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Structural-Stratigraphic Setting of Middle Adriatic Alluvial Plains and its Control on Quantitative and Qualitative Groundwater Circulation

Assetto stratigrafico-strutturale delle pianure alluvionali centro-adriatiche e sua influenza quantitativa e qualitativa sulla circolazione idrica sotterranea

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ABSTRACT - Sedimentary bodies of the Middle Adriatic alluvial plains are generally laid out on transverse tectonic lines that have strongly conditioned the Pleistocenic evolution. They comprise gravelly and gravelly-sandy lenticular bodies and variously extended lenses of fine silty-sandy and silty-clay deposits with thicknesses varying appreciably in the different plains. They are supported in general by the aquiclude comprising Plio-Pleistocenic marly clays, while in southern Abruzzo and in Molise, south of the Aventino-Sangro (Maiella) line, the Plio-Pleistocenic aquiclude is substituted in the piedmont part of the plains by gravitational flow clays and marls. The most important water beds are contained in the middle-high Pleistocene and Holocene low terrace deposits, while the size of the resources in the high terrace deposits is smaller.

The sedimentological layout of the alluvial deposits is such that in the upper part of the valleys gravelly and sandy lithotypes prevail, giving rise to monostrate aquifers. In the lower part there are many different situations so that in some plains, and in particular in the larger ones, the presence of fine deposits denote water beds with multistrate characteristics.

Alluvial deposit transmissivity values range from 10^{-2} to 10^{-4} m^2/s and permeability varies from 10^{-3} a 10^{-4} m/s. Underground circulation is conditioned by the presence of high permeability paleo-beds that allow identification of drainage axes that have generally moved in relation to the present river course, and have sometimes been exploited for drinking water. The groundwater flow rate through these may reach a level of over 0.6 m^3/s.

Supply to the aquifers is essentially due to the fluvial waters of the main watercourses and recharge takes place especially in correspondence with the paleo-beds. A considerable contribution to supplying the plain aquifers is also made by the sub-bed waters of the larger tributaries, while a modest contribution is given by mineralized waters rising from the succession of Plio-Pleistocenic pelites along fracture zones and by the gravitational flow pelites (Varicolor Clay formation).

The hydrochemical facies of the underground waters of the plain aquifers is generally bicarbonate-calcic. However, the presence of waters with different chemical composition, characterized by greater mineralizations, has been identified. Waters with sodium bicarbonate facies are present in numerous zones, while in others, there are waters with sulphate-calcic facies, without dominant ions, sodium-chloride facies and sodium-chloride enriched with sulphates. The presence of waters with anomalous chemism is justified by the rise of mineralized waters (both connate and from solubilisation of evaporitic rocks) through tectonised belts with Apenninic and anti-Apenninic orientation or where they cross, whether outcropping or buried. Emergences of mineralized waters are often located in correspondence with structural highs and outcropping and buried overthrusts where the original brines have accumulated following compressive Pliocenic phenomena. Waters with different chemical compositions are present in the coastal areas of the alluvial valley floors because of marine intrusion. The latter phenomenon is also influenced by the size, geometry and permeability of the alluvial deposits.

KEY WORDS: Hydrogeology, Alluvial Plain, Hydrodynamic Parameters, Mineralized Waters, Chemical Composition, Salt-Fresh Water Ratio.

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RIASSUNTO - I corpi sedimentari delle pianure alluvionali centro adriatiche sono generalmente impostati su linee tettoniche trasversali che ne hanno fortemente condizionato l'evoluzione pleistocenica. Sono costituiti da corpi lenticolari ghiaiosi, ghiaioso-sabbiosi e da lenti variamente estese di depositi fini limo-sabbiosi e limoso-argillosi il cui spessore varia sensibilmente nelle diverse pianure. Essi sono sostenuti in generale dall'aquiclude costituito dalle argille marnose plio-pleistoceniche, mentre nell'Abruzzo meridionale e nel Molise, a sud della linea Aventino-Sangro (Maiella), l'aquiclude plio-pleistocenico è sostituito nella parte pedemontana delle pianure, dalle argille e marne della colata gravitativa. Le falde più importanti sono contenute nei depositi dei terrazzi bassi del Pleistocene medio-superiore ed Olocene, mentre è subordinata l'entità delle risorse nei depositi dei terrazzi alti.

L'assetto sedimentologico dei depositi alluvionali è tale per cui nella parte alta delle valli prevalgono i litotipi ghiaiosi e sabbiosi che danno luogo ad acquiferi monostrato. Nella parte bassa si hanno situazioni variegate per cui in alcune pianure, ed in particolare in quelle più ampie, la presenza di depositi fini individua falde con caratteristiche di multistrato.

I valori di trasmissività dei depositi alluvionali sono compresi tra 10^{-2} e 10^{-4} m^2/s e la permeabilità varia da 10^{-3} a 10^{-4} m/s. La circolazione sotterranea è condizionata dalla presenza di paleoalvei ad elevata permeabilità che permettono l'individuazione di assi di drenaggio generalmente spostati rispetto all'attuale corso del fiume, talora sfruttati anche a scopo potabile. La portata di falda attraverso i suddetti può giungere anche ad oltre 0,6 m^3/s.

L'alimentazione degli acquiferi è dovuta essenzialmente alle acque fluviali dei principali corsi d'acqua e la ricarica avviene soprattutto in corrispondenza dei paleoalvei. Un notevole apporto all'alimentazione degli acquiferi delle pianure è dato inoltre dalle acque dei subalvei degli affluenti maggiori, mentre un modesto contributo è dato dalle acque mineralizzate risalenti dalle successioni delle peliti plio-pleistoceniche lungo fascie fratturate e di quelle della colata gravitativa.

La facies idrochimica delle acque sotterranee degli acquiferi delle pianure è generalmente bicarbonato-calcica. Tuttavia è stata evidenziata la presenza di acque a chimismo diverso, caratterizzate da mineralizzazioni maggiori. In numerose zone sono presenti acque a facies bicarbonato sodica, in altre risultano a facies solfato-calcica e senza ioni dominanti ed in altre ancora a facies cloruro sodica e cloruro-sodica con arricchimenti in solfati. La presenza di acque a chimismo anomalo è giustificata dalla risalita di acque mineralizzate (sia connate che da solubilizzazione di rocce evaporitiche) attraverso fasce tettonizzate ad orientamento appenninico e antiappenninico o all'incrocio tra esse, affioranti o sepolte. Le emergenze di acque mineralizzate sono spesso ubicate in corrispondenza di alti strutturali e sovrascorrimenti affioranti e sepolti dove a seguito dei fenomeni compressivi pliocenici si sono accumulate le salamoie di origine. Acque a diverso chimismo sono presenti in corrispondenza delle zone costiere dei fondovalle alluvionali a causa dell'intrusione marina. Anche quest'ultimo fenomeno risulta influenzato dalle dimensioni, geometria e permeabilità dei depositi alluvionali.

PAROLE CHIAVE: Idrogeologia, Pianura alluvionale, Parametri idrodinamici, Acque Mineralizzate, Idrochimica, Rapporto acqua dolce-acqua salata.

1. - INTRODUCTION

The Middle Adriatic alluvial plain aquifers, with particular reference to those in the Abruzzo region, have been exploited since ancient times for civil, agricultural and then industrial purposes comprising, for many years, the only water supply source for the majority of towns and villages in the Adriatic upland and coastal area. In the 1960s and '70s, at the same rate as the exploitation of the waters on the alluvial plains, especially in the areas in which there are the largest housing and industrial settlements and farming is intensive in type, water pollution phenomena have increased enormously. With the development of irrigation technologies and with the advent of the various reclamation and irrigation consortia in the 1980s, the importance of alluvial aquifers gradually diminished because of the availability of qualitatively and quantitatively better water directly from the Apennines or directly from the middle stretches of the rivers. The recent (late 1990s - early 2000s) reduced availability of water resources due mainly to a greater demand for water for various uses, caused by social changes (habits of greater water consumption), and to a lesser extent to temporary decreases in precipitations, although these have been rising over the past 3 years, has brought to prominence the need to identify strategic and substitutive resources that can meet these greater demands especially in the summer. In this regard, the alluvial aquifers take on considerable importance, or rather, it would be more true say that they assume again the importance that they had historically. They are characterized by high availability for collection, which in the major aquifers can exceed an annual average of 300 l/s without altering the hydrodynamic system, by good water quality and excellent location, since they are present where the demand is highest, that is, in the alluvial plains for industrial and irrigation uses, and near to the coast where a large part of the population lives and works.

This work highlights the importance of the Middle Adriatic alluvial aquifers both quantitatively and qualitatively on the stock of sedimentological and stratigraphic (and therefore lithological), and structural characteristics of these. The relationships and influence are analysed between aquifer geometry and hydrodynamic characteristics, between aquifer geometry and the salt/fresh water relationship near the coast, and between the structural substrate layout and water chemism.

There have been many hydrogeological studies carried out on the Middle Adriatic alluvial plains; these include those on the Sangro and Vomano valleys by ERCOLANI (1970), SCANDELLARI (1970), and DE RISO *et alii* (1994). Research has been done on other Adriatic rivers by CELICO (1983), who highlighted the main hydrogeological characteristics of the Adriatic valley floors between the Tesino and Biferno rivers and by NANNI (1985), who analysed the sub-bed groundwaters in the whole Marche area, examining piezometry, hydrodynamic and chemical-physical parameters and water quality. Subsequently, NANNI & VIVALDA (1987), NANNI (1991), NANNI & VIVALDA (1996), and DESIDERIO *et alii* (1999, 2001a and 2003), conducted numerous surveys into the main sub-bed groundwaters in the Marche-Abruzzo region, with the principal aim of evaluating the potential conditions of pollution vulnerability and risk. Recently, DESIDERIO & RUSI (2004) have dealt with the problem of salt/fresh water in the coastal portions of the alluvial aquifers and of the influence of the structural layout on alluvial water chemism.

2. - GEOLOGICAL FRAMEWORK

The stratigraphic geological layout of the Middle Adriatic area (fig. 1) shows the presence of a succession of limestones, marly-limestones, calcarenites, limestone marls, marls and clay marls from the Jurassic-Oligocene interval (CRESCENTI, 1969; CRESCENTI *et alii* 1969; VEZZANI & GHISETTI, 1998), outcropping along the Apennine chain and found in soundings and oil-wells (ENI-AGIP, 1972) carried out in the Plio-Pleistocenic hills and in the Adriatic sea. The Miocenic sequence however, comprises limestones, marly-limestones limestone marls and marls and is surrounded in the central-northern area by Messinian deposits of marly-arenaceous torbiditic formations and, in the southern area south of the Pescara river, by the terrigenous-evaporitic sequence. The Plio-Pleistocenic sequence deposits (CASNEDI, 1991; CASNEDI *et alii*, 1982; CENTAMORE *et alii* 1992; CRESCENTI, 1971; CRESCENTI *et alii*, 1980) comprise marly clays and clay marls with intercalated arenaceous and conglomeratic bodies. South of the Maiella, there is a gravitational flow (Molise nappe, SELLI 1960) coming from the Apennines within the Plio-Pleistocenic sequence. This flow is composed of predominant clays and marls and subordinate limestones, calcarenites, limestone-marls, marls and reworked gypsum from the Cretaceous-Miocene age with maximum thicknesses of around 2000 m (CASNEDI *et alii*, 1982).

The thicknesses of the Plio-Pleistocene sequence are variable. In the northern sector of the Abruzzo region thicknesses are of between 1500 and 6000 metres, while south of the Pescara river thicknesses reach a maximum of 2000 metres. Large decreases in thickness can be found in correspondence with the structural highs, such as, for example in the medium-high part of the Pescara valley floor (Alanno) in which the Plio-Pleistocenic deposits are reduced to around 500 metres.

The Middle Adriatic foredeep is characterized by a tectonic style of folds and faults, generally not visible on the surface, with an Apenninic and anti-Apenninic pattern typical of the Adriatic area (fig. 11). The fault systems present (BIGI *et alii*, 1997), show different orientations that are concentrated in N-S, NW-SE and SW-NE directions and are not really distributed homogeneously in the sector analysed (fig. 1). Many of these faults have normal transtensive and transcurrent movements with evidence of various, successive activities starting from the Upper Pliocene.

The alluvial plains of the main Adriatic river courses, which originate from the Apennine ridge and reach the Adriatic sea with an approximately W-E and SW-NE orientation, were set in these areas during the Quaternary period.

3. - GEOLOGY, GEOMORPHOLOGY AND HYDROGEOLOGY OF THE AQUIFERS

The Middle Adriatic alluvial plains are located east of the carbonatic Apennine ridges and are delimited by slopes mainly comprising Plio-Pleistocenic pelites (fig. 1). Their extension over the area varies approximately from 30 to over 140 Km^2, while their length is less than 1 Km in the initial stretch and in some cases above 4 Km in the areas near the coast.

They are laid out, with a mainly E-W orientation, on tectonic lines in an anti-Apennine direction and their present morphological layout derives from the interaction between Pleistocenic lifting and Quaternary climatic events. The morpho-structural evolution of the plains has conditioned that of the water courses, influencing the depositional and erosive factors, the geometry of alluvial deposits and the form of the substrate (NANNI & VIVALDA, 1987; AUGELLI *et alii*, 1996; FARABOLLINI & NISIO, 1997).

The alluvial plains comprise terraced alluvia from the middle-upper Pleistocene and Holocene (LIPPARINI, 1939; SCANDELLARI, 1970; COLTORTI *et alii,* 1991; COLTORTI, 1991; DE RISO *et alii*, 1994; BUCCOLINI & TIBERIO, 2001; DESIDERIO *et alii*, 2001a, 2003); they are formed of gravelly, sandy-

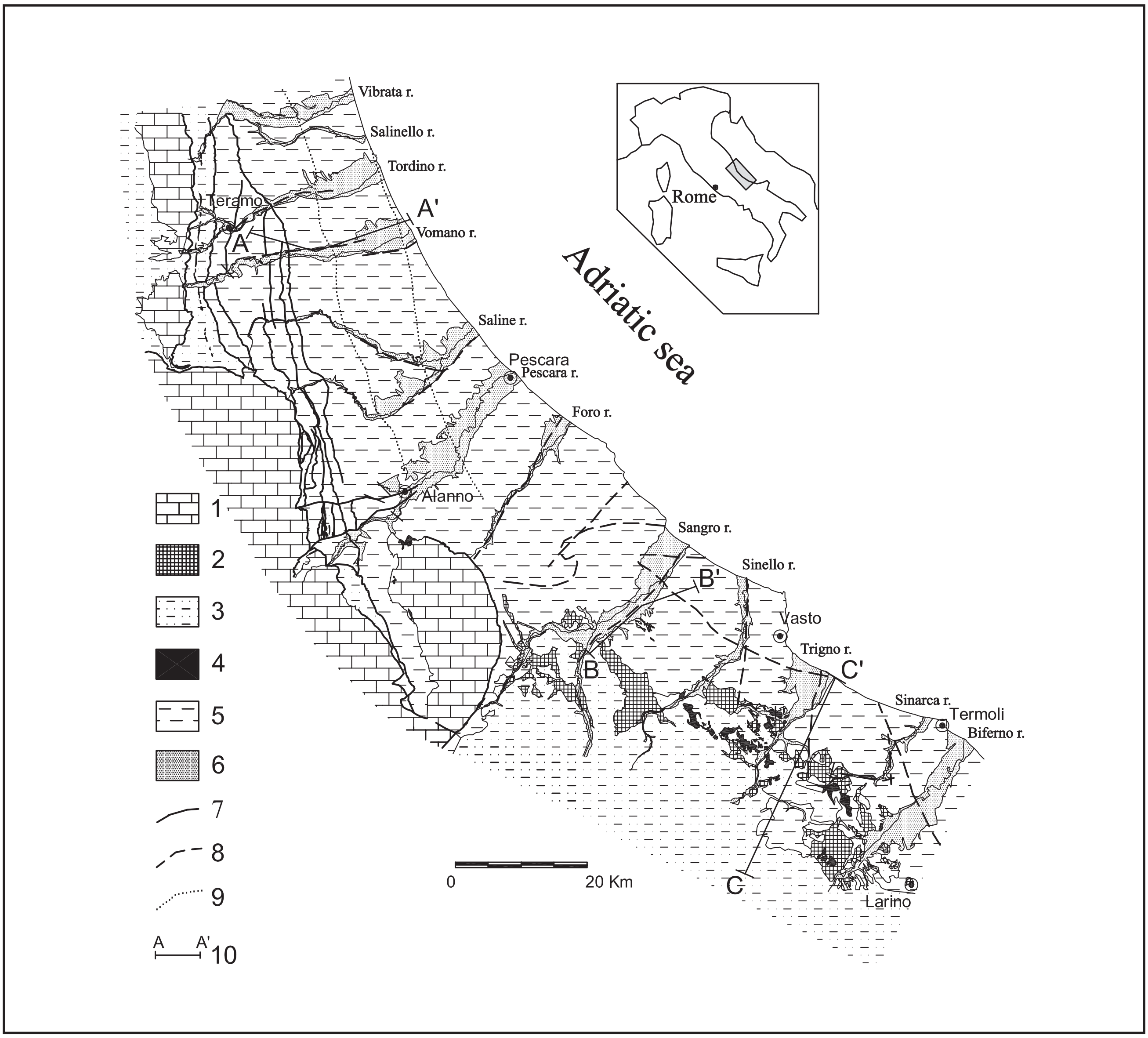


Fig. 1 - Geolithological scheme of the middle adriatic region. 1) Carbonate sequence (Upper Triassic-Miocene). 2) Varicoloured Clays (Upper Cretaceous-Oligocene). 3) Turbiditic deposits (Laga formation and Molise nappe, Miocene). 4) Evaporitic deposits (Upper Miocene). 5) Pelitic deposits of Abruzzo and Molise foredeep (Plio-Pleistocene). 6) Alluvial deposits (Holocene). 7) Faults and thrusts in the Mesozoic-Cenozoic and Miocene deposits. 8) Blind thrust of the allochthonous units in the Adriatic foredeep. 9) Blind thrust in the Abruzzo basin. 10) Trace of geological sections of figure 11.
- Schema geolitologico della regione centroadriatica. 1) Successione carbonatica (Triassico superiore-Miocene). 2) Argille Varicolori (Cretaceo superiore-Oligocene). 3) Depositi torbiditici (Formazione della Laga e coltre molisana, Miocene). 4) Depositi evaporitici (Miocene superiore). 5) Depositi pelitici dell'avanfossa abruzzese - molisana (Plio-Pleistocene). 6) Depositi alluvionali (Olocene). 7) Faglie e sovrascorrimenti nei depositi meso-cenozoici e miocenici. 8) Sovrascorrimento sepolto delle unità alloctone nell'avanfossa adriatica 9) Sovrascorrimento sepolto nel bacino abruzzese. 10) Traccia delle sezioni geologiche di fig. 11.

gravelly, sandy, silty-sandy, silt and clay lenticular bodies, and four orders of terraces are recognisable in general.

The high terraced deposits generally comprise gravels and conglomerates and rounded, selected and centimetric elements, with sandy-silty ground. More rarely, the pebbles are larger in size and badly selected. Sandy-silty lenses and levels are sometimes present.

The high terraces are more developed on the hydrographical left side and only in the lower part of the valleys are in hydraulic contact with the low terraced deposits and the alluvia of the present talweg. The low terraces, the third order ones are generally more developed on both the hydrographical right and left (fig. 2, 5). Because of the fluvial course migration towards the south and south-east, the low deposits are more developed on the hydrographical left side and are in hydraulic contact with the fourth order deposits. The thickness of the low (third and fourth order) deposits varies appreciably between the different

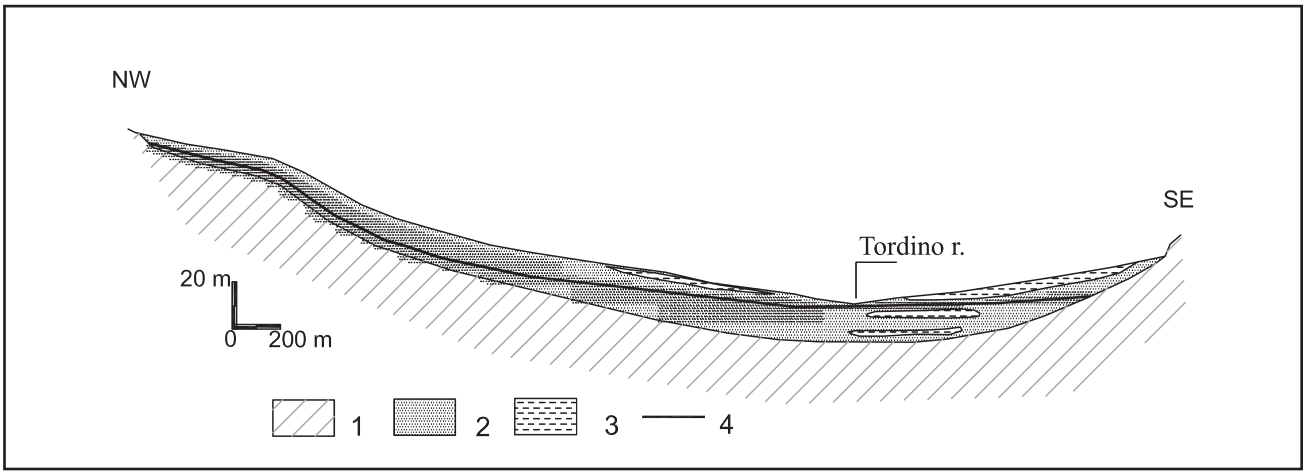


Fig. 2 - Schematic lithological section across the middle alluvial valley of the Tordino river. 1) Plio-Pleistocene clayey substratum; 2) sandy-gravely bodies; 3) silty-clayey bodies; 4) piezometric level.
- Sezione litologica schematica trasversale alla media valle del fiume Tordino. 1) Substrato argilloso plio-pleistocenico; 2) corpi sabbioso-ghiaiosi; 3) corpi siltoso-argillosi; 4) livello piezometrico.

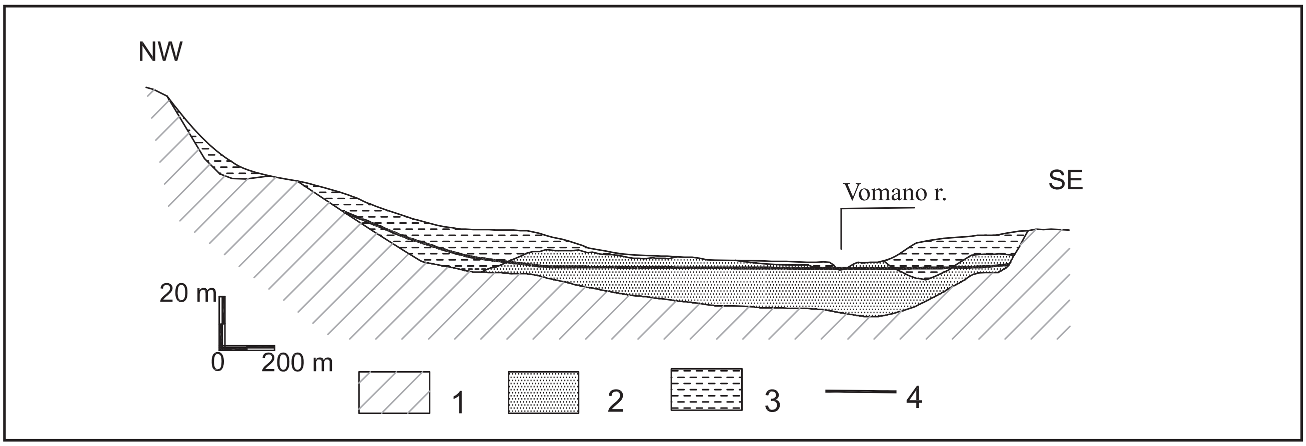


Fig. 3 - Schematic lithological section across the middle alluvial valley of the Vomano river. 1) Plio-Pleistocene clayey substratum; 2) gravely - sandy bodies; 3) silty - clayey bodies; 4) piezometric level.
- Sezione litologica schematica trasversale alla media valle del fiume Vomano. 1) Substrato argilloso plio-pleistocenico; 2) corpi sabbioso-ghiaiosi; 3) corpi siltoso-argillosi; 4) livello piezometrico.

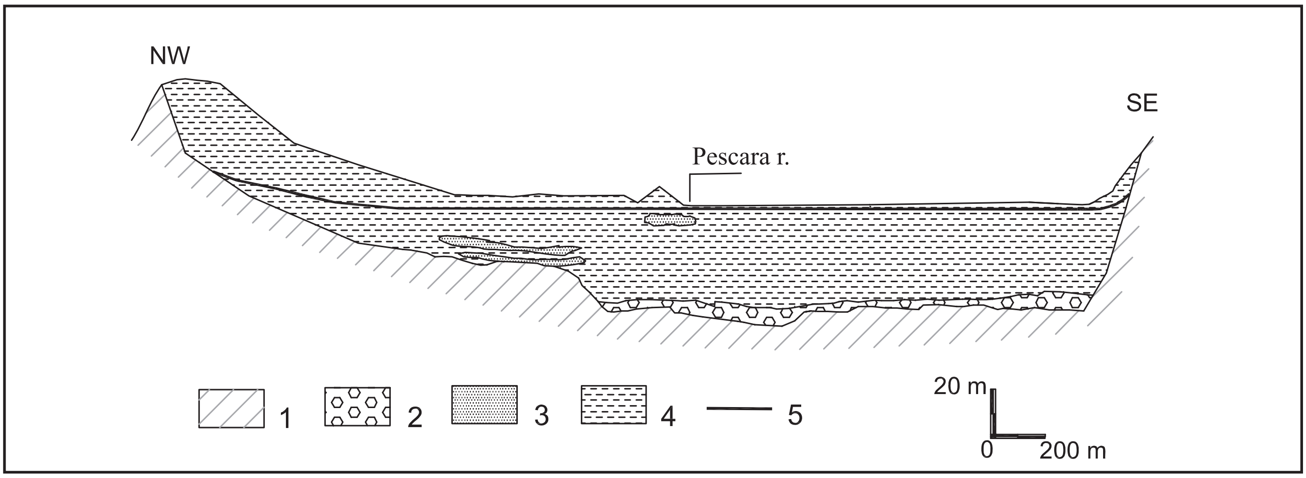


Fig. 4 - Schematic lithological section across the lower alluvial valley of the Pescara river. 1) Plio-Pleistocene clayey substratum; 2) gravely bodies; 3) sandy bodies; 4) silty - clayey bodies; 5) piezometric level.
- Sezione litologica schematica trasversale alla bassa valle del fiume Pescara. 1) Substrato argilloso plio-pleistocenico; 2) corpi ghiaiosi; 3) corpi sabbiosi; 4)corpi siltoso-argillosi; 5) livello piezometrico.

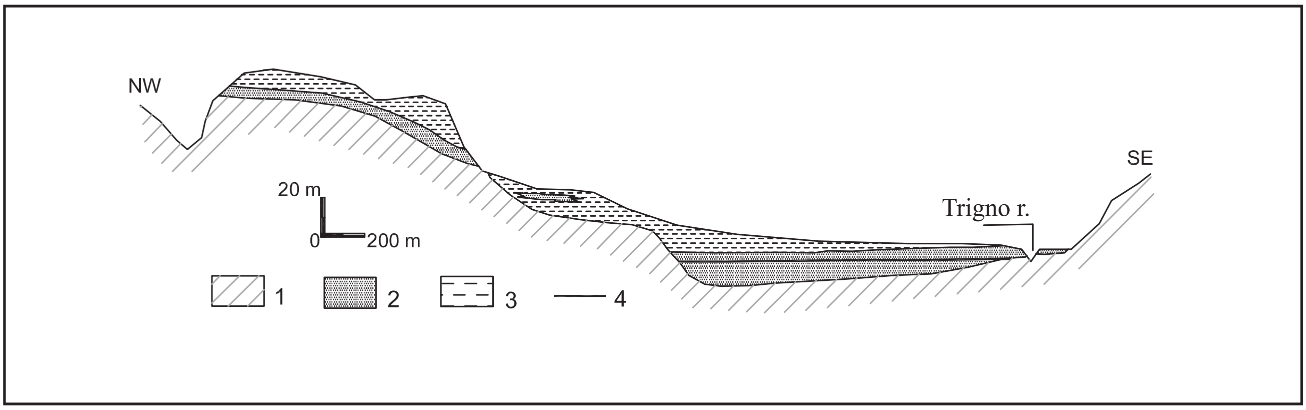


Fig. 5 - Schematic lithological section across the middle alluvial valley of the Trigno river. 1) Miocene-Pleistocene silty-clayey substratum; 2) gravely-sandy bodies; 3) silty-clayey bodies; 4) piezometric level.
- *Sezione litologica schematica trasversale alla media valle del fiume Trigno. 1) Substrato siltoso-argilloso mio-pliocenico; 2) corpi ghiaioso-sabbiosi; 3) corpi siltoso-argillosi; 4) livello piezometrico.*

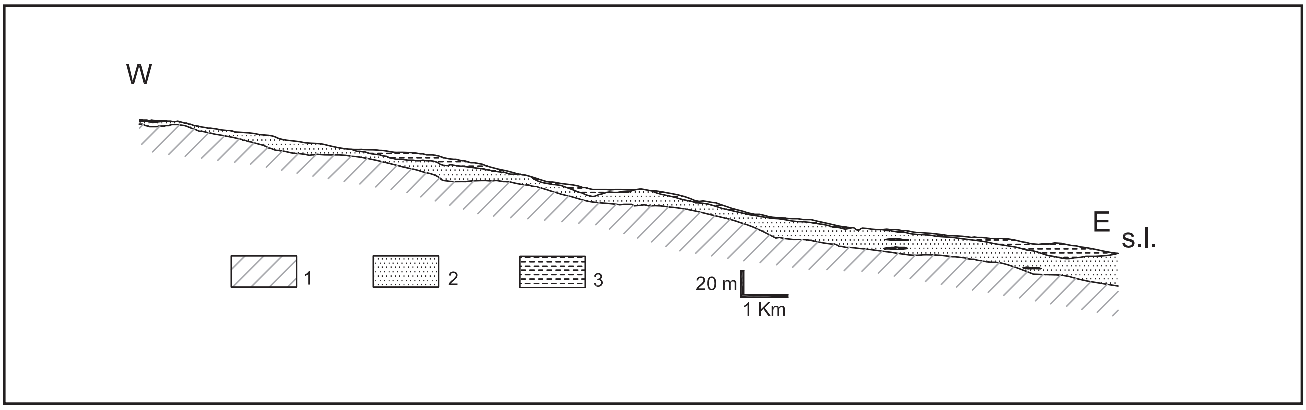


Fig. 6 - Schematic lithological longitudinal section of the alluvial valley of the Vomano river. 1) Plio-Pleistocene clayey substratum; 2) gravely-sandy bodies; 3) silty-clayey bodies.
- *Sezione litologica schematica longitudinale alla valle del fiume Vomano. 1) Substrato argilloso plio-pleistocenico; 2) corpi sabbioso-ghiaiosi; 3) corpi siltoso-argillosi.*

plains and within each of these.

The alluvial bodies of the Vibrata, Tordino, Vomano, Sangro and Trigno rivers mainly comprise gravels and sands with silty lenses and levels of variable thickness (fig. 6 and 7). That of the Pescara river, on the other hand, is mainly silty-sandy (fig. 8).

3.1. - AQUIFER GEOMETRY

The alluvial deposit aquifer geometry was reconstructed through the examination of the geology and the geomorphology of the plains and through information about the subsoil deriving from geognostic soundings and geophysical tests, as well as from observation in over 800 wells located in the alluvial plains.

In a general view of the Middle Adriatic aquifer geometry, the study of the valley floor enabled obvious similarities to be seen between them (fig. 6, 7 and 8). In the high part of all the valleys studied for example, bodies of gravel predominate in the alluvial deposits, often outcropping on the surface, while there are very few silty-clay and silty-sandy coverings. The thicknesses of the deposits vary between 10 and 20 metres and fine material lenses, if present, do not prevent hydraulic contact between the gravel bodies, in any case giving the sub-bed aquifers monostrate characteristics.

In the intermediate part of the plain monostrate conditions also prevail, although large lenses of fine material are present within predominant coarse deposits. The alluvial deposits reach maximum thicknesses of 40 m near the fluvial course with gravel bodies varying from 10 to 20 m in thickness (fig. 6, 7 and 8).

In the lower part of the plains, however, there may be different situations between the various valleys. In some larger plains, for example, such as in that of the Pescara, the Sangro and the Trigno

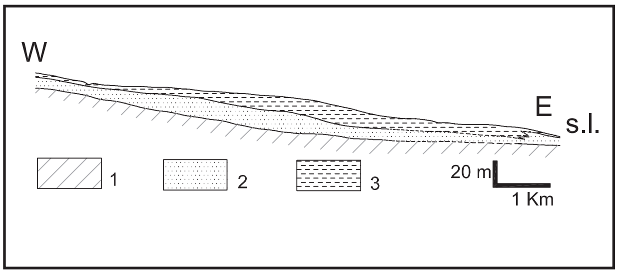


Fig. 7 - Schematic lithological longitudinal section of the alluvial valley of the Trigno river. 1) Miocene-Pleistocene silty-clayey substratum; 2) gravelly-sandy bodies; 3) silty-clayey bodies.
- *Sezione litologica schematica longitudinale alla valle del fiume Trigno. 1) Substrato argilloso mio--pliocenico; 2) corpi ghiaioso-sabbiosi; 3) corpi siltoso-argillosi.*

rivers, the presence of extended, powerful bodies of fine deposits separating the gravel and gravelly-sandy bodies, gives the aquifers multistrate characteristics (fig. 4 and 5); in other plains (Vomano, Saline, Foro and Sinello), on the other hand, monostrate conditions generally obtain, although fairly large fine material lenses may separate the gravel bodies locally (fig. 2 and 3). The maximum thickness of alluvial deposits is around 50 m at the end of the plains. The plain aquifers are supported by aquicludes generally comprising Plio-Pleistocenic clayey deposits and in some cases Paleogenic and Miocenic deposits, as in the case of the aquifers south of the Foro river in which the substrate comprises gravitational (Paleocene-Miocene) flow deposits.

The fluvial bed is normally set on alluvial deposits, but in several cases (e.g. the Vomano, Saline, Sangro and Trigno rivers), because of the current accelerated linear erosion phenomena, the bed also cuts into the substrate for fairly extended stretches. In particular, the Vomano river (Vomano diagram) flows embedded in the substrate and manages to cut into it for over 20 m (DESIDERIO *et alii*, 2003), interrupting the hydraulic continuity between river and water bed.

3.2. - AQUIFER SUPPLY AND CIRCULATION

The common sedimentological stratigraphic layout of the Abruzzo and Middle Adriatic alluvial plains in general (CELICO, 1983; NANNI, 1985; DESIDERIO *et alii*, 1999) determines similar piezometric structures, as it does for the aquifer geometry (fig. 9). Three zones with the following characteristics were identified in each plain. The first zone corresponds to the high part of the plains where the phreatimetric progress is conditioned by a single main underground drainage direction generally coinciding with the river course. The second zone corresponds to the high (I and II order) terraces and to the areas at the limits of the alluvial aquifer especially on the hydrographical left side, where the isophreatics are arranged approximately parallel to the contour lines; the average hydraulic gradient varies from 1‰ to 3‰. Finally, a third zone corresponds to the Upper Pleistocene and Holocene deposits (III and IV order terraces) where the isopiezometric lines are more complex, due to the difference in permeability of the deposits, the presence of numerous deviation works, and the supply to the aquifer by surface waters from the main affluents that cross the plain. The average hydraulic gradient varies between 4‰ and 6-7‰.

The main underground drainage lines are, on one hand, related to the powerful, high permeability gravel bodies and, on the other, they are conditioned by the presence of the numerous paleobeds that are also highly permeable.

The aquifers supply in the middle-low valley zone is due essentially to fluvial waters from the main water courses and recharge takes place especially in the intersection zones between present bed and paleo-beds; a considerable contribution to supplying the aquifers is given also by the subbed waters of the larger affluents demonstrating

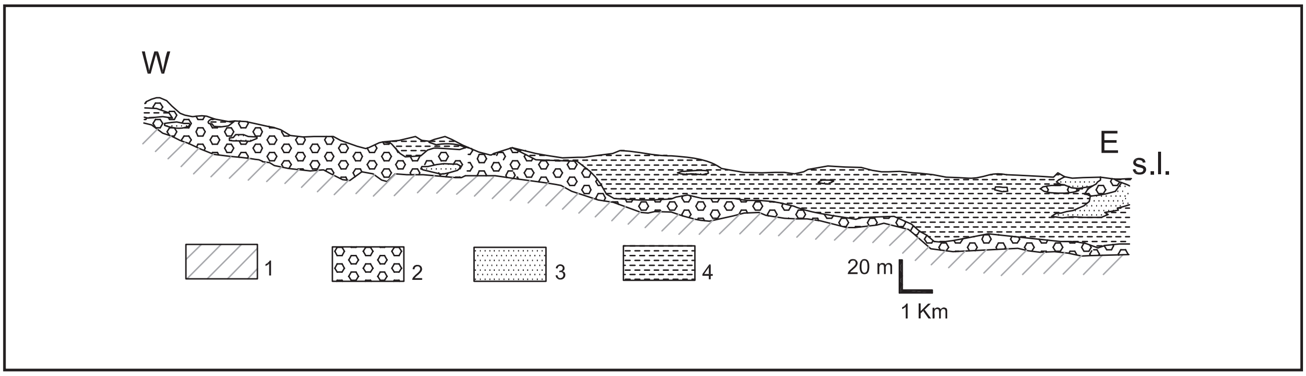


Fig. 8 - Schematic lithological longitudinal section of the alluvial valley of the Pescara river. 1) Plio-Pleistocene clayey substratum; 2) gravely bodies; 3) sandy bodies; 4) silty-clayey bodies.
- *Sezione litologica schematica longitudinale alla valle del fiume Pescara. 1) Substrato argilloso plio-pleistocenico; 2) corpi ghiaiosi; 3) corpisabbiosi; 4) corpi siltoso-argillosi.*

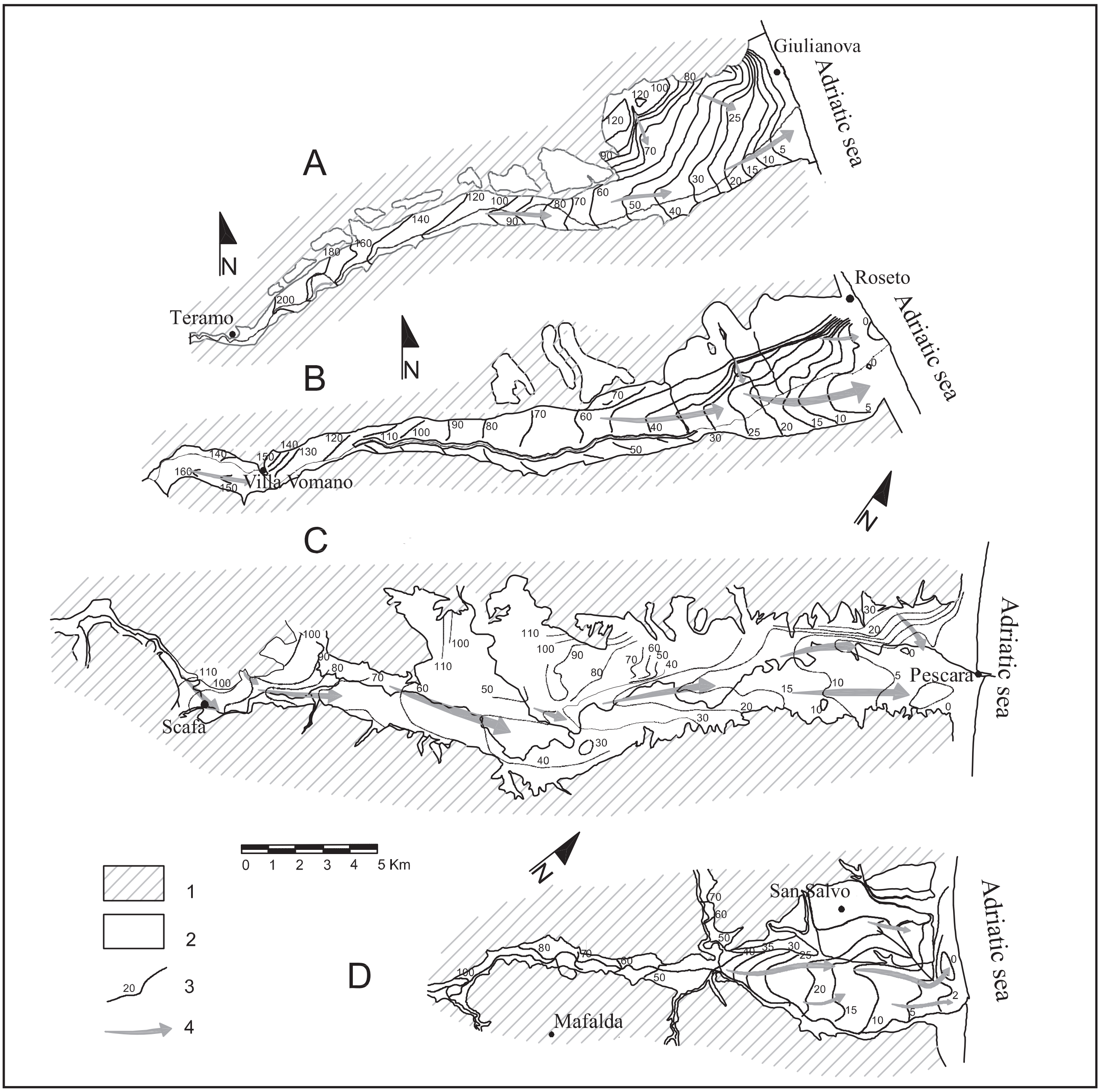


Fig. 9 - Piezometric surfaces of some middle adriatic alluvial aquifers. A - Tordino valley: monolayer aquifer with low transmissivity and main drainage coincident with the present thalweg. B - Vomano valley: monolayer aquifer with high transmissivity and diversion of the main drainage with respect to the present thalweg. C - Pescara valley: multilayered aquifer with variable transmissivity. D - Trigno valley: monolayer aquifer with more drainage zone with high transmissivity. 1) clayey substratum; 2) alluvial deposits; 3) piezometric contour lines and their altitude (m a.s.l.); 4) main groundwater flow.

- Superfici piezometriche di alcuni acquiferi alluvionali centro adriatici. A - valle del Tordino: acquifero monostrato a bassa trasmissività e drenaggio principale coincidente con l'attuale corso d'acqua. B - valle del Vomano: acquifero monostrato ad alta trasmissività e drenaggio principale scostato dall'attuale corso d'acqua. C - valle del Pescara: acquifero multistrato a trasmissività variabile. D - valle del Trigno: acquifero monostrato con più zone di drenaggio ad alta trasmissività. 1) substrato argilloso; 2) depositi alluvionali; 3) linee piezometriche e loro quota in m s.l.m.; 4) flusso sotterraneo principale.

the sedimentological-stratigraphic continuity between different alluvial bodies or that they belong to the same main alluvial body. With regard to the direct contribution by rainfall, this is limited and extremely modest in the low terrace deposits, since the effective precipitation is largely withheld by the clayey-silt coverings that are nearly always present at the ends of the valley floors. In the high terraces, on the other hand, the direct supply from precipitation takes on greater importance, also considering the existence of hydraulic contact with the low deposit aquifers.

The situation is different in the high part of the plains where the gravels outcrop on the surface and where favourable conditions therefore exist for the direct recharge of the groundwater by the rain. A further contribution to the sub-bed aquifers also comes, on a seasonal basis and recharged by the rains, from the water-bearing strata present in the eluvial-colluvial deposits of the valley sides, that are often in heteropic contact, and therefore in hydraulic contact, with the alluvial deposits of the plain.

4. - INFLUENCE OF SEDIMENTOLOGY AND STRATIGRAPHY ON HYDRODYNAMIC PARAMETERS OF AQUIFERS

The data regarding the hydrodynamic parameters of alluvial deposits are generally limited to portions of the aquifers and derive from rare permeability tests (Celico, 1983; Rusi *et alii*, 2004). Available tests have been carried out in the more productive zones of the aquifers, identified according to stratigraphic and piezometric reconstructions of the water beds. This has enabled extrapolation of maximum hydrodynamic parameter values and the correlation of these with the stratigraphic layout of the aquifer, as has already been carried out for the Marche area by Nanni (1985), Nanni & Vivalda (1996), Desiderio *et alii*, (1999). In particular, the following can be highlighted (tab. 1).

- The middle-high portion of the alluvial bodies is characterized by lower aquifer thicknesses and by greater hydraulic conductivity because of the presence of predominant gravel bodies.

- The middle-low part of the alluvial bodies, and in particular the part near the coast, is characterized by larger aquifer thicknesses and by generally lower hydraulic conductivity.

- In the middle-low part of the alluvial bodies, hydraulic conductivity values depend on the hydrographical basin lithology and therefore on the lithology and granulometry of the alluvia: in particular, the alluvia deriving from carbonate and pelitic arenaceous basins have the largest hydraulic conductivity levels.

- Transmissivity levels for the low portions of the aquifers depend above all on the hydraulic conductivity and minimally on the extent of the aquifers. It may be noted, in fact, how the smaller aquifers such as those of the Saline and the Foro have a larger transmissivity than much larger aquifers like those of the Pescara, the Sangro and the Tordino.

The scheme outlined above should be considered as an attempt at a regional correlation between aquifer geometry and hydraulic characteristics. It is clear that the characteristics described may be used for general regional quantization but not for detailed studies of individual aquifers.

Tab. 1 - *Correlations between sedimentilogical-stratigraphic and hydrodynamic parameters of acquifer.*
- Correlazione tra assetto sedimentologico-stratigrafico e parametri idrodinamici degli acquiferi.

Fluvial architecture according to hydrogeology	*Larger alluvial bodies*	*Smaller alluvial bodies*	*Predominant lithology of catchment basin*	*Maximum thickness of alluvial body (m)*	*Maximum permeability in the medium zone of alluvial valley (m/s)*	*Maximum permeability in the lower zone of alluvial valley (m/s)*	*Aquifer*	*Maximum transmissivity in tha lower zone af alluvial valey* *(m^2/s)*
Single paleochannel	Tordino		Pelitic-arenaceous, Pelitic	20	10^{-3}	10^{-4}	Monolayer	$2\ 10^{-3}$
	Vomano		Carbonatic, Pelitic-arenaceous, Pelitic	30	$2\ 10^{-3}$	$2\ 10^{-3}$	Monolayer	$4\ 10^{-2}$
		Sinello	Pelitic-arenaceous, Pelitic	25	10^{-3}	$4\ 10^{-4}$	Monolayer	$6\ 10^{-3}$
		Vibrata	Pelitic, Pelitic-arenaceous	40	-	10^{-4}	Monolayer	$2\ 10^{-3}$
		Saline	Pelitic-arenaceous, Pelitic, Carbonatic	35	-	10^{-3}	Monolayer	10^{-2}
		Foro	Pelitic, Carbonatic		-	$8\ 10^{-4}$	Monolayer	10^{-2}
Several paleochannel in the same aquifer	Pescara		Carbonatic, Pelitic-arenaceous, Pelitic	50	10^{-3}	$10^{-3}\ \ 10^{-5}$	Multi-layered	$5\ 10^{-3}$
	Sangro		Carbonatic, Pelitic-arenaceous, Pelitic	40		$4\ 10^{-4}$	Multi-layered	$5\ 10^{-3}$
	Trigno		Pelitic-arenaceous, Carbonatic, Pelitic	25	$2\ 10^{-3}$	$2\ 10^{-3}$	Monolayer	$2\ 10^{-2}$

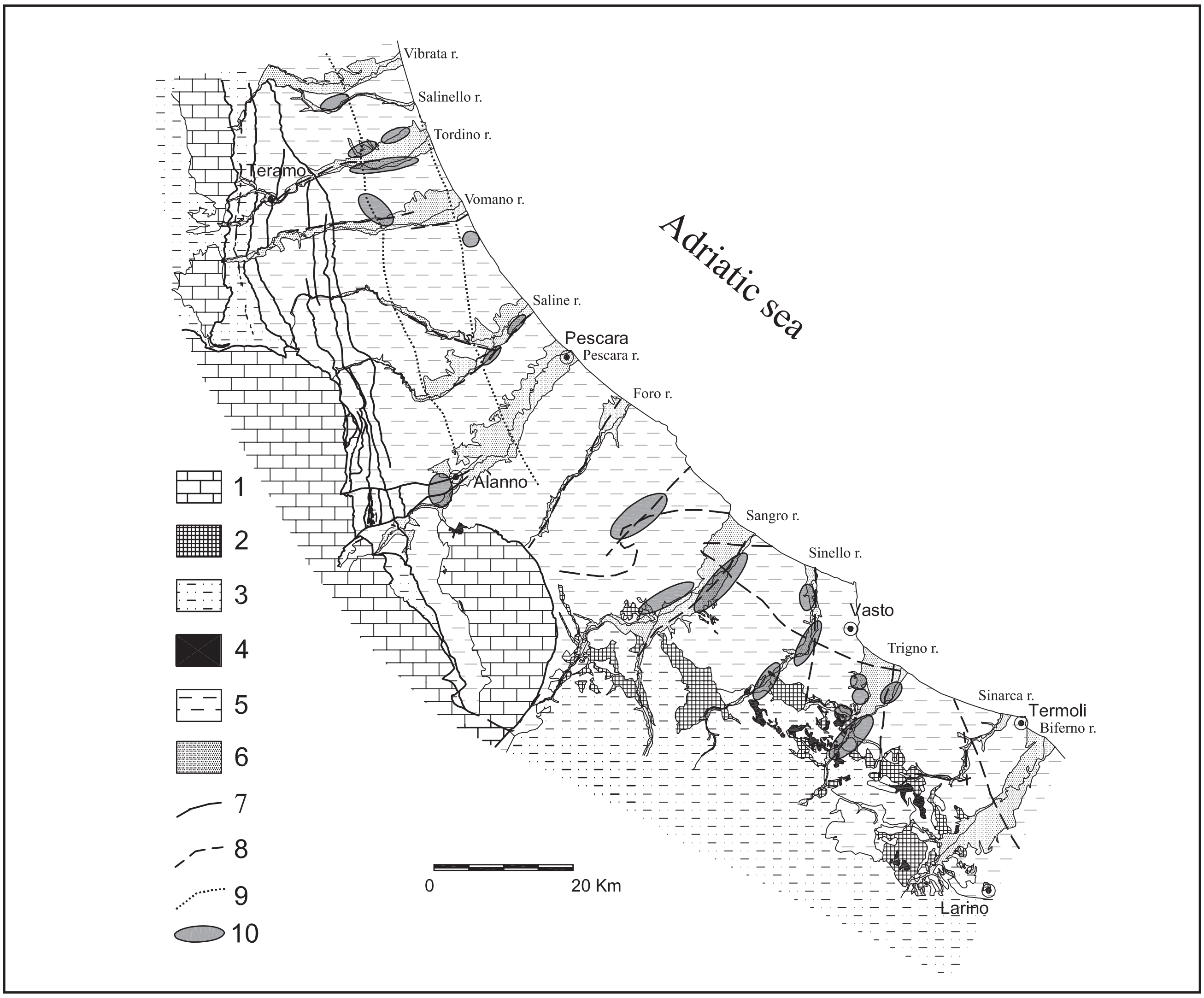


Fig. 10 - Distribution of the mineralized waters in the study area. 1) Carbonate sequence (Upper Triassic-Miocene). 2) Varicoloured clays (Upper Cretaceous-Oligocene). 3) Turbiditic deposits (Laga formation and Molise nappe, Miocene). 4) Evaporitic deposits (Upper Miocene). 5) Pelitic deposits of Abruzzo and Molise foredeep (Plio-Pleistocene). 6) Alluvial deposits (Holocene). 7) Faults and thrusts in the Mesozoic-Cenozoic and Miocene deposits. 8) Blind thrust of the allochthonous in the Adriatic foredeep. 9) Blind thrust in the Abruzzo basin. 10) Zone containing water with high electrical conductivity compared to average values.
- Distribuzione delle acque mineralizzate nell'area studiata. 1) Sequenza carbonatica (Triassico superiore-Miocene). 2) Argille Varicolori (Cretaceo superiore-Oligocene). 3) Depositi torbiditici (Formazione della Laga e coltre molisana, Miocene). 4) Depositi evaporitici (Miocene superiore). 5) Depositi pelitici dell'avanfossa abruzzese - molisana (Plio-Pleistocene). 6) Depositi alluvionali (Olocene). 7) Faglie e sovrascorrimenti nei depositi meso-cenozoici e miocenici. 8) Sovrascorrimento sepolto delle unità alloctone nell'avanfossa adriatica. 9) Sovrascorrimento sepolto nel bacino abruzzese. 10) Zone in cui è stata riscontrata la presenza di acque ad alta conducibilità elettrica rispetto a valori medi.

5. - INFLUENCE OF STRUCTURAL SETTING ON CHEMICAL COMPOSITION OF THE WATERS

From an analysis of the chemical-physical characteristics of over 900 water points located in the Central Adriatic alluvial plains and in adjacent areas (DESIDERIO & RUSI, 2003) the presence of waters with different chemical compositions has been detected, and above all, the presence of mineralised waters with high saline content and negative redox potential, in correspondence with fracture zones connected to mainly anti-Apenninic tectonic lines, in correspondence with structural highs and in correspondence with buried overthrusts (fig. 10 and 11).

The hydrochemical facies (PIPER, 1944) typical of the groundwaters in the Middle Adriatic alluvial plains is bicarbonate-calcic (NANNI, 1985; DESIDERIO *et alii*, 1999, 2001a), with electrical conductivity not above 2000 μS/cm and salinity of around 0.5-1 g/l; they derive mainly from the infiltration of river waters of Apennine origin. The infiltration areas are highlighted by lower electrical conductivity values and by evident seasonal oscillations in water temperature. The lower conductivity values are generally detected near river courses and along the main paleo-beds. Comparing the progress of conductivity with the main drainage lines, a precise correspondence between flow lines and low conductivity values was seen, showing a supply to the water table by river waters with conductivity of between 400 and 800 µS/cm (Desiderio *et alii*, 2001a, 2003).

The presence of waters enriched with chlorides and sodium, to reach a typical sodium chloride saline facies, is found in several zones of the alluvial plains where there is an electrical conductivity level of the underground waters of above 3000 µS/cm.

The origin of these waters too, as in the case of the mineralized springs on the Adriatic-Po front (ENI-AGIP, 1972; Ricchiuto *et alii*, 1985; Nanni & Zuppi, 1986; Nanni & Vivalda, 1999; Desiderio *et alii*, 2001b), can be found in the brines trapped in the sediments of the Messinian and Pliocene succession, which have very little mobility.

The mineralized waters in the Middle Adriatic alluvial aquifers, with salinity varying from around 1 g/l to over 3 g/l, derive from the mix of bicarbonate-calcic waters typical of these areas with the salt waters, from Pliocene and Messinian formations, that rise through fracture zones (fig. 12 A), contributing minimally also to the supply of these alluvial aquifers. In some cases, near fractures or structural elements, for example, the for-

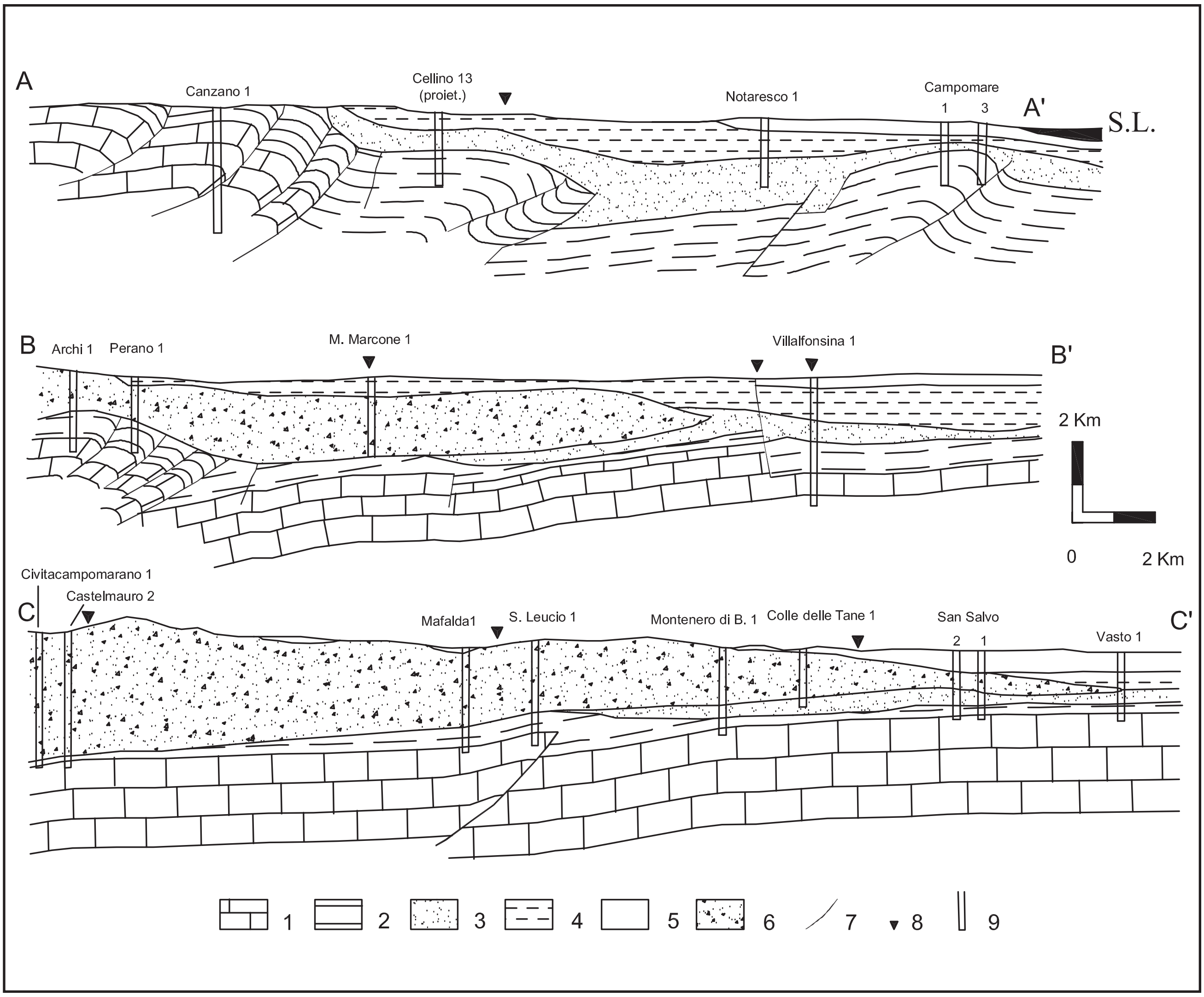


Fig. 11 - Geological cross-sections from the Apennines to the Adriatic sea (traces in fig. 1). 1) Carbonate deposits (Mesozoic-Cenozoic). Pelitic deposits: 2) Lower Pliocene, 3) Middle Pliocene, 4) Upper Pliocene, 5) Pleistocene; 6) Allochthonous units involving Pliocene slab; 7) Faults and thrusts; 8) Mineralized waters; 9) Borehole. AA' and BB' modified after Casnedi *et alii* (1982), CC' after Desiderio & Rusi (2004).

- Sezioni geologiche (traccia in fig. 1). Depositi carbonatici (Meso-Cenozoico); depositi pelitici: 2) Pliocene inferiore, 3)Pliocene medio, 4) Pliocene superiore, 5) Pleistocene; 6) unità alloctone infraplioceniche; 7) faglie e sovrascorrimenti; 8) acque mineralizzate; 9) sondaggi. AA' e BB' modificate da Casnedi et alii (1882)*, CC' da* Desiderio & Rusi (2004).

mation of a typical salt spring can be seen, marked by mud volcanoes or mud wells with emission of gas (Etiope *et alii*, 2003).

On the other hand, the sulphate-calcic and calcic-calcic facies waters with high Cl^-, Na^+, Mg^{++} and SO_4^{--} values are found in areas where the Messinian deposits are not very deep below the surface, or directly comprise the aquifer substrate, as is the case south of the Foro river where the substrate of the alluvial sub-beds often comprises Abruzzo-Molise gravitational flow evaporitic deposits (Desiderio *et alii*, 2001b). The contribution of sulphates is certainly due both to the leaking of gypsum caused by sub-bed waters and to the contribution of waters circulating in the evaporitic Messinian levels and rising along fracture zones aided also in this case by the presence of gas (fig. 12 B).

The saline content of the mineralized waters varies between 0.8 and 38.6 mS/cm according to the different geological conditions of emergence and to the different seasons of measurement. The waters emerging directly from the clays, from the lands belonging to the gravitational flow or deviated by means of drilled wells on these lands, generally have a higher saline content, while those emerging in the alluvial plains have variable, generally lower, contents, because of the dilution by the alluvial aquifer waters.

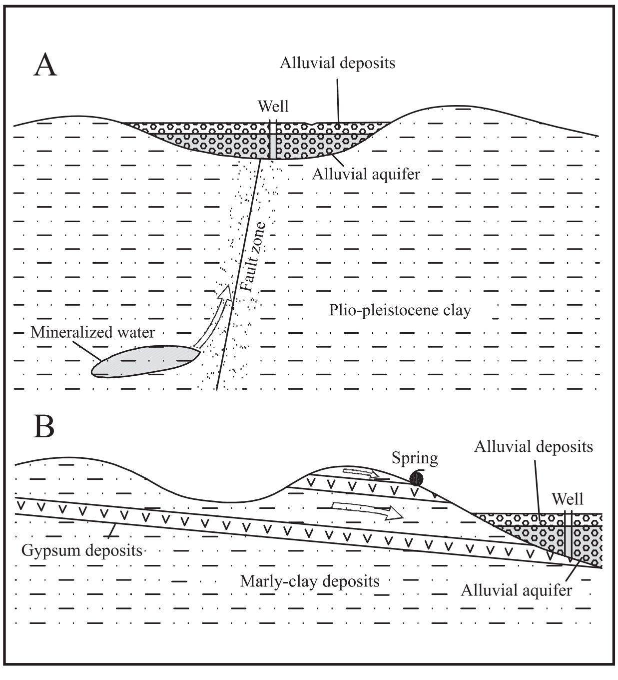


Fig. 12 -Scheme of the mineralized water circuit (not to scale). A) sodium chloride water; B) calcium sulphate and without dominant iones water.
- *Schema non in scala dei circuiti di risalita delle acque mineralizzate. A) acque cloruro sodiche. B) acque solfato calciche e senza ioni dominanti.*

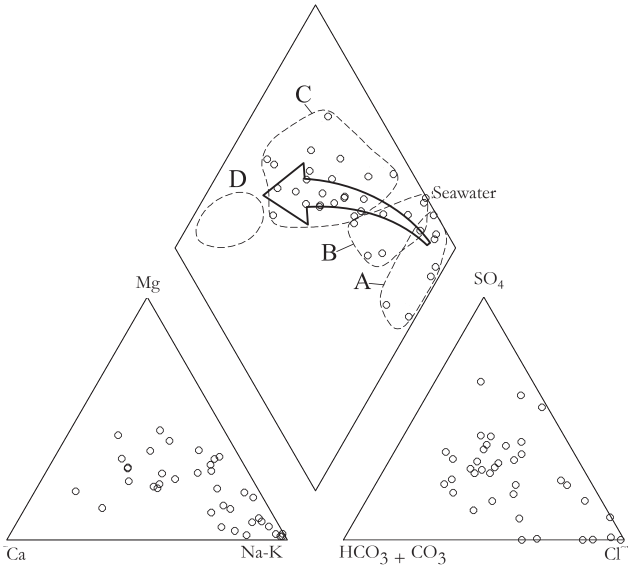


Fig. 13 - Piper diagram of the mineralized waters in alluvial aquifers. A) Sodium chloride facies; B) Sodium chloride facies with enrichment in sulphate; C) mixed or calcium sulphate facies; D) Zone of calcium-bicarbonate facies. The arrow indicates a probable dilution course of deep saline waters during the ascent toward the alluvial aquifers.
- *Diagramma di Piper relativo alle acque mineralizzate nelle pianure alluvionali. A) facies cloruro sodiche; B) facies cloruro sodiche con arricchimenti in solfati; C) facies miste o solfato calciche; D) zona relativa alle acque bicarbonato calciche. La freccia indica il probabile percorso di diluizione delle salamoie basali durante la risalita attraverso gli acquiferi alluvionali.*

The Piper classification of mineralized waters (fig. 13) has enabled the classification of the waters as sulphate-chlorinated-alkaline (or more precisely, chloride sodium) and earthy sulphate-chlorinated-alkaline. The Piper model also shows an evolution, through a dilution mechanism, from chloride-sulphate-alkaline waters (Basal brines) to bicarbonate-calcic waters (typical of the Adriatic alluvial valley floors) through a passage to earthy sulphate-chloride-alkaline waters.

The existence of mixes between different types of mineralized and non-mineralized waters contributes both to a better understanding of the rising processes and to the justification for the presence of waters with "anomalous" chemical compositions in alluvial groundwaters.

6. - INFLUENCE OF SEDIMENTOLOG STRATIGRAPHY ON SALT-FRESH WATER RATIO IN COASTAL AQUIFERS

The exploitation of the Adriatic coastal belt for industrial, civil and tourist purposes, in particular along and adjacent to the river mouths, has over recent decades led to a strong use of underground waters (Nanni, 1985; Desiderio *et alii*, 1999, 2001a) with consequent alteration in the salt-fresh water ratio. The analysis of the piezometric and chemical-physical characteristics of the larger sub-bed groundwaters of the Abruzzo coast (Desiderio & Rusi, 2003) is shown schematically in table 2.

On first analysis, the present results of the hydrogeological research conducted on sub-bed aquifers of the Abruzzo coastal region, highlight the following:

- Marine intrusion is shown in depression areas of the piezometric surface located on the coast or near it.
- The intrusion is absent or modest in the more extensive sub-beds in which circulation is characterized by a single main preferential drainage zone (Tordino and Trigno) and in the sub-beds in which, apart from the previous condition, there is a high permeability (Vomano), even though the anthropic readings are high (fig. 14).
- Marine intrusion is more pronounced in the more extensive sub-beds with medium-low permeability (fig. 15) and with the presence of several main drainage systems (Pescara and Sangro).
- In less extensive sub-beds, the piezometric surface is more sensitive and depression cones can easily be seen (fig. 16); if located near the coast, these give rise to intrusion (Vibrata and Sinello).

The development of the marine intrusion cone depends therefore mainly on the sedimentological stratigraphic layout of the aquifers, which determines the hydrogeological and hydrodynamic conditions governing the flow of fresh water to the sea.

In the Vomano aquifer the high hydrodynamic characteristics and the hydrogeological layout enable high readings from the groundwater (estimated at 300 l/s with high points at 600 l/s) without substantial variations in the salt-fresh water ratio.

7. - CONCLUSIONS

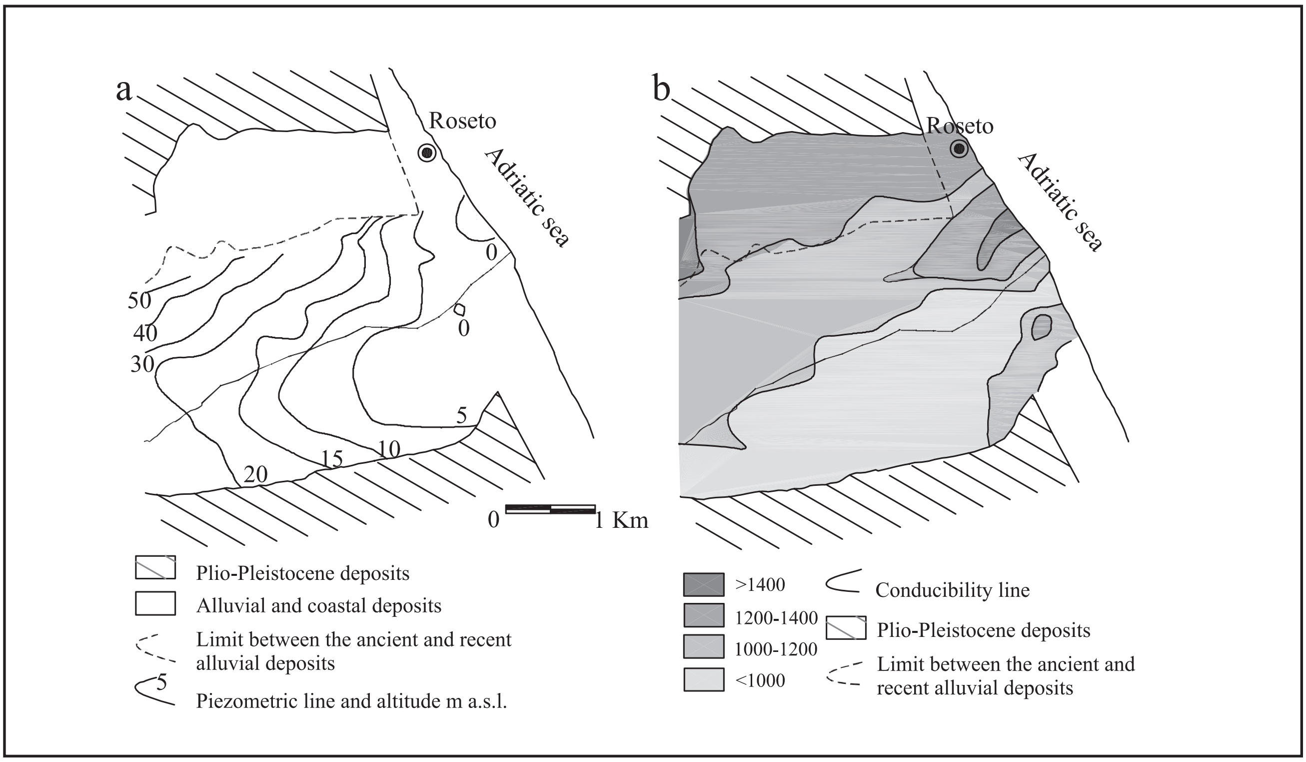
On the basis of the numerous results obtained by the previous studies on the sub-bed aquifers of the medium and large Middle Adriatic plains, and on the stock of correlations appropriately carried out between aquifer geometry and underground water chemism, a general picture of the main aspects concerning the sedimentological, stratigraphic, and therefore lithological characteristics, and the hydrogeological characteristics has been supplied.

The sedimentological, stratigraphic and hydrogeological characteristics can be summarized as follows:

- The alluvial plains comprise terraced alluvia formed of gravelly, gravelly-sandy, sandy, sandy-silty, silty and clayey lenticular bodies.
- The sub-bed aquifers of the plains are essentially contained in low-terrace middle-upper Pleistocene and Holocene deposits.
- In the high part of the aquifers gravelly and sandy lithotypes prevail, producing monostrate conditions. In the low part of the plains there are very differentiated situations. In some larger plains fine deposits separate the gravelly and gravelly-sandy bodies, giving the aquifers multistrate characteristics; on the other hand, in the smaller plains monostrate conditions generally obtain.
- Permeability in the gravelly-sandy lithotypes varies from 2 10^{-3} m/s to 10^{-4} m/s, while in the silty, clayey-silty and silty-clayey coverings it has

Tab. 2 - *Correlations between sedimentological - stratigraphic layout, hydrodynamic parameters and salt-fresh water ratio in coastal aquifers.*
- Correlazioni tra assetto sedimentologico-stratigrafico, parametri idrodinamici e rapporti acqua dolce - acqua salata negli acquiferi costieri.

Fluvial architecture according to hydrogeology	*Larger alluvial bodies*	*Smaller alluvial bodies*	*Presence of depression zones in piezometric surface near coast*	*Presence of high salinity zones near the coast*	*Maximum K near the coast (m/s)*
Single paleochannel	Tordino		NO	NO	10^{-4}
	Vomano		Slight	NO	2 10^{-3}
		Sinello	Slight	YES	4 10^{-4}
		Vibrata	YES	YES	10^{-4}
		Saline	YES	YES	10^{-3}
		Foro	NO	NO	8 10^{-4}
Several paleochannel in the same aquifer	Pescara		YES	YES	10^{-3} – 10^{-5}
	Sangro		Slight	Slight	4 10^{-4}
	Trigno		Slight	NO	2 10^{-3}



Fig, 14 - Example of a high-transmissivity intensely exploitied aquifer where the sea water intrusion is not developed. Coastal alluvial aquifer of the Vomano river; a) Piezometric map; b) Electric conductivity map (μS/cm).

- Esempio di acquifero ad alta trasmissività, intensamente sfruttato, in cui l'intrusione marina non si sviluppa. Acquifero alluvionale costiero del fiume Vomano. a) carta piezometrica; b) carta a isoconduttive (μS/cm).

values of between 2 10^{-4} and 8 10^{-8} m/s.

- Aquifer supply is due essentially to river waters from the main water courses, to the sub-bed waters of the main affluents, to meteoric precipitations and to a lesser extent to the waters rising from the substrate.

- Underground circulation in the plains is conditioned by the paleo-beds and by the distribution and the thickness of gravel bodies.

The main hydrochemical facies of the underground waters of the plain aquifers is bicarbonate-calcic. In many areas of the plains mineralized waters with bicarbonate-calcic facies highly rich in Cl^-, Na^+, Mg^{++} e SO_4^{--} ions are present, and waters with chloride-sodium and sulphate-chloride-sodium facies.

The mineralized waters derive from seawater trapped in the sediments at present comprising the substrate of the aquifers, which have given rise to the formation of Pliocenic brines. This does not seem a possible origin for seawater evaporation phenomena, since Pliocenic sediments are typical of a deep sedimentary basin. In some cases they reach the surface directly through Apenninic and anti-Apenninic tectonised belts or at the crossing of these, outcropping or buried, and in other cases when they rise they mix, in various degrees, with surface waters contained in the aquifers of the alluvial valley floors.

These emergences are, in fact, located along structural highs and outcropping or buried overthrusts. In the southern Abruzzo and in Molise the correlation between tectonic structures and areas with highly mineralized waters is complicated by the presence of the formation of Varicoloured Clays. The conveyance of the salt waters comes about with the probable contribution of the gaseous phase.

In the coastal portions of the aquifers, the salinisation of the groundwaters is connected with the presence of depressions in the piezometric surface, in turn connected with exploitation for industrial and irrigation purposes, while the extent of the saline wedge depends mainly on the permeability and the unitary flow rate of the groundwater.

The analysis of some hydrochemical parameters has allowed us to highlight the fact that marine submergence is present in the sub-beds of the Vibrata, Pescara, Sangro and Sinello rivers, and is noted slightly in the sub-beds of the Salinello, Vomano and Saline rivers, while in the remaining sub-beds (Tordino, Foro and Trigno) the phenomenon is less evident or absent.

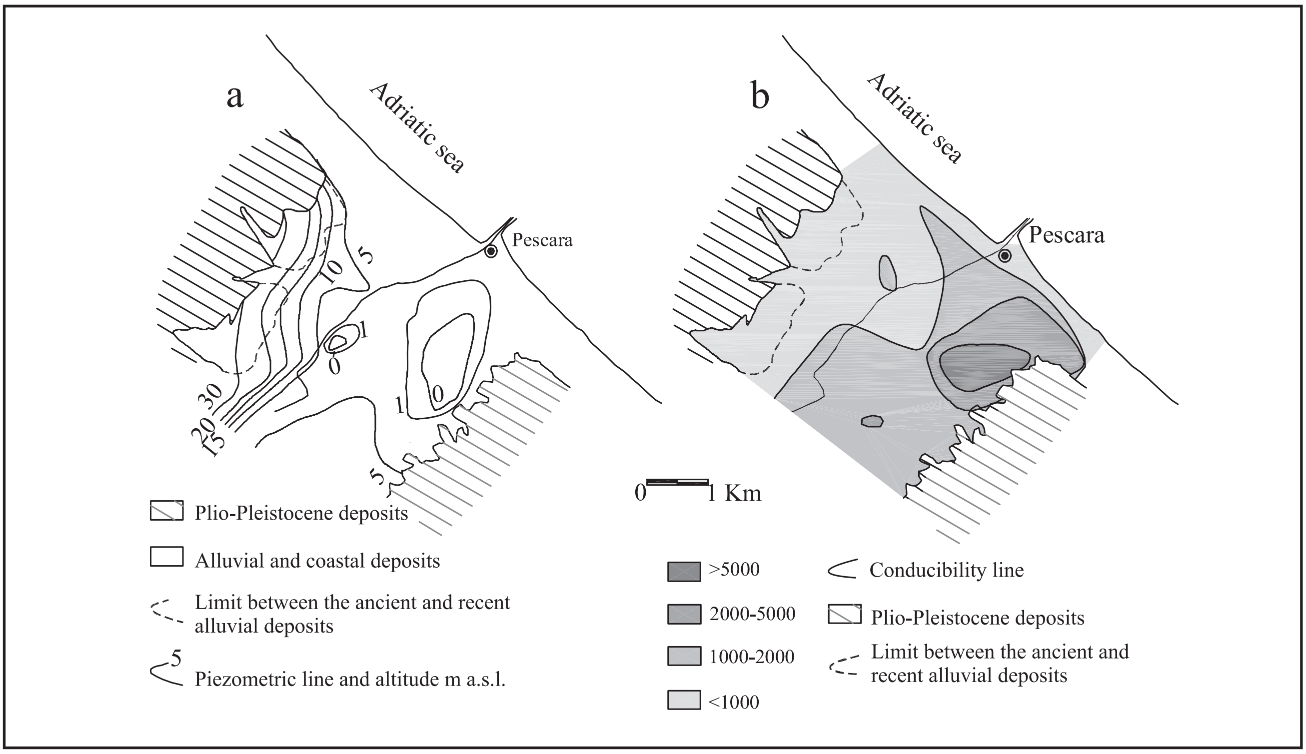


Fig. 15 - Example of aquifer with variable transmissivity, not intensely exploitied, where the sea water intrusion it's evident. Coastal alluvial aquifer of the Pescara river. a) Piezometric map; b) Electric conductivity map (μS/cm).

- Esempio di acquifero a trasmissività variabile, non intensamente sfruttato, in cui l'intrusione marina è evidente. Acquifero alluvionale costiero del fiume Pescara. a) carta piezometrica; b) carta a isoconduttive (μS/cm).

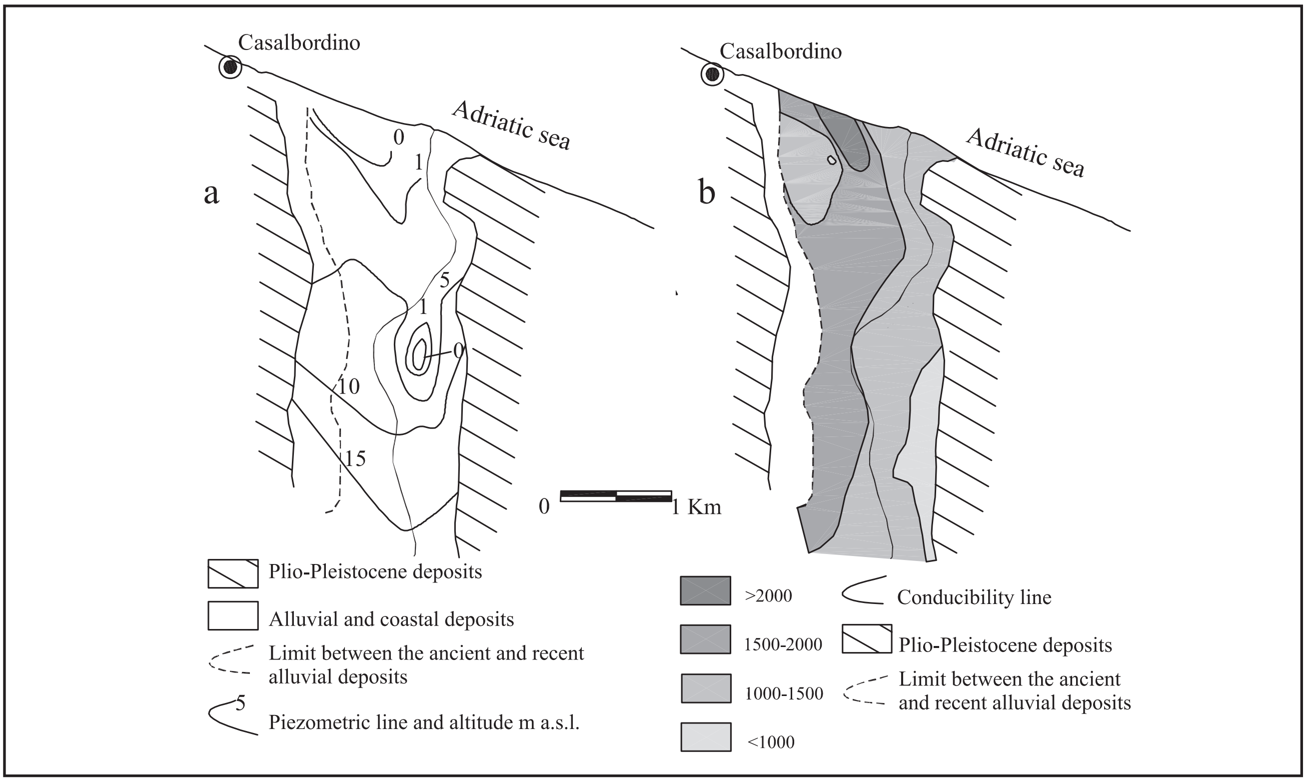


Fig. 16 - Example of aquifer with low transmissivity, intensely exploitied, where the sea water intrusion it's evident. Coastal alluvial aquifer of the Sinello river. a) Piezometric map; b) Electric conductivity map (μS/cm).

- Esempio di acquifero a bassa trasmissività, intensamente sfruttato, in cui l'intrusione marina è evidente. Acquifero alluvionale costiero del fiume Sinello. a) carta piezometrica; b) carta a isoconduttive (μS/cm).

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