh water and back in the diffusion zone.

Great interest attaches to those areas where the fissured limestones go down below the level of the theoretical interface, and where, by the strict application of the *G-H* relation, they should contain actual sea water. Of these, the coastal area between Otranto and Lecce is of outstanding interest, since some of the drillings there have ascertained the presence, not of sea water, but of water which is highly saline but considerably less than seawater itself. For example, a well situated about 10 km North of Otranto and 2.5 km from the coast, in an area which, according to Fig. 6, should contain sea water or highly brackish water, encountered water containing 4 g/l of Cl^- in fissured Cretaceous limestones at a depth of about 190 m below m.s.l. This water flowed up to 4.34 m above m.s.l. According to the hydrological researches made in the area specially near the aforesaid well and always according to the *G-H* relation, sea water should have been found flowing up to sea level.

It is also impossible to trace the piezometric contours among wells drawing upon the zone of diffusion in the aquifer, since the salt contents known generally refer to water samples taken during pumping tests, as well as to calculate the equivalent heights of fresh water, since the salt contents of undisturbed ground water are not known

3.4 INFLUENCE OF SALINE STRATIFICATION ON PUMPING FROM THE WELLS.

It is well known that extremely complex problems are involved in the hydraulic functioning of a well which penetrates a series of superimposed layers of liquid with densities increasing downwards [9].

Reducing the problem to its simplest terms, when only two liquids are present — fresh water on salt water — divided by a clearly defined horizontal

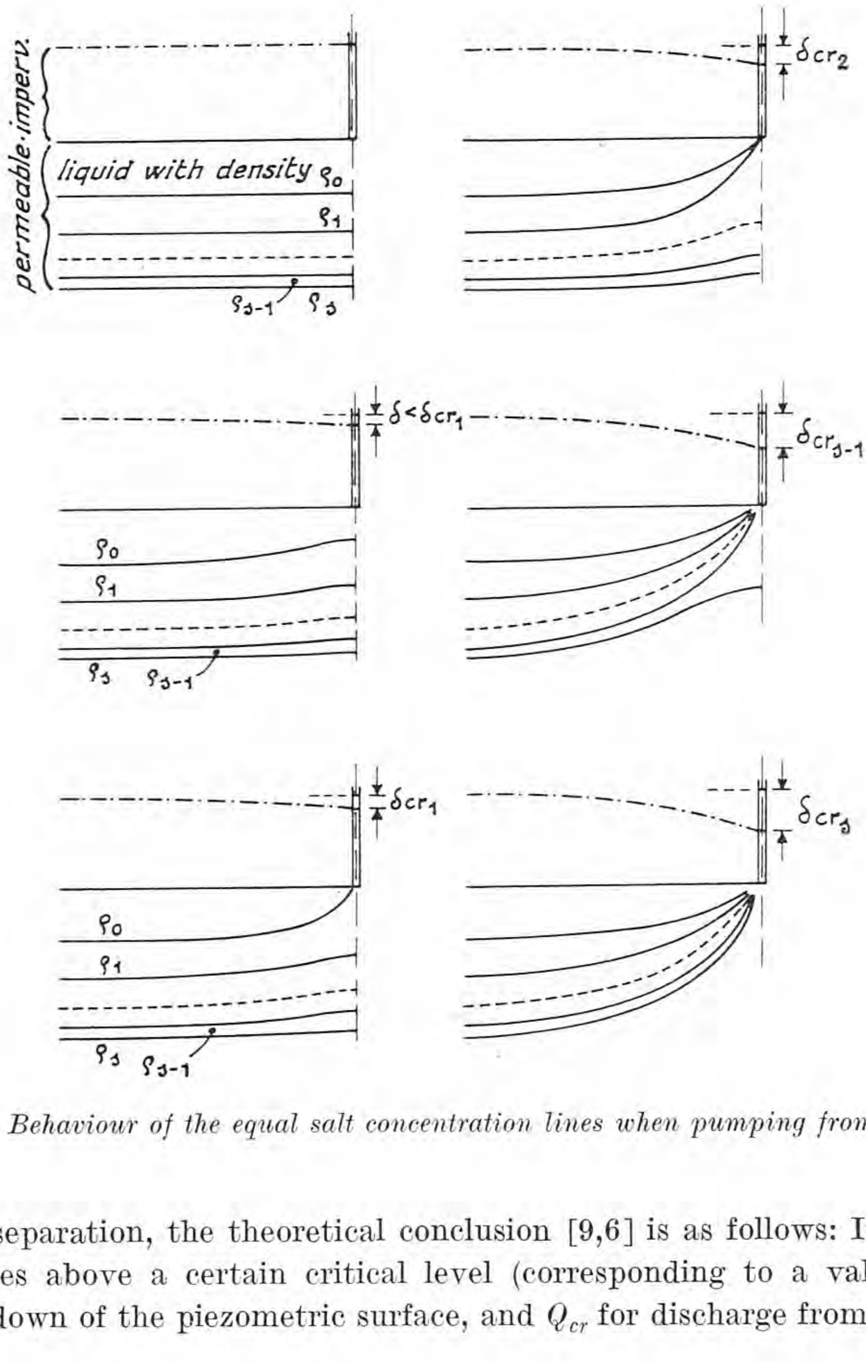


Fig. 8 - Behaviour of the equal salt concentration lines when pumping from a well.

plain of separation, the theoretical conclusion [9,6] is as follows: If the salt water rises above a certain critical level (corresponding to a value of δ_{cr} for drawdown of the piezometric surface, and Q_{cr} for discharge from the well, called *critical drawdown* and *critical discharge* respectively), where the pressure gradients during flow exceed the specific weight of the salt water, conditions of static equilibrium cannot be maintained for any salt water wedge at the base of the well. In such circumstances, the underlying sea water breaks into the fresh water zone before the bottom of the well is reached by the interface (which gradually rises as the rate of withdrawal is increased).

Let us now consider the case of an aquifer consisting of several layers of water with density increasing downwards (e.g. from $\rho_0 = 1.000$ to $\rho_s = 1.030$ kg/l, which is the density of the Adriatic sea water). It will readily be appreciated, on the analogy of the simple case of only two liquid layers, that as the rate of withdrawal gradually increases, and the pressure in the zone of fresh water inflow towards the well correspondingly decreases, the static equilibrium of the water in each layer of increasing density will gradually be disrupted (Fig. 8).

In this new aspect of the problem we see, in effect, the action of various critical drawdowns δ_{cr1}, δ_{cr2}, ... δ_{crs}, progressively disrupting the static equilibria of the liquid layers, starting with that having a density ρ_0 and going down through ρ_1, ρ_2, ... ρ_s. In such a series of superimposed liquids, if it is assumed that the difference between two successive densities ρ_i and ρ_{i+1} is constant, and the thickness of the various layers decreases considerably downwards until reaching sea water at the base (as shown by experience) it follows that when the rate of withdrawal is slowly and gradually increased, the increase in salinity of the pumped water is not equally gradual.

This, in fact, is what takes place in aquifers under such conditions as those described above. Thus, the thinner the zone of diffusion, the quicker the transition from slightly brackish pumped water to water containing almost as much salt as sea water. In some cases this transition is very abrupt.

PART IV

CURRENT METHODS FOR AVOIDING SEA WATER INTRUSION ARISING FROM GROUNDWATER EXTRACTION

4.1 NOTES ON METHODS USED TO REPEL SEA WATER INTRUSION IN COASTAL AQUIFERS.

Leaving aside the economic aspects of the problem, research has been carried out into certain solutions for preventing sea water intrusion into coastal aquifers.

In this connection, we may recall the experiments carried out in California on *artificial recharge* and *pressure ridges* [13] parallel to the shore-line. Such methods are normally uneconomical even in porously permeable formations, while in rocks containing fractures which are often dissolved out to form karst phenomena, they are quite out of the question.

The artificial raising of the piezometric surface immediately inland from the outlet to the sea would require enormous quantities of water and such quantities are either not available or would involve heavy expenditure for pumping, conveyance and injection into the ground. The finding of suitable places for injection also presents difficulties, in view of the frequent and unpredictable occurrence of wide fissures through which the injected water could flow to the sea without causing any rise in the water table.

With regard to the construction of subsurface barriers consisting of impermeable mixtures injected into rock fissures, the cost involved frequently exceeds the economic limits permitted for the utilization of groundwater for irrigation purposes. This is due to the high cost of such barriers, of which the construction in highly fractured rocks involves costly and complex practical problems. It is sufficient to quote the recent example of grouting works (7) carried out in the Cretaceous limestones and the Pleistocene calcareous sandstones (limestone tufas) in the foundations of the crypt of the Basilica of San Nicola in Bari. In this case, various mixtures of sand, cement and bentonite, with various degrees of viscosity, all proved inadequate for grouting the rocks. Success was only achieved by the addition of ground pozzolana and sometimes shredded cellophane, to the aforesaid materials. A large number

(7) In which the writer collaborated.

of holes had to be drilled and the amount of grouting used was considerable. The use of so called *pumping troughs* near the coastline is of doubtful value; in very permeable layers they might not be a remedy but a damage.

The most suitable methods for Apulia are still the traditional ones. It would be highly desirable to avoid withdrawal of water from wells in the areas nearest the coast, whereas there exist many old wells, mostly hand-dug, in many of the coastal areas of Apulia, and the farmers draw highly saline water from these wells by primitive methods. The result, in some cases, is the encroachment of sea water inland. On the other hand, there are springs which flow freely towards the sea, and which are neither diverted to irrigation areas nor used for artificial recharge in order to repel sea water intrusion.

Even the fundamental precaution of limiting drawdown from pumpage is not infrequently disregarded. As a result there are local rises in the interface, which could eventually lead to a slow but progressive increase in salinity of the fresh water.

4.2 Extraction of groundwater by means of drilled wells.

In the region under study there are at present about 2,000 wells, of which more than half were rotary drilled, with an average bore of 300-400 mm., often penetrating the aquifer to considerable depths. Without going into the question of the hydrologic inventory of the region, it is pointed out that the total pumping capacity of these wells could account for a high percentage of the total outflow of the aquifer. Fortunately the wells operate neither regularly nor at full capacity, since irrigation in the area is still in its early stages.

If it is considered that these wells are only drilled in areas where the elevation is suitable, and where convenient to the user, and that in most cases they are constructed and operated without any regard for hydraulic principles, it will be appreciated that the existing wells, and those which are still being constructed in the area, could cause serious infiltration of sea water into the fresh water aquifer concerned.

It is quite common for Apulian wells to pump water with a saline content of 2-3 g/l (0.8-1.3 g/l of Cl^-) but, in order to ascertain the best results that can be obtained from wells drilled in suitable hydrological conditions, and operated according to recognised hydraulic principles (i.e. in aquifers containing a thickness of 60-100 m of fresh water; in rocks with good permeability, preferably horizontal; limited penetration of the aquifer; restricted drawdown), it is worth looking at Table 2, which summarizes the principal data on the wells drilled for drinking water to supply the Acquedotto Pugliese.

TABLE 2.

Well	Depth in m	Occurrence of water, related to m.s.l.	Water table elevation t in m.a.s.l. at date of measurement	Theoretical thickness of aquifer ($H = 33\,t$) in m	Well penetration into the aquifer (% of H) (*)	Q discarge in l/sec (**)	δ Drawdown in m	Cl^- chlorine in g/l	R saline residue at 110 °C in g/l
Veglie	50.25	+ 3.92	3.92	129	8.0	50	Negligible	0.250	0.800
Acquaro N° 2 (Brindisi)	52.00	+ 3.38	3.38	112	7.8	54	0.47	0.131	0.538
Parabita	155.00	— 28.00	2.00	66	38.0	23	Negligible	0.209	0.671
Bagnolo N° 1	112.90	— 14.20	3.60	119	16.6	50	0.10	0.049	0.457
Bagnolo N° 2	115.15	— 14.51	3.41	112	19.6	50	0.10	0.067	0.365
Carmiano	42.20	— 4.40	3.00	99	10.0	50	0.05	0.070	0.438
Galugnano N° 2	90.00	+ 3.49	3.49	115	17.4	41	Negligible	0.088	0.406

(*) The small diameter of the drilled wells means that often, even in fairly fractured limestones, water is not encountered on reaching the water table. In such cases the figure for penetration of the aquifer given in the Table is based on the piezometric surface for the well in question.

(**) Refers to the maximum discharge measured during pumping tests. The figures for Cl^- and R in the Table correspond to this discharge.

To give some idea of the benefits obtained when the limestones are mainly permeable along the sub-horizontal bedding plains, we quote the case of the Torricella well, constructed for an industrial concern at Mesagne, about 15 km from the coast. Despite the fact that this well penetrates 34 m into the fresh aquifers (total thickness about 115 m) and operates with a drawdown of 1 m, it obtains water with a saline residue not exceeding 0.4 g/l (Cl^- about 0.03 g/l) ([8]).

4.3 Avoidance of excessive salinity in pumped water.

The chloride content of water extracted from a drilled well depends upon three variables: *a*) δ/t where δ is the drawdown and t the elevation of the static water level in the well, above sea level; *b*) π, penetration of the wells into the aquifer, expressed as a percentage of the entire thickness of the aquifer ([9]); *c*) f, permeability of the water-bearing stratum.

Despite the fact that only two superimposed fluids are involved, as assumed by the *G-H* relation, the numerous attempts at interpreting the experimental results obtained in drilled wells in Apulia have not succeeded in establishing any general law relating to the variation of the above-mentioned factors, due primarily to the extent to which permeability varies and to its varying effects in each case.

The direct application of hydrodynamic principles to the problem shows, as it has been said, that the wedge of salt water intrusion breaks into the aquifer long before the drawdown in the well reaches the limit $t - L'/32$ indicated by *G-H* (L' denotes the depth of the well below m.s.l.).

This means that the drawdown to be adopted for operating the well must be kept sufficiently below a certain value:

$$\delta_{er} = \frac{1}{K}\left(t - \frac{1}{32} - L'\right) = \frac{1}{32\,K}\,(32\,t - L'),$$

where K is a variable coefficient, in any case much more than 1.

So much for the methods to be observed in operating the individual wells, without any reference to the actual amount of usable groundwater storage.

([8]) In such cases, the effect is similar to that of a horizontal impermeable lens interposed between the bottom of the well and the interface [4].

([9]) If L' denotes the depth of the well below m.s.l., the percentage penetration π is given by $\frac{100\,(t + L')}{33\,t}$.

Using this expression as a basis for the critical drawdown δ_{cr}, there are two ways of exploiting it in practice, namely, by keeping t constant (minimum static level of the *deep aquifer*) or by keeping L' constant (depth of the well below m.s.l., or rather the maximum depth at which the permeable water-bearing stratum is encountered in the well).

In the first case we get $\delta_{cr} = f\,(L')$ or, better still, $L' = f\,(\delta_{cr})$, this formula being the basic one used during construction of a well for the purpose of establishing the most suitable depth. This can also be decided from the discharge curves for various depths reached by the well, since the main point is to know in what conditions the well gives the optimum yield.

In the second case, we have formula $\delta_{cr} = f\,(t)$, which is basically used during the operation of the well. Linear diagrams correspond to these two formulas and examples are given in Fig. 9, with $K = 2$.

The value 2 attributed to K according to the developed practical experience on very numerous wells drilled in the area is compatible with the

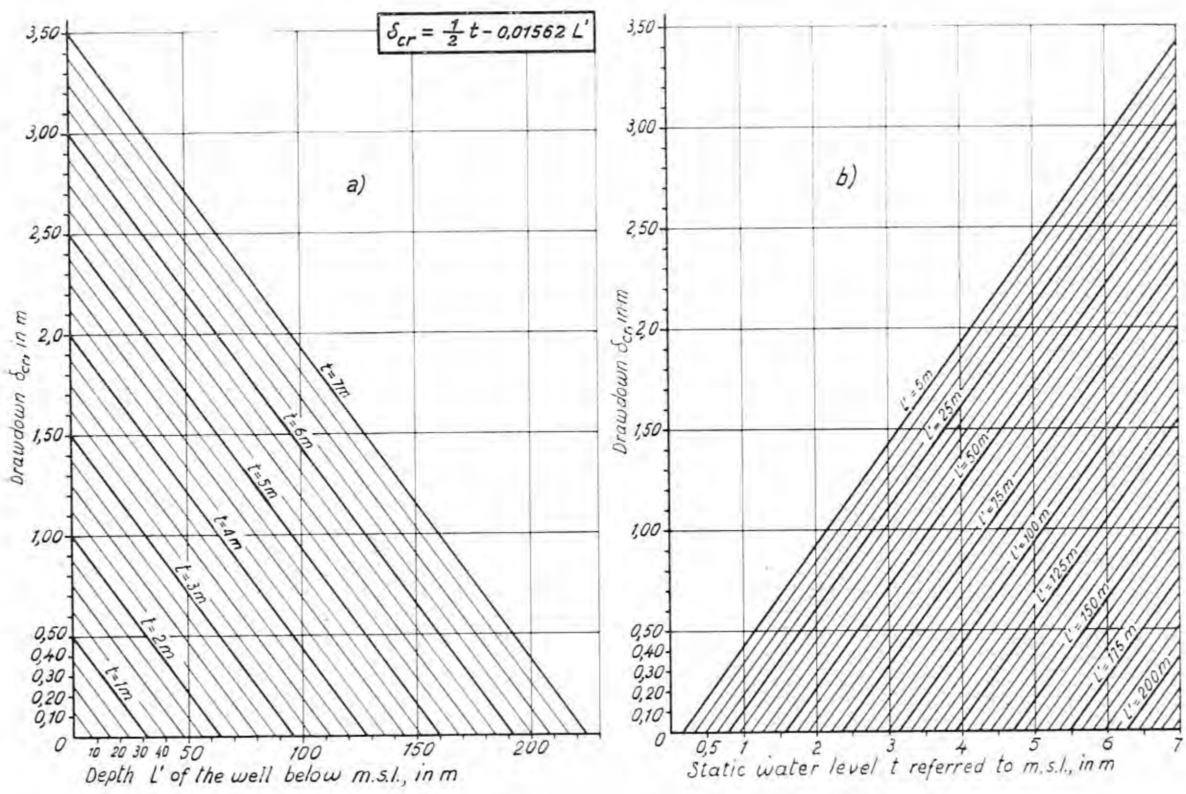


Fig. 9 - Diagrams deriving from the application of the formula giving, for pratical uses, the drawdown:

$$\delta_{cr} = \frac{1}{K}\left(t - \frac{1}{32}\,L'\right).$$

The showed diagrams are for K = 2. *(If the well reaches partially pervious limestone layers,* L′ *means the depth of the deepest aquifer reached by the well).*

hydrogeological conditions (essentially of permeability of the rocks) to be most frequentely expected in Apulia and for penetrations π of the well into the aquifers over 20%.

In most cases (excluding cases of exceptional permeability downwards or through cavities around the well), the pertinent drawdown to $K = 2$ gives rise to salinity which is frequently of the order of 2 g/l. In the case of wells to be used for drinking water, the coefficients for K must be much higher.

4.4 METHODS OF SPRING UTILIZATION.

In Apulia the unconfined springs often flow out along the *shore-line*, in which case serious constructional problems are involved in works for their utilization. They sometimes outflow at less than 1 meter above m.s.l., so that the tidal movements and other adverse effects of saline transmission from the sea may bring about chloride contents of the order of 2-4 g/l and more ([10]).

In the case of the springs near the shore-line, it has been demonstrated on several occasions that the construction of subsurface barriers keyed in to the rock and surmounted by spillways is not advisable. Apart from the constructional difficulties involved in this solution, the groundwater can circumvent the barrier and flow out around its edges.

The best method consists in constructing a draining shaft a few hundreds meters inland from the spring; this should penetrate the aquifer surface for a few score of cm and be positioned so as to intercept the water-bearing fissures supplying the spring.

By fixing the work of a suitable length, and establishing an appropriate depth of aquifer penetration in the draining shaft, the water is raised through a vertical access well. Pumping must not produce a drawdown of more than 10-20 cm. In this way only the water near the surface of the aquifer, and hence removed from the zone of diffusion, is affected, and the quality of this water is much better than that of the spring ([11]).

([10]) In this connection, it is recalled that in experiments carried out by KOHOUT [8] in the zone of diffusion, water containing up to 16 g/l of chlorides was discharged towards the sea.

([11]) At the coastal spring of Irchio, Gargano, the water flowing from the aquifer surface by a draining shaft constructed about 90 m uphill from the spring outlet, proved to have a chloride content of 0.21 g/l ($Cl^- = 0.13$ g/l) against 2.19 chloride content ($Cl^- = 1.33$ g/l) at the spring. When drawing water from the draining shaft in such a quantity to lower the aquifer by 15 cm, the salinity reached a value sensibly inferior to the salinity of the spring.

In all this it is evident that the salt content of the latter rises mostly from a very strong mixing of the aquifer with sea water, which takes place where the former reaches the sea.

In the case of artesian springs lying some distance from the coast, as at Chidro, near Avetrana [5, 12], the problem of utilization is simplified. Fig. 10 shows the hydrogeological conditions giving rise to this spring [12]; a notable depression in the piezometric surface is caused by the discharge of over 2,000 l/sec which at present gushes out under pressure from the lower orifice and has scoured a passage through the impermeable surface deposits. In such

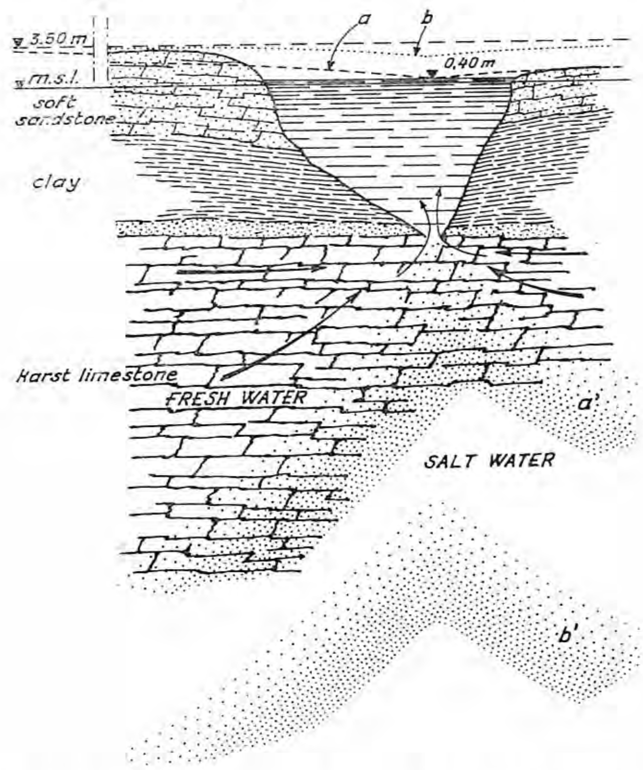


Fig. 10 - Present conditions of the artesian opening of Chidro spring and results which can be got by arising artificially the threshold and reducing consequently the spring yield.

From the researches carried out, the piezometric surface near the spring is 3.50 m above m.s.l.; in such conditions the theoretical interface is 112 m below sea level.

The curves labelled A *and* A′ (B *and* B′) *represent respectively the piezometric hollow conoid and the salt water intrusion cone in the actual (future) condition.*

circumstances, it is obvious that by sufficiently raising the level of the lip over which the spring discharges it is possible to raise the piezometric level. This will reduce the discharge, and consequently lower the fresh water-salt water interface. In this way it is considered that a considerable reduction could be effected in the salinity of the spring, which at present varies from 4-4.5 g/l (Cl^- in the range 1.9-2.2 g/l).

4.5 Tapping of the aquifer by draining shafts.

It is clearly unnecessary to stress the benefits presented by drainage shafts running along the surface of the aquifer, since these reduce drawdown and avoid drawing water up from the depths (as is the case with drilled wells) (Fig. 11). In the Salento peninsula there are already six works of this kind, at depths down to 50-60 m below ground level, and others are planned.

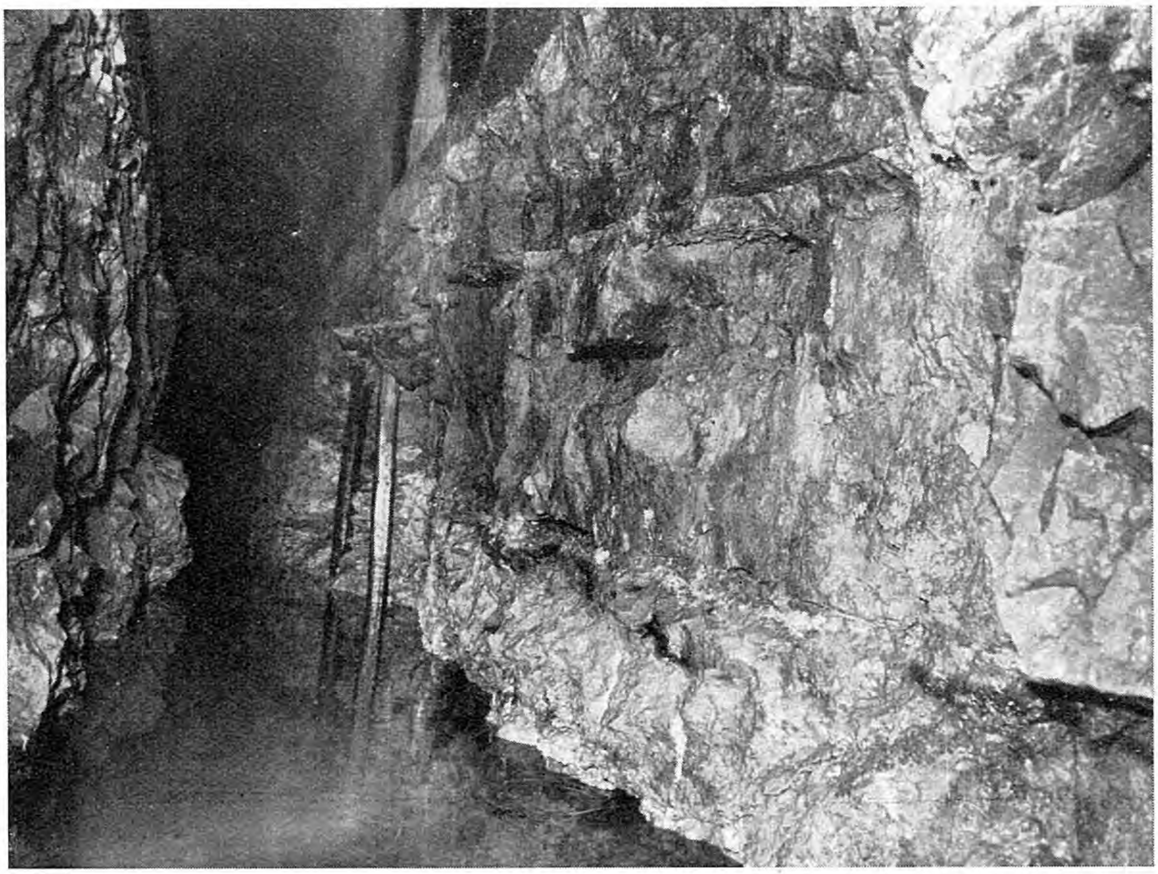


Fig. 11 - Draining shaft in limestone horizontal beds, where permeability derives chiefly from bed rock joints. The draining shaft was made at about 50 m below ground surface at the base of a well supplying water for industrial use in Mesagne area.

At first sight, the method seems extremely rudimentary, but the conditions governing saline intrusion into the Apulian limestone aquifer impose the adoption of this system, notwithstanding the cost of excavating the vertical access shaft (Fig. 12). The method is particularly appropriate for obtaining drinking water or water suitable for industrial use. Fig. 13 shows an example at Trepuzzi, constructed in rock which is so fissured (Fig. 14) that it was only necessary to excavate the chamber for the pump room in order to obtain, by means of a very short shaft below it, a discharge of no less than 150 l/sec for a drawdown of only 15 cm (Fig. 15). The chlorine content has so far reached peak values of 0.18 g/l during the operation of the shaft, compared to a chlorine content of 0.35 g/l for a discharge of 35 l/sec, and a considerable drawdown, in the test drilling carried out at a distance of some 30 m from the excavated well in the same area.

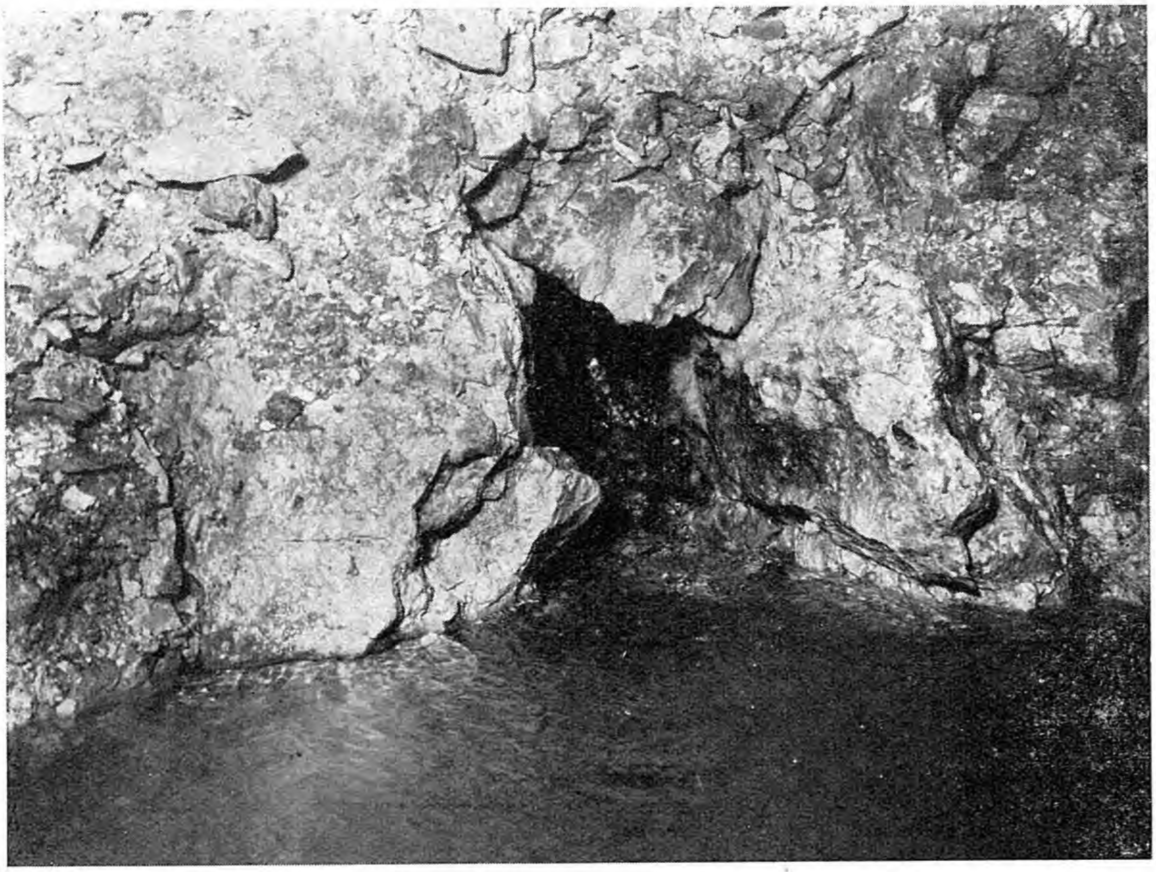


Fig. 14 - *Karst cavity in the draining shaft at the base of an industrial use well in Brindisi area.*

When draining shafts are constructed in limestones with only slight permeability taking place mainly through the bedding planes (Fig. 11), it may require a shaft length of 100-200 m and more to obtain discharges of the order of 100 l/sec. It is sometimes worth drilling a network of shallow holes along the floor of the shaft to facilitate circulation between the bedding planes.

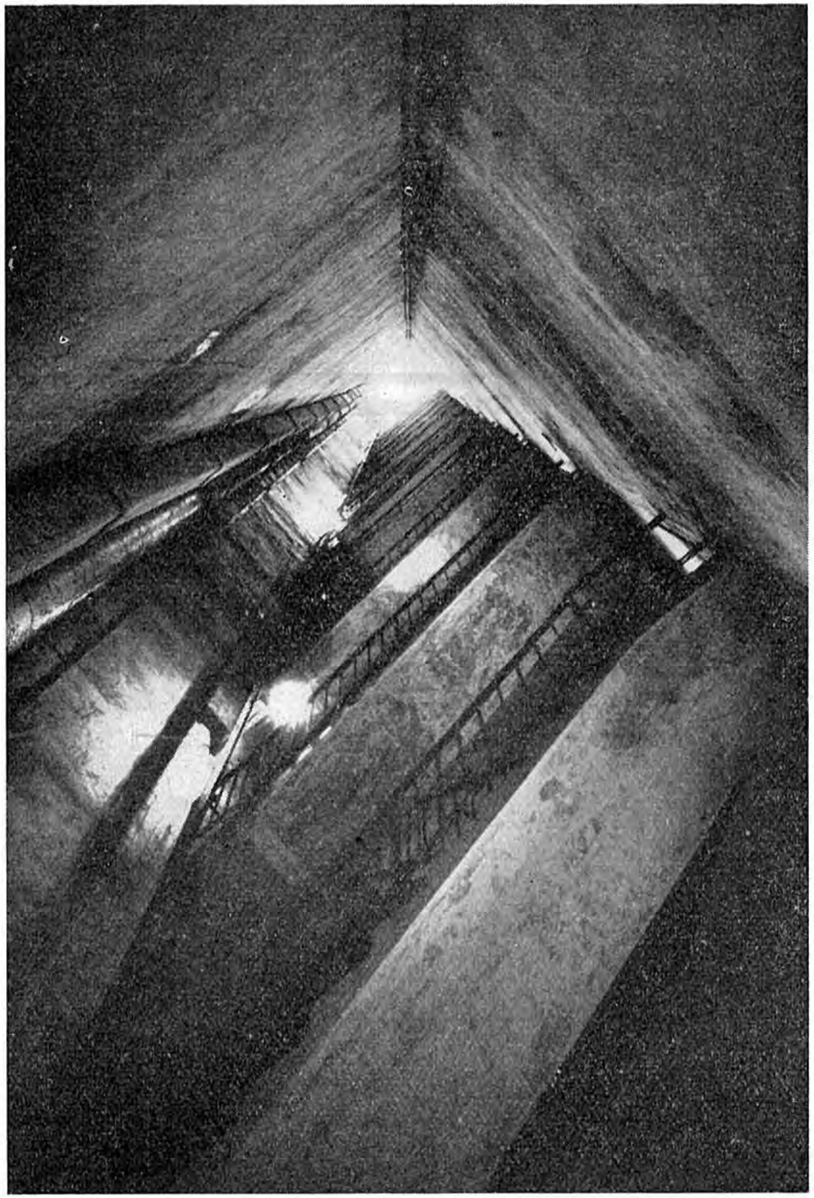


Fig. 12 - Adit to the draining shaft at Trepuzzi.

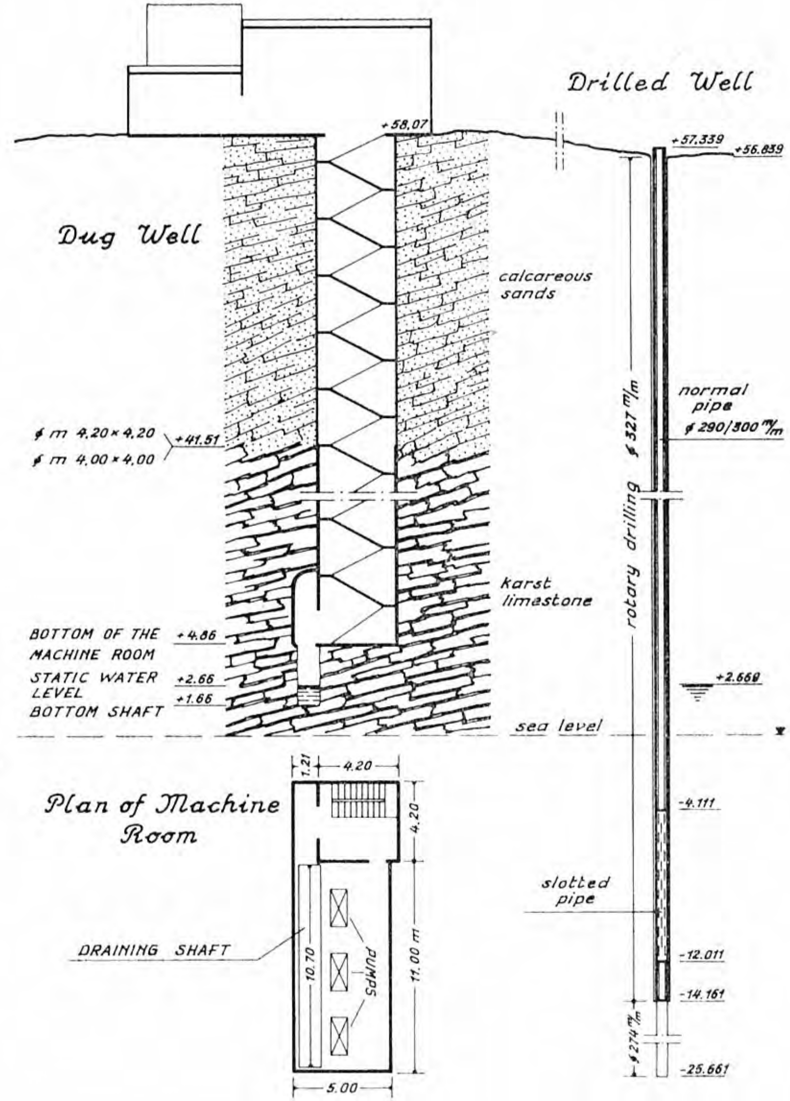


Fig. 13 - Drilled well and dug well with draining shaft at Trepuzzi.

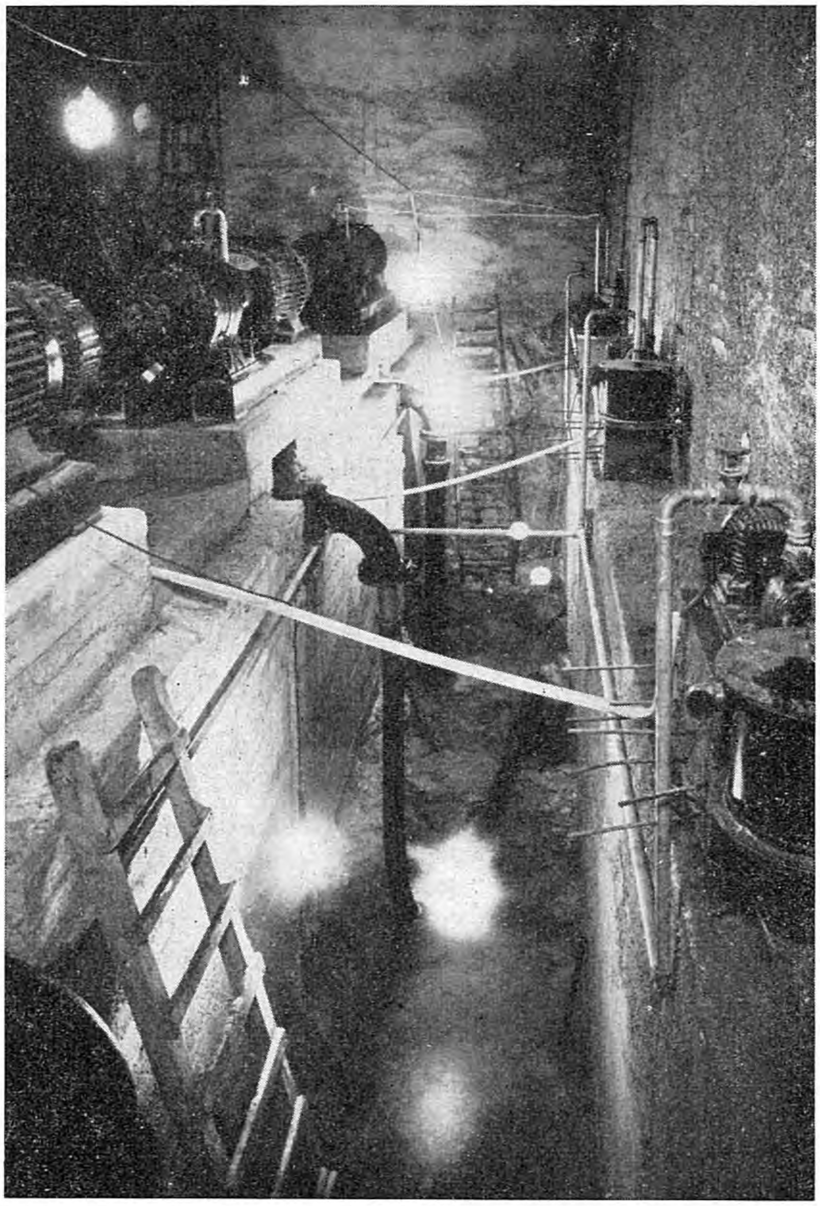


Fig. 15 - *Pump room and sucking pipes in the draining shaft of Trepuzzi well, while building.*

4.6 THE USE OF GEOPHYSICAL PROSPECTING TO ASCERTAIN OR CHECK THE POSITION OF THE INTERFACE.

In connection with the designing and dimensioning of the wells, and also to check any variations in the interface level, experiments have been carried out on the Apulian limestone aquifer using electrical prospecting methods. This method is unquestionably both cheaper and quicker than sinking observation wells for the purpose of measuring salt-water position by means of an electrical salinometer.

Fig. 16 concerns an experiment carried out in the Province of Brindisi

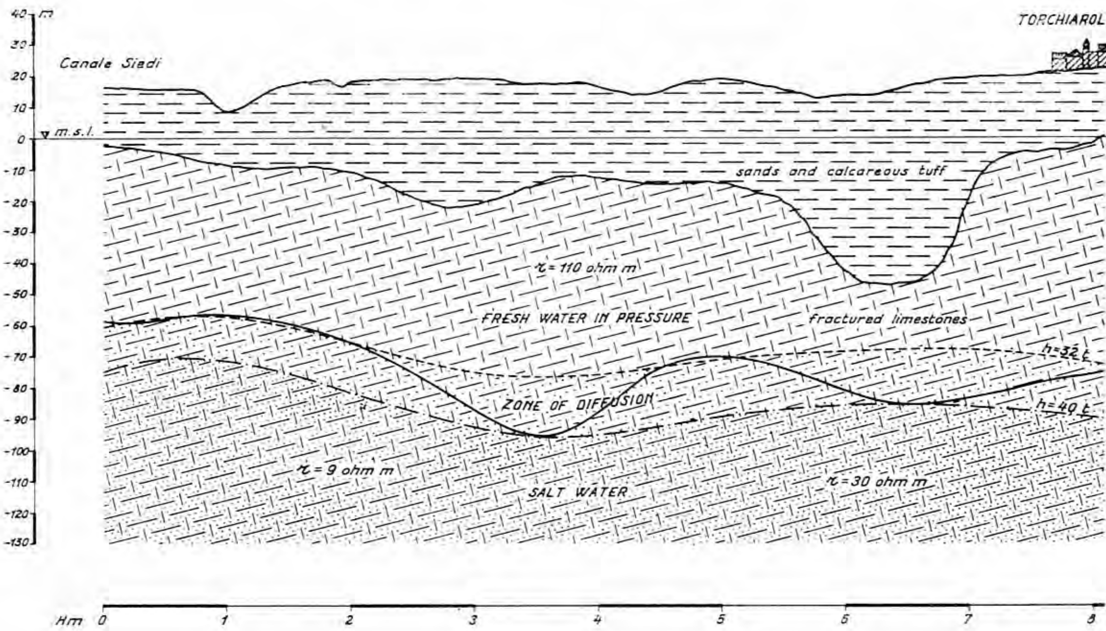


Fig. 16 - *Geoelectrical section between Siedi and Torchiarolo, where the full line shows the usefulness of geophysical exploration to ascertain salt water.*

by the Trieste Geophysical Observatory, and shows that the depth of the interface, as ascertained by electrical prospecting, varies in the range $h = 32\text{-}40\ t$, i.e. it falls within the *zone of diffusion* at the base of the fresh water aquifer ([12]).

CONCLUSIONS

The aquifer contained in the Cretaceous limestones of Apulia is a typical example — and certainly one of the most extensive and interesting examples — of those found in fractured rocks (in some cases containing marked karst phenomena) around the Mediterranean shores. The interest attaching to this aquifer is also due to the conditions of equilibrium with the encroaching sea water.

It is superfluous here to recall the fact that larger limestone aquifers — such as are capable of extensive development particularly for irrigation —

([12]) About this subject other and more detailed results will be given in the paper by O. Vecchia published in this review are much more common in the Mediterranean coastal areas, where the same problems of sea water intrusion exist as those described for the Apulia aquifer. The latter is already being developed (and to a considerable extent in some zones), and since the number of works tapping the aquifer has increased so rapidly in the last few decades, serious legislative problems are posed, if this resource of groundwater is to be safeguarded for the public benefit. In the foregoing pages we have seen how the prospects of pumping up the required amount of water, with an acceptable saline content, are strictly linked to the position of the interface in relation to the depths reached, when the wells concerned are drilled. Since the majority of wells in Apulia are, in fact, for economic reasons drilled wells, their proper management is much more complicated than in the case of normal aquifers resting on a fixed and definite *impermeable floor* of bed rock.

Wherever groundwater reservoirs have been exploited throughout the world, experience has shown that a progressive drop in the piezometric surface takes place. This is because it has rarely been possible to keep extraction within the limits indicated by the actual amount of recharge. So far as normal aquifers are concerned, the only consequence is a progressive depletion of groundwater storage. In the case of coastal aquifers floating on sea water, the result is often very different; before extraction leads to actual depletion of the reservoir, it causes such an increase in salinity of the once fresh water that a large number of the wells have to be abandoned because of brackishness.

The brief treatment of the subject given in the foregoing pages clearly demonstrates that the most fruitful method of exploiting limestone aquifers varies from case to case, but it is always strictly governed by the behaviour of the individual aquifer. Thus, apart from the need to regulate the dimensions and operation of individual wells, it is most essential to have an overall and integrated plan to control all extractions. Such regulation must be combined with a constant check on groundwater discharge throughout the aquifer, and this check must be extended to fluctuations in the interface level and to the so-called zone of saline diffusion.

The investigations carried out in Apulia, and the difficulties encountered there by private users in exploiting the aquifer, lead to a useful suggestion. In order to ensure that wells are constructed and operated in the proper manner and in the right places, thus guaranteeing the long term supply and quality of the water, it is highly desirable that decisions on groundwater extraction should not be left to the individual. Instead, there should be a common policy of groundwater management to decide the positions and methods of extraction so that each single well is operated with a view to avoiding depletion or contamination of the reservoir.

Such a procedure would undoubtedly simplify the problem, in the sense that the water would be tapped initially in the places where the geological and hydrological conditions are most suitable, and would then be conveyed to the place of use. Private enterprise, on the contrary, only taps the aquifer at the point where the water is required, with obvious adverse effects. The same applies to the numerous springs in the cavernous limestones which at present are allowed to run unused into the sea, whereas suitable works, as described in the preceding pages, could provide a large amount, of water suitable for irrigation. This is obviously due to the fact that the utilization of this water would entail the construction of collective conveyance and distribution works, which would cost considerably more than the local exploitation by means of individual wells.

REFERENCES

[1] Brown R. H. and Parker S. G., *Salt water encroachement in limestone at Silver Bluff, Miami, Florida.* Economic Geology, vol. XL, n. 4, 1945.

[2] Citrini D., *Studio elementare delle falde freatiche sfocianti a mare.* Istituto Lombardo (Rend. Sc.) A 94, 1960.

[3] Cooper H. H. Jr., *A hypothesis concerning the dynamic balance of fresh water and salt water in a coastal aquifer.* J. Geophys. Research, 64 n. 4, April 1959.

[4] Cotecchia V., *Influenza dell'acqua marina sulle falde acquifere in zone costiere, con particolare riferimento alle ricerche d'acqua sotterranea in Puglia.* Geotecnica, n. 3, 1955.

[5] Cotecchia V., *Sulle caratteristiche delle sorgenti e sulle modalità di rinvenimento della falda profonda nella Penisola Salentina in rapporto alla struttura dei calcari cretacici della regione.* Ann. Fac. Ing. Univ. Bari, vol. II, 1955-56.

[6] Cotecchia V., Orabona E., *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, 1959.

[7] Hubbert M. K., *The theory of ground water motion.* J. Geol. 47, 1940.

[8] Kohout F. A., *Cyclic flow of salt water in the Biscayne aquifer of southeastern Florida.* J. Geophis, Research, 65, n. 7, July 1960.

[9] Muskat M., *The flow of homogeneous fluide through porous media.* Arbor (Michigan), 1946.

[10] Palmer H. S., *The geology of the Honolulu artesian system.* Suppl., Honolulu Sewer and Water Comm. Rept. 1927.

[11] Parker G. G., *Geologic and hydrologic factors in the perennial yield of the Biscayne aquifer.* J. Am. Water Works Assoc., 43, 1951.

[12] Reina C., *Fondamenti idrogeologici e possibilità pratiche di ridurre la salinità dell'acqua delle sorgenti carsiche salmastre del Chidro in Puglia.* Boll. Geofisica Teorica ed Applicata, vol. IV, n. 16, Dic. 1962.

[13] Todd D. K., *Ground water hydrology.* J. Wiley & Sons, Inc., New York, 1959.

[14] Wentworth, C. K., *Growth of the Ghyben-Herzberg transition zone under a rinsing hypothesis.* Trans. Am. Geophys. Union, 29, 1948.