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Lithostratigraphical and Hydrogeological Characteristics of the Aquifers of the Low Friuli Plain and Sustainability of Groundwater Extractions

Caratteristiche litostratigrafiche e idrogeologiche degli acquiferi della Bassa Pianura Friulana e uso sostenibile della risorsa

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ABSTRACT - The hydrogeological characteristics of the Friuli Plain derive from the depositional processes which occurred in the Upper Pleistocene. Such processes led to a sedimentation of materials whose geometry and development were conditioned both by the geological-structural evolution of the pre-Quaternary substratum and by sea level fluctuations connected with climatic events of Quaternary glaciations. The consequent changes in the dynamics of the alluvial plain hydrographic network led to a subdivision of the area into two distinct sectors: *High Plain*, formed by coarse-grained detrital sediments, prevalently gravels, irregularly cemented in conglomerate horizons and intercalated with layers of sand and, less frequently, of clay; *Low Plain*, characterized by sandy-pelitic deposits intercalated with gravel horizons which become increasingly deep and rare southwards.

The progressive transformation of the alluvial body in the north-south direction from a homogeneous and highly permeable predominantly gravel body to a differentiated structure with superimposed permeable and impermeable layers, determines the transition from unconfined aquifer to a multilayered aquifer system, the two being strictly interconnected. It is along this transitional belt between the two aquifer systems that a springs zone occurs extending approximately 100 km in an EW direction either side of the Tagliamento river. The reconstruction of the aquifer systems of the Low Friuli Plain, using stratigraphic data collected from a set of 339 water-wells, enabled the identification of:

- a confined aquifer system, formed by 8 variously branched superimposed artesian aquifers (A, B, C, D, E, F, G, H) at average depths between 20 and over 500 m below sea level (bsl);
- a transition aquifer system, comprising two confined layers (S_1, S_2) at average depths between 27.2 m above sea level (asl) and 12.2 m bsl;
- an unconfined shallow aquifer system, laterally discontinuous, at average depths between 44 m asl and 18 m bsl.

The groundwater of the Friuli Low Plain is exploited by means of a dense network of water-wells for drinking, agricultural, industrial and trout breeding purposes. The total quantity of groundwater drawn from the Low Plain has been estimated to be approximately 701×10^6 m^3 annually, 75% of which derives from the confined system. The most exploited artesian aquifers are A and B with a volume of 443×10^6 m^3 per year. These data allow the evaluation of the sustainability of current levels of exploitation of the confined aquifer system of the Friuli Low Plain.

KEY WORDS: Alluvial Plain, Aquifer System, Cross-Section, Lithostratigraphy, Exploitation, Sustainability.

RIASSUNTO - I caratteri idrogeologici della Pianura Friulana derivano dai processi deposizionali del Pleistocene superiore, che hanno determinato una sedimentazione di materiali la cui geometria e sviluppo sono stati condizionati sia dall'evoluzione geologico-strutturale del substrato prequaternario, sia dalle migrazioni della linea di costa legate agli eventi climatici del Quaternario. Le conseguenti variazioni delle dinamiche evolutive dei corsi d'acqua che attraversano la pianura hanno portato ad una suddivisione del territorio in due domini distinti: *Alta Pianura*, caratterizzata da depositi detritici grossolani prevalentemente ghiaiosi, irregolarmente cementati in orizzonti di conglomerato ed intercalati a livelli di sabbia e raramente di argilla; *Bassa Pianura*, caratterizzata da depositi sabbioso - pelitici intercalati ad orizzonti ghiaiosi sempre più rari e profondi man mano che ci si sposta verso Sud.

La progressiva trasformazione del materasso alluvionale, procedendo in senso meridiano, da una struttura omogenea prevalentemente ghiaiosa ad elevata permeabilità, ad

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una struttura complessa con livelli sovrapposti permeabili ed impermeabili, determina il passaggio da un sistema acquifero indifferenziato di tipo freatico a monte, ad un sistema acquifero multistrato a valle in stretta connessione l'uno con l'altro. Lungo la fascia di transizione tra i due sistemi acquiferi, la falda freatica viene a giorno dando origine alla zona delle risorgive che si sviluppa, per una lunghezza di circa 100 km, in destra e sinistra Tagliamento.

La ricostruzione dei livelli acquiferi presenti nel sottosuolo della Bassa Pianura, nel settore udinese, effettuata utilizzando i dati litostratigrafici provenienti da 339 pozzi idrici, ha consentito di riconoscere tre sistemi acquiferi: un sistema acquifero "confinato", costituito da otto falde artesiane denominate A, B, C, D, E, F, G, H variamente sovrapposte e ramificate, che si sviluppa tra la quota -20 m s.l.m. e la quota -500 m s.l.m. ed oltre; un sistema acquifero "di transizione", costituito da due falde artesiane denominate S_1, S_2 con profondità comprese tra +27.2 m s.l.m. e -12.2 m s.l.m.; un sistema "freatico", costituito da una falda freatica che si sviluppa nell'area in modo discontinuo e si trova a profondità comprese tra -18 m s.l.m. e + 44 m s.l.m.

Le acque sotterranee della Bassa Pianura sono sfruttate da una fitta rete di pozzi idrici, adibiti ad usi civili, irrigui, industriali e ittiogenici, per i quali è stato stimato un prelievo annuo pari a circa 701×10^6 m^3, proveniente per il 75% dal sistema acquifero "confinato". Le falde artesiane più sfruttate sono la A e la B con un volume idrico annuo estratto pari a 443×10^6 m^3. Sulla base di questi dati è stata effettuata una valutazione di sostenibilità dell'attuale sfruttamento per il sistema acquifero confinato.

PAROLE CHIAVE: Pianura alluvionale, Acquifero, Sezione idrostratigrafica, Dati litostratigrafici, Prelievo, Sostenibilità.

1. - PRE-QUATERNARY BASEMENT

The Friuli Plain is part of the northern sector of the Adriatic Plate, whose motion in relation to the Euroasiatic Plate produced the deformations of the Alpine region (BARNABA, 1990). Since the Upper Palaeozoic, this area has been characterized by epicontinental sea conditions, leading to the deposition of prevalently carbonate sediments, over 6,000 meters thick (CALORE *et alii*, 1995). These sediments formed the Friuli Platform which, together with the Venetian and North Adriatic Platforms, formed the foreland for the Dinaric, South-Alpine and North-Apenninic chains throughout the Cenozoic era. During the Liassic period, Mesozoic rifting caused the carbonate platform to fragment into blocks leading to the formation of the Belluno Basin at NW and of the Julian Basin at NE (CAVALLIN *et alii*, 1987; AMATO *et alii*, 1976; CATI *et alii*, 1987a, 1987b).

These physiographic-structural elements, present in the outcrops of the Carnic Alps and Pre-Alps and identified in the subsoil of the Veneto-Friuli Plain (CATI *et alii*, 1987a), preserved their integrity until the end of the Lower Cretacic, when the Alpine compressive phase began.

Between the Maastrichtian (Upper Cretacic) and the Priabonian (Upper Eocene), an active mountain chain-foredeep system developed in the Friuli-Julian and eastern Venetian areas; the motion of this structure towards the SW, from the western sector of the Slovenian Basin to the eastern sector of the Veneto Basin (DOGLIONI & BOSELLINI, 1987; CASTELLARIN & CANTELLI, 2000), determined the deposition of the Eocene Flysch: the Grivò Flysch (Upper Palaeocene-Lower Eocene), traversed by the "Bernadia 1" AGIP borehole (to the N out of the area shown in figure 1), and the Cormons Flysch (Ypresian), outcropping at the boundary of the southern Julian Pre-Alps. Following a protracted stage of emersion spanning from the Priabonian (Upper Eocene) to the Late Oligocene - Miocene marine transgression led to the sedimentation of terrigenous-carbonate deposits in the present Friuli Plain area; these sediments, outcropping at the southern boundary of the Carnic Pre-Alps - referred to as Cavanella Group (GELATI, 1969; MARTINIS, 1971) - were identified in the subsoil of the Friuli Plain through an analysis of the stratigraphic data collected from the "Cargnacco 1" and "Lavariano 1" AGIP boreholes, and additio-

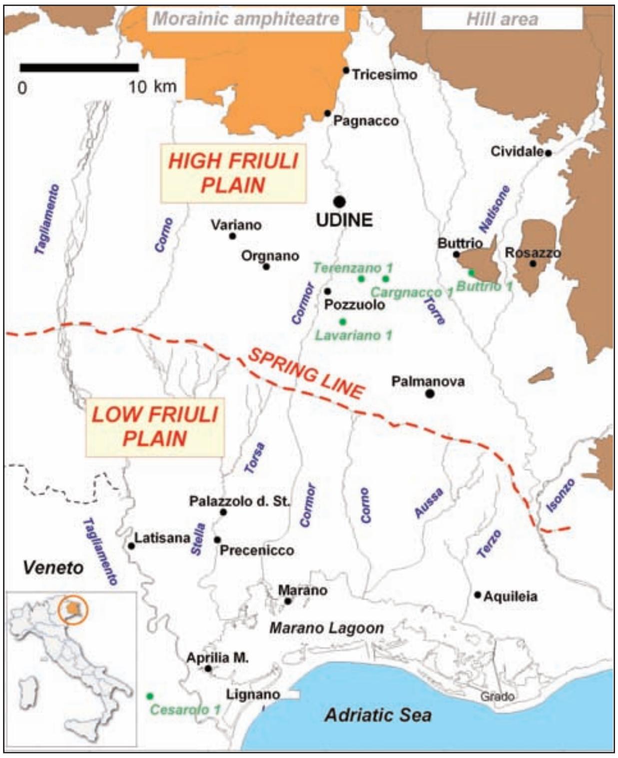

Fig. 1 - The Friuli Plain between the Tagliamento river to the W and the Natisone river to the E. The red dashed line points out the Spring Line; the AGIP boreholes are indicated by green dots.
- Il reticolo idrografico della pianura friulana tra i fiumi Tagliamento a Ovest ed Isonzo ad Est. La linea rossa tratteggiata indica la linea delle risorgive; in verde sono evidenziati i pozzi AGIP.

nally, as outcrops to the S of Udine, near Pozzuolo del Friuli, on the left bank of the Cormor river; in the latter case, the deposit (Lower Miocene) is formed by sandstone and arenaceous-glauconitic calcarenite lying beneath pre-Wurmian conglomerates.

The "Cargnacco 1" borehole (VENTURINI, 2002) is located in the Friuli Plain about 6 km to the S of Udine, in correspondence with the Meso-Alpine structural front represented by the Palmanova Line (AMATO *et alii*, 1976; MERLINI *et alii*, 2002). The borehole was drilled in an inner area of the Friuli Platform, which was bordered by the Julian Basin to the NE and by the Belluno Basin to the NW during the Jurassic-Cretaceous age. It passed through a thick carbonate sequence characterized by tectonic repetitions, with a total throw of 2 km, up to the Ypresian-Lutetian passage (Lower Eocene), where the final submersion of the area is marked by the Cormons Flysch; discordant sandstones of the Cavanella Group (Middle Miocene) are superimposed on the Eocene deposits.

In the "Lavariano 1" borehole, located 5 km to the SSW of the "Cargnacco 1" borehole, deposits of the Lower-Middle Miocene (MARTINIS, 1971) have been identified and can be correlated with those of the Cargnacco and Pozzuolo outcrops. The current difference in level between the Cavanella Group of "Lavariano 1" and the "Cargnacco 1" boreholes is approximately 700 m and is due to later tectonic movements involving underlying Pleistocene deposits, characterized by a throw of about 300 m between the two boreholes.

In a water-well located in Variano, about 10 km to the W of Cargnacco, marly siltites of Tortonian age were found at a depth of between 54 and 57 m (VENTURINI, 1987). These showed faunal characteristics similar to those identified in the Tortonian deposits of the Carnic Pre-Alps (STEFANINI, 1915; GELATI, 1969; STEFANI, 1982). The presence of Tortonian deposits at such shallow depths testifies to the important upwarps which took place along the Palmanova Line, a line which does not in fact constitute a single continuous structural front but is formed by several overthrust fronts interrupted by transcurrent or transpressive faults oriented in a NNW-SSE direction.

The well passed through several levels of alluvial conglomerates (also identified in a second water-well located about 370 m towards the SSW) up to a depth of 54 m from the ground surface. These conglomerates are intercalated by both a gravel horizon and a thick gravelly-sandy clay layer (21.5 m - 33 m), the upper part of which includes decalcified cobbles and is red in colour, and is probably a palaeosoil. The presence of Pleistocene marine deposits, transgressive over the Tortonian, suggests that these deposits were also part of a Pleistocene sedimentary cycle.

2. - MORPHOLOGICAL CHARACTERISTICS OF THE ALLUVIAL PLAIN

The Friuli Plain (fig. 1) is divided into two distinct sectors (COMEL, 1958; VECCHIA *et alii*, 1968):
- the High Plain, formed by coarse-grained detrital sediments, prevalently gravels, irregularly cemented in conglomerate horizons and intercalated with sand and less frequently with clay layers. These deposits are a consequence of the rapid progradation of an alluvial fan system formed in the Upper Pleistocene as a result of the LGM (Last Glacial Maximum - between 20 ka and 18 ka BP) (OROMBELLI & RAVAZZI, 1996; FLORINETH & SCHLUCHTER, 2000);
- the Low Plain, characterized by sand and clay deposits intercalated with gravel horizons which become increasingly less frequent and are present at increasing depths as one moves southward. These sediments are partly of fluvioglacial origin and partly of marine, lagoon and marshy origin.

In the Friuli High Plain, the "Lavariano 1" borehole, which reaches a depth of 1011.5 m, first passes through 580 m of Quaternary sandy gravels, of marine origin from 370 m in depth and transgressive over the Tortonian marl substrate. The "Terenzano 1" borehole, located to the N of "Lavariano1", is drilled to a depth of 701.70 m and passes through 213 m of Quaternary continental gravelly-sandy deposits.

The "Cesarolo 1" borehole, located to the W of Lignano to the right of the Tagliamento river, is the nearest AGIP borehole to the Friuli Low Plain. It passes through 475 m of Quaternary deposits, over sands and calcarenites of Middle Miocene age. By analysing and correlating the lithostratigraphical data obtained from several deep water-wells in Latisana (542 m), Aprilia Marittima (590 m) and Lignano (550 m), it was possible to determine the Quaternary base at depths of 480 m and 466 m with reference to Latisana and Lignano respectively.

Studies achieved on the basis of geophysical surveys carried out by the AGIP Group in the Friuli Low Plain allowed the reconstruction of the Quaternary base to be extended over the entire area (CAVALLIN & MARTINIS, 1980; CALORE *et alii*, 1995). The bathymetric maps show a thickening of the Quaternary deposits proceeding from

NE (250 m in the vicinity of Palmanova) to SW (over 500 m to the W of Lignano).

The geomorphological evolution of the Friuli Plain during the Quaternary age was conditioned by both Pleistocene glaciations and eustatic oscillations. Sea-level changes led to significant erosion and deposition as a consequence of the transgression or regression of the river delta.

The last glaciation (Wurm AA) led to the formation of the three principal concentric morainal arcs of the Tagliamento river. These decrease in height from the external to internal sectors and correspond with certain glacial periods.

The Wurmian fluvio-glacial sediments of the northern sector of the High Plain almost completely cover the more ancient deposits, which emerge in narrow terraced strips. These sediments are represented by both the outcrops of weathered moraines near Pagnacco and Tricesimo and by the conglomerate horizon extending to the S of Udine in the vicinity of Variano, Orgnano and Pozzuolo, and together constituted a single continuous surface of between 5 and 10 m above the present ground surface. The pre-Wurmian terraces are ancient alluvial remains, which rise above the rest of the plain as a consequence of movements of the Miocene substratum (COMEL, 1955).

There is probably a third older alluvial horizon, preceding the penultimate glaciation (Riss AA), which includes some conglomerate outcrops in the Cormor river valley. This Pleistocene horizon is associated with several terraces in the vicinity of the Udine hill, near the Rosazzo hills, to the E of Cividale and at the base of the Buttrio hills. These joined together in a continuous alluvial horizon of between 10 and 30 m above the present ground surface (FERUGLIO, 1925).

During the LGM, four main fluvioglacial currents developed in the Friuli High Plain. These correspond with the present courses of the Torre, Cormor, Corno and Tagliamento rivers. The alluvium carried by the Torre and Cormor rivers derived from both the arenaceous-marly Eocenic rocks and the calcareous-dolomitic rocks of the Fella river basin, while the materials transported by the Corno and Tagliamento rivers (calcareous-dolomitic elements, sandstones of various ages, ancient igneous rocks, siliceous conglomerates) originated from the Carnia region. As these fluvioglacial currents flow towards the Adriatic Sea, their speed and force progressively decrease and this has led to the deposit of coarse-grained alluvium and sandy-clayey sediments in the northern (High Plain) and in the southern (Low Plain) areas of the Friuli Plain respectively.

During the subsequent cataglacial period, significant terracing took place in certain areas of the Friuli Plain and is most evident in the Low Plain, where fluvioglacial currents hollowed the clayey sediments and deposited some parallel gravel strips in the NNE-SSW direction. Today, these alluvial gravels can be found in crevices and are located in areas visibly lower than the clayey banks by which they are bound. These gravels, which are increasingly intercalated with sands, decrease in thickness as they move southward, finally disappearing. The largest terrace system is located on the right of the Stella-Taglio rivers (BOSCHIAN, 1993; CAVALLIN *et alii*, 1987).

As regards the evidence of possible eustatic oscillations in the Low Plain, a number of drillings carried out near Palazzolo dello Stella (Bonifica Fraida, Piancada) have revealed the remains (FERUGLIO, 1936) of living species of marine molluscs (Cardium, Turritella, Chlamys, Cerithium). In the Piancada drilling, sediments of marine origin (clay, marl and fine sand of Pleistocene age), enriched with fossils, were found beneath a peaty horizon at a depth of between 40 m and 168 m. These marine deposits were underlain by a layer of loose gravel, most likely of pre-Wurmian alluvial origin, mixed with large cobbles (sandstones, siliceous limestones, limestones, dolomites), to a depth of 175 m.

The presence of marshy areas within the alluvial plain (MAROCCO, 1989, 1991) is testified by peaty horizons of varying ages identified in the vicinity of Aquileia (21,700 ± 580 years BP), Aprilia Marittima (28,100 ± 250 years BP) and Marano (20,200 ± 720 years BP) at 6.3 m bsl, 29.7 m bsl and 23 m bsl respectively. The difference in depth has been attributed to subsidence (BORTOLAMI *et alii*, 1977) or to the natural slope of the palaeoplain (MAROCCO, 1991), estimated to be approximately 1.5% - 2.0% (BRAMBATI & VENZO, 1967; BRAMBATI, 1970, 1985; MOSETTI & D'AMBROSI, 1966; BONDESAN & FONTANA, 1999; BOSCHIAN, 1993; MARTINIS, 1953, 1957; GIOVANNELLI *et alii*, 1985). Radiometric datings (^{14}C) carried out at boreholes drilled to a depth of approximately 30 m in the Marano Lagoon (MAROCCO, 1989) established the age of deep continental deposits (present at a depth of 23 m) to be 20,200 ± 270 years BP; superimposed lagoon deposits (at 10.05 m) to be 5,540 ± 225 years BP and coastal sediments (at 2.60 m) to be 1,400 ± 290 years BP.

During the LGM, a wide alluvial plain, traversed by the Isonzo and Tagliamento river systems, extended over the area of both the present Low Friuli-Veneto Plain and the Gulf of Trieste, frequently turning into swamps. The sea-level, after reaching the lowest position (-100/-130 m below the present mean level), rapidly rose in the post 18-ka over the low gradient palaeoplain (GAMBOLATI, 1998; ANTONIOLI & VAI, 2004). The maximum marine ingression can be dated at about 5,000 years BP (CORREGGIARI *et alii*, 1996).

After the LGM, the Friuli Low Plain (MAROCCO, 1989, 1991) was characterized by very low levels of sedimentation which continued in the historical age, as verified by the discovery of archaeological remains, attributable to the Roman colony of Aquileia (founded in 181 B.C.), at the shallow depth of 1.0-1.5 m.

The evolution of the Friuli Low Plain was also conditioned by the meandering of the Tagliamento and Isonzo rivers. The afore mentioned radiometric analysis (^{14}C), carried out at the Marano lagoon (MAROCCO, 1991) and at the Tagliamento river delta (MAROCCO, 1988, 1991), identified a sequence of mostly continental and subordinately pelitic sediments (Pleistocene). The origin of these deposits is principally from the Isonzo-Natisone-Torre river systems and overlaid by transgressive lagoon-coastal deposits. This would seem to strengthen the hypothesis that the location of the Tagliamento river delta prior to LGM, lay to the W (probably in the Caorle Lagoon). The present Tagliamento river delta (MAROCCO, 1988) formed over the last 2,000 years following a deviation of the river's course towards the E in the pre-existent Marano palaeo-lagoon area.

In the Holocene, the Tagliamento river, probably together with the Corno river, formed the western sector of the Friuli Plain to the point of the eastern boundary represented by the Stella river; several palaeo-riverbeds, in some cases already abandoned in the Neolithic age (BOSCHIAN, 1993; BONDESAN & FONTANA, 1999), have been identified in the Latisana-Precenicco area.

The Corno river, an important fluvio-glacial current during Pleistocene times, had a significant impact on the High Plain, while its traces in the Low Plain have been eliminated by the meandering of both the Tagliamento and spring rivers (BONDESAN & FONTANA, 1999). The fluvioglacial deposits of the Cormor river formed the plain on the E of the Stella river. To the E of the Cormor river, the Aussa-Corno hydrographic network flows over the remains of the wide, late-glacial alluvial plain, the river bed traces of which are represented by gravelly-sandy fluvial ridges stretching N to S, while the ancient overflow area, traversed by the present spring rivers, is characterized by the presence of both fine-grained sediments and buried river-beds (BONDESAN *et alii*, 1995).

3. - HYDROGEOLOGICAL AND LITHOSTRATIGRAPHICAL CHARACTERISTICS OF THE FRIULI PLAIN

The Friuli Plain in the Province of Udine (fig. 1) is bordered by the Tagliamento river to the W, by the hydrographic system of the Torre and Natisone rivers to the E, by the morainal amphitheatre of the Tagliamento to the N, and by the Adriatic Sea to the S. The hydrogeological characteristics of this area are the result of depositional processes which occurred in the Pleistocene age.

The progressive transformation, moving southward, of the alluvial sediments from a homogeneous structure of highly permeable gravel deposits to a differentiated structure with superimposed sand, gravel and clay layers, determines the transition of an unconfined aquifer to a multilayered aquifer system, the two being strictly linked (STEFANINI & CUCCHI, 1977; GRANATI *et alii*, 2001; MARTELLI & RODA, 1998; MARTELLI *et alii*, 2003). A similar structure can be identified throughout the Po Plain (REGIONE EMILIA-ROMAGNA, ENI-AGIP, 1998).

It is along this transitional stretch between the two aquifer systems that part of the High Plain groundwater surfaces, give rise to the area of springs which extends approximately 100 km in an EW direction and feeds the Low Plain's hydrographical network. This series of springs develops beyond the Friuli region as an almost continuous element on the left of the Po river as far as the Mondovì area, to the S of Turin (FERUGLIO, 1925; ANTONELLI & STEFANINI, 1982; DAL PRÀ *et alii*, 1989; MARTINIS *et alii*, 1976).

The High Plain water-table aquifer is primarily fed by direct recharge, seepage from surface waters and underground sources from both the moraine hills and the Pre-Alps (STEFANINI, 1978; MOSETTI, 1983). The multilayered aquifer system is recharged by the unconfined aquifer (MOSETTI, 1983; VECCHIA *et alii*, 1968).

4. - METHODS

A total of 339 stratigraphies selected from the *Infopozzi* data bank - a special computer-aided data bank started in 1994 which contains data collected from over 25,000 wells (GRANATI *et alii*, 2000) - formed the basis of the study. These stratigraphies were obtained from water-wells located either in the Friuli Low Plain or in the southern Friuli High Plain over an area of about 900 km^2.

In order to synthesise the available stratigraphies into a coherent geological framework, the terms used by the drilling operators to describe the lithological characteristics of the strata were simplified and consist of four main classes: "clay", "sand", "gravel and conglomerate" and pre-Quaternary "substratum" were defined as the reference for the lithological description of the subsoil. While these are not precise sedimentological definitions, they enable the lithostratigraphical data to be used as hydrogeological criteria based on the hydraulic conductivity values of the examined lithologies, for the purpose of locating the permeable alluvial bodies of the subsoil. These values are higher than 10^{-3} m/s in gravels, vary from 10^{-3} to 10^{-7} m/s for sands (from clean to silty) and are lower than 10^{-9} m/s in clayey deposits (FREEZE & CHERRY, 1979). Data concerning hydraulic conductivity and transmissivity, obtained by means of aquifer tests carried out in both water-table and confined aquifers identified in hydrogeologically similar areas of the Po Plain, revealed hydraulic conductivity values of approximately 10^{-3}-10^{-4} m/s and transmissivities of approximately 10^{-2}-10^{-1} m^2/s in the prevalently gravelly water-table aquifer of the alluvial plain of the Piave river (ANTONELLI, 1986; VORLICEK *et alii*, 2004), while the gravelly and sandy confined aquifers in the Pavia and Treviso sectors of the Po Plain are characterized by hydraulic conductivity values in the region of 10^{-3}-10^{-5} m/s and by transmissivities of approximately 10^{-2}-10^{-4} m^2/s (DAL PRÀ *et alii*, 1989; PELOSO & COTTA RAMUSINO, 1989).

Following the preliminary stage, the lithostratigraphical columns were compared along certain cross-sections (figs. 3-8) which develop sub-parallel and crosswise to the groundwaters and main directional flow of the rivers (fig. 2). These correlations, made with reference to the productive horizons identified by the drilling operators, permitted the reconstruction of the aquifer layers present in the Low Plain. These horizons were located at the same average depth and were lithologically similar. The aquifer layers are marked with a capital letter and each identified sublayer is also specified by a number.

The graphic representation of the geometrical characteristics (average depth and thickness) of each layer of the confined aquifer system was successively visualised by means of isobath and isopach maps respectively (figs. 9-20). The maps were plotted using Surfer 6.04 (Win 32), a two-dimensional contouring, gridding and surface mapping package that runs under Microsoft Windows. This program, extensively used for terrain modelling, is provided with a sophisticated interpolation engine which can transform the Z attributes of an unlimited number of scattered data provided with X, Y co-ordinates into outstanding contour maps and surface plots, using appropriate gridding methods. These plots, superimposed on base maps, synthesize the geographic distribution of processed data. In order to interpolate the available depth and thickness data onto an appropriate grid, superimposed on a geographic map of the area, geostatistic ordinary kriging was chosen as the gridding method (DAVIS, 1986; KITANIDIS, 1997).

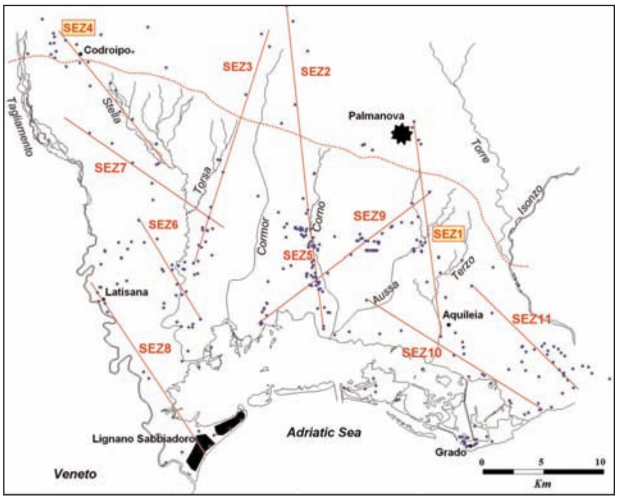

Fig. 2 - Map of the lithostratigraphical cross-sections. The red dashed line points out the Spring Line. The blue dots represent the wells whose lithostratigraphical columns have been correlated.
- *Ubicazione delle sezioni litostratigrafiche. La linea rossa tratteggiata indica la linea delle risorgive. I pozzi le cui colonne litostratigrafiche sono state utilizzate per le correlazioni sono rappresentati con simboli blu.*

5. - DESCRIPTION OF THE CROSS-SECTIONS

The most significant cross-sections (figs. 3-8) are described in succession. Moving from E to W (fig. 2), cross-sections n. 1, 2, 3 and 4 concern the transition zone between the High and Low Plain, while cross-sections n. 5 and 6 develop in the SW sector and in the central part of the Low Plain respectively.

In the description of the identified aquifer layers, the average depth was calculated as a mean value between the top and the bottom of the layer; if the bottom is unknown, only the depth of the top is indicated. The exploited horizons are marked with a different coloured dot for each identified aquifer layer.

Each utilised water-well is initialled according to the municipality in which it is located, as shown in table 1. These initials are followed by a number (and finally by further letters) which is used to identify the well within the data-bank *Infopozzi* (GRANATI *et alii*, 2000).

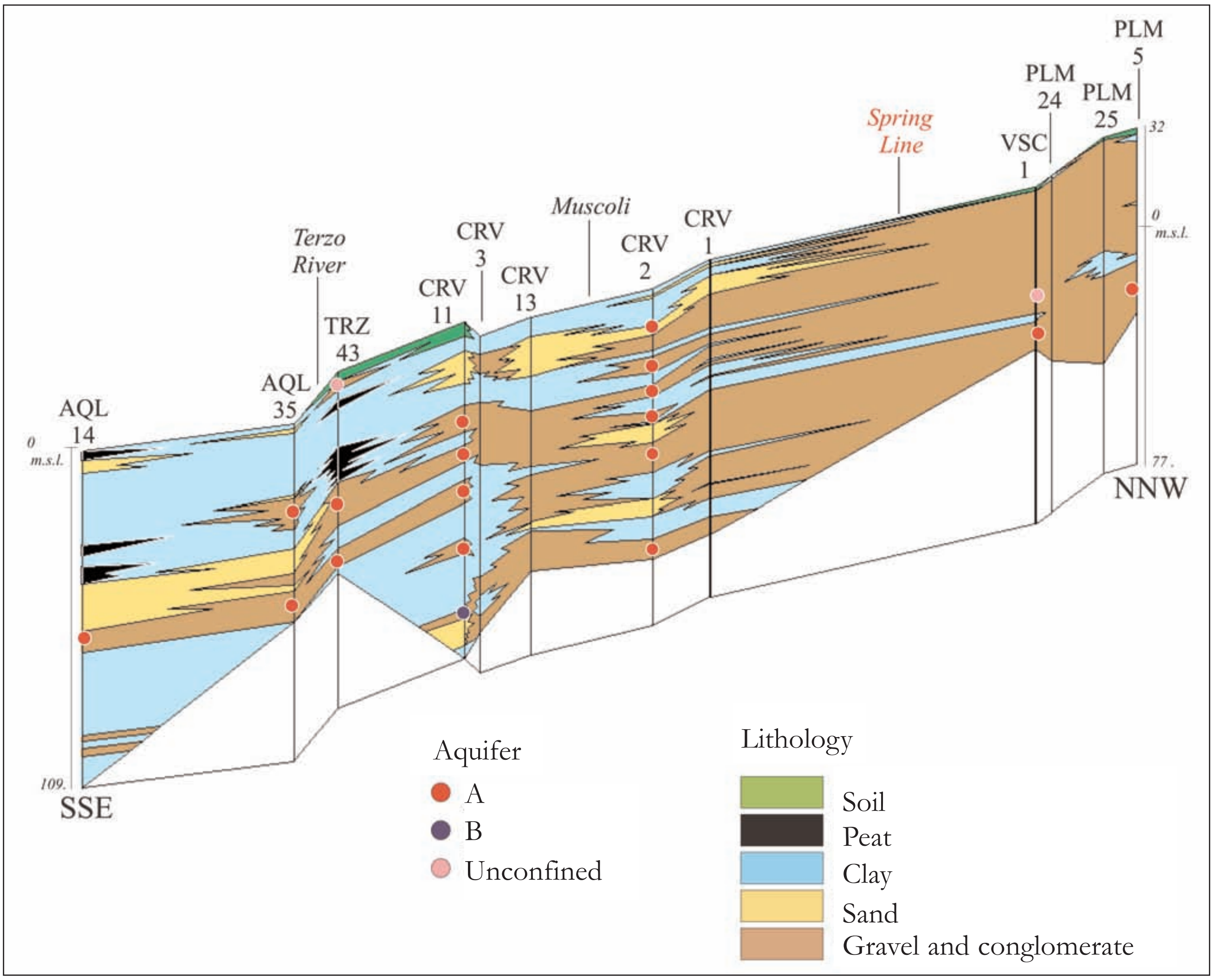

Fig. 3 - Cross-section n. 1. - *Sezione litostratigrafica n.1.*

In figures 3-8, the lower white area within each cross-section does not refer to any specific lithology or to the substratum, but is merely a result of *the graphic program used and in each section the wells are considered at the same depth.*

Section 1. This extends about 18 km in a NNW-SSE direction (fig. 3). It was produced using lithostratigraphical data obtained from 12 water-wells, each of which is between 53 and 175 m in depth. In correspondence with the spring line, the section shows the transition from the gravel deposits of the High Plain to the first clay horizon, ranging between 1 and 6 m in thickness, which develops uninterruptedly along the entire section. Subsequent clay horizons appear at greater depths, between gravel and sand; lenticular bodies of sand can be identified starting from the CRV1 well. Moving southward, the gravel horizons are located at increasingly greater depths and are of a reduced thickness. In the lower part of the section, five peat horizons appear at depths of 0-3 m, 30-34 m, 37-43 m, 9-12.2 m, 24.2-35.6 m. Two of these are underlain by sand, one by gravel, while the remaining two are intercalated with clay horizons. Analysis of this section revealed the presence of a total 29 exploited horizons in the subsoil (tab. 2) until an average depth of 162.6 m bsl. These horizons are confined with the excep-

Tab. 1 - *Water-well initials.* - Sigle dei pozzi.

AQL	Aquileia	PRP	Porpetto
CDR	Codroipo	PZZ	Pozzuolo del Friuli
CRV	Cervignano del Friuli	RNC	Ronchis
LST	Lestizza	RVG	Rivignano
PCN	Pocenia	SNG	San Giorgio di Nogaro
PLM	Palmanova	TLM	Talmassons
PLZ	Palazzolo dello Stella	TRZ	Terzo d'Aquileia
PRC	Precenicco	VSC	Visco

tion of the most shallow gravel layer located at anaverage depth of 2.6 m asl in the VSC1 well and at 2.5 m bsl in the TRZ43 well.

Three confined layers (A, B and D) are identified in the section:

- the most superficial layer A is particularly complex and is characterized by a horizon of prevailing gravel (VSC1), with subordinate sandy bodies (CRV2), interrupted by clayey horizons which determine the separation of the single confined

Tab. 2 - *Section 1: depth of the top/bottom of the exploited horizons.*
- Sezione 1: profondità del tetto/letto (in ± m s.l.m.) degli orizzonti acquiferi sfruttati.

	Wells								
	PLM5	VSC1	CRV1	CRV2	CRV13	CRV11	TRZ43	AQL35	AQL14
Layers (+m asl. -m bsl.)	-10.9/-27.9	+23.2/-18.0	+3.5/-13.5	-5.1/-13.1	-66.6/-79.6	-25.0/-34.0	-1.0/-4.2	-21.6/-32.6	-43.6/-65.6
		-20.6/-29.5	-15.5/-18.5	-15.1/-20.6		-38.0/-43.5	-33.6/-48.0	-38.6/-62.6	-150.6/-158.6
			-19.5/-23.5	-24.4/-28.1		-49.0/-57.0	-55.2/-61.0		-159.6/-165.6
			-33.5/-53.5	-33.1/-36.1		-68.0/-73.0			
			-55.0/-68.9	-37.1/-52.7		-91.0/-103.0			
			-74.5/-80.5	-74.1/-80.7					

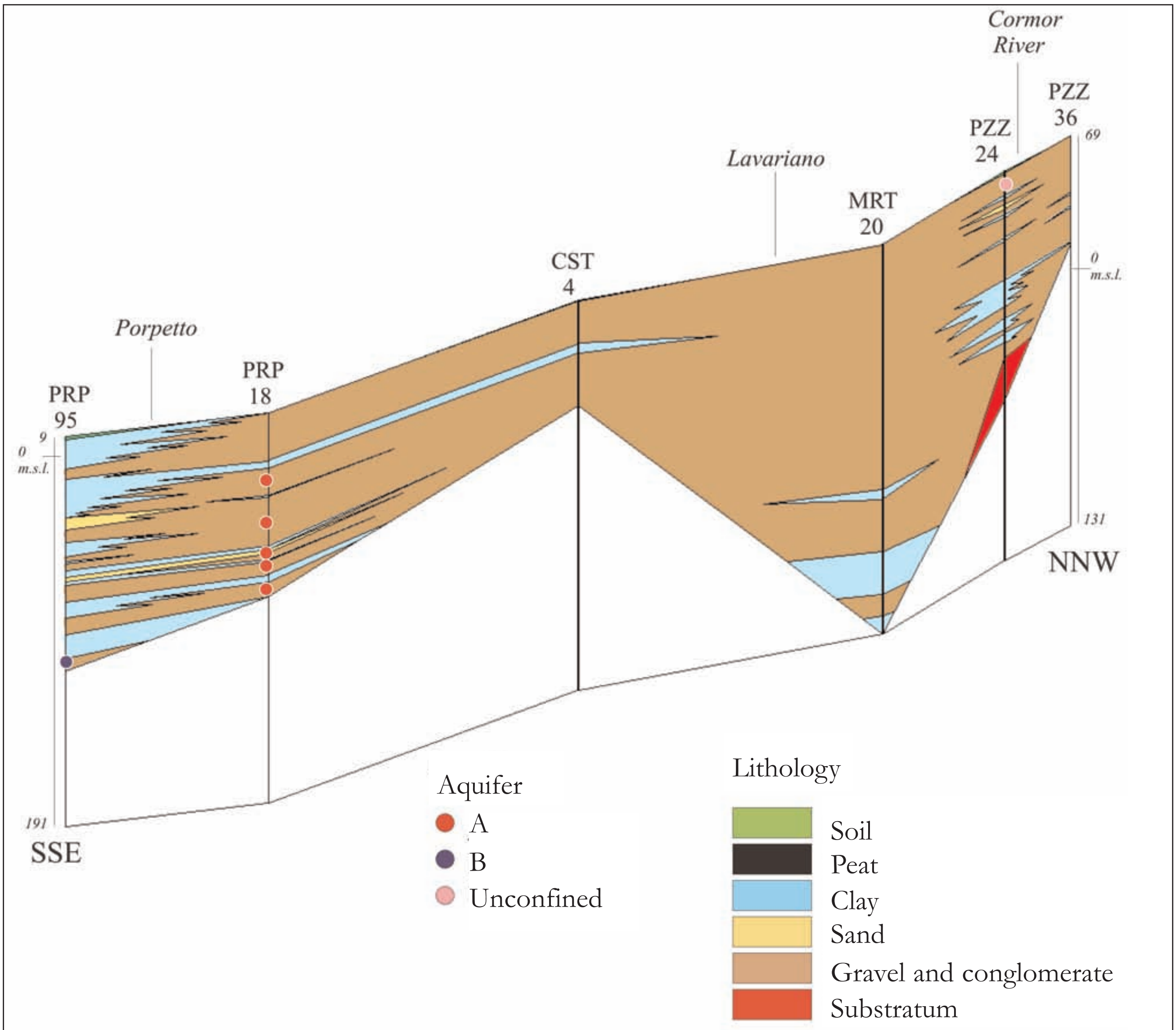

Fig. 4 - Cross-section n. 2. - *Sezione litostratigrafica n. 2.*

Tab. 3 - *Section 2: depth of the top/bottom of the exploited horizons.*
- Sezione 2: profondità del tetto/letto (in ± m s.l.m.) degli orizzonti acquiferi sfruttati.

	Wells		
	PZZ24	PRP18	PRP95ST
Layers (+m asl; -m bsl)	+26.5/+6.7	-15.3/-29.3	-105.3/-111.3
	-7.2/-12.9	-30.3/-55.3	
	-19.0/-20.8	-57.3/-62.3	
	-25.9/-33.5	-63.3/-70.3	
		-74.1/-81.4	

sub-layers; this aquifer develops at an average depth of between 6.7 and 76.5 m bsl; three sub-layers are clearly identifiable: the first (A_1) is located at an average depth of 20.8 m bsl, the second (A_2) at an average depth of 52.4 m bsl, beneath a peat horizon (AQL14, AQL35, TRZ43, CRV11, CRV2, CRV1), the third (A_3) at an average depth of 74.6 m bsl;
- the top of layer B is located at a depth of 91 m bsl in the CRV11 well;
- two sub-layers identified in the AQL14 well at average depths of 154.6 and 162.6 m bsl are probably a part of layer D.

Section 2. This extends about 15.5 km in a NNW-SSE direction (fig. 4) and was realized using lithostratigraphical data obtained from 6 water-wells, ranging from 53.9 to 200 m in depth. Most of this cross-section lies to the N of the spring line, where very thick gravel and conglomerate horizons are present.

In the PZZ24 well, at a depth of 90 m, a pelitic arenaceous substratum was observed. On the basis of an analogy with the stratigraphic sequence of the AGIP well "Cargnacco 1", where the Lower Miocene of the Cavanella Group was identified starting from 90 m in depth, this is presumed to be of Miocene age. In the Pozzuolo area, the lifting of the Miocene substratum and the overhanging Pleistocene conglomerates, which can be recognised both as outcrops (Variano, Orgnano, Pozzuolo) and within the wells ("Cargnacco 1", "Lavariano 1"), creates a watershed as regards groundwater circulation (STEFANINI, 1978).

Along this cross-section, the spring line near the surface is marked by the lithological transition of the thick gravel horizon and the clayey levels which appear with increasing frequency and at greater depths in a southward direction.

Ten confined exploited horizons were identified in gravels (tab. 3) and are part of the confined layers A and B:
- layer A is found at average depths of between 22.3 and 77.7 m bsl; the upper limit of sub-layer A_1 is found at a depth of 74.1 m bsl;
- the upper limit of layer B is located at 105.3 m bsl in the PRP95 well.

The three confined layers identified in the PZZ24 well are formed by local clayey levels which confine the gravel horizon. In fact, section n. 2 is the most northern of the reconstructed cross-sections and principally concerns the unconfined aquifer of the High Plain.

Section 3. This extends about 19 km in a NNE-SSW direction (fig. 5) and was realized correlating the lithostratigraphical data of 10 water-wells, ranging from 60 to 385 m in depth. With reference to the TLM23 well, starting at a depth of 31 m bsl, clayey horizons begin to interrupt the continuity of the gravel layers. Moving southward along the cross-section, the lithological transition from gravel to clay also occurs close to the ground surface. In the southern section, starting from the PCN20 well, sandy bodies of increasing frequency and thickness appear. With reference to the PLZ5 well, a peat layer, 19 m thick, was identified at a depth of 12.7 m bsl. A total of fourteen exploited horizons (tab. 4) were identified in this section, three of which refer to the water-table aquifer (LST24, LST22, TLM23). These are of gravel until the PCN20 well, at which point they are prevalently in sand for the remainder of the cross-section.

Tab. 4 - *Section 3: depth of the top/bottom of the exploited horizons.*
- Sezione 3: profondità del tetto/letto (in ± m s.l.m.) degli orizzonti acquiferi sfruttati.

	Wells							
	LST24	LST22	TLM23	PCN101	PCN20	PCN74	PLZ5	PLZ7
Layers (+m asl -m bsl)	+50.9/-9.0	+50.3/-9.9	+30.0/-31.0	-191.0/-205.0	-38.6/-48.0	-128.3/-139.8	-155.7/-161.7	-45.5/-65.5
			-95.0/-109.0					-121.5/-130.5
			-193.0/-206.0					-149.0/-161.5
			-241.5/-250.0					-162.5/-168.5

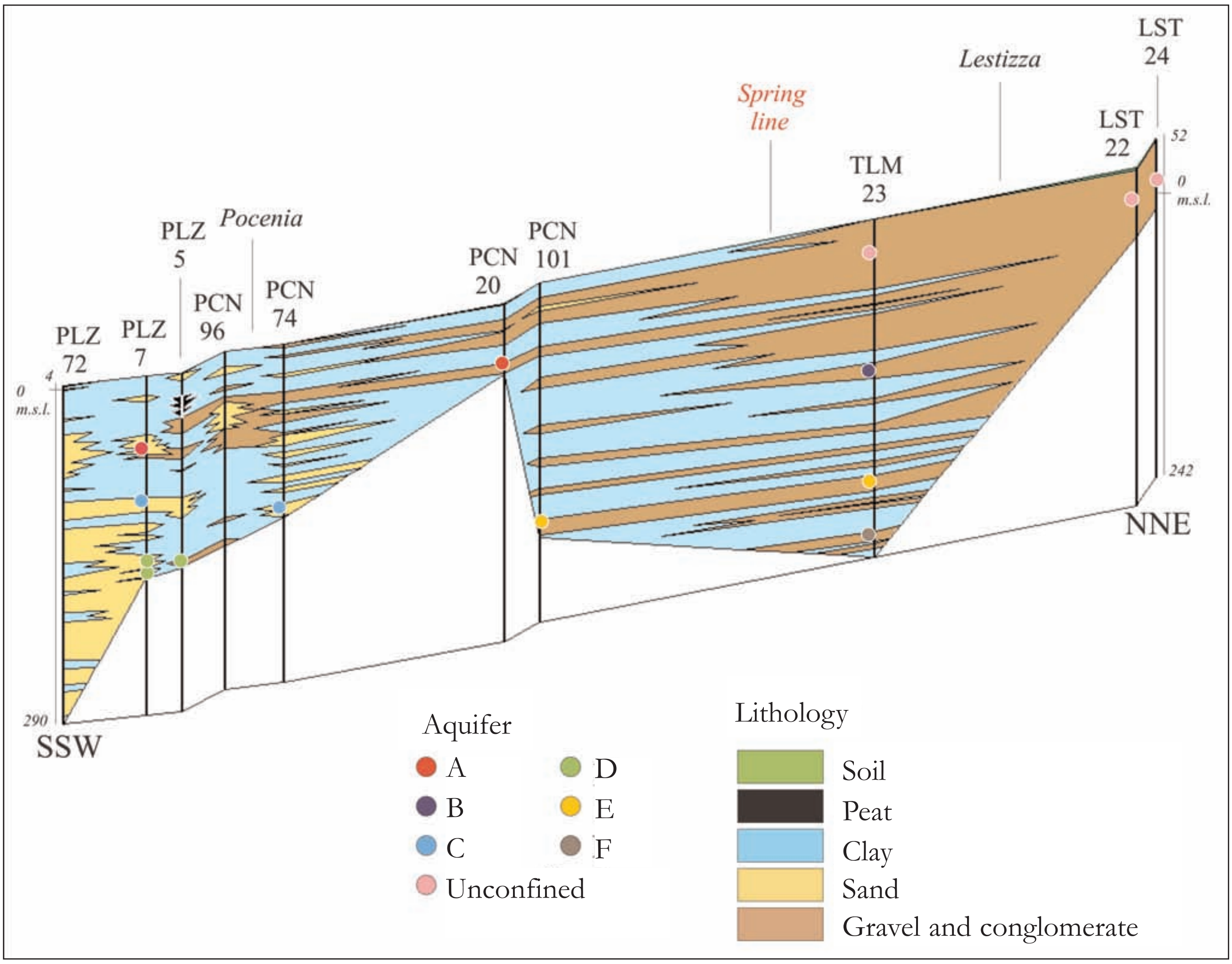

Fig. 5 - Cross-section n. 3. - *Sezione litostratigrafica n. 3.*

Six confined layers (A, B, C, D, E, F) can be identified:
- the upper limit of layer A can be observed in the PCN20 well (38.6 m bsl) and can be correlated with a continuous horizon located at an average depth of 40 m bsl which extends southward from the TLM23 well to the PLZ5 well; the A_2 sub-layer is present in the PLZ7 well at an average depth of 55.5 m bsl;
- B is located at an average depth of 102 m bsl (TLM23);
- C is found at an average depth of 130 m bsl;
- D is located at an average depth of 159.8 m bsl and can be divided into two sub-layers (at an average depth of 156.9 and 165.5 m bsl respectively);
- E is represented by a single gravel horizon, located at an average depth of 198.7 m bsl between wells TLM23 and PCN101;
- F is present in the TLM23 well, at an average depth of 245 m bsl.

The water-table aquifer can be identified at an average depth of 20 m asl in the LST22 and LST24 wells. This becomes deeper (average depth of 0.7 m bsl) moving southwards.

Section 4. This extends about 14 km in the NW-SE direction (fig. 6). It is located in the western sector of the studied area and was reconstructed using lithostratigraphical data of 11 water-wells, ranging from 54 to 300 m in depth. Unlike the sections described above, this is characterized by the presence of a continuous gravel horizon, uninterrupted even near the ground surface. It is intercalated with clayey horizons, which become increasingly frequent moving southward. In the southern section, at a depth of 89.9 m bsl, a sandy body can be found.

Nineteen exploited horizons (tab. 5) were found in gravels. The water-table aquifer was identified in wells CDR78 and RVG92.

Three confined layers (A, C, E) can be observed in this section:
- A develops in the lower part of the section with

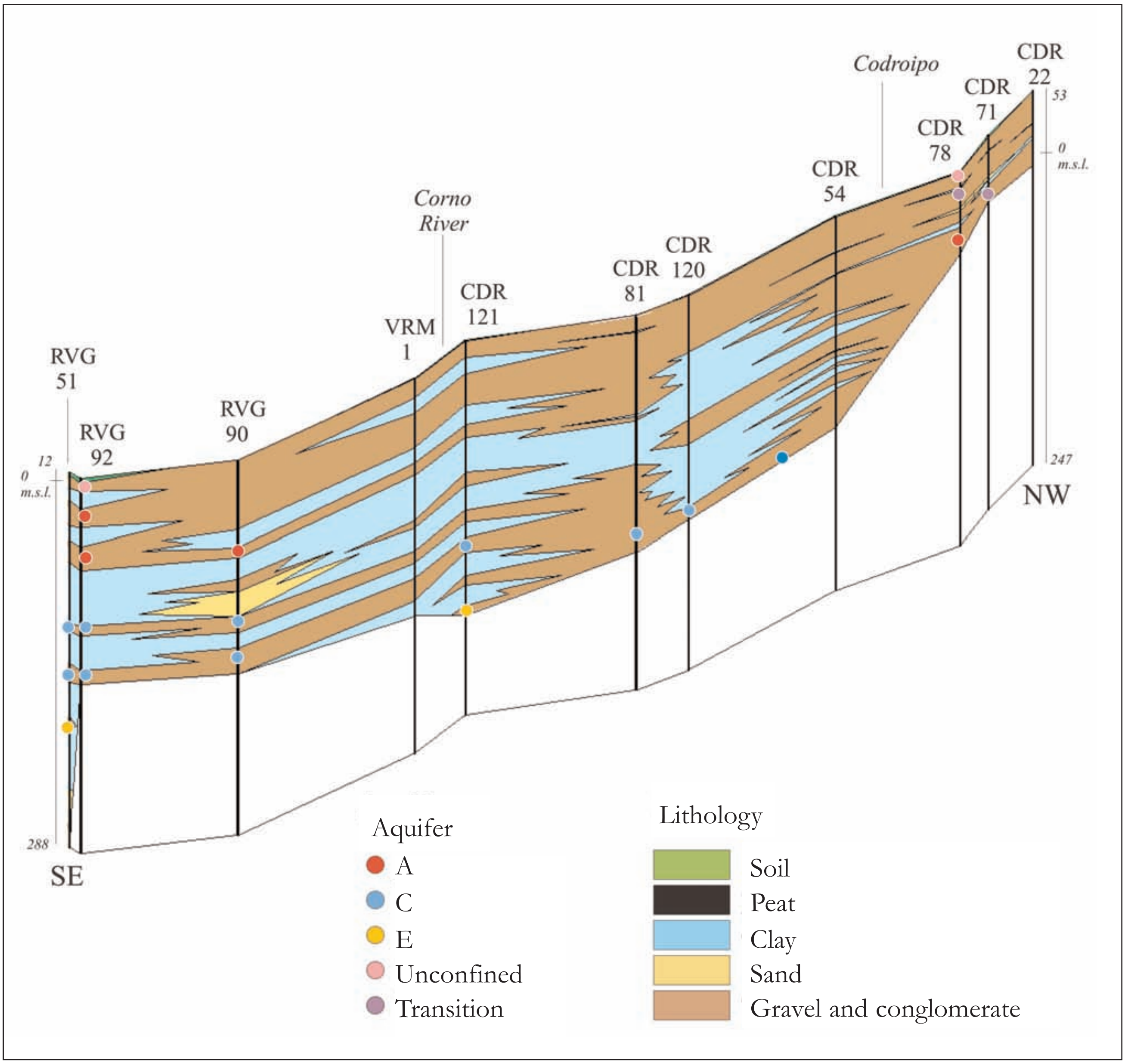

Fig. 6 - Cross-section n. 4. - *Sezione litostratigrafica n. 4.*

Tab. 5 - *Section 4: depth of the top/bottom of the exploited horizons.*
- Sezione 4: profondità del tetto/letto (in ± m s.l.m.) degli orizzonti acquiferi sfruttati.

	Wells							
Layers (+m asl -m bsl)	CDR71	CDR78	CDR120	CDR81	CDR121	RVG90	RVG92	RVG51
	+5.5/-8.5	+43.7/+30.5	-141.4/-154.4	-133.3/-163.3	-135.3/-147.3	-54.9/-62.9	+12.0/+1.0	-117.7/-122.7
		+28.5/+3.0			-189.3/-197.3	-114.9/-122.9	-13.0/-27.0	-139.7/-155.7
		-1.3/-22.6				-134.9/-155.9	-43.0/-62.0	-182.7/-193.7
							-106.0/-114.0	
							-142.0/-153.0	

sub-layers A_1 (at an average depth of 19.5 m bsl) and A_2 (at an average depth of 53.9 m bsl);
- C can be identified beginning from well CDR120 (at an average depth of 146.3 m bsl); from the CDR121 well, it is subdivided into two layers with the more shallow of the two located at an average depth of 118.3 m bsl;
- E is located at an average depth of 190.7 m bsl.

The water-table aquifer lies between 37.1 and 6.5 m asl. With reference to the CDR78 and CDR71 wells, two confined layers, not belonging to any of the aquifers described above, can be observed. These are referred to as the "transition system".

Section 5. This is the southern continuation of Section 2 (fig. 7). It extends about 10 km in a NNW-SSE direction and was reconstructed on the basis of lithostratigraphical data from 16 water-wells, between 83 and 234 m in depth. Sandy bodies intercalated with clayey sediments characterise the section. Gravel horizons, located at varying depths, become increasingly infrequent moving southward. One such horizon, present in the PRP95 well at a depth of 67.3 m bsl, develops virtually uninterrupted along the entire section. Four peat horizons are located at depths of between 29.2 and 47 m bsl.

The thirteen productive horizons identified were of gravel (tab. 6).

Five confined layers (A, B, C, D, E) are identified:
- A, located at depths of between 26.5 and 75.2 m bsl, develops in two sub-layers (A_2, A_3); these are exploitable only in the cases of wells SNG54, SNG53 and SNG45 but can be observed along much of the section, at average depths of between 56.7 and 78.3 m bsl;
- B, present in the PRP95 and SNG48 wells, is

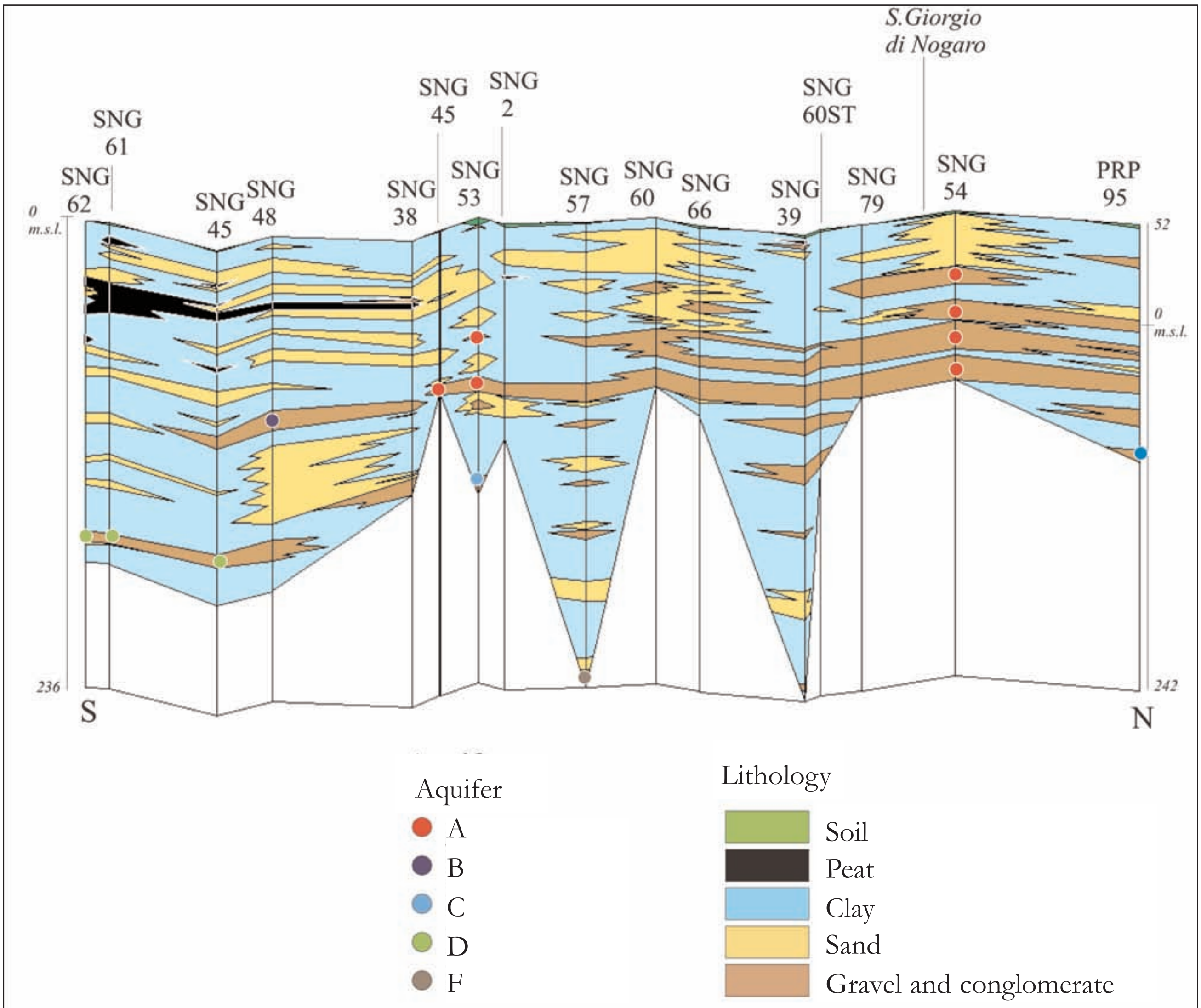

Fig. 7 - Cross-section n. 5. - *Sezione litostratigrafica n. 5.*

Tab. 6 - *Section 5: depth of the top/bottom of the exploited horizons.*
- Sezione 5: profondità del tetto/letto (in ± m s.l.m.) degli orizzonti acquiferi sfruttati.

	Wells								
	PRP95	SNG54	SNG57	SNG53	SNG45ST	SNG48	SNG45	SNG61	SNG62
Layers (+m asl -m bsl)	-105.3/-111.3	-22.0/-31.0	-217.4/-230.4	-55.6/-58.6	-73.3/-81.3	-88.5/-98.5	-153.5/-160.0	-157.4/-162.7	-156.9/-163.9
		-39.0/-49.0		-77.6/-85.6					
		-50.0/-64.0		-127.6/-137.6					

located at average depths of between 93 and 108 m bsl;
- the upper limit of layer C is found at a depth of 127.6 m asl in the SNG53 well;
- D is found at depths of between 156 and 160 m bsl in the lower part of the section;
- E, present in the SNG57 well, is found at an average depth of 223.5 m bsl.

Section 6. This is located in the SW sector of the studied area (fig. 8). It extends about 9.5 km in a NW-SE direction and was realized using lithostratigraphical data obtained from 8 water-wells of between 170 and 291 m in depth. The section is characterized by the presence of a shallow and almost continuous clayey horizon, intercalated with gravel horizons in the first half of the section and with thick sandy lenticular bodies as identified in the PLZ14 well. Peat horizons are distributed at depths of between 5 and 29.3 m bsl.

Fourteen exploited horizons were recognized in gravel and sand (tab. 7).

Four confined layers (A, C, D, F) can be identified:
- A shows two continuous sub-layers (A_2, A_3) at average depths of 51.9 and 68.6 m bsl;
- C is located at an average depth of 138.4 m bsl;
- D is divided into two sub-layers (D_1, D_2) at average depths of 173.7 and 160.9 m bsl;
- F is divided into sub-layers (F_1, F_2) which are located at average depths of 235.9 and 251 m bsl.

Six confined layers were identified in the analysis of the cross-sections mentioned above. Layer A is present in all sections and can therefore be regarded as the most exploited horizon of the area. Layer B can be found in all sections with the exception of Sections 4 and 6. Layer C is neither present in Section 2 - due to the shallowness of the water-wells - or Section 1, where only one well reaches a depth of more than 110 m. Layer D is absent from Sections 2 and 4. Layer E is evidenced in all sections with deep wells with the exception of Section 6, where it presumably lies at an average depth of 207.2 m bsl. Layer F is located in Sections 3 and 6.

The presence of two further artesian layers (G, H), found at greater depths, were evidenced by means of an analysis of the other cross-sections shown in figure 2.

6. - THE AQUIFER SYSTEM OF THE FRIULI LOW PLAIN

The correlations carried out in the lithostratigraphical sections revealed the existence of three aquifer systems:
- a confined aquifer system, composed of eight artesian layers located from 19 to over 500 m bsl;
- a transition aquifer system consisting of two confined layers located at average depths of between 27.2 m asl and 12.2 m bsl; this displays different characteristics from those of the confined system, from which it has been separated;
- an unconfined aquifer system located at average depth of between 44 m asl and 18 m bsl.

Tab. 7 - *Section 6: depth of the top/bottom of the exploited horizons.*
- Sezione 6: profondità del tetto/letto (in ± m s.l.m.) degli orizzonti acquiferi sfruttati.

	Wells						
	RNC4	PLZ63	PLZ67	PRC94	PRC15	PLZ14	PLZ50
Layers (+m asl -m bsl	-138.0/-144.5	-60.2/-67.2	-168.7/-178.7	-158.6/-162.3	-40.3/-57.3	-168.8/-178.8	-234.7/-242.7
		-127.2/-144.2	-246.7/-252.7		-66.3/-72.3	-234.8/-238.8	
		-228.2/-236.2			-167.8/-179.3	-246.8/257.8	

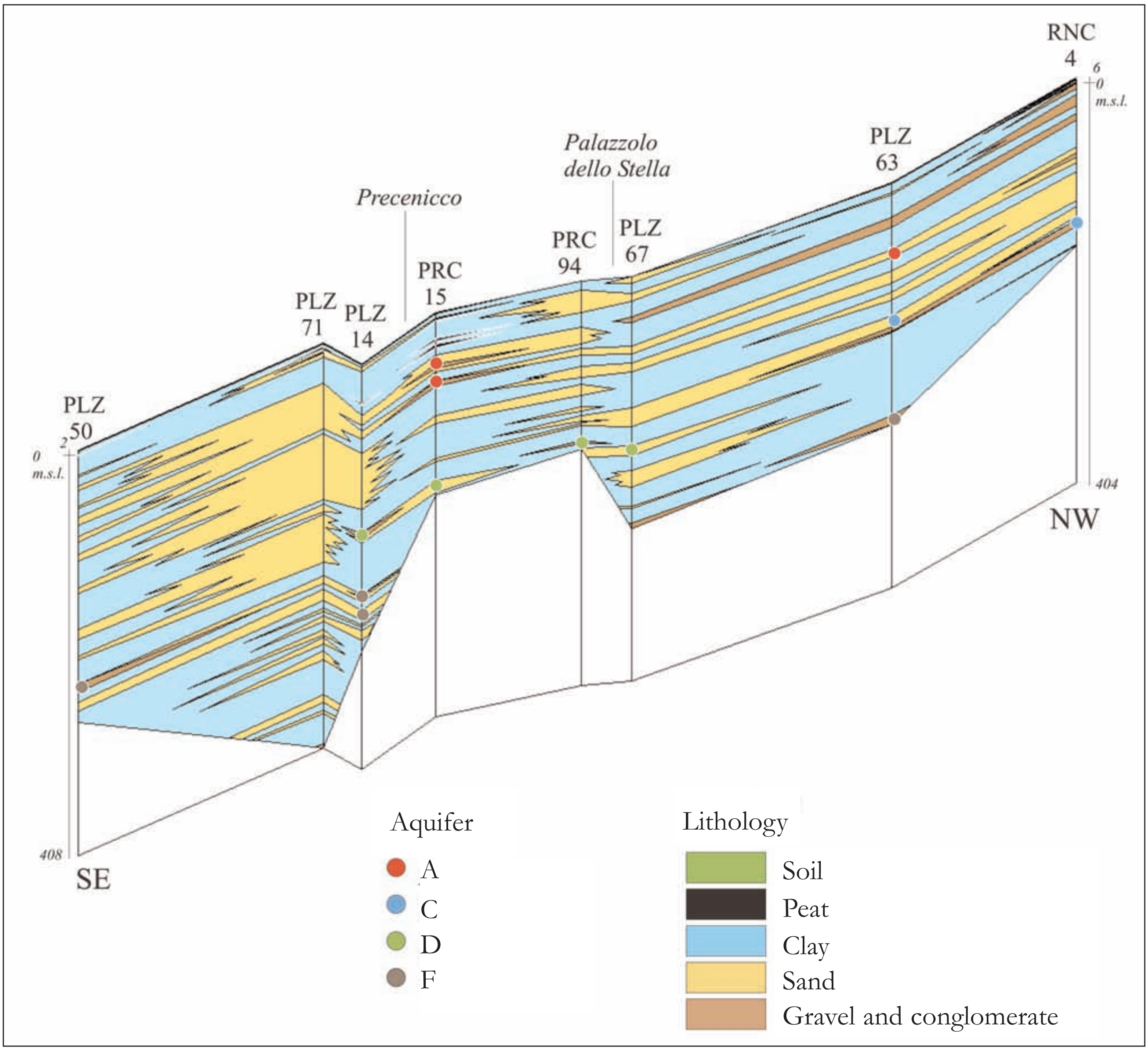

Fig. 8 - Cross-section n. 6. - *Sezione litostratigrafica n. 6.*

6.1. - Confined aquifer system

This is characterized by the presence of eight artesian layers (A, B, C, D, E, F, G, H), most of which are subdivided into sub-layers. Table 8 summarizes the thickness and the average depth of each layer and respective sub-layers. The calculated thickness and depths of layer H are purely indicative due to fact that data was only available for the depth of the top.

Observations arising from an analysis of this data are as follows:

- the average depth of layer A (fig. 9) increases in a southward direction from 25 to 75 m bsl (reach the maximum value of 80.3 m bsl) and the thickness reaches a maximum of about 50 m near the spring line in correspondence with the hydrographic systems of the Aussa-Corno and Terzo rivers; two zones, which roughly correspond with the present water-courses of the Terzo and Stella rivers, are characterized by a thickness of between 25 and 50 m which increases moving westward to the Tagliamento river (fig. 10);
- the greatest average depths of layer B are identified in the hydrographic system of the Stella and Torsa rivers (fig. 11); the thickness is at its greatest in the western section of the Stella river and in correspondence with the Corno river (fig. 12);
- the average depth of layer C is at its greatest in the vicinity of the spring line along the upper

Tab. 8 - *The confined system: summary of data on aquifers depth and thickness.*
- Sintesi dei dati di profondità media e spessore di ciascun livello e sottolivello acquifero del sistema confinato.

LAYER	N° wells	THICKNESS (m)			AVERAGE DEPTH (m bsl)	
		min	max	med	min	max
A	152	0.7	58.3	29.5	19.4	80.3
A_1	46	1.2	20.0	10.6	19.4	34.8
A_2	82	2.0	37.0	19.5	38.5	63.9
A_3	88	1.5	27.0	14.3	62.0	80.3
B	102	1.5	27.4	14.5	80.1	112.4
B_1	61	2.0	21.5	11.8	80.1	91.7
B_2	44	1.5	20.0	10.8	91.5	104.2
B_3	9	4.5	11.3	7.9	106.9	112.4
C	57	2.8	37.0	19.9	114.6	148.3
C_1	15	3.0	11.0	7.0	114.6	122.3
C_2	21	2.0	19.0	10.5	125.8	137.2
C_3	20	4.0	21.0	12.5	140.7	148.3
D	76	1.1	20.0	10.6	152.5	179.3
D_1	57	1.1	18.5	9.8	152.5	168.5
D_2	22	3.5	15.0	9.3	165.8	179.3
E	40	3.7	32.0	17.9	181.5	215.8
E_1	7	4.0	15.0	9.5	181.5	190.9
E_2	11	4.0	16.0	10.0	193.3	206.6
E_3	21	3.7	13.2	8.5	211.2	215.8
F	52	1.5	40.3	20.9	219.5	261.8
F_1	11	4.3	20.9	12.6	219.5	230.5
F_2	23	1.5	11.0	6.3	232.2	241.1
F_3	13	4.0	11.0	7.5	244.8	255.1
F_4	4	7.7	11.0	9.4	258.2	261.8
G	3	9.0	12.7	10.9	267.3	276.4
H	22	2.7	62.0	32.4	303.3	553.0

Stella river (148.3 m bsl), in the western sector of the area (fig. 13) between the Tagliamento and Stella rivers, and on the right of the middle Corno river; the greatest thickness of 37 m is found along the middle watercourse of Corno river (fig. 14);
- layer D is located at consistent average depths (170 m bsl) along the middle watercourse of the Stella river towards the Tagliamento river (fig. 15) and has an average thickness of 10.6 m; in the area between the Stella and Aussa rivers, the thickness of the layer is modest (approximately 4 m); the greatest thickness is to be found in the area between the Tagliamento and Stella rivers and in the Marano Lagoon (fig. 16) in correspondence with a NE-SW axis;
- layer E is located at the average depths of 215,8 m bsl and is present in the area between the Stella-Taglio and Cormor rivers (fig. 17); the thickness (average value of 17.9 m) is greatest in the vicinity of the spring line in correspondence with the upper Stella-Torsa river system (fig. 18);
- layer F is located at a maximum average depth of 261.8 m bsl, along the lower Tagliamento river (fig. 19); it reaches the greatest thickness in the vicinity of the Tagliamento river (fig. 20).

6.2. - Transition aquifer system

This is particularly developed in the NW sector and represents the transition of the unconfined aquifer of the High Plain to the confined system of the Low Plain. On the basis of data obtained from 11 water-wells, it was possible to identify two confined layers (S_1, S_2), at the average depths of between 27.2 m asl and 12.2 m bsl. These are determined by the appearance of superficial clayey horizons near the spring line. The presence of clayey horizons, which interrupt the continuity of the gravel horizon, was described in Section 4 (fig. 6). The thickness and the average depth of each layer are indicated in tab. 9.

Tab. 9 - *The transition system: summary of data on aquifers depth and thickness.*
- Sintesi dei dati di profondità media e spessore di ciascun livello acquifero del sistema di transizione.

Layer	N° wells	THICKNESS (m)			AVERAGE DEPTH (+m asl; -m bsl)	
		min	max	med	min	max
S_1	7	1.2	25.5	13.4	+3.8	+27.2
S_2	8	5.5	22.0	13.8	-1.5	-12.2

6.3. - Unconfined aquifer system

This is particularly evident in the northern sector where a continuous water-table aquifer develops between 44 m asl and 18 m bsl, parallel with the spring line. The thickness varies from 10 to 40 m with modest values found along a NW-SE axis which approximately corresponds with the upper Stella river where they generally decrease moving southward.

7. - EVALUATION OF ANNUAL WITHDRAWAL IN THE FRIULI LOW PLAIN

The Friuli Low Plain in the Province of Udine district is approximately 880 km^2 wide; it comprises 31 municipalities with a total population of approximately 120,000. The confined aquifers of this area are exploited by over 30,000 wells for domestic, drinking, agricultural, industrial and trout breeding purposes. In spite of extensive groundwater exploitation, documentary evidence on the existing wells is poor. What technical information exists, concerns only a small percentage of the wells in question.

An evaluation of the annual volume of groundwater drawn from the Low Plain aquifers was

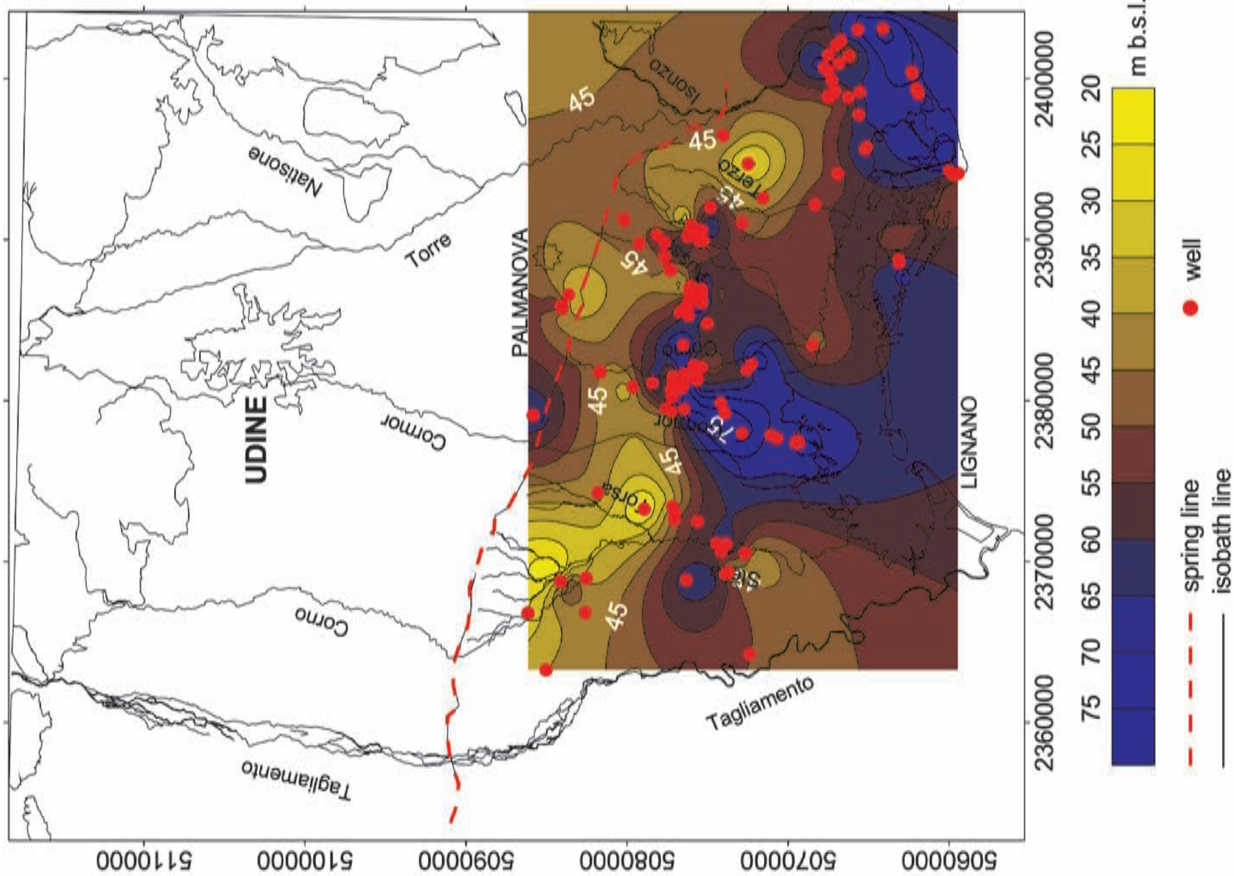

Fig. 9 - Aquifer A: average depth (m b.s.l.) - *Acquifero A: profondità media (-m s.l.m.)*.

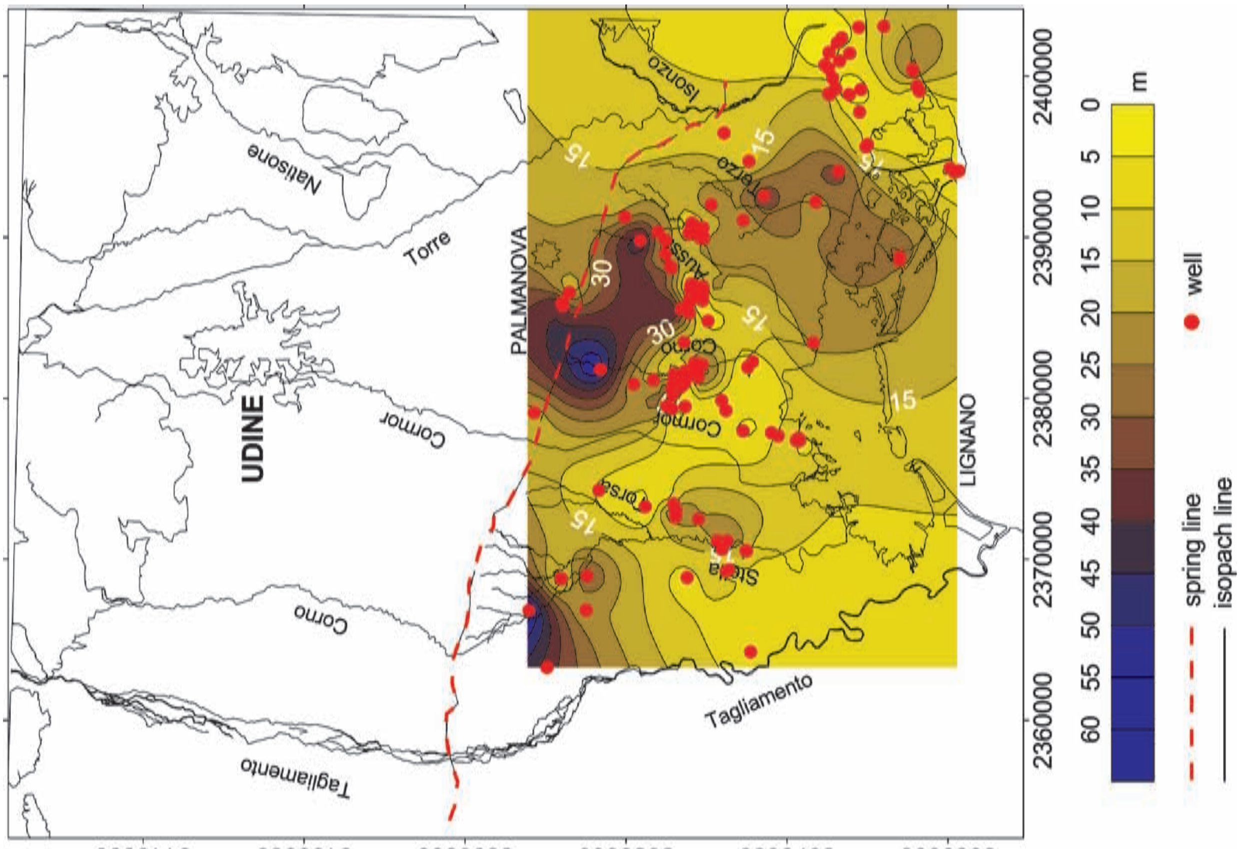

Fig. 10 - Aquifer A: thickness (m) - *Acquifero A: spessore (m)*.

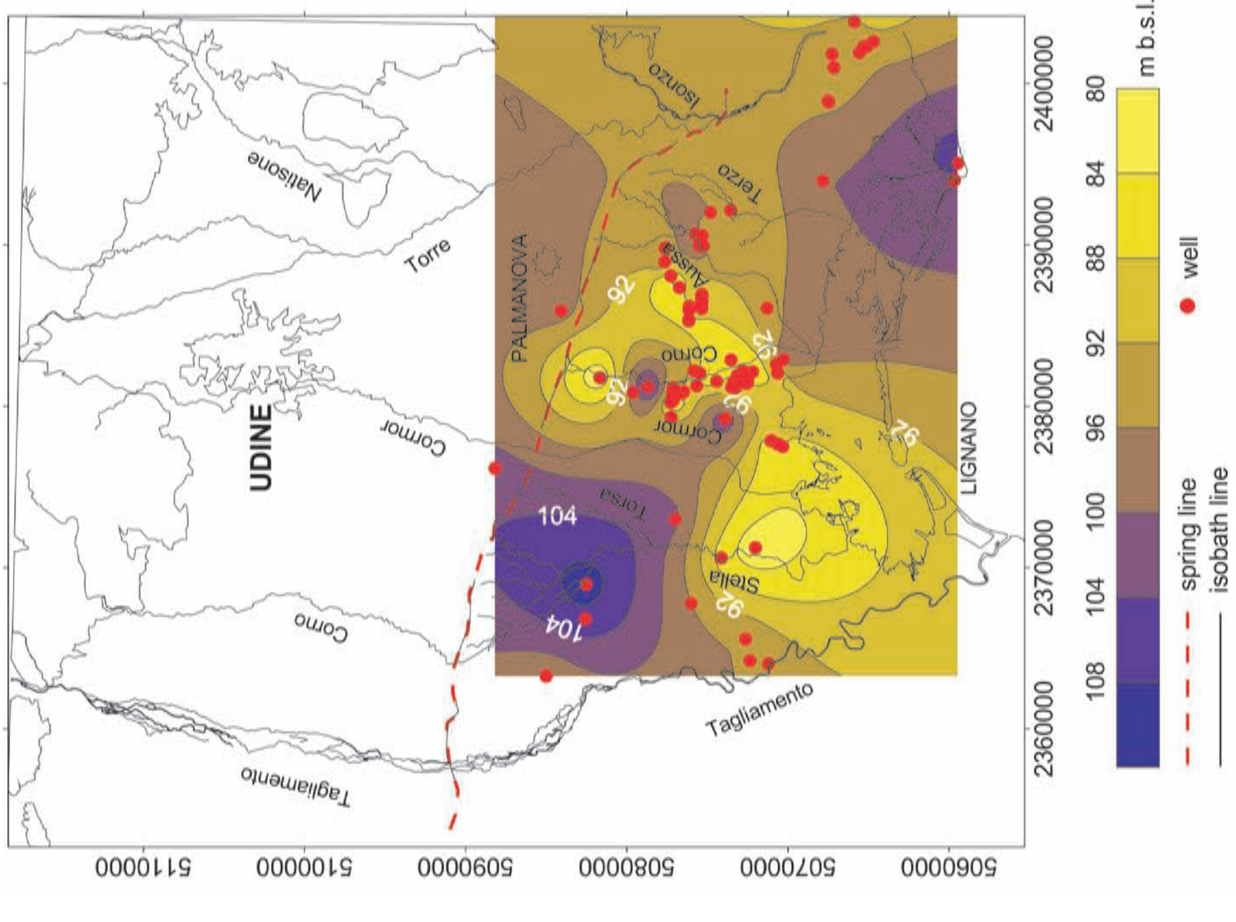

Fig. 11 - Aquifer B: average depth (m b.s.l.) - *Acquifero B: profondità media (-m s.l.m.).*

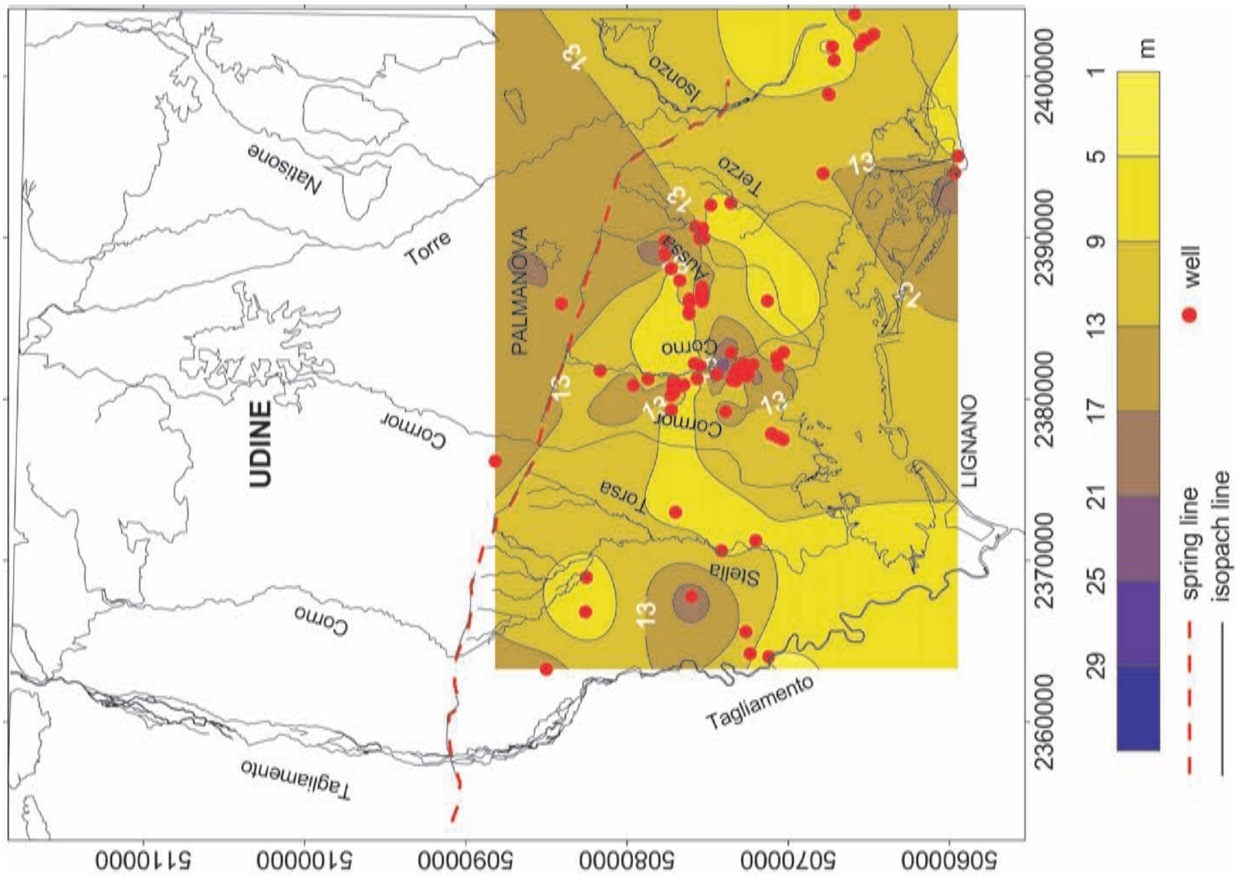

Fig. 12 - Aquifer B: thickness (m) - *Acquifero B: spessore (m).*

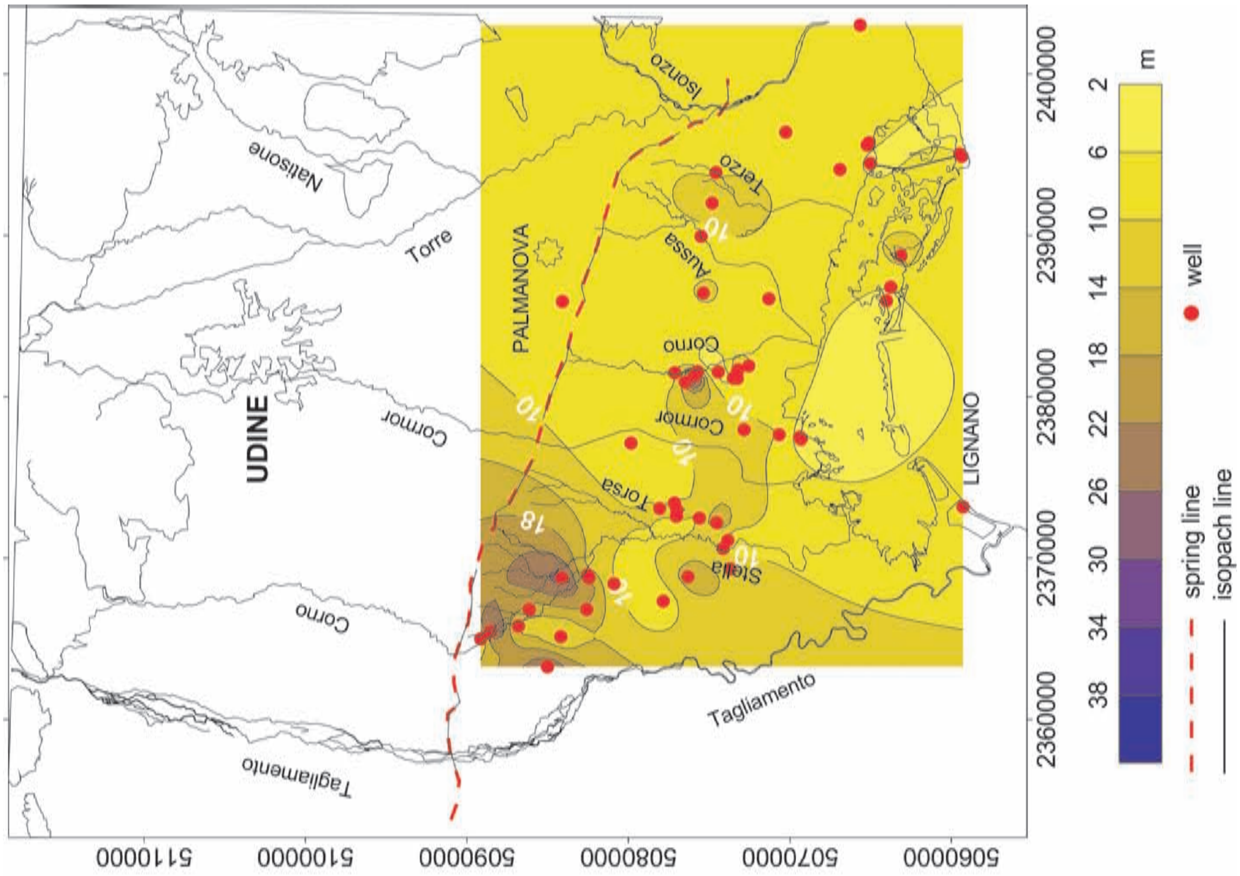

Fig. 14 - Aquifer C: thickness (m) - *Acquifero C: spessore (m).*

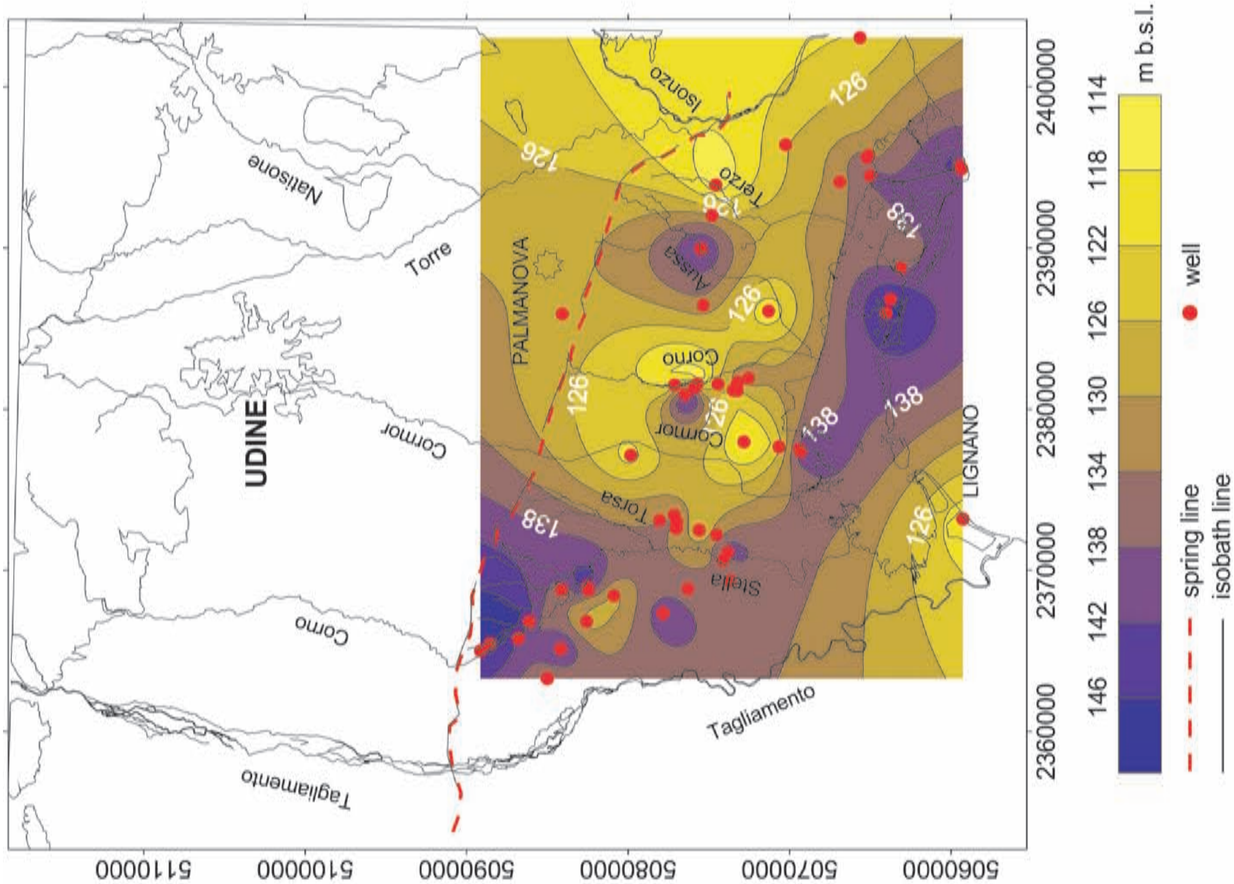

Fig. 13 - Aquifer C: average depth (m b.s.l.) - *Acquifero C: profondità media (-m s.l.m.).*

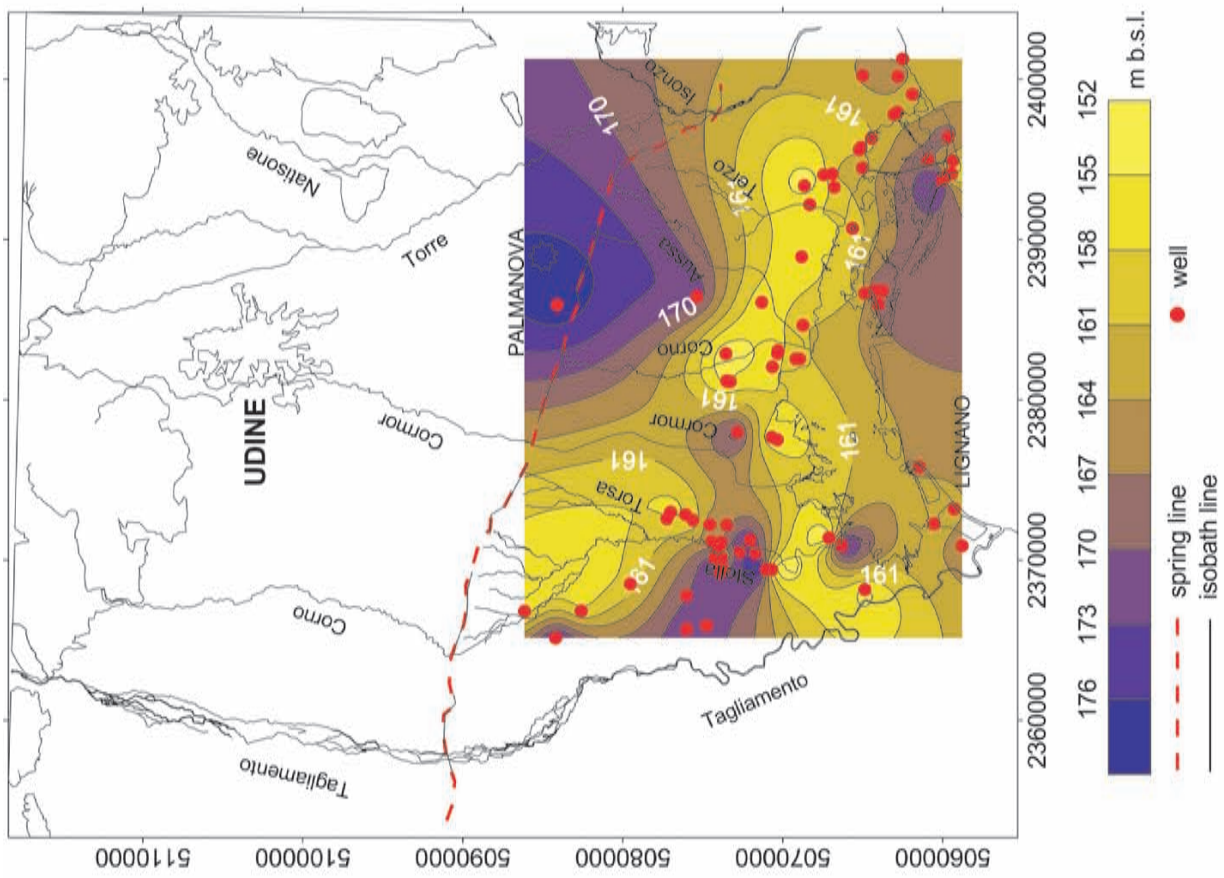

Fig. 15 - Aquifer D: average depth (m b.s.l.) - *Acquifero D: profondità media (-m s.l.m.).*

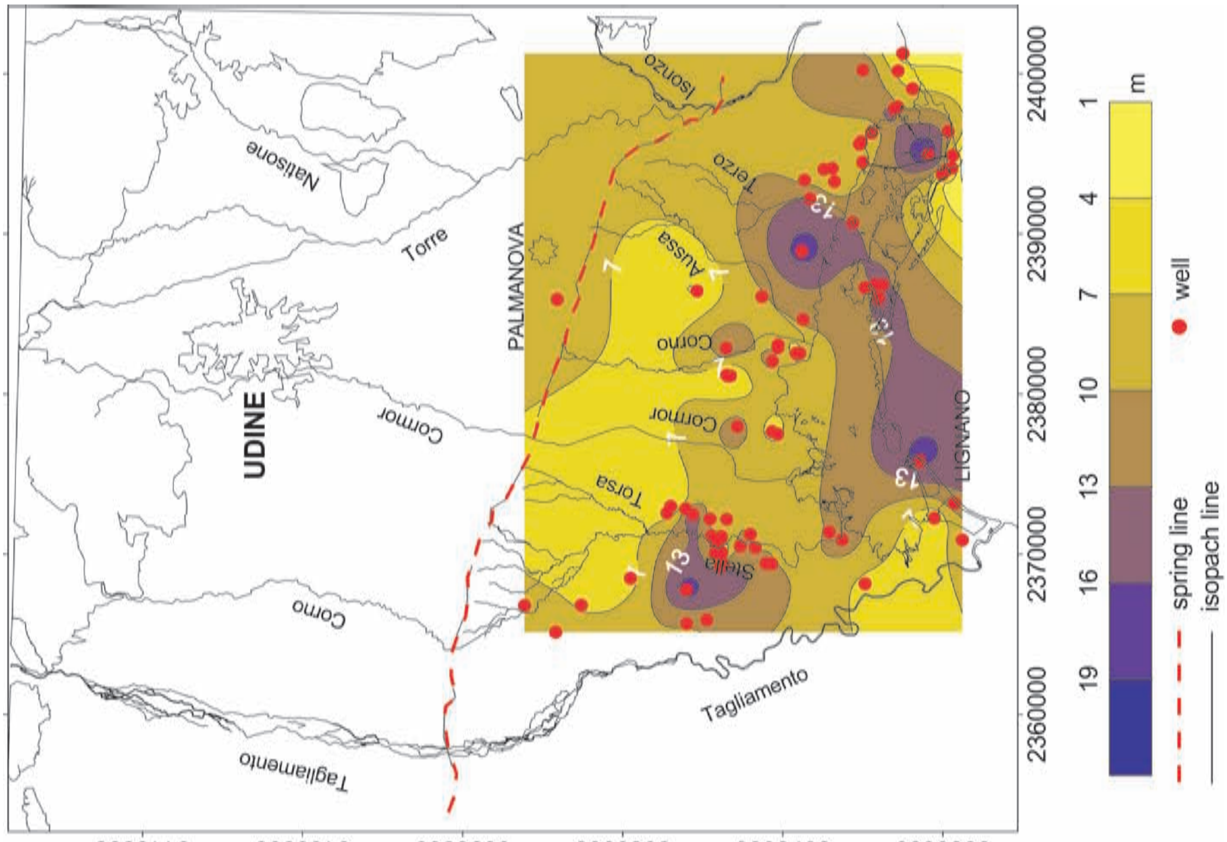

Fig. 16 - Aquifer D: thickness (m) - *Acquifero D: spessore (m).*

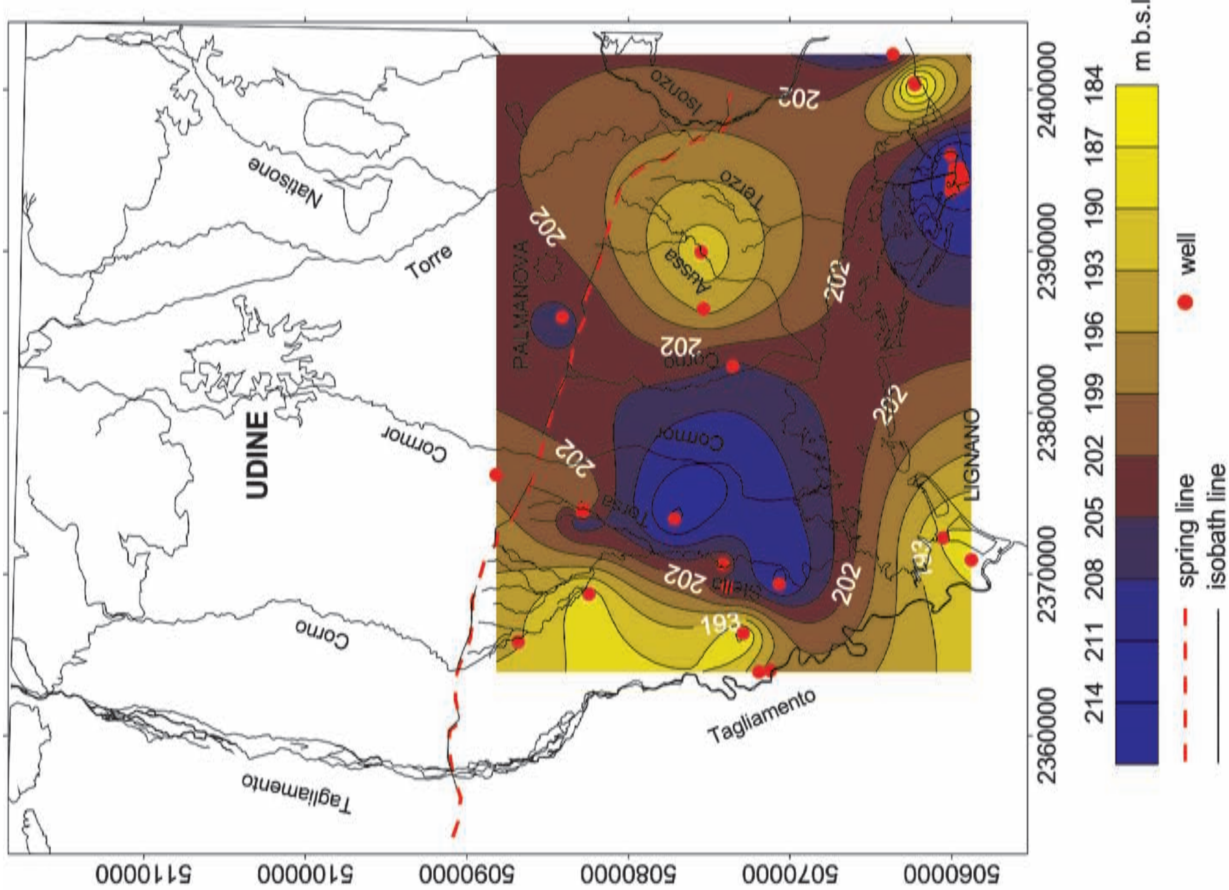

Fig. 17 - Aquifer E: average depth (m b.s.l.) - *Acquifero E: profondità media (-m s.l.m.).*

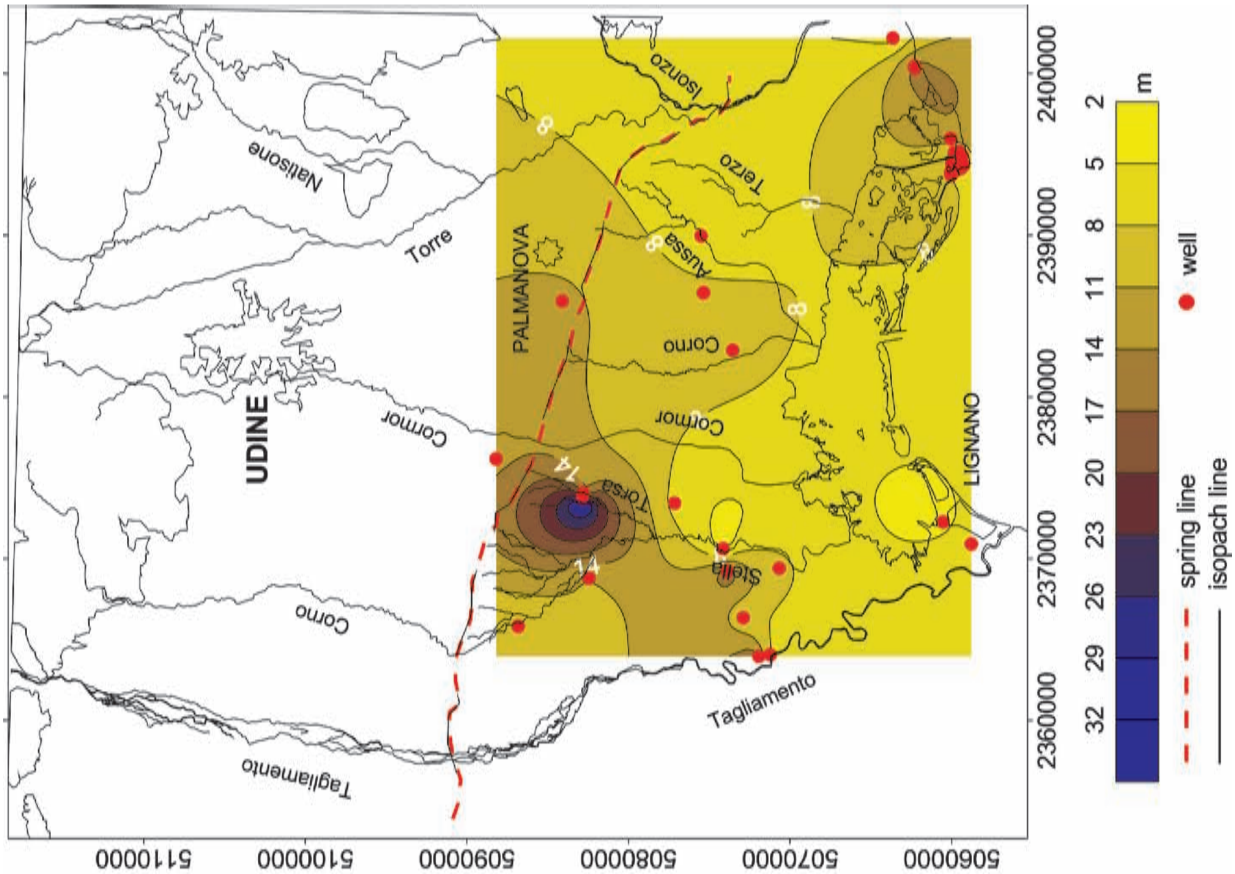

Fig. 18 - Aquifer E: thickness (m) - *Acquifero E: spessore (m).*

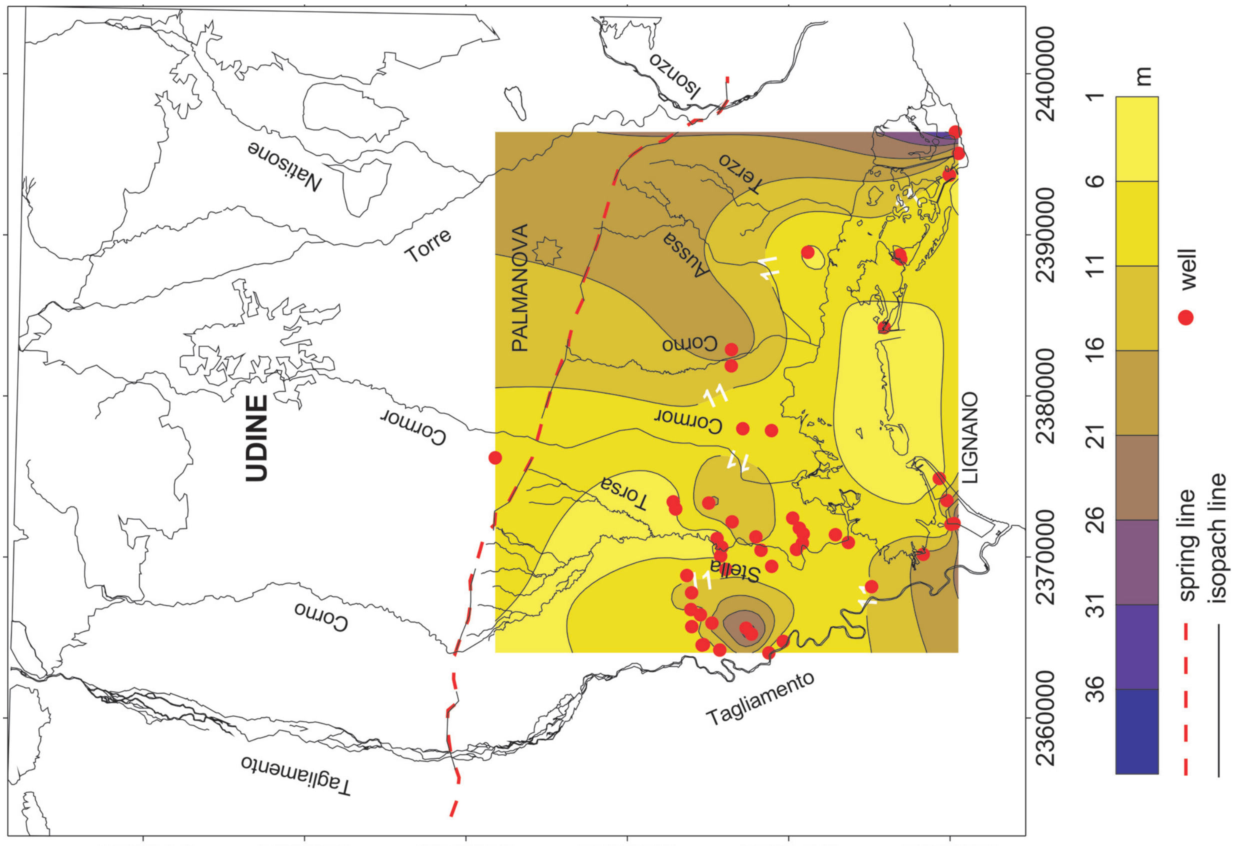

Fig. 20 - Aquifer F: thickness (m) - *Acquifero F: spessore (m).*

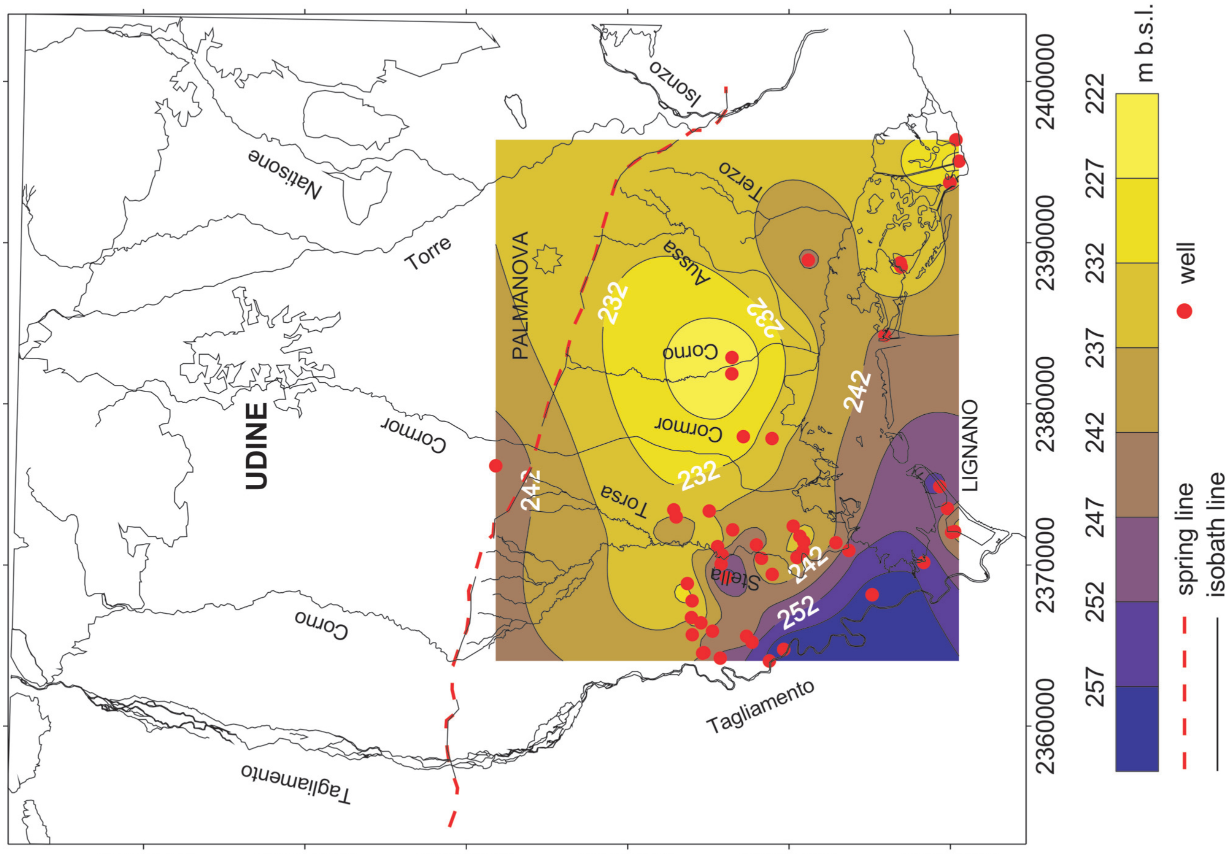

Fig. 19 - Aquifer F: average depth (m b.s.l.) - *Acquifero F: profondità media (-m s.l.m.).*

carried out based on a sample of 11,864 water-wells, only 605 of which were provided with discharge data. With regard to the remaining 11,259 water-wells, extraction values were estimated using analogical criteria: a flow coefficient of 0.78 l/s, equivalent to the average extraction from documented wells of the same use, was applied to domestic water-wells, most of which are continuously active. A flow coefficient of 0.35 l/s was applied to agricultural wells which are actively used for a period of three months per year. As regards industrial wells, a coefficient of 0.7 l/s was applied, based on the assumption that these flow continuously 24 hours a day. Flow coefficients of 3.1 l/s and 0.78 l/s were applied respectively to trout breeding wells and those for livestock use. A flow coefficient of 0.78 l/s was applied to not defined use wells (Granati *et alii*, 2000).

The total volume of groundwater extracted annually from the Low Plain (tab. 10) has been estimated at 701×10^6 m^3. Water extraction for domestic use represents about 36% of the total volume.

In order to estimate extraction levels from the confined aquifer system, 567 water-wells supplied with depth and discharge data were examined. Each well is attributed to an aquifer layer (confined or unconfined) according to depth and the stratigraphic data available. The known extraction rate is estimated at 394×10^6 m^3/year, 25% of which comes from the unconfined aquifer system. The same percentage was applied in analogy to the total groundwater volume in order to evaluate extraction rates from the confined aquifer system. Results revealed a total extraction rate of 526×10^6 m^3/year, of which 294×10^6 m^3/year - approximately 56% - represents the known extraction rate, while 232×10^6 m^3/year represents the estimated extraction rate. The latter was distributed among the confined layers in proportion to known extraction rates.

The division of each artesian layer according to known and estimated extraction rates (fig. 21) shows that 84% of the total volume extracted (443×10^6 m^3/year) derives from the two most shallow layers A and B.

8. - SUSTAINABILITY OF THE EXPLOITATION OF THE CONFINED AQUIFER SYSTEM

The rational planning and management of renewable groundwater resources in the Friuli Low Plain requires measures to ascertain both the current and potential availability status of each aquifer system. Estimates of groundwater resource availability require information data of the hydraulic head distribution, of the characteristics of aquifers (hydraulic conductivity, transmissivity and storativity), of the groundwater discharge and recharge. However, in spite of the extensive exploitation of groundwater resources in the area, hydrogeological and technical data concerning the Low Plain is scarce and that which is available is invariably incomplete and of poor quality.

An evaluation of the hydraulic conductivity of some identified confined layers of the Friuli Low Plain was carried out by obtaining the value of K on the basis of the average thickness, hydraulic gradient and discharge data of the single artesian layers.

In particular, the hydraulic gradients (tab. 11) for layers A, B, C, D, F, were calculated on the basis of measurements of groundwater levels obtained from a sample of 80 water-wells appertaining to these aquifers: the values ranging from 0.00082 to 0.002. The similar value for the layers

Tab. 10 - *Summary of extraction rates.*
- Sintesi dei prelievi.

Use	Known extraction (millions of m^3)		Estimated extraction (millions of m^3)		Total Extraction (millions of m^3)
	N° wells	Extraction	N° wells	Calculated Extraction	
Domestic	181	10.47	9,968	245.19	255.66
Drinking	5	40.27	0	0.00	40.27
Agricultural	198	130.09	656	7.24	137.33
Industrial	99	100.07	247	5.45	105.52
Trout breeding	112	143.61	73	7.14	150.75
Livestock	5	0.22	16	0.39	0.61
Not defined	5	3.19	299	7.35	10.54
Total	605	427.92	11,259	272.76	700.68

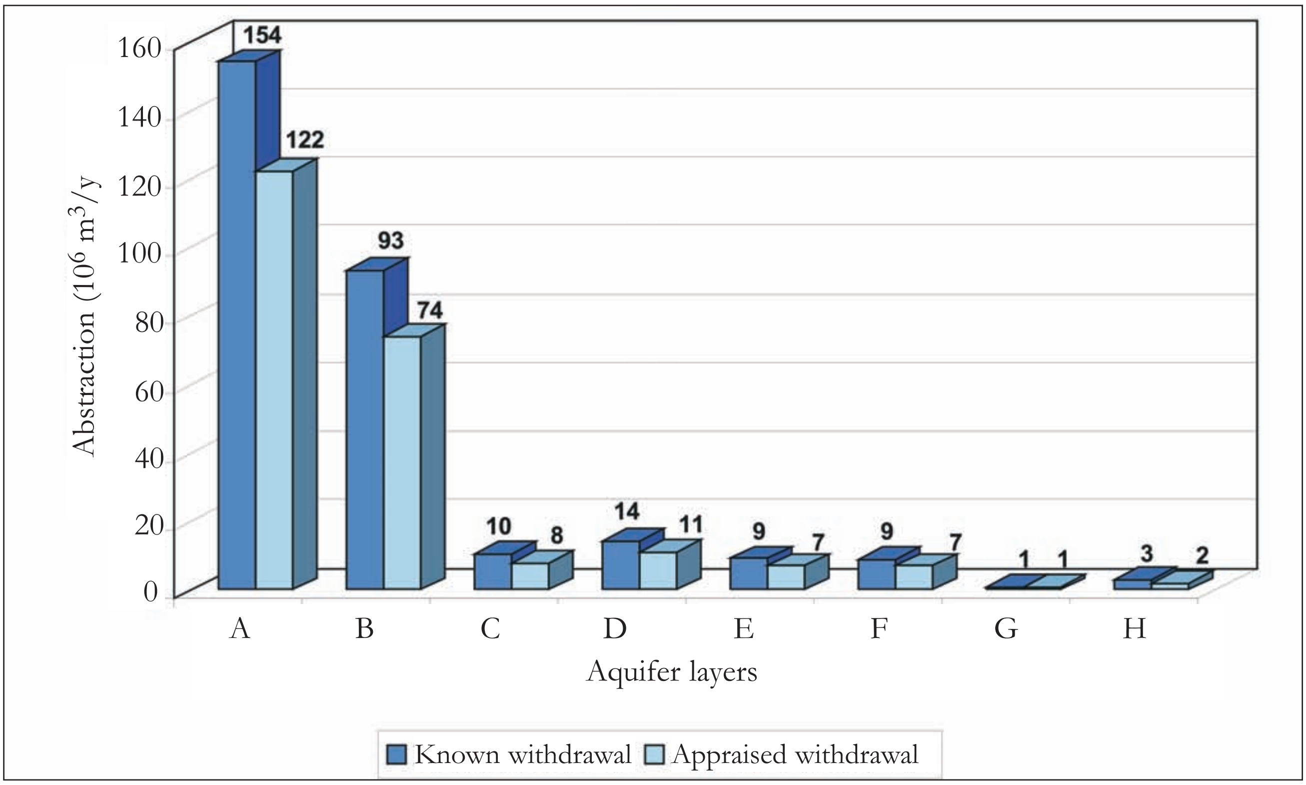

Fig. 21 - Known and appraised withdrawals concerning the confined aquifer system.
- Prelievi noti e stimati relativi al sistema acquifero confinato.

B, C, D, suggests a possible hydraulic continuity between the different aquifer layers and that therefore the silty-clayey levels act as be aquitards. The cross-sectional flow area used for the calculation, 43,700 m long, is located in correspondence with the spring line between the Tagliamento and Torre rivers.

As a result, the hydraulic conductivity values of aquifers A and B, are particularly high, ranging between 6.8×10^{-3} and 4.6×10^{-3} m/s, thus indicating that exploitation rates are at border-line level with aquifer capacity. These hydraulic conductivity values were compared with data obtained from both falling-head permeameter tests (tab. 12) carried out in samples coming from boreholes of the Friuli Low Plain (OSSERVATORIO GEOFISICO SPERIMENTALE DI TRIESTE, 1988) and pumping tests (tab. 13) carried out in the Mestre area (ANTONELLI, personal communication; ANTONELLI *et alii*, 1995).

It can be observed that the estimated hydraulic conductivity values (tab. 11) are somewhat higher than those measured in the Friuli Low Plain and in the Veneto Plain.

The confined aquifers of the Mestre subsoil are prevalently in sands, while the confined aquifer system of the area studied here is characterized by both sand and gravel. In particular, the lithology of layers A and B is predominantly gravelly in the northern sector of the Low Plain and

Tab. 11 - *Hydraulic conductivity calculated from available data.*
- Coefficiente di permeabilità stimato per ciascun acquifero.

Aquifer (depth m bsl)	Thickness (m)	K (m/s)	i	Extraction (10^6 m^3/year)	Q (m^3/s)
A (19-80)	29.5	6.8× 10-3	0.001	276	8.75
B (80-112)	14.5	4.6× 10-3	0.0018	167	5.30
C (112-148)	19.9	3.4× 10-4	0.0019	18	0.57
D (148-179)	10.6	8.8× 10-4	0.002	26	0.82
F (216-262)	20.9	6.8× 10-4	0.00082	16	0.51

Tab. 12 - *Hydraulic conductivity values of the Friuli Low Plain (Osservatorio Geofisico Sperimentale di Trieste, 1988).*
- Valori del coefficiente di permeabilità calcolati per il sottosuolo della bassa pianura friulana.

Municipality	Gravel (depth, m)	Sand (depth, m)	K (m/s)
Talmassons	21.5-22.0		$3.9 \cdot 10^{-5}$
Codroipo	28.0-28.5		$7.1 \cdot 10^{-5}$
S.Giorgio di Nogaro		42.0-42.5	$8.3 \cdot 10^{-6}$
Talmassons	46.0-46.5		$3.1 \cdot 10^{-5}$
Gonars	51.0-51.5		$5.0 \cdot 10^{-5}$
Codroipo	61.0-61.5		$4.2 \cdot 10^{-5}$
Latisana		77.5-78.0	$7.2 \cdot 10^{-6}$
Gonars	91.0-91.5		$2.9 \cdot 10^{-5}$
Talmassons	91.0-91.5		$2.8 \cdot 10^{-5}$
S.Giorgio di Nogaro		116.0-116.5	$7.4 \cdot 10^{-6}$
Latisana		192.5-193.0	$5.4 \cdot 10^{-5}$
S.Giorgio di Nogaro		219.5-220.0	$3.4 \cdot 10^{-6}$
S.Giorgio di Nogaro		263.0-263.5	$4.3 \cdot 10^{-6}$
Latisana		268.0-268.5	$8.4 \cdot 10^{-5}$
Latisana		315.5-316.0	$6.6 \cdot 10^{-5}$
S.Giorgio di Nogaro		341.5-342.0	$5.5 \cdot 10^{-6}$
S.Giorgio di Nogaro		390.0-390.5	$7.7 \cdot 10^{-6}$

prevalently sandy in the southern sector. Layers C corresponds principally to sand horizons, while layers D and F are characterized by both lithologies.

9. - CONCLUSIONS

The Friuli Low Plain is characterized by a thick Pleistocene sedimentary body, of both fluvioglacial and marine origin. Lithostratigraphical correlations carried out on a sample of 339 water-wells on the basis of the productive horizons identified by drilling operators, revealed the existence of three aquifer systems. (a) The confined aquifer system is formed by eight artesian layers, some of which are divided into sub-layers. This system, found at average depths of between 20 and more than 500 m bsl, is located in gravel horizons to the N and in sandy strata to the S. The average thickness of the single layers varies from approximately 11 m (D, G) to over 32 m (H). (b) The transition aquifer system, particularly evident in the NW sector, is determined by lithological changes between the High and Low Plain. It consists of two confined layers (S_1, S_2), characterized by averages depths of between 27.2 m asl and 12.2 m bsl, in marked contrast to those of the confined system. The thickness of these layers ranges from 1.2 to 25.5 m. (c) The unconfined system, which is particularly evident in the northern sector of the examined area, extends continuously and is located at depths of between 44 m asl and 18 m bsl.

The Friuli Low Plain is characterized by a dense network of artesian water-wells, for which there is scarce documentation. These principally pertain to the confined aquifer system. An evaluation of the volume of groundwater annually extracted from each single aquifer was carried out using available data. The total volume extracted from the confined aquifer system was estimated at 526×10^6 m^3, 84% of which derives from layers A and B.

The confined aquifer system of the Friuli Low Plain was also examined in order to assess the sustainability of current rates of groundwater exploitation. The status of layers A and B is critical in this respect. However, a comparison between estimated hydraulic conductivity values for the confined aquifer system and those obtained from tests carried out in the Friuli Low Plain and in the Mestre area indicates precarious conditions for the entire confined aquifer system of the Friuli Plain. In fact, the average K values measured for the two areas are one or two orders smaller than those estimated. This situation is testified by a large number of artesian wells which are no longer productive in the most exploited aquifers, A and B.

The results of the survey stress the need to improve hydrogeological knowledge of the aquifer systems of the Friuli Low Plain in order to facilitate the formulation of appropriate policies for the protection, management and planned use of groundwater resources.

Tab. 13 - *Hydraulic conductivity values in the Mestre area of the Veneto Plain* (Antonelli, personal communication).
- Valori del coefficiente di permeabilità calcolati per il sottosuolo della pianura veneta (zona di Mestre).

Depth (m)	K (m/s)
93	$1.5 \cdot 10^{-5}$
110	$1.1 \cdot 10^{-5}$
201	$8.0 \cdot 10^{-6}$
258	$4.4 \cdot 10^{-6}$
406	$7.2 \cdot 10^{-7}$

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