AN APPLICATION OF THE ARCHIE’S LAW TO THE
HYDROGEOLOGICAL INVESTIGATION OF AN ALLUVIAL COASTAL
PLAIN

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SUMMARY

A calibration of the so called Archie’s law, based on hydrogeological and
geophysical data, is presented. This petrophysical law, originally employed by
petroleum geologists as an aid to interpret geophysical well logs, if suitably calibrated
with direct measurements of the involved parameters, may represent an useful tool for
the hydrogeological prospecting in areas with a quifers encroached by salt water.
Particularly, the vanishing of surface conductance effect in the electrical flow inside the
porous medium, permits to express total porosity only in terms of formation factor
without regards to textural composition of finer matrix.

As an example of this approach, the hydro-geophysical investigation of lower
Cornia plain (Western Tuscany) is presented; data coming from 50 Vertical Electric
Soundings, the majority of which calibrated with stratigraphical records, from direct
testing of groundwater salinity in wells and from granulometric analysis of acquifer,
were used.

According the colected data, Archie’s law is validated in the tested area; average
value obtained of apparent formation factor for the acquifer of Cornia plain is 5,4; the
intrinsic formation factor, depending only on total porosity, is 12. The value of total
porosity obtained is 25%; on the basis of this datum and the granulometric composition
of acquifer, it is estimated a value of 15% for the effective porosity.

1. INTRODUCTION

The hydrogeologic study of alluvial coastal plains is frequently carried out with
the aid of geophysical, and specifically geoelectrical studies, because these techniques
are particularly useful in determining the extent of salt water intrusion into the coastal
aquifers. The considerable difference between the resistivities of alluvial deposits that
have been encroached by salt water and those that have not, results in anomalies that
can be easily shown on resistivity maps drawn from a given number of VES (Vertical
Electric Sounding).

Even though the technique is extremely effective, careful verification of the results
by a comparison with subsurface data supplied by well stratigraphies is indispensable,
because it is often impossible to determine, on the basis of the VES results alone, if a
highly conductive layer is a contaminated aquifer, an organic rich argillaceous deposit,
or if it is highly salinized because it was only recently deposited in a briny lagoonal
environment (in this regard, we remind the reader of the importance of combining the resistivity and induced polarization techniques; [14]).

Finally, it is important to know the real salinity of the groundwater, as it provides a further direct verification and a control datum for the geophysical data collected at the surface.

Several years ago, the Department of Earth Sciences of the University of Florence began a hydrogeological-geophysical study of the so called Piombino Plain, located in the central part of the Tuscan coast. In particular, the part of the plain formed by the sediments of the Cornia River (Cornia plain) was studied, both directly by one of the authors [10], and by students working on theses in hydrogeology. A considerable body of data has been collected (stratigraphic data, VES, conductivity measurements of well waters, well tests, granulometric analyses), which, in conjunction with the large number of studies, some of which are highly detailed, that have been done on the area or are in press, make the direct verifications mentioned above possible.

In the present paper we shall not discuss the hydrogeology of the Cornia plain directly, which will be discussed fully in a paper to be published in the near future, but rather use the data available to make a few observations on the correlations between geoelectric and hydrogeological parameters, and, in particular, on the validity of the well known Archie's law and on its applicability and limitations in the hydrogeologic study of a coastal alluvial plain.

2. STUDY AREA

The Piombino Plain is located in the central part of the Tuscan Tyrrhenian coast; it is bounded to the west by the Piombino promontory, to the east by the south westernmost Colline Metallifere, to the north by the Ligurian Sea, and to the south by the Tyrrhenian Sea (Fig.1).

The geology and geomorphology of the plain have been extensively studied; in particular we refer the reader to the recent paper by Censini et al [8]. The plain is of recent age, having formed in the Quaternary through the accumulation of prevalently fluviatile or transitional (and, subordinately, eolic and colluvial) Upper Pleistocene to Holocene sediments in a graben formed as a result of tectonic down dropping in the Neogene (probably post-Lower Pliocene). The down dropping continued at least through the Lower Pleistocene, while the successive sedimentary dynamics and lateral relationships between fluviatile and transitional deposition appear to have been governed mainly by the eustatic sea level variations.

Though the plain is fairly homogeneous morphologically, it can be divided into two distinct geological domains along a line connecting Venturina to the Piombino promontory, which coincides with a major Apennine tectonic lineation. North of the line Upper Pleistocene Eolic-Colluvial deposits are exposed (the Palmentello-Lumiere Plain), while the Cornia River's alluvial plain, with considerable thicknesses of alluvial, marshy, and lagoonal sediments, lies to the south. The fluviatile depositional environment has never crossed the line, at least during Holocene [13].
The cross sections shown in Figure 3, which were drawn using the stratigraphic data collected and the VES performed, indicate there is, in the mid to lower part of the Cornia Plain, a unit made up of gravels alternated with clays and silts (a sequence typical of low lying alluvial plains with poor drainage), whose thickness varies between 10 and 80-90 meters. Said unit is underlain by frankly pelitic open water deposits (transgressive clays appear in the upper part of the Upper Pliocene), which are in turn underlain by consolidated bedrock (not shown in the section 3A).

Where the Cornia enters the coastal plain it has deposited what can be termed an alluvial fan with a distinct predominance of macroclastites. Towards the river mouth the fine fraction of the sediments increases steadily, and they interfinger with clayey and clayey sandy lagoonal-marshy sediments. We remind the reader that there were extensive salt marshes and briny lakes along the coast until recently [9], Fig. 2; reclamation, through the use of fill, began in 1830, and was only completed in 1960; along the coast line there are more or less well cemented sands that were barrier beaches and littoral dunes.
The first fifty meters of the Palmentello-Lumiere Plain are for the most part variably cemented sands of Wurmian age; in the lower part of the sequence appear gravel and sandy gravel deposits; the boundary with respect to the Cornia Plain is formed by a terrace that is clearly visible in the area crossed by the section, though it has been completely hidden elsewhere by agricultural activities. The bedrock is present at a shallower depth than it is in the Cornia plain.

With regards to the hydrogeology, the main aquifer of the plain is of course formed by the macroclastic-clayey complex, which is fed by the superficial waters (in particular, the Cornia), by the carbonate rocks that surround the upper part of the plain, by the sandstones exposed in the Piombino Promontory (the piezometric high of section 3B), and by thermal waters that upwell to the north east, at the apex of the fan, and to the north at Venturina [16]. The poorly cemented coastal sands also form aquifers, though their waters are quite saline.

Since the 1960's human activities have had a considerable impact upon the groundwaters of the plain; the transition from a traditional agricultural economy to intense cultivation [3], associated with the development of a sizable tourist industry and the construction of water intensive industries (the Torre del Sale power plant, steel mills,
and metal working), has resulted in the deterioration of the aquifer and a clear drop in
the level of the piezometric surface (see sections). As one might expect, this has resulted
in a steadily more pronounced salt water intrusion that has created serious difficulties
for the water supplies of the towns of Piombino and Campiglia Marittima.

The degree to which the aquifer has been overexploited becomes evident if one
considers that, during the 1960's, the groundwater in the macroclastic unit was under
pressure and many of the wells in the plain were artesian, while now, as is clearly shown
by the cross section, not only is the piezometric surface uniformly below ground level,
but in some areas, especially inland, some of gravels are drained. Several studies have
clearly demonstrated the hydrologic deficit of the Cornia aquifer [3,7].

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Fig. 3 - a) Longitudinal cross section of Cornia plain: 1) Recent reclamation deposits; 2) Eolic and littoral
sands; 3) Lagunal, marshy and alluvial silts and clays; 4) Gravels with interbedded finer deposits; 5)

b) Transversal cross section of Piombino Plain: 1) Lagunal, marshy and alluvial silts and clays; 2)
Gravels with interbedded finer deposits; 3) Eolic and colluvial sands and poorly cemented sandstones;
4) Gravels and sands; 5) Pliocene clays; 6) Bedrock (sandstones); 7) VES; 8) Stratigraphic record; 9)
Water table (Summer 1991).
3. GEOLOGICAL AND GEOPHYSICAL DATA

As noted above, we plan to publish all of our data, integrating it with new geophysical data (induced polarity measurements), in a detailed hydrogeological study; we shall also list them here, since they were used in the preparation of the present paper.

For the reconstruction of the piezometric surface we used the measurements taken by the C.I.G.R.I. (Intertownship consortium for the management of hydrologic resources of Venturina) in 1991, under both low (October) and high (May) flow conditions, as well as the data from over 100 stratigraphic columns, which are unfortunately not associated with complete granulometric analyses.

With regards to the granulometry of the aquifer, we collected grain size data from the bed of the Cornia, since no well data were available [17]. The data from the river show that average grain diameter decreases from the upper to lower part of the plain towards the river mouth, following a trend similar to that of the underlying aquifer. The river bed analyses can therefore be considered representative of the aquifer, at least with regards to the more coarse grained levels.

The data on the salinity of the ground water were obtained from a study carried out on 44 wells by the local department of Public Health during the summer of 1991; since the samples were taken at the mouths of the wells, the values are averages of the water in all the horizons crossed by the wells. In addition, the type of casing and the depth of the filters are only rarely known.

Finally, for the geophysical aspect of the study we took 50 VES, with Schlumberger type quadripolar array and AB/2 max varying between 500 and 2000 m (1000 m in most cases). The VES were concentrated in the strip of coastal plain parallel to the

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**Fig. 4 - VES n. 1 with model and correlation stratigraphy (location: Cornia plain near the sea).**
sea (in both the Cornia and Palmentello-Lumiere plains) over a band about 5 km broad that is bordered to the S.W. by the Piombino Promontory (Fig.1). This is in fact the area most affected by salt water intrusion. 26 of the 50 VES were calibrated with stratigraphies taken nearby, thus allowing the most probable electric model to be selected through the use of an automatic program of forward and inverse modeling. We based our interpretations also upon a recent geophysical survey of the area [8].

The electrical soundings of the lower part of the Cornia plain frequently yield HK type curves with a thin superficial resistive layer, a strong conductor formed by the highly salty recent clays, a relative resistor (low values) made up of the aquifer complex, and a final conductor, the underlying argillaceous Pliocene substrate (Figs.4-6). There is

Fig. 5 - VES n.19 with model and correlation stratigraphy (location: middle part of Cornia plain near "La Sdriscia").

Fig. 6 - VES n.28 with model and correlation stratigraphy (location: Palmentello-Lumiere plain).
always a certain degree of uncertainty in the identification of the upper boundary of the lower conducting unit (in part because few stratigraphic columns reach that depth); however, the transversal resistance of the coarse grained complex is always clearly identifiable.

4. THE ARCHIE'S LAW

Several models have been proposed to explain the capacity for conducting an electric current demonstrated by a saturated porous medium. Assuming a two component model (one non-conducting and dispersed, and one continuous and conducting consisting of the electrolytic solution), it is logical that the capacity for conducting current (expressed by the electrical conductivity, or its reciprocal, the resistivity) is a function of the conductivity (resistivity) of the fluid and the disposition of the space that hosts it, and therefore, in practice, the total porosity.

Archie [1] was the first to experimentally define an empirical petrophysical law with a simple equation, valid originally for non conducting sands without fine matrix and saturated with brine solution, that relates the resistivity of the sediments $r_s$, normalized on the basis of the resistivity $r_w$ of the fluid and termed the intrinsic formation factor $F_i$ to the total porosity

$$F_i = r_s/r_w = n^{-m}$$

where $m$ is an empirical coefficient equal to 1.3 for sands studied by Archie. The relationship was later refined by other researchers, who introduced a new multiplicative coefficient at the third member of (1) [20,11].

In practice, if one assumes that the resistivity of the fluid remains constant, a sediment is crossed by a current, the conduction of the electric charge will be enhanced with increasing pore space, while the closer the resistivity of the material is to that of the fluid, the lower the factor of formation will be. The coefficient $m$ (or the coefficient $m$ and $a$, depending upon the form chosen for the law) are related to the disposition of the space of the pores, and therefore to their degree of concatenation (which is tied to the degree of cementing of the pores and/or the compaction of the sediment) and to the tortuosity of the passages between them (a factor related to the shape of the grains).

Various authors have experimentally investigated the applicability of sediments other than sands [12,21]; with brine as saturating fluid, the value of $m$ remains 1.3 for clastic granular sediments with rounded grains, but tends to increase with larger grains, reaching 2 and more for clays.

If the saturating fluid is normal fresh groundwater and the sediment also contains a certain percentage of fines (clays, silts, or even fine sand), its electrical behavior changes radically [18]. The electric current, which physically consists of a flow in solution, is preferentially concentrated along the interfaces between the grains and the solution; as is known, the grains with high specific surfaces tend, for reasons related to electrostatic counterbalance, to surround themselves with a prevalently cationic cloud of ions, which in turn act as a preferential path for the electric current, and thus explains the electrical characteristics of argillaceous deposits. Because of this however, the formation factor cal...
following Archie's method tends to become independent of the geometry of the pores; it is instead conditioned by the percentage of fines present and their specific surfaces and for this reason is referred to as an apparent formation factor $F_a$. The physical parameter which regulates the ease of surface conduction seems to be the capacity for cationic/anionic exchange [5].

The above described model is known as the three resistors in parallel (or the Pfannkuch Model [15]); its experimental formulation implies however that when the solution has a high electrolyte concentration (strongly mineralized interstitial waters), the superficial effect tends to decrease (both because of a reduction in the contrast between the conductivity of the double layer and that of the solution, and because the double layer is compressed). Because of this, the apparent formation factor $F_a$ tends to shift towards the intrinsic formation factor $F_i$. For a theoretical discussion of the complex conductivity characteristics of porous media, we refer the reader to [5,18,19].

As noted by Wyllie & Gregory [21], in the presence of sea water, the electrical conductivity can be considered to depend exclusively upon the distribution of the porosity, even when clay minerals are involved.

The studies mentioned above were conducted for the most part by geophysicists who are engaged in petroleum research, while the experiments were mostly carried out in the laboratory, under carefully controlled conditions. Confirmations of Archie's law based on field data are rare. This hydrogeologic study, in which the high salinity of the interstitial waters probably attenuates the influence of surface conductivity, has offered us an opportunity to attempt to confirm the validity of the law in the field.

5. TREATMENT OF THE DATA

To evaluate the apparent formation factor of the aquifer with the data at our disposal we had to first calibrate the electrical soundings so as to assign as exact a resistivity as possible to the beds which make up the aquifer. The problem of calibration, which is central to all geophysical studies, becomes even more important in a highly saline, recently emerged area like the study zone. In fact, as has been noted by other researchers [7,10], the presence of silty-clayey fill or recently deposited saline lagoonal sediments, which contain large volumes of connate marine waters that have not yet been expelled by compaction or normal diagenetic processes, means that the low resistivity suggested by the classic pattern will be displayed not just by the water bearing strata that have been intruded by salt water; indeed, the pelitic deposits themselves will display values of just a few Ohm-m, which are even lower than those assignable to a clayey layer.

The presence of a high number of H type resistance curves (a highly conducting layer at 2-3 meters of depth which is sandwiched between two relatively resistant layers) frequently indicates the presence of these saline clayey layers, which are sometimes, but not always, accompanied by salinized aquifers. One must recall that much of the lower part of the Cornia Plain was either marshy or lagoonal until 1830, and therefore the salinization of the superficial argillaceous layers is widespread.

Figure 2 shows the extent of the phenomenon through the resistivity map, with AB/2 equal to 10 m (the depth sounded is less than 5 m, and therefore almost always above the water table). The more or less complete superposition of the area with low
resistivity and that one in which the ground water is more or less affected by salt water intrusion (residue higher than 700 mg/l) might suggest that the salts of the clay minerals migrate to the underlying aquifer through some sort of forced drainage caused by heavy pumping, as Bencini and Pranzini have proposed for the Grosseto Plain [4]; by the way, it is evident also the effect of heavy pumping in the aquifer, as for example in the southeastern part of the plain (deep salt water intrusion enhanced by wells of Torre del Sale power plant).

Of the 50 VES available, 26 were performed where detailed local stratigraphies were available; despite being forced to discard stratigraphic columns that were either doubtful or did not go to sufficient depth, and despite the impossibility of performing VES in some locations with known stratigraphies, due to difficulties related to the setting of the array or the presence of major artificial sources of disturbance, we feel that the number of calibrations obtained provide a sufficient basis for our study.

Since 9 of the VES, which had not been calibrated, follow patterns extremely similar to those of VES that had been calibrated, we extended our interpretation to them too.

Figures 4, 5, 6 are three examples of such calibrations, each one showing the model which matches the stratigraphic reference section; other electrically equivalent models are also shown. Examples 4 and 5 are representative of Cornia plain (respectively near and far from the sea); in the case of Figure 4, the presence of alternating hypersaline clays and groundwaters contaminated by salts minimizes the differences in the resistivity of the aquifers and the aquicludes, and even inverts their relationship; the detection of individual horizons would have been impossible without an adequate calibration. Example 6 is representative of the Palmentello-Lumiere plain, where a not saturated resistive sandy layer overlies the contaminated groundwater.

The degree of fitting necessary to match the theoretical curve to the experimental data is always less than 2.55%, and frequently less than 1%. The depth of sounding, in other words the depth of the last horizon identified, is generally about AB/10, but is sometimes less due to the high conductivities of the superficial layers.

The resistivity of the aquifers (more or less silty-argillaceous gravels in the Cornia Plain, and sandy gravels in the Palmentello-Lumiere Plain) varies from a few Ohm-m where there is salt water intrusion, to 80-100 where the gravels are clean and the water is fresh. On average, however, the resistivity of the aquifers is about 20 Ohm-m, a fairly low value that indicates salinization of the waters.

In the interpretations confirmed by stratigraphic data, the lowermost water bearing level often has a single resistivity value assigned to a unit of gravels interlayered with about 30% of their thickness in clays; in this case the resistivity is certainly not that of a single aquifer. It is also true, however, that a comparison of these values with those obtained just from aquifers shows that the differences are not that great. Therefore, one can hypothesize that the presence of salt attenuates the differences in the resistivities of the deeper gravelly and clayey horizons.

The salinities of the waters were calculated by interpolating the curves of equal salinity (expressed as residue) and assigning the interpolated values to the location points of VES. The high number of salinity measurements allowed us to minimize the error inherent in the process of assigning values.

To obtain the formation factor we divided the resistivities of the aquifers, taking
into account the thickness of each, by the resistivities of the groundwaters. This procedure is made necessary by the fact that the sampling wells, which are all deep enough to draw from the aquifers being studied, are filtered at various, frequently unknown depths. Therefore the samples, whose electrical conductivities and residue are measured at the mouths of the wells, are certainly from several different levels. The resistivity of the water is calculated from their conductivities at 20 degrees, which is in turn calculated from the residue.

To obtain a directly measured total porosity value to compare with that obtained from the application of Archie's law, we used the granulometric analysis of the macroclastic deposits of the Cornia; in the lower part of the plain, they consist prevalently of gravels, with about 50% of prevalently fine sand matrix. On the basis of the $D_{50}$ effective diameter measurements and the coefficient of uniformity $U = D_{90}/D_{10}$, we calculated, through the use of the formula proposed by Urish [18], the maximum and minimum porosities for a sediment with that make up; the value falls between 26 and 34%, depending on the degree of compaction. For buried sediments the first value is preferable.

On the basis of the granulometric composition of the alluvial deposits, which certainly contain a sizable fine grained fraction also at depth, we feel that the value of $m$ should be above 1.3, and lie between 1.3 and 2.

6. RESULTS

Figure 7a shows as hystogram the frequency distribution of the calculated values of apparent formation factors; the average value is about 5.4. The normal distribution of the values is encouraging, as it suggests that the population has ordered characteristics, and that the measurements are therefore fairly reliable. Among other things, the data from the Palmentello-Lumiere plain show the same average value, given that the deeply buried gravels which make up the principal aquifer are similar, at least in respect of porosity, to those ones of the Cornia Plain.

However, in our opinion, it would be a mistake to take 5.4 as the value of intrinsic formation factor of the alluvium of the Cornia plain. One must in fact recall that the intrinsic formation factor, which is the only value that adequately represents the geometric characteristics of the formation, is equal to the calculated formation factor (apparent) only if the salinity of the fluid is quite high. Since we have not been able, at this time, to precisely determine how high must be the degree of salinity, we have attempted to solve the problem by plotting the calculated formation factor versus the salinity of the water (Fig. 7b); the graph clearly follows a trend in which the apparent formation factor increases as the resistivity of the fluid decreases (and its salinity therefore increases). For high salinities, the formation factor tends to be about 1.2. We feel that this is the value of intrinsic formation factor of the coarse grained sediments of the Cornia and Palmentello-Lumiere plain.

Assigning to $m$ an average value varying from 1.3 (macroclastic monoglastic deposits) to 2 (argillaceous deposits), we obtain a porosity value respectively of 15% and 28%; for a porosity value of 25%, in agreement with direct granulometric analysis, we obtain a value for $m$ of 1.8, more or less typical of a mixture of granular (macroclastites) and lamellar ones (clays), mixture which is a good representation of the Cornia plain.
real aquifer complex involved.

The assumed total porosity value of 25%, which is fairly uniform throughout the Cornia and Palmentello-Lumiere Plains, allows one to hypothesize, on the basis of known empirical curves [6] and on the textural composition of aquifer known by stratigraphies, that the effective porosity of macroclastic layer is about 15%.

Fig. 7 - a) Frequency histogram of apparent formation factor values for Piombino plain aquifer (33 data); b) Plot of apparent formation factor versus groundwater resistivity with regression line of the data.
This datum, which must be considered a simple estimate, is new for the study area, since the partial or total confinement of the aquifers makes the direct determination of the effective porosity (expressed by the storage coefficient), through wells tests, impossible.

Archie’s law, whose validity has been locally confirmed for the hydrogeologic conditions of the Cornia Plain, will aid in planning the management of the local hydrologic resources. Indeed, knowing the resistivity of the aquifer, it will be possible to estimate the salinity of the water that has intruded a given bed and follow its variations in time; in this way it will be possible to measure the contamination of the individual aquifers. We plan to work in this direction in the course of the further hydrogeologic study of the area.

7. CONCLUSIONS

A confirmation of the validity of Archie’s law through the use of surface electrical soundings, that were rigorously calibrated on the basis of stratigraphic data and well water salinities, has been obtained, taking advantage of the highly salinized local groundwaters and the relatively low surface conductance effect of the alluvial aquifer. Despite the results displaying a lack of precision that is typical of field studies, laboratory results are substantially confirmed showing that Archie’s law is also valid for matrix rich deposits.

An intrinsic formation factor value of 12 was obtained for the aquifer complex in the lower part of the Cornia plain alluvial deposits. Assuming a cementation factor between 1.3 and 2, this value indicates a porosity between 15% and 28% this result agrees with the 25% porosity calculated on the basis of the granulometric properties of the aquifer. On the basis of these data and assuming an effective porosity of about 15% for the macroclastic levels, one can estimate that there are 320 million cubic meters of total reserve in the gravel aquifers of the alluvial sediments in the lower part of the Val Cornia. This value was calculated by assuming an average thickness for the aquifer complex of 70 m throughout the plain (about 50 Km²) with an average percentage of 72% of macroclastic levels in respect to finer ones.

REFERENCES


