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HYDROGEOLOGICAL SURVEYS AND ANALYTICAL APPLICATIONS OF THE VENETIAN AQUIFER SYSTEM.

IMPLEMENTATIONS OF SAFETY MEASURES FOR THE VENICE LAGOON AREA

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For my Angels,

Elisa, Giulia and Francesca

"Non aetate,
verum ingenio apiscitur
sapientia"

Trinummus, Titus Maccius Plautus

"Not by age but by capacity
is wisdom acquired"
"Non con l'età, ma con l'ingegno
si raggiunge la sapienza"

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ABSTRACT

In the study area (Venetian hinterland, Porto Marghera) there is an average of a few hundred artesian wells (80-350 m in depth) drilled between 1910-1970 and later abandoned. These wells represent a means through which the artesian waters rise; therefore a dispersion process takes place between the groundwaters in the Shallow Aquifer System (0-80 m) and those in the deep artesian aquifers (Artesian Aquifer System, 80-350 m below ground level), in which the hydraulic head has steadily risen for the last 40 years. In this instance the shallow aquifers (about 0-30 m) could be subjected to a recharge through the abandoned wells. This recharge effect adds itself to a hydro-geological system greatly influenced by anthropic activities, such as: safety measures by means of a drainage system made up of many pumping stations which guard both the phreatic level in wide-spread areas and the hydraulic head; diaphragm walls in the whole area of Porto Marghera both near the lagoon border and the inland. The diaphragm wall goes down to 15-20 m in depth.

These diaphragm walls should remove the superfluous groundwaters that – by passing through highly polluted lands – must necessarily be dealt with and treated in suitable plants.

The spontaneous rise of the groundwaters through abandoned wells due to the increase of the hydraulic head in the deep aquifers has not been studied in depth from a scientific point of view.

The analytical and numerical models available in scientific literature mainly deal with the definition of a system made up of abandoned deep wells, through which fluids may run because of the injection of fluid waste or carbon dioxide through injection wells.

Starting from the analytical solutions suggested by different authors new ones have been achieved which may be more effectively adapted to the unusual problems occurred in defining the vertical flow through abandoned wells.

The use of these solutions requires the analysis of a series of hydrogeological parameters. The most important is the geometrical reconstruction of the aquifers involved. An updated hydro-geological model of the whole study area is necessary. As there is no data on explorations at such depths, an updated hydrostratigraphic reconstruction has been developed of the only core drilling on which there is a lot of information: the Ve-1 drilled at 951 m in 1971. The reference hydrostrati-graphic sequence required an analysis of the earliest scientific publications on Ve-1 on a sedimen-tological, palynological and magnetostratigraphic level.

The data from the stratigraphies of some wells built through full drilling has been used in a new software package completed in this paper (modalstrata). Modalstrata allows the establishment of a mean stratigraphy from a series of reference verticals in a certain area. In the areas in which

there is not much stratigraphic data, the geophysical method of passive seismic was used which allows the identification of lateral continuity in the main reflectors.

This hydrostratigraphic model is confirmed by the comparison of a first hydrostratigraphic series developed for Ve-1.

Therefore the updated hydrostratigraphic model of the study area allowed the definition of the geometries included in the analytical solutions in order to identify the leakage rates in the specific instance a sufficient number of hydrogeological parameters are known.

The GIS environment manages a great amount of data and information. The use of GIS means also allows the development of further geostatistical assessments.

1. STUDY AREA SETTING

1.1. GEOGRAPHIC SETTING

The study area is located in North-eastern Italy in the region set in the North-west of the Venetian lagoon, on the border of the Provinces of Treviso and Padua (fig. 1).

From the plano-altimetric point of view, the ground level appears quiet flat, with heights referring to the mean sea level ranging between 15 metres asl in the North-western area and below one metre in height in the areas just above the industrial site of Porto Marghera, where a dense system of pumping station are always checking the phreatic surface.

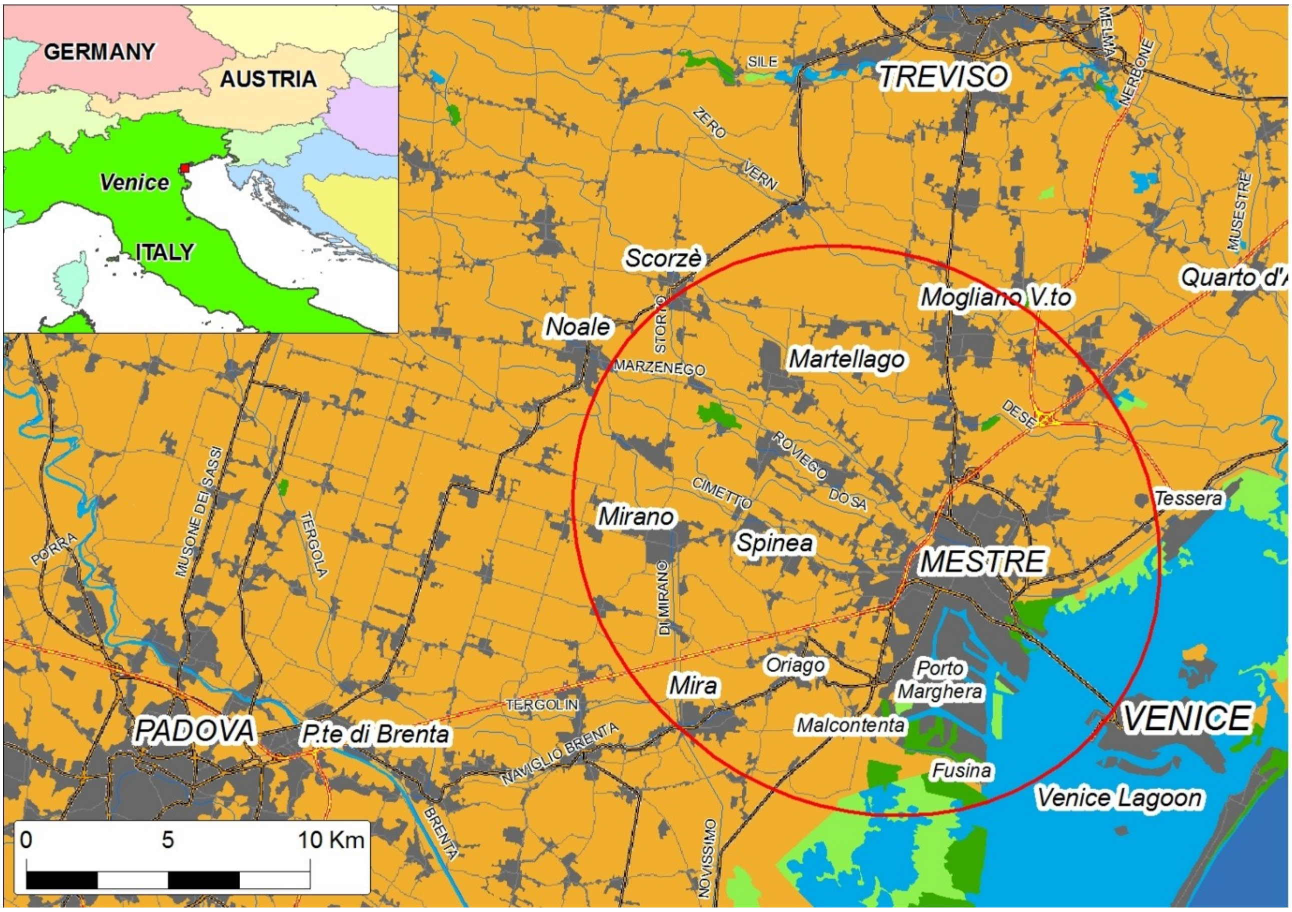


fig. 1: geographic setting of the study area

From the hydrographic point of view the area is covered by a complex channel network often altered by anthropic activity as in the symbolic example of the Brenta river. This river was diverted from the lagoon border between the XIII and the XVI century by the Venetian Republic, in order to lessen the inflow of sediments from the rivers which used to fill up the lagoon basin; in the XVII century the Venetians also intervened on the Sile river which flowed in the East of the built-up area of Mestre and nowadays reaches the Adriatic near the Lido di Jesolo.

The geomorphological imprint of these important rivers is still clearly recognizable nowadays.

Besides the impressive deviation work of the main rivers which flowed in the Lagoon, the Venetians undertook, mainly between the end of the XIX century and the beginning of the XX, the drainage of the lower areas closer to the Venice lagoon. As mentioned above there are many pumping stations that, mostly in wintertime, allow agricultural and anthropic activities in areas which were once marshlands. This removal of surface waters and groundwaters from the aquifers closer to the ground level also alters the normal hydrogeological budget.

The main rivers which cross the area are: the Marzenego river, the Roviego, the Naviglio del Brenta, checked by a network of dams close to the outlet near Moranzani which makes it navigable right up to Padua. The Dese river flows to the East of the above mentioned ones.

The main urbanized area is the city of Mestre which underwent a sudden population growth in the second half of the post-war period mainly due to the Venetians moving inland.

The industrial area is developed on the Southern side of Mestre, which includes the biggest Italian chemical plant, represented by Porto Marghera. Other minor urban centres are: the towns of Oriago, Martellago, Scorzè, Spinea, Dolo, Mogliano, Salzano (fig. 1).

1.2. REGIONAL GEOLOGIC AND TECTONIC SETTING

The Adriatic microplate represents the Northern highest area of the African plate: in the Northern region it is defined by the South-verging Southern Alps, to the East by the Dinaridi and the Albanidi, to the South by the Kephallinia and the Apulian wedges and to the West by the outer Apennine border. (Mantovani et al., 2009).

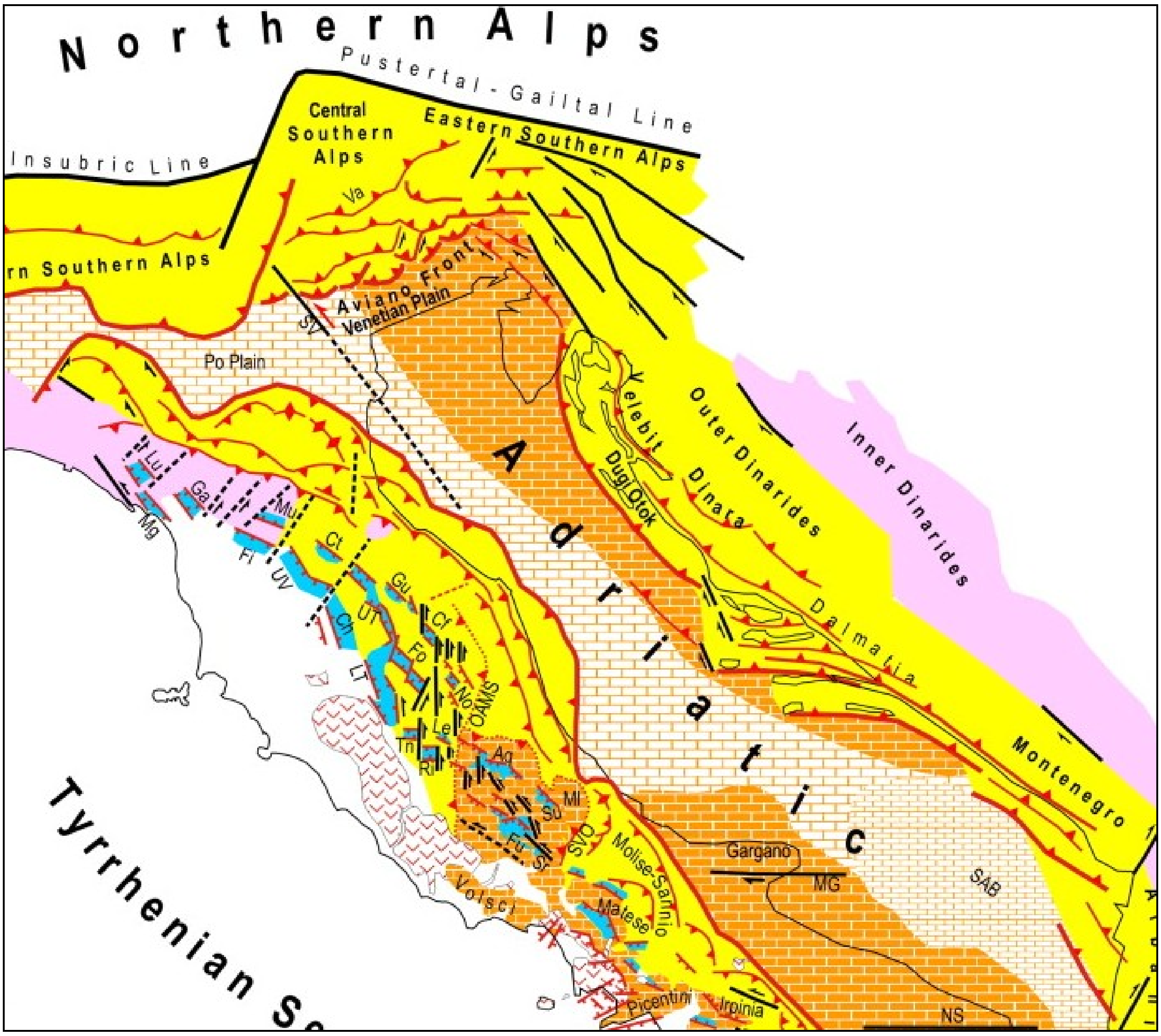


fig. 2: Present - Pleistocene tectonic system (from Mantovani et al. 2009)

The South alpine system is the result of a polyphasic evolution active in the Tertiary period. The oldest structural system coincides with the Mesoalpine (Eocene) and the following phases of Neoalpine compression (Oligocene-Miocene), which produced the Dinaric System (NW - SE) and follow a NE direction in the Eastern Southern Alps (Barbieri et al., 2004; Castellarin et al., 2006).

Starting from the Oligocene period the Po basin progresses into the foreland basin as regards the Southalpine area; in more recent times into the foreland basin also as regards the Apennine System (fig. 3).

The central Venetian plain is set, from the structural point of view, between the Northern border of the Adriatic monoclinal and the Pedealpine one: to the West the boundary is represented by the Schio-Vicenza, a sinistral transform fault whose direction is resumed by the neotectonic lineaments recognisable by the NW-SE fault system.

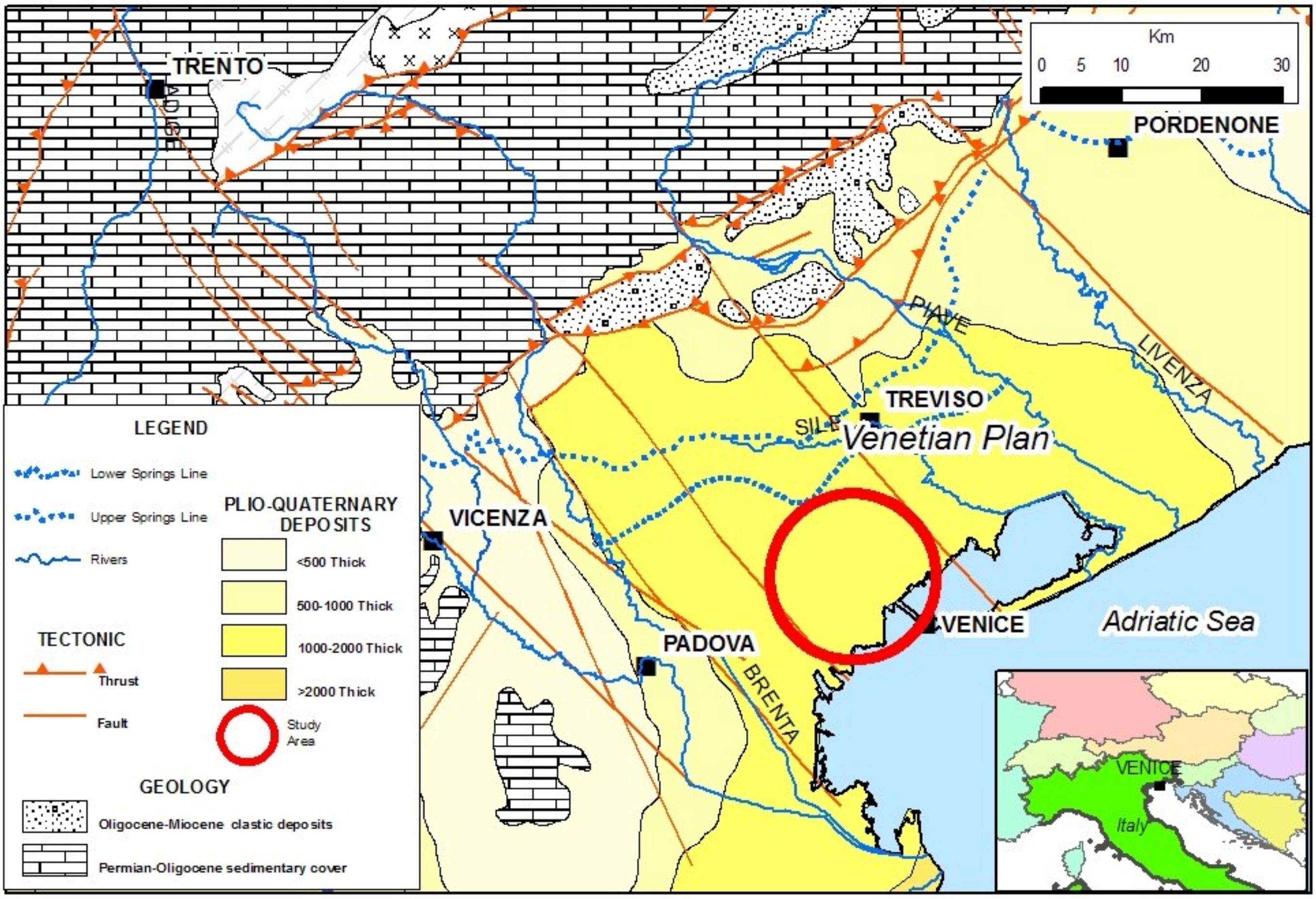


fig. 3: geologic and structural scheme of North-Eastern Italy (modified from AA.VV, Regione del Veneto, 1990)

From the Pliocene period the whole Venetian basin is affected by a land subsidence, mainly connected to the collisional force produced by the Apennine chain in the SW (Barbieri et al., 2004). The Venetian area is influenced by the Apennine tectonics whose tilling presents a dip direction towards the South (Carminati et al., 2003): therefore the Northern Apennine tectonics are responsible for about the 50% of the subsidence registered in the lower Venetian plain during the Pleistocene period. This tectonic subsidence rate is still active from East to West, from the region of Friuli to the Apennines (fig. 3).

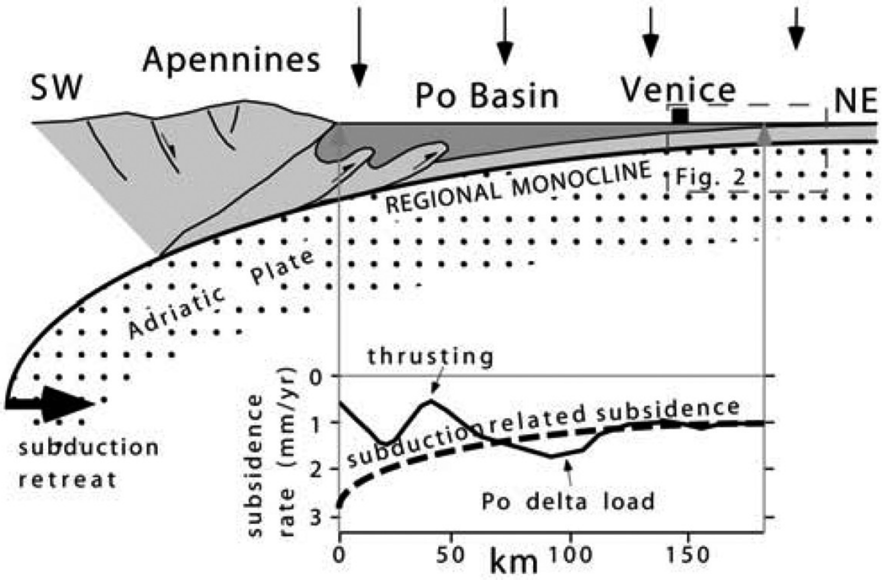


fig. 4: tectonic land subsidence of Venice area (Carminati *et al.*, 2003).

The prevailing direction of the fault proves how the whole region's tectonic and evolutive structure is influenced by the Schio-Vicenza, following the NNW-SSE direction. This direction is also recognisable in neotectonic structures that influence the whole quaternary morphological evolution.

1.3. GEOMORPHOLOGICAL SETTING

The regressive Messinian Event has strongly affected the Plio-Quatenary geomorphologic evolution of the area. Due to the decrease of the eustatic level the area developed continental features and therefore was influenced by strong erosive forces produced by a particularly depressed ground level in the whole Mediterranean basin. In this context a complete reorganization of the entire hydrographic network take place with an intense development of the Alpine valleys and also of the depressions in the level areas which underwent an obvious terracing. These elements, with the rise of the eustatic level and the sedimentary processes, greatly influenced the Plio-Pleistocenic sea and alluvial evolution that marked the late Quaternary age.

The Venetian plain is made up of big composite alluvial fans (megafan), polychronologic and polyphasic (Plio-Quaternary deposits); their thickness increases towards SSE (Bondesan et al., 2004; Fontana et al., 2008). The distal part of the megafans of the Brenta river and the Piave river contributed to the creation of the Venetian lagoon (Holocene). In the upper plain areas these megafans are also mainly made up of gravel and sand (fig. 5).

The geomorphological patterns that can be most easily recognised at the moment are represented by the fluvial bends or depressions. The main courses of the Paleo Brenta river are identifiable to the North of the present Naviglio del Brenta, according to the direction of maximum gradient (NW-SE). When the activity of the Brenta river's oldest fan run out in order to move by the present fan (Brenta's megafan near Bassano, fig. 5), the development of the minor hydrographic network began.

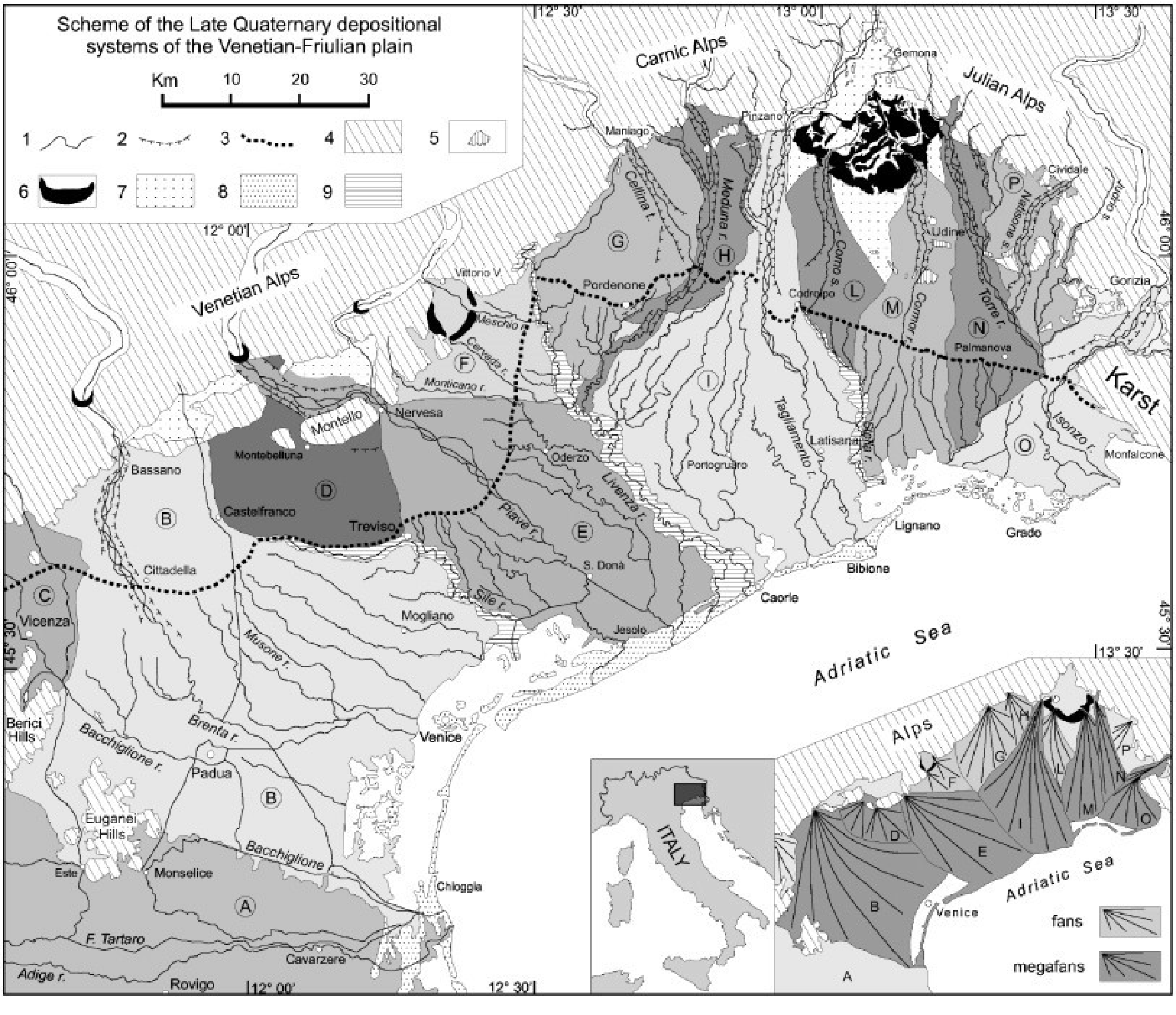


fig. 5: scheme of the Late Quaternary depositional systems of the Venetian-Friulian Plain. (A) Adige Alluvial Plain, (B) Brenta megafan, (C) Astico fan, (D) Montebelluna megafan, (E) Piave megafan, (F) Monticano–Cervada–Meschio fan, (G) Cellina fan, (H) Meduna fan, (I) Tagliamento megafan, (L) Corno fan, (M) Cormor megafan, (N) Torre megafan, (O) Isonzo megafan and (P) Natisone fan (Fontana *et al.*, 2008).

The plain spring rivers substituted the wide fluvial stretches of the Brenta; these rivers represent a clear genetic, morphologic and hydrographic imprint connected to the previous downflow directions of the Paleo-Brenta and of the rivers connected to it (e.g. Musone). The direction of the river bends established the hydrographic structure of these plain spring rivers that had to set themselves by the lengthened depressions of these landform rivers. (Bondesan et al., 2008).

1.4. HYDROGEOLOGICAL SETTING

In the mouth of the valleys the megafans are made up of coarse alluvium and store an important undifferentiated aquifer. The Hydrogeologic System on regional scale is sketched in fig. 6 where it is possible to observe the shift from the Undifferentiated Hydrogeological System that characterizes the Upper Venetian Plain, and the Multilayer Aquifer System in the Middle and Lower Plain. This Multilayer Aquifer System can be further divided in:

- Sistema Acquifero Superficiale (**SAS, Shallow Aquifers System**), costituito da un insieme di livelli acquiferi confinati;
- Sistema Acquifero Artesiano (**AAS, Artesian Aquifers System**), costituito da acquiferi confinati artesiani.
- Sistema Acquifero Profondo (**DAS, Deep Aquifers System**), costituito da acquiferi confinati artesiani nei quali le acque sotterranee sono caratterizzate da elevata salinità e pertanto non sfruttabili dal punto di vista idropotabile.

SAS, Shallow Aquifers System, made up of a set of confined aquifer layers;

AAS, Artesian Aquifers System, made up of artesian confined aquifers.

DAS, Deep Aquifer System, made up of confined artesian aquifers in which the groundwater is characterized by a high salinity and is therefore not exploitable for hydropotable purposes.

This paper focuses on both the natural processes and those resulting from anthropic involvement which mainly govern the AAS and the SAS; in the study area the hydrostratigraphic setting can be divided into two parts: (1) the Shallow Aquifer System (SAS) from the ground level to a depth of 70 – 80 m, where there are mostly continental sediments (Upper Pleistocene – Holocene); (2) the Artesian Aquifer System (AAS) that reaches an indicative depth of 340 – 400 m (Gatto et al., 1981). The sequence of the latter is made up of a series of six transgressive – regressive sequences in which sea, littoral, lagoon and fluvial sediments alternate (Brambati et al., 2003; Kent et al., 2002; Massari et al., 2004).

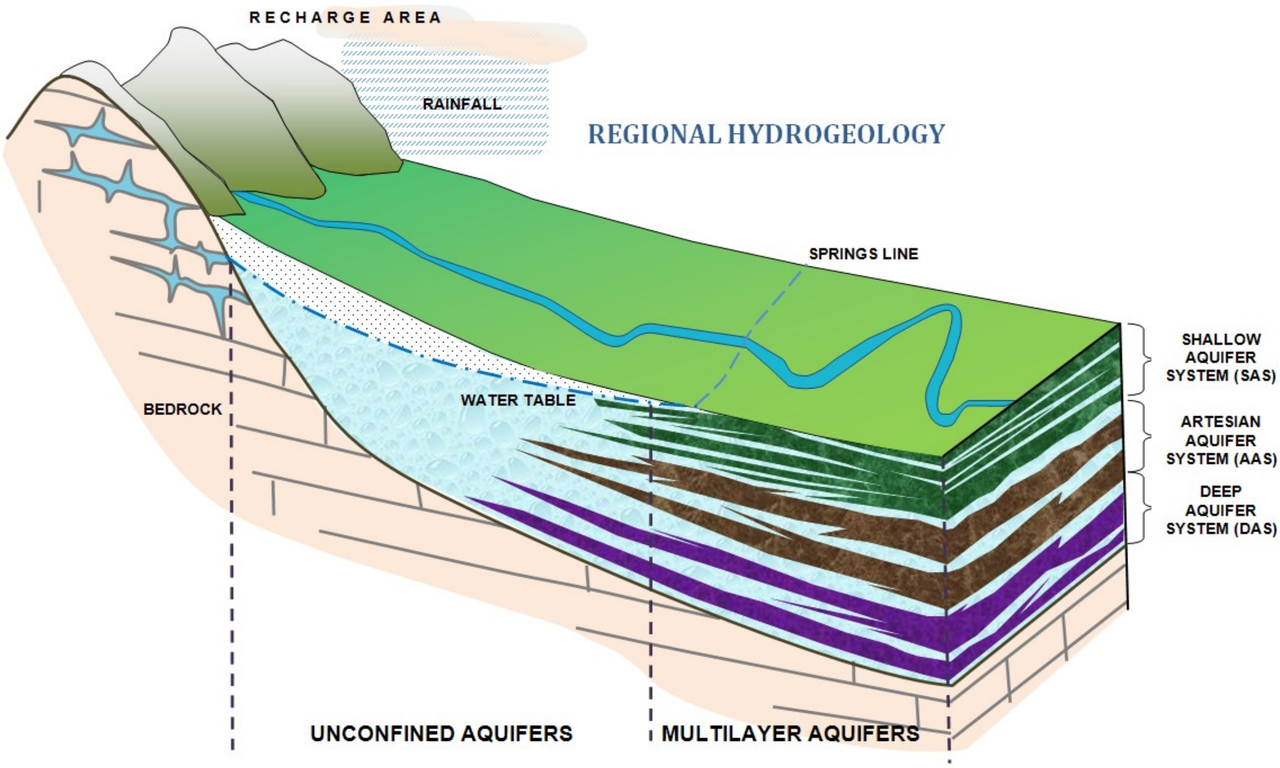


fig. 6 : Regional Hydrogeological Plant

The regional flownet is checked by the recharge and discharge of both the Brenta and Piave basins and can also be considered representative of the shallow aquifers system (SAS) (fig. 7) (AA.VV., 1990; Antonelli et al., 2007; Boscolo et al., 2008).

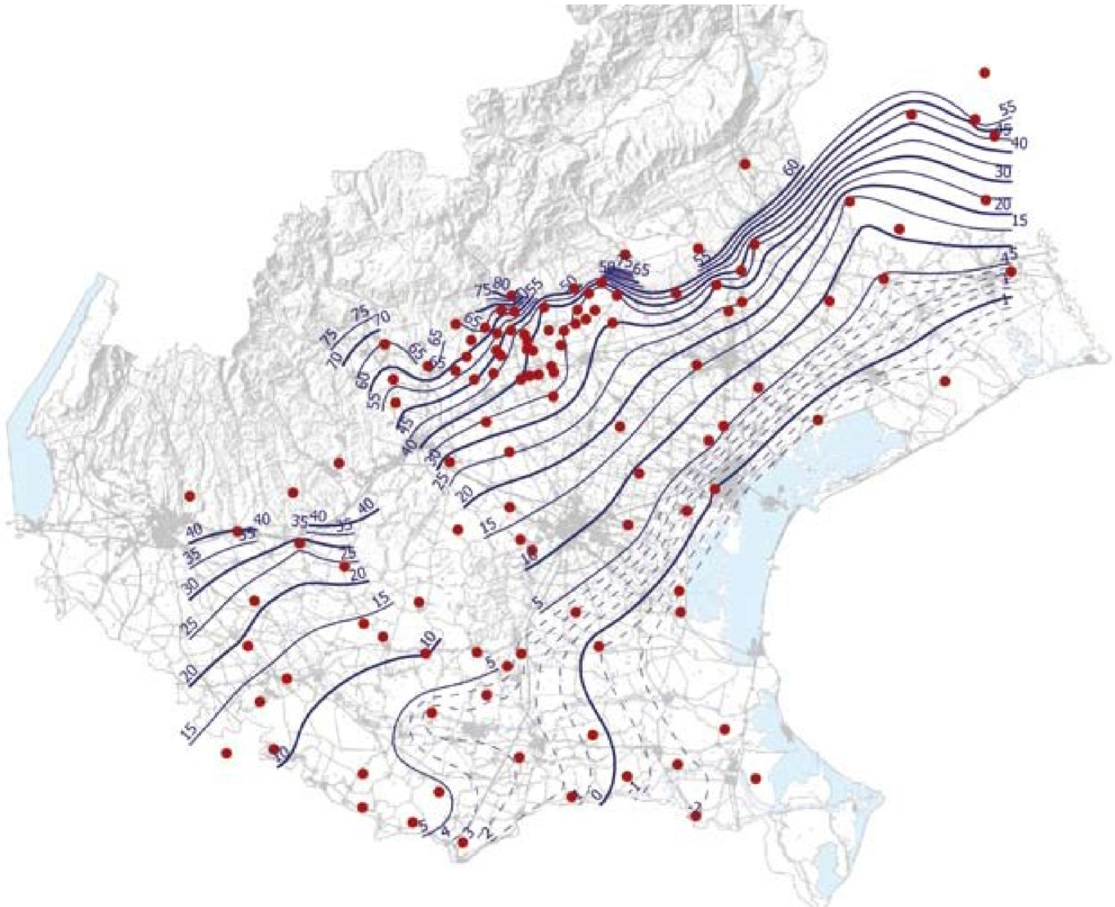


fig. 7 : flownet in shallow aquifers (Boscolo *et al.*, 2008)

On a local scale the of the flow pattern concerning the shallowest part of the SAS is better represented by fig. 8, in which it is possible to observe the progressive and regular adjustment of the piezometric level to the mean sea level (Beda, 2004; Mari, 1985).

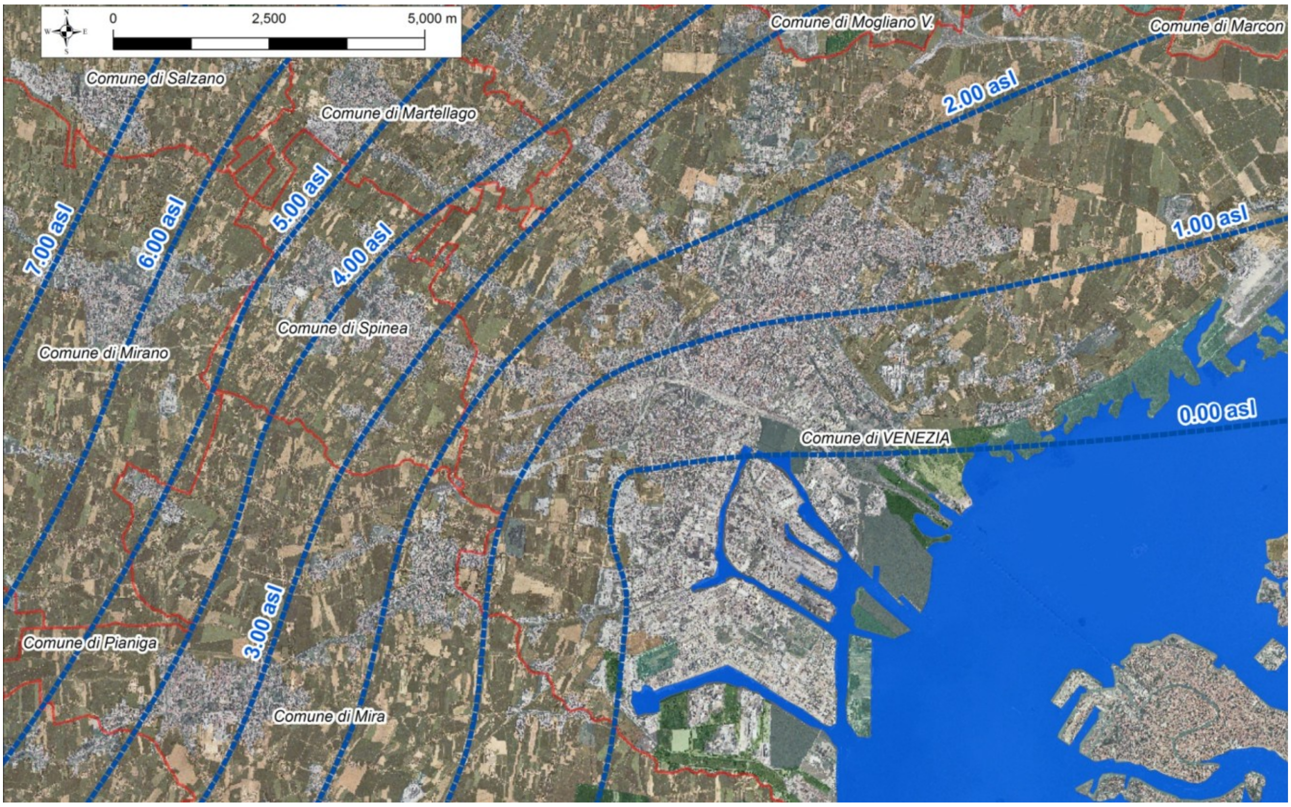


fig. 8: Regional piezometric level pattern related to the first pressure sensitive layer (Aquifer depth max. 20 m ca), modified from Beda, 2004; Mari 1985.

Actually the hydraulic head pattern of the shallow aquifers is particularly complex both because of the lithological and geomorphological variations and because of the effects of the anthropic activities; besides all these factors there are also: the leakage from the shallow hydrographic network, the effects of the recharging by the meteoric events, the saline wedge intrusion and the tide pressure which also affects the inland through the channel network (Zangheri et al., 2009).

For all these reasons and more that will be discussed below, fig. 8 must only be considered as indicative of the study area's flownet.

1.1. LAND SUBSIDENCE IN THE VENETIAN AREA

1.1.1. Historical introduction

During the period of the Serenissima Republic of Venice the difficulty of water provisioning was solved by the clever system of collecting rainwater; the Venetians used to build a heap of sand on top of a basin made waterproof by a layer of clay, the so-called "cree"; this "pool" was spread over all the surface of a square; the water stored by the sand was gathered through a central masonry pipe of special bricks called "pozzali".

The water provisioning used to not be sufficient anyway and so the underground fresh water started to be exploited through the excavation of wells.

Authorizations are known for the withdrawal of groundwater since the XV century, as reported by many available sources (Dandolo et al., 1796; Sanudo, 1533).

The demand of water provisioning through the drilling of new wells greatly increased throughout the XX century.

The increase of water demand is due both to the progressive population growth, which forced a bigger and bigger number of inhabitants to move inland, and to all those needs strictly linked to the industrial development.

At the end of the XIX century Venice proved itself unable to become an industrial and harbour centre which could compete with other Mediterranean landmarks, mostly because of the lack of an area suited to this purpose. The problem was solved thanks to the project of captain Luciano Petit who planned the drainage of the Bottenighi area. In 1907 a new law on harbours was enacted and in 1917 a quarter of the territory of the Mestre municipality at the time was expropriated and entrusted to the Industrial Harbour Society of Venice which accomplished the works that were meant to create the first core of Porto Marghera (Miozzi, 1969).

The industrial expansion underwent a new boost in the second half of the post-war period. In order to develop new industrial and harbour areas and solve many of the problems linked to the mud disposal coming from the industries, many humid shoal areas were taken from the Lagoon and filled up with often contaminated material; on this land many industrial sites were built whose activity increased the level of ground and water contamination. At the same time of the industrial growth there was an increase of demand for groundwater provisioning, as is described in chapter 1.1.2.

1.1.2. Exploitation of the artesian aquifers and induced subsidence

The Venetian area has been subjected for a long time to the raising of the water level and a resulting increase of the occurrence of “acqua alta” (high water) incidents in Venice, especially since the second half of the post-war period. (fig. 9) (Gatto et al., 1981).

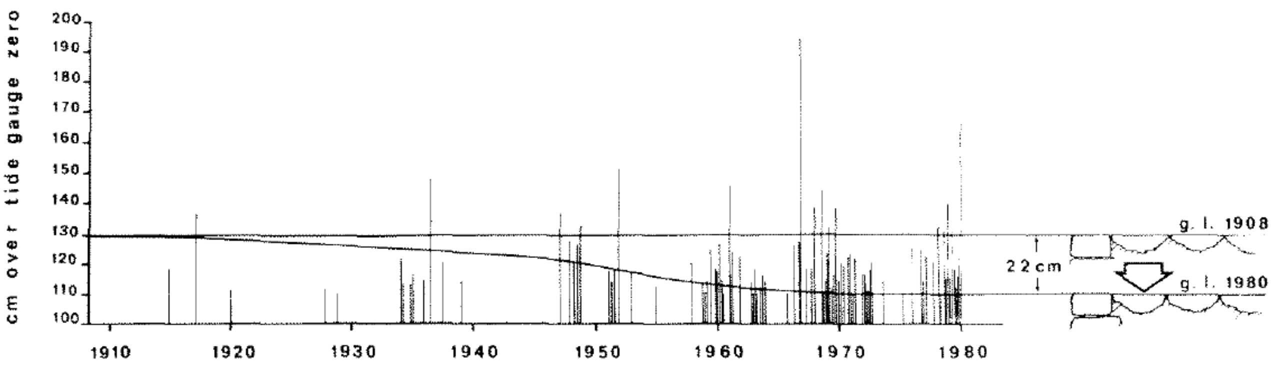


fig. 9: Frequency of "high water" incidents in Venice (Gatto *et al.*, 1981)

The survival of Venice, the Lagoon and the neighbouring areas was (and is) greatly influenced by the variations in the sea level (Camuffo et al., 2003). An interesting check of the relative eustatic variations is supplied by the level of the "algae front" on the Venetian buildings; in some paintings by Canaletto – accomplished with an almost "photographic technique" – it is possible to compare the tidal wetting in the XVII century with the present day one. This comparison highlights the fact that in over two and a half centuries the mean tidal wetting in Venice has increased of over 66 centimetres.

The variation of the mean sea level is chiefly influenced by the following factors (fig. 10):

- eustatism;
- natural land subsidence;
- tilting;
- natural consolidation;
- induced land subsidence.

Eustatism involves the rising or falling of the sea level, the causes of which can be different depending on the region and on the geological age. It seems however obvious that during the glacial and interglacial phases, the freezing and thawing involve variations of the water volume with an ensuing falling or rising of the sea level (Carbognin et al., 2004). In the last centuries the eustatic level has risen progressively, even if there are impulses that sometimes go in the opposite direction (Bonardi et al., 2006).

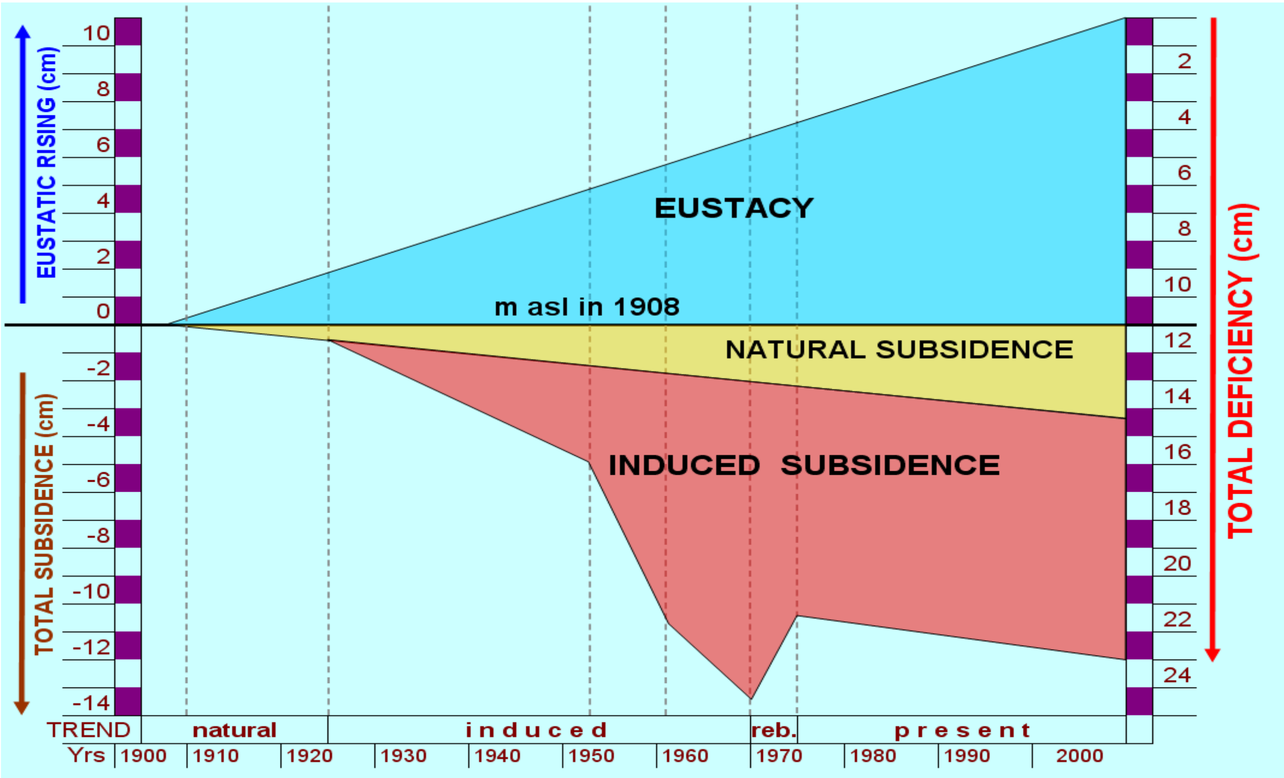


fig. 10: Subsidence registered in the centre of Venice (modified from Carbognin et al., 1981).

As regards the **natural subsidence**, in relation to the tectonic activity, paragraph 1.2, referring to the Apennine - Adriatic subduction reactivation (tilting) may be viewed (Carminati et al., 2003).

In the Venetian area the natural subsidence is basically linked to the **consolidation** of Quaternary sediments and new sediment accumulation (Serandrei-Barbero et al., 2006; Tosi et al., 2007) (fig. 10). The subsidence of the lagoon basin and of the surrounding areas developed in a differential mode both in time and space, in relation to the various depositional events following one another, to the complex phenomena of soil consolidation, caused by the substitution of the original interstitial fresh waters with the salty ones and, in recent times, to anthropic intervention (Di Sipio et al., 2007).

Natural land subsidence can be greatly increased by the **subsidence** effects **induced** by human activity. In the Fifties it seemed obvious that at a worldwide level there were many study cases related to subsidence effects induced by anthropic activities involving an increased withdrawal of groundwater.

In a particularly delicate environment such as the Venetian one, it seemed obvious the gradual loss in ground level had to be first explained and then solved.

The proliferation of a number of wells intercepting the SAS produced a considerable increase in the withdrawn groundwater volumes, as pointed out by surveys and studies dating back to the first years of the Seventies (Serandrei Barbero, 1972) and that may be summed up in fig. 11.

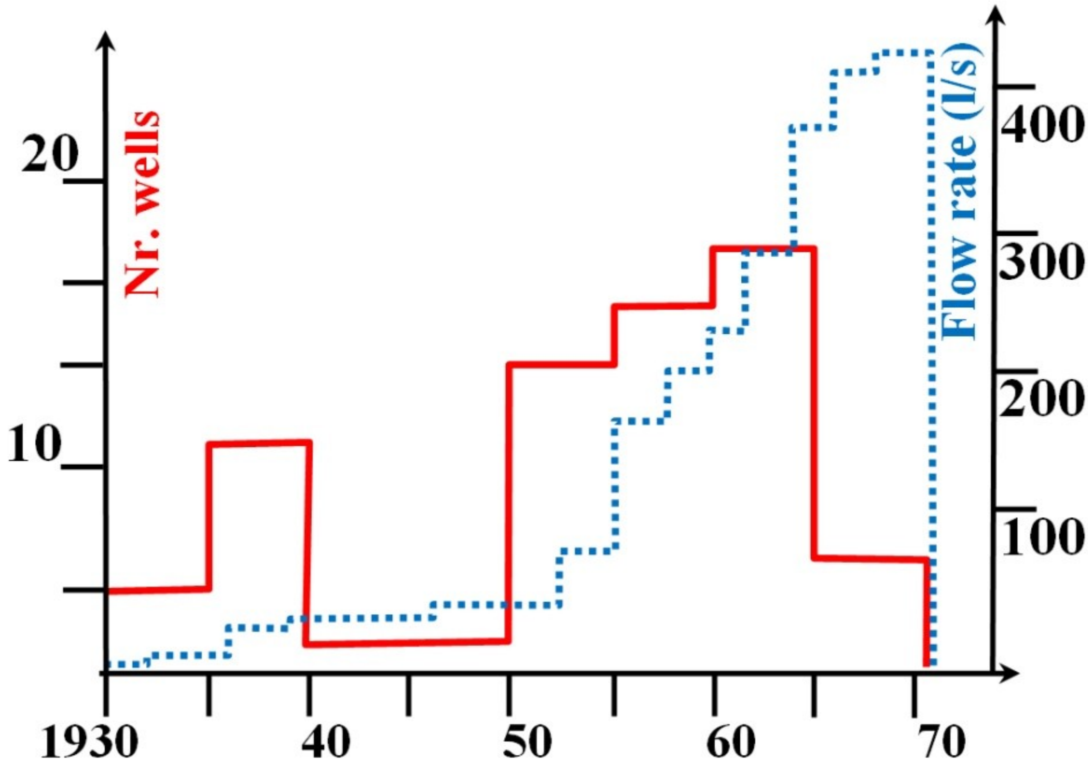


fig. 11: number of wells drilled every 5 years (red) and total capacities withdrawn from the SAS from 1930 to 1975 (modified from Gambolati et al., 1974a).

The groundwater exploitation had as a first consequence a rapid decline of the available water resources, basically connected to an evident decrease of the hydraulic head in the AAS (fig. 12).

In this context in 1971 the Water Authority of Venice (Magistrato Alle Acque, MAV) declared the interruption of all groundwater withdrawing, in order to stop the SAS exploitation (fig. 12).

Actually the industries located in the Porto Marghera area had already started to abandon the wells for the last years, as the water resources had become insufficient, especially as regards the mostly exploited aquifers (I and IV), connecting instead to the aqueduct network that was beginning in those years to branch off in the industrial areas.

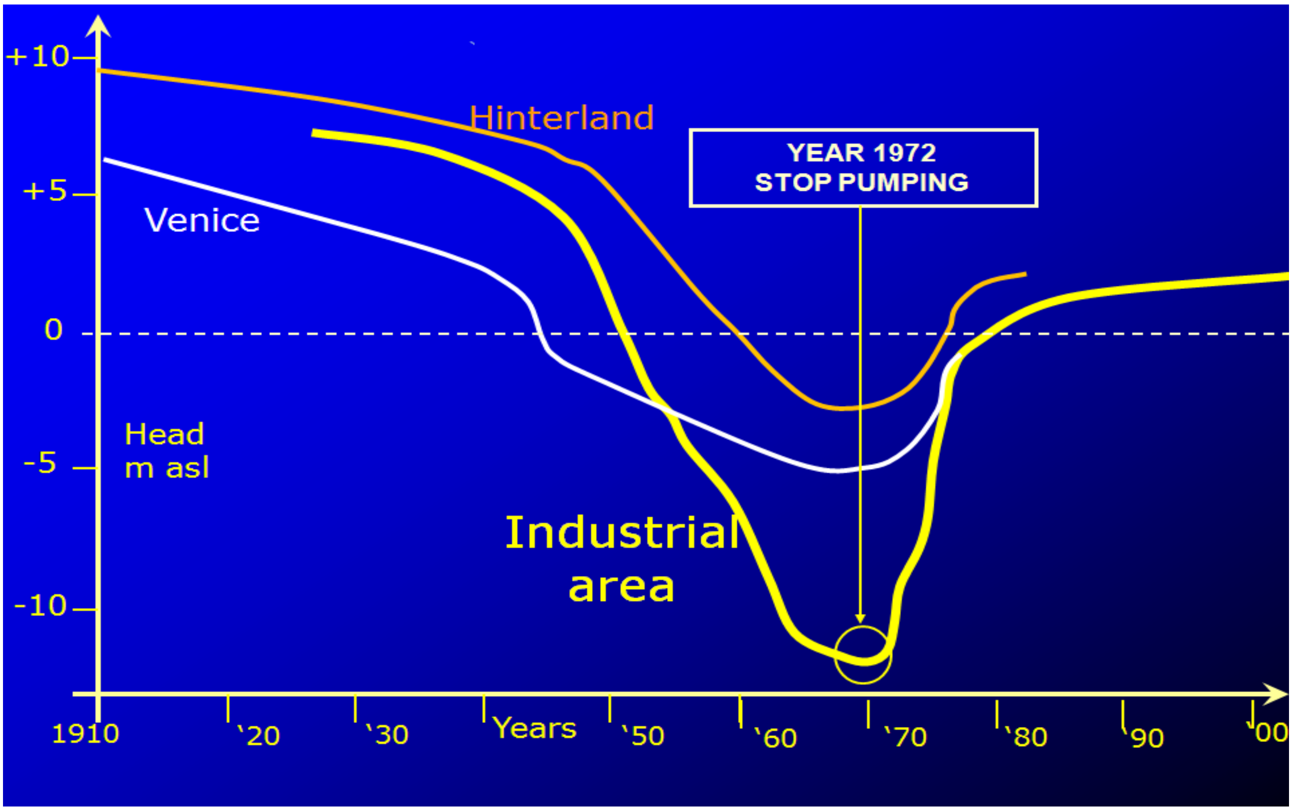


fig. 12: Piezometric level variations in the last century in three different sections of the Venetian area (modified from Carbognin et al., 1981).

Following the imposition decreed by the MAV all the wells were completely abandoned; of the over 450 existing wells only a few dozens remained, by the CNR (National Council of Research) of Venice.

The consequence was a first rapid and later more gradual rising of the piezometric head in the artesian aquifers (fig. 12); this groundwater recharge coincided with a considerable slowdown in land subsidence in the Venetian area (fig. 10).

1.2. DIAPHRAGM WALL AROUND PORTO MARGHERA

As regards the pollution sources which Porto Marghera produces both in the Venice Lagoon waters and its ecosystems it is appropriate to remember that Porto Marghera's industrial centres were built, from the 1920s to the 1960s, refining the lagoon areas with shoals made up of landfills of heterogeneous materials such as harbour dredgings, industrial and solid urban waste. Nowadays, in some cases, along the banks of the industrial channels, these materials are in contact with the lagoon's water, so a release of polluting substances takes place due to the wave-motion, the tides and the washing away caused by the rain. Besides on the channel floor polluting substances have gradually built up from the flowing back of harbour and industrial processing: a problem that has revealed all its seriousness only these last years and is nowadays systematically and organically dealt with.

The planned intervention consists therefore in the creation of shore diaphragm walls, connected to inland drainage and treatment of meteoric waters, to the organization and regulation of the draining system and the creation of inland diaphragm walls for a complete "belting of the macro-islands" (macro isole)along the perimeter (Regione del Veneto, 2004).

In this way the following would be eliminated (fig. 13):

- erosion and dispersion of polluting shore material;
- the inflow of contaminated groundwater (superficial layer);
- meteoric water washed over contaminated land.

It appears obvious that the drained groundwater of the shallow aquifers intercepted by the diaphragm walls, which averagely reaches 15-20 m in depth, must be removed (fig. 13) and treated in suitable facilities as the study area is set inside an Area of National Interest (Sito di Interesse Nazionale, SIN) with a high risk level.

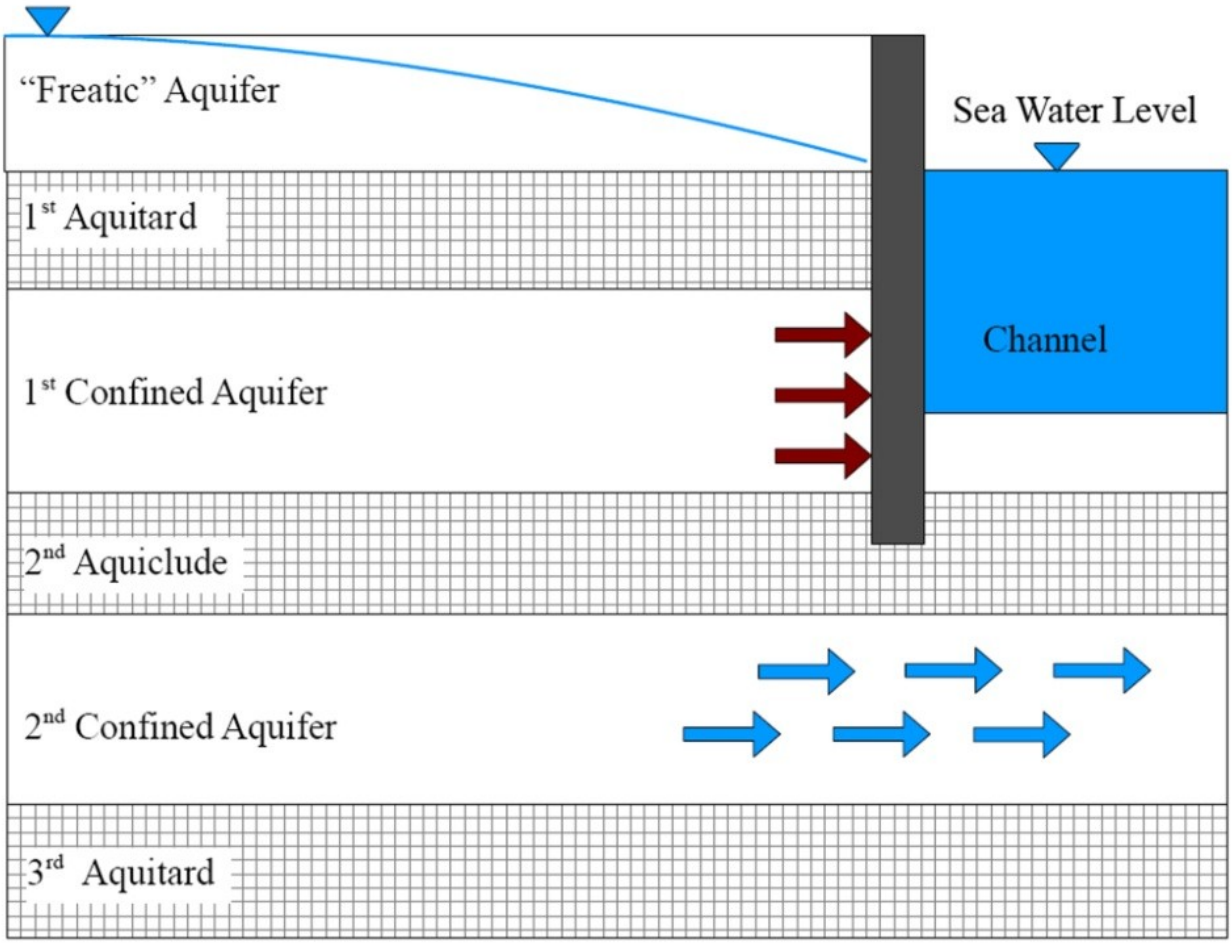


fig. 13: diaphragm wall scheme.

The studies developed in order to test this project (MAV, 2007a), highlight a series of particularly significant incidents which will have to be dealt with later.

First of all the observed piezometric levels turn out to be conflicting as regards to what should be the local trend: according to what is shown in fig. 7, in which there are values close to the mean sea level or variable in a range mainly influenced by tide impulse.

The conditions actually measured are very different from the expected ones, because anomalous conditions of "high piezometric levels" compared to the general context have been observed (fig. 14). This hydraulic head sometimes even produces an inversion of the head gradient (fig. 14).

Another conflicting element as regards a first evaluation of the hydrogeologic budget of the Shallow Aquifers System is provided by the simulated and measured results of the already existing drainage systems, adjoining the diaphragm walls.

Only after an appropriate adjustment it was possible to correctly estimate the withdrawn flow rate that proved to be superior to expectations.

The high groundwater levels obtained in certain industrial areas (sometimes even higher than those noticed inland) suggest that many abandoned wells, not correctly sealed, allow a direct communication between AAS (80-350 m) and the SAS (0-80 m).

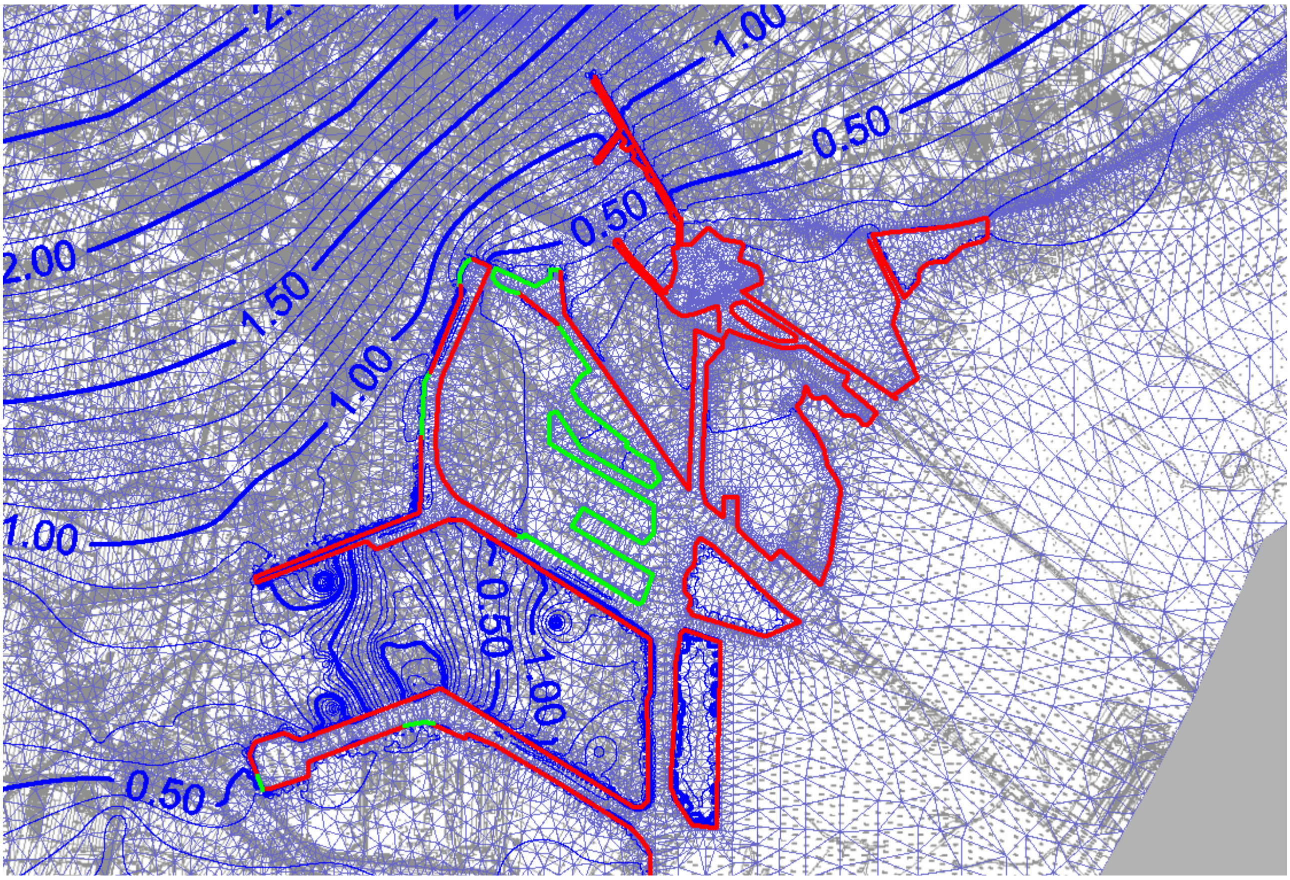


fig. 14: Piezometric pattern simulated with FEM, in a past calibration (MAV, 2007a).

Therefore it is inevitable to consider that a big part of the flow rate withdrawn from the draining system for the necessary treatment could originate from the Artesian Aquifers System whose waters are, at least in origin, of a good quality from the hydrogeochemical content point of view.

2. SUGGESTIONS FOR EXPERIMENTAL METHODOLOGY

In this paper are also quoted the methodologies that could most easily allow – according to the author - the assessment of such a neglected process by scientific literature as the flow through abandoned wells.

The suggestions below may represent a useful means to define a schedule that may both be applied to the study area for the experimental testing of the flow through passive wells and used in other logistic contexts.

2.1.1. Borehole video inspection

The deep artesian wells in the study area were dismissed in 1971, if not earlier, that is when the piezometric levels (at the end of the Sixties) were so low as to make the exploitation of the deep artesian wells fruitless (paragraph 1.1.2 and fig. 12).

The full drilling of these wells dates back to the 1910s, though most of it took place between the Fifties and Sixties (fig. 11) (Gambolati et al., 1974a).

Therefore their maintenance is not known, as a lot of the completion data (diameters, filter positioning, well screen position) results incomplete, deficient or missing.

The direct video inspection of the wells allows the achievement of a lot of necessary information in order to have a clear pattern of the well's geometric conformation, both of its preservation and piping.

The results of these video inspections also allow the checking of possible corrosion or deterioration of the casing's upper length. This feature is extremely important in the choice of analytical and numerical solutions which have to be applied in order to effectively represent the leakage rate through abandoned wells. The identification of the casing structure along the superficial length is very important both for the detection of the flow type (radial or spherical) and the parameters to be set for analytical solutions (chapter 5).

The direct testing of the wells maintenance also allows the correct planning of the best methodologies for a groundwater sampling and the use of the wells for the monitoring of the main parameters: temperature, hydraulic head, electrical conductivity.

2.1.2. Hydrogeochemical characterization

The possible recharge of the shallow aquifers by the artesian ones through abandoned wells should produce variations to their chemical pattern, their isotopic content and physical parameters caused by a combination of different kinds of waters (Bortolami et al., 1973a).

Therefore both hydrogeochemical and isotopic studies can be undertaken as a useful means in order to describe the stratified aquifer layers at different depths.

The whole data could then be managed in a GIS environment (see chapter 8) through a geo-statistic analysis for the creation of thematic charts and classification and correlation diagrams which could allow the identification of migration phenomena, dispersion and diffusion of different waters.

<u>Isotopic analysis</u>

Altitude, latitude and seasons directly influence the fractioning of $\delta^{16}O$ and $\delta^{18}O$, deuterium and protium. In order to better explain the concept, let us follow an imaginary rain drop from when it actually falls; according to the height and latitude of the area in which it filters well defined isotopic values (seasonally variable) may be recorded, thanks to a vast network of monthly monitoring managed by Vienna's IAEA for many years (IAEA/WMO, 2007).

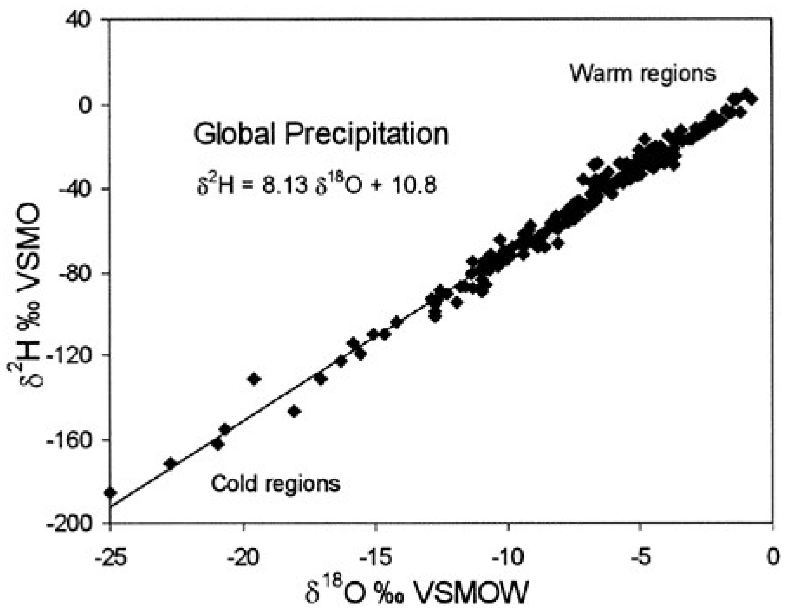


fig. 15: Isotopic plot of groundwater and rainwater (Clark *et al.*, 1997).

The raindrop with its fully defined isotopic values falls to the ground; if it filters directly they will be preserved in the water particle throughout its journey inside the layer, independently from any chemical transformation it may sustain.

The isotopic contents therefore clearly mark the recharging area of the groundwater detected in some layer downstream. On the contrary if the particle does not filter directly but rather streams superficially, or stays on the surface for a long time, it undergoes evaporation processes that will alter its isotopic values (Tazioli et al., 2005).

The isotopic content detectable in the groundwaters can also be exploited as a chemical tracer, therefore allowing the validation of a mass transportation model. The comparison between numerical simulation of the flow and dispersion of a few isotopes (e.g. deuterium) with experimental measurements allows a good calibration of the same model (Reynolds et al., 2007).

The sampling phase, analysis and interpretation represent very tricky phases that require great precision and attention, especially in the difficult context of the study area in which there should be a groundwater vertical flow, a highly contaminated superficial hydrogeological system and a possibly precarious maintenance of the old wells.

Oxigen 18 and Deuterium

In the hydrogeological context the study of both the stable oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) isotopes in the water particle has a special importance as it holds the groundwater "history". The values of both $\delta^{18}O$ and $\delta^{2}H$ in a rainfall are strictly influenced by the season, latitude and altitude of the recharging areas of the different aquifer layers (fig. 15).

As regards this study case oxygen and hydrogen isotopic composition in deep layers should be suitable to a recharging basin mainly of a mountainous or piedmont type, therefore sufficiently differentiable from the one of more superficial waters locally recharged (tab. 2).

Tritium

Tritium ($\delta^{3}H$) is an unstable isotope of hydrogen: it develops in the atmosphere because of cosmic radiation. The decay is of 4500 days (12,32 years): the reference measurement is tritium ($1\ U.T. = 10^{-18} H/T$where H is the isotope $\delta^{1}H$ more common than hydrogen, with the 99.984%).

Once it filters underground, there are fewer tritium supplies and therefore its concentration diminishes in time.

Very low tritium levels (1-3 UT) mark groundwaters that have been underground for a long time, whereas higher values (9-13 UT) are distinctive of a very short time (a few months). In groundwaters (in confined aquifers) for over 10 years, the tritium values dissolve.

Higher levels (above 16 UT) confirm outside sources of tritium: therefore this isotope is often used as a tracer tab. 2 in environmental studies on landfills.

The shallow groundwater dispersion in deeper ones, necessarily alters the rate of matching tritium.

Once the reference range in shallow aquifers is identified, the incidental dilution with deep aquifer layers would support the theory of an interconnection between deep artesian aquifers and superficial ones.

Chemical analysis

Together with water samples for isotopic analysis it is also possible to anticipate sample-taking for chemical analysis in order to achieve a more complete hydrogeochemical identification (tab. 1).

CATIONS	ANIONS
Ca^{2+}	SO_4^{2-}
Mg^{2+}	Cl^{-}-
Na^{+}	CO_3^{2}
K^{+}	HCO_3^{2-}

tab. 1: cations and anions for hydrogeochemical analysis.

The analysis of each monitored aquifer can be included in a classifying Piper diagram or in any other means of graphical data representation: in this diagram cations and anions are represented by separate ternary plots. These two diagrams are plotted in a diamond diagram that defines the hydrogeochemical facies of the water sample.

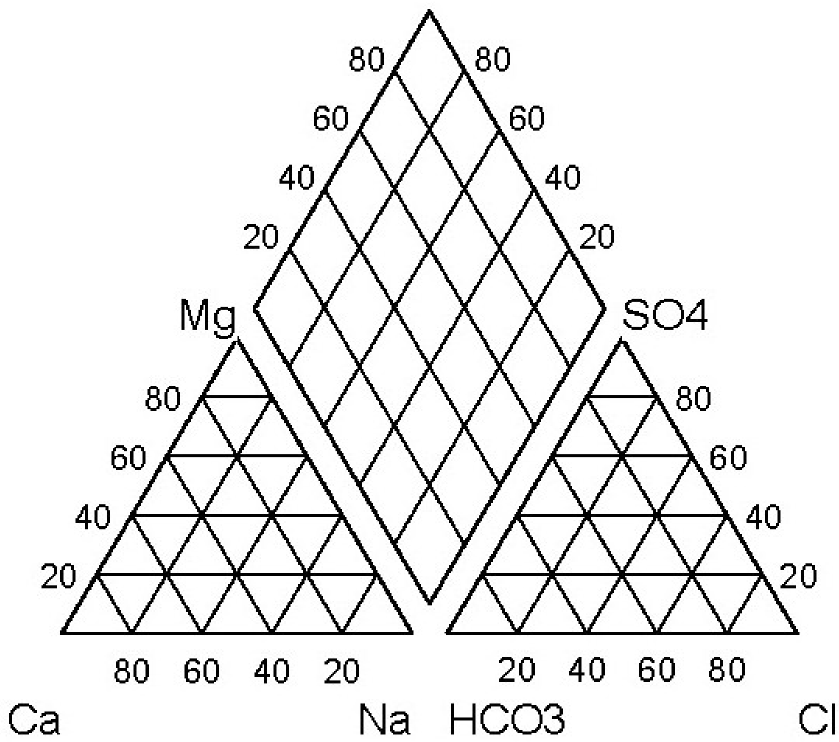


fig. 16: Piper diagram (Piper, 1953)

The study of this kind of chart helps to identify both incidental dispersion and dilution. It is also possible to achieve information on the quality and features of the various groundwaters from a hydrogeochemical point of view.

2.1.3. Continuous monitoring

The continuous monitoring (at least a year) both of the Artesian Aquifer System and the Shallow Aquifer System is believed to be useful for the identification of a possible interference between hydrogeological regimes. This monitoring has to be spread to more deep wells and to more nearby piezometers.

The trend of the piezometric oscillations of an aquifer (hydrogram) directly depends on:

- Recharging typology;
- Distance from the recharging area;
- Aquifer type;
- Aquifer dimensions.

The superficial aquifers usually show hydrograms with high frequency fluctuations, moderate amplitude and impulses linked to often extremely obvious weather events: in the example in fig.

17 these impulses are marked by the continuous black line which shows high frequency fluctuations.

The layers set in deep aquifers are usually characterized, during a hydrologic year, by an absolute maximum and minimum and a relative maximum and minimum (marked by the red circles in fig. 17). The impulses linked only to local meteoric events are less recognizable

In this study case the analysis of the different hydrograms confirms a recharging from deep aquifers that alters the general trend of the shallow aquifer hydrograms.

In the example in fig. 17 it is shown how the maximums and minimums recorded in the artesian aquifer (the bold continuous blue line) could control the basic trend of the shallow aquifers (continuous black line) on which low fluctuation influences produced by weather events are introduced.

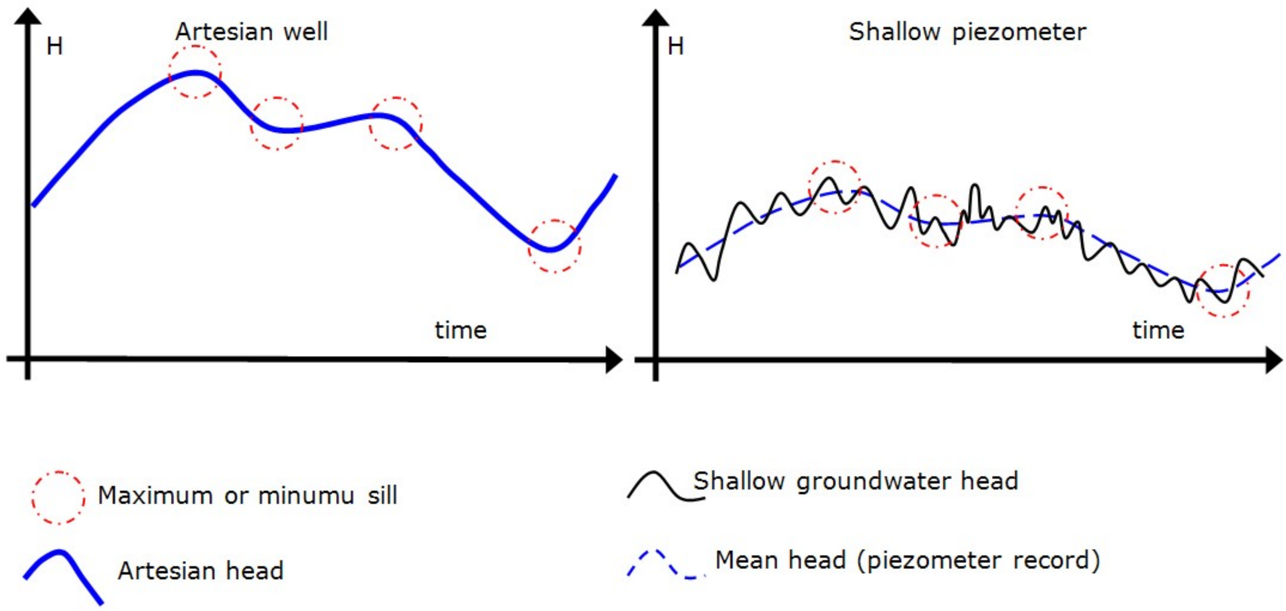


fig. 17: example of a comparison between hydrograms with different hydrogeological regimes.

These hydrograms can be related to:

- lagoon fluctuations of the tide;
- pluviometries;
- barometric pressure;
- eventual hydrograms available in different areas.

2.1.4. Aquifer tests

In an artesian flow, the coating of a well that is not complete in its upper part allows the shift of fluids from deep aquifers to superficial ones and viceversa. In this situation the piezometric level of the shallow aquifers is influenced by the effects produced by the depression or pressurization induced in deep wells (Theis, 1935).

During the progress of the extraction or injection test the possible stresses in the shallow aquifers must be monitored in the control piezometer through a pressure sensor registering the continuous variations.

This methodology can be applied by adapting to the specific instance the use of tracer tests (Chesnaux et al., 2006); this methodology should be studied carefully as up to now it has concerned problems very different to these, that is when the lower aquifer is closer to the shallow one unlike what is studied in this paper (fig. 18).

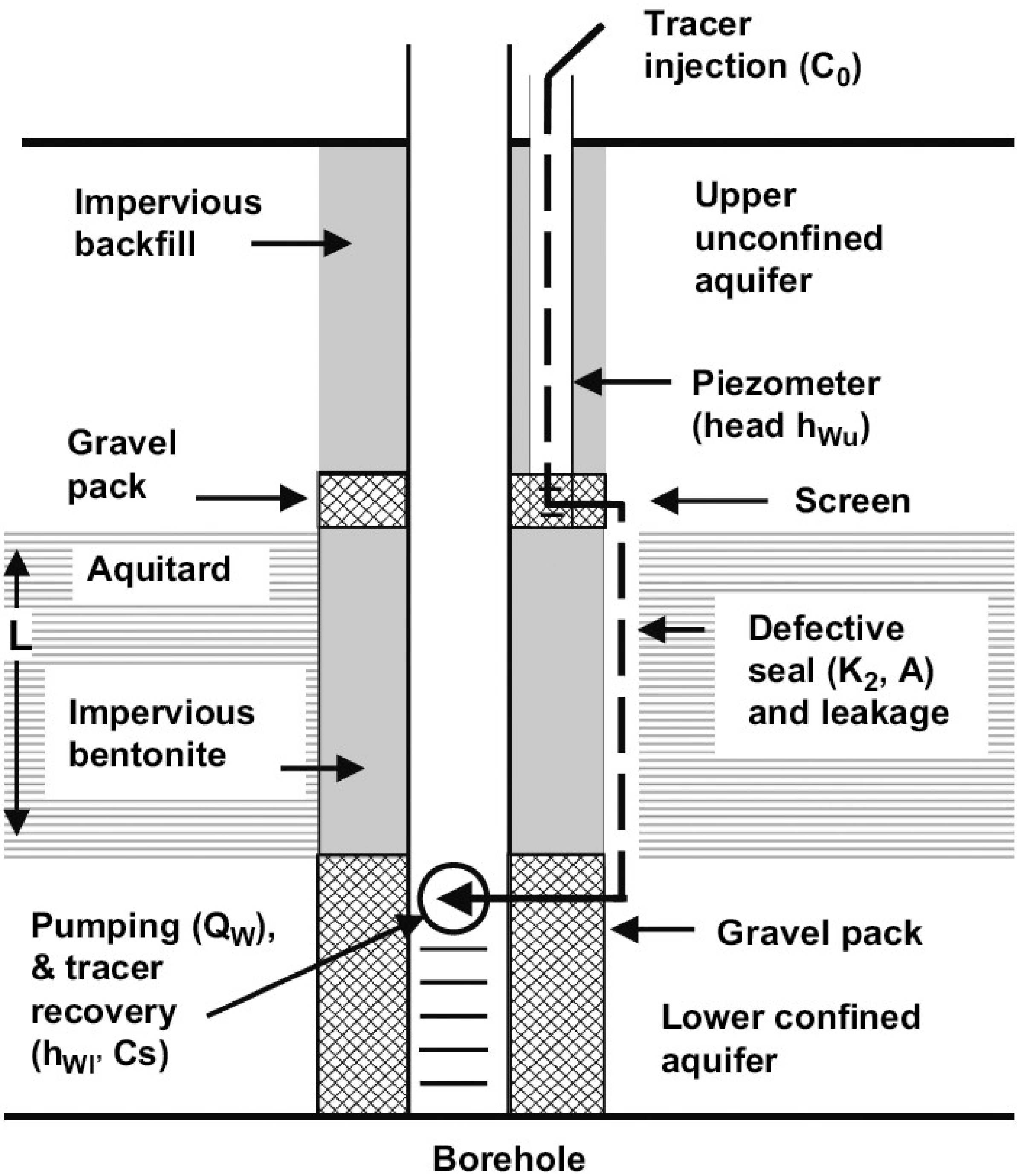


fig. 18: instrumentation to detect and characterize a hydraulic short-circuit (Chesnaux et al., 2006)

3. VE-1 HYDROSTRATIGRAPHIC MODEL

In reply to the worsening of the land subsidence problem in Venice, increased by the water withdrawal from the deep artesian aquifers (100-400 m), in 1971 the CNR directed the creation of the Ve-1 well (see paragraph 1.1). This well was core drilled to a depth of 951 m below ground level on the Tronchetto peninsula (Venice); in this occasion also laboratory analysis were carried out on samples, hydrogeological tests, geophysical logs.

The survey's aim was to achieve the necessary geological, geotechnical and hydrogeological information in order to learn more about the subsoil (Chierici, 1971a; Chierici, 1971b; Chierici et al., 1971; Consiglio Nazionale delle Ricerche, 1971; Favero et al., 1971; Frassetto, 1971; Gatto et al., 1971; Mazzini, 1971; Roccabianca, 1971).

Following the data gathered through the Ve-1 core drilling and the full drilled holes in Marghera and the Lido di Venezia, a new hydrogeological model was developed. Some of the stratigraphies deducted from the full drilled holes were analysed in order to complete the whole hydrogeological pattern (Gatto, 1973).

The suggested model adopted in the Seventies (fig. 19) was employed in order to study and foresee the consequences linked to land subsidence acceleration (Gambolati et al., 1975; Gambolati et al., 1974a; Gambolati et al., 1974b).

The purpose of both this model and the following reviews was the development of a representative scheme of the different artesian aquifers, in order to apply the necessary numerical methodologies to the vertical ground displacement (Teatini et al., 1993; Teatini et al., 1995).

More in depth recent studies on the Ve-1 core drilled well have suggested the use of the most up to date environmental studies of a stratigraphic, pollinic, magnetostratigraphic, mineralogical, sedimentological, environmental type for a further review of the hydrogeologic series (Brambati et al., 2003; Kent et al., 2002; Massari et al., 2004; Mullenders et al., 1996; Stefani, 2002; Teatini et al., 1995).

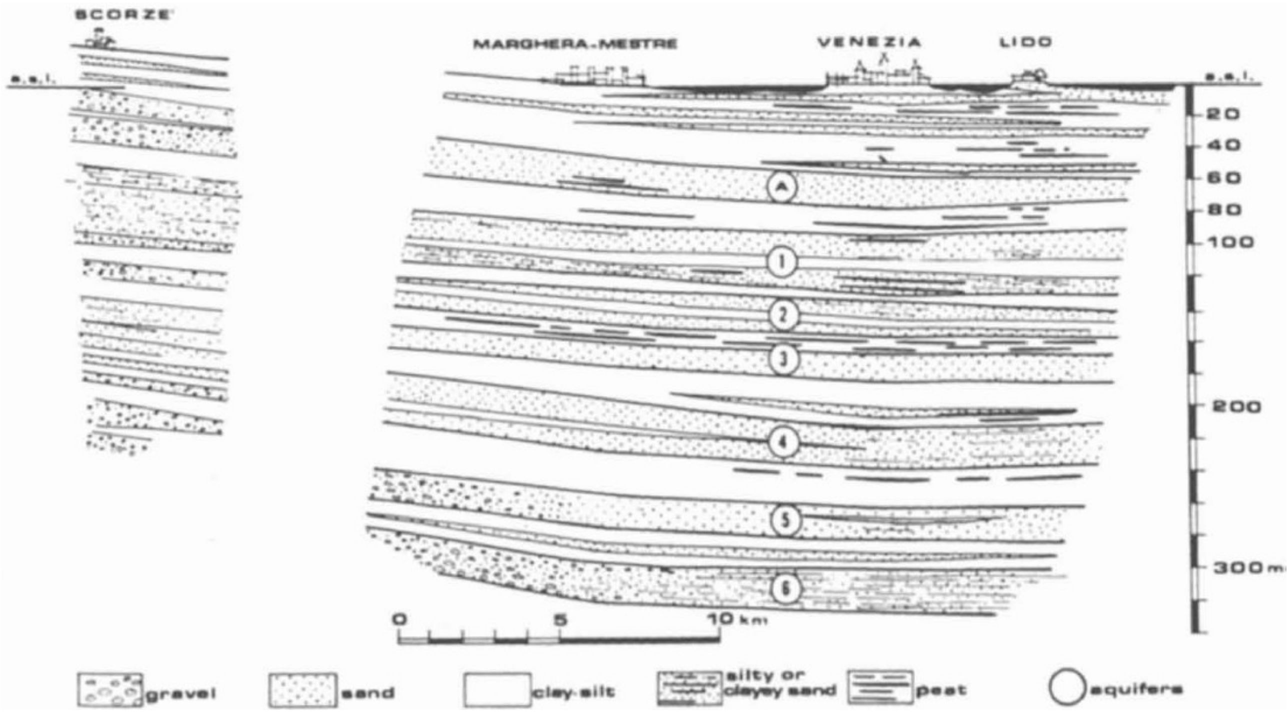


fig. 19:litohstratigraphy section of '70 (Carbognin *et al.*, 1976; Gambolati *et al.*, 1974a; Gatto, 1973; Gatto *et al.*, 1981)

3.1.1. Marine Isotopic Stage of the Venetian area

In support to the stratigraphic analysis, the Ve-1 core was studied in order to identify the various marine isotope stages registered in the Venetian area (Massari et al., 2004; Mullenders et al., 1996).

The MIS (Marine Isotope Stages), also defined as OIS (Oxygen Isotope Stage), is a succession of hot and cold periods in the terrestrial paleoclimate, deduced from the oxygen isotope data (fig. 20); this data shows the temperature curves achieved by the analysis of ocean floor samples (Lisiecki et al., 2005).

The analysis of the chronostratigraphic successions can be correlated to the results achieved with the radiocarbon methodology and the pollinic studies (Mullenders et al., 1996). Some correlations have been suggested between the MIS curves and those taken from the core of the Ve-1.

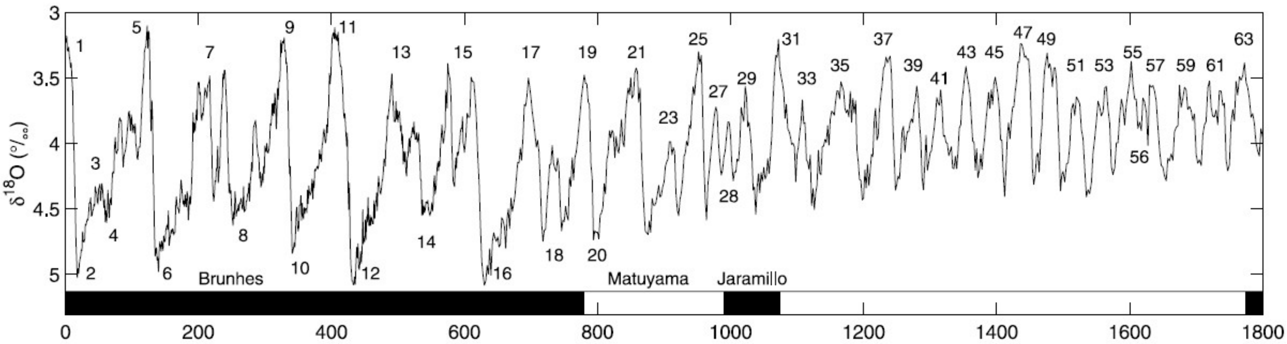


fig. 20: variation of the O18 content in the last 1.800.000 years; the higher the percentage of $\delta^{18}O$, the lower the global temperature (Lisiecki *et al.*, 2005)

3.1.2. Depositional facies of Ve-1

The recent geological history of the Venetian area has been reconstructed starting from the Gelasian, fig. 17.

SYSTEM PERIOD	SERIES EPOCH	STAGE AGE	AGE Ma
Quaternary	Holocene		0.012
	Pleistocene	Upper	0.126
		"Ionian"	0.781
		Calabrian	1.806
		Gelasian	2.588
Neogene	Pliocene	Piacenzian	3.600
		Zanclean	5.332
	Miocene	Messinian	7.246

fig. 21: sketch of the International Stratigraphic Chart of the International Commission on Stratigraphy of IUGS (2008).

The stratigraphic succession of the Venetian area is divided both into five lithostratigraphic units and different depositional areas (fig. 22).

The lower unit (unit V of fig. 24) is made up of sediments that are characteristic of shoreface and self margin type areas (fig. 24). The depositional area is characterised by an extremely subsident self margin which is also influenced by a not very deep sea level. This facies is suddenly interrupted by an unconformity surface: this hiatus is then followed by a lowering of the eustatic level that characterises the late Gelasian and the Lower Pleistocene (unit IV fig. 24) (Massari et al., 2004).

The terrigenous contribution from the Southalpine region produced a series of abundant sediments of turbiditic layers (Unit III fig. 24). The sand samples of these units (from the V to the III) are litharenitic: the population of rocky fragments (lithoclasts, calcareous and dolomitic) denote a typically Northern origin, that is the sedimentary covering of the Southeastern Alps (fig. 24). These petrofacies are very similar to the composition of the sand that characterizes the Piave and Brenta rivers (Stefani, 2002).

CHRONOSTRATIGRAPHY	UNIT	ENVIRONMENT	DEPTH
HOLOCENE UPPER PLEISTOCENE MIDDLE PLEISTOCENE	I	SHALLOW-MARINE TO CONTINENTAL SEQUENCES	288.9
MIDDLE PLEISTOCENE	II	SHELF-TYPE DELTA LOBS DEEP-WATER DELTA	541.1
MIDDLE PLEISTOCENE	III	BASINAL TURBIDITES	768
LOWER PLEISTOCENE	IV	STARVED SLOPE	818
UPPER PLIOCENE (Gelasian)	V	SELF TO SURFACE	949.7

fig. 22: chronostratigraphy, units and environment of Venice area (derived from Massari et al., 2004).

Later the basin area was filled up with a complex series of deltaic sediments: unit II therefore represents the record of the most important phase of deltafront construction (fig. 24 and fig. 25).

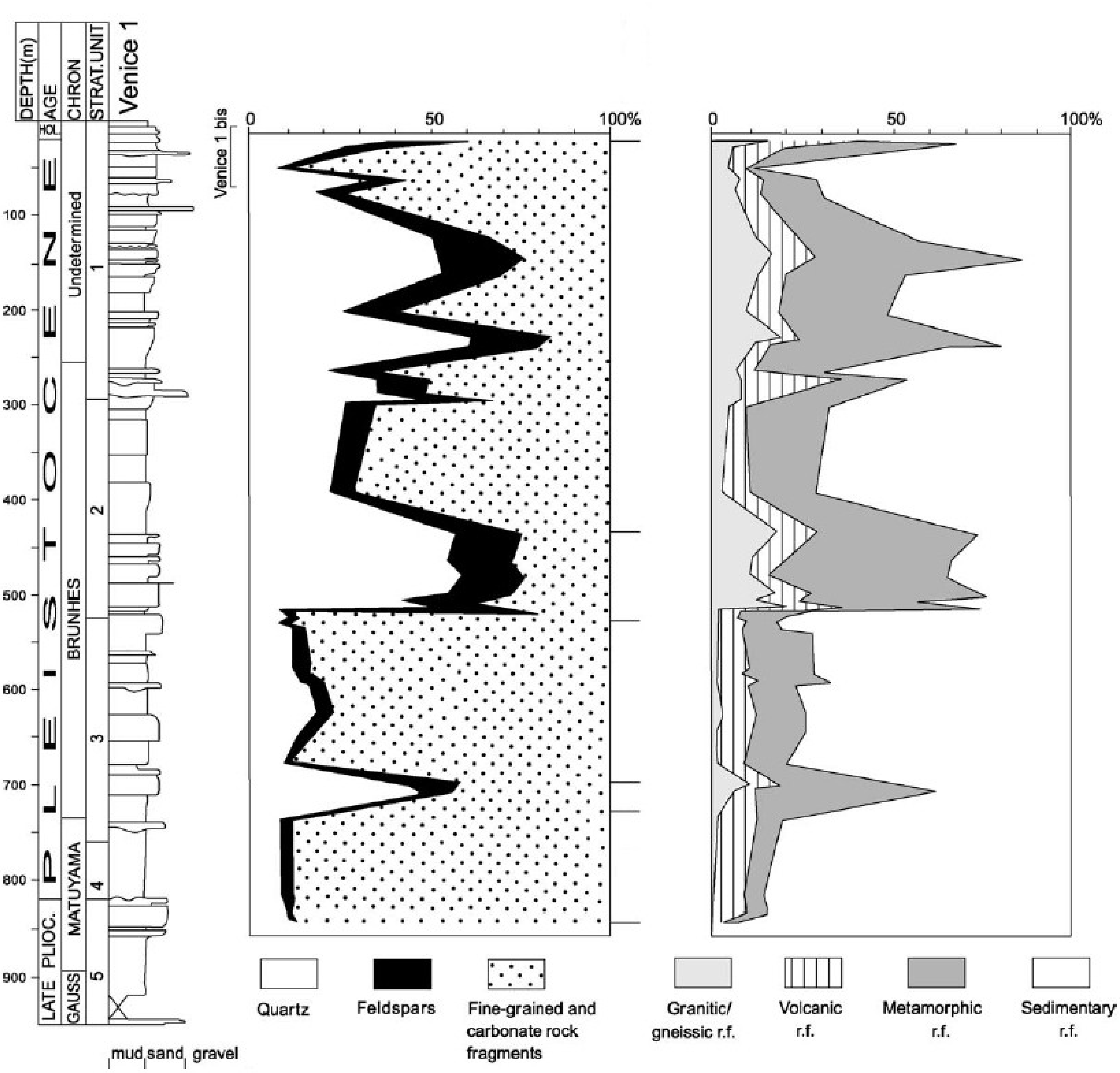


fig. 23: association of petrofacies recognisable along the Ve-1 vertical (modified from Stefani, 2002)

During the middle Pleistocene the terrigenous contribution of the Po river depositional basin is more obvious; this, in fact, is marked by granular sediments that indicate a high tenor in glauconite and quartz: this petrofacies can be found in the lower part of unit II (fig. 23) (Stefani, 2002). The upper interval of the stratigraphic sequence is made up of sands of heterogeneous origin, that is both from the Southalpine and Apennine areas.

Unit I coincides with the first apparition of sediments typical of an alluvial plain. The correspondent stratigraphic succession is therefore made up of an alternated series of marine, coastal, lagoon and fluvial sediments (fig. 25).

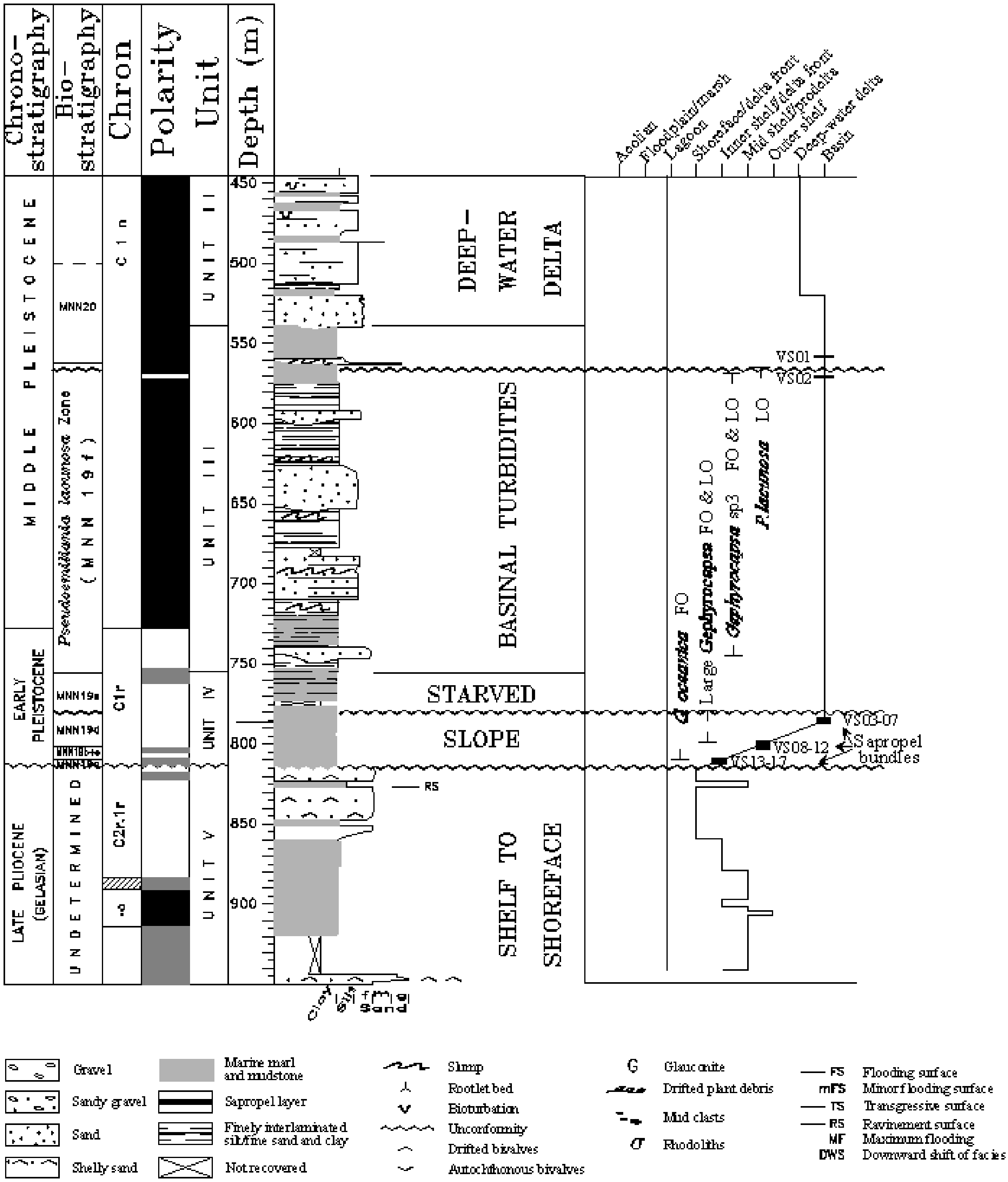


fig. 24: stratigraphy, units from II to V (modified from Massari, 2004)

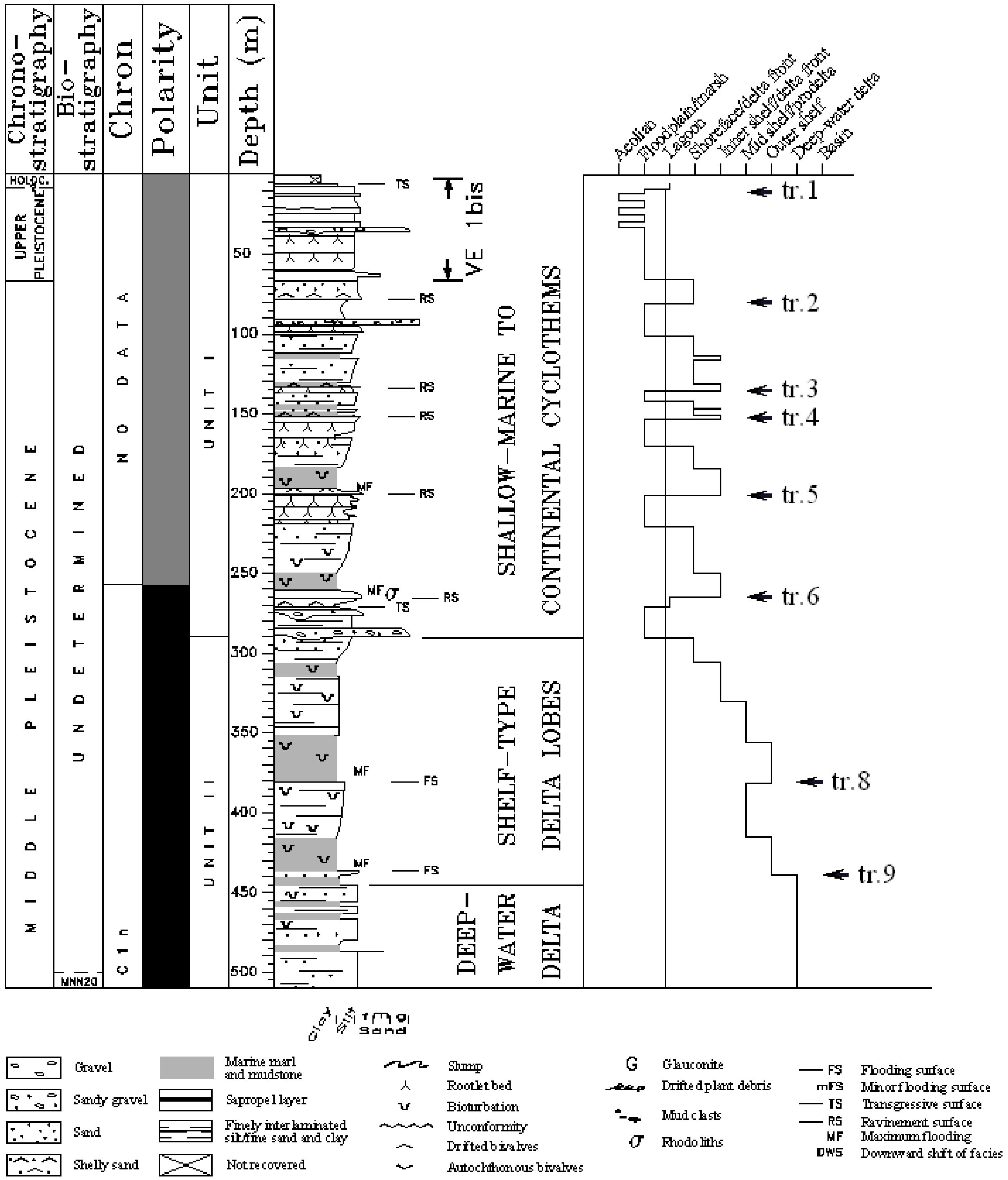


fig. 25: stratigraphy, units I and II (modified from Massari, 2004)

3.1.1. Relative sea level: Transgressive and Regressive cycles (T/R cycles)

As fig. 25 highlights, inside units I and II it is possible to make out a series of 9 transgressive/regressive cycles. These cycles are a direct result of the eustatic variations that involve erosion surfaces of superficial sediments open to subaerial weather agents of one or more sequences.

The long-term subsidence rate (less than 0.5 mm/year) mainly represents the tectonic processes; this subsidence rate is definitely lower as regards to what takes place in the Upper Pleistocene – Holocene, in which the registered subsidence rate is 1.3 mm/year. This increase of subsidence rate basically represents the effect of sediment consolidation (Kent et al., 2002).

3.2. DEEP AQUIFER SYSTEM (DAS)

Starting from the rocky basement, set at over 1000m in depth, alluvial sediments from the erosion of the Alpine chain and later from the Apennine one follow one another (AA.VV., 1990; AGIP, 1976; AGIP, 1987). These represent mostly neritic and pelagic areas from the bedrock to a depth of about 350-400 m, Units from V to II of fig. 24).

During the construction of VE-1 salty waters are signalled from a depth of 570 m (National Research Council, 1971).

Bortolami et al (1973) assume the supply area of these aquifers to be basically different from the above ones, as seems to be confirmed by the isotopic studies which took place at the beginning of the Seventies: below 445 m in depth the $\delta^{18}O$ content shows values of $\approx -8‰$ as regards to the SMOW (Standard Mean Ocean Water) (IAEA/WMO, 2007), versus $\approx -10 - 12‰$ of the above aquifers (tab. 2) (Bortolami et al., 1973a; Bortolami et al., 1973c; Fontes et al., 1973).

Depth	°C	HCO_3	CO_3	$\delta^{14}C$ %	$\delta^{13}C$ ‰	$\delta^{18}O$ ‰
445		1510	22			-10.4
627	22.8	525	24			-8.2
816	27.1	1537	18	2.6 %	-2.9	-8.9

tab. 2: isotopic and chemical data of Ve-1 in mg/l (Bortolami *et al.*, 1973c)

The grade in $\delta^{14}C$ suggests very remote ages (not assessable) (tab. 2); the infiltration degree evaluated through the $\delta^{18}O$ analysis, suggests a high up recharge area, which can be identified with the Alpine one in Adige where mean heights of 1630 m can be observed (alpine area) (Bortolami et al., 1973c).

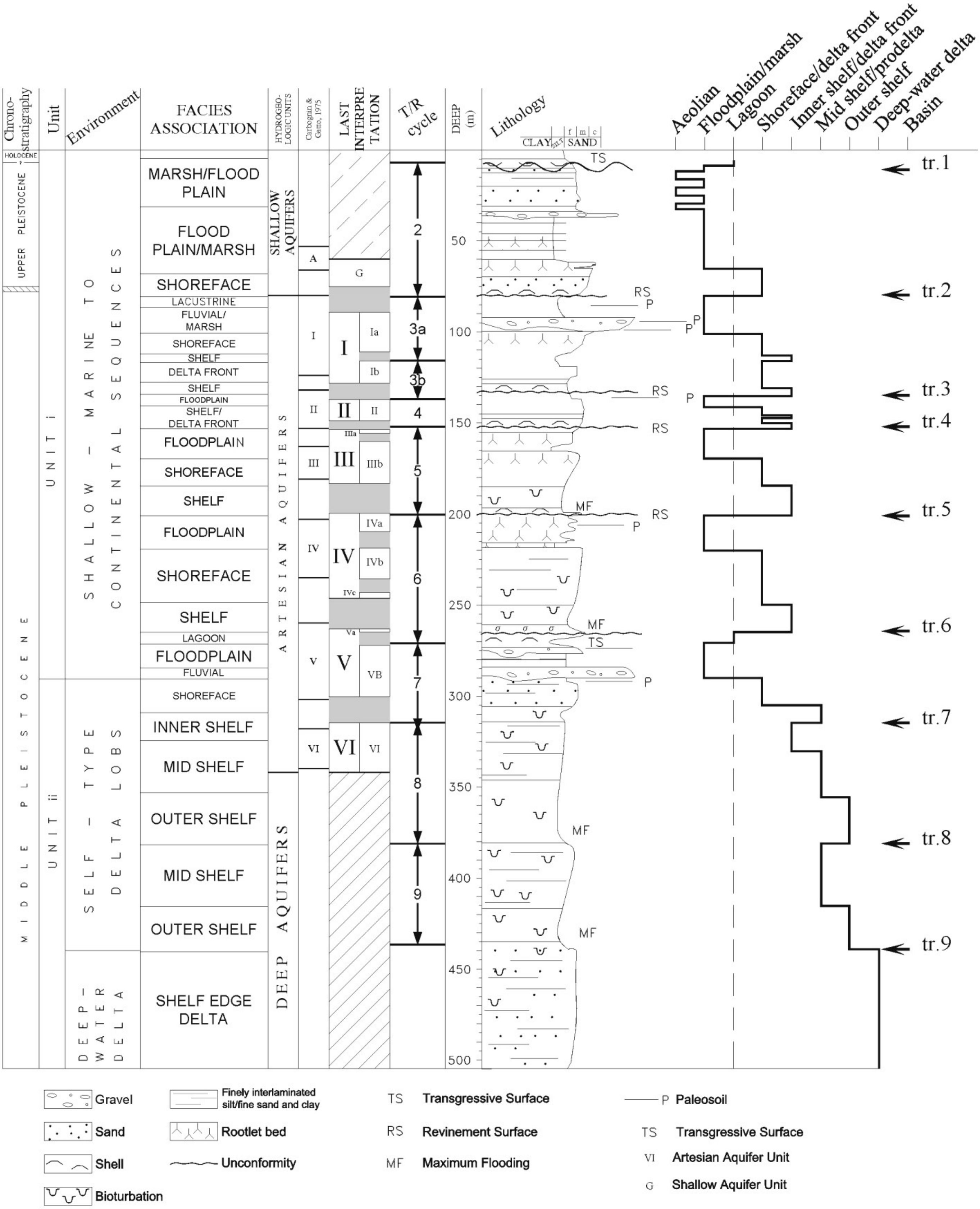


fig. 26: hydrostratigraphy of Ve-1 core.

3.3. ARTESIAN AQUIFER SYSTEM (AAS)

The AAS (Artesian Aquifer system) is placeable between 350 and 89.0 m in depth and is characterised by sweet water (Consiglio Nazionale delle Ricerche, 1971). Other wells drilled in the lower plain for explorative purposes denote the presence of fresh waters in the same intervals observed in the Venetian area (fig. 26) (AA.VV., 1990; AGIP, 1976; AGIP, 1987).

The facies analysis carried out by the various authors in units I and II of fig. 25, also allows the organization of the hydrogeologic properties, for instance the shoreface facies are often associated to medium or fine sands, locally glauconitic, with sedimentary structures associated to the effects produced by wave-motion. Therefore the associable sediments denote both a high porosity and permeability.

On the other hand the self margin areas are characterized by mainly pelitic sediments; this type of facies can therefore be associated to low hydraulic conductivity in sedimentary levels.

3.3.1. Aquifer VI (342-315 m) - Sequence T/R 8

The collocation of the VI aquifer along the core sequence of the Ve 1 - CNR fundamentally coincides with the one suggested by the authors in the Seventies (fig. 26) (Carbognin et al., 1975; Carbognin et al., 1974; Gatto, 1973).

Compared to the MIS, the sediments characterising aquifer VI are contemporary to the MIS 8.

The lower limit is set at 342 m in depth, below which granulometry gradually diminishes.

The lithology is made up of silt with often bioturbated millimetric sand bands that decrease in frequency towards the bottom.

The higher limit (315 m) is established by the ending of the transgressive/regressive 8 (T/R 8), defined by tr 7 transgression. In this case the transgressive phase is less obvious as the environment is chiefly marine (inner shelf – prodelta) and a eustatic rise does not produce particularly significant local variations (fig. 26).

The definition of this superior limit is also highlighted by a progressive decrease of electrical resistivity towards the top, as a proof of the increase of the thinner granulometric fraction, as suggested by the clayey laminations that in this stretch alternate with silt sediments (Alberotanza et al., 1974).

3.3.2. Aquifer V (300 – 263 m) – Sequences T/R 7-6

After the tr.7 transgressive phase a regression takes place during which there is a first shift from a marine environment (shoreface/delta front) to a continental one, governed by fluvial sediments at 289 m. This event marks the shift from unit II to unit I and is set at about 0.266 Ma (MIS 8.4) (Massari et al., 2004).

The aquifer is between transgression tr.7 and transgression tr. 6, in the T/R 7 cycle (fig. 22).

Aquifer Vb (300 – 272 m) - Sequence T/R 7

The base of the Vb aquifer is set at 300 m between sediments mostly made up of silt and the above bodies with sand granulometry; from 300 m alternations of 1-5 mm laminations of fine sands alternated to silts take place. The incidence of gravel sediments belonging to a fluvial area are to be observed between 287.50 m and 289.68 m; after this level the alternations of medium-fine sand and sandy silt start again. At 276 m a level of various dm of sand with fine gravel can be observed (fig. 26).

The T/R 7 sequence ends with a paleosoil (with transgressive surface) set at 272 m above which the lagoon sediments settled of the above sequence 6: peat and clayey silt with frequent vegetable residues and mollusc shells (fig. 26).

Aquifer Va (265 – 263 m) - Sequence T/R 6

Between 265 and 263 m, above a possible erosive ravinement surface, the core is characterised by bioclastic sands with corallinaceous fragments: this sediment constitutes a very permeable layer that because of the geometric closeness of permeable bodies below has to be set in aquifer V instead of IV (fig. 26).

3.3.3. Aquifer IV (249-200) – Sequence T/R 6

As described above, sequence 6 begins with lagoon deposits above which an hydrogeological permeable layer inserted in aquifer V is set.

At this level mainly silt- clayey sediments follow, with rare fine levels of sand (fig. 26).

Aquifer IV is placed inside T/R 6 and is divided into three subunits (fig. 26).

Aquifer IVc (246-243 m)

Between 243 m and 246 m there is a series of levels with higher permeability, made up of alternations of fine sand and sandy silts, belonging to a prodelta environment (deltafront) (Consiglio Nazionale delle Ricerche, 1971).

Aquifer IVb (236 – 218 m)

From 236 m clayey silts start to give way to fine silty sands up to 218.5 m where there are clays rich in vegetable substances that give way to peat, revealing a marshland.

The specific aquifer in these sediments usually shows high hydraulic transmissivity values, chiefly linked to local decimeter levels of medium sand and fine micacea.

The depositional area is typical of a shoreface, in which mainly sand deposits take over.

Permeability measurements carried out in laboratories on core samples drawn between 221.02 m and 221.34 m have shown hydraulic permeability values of 10^{-4} m/s and a total porosity of 31.5 % (Chierici, 1971a).

These are followed by not very permeable clayey and sandy silts in a paleosoil set at 210.00 m (Gambolati et al., 1975; Massari et al., 2004).

Aquifer IVa (210-200)

Above the subsoil at 210 m, the core is characterized by more permeable silty fine sand (fig. 26).

Aquifer IVa is typical of a continental area (Floodplain/marsh) linked to a glacial phase. In these conditions, as confirmed both by geophysical logs carried out in the well and stratigraphic analysis, very frequent alternations between more or less resistive levels can be detected. Therefore many layer alternations with a more or less high permeability take place, as revealed by the laboratory tests.

This aquifer's higher limit is characterised by the Ravinement Surface (RS) coinciding with the tr. 5 transgressive surface set at 200 m, followed by a sandy level up to 199.5 m.

3.3.4. Aquifer III (183 – 154) – Sequence T/R 5

With the tr. 5 transgressive phase the depositional area is represented by shelf deposits as the detected clayey limits prove (fig. 22).

Aquifer IIIb (183 - 165)

Only the eustatic fall linked to a facies downward shift (DWS), that is at a lateral translation of the facies set at 183.5 m sandy silty levels start to appear more often compared to silty sandy sediments. Moving towards the top there is also a granulometry increase (Gambolati et al., 1975).

Starting from 168 m continental type sediments are recorded (incidence of vegetable residues), due to a further regressive impulse connected to a glacial phase (Mullenders et al., 1996), mainly sandy silty up to 165.2 m. Above this level the core is characterised by marshy sediments.

The function of separating aquifer IIIb from IIIa is given to marshy deposits rich in peat and vegetable residues that make up a brief not very permeable length; these sediments are characterised by silty sands, once again interrupted by levels of highly organic content starting from 160.3 m.

Aquifer IIIa (156 – 153.6)

The peat-silt levels stop at 156 m, by a shift to a facies characterised by medium and fine sands with a high permeability that show a limited thickness, as it ends at 153.60 m by a shift to a silty facies with a low sand level (Gambolati et al., 1975; Gatto et al., 1971).

The sequence T/R 5 finishes with an RS set at 152.2 m.

3.3.5. Aquifer II (149 – 137) – Sequence T/R 4

Above the previous RS, equivalent to tr.4, mainly silt sediments with frequent bioturbation traces and shell fragments can be observed. Starting from 149 m sand and silt with a plentiful mica-cea fraction can be recorded up to the paleosoil at 163.9 m.

Aquifer II has been almost entirely inserted into T/R 4.

Permeability measurements carried out in laboratories on a core sample taken from 142.29 and 142.50 m have shown hydraulic permeability values of 5*10-3 m/s and a total porosity of the 40.5 % (Chierici, 1971a).

3.3.6. Aquifer I (128 – 82.0 m) – Sequence T/R 3

Above the paleosoil set at 136.9 m silt-clayey layer rich in vegetable residue, roots, peat up to the RS of 133.33 m can be found.

Aquifer Ib (128 – 116 m) – Sequence T/R 3b

The bottom of aquifer Ib is set at 128.3 m by a permeability increase followed by a facies shift made up of silty sand and sandy silt (Gatto et al., 1971).

The prodelta facies stays the same up to 115.75 m; afterwards the sediments decrease their granulometry as the depositional area, following a transgressive eustatic impulse, is a self, though effects linked to slumps can be locally noticed.

Aquifer Ib is set inside the T/R 3b cycle.

Aquifer Ia (111 – 89 m) Sequence T/R 3a

At 100.1 m a paleosoil can be found above which there are continental fluvial sediments of medium and coarse sand for a few metres. Often sediments with a lower granulometry follow one another. To be observed a level of a few decimetres at 92.2 m made up of coarse and medium subangular gravel, followed by alternations of sandy silt and silty sand up to 89.0 m. Afterwards mainly silty sediments prevail.

Permeability measurements – carried out in laboratories on a core sample taken between 106.20 and 106.38 m – have shown hydraulic permeability values of 6.3*10-3 m/s and a total porosity of the 35.5 % (Chierici, 1971a).

Aquifer Ia is set inside TR 3a.

3.4. SHALLOW AQUIFERS

Afterwards at tr. 2 the eustatic level increases: the Eemian interglacial phase begins. Except for this phase that establishes environmental conditions of the shoreface type, the study area will be chiefly continental.

Aquifer I marks the shift, agreed on in this paper, between the domain of the deep artesian aquifers and the Shallow Aquifers System.

3.4.1. Aquifer G/I (75 - 60 m) Sequence T/R 2

The bottom of aquifer I of the SAS can be placed at 75 m, a level which marks the shift to laminated sandy silts (Favero et al., 1973).

The sandy interval can be closed at 60 m, by the conclusion of the eemian transgression.

This aquifer can be considered as a translational level between the artesian aquifers and the superficial ones, which are not dealt with in this study.

4. HYDROSTRATIGRAPHY OF VENICE AREA

As previously mentioned two environmental problems affect the Venetian area. (1) The subsidence, which has been increasing because of the intensive abstraction of water in the second post-war period; (2) the soil and shallow aquifer contamination.

In order to correctly face these problems, which are decisive factors for the entire Venetian ecosystem, the aquifer system structure must be known in detail. The lithologic data are abundant and of good quality in the first 50 m of deep; over this limit they are much more rare, their distribution is not homogeneous and of poor reliability.

This paper, using the available data, wants to provide a further knowledge of the deeper hydrogeologic domain. For this reason, a simple software package (modalstrata) has been developed to obtain some modal stratigraphies for each selected homogeneous area.

The HVSR (Horizontal to Vertical Spectral Ratio) passive seismic surveys have confirmed the lateral correlations among the sample areas at least for the two main aquifer horizons.

Analysis and comparisons of several previous studies performed on the data related to VE-1-CNR, i.e. the only drilling continuous coring 951 m deep in the interest area, have allowed a satisfactory validation of the proposed hydrogeologic model.

4.1. ANALISYS OF MATTER

A reliable geometric model of the multi-layered aquifer domain is essential for any analytical or numerical approach aimed at the safeguard of the Venetian territory and its groundwater system control.

The previous hydro-stratigraphic models of the studied area gave an useful support to identify the hydrogeological succession (Bortolami et al., 1973c; Carbognin et al., 1976; Carbognin et al., 1975; Carbognin et al., 1974; Gambolati et al., 1974b; Gatto, 1973; Gatto et al., 1981). More recent papers on stratigraphic, climatic, magnetostratigraphic, mineralogical, sedimentological and environmental analysis of the area supplied further interesting contributions for a significant updating of the aquifer system (Brambati et al., 2003; Kent et al., 2002; Massari et al., 2004; Mullenders et al., 1996; Stefani, 2002; Teatini et al., 1995).

The model accepted in the seventies was applied in order to solve the heavy consequences of the Venetian subsoil subsidence strictly connected with groundwater abstraction (Gambolati et al., 1975; Gambolati et al., 1974a; Gambolati et al., 1974b).

The hydrostructural model shown in this paper is aimed to management and prediction studies by flow and/or transport analytical and numerical models.

4.2. MODALSTRATA

In the Venetian Hinterland the stratigraphic data are numerous and of good quality up to 50 m below ground surface (continuous coring drillings), whereas over this limit data are scarce, not homogeneous in distribution and of poor reliability (full hole drillings).

The lithologic sequences coming from several archives, are roughly described and are far from any standard reference (Alberotanza et al., 1972; Dazzi et al., 1994; IRSA, 1972). The use of a non-uniform, subjective language reduces the possibility of a standardization of the available information and consequently prevents a correct analysis of the correlations aimed to the development of a representative hydrostructural model (Allen et al., 2008).

A standard geostatistical approach founded on the spatial continuity analysis by experimental variograms and geostatistic interpolations (e.g. kriging) cannot be developed because of a low number of available data (Cressie, 1993). A stratigraphical analysis based on other statistical descriptors like the mode has been therefore performed. The mode is the modality characterized by the maximum frequency (in the case of a continuous distribution, the mode corresponds to the maximum of this distribution). Unlike average and median, the mode can be used also to study qualitative characters, i.e. characters that can be defined in a sufficiently precise way to allow measurements but that cannot be measured or expressed by a number. In the performed analysis the character is the lithology. The modalities are the labels of the lithological types and the analysis is therefore qualitative or at the limit semi-quantitative.

A MATLAB package, called modalstrata, has been developed to maximise the available information. It is able to provide a single representative stratigraphic sequence of an assigned spatial domain through analysis of the available information.

The studied area has been subdivided in some sub-areas to manage the frequent discontinuity of information. The choosing of sub-areas has been controlled by a geometrical and a numerical criterion: in every sub-area the radius does not exceed 500 m and at least 3 stratigraphic surveys are included (fig. 27).

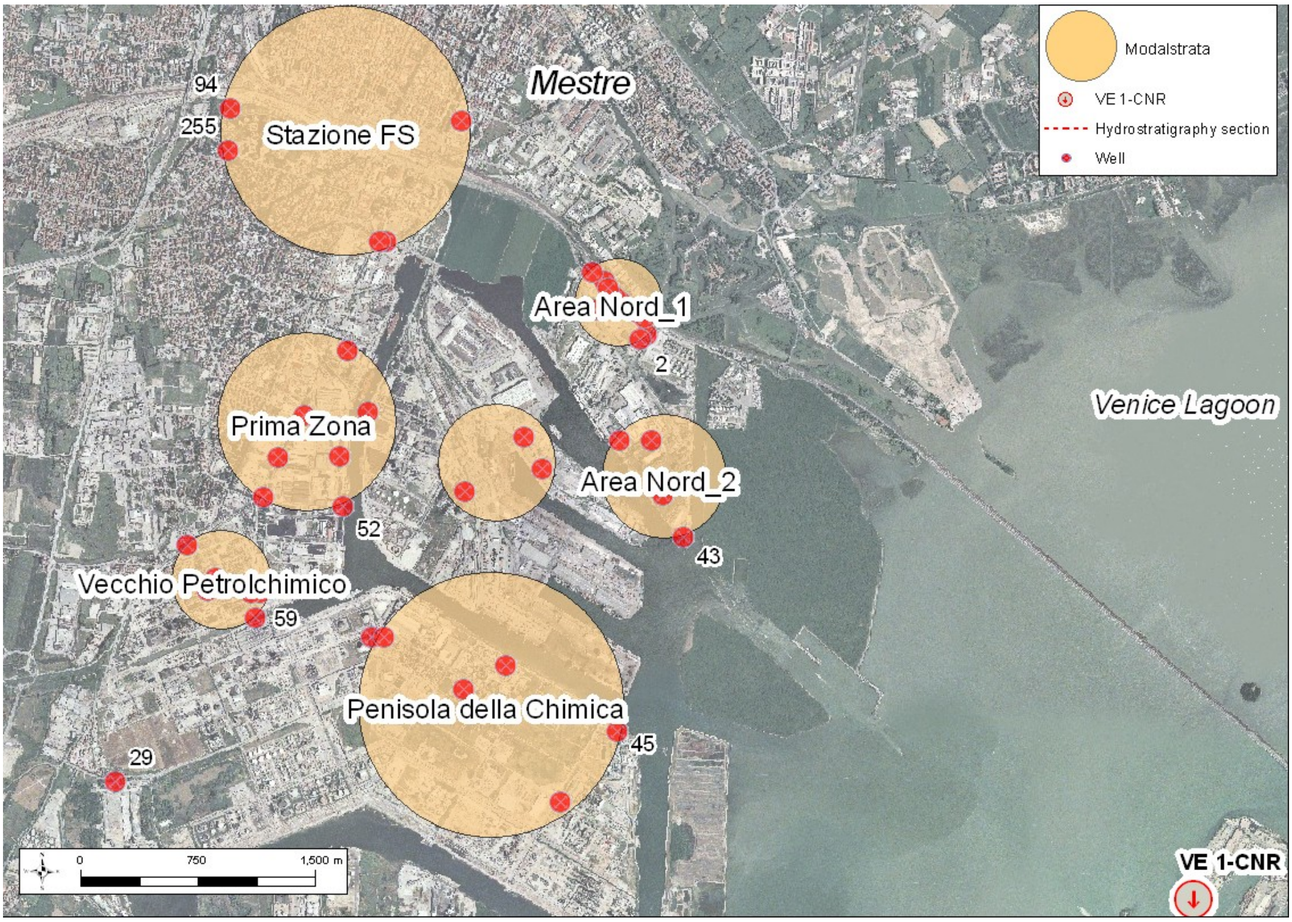


fig. 27: sub-areas for modalstrata.

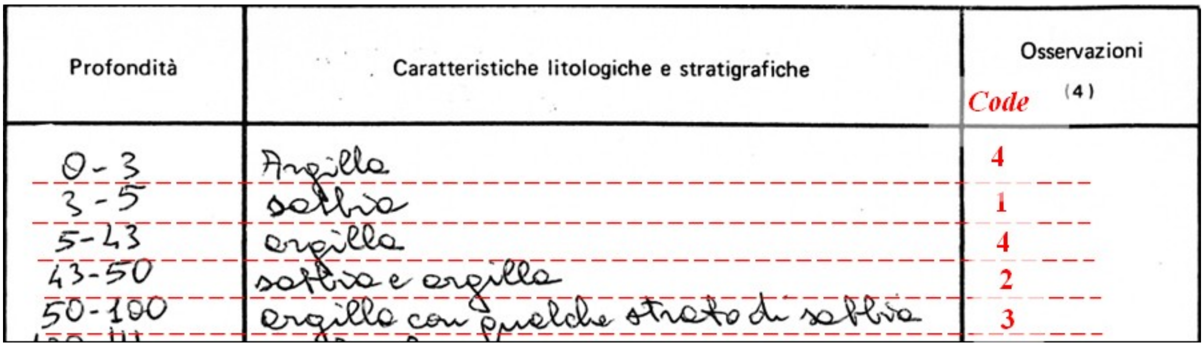
In every single selected sub-area, a fairly lithologic homogeneity can be assumed. The environmental facies are substantially persisting at regional scale, starting from upper Pliocene (Kent et al., 2002; Massari et al., 2004). In particular, starting from middle Pleistocene, the sea level decreased and the platform feature gradually changed into a continental environment in the whole depositional area (Mullenders et al., 1996).

In order to code a new discrete lithologic succession by an analytical procedure, six numerical codes are been assigned to the possible descriptive lithologic types (i.e. lithologic species). A reduction of the number of modalities is therefore obtained (tab. 3). This procedure is aimed to transform continuous inhomogeneous models into a discrete sequence of homogeneous data easily treatable by statistical methods. These codes are labels and therefore their nature is not quantitative. However, there exist a precise order from code 0 (gravel) to 5 (organic soil exists) through sand, clayey sand, clayey silt and silt. In this way, if the distribution is bimodal, its form can be evaluated to allow the choice of the most significant value.

CODE	SINTETIC DESCRIPTION	HYDROGEOLOGIC DOMAIN
0	GRAVEL	AQUIFER
1	SAND	
2	CLAYEY SAND	
3	CLAYEY SILT	AQUITARD
4	CLAY	
5	ORGANIC SOIL	

tab. 3: lithologic codes of quantization

The stratigraphies were coded according to the codes defined in Tab. 3, so that at each level corresponded identified and described a code (see example in fig. 28).



Profondità	Caratteristiche litologiche e stratigrafiche	Osservazioni (4) Code
0-3	Argilla	4
3-5	sabbia	1
5-43	argilla	4
43-50	sabbia e argilla	2
50-100	argilla con qualche strato di sabbia	3

fig. 28: e.g. stratigraphies codes.

In order to obtain the desired modal stratigraphy, a four step procedure, implemented in modalstrata, has been developed. These steps are:

- Preliminary recognition of representative homogeneous sub-areas. The proposed procedure is then carried out for each recognized sub-area.
- Settlement of a initial depth z_0 (e.g. $z_0 = 0$), of a the final depth and of a suitable depth step (Δz).
- For each depth interval (e.g., z_{k-1}, z_k where $z_k = z_{k-1} + \Delta z, k = 0, 1, \dots, nf, z_f = z_f$ verification of the unimodality of the specie distribution. If the distribution is unimodal, the corresponding mode is the stored value. If the distribution is sharply bimodal, since the distribution character has semi-quantitative nature, the median can computed and the mode closest to this median is the stored result is (in order to minimize the effects of possible large but not significant tails, the median is used instead of the average). This operation is performed in automatic way assuming that two frequencies are equal is their difference is within the interval 15%. However, in

order to provide useful information about the validity of the automatically chosen value, in all the bimodal cases the corresponding histogram is shown.

- Graphic visualization and exportation of results.

fig. 29 shows the modalstrata dialog window.

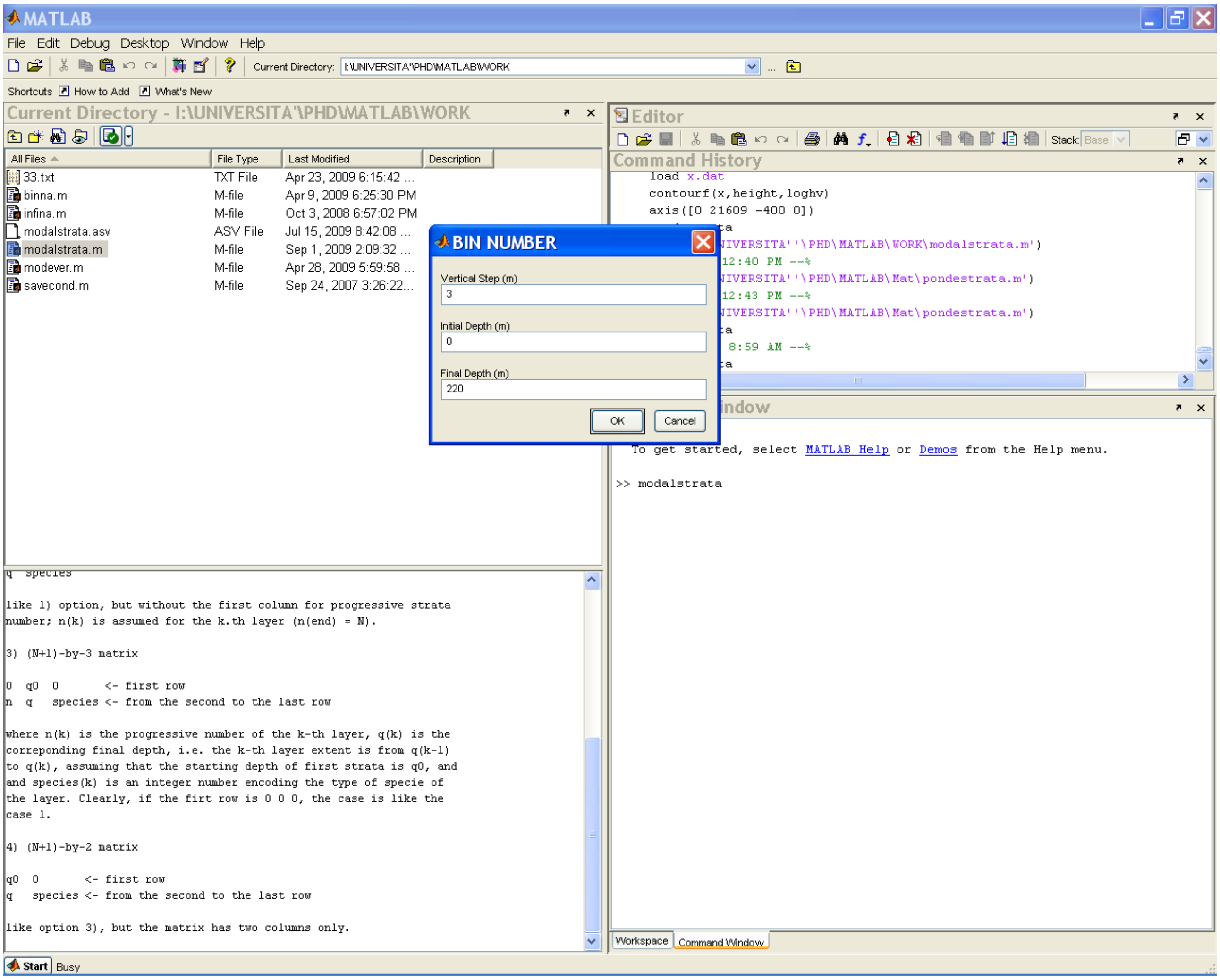


fig. 29: dialog window of modalstrata

The proposed approach, in particular its implementation through modalstrata package, can be directly used in each similar environment. No significant changes in the procedures are necessary. In the particular case study, after the fine tuning of the procedure, the statistical analysis of the data for each well log has required few seconds on a common PC (CPU dual-core 2.6 Ghz, RAM 2 Gb).

4.3. THE SUPPORT OF THE PASSIVE SEISMIC EXPLORATION

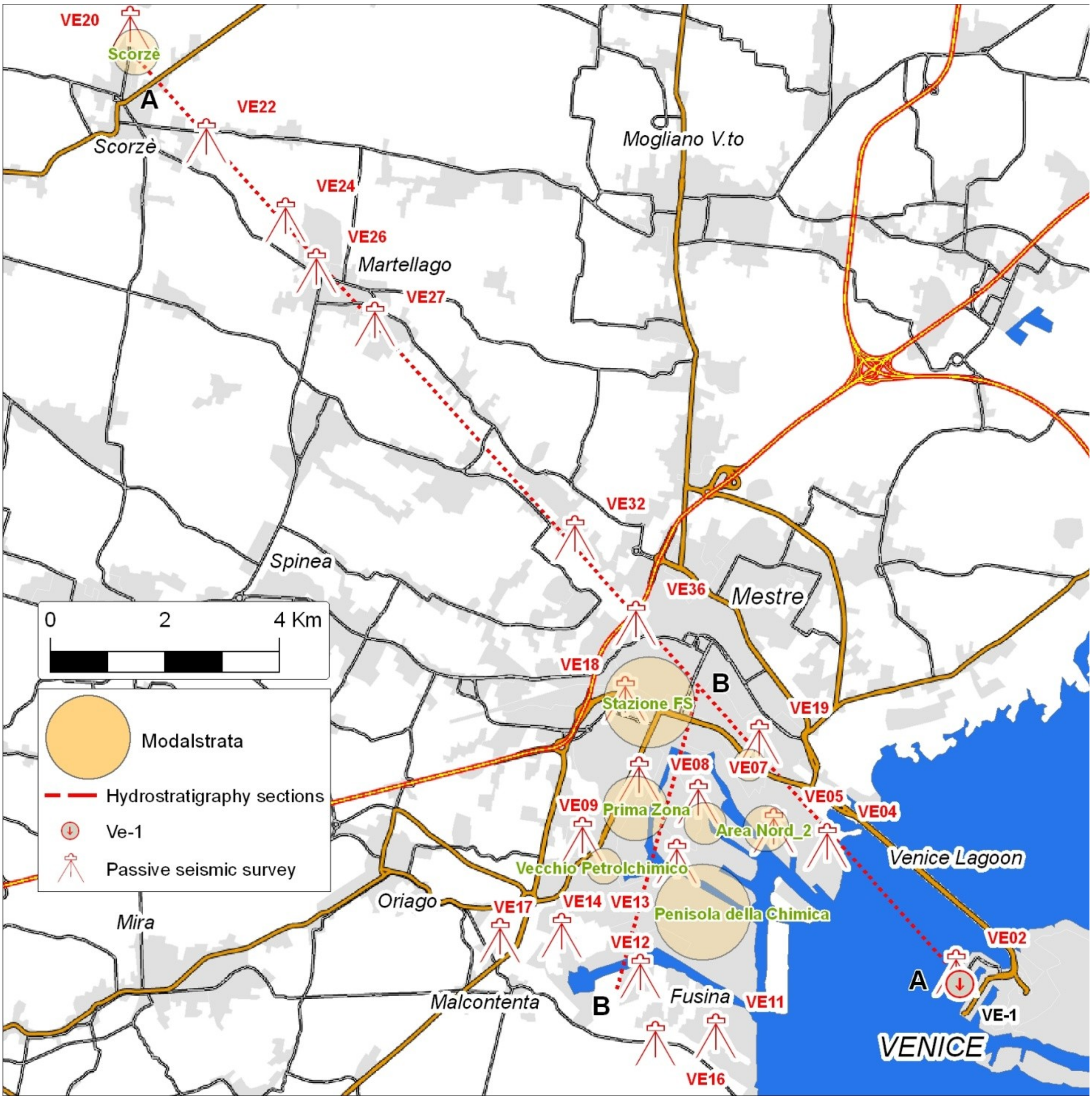


fig. 30: seismic passive surveys, sub-areas and sections line.

In the areas where data are more dense the modal stratigraphic sequences have allowed a fairly good hydrogeological identification. Nevertheless, there are wide zones where data are not enough. A passive seismic survey has been achieved to verify the lateral continuity of the main aquifer units in the entire study area (fig. 30) by means spectral ratio technique (Castellaro et al., 2005). The seismic tremor recordings have been acquired with the digital tromograph TROMINO (www.tromino.it), which is particularly suitable for these applications (fig. 31).

The seismic engineers often use this instrument for an estimation of resonance frequency of soils. Thanks appropriate constrains, this technique allows to obtain a seismic shear waves profile of subsoil (Castellaro et al., 2009b). In this paper these rules will be applied for stratigraphic purposes (Amorosi et al., 2008).

The natural seismic noise surveys have been recorded in 21 sites located in the most reachable areas where the possible inversion of H/V signal could be limited (fig. 30). This inversion is generally due to anthropic structures as filling material, urban area etc., such inversions of H/V ratio can reduce the resonance frequency magnitude (Castellaro et al., 2009a).

The recordings have been extended on an average time interval of 40 minutes instead of 20 minutes for the standard passive seismic measures. This time recording extension provides a better sampling of the lowest frequencies.

The acquired data via Single Station are later drawn by software Grilla, to check the resonance frequencies and to develop a seismic model (fig. 31). To process the model of ratio spectral H/V a known reference like the Vs of first seismic layer or the deep of a seismic reflector available in H/V curve is necessary.

In the studied area the Vs deduced from adjacent seismic models were well known, moreover the first aquifer deep on the entire lagoon area is located at about 80 m from the ground level.

As e.g., the spectral HV ratio recorded at site Ve-02, near the continuous coring drilling Ve-1 (fig. 30), allows to identify a reflector sequence in which those probably pertinent to aquifer I and IV are highlighted (fig. 31).

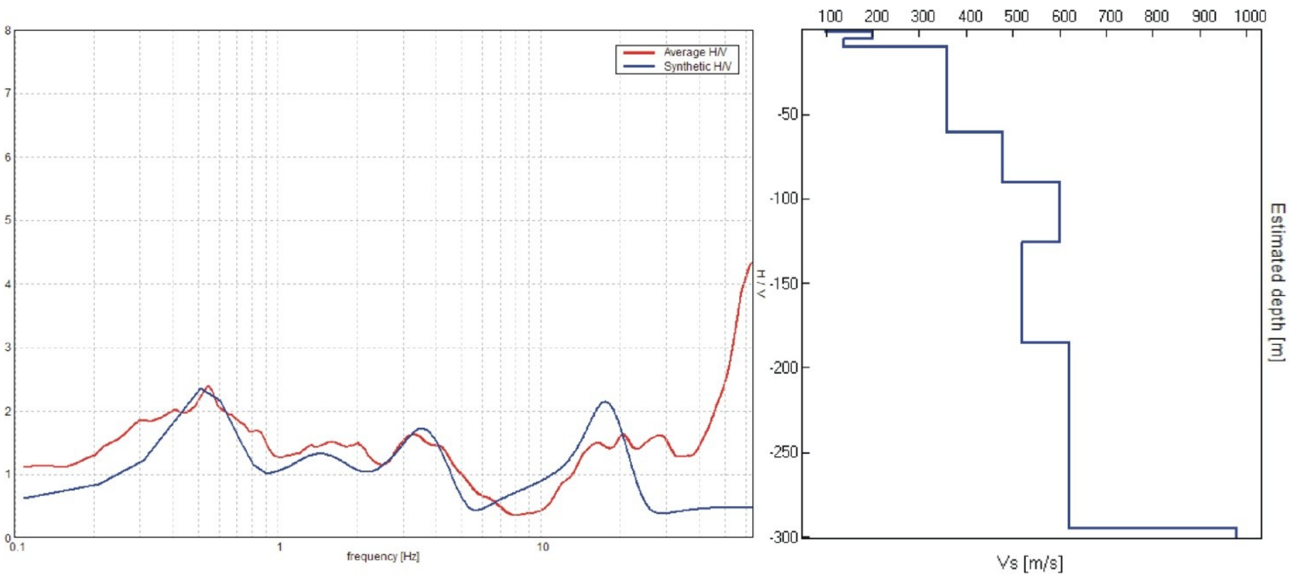


fig. 31: Tronchetto island (Venezia): model of seismic data; seismic reflector are at 79.5 m (I aquifer) end at 179.5 m (IV aquifer).

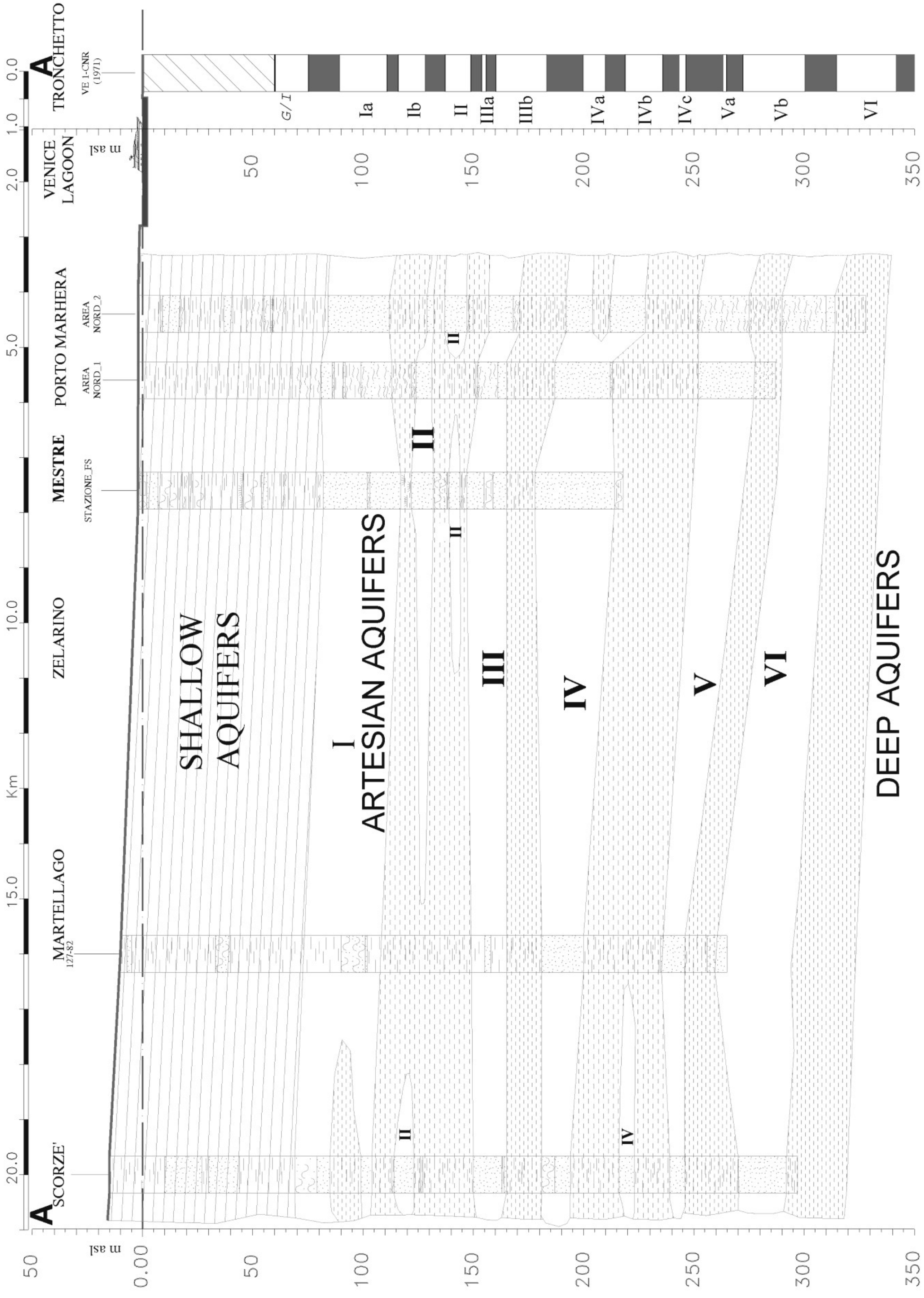


fig. 32: hydrostratigraphic section AA of fig. 30.

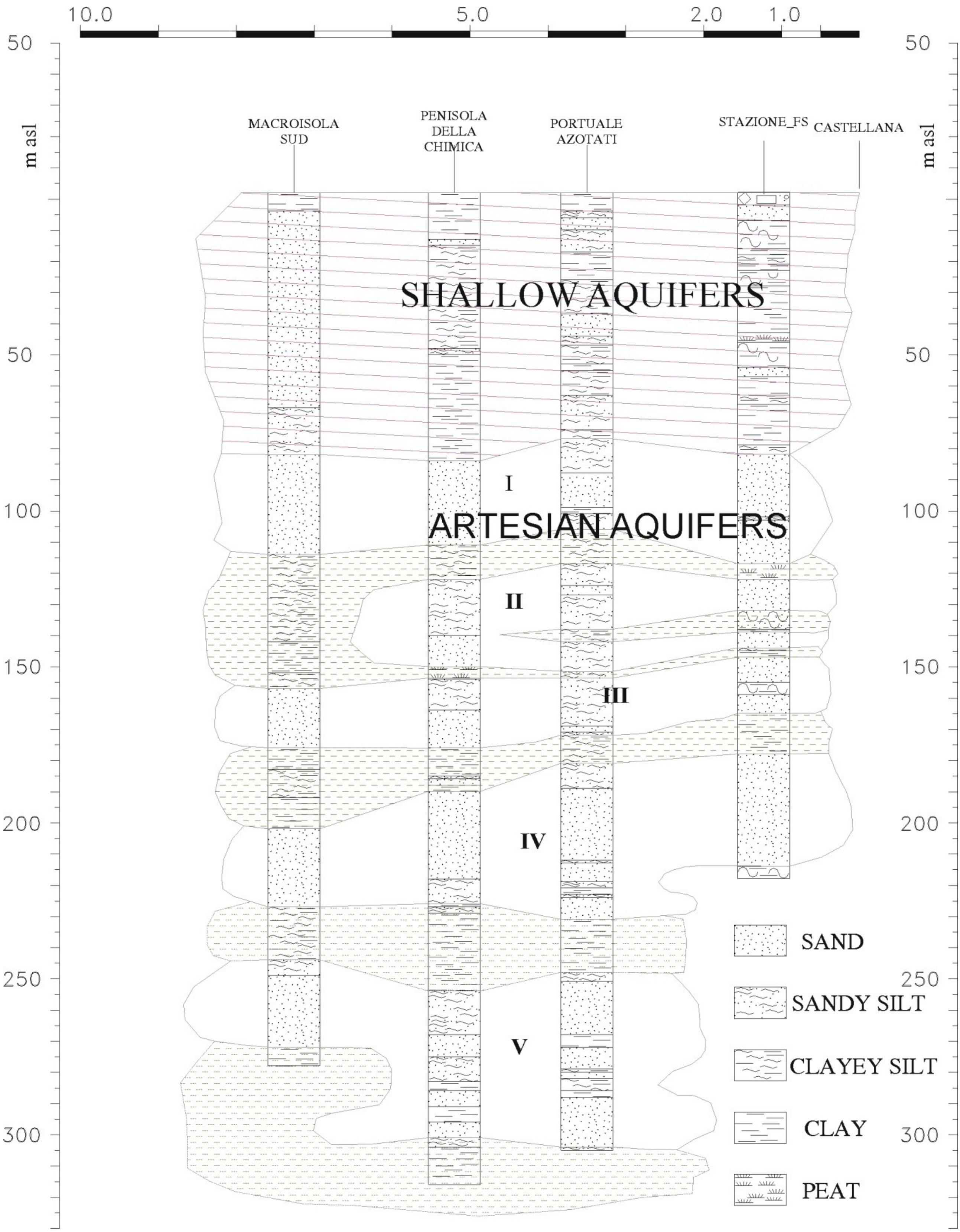


fig. 33: hydrostratigraphic section BB of fig. 30

4.4. MODEL VALIDATION BY HYDROSTRATIGRAPHY OF VE-1

The modal stratigraphies of homogeneous areas allow to suggest an up-to-date hydrogeological model compared with the previous geological section. This last result is due to a work of interpretation and correlation of seismic and stratigraphic data (fig. 32).

Nevertheless in this paper the most interesting aim is the validation of the results by means of a comparison with the one drilling continuous coring in the interest area.

As mentioned in chapter 3, in fig. 26 the chronostratigraphic and facies association sketch (Massari et al., 2004), revised and interpreted for hydrogeologic purposes, is shown.

All the available geotechnical, hydrogeological and geophysical analysis performed on the coring series have been used for an accurate identification of six confined aquifer levels deduced from so different stratigraphic reconstructions (Chierici, 1971a; Chierici, 1971b; Chierici et al., 1971; Favero et al., 1971; Frassetto, 1971; Gatto et al., 1971; Kent et al., 2002; Massari et al., 2004; Mazzini, 1971; Mullenders et al., 1996; Roccabianca, 1971; Stefani, 2002).

A quite good correspondence between transgressive and regressive depositional cycles (Massari et al., 2004), defined T/R cycle in fig. 26, and the deduced aquifer sequence can be noted.

Some authors argue a close correspondence of the aquifer levels with the transgressive events only (Brambati et al., 2003; Tosi, 2007)

The facies associations are varying within each depositional cycle as a result of subsidence , accumulation sediment rate and eustatic changes. In this way, a shoreface environment is often associated with medium and fine sands. Laboratory tests have attributed to these sediments values of permeability and porosity compatible with aquifer levels.

Otherwise in the shelf depositional environment the cohesive sediments are prevailing and checked as aquicludes or aquitards (fig. 26).

During the Middle Pleistocene the oscillations of sea levels had a moderate and quite constant amplitude allowing a relatively regular facies successions (IV,VI and VI aquifers in fig. 26).

Starting from the upper part of the Middle Pleistocene the progradational episode (paleo-Po system) was a major building phase and ended with the first appearance of continental sediments (Massari et al., 2004). The progressive decrease of sea level reduced a regular change of depositional environment together with the thickness of sediments both because erosion and sedimentary hiatus (I, II and III aquifers in fig. 26).

Since the Upper Pleistocene during glacioeustatic highstands and lowstands (Riss-Wurm interglacial period, Eemian) the facies successions were varying quickly both in time and space.

4.5. THE HYDROSTRATIGRAPHY

In a first phase, the collection of rough data and their interpretation and statistical analysis has lead to the elaboration of a physical model of the most exploited hydrogeologic system of Venetian territory. In a second phase, a detailed comparison between the obtained results and the stratigraphic succession recovered by VE-1 cores has allowed their validation (chapter3 .

The hydrostratigraphic model obtained in this work allows to confirm and define in detail the presence of a multiaquifer in Venetian area (paragraph 1.4, fig. 6):

- Deep Aquifer System, DAS;
- Artesian Aquifer System, AAS;
- Shallow Aquifer System, SAS.

4.5.1. Deep Aquifer System, DAS – Upper Pliocene (Gelasian)/Middle Pleistocene

Over the bedrock basement dip down toward SE (AA.VV., 1990; AGIP, 1976; AGIP, 1987), there are the Quaternary alluvial sediments derived from erosion of the Alpine and Apennine chains.

These deposits allow the presence of a number of deep aquifers; they are never exploited, due to the high salinity that limits the uses for drinking purposes (Bortolami et al., 1973b; Bortolami et al., 1973c; Consiglio Nazionale delle Ricerche, 1971; Favero et al., 1973; Frassetto, 1971; Roccabianca, 1971).

In the well Dolo 001, not far from the domain of present work, the limit is put since 404 m deep (AGIP, 1987). Even in the well Assumption 001, located in the Upper Adriatic indicates the interface fresh/ brackish water since 360 m deep (AGIP, 1976).

It is believed that the area of supply of these aquifers is substantially different from those superimposed, as confirmed by isotopic investigations undertaken in the early 70s (Bortolami *et al.*, 1973a; Bortolami *et al.*, 1973c; Fontes *et al.*, 1973): below 445 m depth the oxygen content of 18 (δ18O) presents values of ≈ -8 ‰ with respect to SMOW (Standard Mean Ocean Water) (IAEA / WMO, 2007), compared with ≈ - 10 ÷ 12 ‰ of the overlying aquifers.

The content of δ14C and δ3H (tritium) suggests a very high age (not estimable). The altitude of water infiltration, that was estimated through analysis of δ18O, suggests a drainage area very high in altitude, which can be identified in the Alpine Adige Basin, where observed average altitude of 1630 m (“alpine zone ") (Bortolami *et al.*, 1973c).

4.5.2. Artesian Aquifer System, AAS – Middle Pleistocene

The AAS (Artesian Aquifer System) is placed at a depth between 350 and 80.0 m. and is characterized by fresh water (National Research Council, 1971). Some wells in the lowlands of Venice Plan for exploratory purposes, indicate the presence of fresh water in the same intervals shown in the Venice area (AA.VV., 1990; AGIP, 1976; AGIP, 1987).

The groundwater recharge area of these aquifers is detectable both in the high plains of Veneto, where there are abundant leakages of major rivers (the Brenta and Piave), and in the Prealps chain (Antonelli *et al.*, 1980; Antonelli *et al.*, 1989; Antonelli *et al.*, 2007; Bortolami *et al.*, 1973a; Vorlicek *et al.*, 2004).

VI Aquifer

Only few wells intercept the aquifer VI that lies between 290 – 320 m asl and is persistent in all studied area. The piezometric head of such an aquifer exceeded 10 m the ground level in the past (Carbognin et al., 1975) and at present stands around 4 m.

V Acquifer

The aquifer V, which has a variable thickness between 250 – 270 m below sea level, is probably in hydraulic connection with the lower aquifer VI throughout a semi-pervious silty-clayey layer (Chierici, 1971c; Gambolati et al., 1974a).Ffor this reason the numerical models developed to model the subsidence of the subsoil has been associated Venetian VI to the underlying aquifer (Gambolati *et al.*, 1974a).

The aquifer V can be related with the final shallowing-up stage of Venetian area, where for the first time typical continental conditions take place (Stefani, 2002) (fig. 25).

IV Aquifer

The aquifer IV is confined by a thick impervious layer (20 – 30 m) that lead to a greater seismic impedance with respect to the others aquifers (III and V) induces (fig. 31). Moreover, in proximity to the lagoon area, such an aquifer can be subdivided into two sub-units: IVa and IVb (fig. 34).

This aquifer can be broken down - in the Lagoon of Venice Area - in at least two subunits (IVa and IVb) (Fig. 8). The level at about 225 m above sea level at the Scorzè area could be associated with the episode in Ve-1 is put in aquifer IV-c and characterized by coarse grain size at both sites.

III Aquifer

Although the aquifer III is substantially continuous and lies between 150-170 m below sea level, it is prevailingly constituted by silty sand with a permeability degree relatively low.

II Aquifer

The aquifer II is not everywhere distinguishable from the overlying and underlying aquifer layers, probably because of active erosional phases (fig. 26). Its thickness and its hydraulic conductivity values are extremely variable.

I Aquifer

The most exploited aquifer in the inland lagoon area is the aquifer I, which is located between 80 – 120 m below sea level and could be subdivided into two sub-units (fig. 34). Medium and fine sands form the first (Ia) sometimes alternating with gravels, whereas in the second (Ib) more silty sediments prevail.

The passive seismic survey gives everywhere a good evidence to the aquifer I because of strong impedance induced by the massive overlying clayey layer. This aquiclude corresponds to the Upper Pleistocene Eemian transgression (fig. 26).

4.5.3. Shallow Aquifer System, SAS – Upper Pleistocene / Holocene

The SAS starts at Riss-Wurm interglacial Eemian stage. With the exception of this step that determines the shoreface environmental conditions, the study area will occur mainly continental conditions (Fig. 7), with alluvial plain facies, lagoons, marshes, marine environmental. (shoreface, deltafront).

The G aquifer marks the transition between the DAA domain the SAS domain; it is poorly documented in the study area. This fact is probably related to a lack of lateral continuity of this aquifer and to a limited exploitation in the past for drinking purposes. It is believed that in the survey between 50 and 70 m deep aquifer is at least one level - defined as G or I to continue the schemes proposed (MAV, 2007a)- several meters thick, tied to evolutionary processes the Upper Pleistocene acting on low plains then at periodic emergence

From ground level to 50-70 m we can identify Shallow Aquifer System that has a weak artesian with regard to the deeper levels. The SAS is being studied for some time and are no studies of great detail even at the local scale (Bondesan et al., 2008; MAV, 2007a; Vitturi et al., 2008; Zangheri et al., 2009), which we refer to further information.

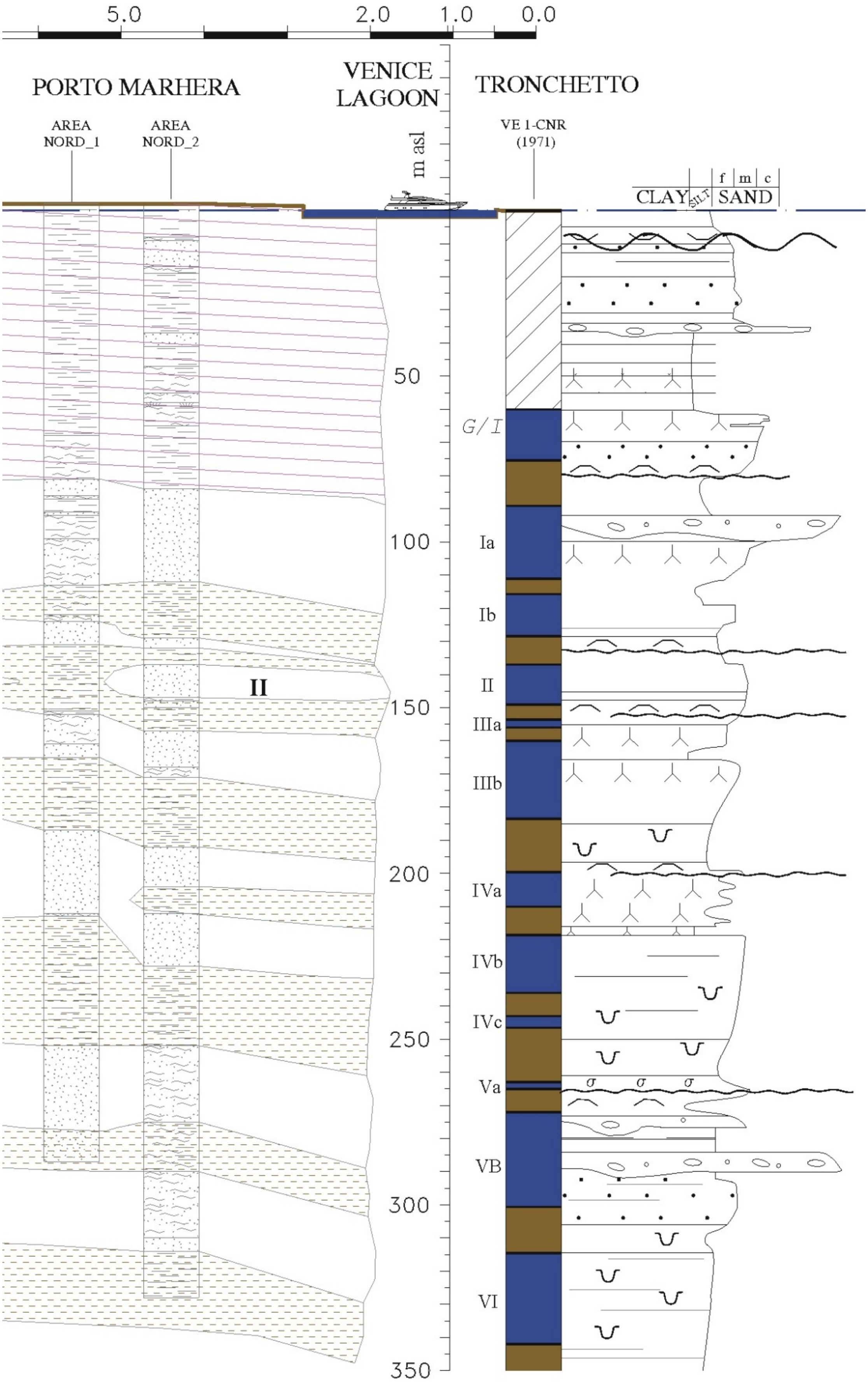


fig. 34: validation of hydrostratigraphic model with comparison of Ve-1.

4.6. CONCLUSIONS

An update of the hydrogeological model of the Venice has been obtained by means of a statistical analysis of the lithologic sequences, taking into account of the data provided by purpose-made geophysical surveys. The results about the hydrostratigraphic section are satisfactory, in particular they agree with the ones provided by the continuous coring well Ve-1.

As compared with the previous knowledge, this contribution has allowed a better description of the two main aquifer units (I and IV), both in their true thickness and in spatial continuity.

These two elements established by direct and indirect surveys the settlements of the whole hydrogeologic succession (AAS) have favoured.

The fact that the hydrogeologic section has a good correspondence with the transgressive-regressive cycles and the geotechnical, hydrogeological and geophysical parameters detectable in the coring well Ve-1 must be noted.

The hydrogeological model and the developed methodology represent a benchmark for the possible future surveys extended to other sectors of the lagoon area. Such an extension needs not much new geognostic data.

5. FLOW THROUGH ABANDONED WELLS: NEW ANALITYCAL SOLUTIONS

The description of the hydrostratigraphic model developed in chapters 3 and 4 allows the correct contextualization of the hydrogeologic structure. The previous analysis (chapter 0) provides a clue to a possible detection of an experimental methodology for a scientific support of the study case.

The following analysis is based on some scientific studies in order to find new analytical solutions to the leakage rate through abandoned wells both in a steady state and in a transient flow.

5.1. CRITICAL REVIEW

The scientific literature has not been much improved on. The few available studies focus on a geological context and problems which are usually different to those uncovered in this study area. The specific bibliography takes into account abandoned oil wells which are usually drilled very deep (>1000 m).

In the North-American continent the waste fluids of industrial processing and energy plants are often injected in the deeper layers characterized by brine aquifers (Environment Protection Agency, 2001; Smith, 1996). More recently the most serious problems linked to the excessive production of carbon dioxide are going to be dealt with by its disposal in underground geological formations (Haszeldine, 2006; Torvanger et al., 2005).

The storing of these fluids causes a rise of pressure in the aquifer intercepted by the injected well (Class et al., 2009; Nordbotten et al., 2004b).

This rise causes an increase of pore pressure that therefore is conveyed and produces a flow also towards the shallow aquifers through eventual inactive wells set near the injection ones (fig. 35).

The detection of passive wells is possible thanks to geophysical techniques, especially if in not particularly anthropized areas (Aller, 1984). In rare cases, if there are at least two monitoring points, analytical and numerical methods may be exploited, (Javandel et al., 1988).

In the study area injection wells (fig. 35) do not represent an unknown factor in the system as they are absent. Also the location of some passive wells is known, so at least in this phase the techniques to detect them will not be necessary.

The equations developed in this paper refer to those in scientific literature and seem more suitable to solve the problems uncovered in the study area (Aller, 1984; Avci, 1994; Gass et al., 1977; Hunt, 1985; Hunt et al., 1989; Hunt et al., 2007; Javandel et al., 1988; Jordan et al., 2002; Lacombe et al., 1995; Nordbotten et al., 2004a; Nordbotten et al., 2004b; Striz, 1999).

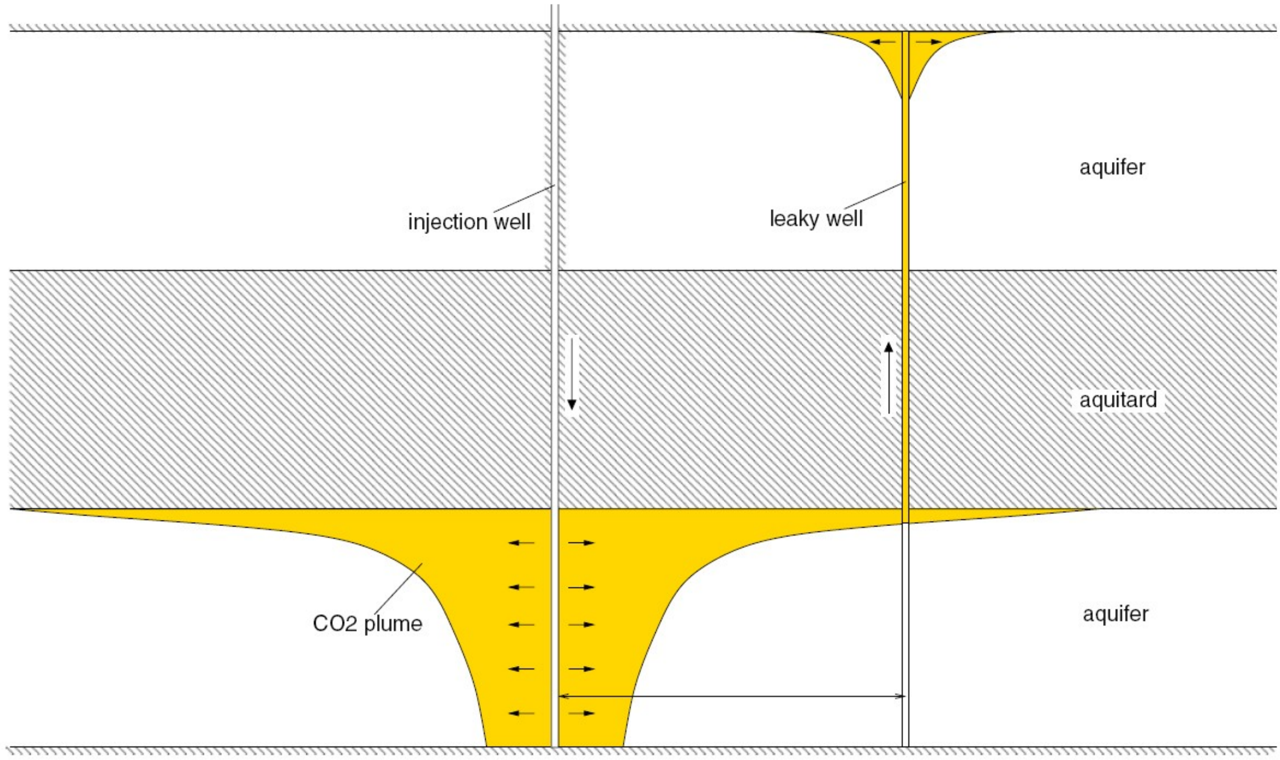


fig. 35: underground CO2 disposal (Class *et al.*, 2009).

Differently from the leakage through abandoned wells being caused by a rapid increase of neutral pressure (injection well), in the study area the rise of potential in the deep aquifer is of the regional and not impulsive type.

In this context - increase of neutral pressure without injection wells - solutions can be found both in a steady state and transient flow.

5.2. STEADY STATE ANALYTICAL MODEL

fig. 36 refers to a general model. In our case the presence of two different aquifers separated by an aquiclude is surmised: the system is therefore defined by two homogeneous aquifers, infinitely widespread, of known and confined thickness and hydraulic transmissivity. Also the existence of a fully penetrating well is surmised as being inferior and communicating with a shallow one through a borehole casing (fig. 36).

The flow through the well is functional to the difference in hydraulic potential between the two aquifers, the permeability (K_1, K_2), the thickness of the two aquifers (L_1, L_2), the well's length and diameter, the resistance to groundwater flow.

Both aquifers are supposed to be saturated by a monophasic liquid with a steady density. The well, which functions as hydraulic connection between the two aquifers, is supposed to be full of the same fluid. The considered system therefore includes an active well (withdrawing or injecting) open only in the deep aquifer, and a passive well open on both aquifers. The first heads in the deep aquifer and in the shallow one are marked as H_2 e H_1 (fig. 36).

After a certain amount of time t from the injection's beginning, the potential in the lower aquifer increases, creating a gradient of vertically direct potential. This gradient produces a flow which is radial at the bottom of the abandoned well, linear in the rising and once again radial or spherical coming out of the shallow aquifer.

Below the equation in a permanent flow situation (Silliman et al., 1990):

$$Q_c = \frac{2\pi(\Delta \mathrm{H} - H_L)\alpha\beta}{\alpha + \beta}$$

eq. 1

where

$$\Delta \mathrm{H} = \mathrm{H}_2 - \mathrm{H}_1$$

eq. 2

$$\alpha \equiv \frac{T_2}{\ln(r_2/r_{a2})}$$

eq. 3

$$\beta \equiv \frac{T_1}{\ln(r_1/r_{a1})}$$

eq. 4

eq. 1 shows how the leakage rate in the abandoned well is functional to the natural hydraulic heads (H_2 e H_1) considered as constant to certain radial distances r_1 ed r_2. It is also functional to α e β that represent the productivity indexes of the formations and the term H_L that considers the well leakages. T_1 equals $K_1 L_1$.

The analytical model in eq. 1 takes into account the head constant in time that have a gradient which produces a continuous flow between the two aquifers communicating through the passive well. If there are no piezometers available for the monitoring of the variations of the piezometric level of the two aquifers in the study area, for instance the empiric formula of Siechardt would have to be exploited in order to estimate the radius of influence required in eq. 1 (Bear, 1979). Below it will anyway be possible to demonstrate how important the influence radius is to leakage rate evaluation by means of sensitivity analysis.

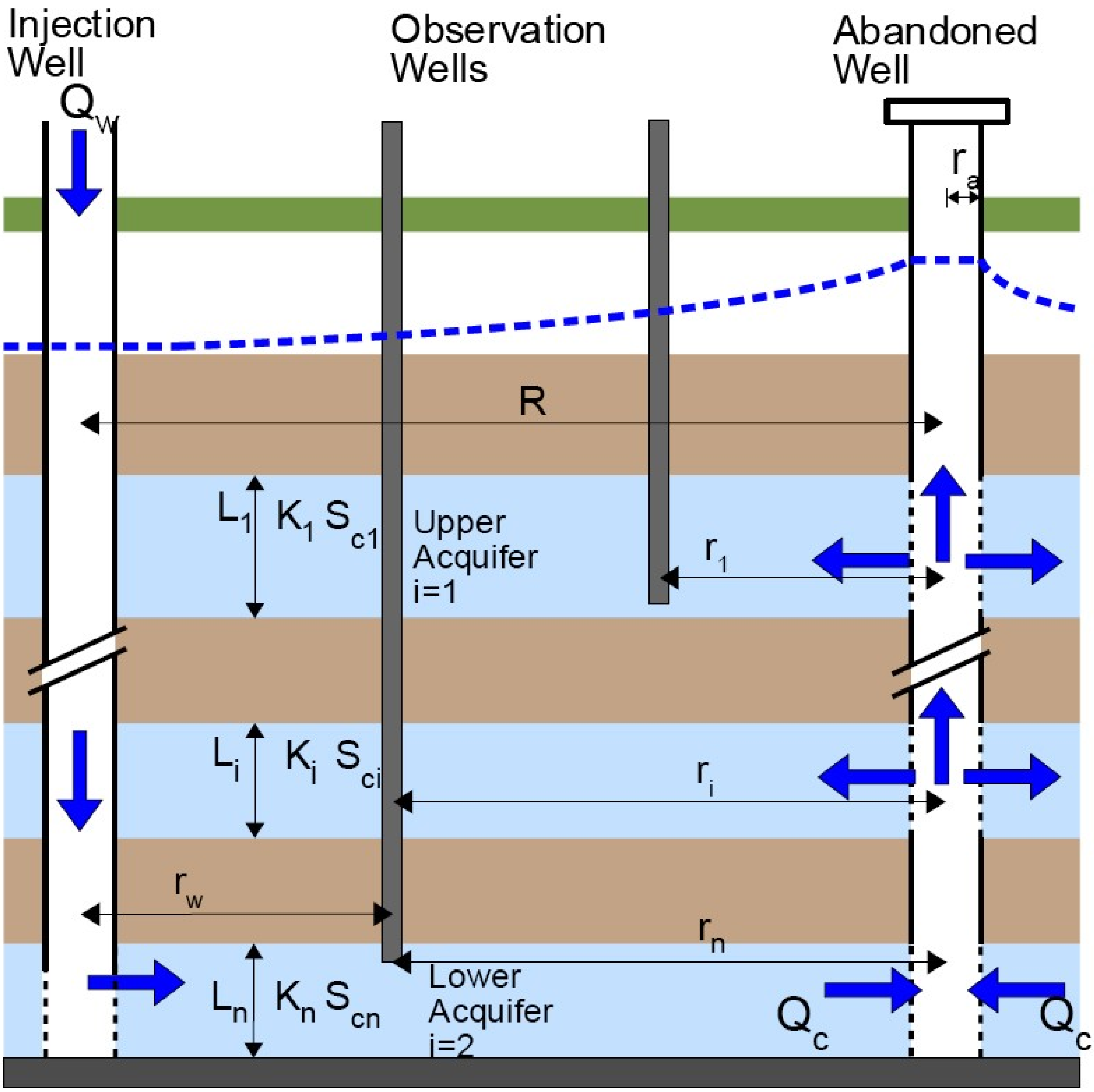


fig. 36: reference plot for the analysis of the flow through abandoned wells.

<u>Head losses</u>

In order to establish an equation for the steady-state flow starting from eq. 1 it is interesting to evaluate the term of head loss H_L. The Authors believed the loss to be caused by turbulent flow which seems unlikely in this model (Silliman et al., 1990).

The measurement of all the different factors of resistance the fluid may encounter through the abandoned well is instead believed to be useful in order to estimate the well loss (Avci, 1994).

It seems obvious how whatever resistance there is in the well works by diminishing the flow that passes through it. By establishing in the model the well loss as a term of head loss (in metres) it is possible to use standard equations dependent on the well's maintenance (fig. 37).

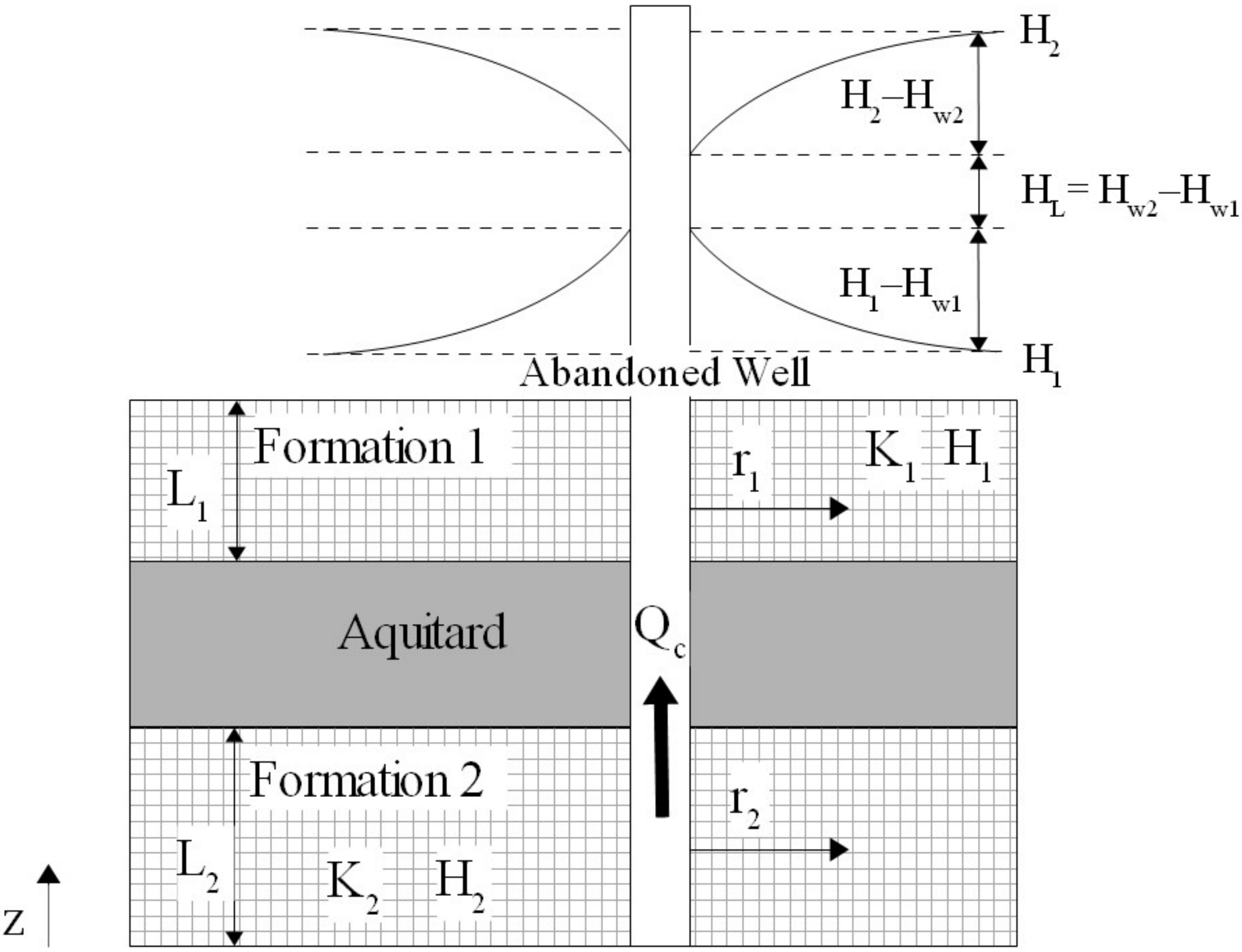


fig. 37: head distribution.

The main causes of head loss are represented by **pipe friction**; these losses are different according to whether the flow is laminar or turbulent; in both cases the head loss caused by pipe friction is defined as (Striz, 1999):

$$H_{pf} = f\frac{L}{D}\frac{v_{aw}^2}{2g}$$

eq. 5

where,

H_{pf} = pipe friction in metres

f = friction factor (dimensionless);

L and D = piping's length and diameter;

v_{aw} = fluid's velocity in the well.

For the laminar flows the friction factor is:

$$f = \frac{64}{N_{Re}}$$

eq. 6

Reynolds number can be found with the equation below:

$$N_{Re} = \frac{\rho v_{aw} D}{\mu}$$

eq. 7

where ρ is the fluid's density and μ its viscosity, D the interstices diameter, v_{aw} the fluid's mean velocity.

In turbulent flows (N_{Re}>2000), the friction factor is functional to the Reynolds number and the roughness ε/D:

$$f = f\, N_{Re} \frac{\varepsilon}{D}$$

eq. 8

As mentioned above, it is possible the fluid's circulation through the passive well to be limited to laminar flow. Considering the leakage rate flowing through the abandoned well after streaming into the lower aquifer, it's rightful to assume its Reynolds number to be equal to the typical one of the laminar flow through a porous means, having therefore a value between 1 and 10 (Bear, 1979). For this reason, in this paper the head loss is not referred to the turbulent flow as much as to the loss of the physical conditions of the well-aquifer system (Silliman et al., 1990).

In eq. 1 adding the representative term of the loss caused by piping friction, the general equation becomes:

$$Q_c = \frac{2\pi\alpha\beta}{\alpha + \beta} \cdot \left[\Delta \mathrm{H} - f \frac{L}{D} \frac{(Q_c/A_c)^2}{2\mathrm{g}}\right]$$

eq. 9

where

$$\frac{Q_c}{A_c} = v_{aw}$$

eq. 10

the velocity given by the ratio between the abandoned well's leakage rate Q_C and section (A_C) of the pipe (usually cylindrical).

eq. 9 can also be rewritten

eq. 11

with:

$$A = f\frac{L}{D}\frac{(1/A_c)^2}{2g}$$

eq. 12

$$B = -\frac{\alpha + \beta}{2\pi\alpha\beta}$$

eq. 13

$$C = -H_2 - H_1$$

eq. 14

Once coefficients A, B and C are determined, eq. 9 may be solved as a quadratic equation and provides the requested value of the leakage rate.

As the friction factor f depends on the flow rate (which represents the requested unknown value) it is necessary to set an initial flow rate to define its value. Actually the initial flow rate can be made simply by first considering as void the well's losses H_L in every passive well; the calculated flow rate is used to determine both the fluid's velocity in the well and Reynolds number. Therefore it is possible to measure the friction factor that represents coefficient A; this allows the recalculation of a discharge flow rate that accounts for the loss caused by piping friction.

The drilling mud, the clayey soils and the grouting plug represent possible elements of head loss: these materials can be included in with the porous means in the well, in order to estimate their influence on the final leakage.

For instance considering a grouting plug for an abandoned well, the pressure loss is given by Darcy's law for a linear flow (Striz, 1999):

$$H_{PM} = \frac{Q_c \mu}{k_{PM} A_c \rho g} L_{PM}$$

eq. 15

H_{PM} indicates "**pressure loss through the plug**" (in this case a cement plug), L_{PM} and k_{PM} represent the length and permeability of the cemented piping length (respectively represented through metres and darcies), and A_C the plug section that should coincide with the pipe's transversal section.

It is also possible to include in the general term of loss H_L, eventual well losses linked to **single perforation** in the upper borehole casing:

$$H_{perf} = \frac{0{,}2369 Q_c^2}{N_p^2 D^4 C_D^2 g}$$

eq. 16

where Q_C always represents the flow through the abandoned well, ρ the fluid's density, C_D and N_P the outflow coefficient and the number of drillings (dimensionless), and D their diameter.

As above this equation can be included in the general term of well loss in the general equation (eq. 9). The ensuing expression can therefore be rewritten in the quadratic form described in eq. 11, being careful to redefine coefficient A according to this new loss and leaving coefficient B and C unchanged.

$$A = \frac{0{,}2369}{N_p^2 D^4 C_D^2 g}$$

eq. 17

The last type of loss that may be considered in the evaluation of the flow between the two formations in the abandoned well is the one which takes place in an **annular flow** (Striz, 1999). This loss is so little it may be overlooked in this study. The equation is:

$$H_{PMF} = \frac{1{,}149 \bullet 10^{-10} Q_c \mu L}{W_F^2 A_F \rho g}$$

eq. 18

where W_F represents the width of the fracture and A_F the area of its section.

Spherical flow

All the analytical models examined up to now take into account a screen well in an upper aquifer. In most cases there's a dispersing well instead, therefore the outflow should not be viewed as radial but rather as spherical.

Physically, a hole in the casing causes a point source and therefore a spherical flow in the upper geological formation; this theory is supported by many laboratory tests (Striz, 1999).

The idea of a spherical flow represents an important change in the studied groundwater flow models as it involves a higher pressure loss in the recharging formation; this involves a decrease in the flow rate in the passive well calculated through the above analytical models.

The flow rate's equation, for the steady state and the spherical system is given by (Muskat, 1938; Vigneswaran et al., 1984):

$$Q = \frac{4\pi K(H_e - H_w)}{\mu \frac{1}{r_w} - \frac{1}{r_e}}$$

eq. 19

where:

Q is the measured flow rate;

H_W indicates the potential measured on the well's radius r_W;

H_e is the potential measured outside the well, at r_e distance;

μ is the viscosity.

It may be noticed how the discharge is functional to the potential's difference, but not to the formation's thickness as in a radial flow.

Up to now the examined solution (eq. 9) (Silliman et al., 1990), presumes a radial flow in both formations. By changing its solution in order to consider a spherical flow as in the upper aquifer, the result is (Striz, 1999):

$$Q_c = \frac{2\pi(\Delta\mathrm{H} - H_L)\alpha\beta_{sph}}{(\alpha + \beta_{sph})}$$

eq. 20

where α is defined according to the radial flow in the lower aquifer, whereas β becomes β_{sph} and will have to be rewritten considering a spherical flow. Therefore:

$$\alpha = \frac{K_2 L_2}{\ln \frac{r_2}{r_{w2}}}$$

eq. 21

$$\beta_{sph} = \frac{K_1}{\frac{1}{r_{w1}} - \frac{1}{r_1}}$$

eq. 22

By including a spherical flow and not a radial one in the upper aquifer in the equation (eq. 9) (Silliman et al., 1990) a decrease of the leakage is inferred which would otherwise be overestimated.

5.3. TRANSIENT FLOW ANALYTICAL MODEL

In the last decade in the study are the mean hydraulic head of the SAA has registered some important variations (fig. 12), even of many dozens of metres. These variations - caused by the exploiting activity of the groundwater resources – add to the fluctuations related to the regional hydrogeological flownet (fig. 17). It is therefore necessary to detect an analytical solution to describe the flow through abandoned wells in a transient flow.

Some of the mentioned analytical solutions (eq. 9) involve the studying of the hydraulic heads of both aquifers, near the well and at a certain distance from where the hydraulic head's level may be undisturbed. According to the actual difficulty in finding this type of information, it seems useful to detect a different way in order to achieve an analytical solution to the transient flow which can be applied to the assessed conditions.

An infinitely widespread aquifer is examined, with an hydraulic conductivity K, thickness L, specific storage S_s and therefore transmissivity $T = KL$ and storage $S = S_s L$. Surmising an horizontal flow, induced by an injection well with a steady flow, the system's general equation will be (Nordbotten et al., 2004a):

$$S\frac{\partial h}{\partial t} - T\nabla^2 h = Q_w \delta(x - x_w)$$

eq. 23

$$h_2(x, 0) = h_{2init}$$

eq. 24

Where:

$h(x, y, t) = h(\boldsymbol{x}, t)$ represents the mean vertical hydraulic head

$h_{2\ init}$ = the initial head in the deep aquifer;

Q_w = the flow rate of the injection well;

$\delta(x - x_w)$= the Dirac delta function.

For a constant flow rate, this equation has the peculiarity of having a well function as solution, therefore the equation will be (Theis, 1935):

$$h_2(x, t) - h_{2init} = \frac{Q_w}{4\pi T} W(u)$$

eq. 25

$W(u)$ is the well function ((Bear, 1979), whereas in order to define u, r is the radial distance from a point $x = (x, y)$ and the position of the active well $x_w = (x_w, y_w)$

u is given by (Theis, 1935):

$$u = \frac{r^2 S}{4Tt}$$

eq. 26

S = storage;

t = time from the beginning of the pumping.

For active wells the volumetric flow rate (or extraction) Q_w is known. For passive wells the leakage rate Q_c is the unknown factor which has to be made explicit.

If the system is made up of two confined aquifers separated by an aquiclude, it may be surmised the storage effects in the well to be negligible; the flow in the passive well is given by (Nordbotten et al., 2004a):

$$Q_c(t) = K_w \pi r_a^2 \frac{h_1(x_a) - h_2(x_a, t)}{B(x_a)}$$

eq. 27

where:

K_w = the hydraulic conductivity of the material that fills the well in;

r_a = the radium of the passive well;

h_1 = the hydraulic head in the upper aquifer by the passive well ($\boldsymbol{x} = \boldsymbol{x_a}$);

h_2 = the hydraulic head in the lower aquifer by the passive well ($\boldsymbol{x} = \boldsymbol{x_a}$);

B = the aquitard's thickness;

$\boldsymbol{x_a}$ = the position of the abandoned well.

Because the system is linear, the superposition principle applies.

Therefore this solution defines the flow determined by the injection flow rate through the active well; this contribution to the present study is void and can be substituted by the initial head h_{2init}.

A void flow rate in the passive well before the starting time is considered. Afterwards the flow rate Q_c that is not void after $t > 0$, the answer to the system is achieved according to the equation:

$$h_2(x,t) - h_{2init} = \frac{1}{4\pi T}\int_0^t \frac{\partial Q_c(t')}{\partial t'} Wu(x, t-t')dt' = \frac{1}{4\pi T}\frac{\partial Q_c}{\partial t} * W$$

eq. 28

The solution suggested in eq. 28 shows how the leakage rate increases steadily and rapidly at the beginning of the pressurization. After the first phases of pressurization, the hydraulic head and the outflows from the abandoned well decrease and are adjusted by the well function.

The representation of this conduct requires a convolution function, an intricate and complex procedure that is activated by the Laplace transform. The convolutive terms follow a temporal scale; therefore it is possible to substitute the flow in the integral convolution with a simple step function.

Following prof. J.M. Nordbotten suggestions, it has been possible to substitute the flow term in the convolution integrals with a step function. In the easiest instance a steady function made up at intervals only by two regions may be considered; by doing this it is possible to come near the convolution integral by substituting the variable flow in time $Q_c(t')$ with a "Heaviside step function" in eq. 28 by putting:

$$Q_c(t') \approx Q_c(t)H(t' - t^*)$$

eq. 29

where H is the Heaviside step function.

As a result the integral derivative in eq. 28 becomes a Dirac delta function esteemed in $t' = t^*$, making the solution of the convolution integral trivial.

Considering the reference temporal scale, the t^* value was chosen as a fraction of time t^*, that is:

$$t^* = \gamma t$$

eq. 30

On the basis of a numerical comparison between the solutions achieved by the "simplified" equations given by Heaviside approximation and the "complete" ones achieved by solving the convolution integrals, $\gamma = 0.92t$ was assumed (Avci, 1994; Nordbotten et al., 2004a). The choice of $\gamma = 0.92t$ (γ is used to define the step's position in the temporal scale) was made by repeating and testing the results in order to reach the best adaptation of the two solutions. The choice of this value guarantees excellent results.

It therefore seems appropriate to rewrite the general equation (eq. 28):

$$h_2(x,t) = h_{2init} + \frac{1}{4\pi T} Q_c(t) W[u(x, t - t^*)]$$

eq. 31

where h_2 as usual refers to the hydraulic head of the lower aquifer and W(u) is the well function.

Remembering that K_w refers to the hydraulic conductivity of a material that may fill the well in, r_a and x_a are the radius and position of the abandoned well, h_1 is the hydraulic head in the shallow aquifer and B is the aquitard's thickness, including in eq. 31 the Q_c leakage rate ensuing from eq. 27, the outcome is:

$$h_2(x,t) = h_{2init} + \frac{K_w \pi r_a^2}{4\pi T} \cdot \frac{h_1(x_a)}{B(x_a)} - \frac{h_2(x_a,t)}{B(x_a)} \cdot W[u(x, (1 - 0{,}92)t)]$$

eq. 32

Because $t^* = \gamma t$, with $\gamma = 0.92t$:

$$(t - t^*) = (t - 0{,}92t) = (1 - 0{,}92)t = 0{,}08t$$

eq. 33

In order to calculate the h_2 head in the lower aquifer at a distance from the passive well equal to its radius $\boldsymbol{x} = x_a$, it's possible to write:

$$h_2(x_a,t)\left\{1+\frac{K_w\pi r_a^2}{4\pi T}\cdot\frac{1}{B(x_a)}\cdot W[u(x_a,0{,}08t)]\right\}=h_{2init}+\frac{K_w\pi r_a^2}{4\pi T}\cdot\frac{h_1(x_a)}{B(x_a)}\cdot W[u(x_a,0{,}08t)]$$

eq. 34

By explicating this equation as regards to $h_2(x_a,t)$, the outcome is:

$$h_2(x_a,t)=\frac{h_{2init}+\frac{K_w\pi r_a^2}{4\pi T_2}\cdot\frac{h_1(x_a)}{B(x_a)}\cdot W[u(x_a,0{,}08t)]}{\left\{1+\frac{K_w\pi r_a^2}{4\pi T_2}\cdot\frac{1}{B(x_a)}\cdot W[u(x_a,0{,}08t)]\right\}}$$

eq. 35

eq. 35, provides the $h_2(x_a,t)$ value to be inserted in the following eq. 27 in order to achieve the leakage rate through the abandoned well.

$$Q_c(t)=K_w\pi r_a^2\frac{h_1(x_a)-h_2(x_a,t)}{B(x_a)}$$

eq. 36

It may be reminded that K_w is a parameter that is meant to describe a flow through a possible material that fills the well in. This parameter's sensitivity analysis has been developed above (paragraph 5.4).

eq. 35 and eq. 36 have to be exploited if the hydraulic head in the deep aquifer is considered as variable in time and if the head of the above formation is steady. In this system, the u value - and therefore the well function $W(u)$ - has to be found by considering $r=r_a$ as values of transmissivity T and storage S in the deep formation and $t^*=0.08t$.

By observing eq. 36 it may be noticed how, as the hydraulic head values of the lower aquifer are usually higher if compared to the ones of the shallow aquifer, the calculated leakage rate will conventionally have negative values. The flow rate with a minus sign marks a flow coming from deep formations that breaks into the upper aquifer.

In the same way an analytical solution is provided by considering the instance where the system is made up of a deep aquifer having a steady flow in time and a superficial one having a variable hydraulic head:

$$h_1(x_a,t)=\frac{h_{1init}+\frac{K_w\pi r_a^2}{4\pi T_2}\cdot\frac{h_2(x_a)}{B(x_a)}\cdot W[u(x_a,0{,}08t)]}{\left\{1+\frac{K_w\pi r_a^2}{4\pi T_2}\cdot\frac{1}{B(x_a)}\cdot W[u(x_a,0{,}08t)]\right\}}$$

eq. 37

Giving a value constant in time to the initial head in the aquifer (h_2) and inserting leakage rate values (known or calculated through eq. 35 and eq. 36), eq. 37 follows the piezometric evolution in time in the upper aquifer.

5.4. SENSITIVITY ANALYSIS

The need to measure the importance of each parameter in the analysed equations has spurred the necessity to make sensitivity analyses on the suggested solutions.

5.4.1. Steady State flow

The sensitivity analysis was made on the different parameters requested by eq. 38, in order to establish how the variation of each one influences the flow rate.

For the steady state flow the reference equation is:

$$Q_c=\frac{2\pi(\Delta\mathrm{H}-H_L)\alpha\beta_{sph}}{(\alpha+\beta_{sph})}$$

eq. 38

The initial rate of the head losses, carried out as described in paragraph 5.2, has provided low values of H_L. As reference value $H_L=0.01$ m was considered and, as in fig. 38, the high variation percentages as regards to this value do not change in any way the fixing of the flow rate.

The analysis of fig. 38 shows how the differential head clearly represents a highly sensitive parameter and, therefore, greatly influences the leakage rate if compared to other parameters.

In this instance it is necessary to focus on researches and analysis for the correct definition of the most sensitive parameters, that is the differential head and subsequently the assessment of permeability in the upper aquifer.

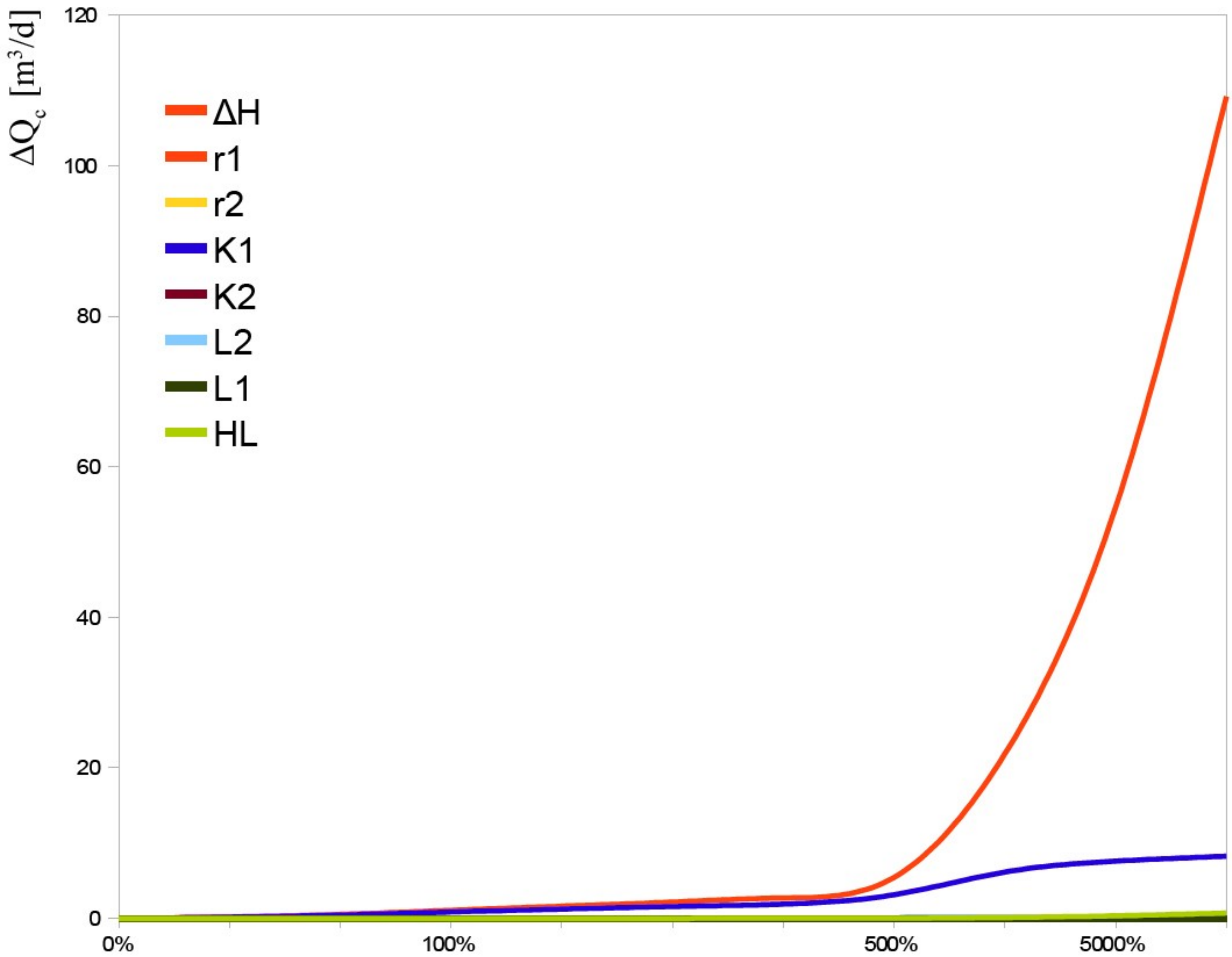


fig. 38: sensitivity analysis of the steady state flow analytical solution (eq. 38).

5.4.2. Transient Flow

The sensitivity of the transient flow's new solution was tested. The line chart developed by means of the results of this sensitivity analysis shows how the leakage rate is closely connected to the differential head between the formations; the flow rates depend less on the parameters variation (fig. 39).

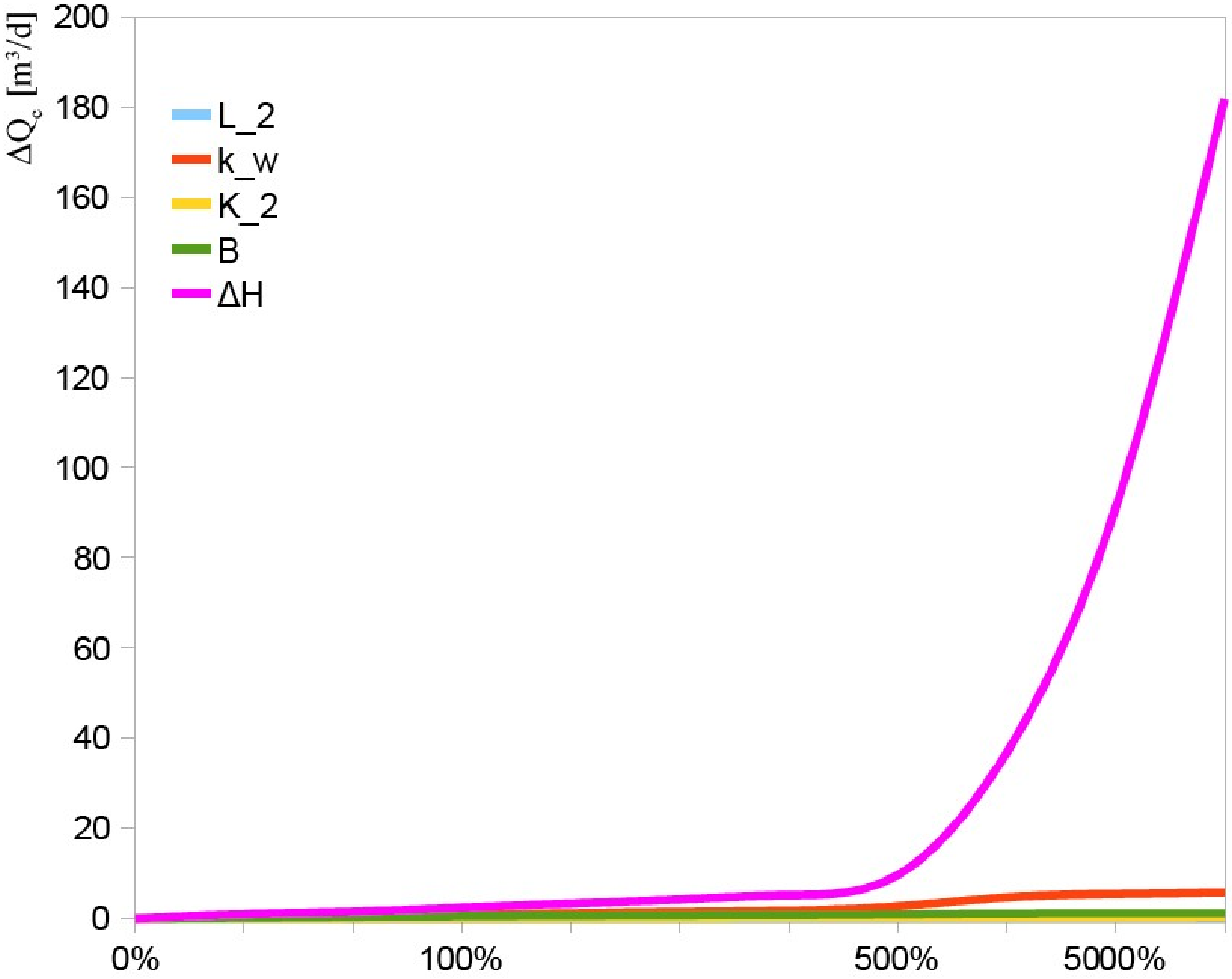


fig. 39: sensitivity for transient flow analytical solution

The analysis was made considering two confined aquifers and a fully penetrating abandoned well. The reference equation eq. 39 where $h_2(x_a, t)$ was calculated step by step in eq. 35 can be viewed below:

$$Q_c(t) = K_w \pi r_a^2 \frac{h_2(x_a) - h_1(x_a, t)}{B(x_a)}$$

eq. 39

fig. 39 shows how the leakage rate in the transient flow basically depends on the differential head between the deep formation and the shallow one.

5.5. THE STUDY CASE OF P58

The analytical solutions regarding the leakage rate through abandoned wells achieved both in a steady state flow and a transient one can be effectively applied to actual study cases. Their use requires a high level of information as regards:

- well geometries;
- hydrostratigraphy;
- hydrogeological parameters;

Therefore in order to achieve the maximum detail in the information, 150 known wells were considered from the archives:

- CNR ISMAR of Venice and of which historical details are available (Alberotanza et al., 1972; Dazzi et al., 1994);
- Istituto Superiore di Ricerca sulle Acque (ISRA) (Superior Institute of Water Research, Department of Geology, University of Padua (ISRA, 1972);
- Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto (ARPAV) (Regional Agency for Environmental Protection and Prevention of Veneto);
- Private entities (aqueducts and concessionaries);
- Civil Engineers Administrative Office (Genio Civile) in Venice

For each well the necessary information was dealt with for a correct analytical description of the problem.

The high number of wells and of inquiries aimed at the reconstruction of the hydrogeological and geotechnical parameters in the harbour area and especially in the old petrochemical plant in the industrial area of Porto Marghera has allowed the gathering of research on the so-called "well 58" (in this paper P58) of the Wells Registry of National Research Council (fig. 40 and fig. 41) (Alberotanza et al., 1972; Dazzi et al., 1994)

There is information on this well dating back to its drilling (1961). Its use was very brief (the end of all withdrawals dates back to 1964) probably because of the piezometric fall: the many hydropotable and industrial wells spread in this area have caused a rapid reduction of the exploited aquifer's head (I aquifer, 80-120). More updated information is available up to 1994 and beyond (Dazzi et al., 1994; Vecchiato, 2009).

Some hydrogeological parameters are available, achieved by direct test and mathematical models (Antonelli, 1994; Teatini et al., 1993; Teatini et al., 1995).

The present piezometric levels were measured through the data provided by the Regional Water Observatory in the Regional Agency for Environmental Protection and Prevention of Veneto (ARPAV) (fig. 44).

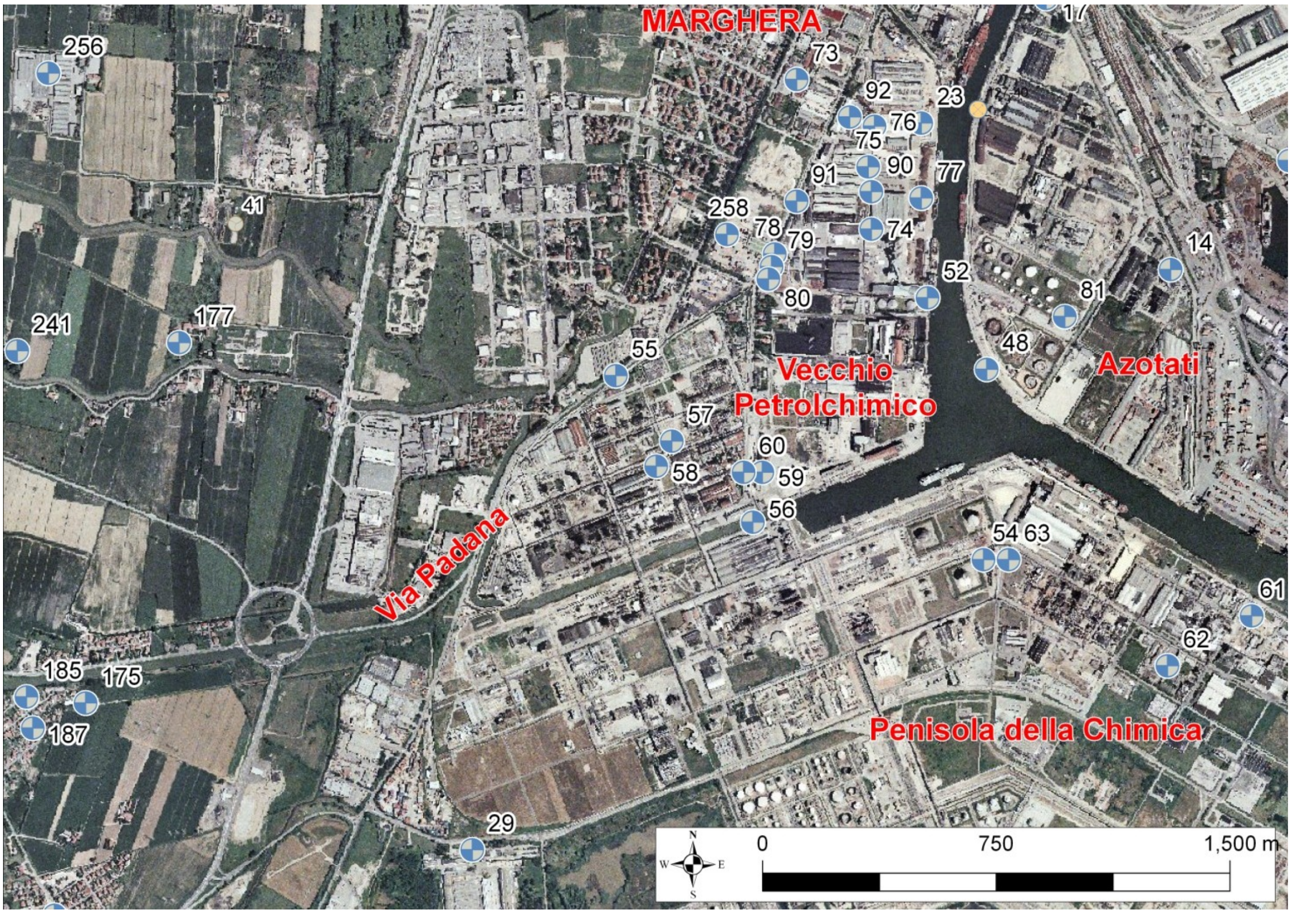


fig. 40: Vecchio Petrolchimico, Porto Marghera (Venezia). Wells location.

fig. 41: location of P58 (from http://www.bing.com/maps, 30 jan. 2010)

As regards the SAS, the stratigraphy comes from the many core drilling explorations possible in this area (MAV, 2007a); the deep stratigraphic succession was achieved through the hydrostratigraphic model developed above (chapter 4) and its further comparison with the stratigraphy quoted in the bibliography (Alberotanza et al., 1972). In order to support this data passive seismic exploration was conducted in the areas near P58 (fig. 43).

The seismic model achieved thanks to the various studies identifies a series of seismic reflectors particularly evident as regards the study area.

Above all it was possible to detect the following seismic reflectors (fig. 43):

- 1.5 m, landfill's end;
- 9.5 m, clay/sand limit;
- 89.5 m, beginning aquifer I;
- 189.5 m, beginning aquifer IV.

This information confirms the facts achieved through the "modalstrata", as in the modal stratigraphy of the sub-area in fig. 42.

Below the structural data of the well:

Name	P058	**X coordinate**	2302767
Site	Marghera	**Y coordinate**	5037250
Location	Venice	**Deep (a gl)**	95 m
Drillied	1961	**Radius**	300 mm
Abandoned	1964	**Screen**	79.78-94.5 m

tab. 4: data for P058

Therefore the data entered in eq. 20 and eq. 36 is:

- r_a=0,15 m;
- L_1=10 m;
- L_2=13 m;
- K_1=1x10^{-5} m/s;
- K_2=6,05x10^{-6} m/s;
- r_1 = 120 m;
- r_2 = 80m;
- B = 65 m

where r_1 and r_2 are achieved by the empirical formula of Siechardt (Bear et al., 1981); anyhow variations of the radius of influence cause little variations in the leakage rate as confirmed by the sensitivity analysis (paragraph 5.4).

The h_1 value was marked as always equal to 0,8m and $K_w = 10^{-2}$ m/s, whereas $h_{2\,init}$ values come from the registered and tabulated ones of the well from 1970.

The estimate of the leakage rate in P58 was developed both for the analytical solutions in a steady state flow as in a transient one; this solution was used considering a two-year time step.

Nowadays according to the various analytical models suggested, the leakage rate between AAS and SAS has been reckoned to be about $1 - 1.5\ m^3/d$..

Results are reported in tab. 5: the difference between the two solutions seems minor, as the steady state flow and the analytical one produce, as expected, very similar results given a suitably long time.

Years	Steady State Flow Rate	Transient Flow Rate
1970-1972	-6.08	-5.66
1972-1974	-4.77	-4.44
1974-1976	-3.87	-3.60
1976-1978	-0.75	-0.71
1978-1980	-0.31	-0.30
1980-1982	-0.02	0.02
1982-1984	0.47	0.43
1984-1986	0.88	0.81
1986-1988	0.94	0.87
1988-1990	1.07	0.99
1990-1992	0.90	0.83
1992-1994	0.96	0.88
1994-1996	1.04	0.96
1996-1998	1.17	1.09
1998-2000	1.32	1.22
2000-2002	1.40	1.30
2002-2004	1.43	1.32

tab. 5: leakage rate obtained with eq. 20 and eq. 36; the negative value refer to vertical flux from shallow aquifer towards lower aquifer.

The leakage rates may be compared to the surplus rates withdrawn from the drainage system by the diaphragm walls (MAV, 2007b).

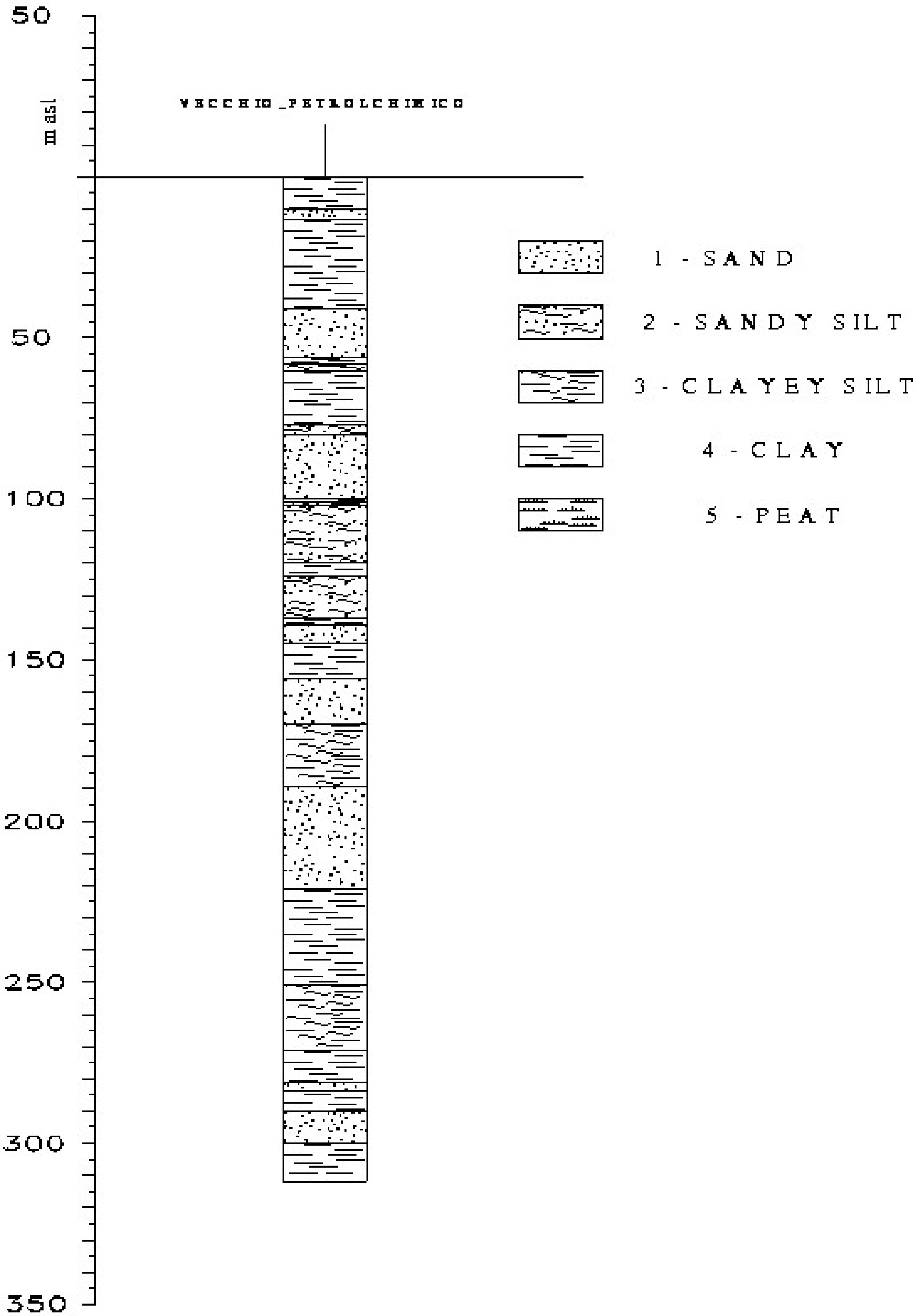


fig. 42: modal stratigraphy of P58 area obtained by modalstrata

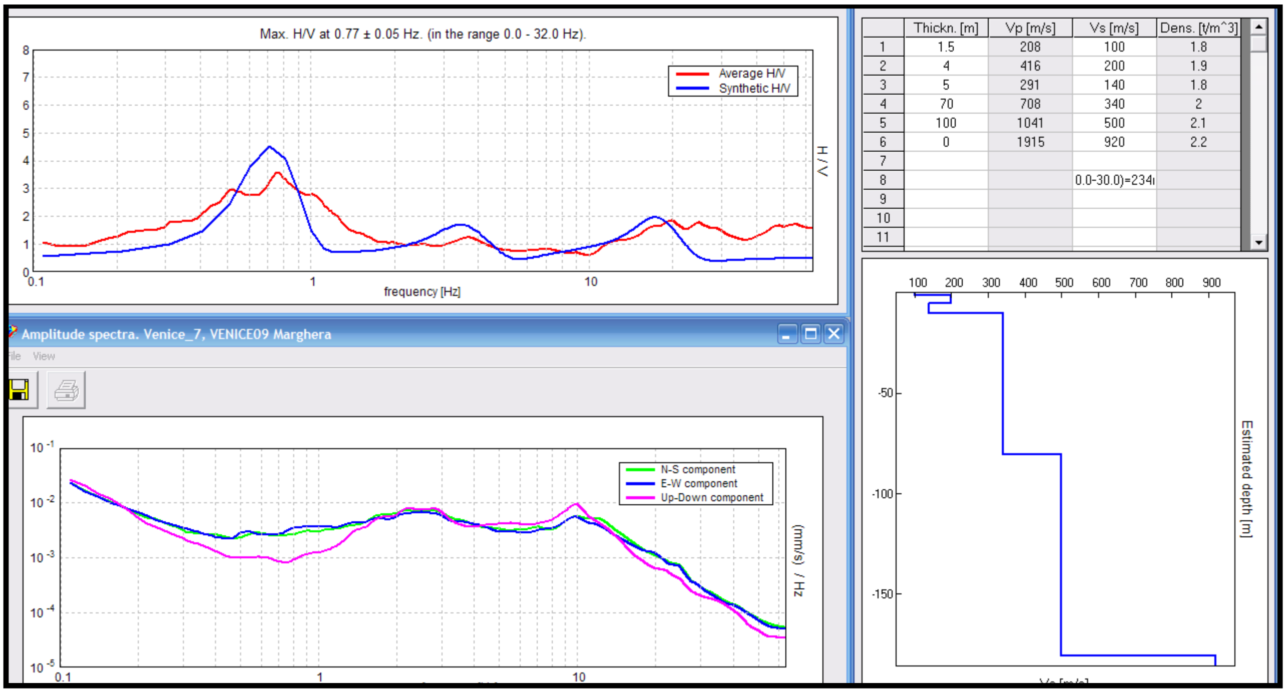


fig. 43: seismic model of of registration in P058 area (for location see Ve-09 of fig. 30).

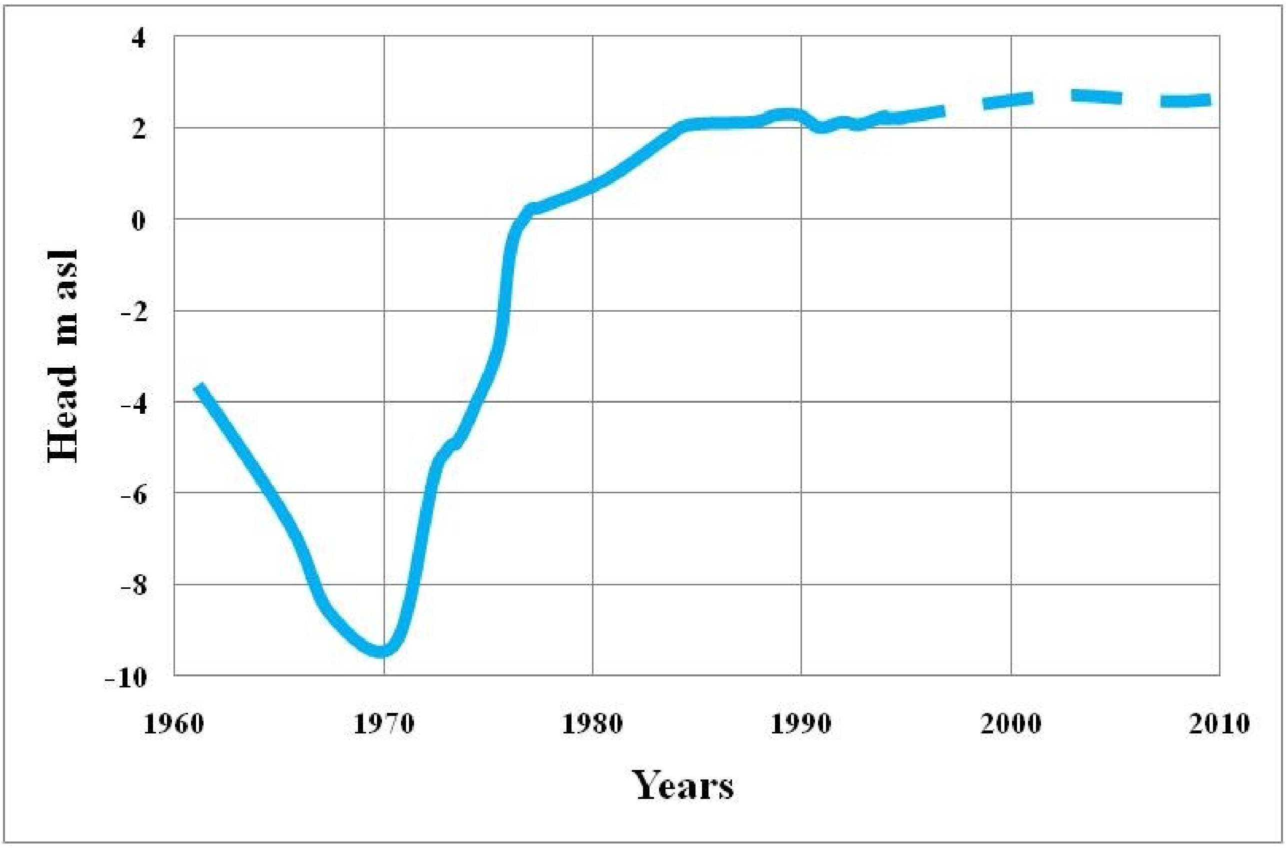


fig. 44: hydraulic head of P058 from 1961 to 2010.

6. NUMERICAL MODEL

The use of numerical models is justified by the need to represent the phenomena which turn out to be too difficult to be described only through analytical models. As regards groundwaters, on a scientific level, there is a lot of available software which can represent its flow.

However these systems require a certain degree of ability on the operator's side in order to manage and deal with the input data, in the choice of the most useful software and in the development of numerical models. This work may be viewed as an effective means for the creation of a particularly complex numerical model of the Shallow Aquifer System, the Shallow Artesian System and the communication between passive wells plus the elements which alter the hydrogeological budget in the study area: recharge/discharge by watercourses, rainfalls and pumping stations.

Therefore the development of this model requires a great deal of detailed information for which the aquifer analysis referred to in chapter 2 is necessary. In this paper important clues to the development of a mathematical model have been developed, the fulfilment of which would require experimental studies for at least another 2-3 years.

Among the selected software Feflow represents the most advanced, not only because of its great flexibility and capacity to deal with extremely difficult boundary conditions, but also because it is possible to use an inside instrument (IFM, Interface Manager) capable of reaching outside elements, such as the new analytical solutions which define the flow through abandoned wells.

After a brief introduction to the calculus code, its use in a study case in the reference area is described highlighting some of its potential.

6.1. FEFLOW

FEFLOW® (Finite Element subsurface FLOW system) is a proprietary software (DHI WASY GmbH) which allows a 2D and 3D simulation in porous means (Diersch, 2007):

The calculus code employs the finite element analysis (FEM, finite element method) in order to solve the flow equation both in saturated and unsaturated conditions. FEM is a numerical method which allows the achievement of approximate solutions to partial differential equations (PDE) by reducing them to a system of ordinary algebraic equations through various numerical techniques (e.g. Euler method and Runge-Kutta method).

The calculus code was first written at the end of the Seventies by Hans-Jörg G. Diersch in Unix and holds over 1.100.000 command lines in ANSI C/C++ (Trefry et al., 2007).

The software's potential is increased by the possibility to connect FEFLOW to other softwares or to directly write the programmes in C++ code (IFM, Interface Manager) which can apply the reference equations to the system meant to be modelled.

For instance it is possible to exploit the calculus code PEST in order to automatically calibrate any type of numerical model (Doherty, 2004).

For its potential and versatility, FEFLOW is believed to be the most up to date and complete calculus code for water simulation.

6.2. CASE HISTORY: GROUNDWATER INTERFERENCE OF VENICE SUBWAY.

6.2.1. Introduction

The underground tunnel joining "Marco Polo" Airport to the city of Venice is part of a series of sustainable development projects under consideration for the Venice area. A preliminary feasibility study was done and submitted to the Ministry of Environment (VIA Committee) to assess the environmental impact.

The Regional Committee required deeper analysis and elaboration in order to move forward. The present investigations focus on the shape, thickness and hydraulic properties of the main hydrogeologic units.

The study uses a numerical approach to simulate the interference caused by the tunnel on the natural groundwater flow.

The data comes from specific tests done along the proposed path of the tunnel and also from the results of several past experimental investigations executed around the area of interest.

6.2.2. Conceptual model

The project has planned the digging of a circular tunnel by Tunnel Boring Machine method (TBM), Earth Pressure Balanced type (EPB) (Herrenknecht, 1997; Melis et al., 2002). The total length would be of about 8500 m with an internal diameter of 6.7 m. The axis is planned at an average depth of 13.5m below the bed of the lagoon so that the inverted arch is 16.5 - 17.0 m deep. The outer wall of the tunnel would be built by bringing in precast concrete sections that are jacked into place as the TBM moves forward; meanwhile concrete is injected into the lining outer face to fill any voids (fig. 45).

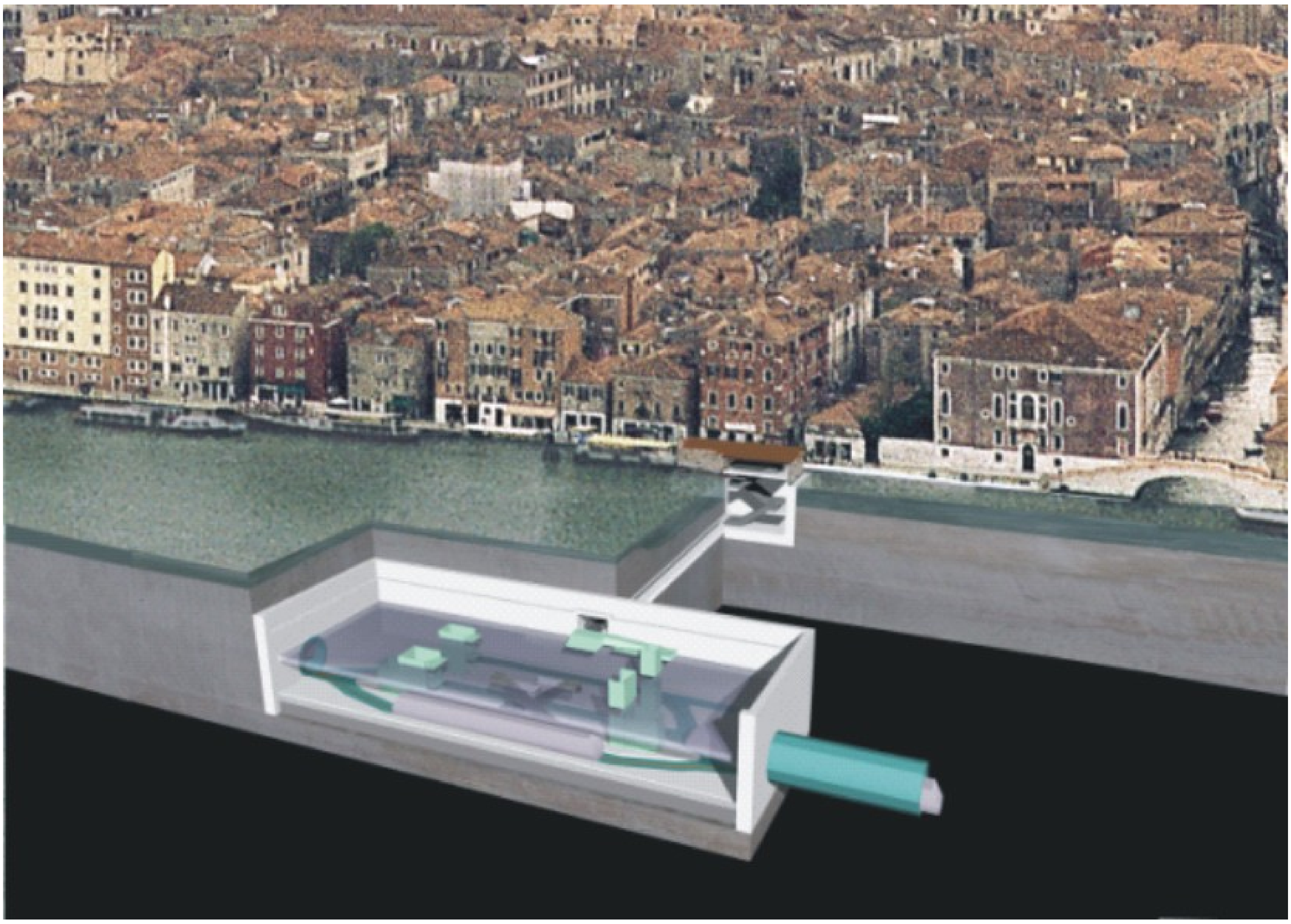


fig. 45: sketch of subway station change.

A geological section coinciding with the whole path of the tunnel has been achieved using 17 drill core samples and 13 CPTU located within 500 m of the tunnel axis (fig. 46). The values of cone resistance, sleeve friction and water pressure, derived from the CPTU tests, have enabled us to identify the cored stratigraphic sequences more carefully (Fellenius *et al.*, 2000; Lunne *et al.*, 1997; Robertson, 1990).

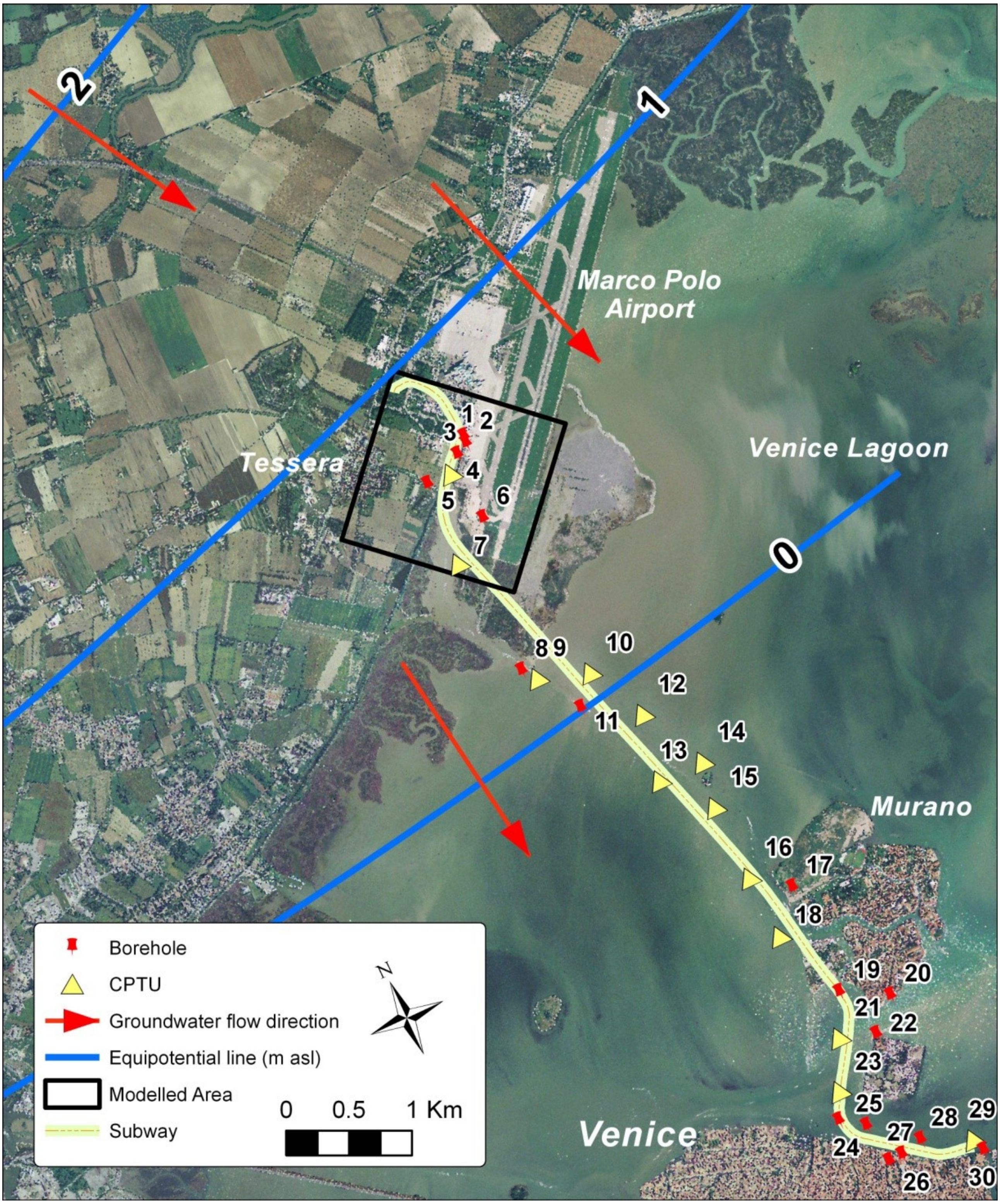


fig. 46: measured potentiometric map (modified from AA.VV., 1990; Antonelli & Mari, 2007; Boscolo & Mion, 2008) and tunnel layout and location of the drilling corings and CPTU

fig. 47 shows the first 2300m of the tunnel path's geological section as this initial part contains the domain's most critical hydrogeological conditions. In this section, the tunnel is almost completely within the second level aquifer (fig. 47) and is perpendicular to the flow of water (fig. 7 and fig. 46).

Facies made up of layers of clay, peat, sand and organic silt alternate along the entire tunnel path(Canali et al., 2007); the geological survey was done at an average depth of 25-30m below sea level and up to a maximum depth of 50m (fig. 47).

The following observations concern the modelled tract of the tunnel represented in fig. 46, but can be extended to the entire geological section.

The first semi-confined sandy aquifer (defined by letter **A**) can emerge locally on the lagoon bed while its lower boundary lies 8-10 m deep. Sometimes its geometry becomes lenticular with a decreasing thickness and grain size towards SSE. In the areas close to the edge of the lagoon, the aquifer is affected by the sea tides.

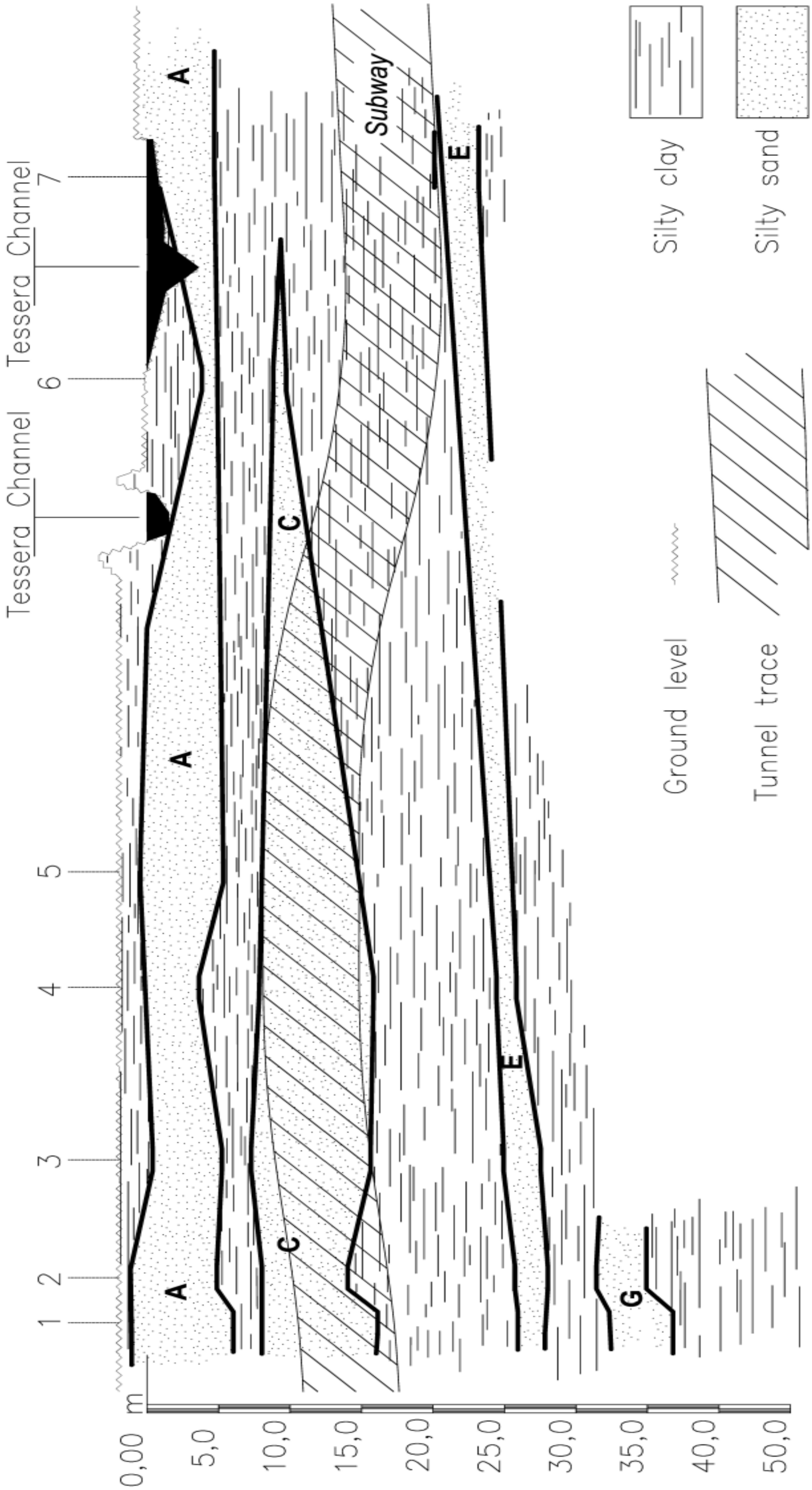


fig. 47: simplified geological section of the modelled area of fig. 46.

The second sandy aquifer, (or first confined aquifer - letter **C**), reaches a maximum thickness of 7m. It is fairly continuous but has some small interruptions. This aquifer is affected by the tides which shows a possible link with lagoon basin.

The third aquifer (**E**) is located 20-27m below sea level, has a maximum thickness of 5m and is continuous along the entire section. In this aquifer there are no variations of pressure connected to the tide cycles.

Some deeper investigations have identified a fourth aquifer (**G**) which is a few meters thick, lying about 35 m deep.

The available hydrogeological data found in scientific literature relates mostly to aquifers A and C. On the other hand, there is not much available information pertaining to aquifer E. Nearly all hydraulic data has been retrieved by aquifer tests, interpreted by Theis and Cooper–Jacob methods, or by slug tests (MAV, 2007a). tab. 6 shows the variation range of some of the hydrogeological parameters (Bassan *et al.*, 2003; Boscolo *et al.*, 2008; Dal Pra *et al.*, 2000; MAV, 2007a; Vitturi *et al.*, 2008; Zangheri *et al.*, 2001).

As far as the hydraulic characters of the cohesive levels, we refer to some specific hydrogeological and geotechnical studies performed in the surrounding areas, where a conductivity range of $10^{-7} – 10^{-10}$ m/s has been estimated (Critto et al., 2004; Ricceri et al., 2002).

AQUIFER	k_{max}	k_{min}	i_{max}	i_{min}
A	1.00E-04	1.00E-06	*na*	*na*
C	1.02E-04	4.03E-05	0.0007	0.0003
E	9.78E-05	2.47E-05	*na*	*na*

tab. 6: hydrogeological data available.

The tunnel excavation mainly involves the aquifer **C**, while in the South-eastern part of the domain the aquifer E is intercepted (n.19 and n. 27) (fig. 46).

6.2.3. Groundwater flow model

The interference between the planned subway and the groundwater flow has been calculated by a 3D finite element mathematical model, assuming steady state flow conditions and porous media saturated by fresh water (Feflow code) (Diersch, 2007).

This interpretative flow model type does not necessarily require calibration (Anderson *et al.*, 2002).

In order to underline the maximum hydrogeologic impact only the initial part of the tunnel subway near Marco Polo airport has been considered. In this tract the interference with groundwater flow is very unfavourable: the subway almost completely blocks the second sandy aquifer (Fig 5) and it is almost perpendicular to the main flow direction (Fig 3). Excluding this sector, the groundwater flow can be assumed parallel to the subway with negligible levels of interference.

The construction of a 3D model for the interest region with x-y axis 1500 x 1500 m has required the following conditions: the ground level has been assumed constant and fixed at 1.96 m a.s.l.; the numbered scheme of the layers derived from geognostic investigations has been obtained by the ordinary kriging interpolation (Isaaks *et al.*, 1989); the C aquifer has been subdivided in two layers: n. 4 and n. 5 respectively free and occupied by the tunnel (fig. 48).

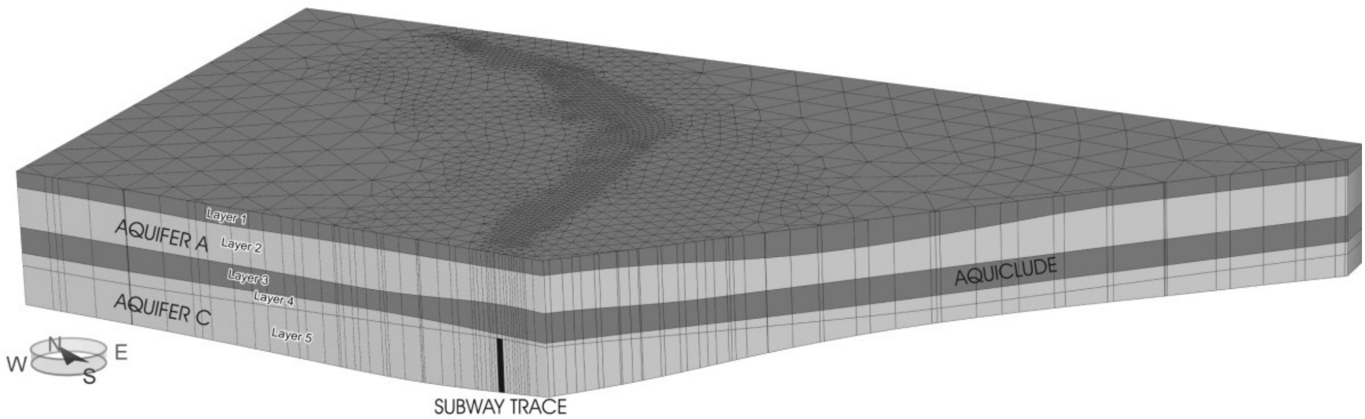


fig. 48: three-dimensional view of the calculation mesh. Subscript (1) indicates the considered layers

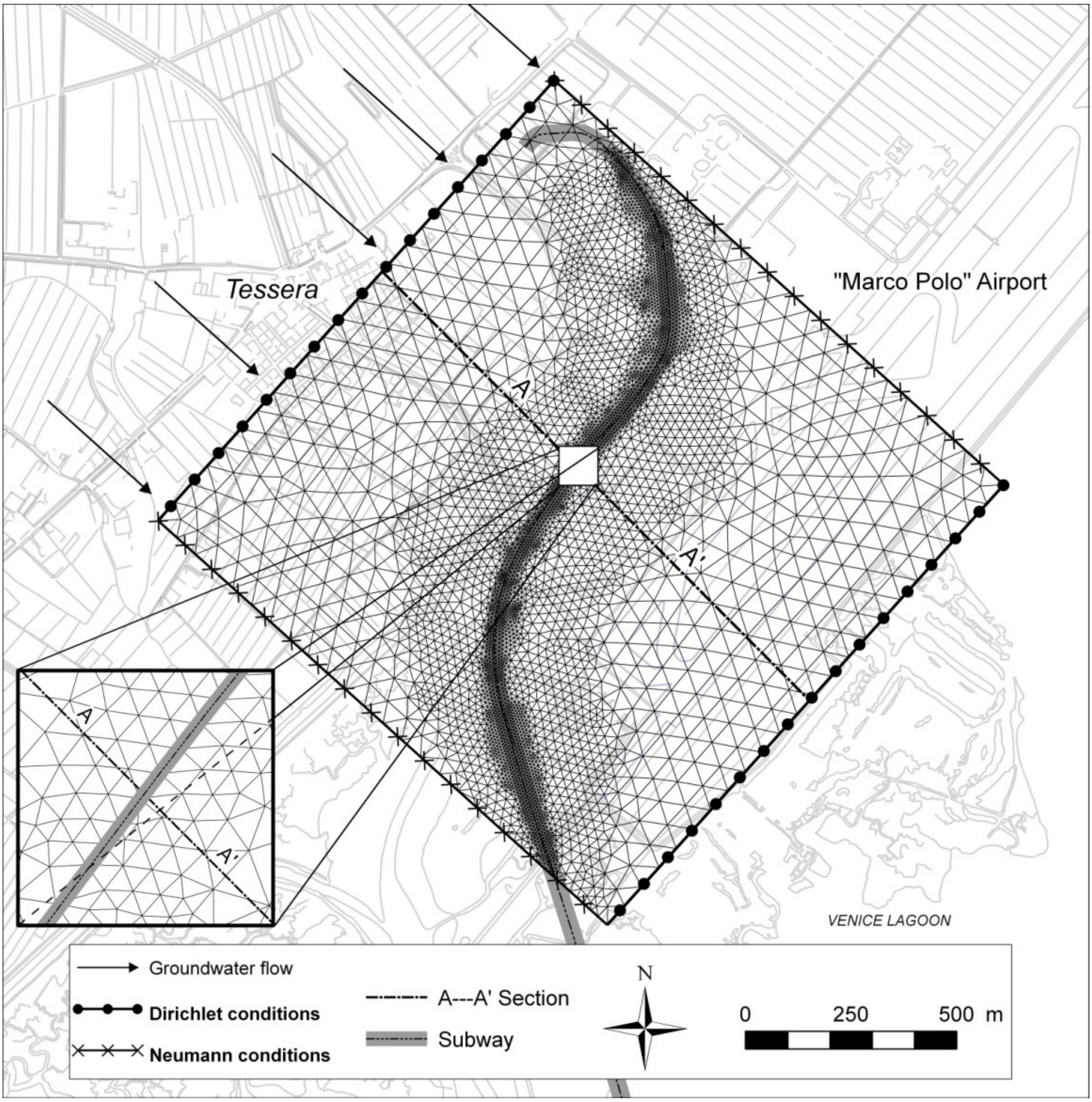


fig. 49: discretization of the area of interest and boundary conditions

fig. 49 shows the discretization of the three-dimensional system by a grid of 26052 nodes and 42845 elements on 6 slices and 5 layers.

The hydraulic gradient direction is orthogonal to the NW boundary and parallel to NEE and SW sides (no flow boundary).

Imposing a hydraulic head varying between 2.00/0.00 m and 0.20/0.00 m a.s.l. from NW to SE sides of the computational mesh, 4 hypothetical scenarios have been considered in steady state flow condition (tab. 7): the input data derive from available hydrogeologic parameters and they regard lower and upper hypothetical values.

CASE	Upper Head (m asl)	Lower Head (m asl)	Gradient *i*	Aquifer Conductivity k m/s	Aquiclude Conductivity k m/s	Tunnel Conductivity k m/s
I	0.20	0.00	0.00013	1.00E-04	1.00E-08	1.00E-09
II	**2.00**	**0.00**	**0.0013**	**1.00E-04**	**1.00E-08**	**1.00E-09**
III	0.20	0.00	0.00013	1.00E-05	1.00E-08	1.00E-09
IV	2.00	0.00	0.0013	1.00E-05	1.00E-08	1.00E-09

tab. 7–scenarios for various input data assigned to the aquifer C

6.2.4. Results

For all assigned conditions the effects induced by the planned subway on groundwater flow field turn out to be low.

If one considers the second scenario of tab. 7, which assumes more unfavourable hydro-geological conditions, the increase of hydraulic head is highly localized with a magnitude of about + 0.15 m upstream and - 0.15 m downstream (fig. 50).

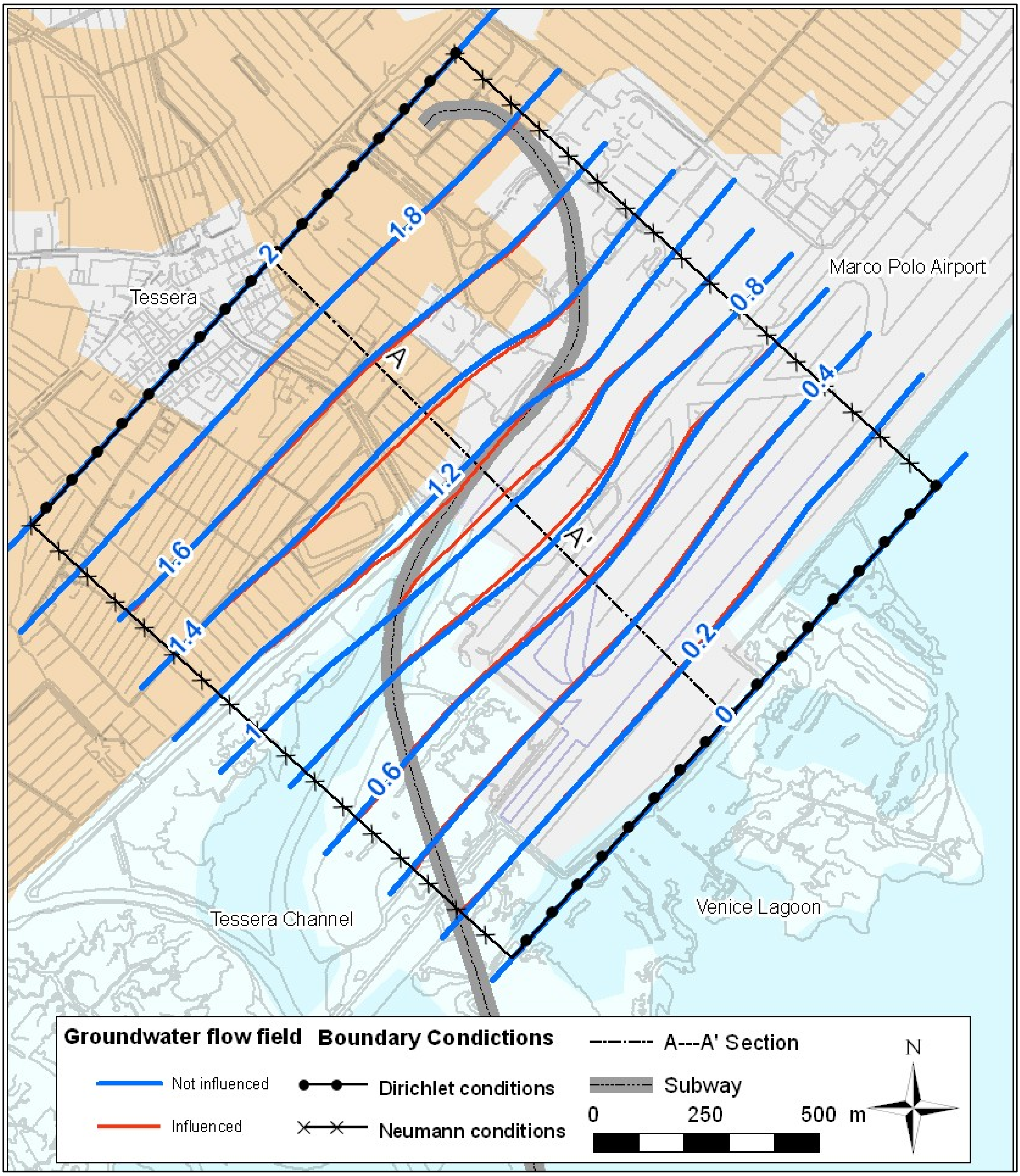


fig. 50: map of simulated distribution of hydraulic head in the aquifer C (case II of Tab.2)

Further North-East of the modelled area the calculated contour lines of fig. 50 also show a closer space. This can be attributed to a gradual thickness decrease of aquifer **C** (fig. 47 e fig. 48).

The cross section of fig. 51 draws the head-spacing interval variation through the subway simulation.

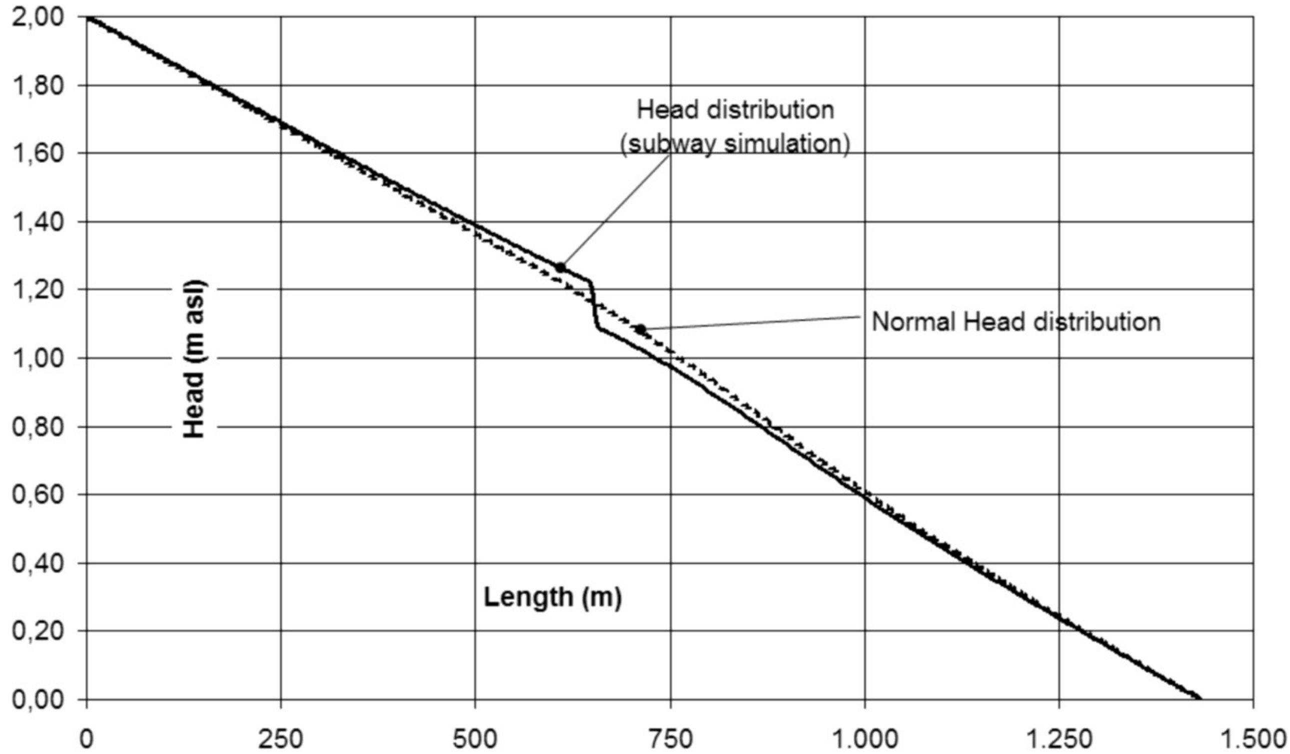


fig. 51: graph of head – space distribution across the tunnel

The velocity distribution field underlines once more the moderate impact on the natural flow regime of aquifer **C** by the tunnel (fig. 52).

The velocity field changes between 0.03 m/d a 0.2 m/d. A wider and evident increase at the right end can partly be due to the decreasing thickness of aquifer **C**.

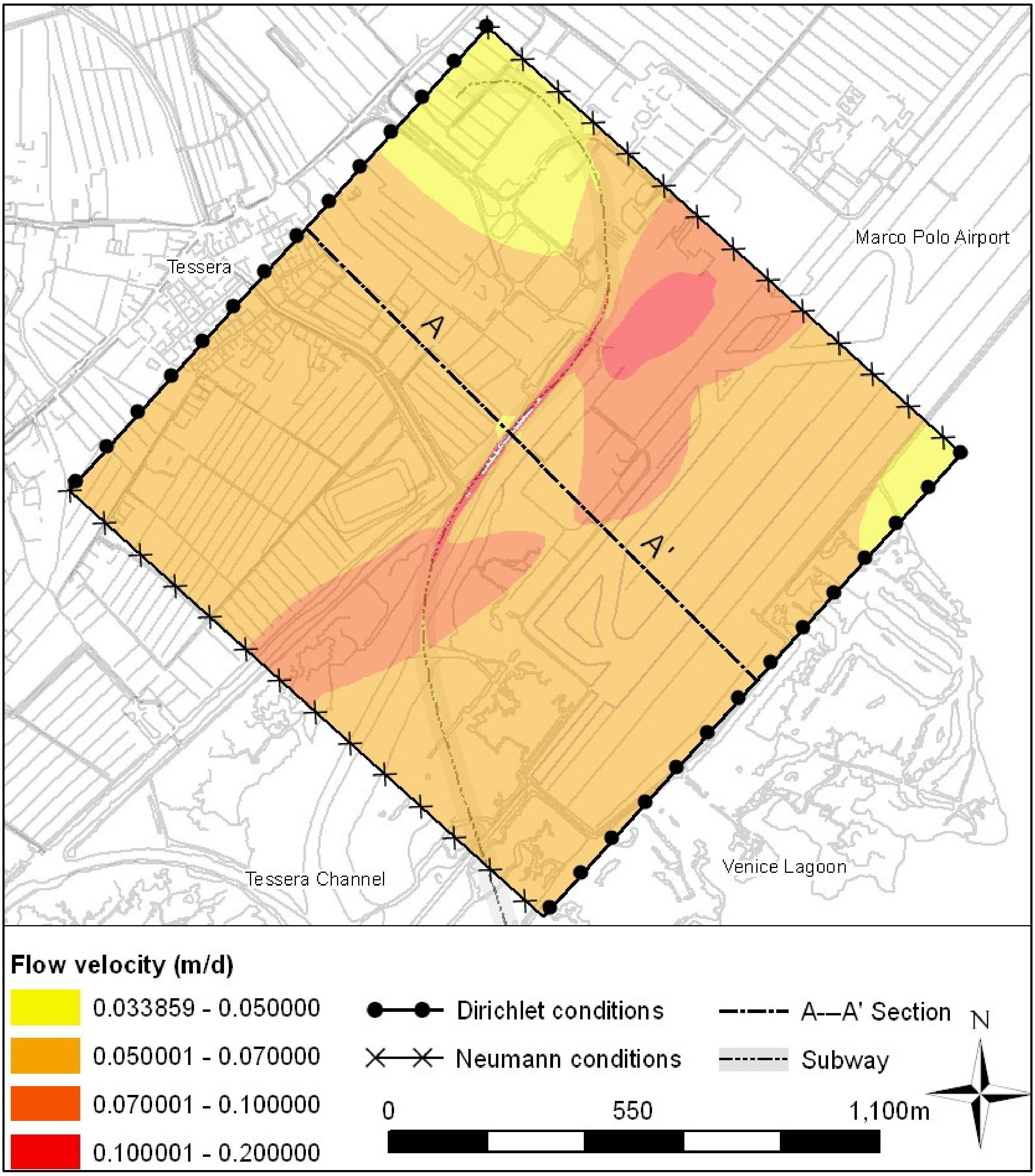


fig. 52: groundwater flow velocity field of aquifer C

6.2.5. Conclusions

The preliminary underground tunnel project linking Marco Polo airport and the city of Venice has been submitted to an analysis of the effects that the tunnel will have on the natural flow of underground water in the aquifers concerned.

To this end, a 3D mathematical model has been created using finite element code (Feflow). The model is based on a discrete number of core drill samples taken up to a depth of 50 m and numerous hydraulic tests conducted around the edge of the first confined aquifer. This aquifer is interrupted the most by the tunnel.

In order to take a cautious approach, the highest hydraulic conductivity and gradient values were used for the calculations, comprising a range of 10-4 - 5x10-6 m/s e 0,1 – 1,1 ‰.

Moreover, the most unfavourable conditions of interference between the tunnel and the hydrogeological system of the lagoon with the tunnel axis perpendicular to the underground water flow has been assumed.

The model shows an incremental increase of the hydraulic head of a few centimetres immediately upstream from the tunnel and a decrease of the same size immediately downstream. In this regard we can show that the variation of hydraulic head in the affected aquifer, both along the coast of the lagoon and within the lagoon itself, is within a maximum interval of -0,15/0,50 m a.s.l. (aquifer C); these variations are essentially determined by tidal fluctuations.

Even if the results of the numerical analyses obtained using the latest available methods are largely interpretive rather than predictive, they seem to be compatible with the hydrogeological equilibrium of the sub-structure of the lagoon and with the safety parameters of the tunnel project.

7. DISCUSSIONS

A multidisciplinary study took place by the central area in the Province of Venice. The need to develop the study came from the small amount of international scientific literature available on the problem, that is the leakage rate through abandoned wells. These leakage rates cause the transfer of great volumes of groundwaters from the AAS to the SAS.

It was therefore necessary to create new analytical equations that could mathematically describe this phenomenon. An equation in a steady state flow was identified which includes a spherical flow in the upper aquifer.

Two new analytical solutions describe the leakage rate in a transient flow. The equations differ as regards to the unknown factor which has to be made explicit: in one instance the flow in the lower aquifer is identified, in the other the one in the upper aquifer.

In order to improve this method a high number of parameters is necessary: the main ones are made up of hydraulic heads and, above all, their differences. These parameters are known both because of all the available literature and of the periodical surveys made by the various entities involved (ARPA, the Province of Venice, the Municipality of Venice, etc).

A first acquaintance with the reference hydrostratigraphic structure is essential. In order to achieve a detailed hydrostratigraphic setting updated to the latest publications available in the whole study area, **a new methodology of hydrostratigraphic analysis** was suggested.

This methodology requires the use of stratigraphic data which alone is not very reliable because of the exploited methodology (full drilling hole surveys) and the lack of known standard references. Therefore a **new software package** was conceived, called **modalstrata**. On an homogeneous area modalstrata can achieve a "modal stratigraphy" by identifying the most recurrent stratigraphy in every considered interval of depth.

In the areas with not much data available, the stratigraphic use of passive seismic was necessary, through the **SSPSS** method (**Single-Station Passive Seismic Stratigraphy**). These passive seismic surveys allowed the testing of lateral continuity in the main seismic and stratigraphic discontinuities.

The final result was the updating of the **hydrostratigraphic model in the deep Venetian area**, sufficiently detailed as to also identify subunits. This model was confirmed by the only core drilling available: Ve-1. Many authors have dealt on this survey: the latest publications have reviewed the whole sequence in detail in order to define the **Ve-1 hydrostratigraphy**, used in the validation process.

Among the main results the development of a new instrument for stratigraphic purposes, modalstrata, which can be effectively employed in other geological circumstances. The combination of this instrument with the SSPSS technique allows the defining of the hydrostratigraphic model.

The solutions, the hydrogeological and hydrostratigraphic model permit the sketching of very interesting situations. It is believed the analytical solutions achieved here and concerning a single study case can be spread to various studies and applied to a calculus code in order to establish the leakage rate through abandoned wells in a programming language. Among the many available, Feflow has proven its versatility in the analysis of the anthropic involvement on the groundwaters. This software was used in a case study in order to test the possible influence of a tunnel on the hydrogeological system. This software is an excellent instrument for the integration of the suggested new analytical solutions (IFM, Interface Manager). This combination may represent an essential step to the solution of the problem of leakage rate through abandoned wells and to the development of these methodologies on an international scientific level.

The results of this thesis can be applied to many situations which may take place more often in future because of the economical progress in the last decades which required and still requires the drilling of a high number of wells. With the deterioration of the mechanical resistance in the wells (if provided with casing) and the change in hydrogeological flows, the problem of the leakage rate through abandoned or improperly plugged wells is believed to take place always more often in the next decades.

8. APPENDIX 1: THE GEOGRAPHIC INFROMATION SYSTEM ENVIRONMENTAL

A precise organization of the information represents a necessary step not only in order to optimize data, but also to better understand the dynamic processes at hand.

Therefore the use of a GIS system (Geographic Information System) is essential to the representation and management of territorial data (and not only).

The GIS also permits a geostatistic approach to spatial data processing and an efficient support both to the creation of maps and to decisional processes.

It is believed the completed data bank may represent an excellent beginning to the development of an functioning support of the GIS data and a basis for a possible detailed numerical model of the study area.

8.1. GEOGRAPHIC COORDINATE SYSTEM

It is a "georeferenced" data bank, that is all information doesn't only provide the actual data (e.g. piezometric level, concentration of a chemical species), but also an element connected to the geographic setting. This is only possible if each element keeps its information regarding the reference coordination system. In this instance the below map coordinates were employed:

GEOGRAPHYC COORDINATE SYSTEM: MONTE_MARIO	
Projection	Transverse_Mercator
False_Easting	2520000.000000
False_Northing	0.000000
Central_Meridian	15.000000
Scale_Factor	0.999600
Latitude_Of_Origin	0.000000
Linear Unit	Meter
Datum	D_Monte_Mario

tab. 8: reference data for geographic coordinate system

Each element is dealt in the GIS and must hold the right information as regards to the reference coordinate system.

8.2. ARCGIS

The employed system for the GIS is ArcGIS 9.3.1 by ESRI. This choice is not only linked to its availability in the university, but also (and above all) to the software's philosophy.

The need to combine the information from various sources and create a cross area of cooperation is supported by intuitive and cognitive means; it's necessary to join these means with a powerful visualizing system of the analytical and moulding structure rooted in the geographic sciences (ESRI).

In order to support this function, the GIS must follow three different procedures:

1. The approach to geographic data (geo-data): a GIS is a spatial database, that is a database holding a dataset which represents geographic information as a generic data model and allows the managing of features, raster images, attributes, topologies, networks and so on.

2. The geo-visualizing approach: a GIS allows the development of complete and complex geographic representations (maps) in which geographical elements (features) and their spatial connections to the land surface are viewed. Views on the informative system below can be created which are used as windows on the database, by means of questioning, analysis and editing of the geographic information. Every GIS has its set of bidimensional (2D) and tridimensional (3D) mapping instruments which provide the interaction with the geographic information.

3. The geoprocessing approach: a GIS is a set of operative instruments for geographic analysis and data processing. The geoprocessing functions, starting from existing geographic datasets, allow the use of analytical functions and the filing of the results in new datasets. Geoprocessing allows the programming of activities and work automation through the assembling of ordered sequences of processes.

All these three approaches exist in ArcGIS, respectively represented by ArcCatalog (the GIS is a series of geographic datasets), by ArcMap (the GIS creates and processes maps) and by ArcToolbox (the GIS is a series of geoprocessing instruments).

These three different approaches represent the basics for a functional GIS and are in all the geographic programmes with various functions (ESRI).

8.3. CONCEPTUAL MODEL

The basic logical structure applied in order to deal with all the available data is represented by fig. 1, in which hierarchic levels can be viewed up to the third one.

The data is organized into different areas according to its typology in order to be traced more effectively.

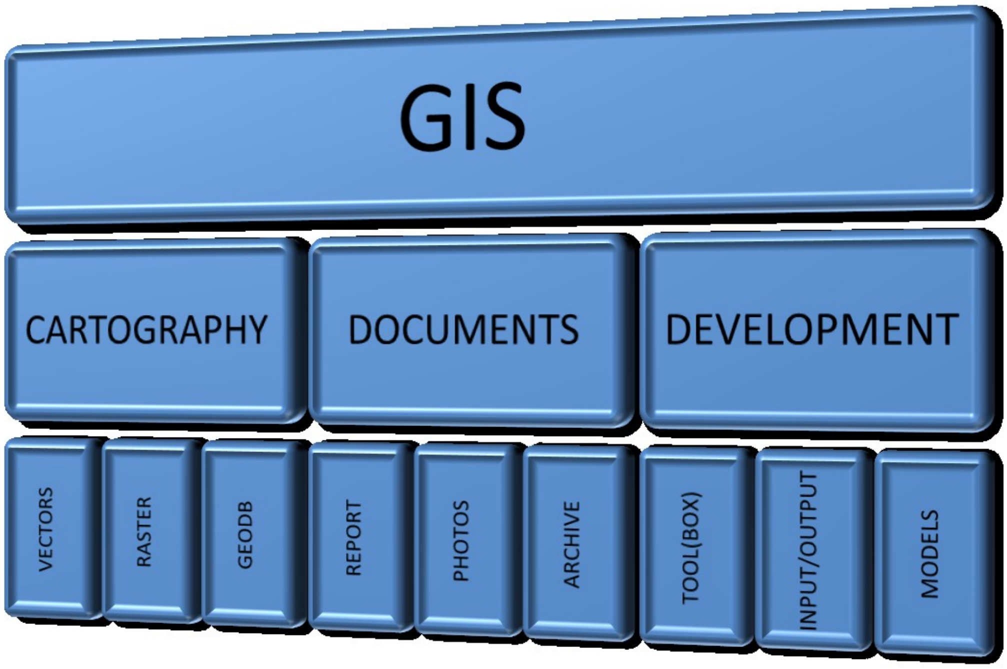


fig. 53: conceptual model employed by the GIS

8.4. CARTOGRAPHY

The cartographic data provides land references such as: topography, hydrography, anthropic structures (houses, roads, etc), but also elements (datasets) such as wells, search locations, etc. This information can be held in rasters (bitmaps, grids, etc.) or in vector files (dxf, shape, dwg); finally there are geodatabases which can hold vector files (feature datasets) and rasters (raster catalogues), besides being able to deal with complex data banks and manage connections between different elements.

8.5. DOCUMENTS

The organization of the documents is particularly advanced in the GIS as, for instance through special links, it's possible to associate a territorial element to any kind of information.

For example in this database there are photos of the surveyed areas, files regarding technical records, results of specific studies such as passive seismic.

In this part there is also all the information concerning study areas, such as pumping tests, stratigraphies, stratigraphic sections, etc.

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FIGURES INDEX

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