Deep alluvial aquifer system: an example from the Tagliamento River hydrogeological basin (NE Italy)

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ABSTRACT Over the past decades, the socio-economic development of the investigated area led to a strong increase of water demand for agricultural, industrial and drinking purposes paired with a similar increase of potential pollution sources at the surface. The Friuli-Venezia Giulia Region (northern Italy) is characterised by important water resources, both at the surface and underground. In particular, several artesian aquifer systems exist in the Quaternary deposits of the plain, to a depth of 500 m. The present research is devoted to determining the geometric, hydrogeological and hydrogeochemical characteristics of the underground water resources in the western sector of the Tagliamento River, from the town of Spilimbergo (north) to the delta (south).

1. Introduction

During the last century, climatic changes have occurred at a global scale, especially in the Mediterranean Basin which has caused a decrease in precipitations, while the socio-economic development has called for progressively more and more amounts of water (Barrow *et al*., 1995; Palutikof and Wigley, 1996; Cubasch *et al*., 1996; Palutikof *et al*., 1996; Dragoni, 1998; Mitchell and Hulme, 2000). In the western sector of the Tagliamento River (Fig. 1), where the need for water for the Pordenone Province and the area of Portogruaro is estimated at about $383 \cdot 10^6$ m^3/year and $14.6 \cdot 10^6$ m^3/year, respectively (Bellen, 1998; Consorzio di Bonifica Pianura Veneta tra Livenza e Tagliamento, 2001). In the meantime, the lowering of the piezometric level in the period 1967-1998, in the area of Spilimbergo, was 26 cm/year (Cucchi *et al*., 1999b).

At present, to satisfy the needs for drinking water, the aquifer systems are exploited (e.g. Torrate borehole field; Fig. 1) to a depth of ca. 200 m. At a regional scale, several hydrogeological research projects have been performed, but the investigation depth rarely exceeded 200 m (Stefanini, 1972; Stefanini and Cucchi, 1977, 1979; Grassi, 1995; Carniel, 1999; Cucchi *et al*., 1999a; Martelli and Granati, 2006).

In the frame of the CAMI Project (Water-bearing characterization with integrated methods; www.cami-life.net) and based on stratigraphic, geological, hydrogeological and hydrogeochemical data, the major strategic hydrogeological units of the western sector of the Tagliamento River have been recognised and characterised to a depth of 500 m.

2. Hydrogeological conceptual model

From the geological point of view, the Friuli Plain is divided into two distinct sectors, the High Plain and the Low Plain, respectively (Comel, 1955, 1958; Vecchia *et al*., 1968).

The High Plain consists of coarse-grained clastic sediments, mainly gravels, irregularly cemented in conglomerate horizons. These deposits are a consequence of the rapid progradation of an alluvial fan system formed at the end of the Late Pleistocene, mainly during the Last Glacial Maximum [20-18 ka BP (Orombelli and Ravazzi, 1996; Florineth and Schluchter, 2000)].

The Low Plain is characterised by sand and clay deposits alternating with gravel and peat horizons. These sediments are partly of fluvio-glacial origin and partly marine, lagoon and marshy origin. The thickness of the Quaternary deposits, which overlay Middle Miocene sands and calcarenites, is about 475 m in the Cesarolo area (AGIP, 1977; Fig. 1). From a structural point of view, the Low Plain is characterised by the Mesozoic ridge of Cesarolo-Lignano representing a WSW-ENE trending horst within the Friuli Carbonate Platform. The top of this structural high is at a depth of 725 m, progressively deepening northwards [e.g.: 1050 m in the area of San Michele al Tagliamento; (Calore *et al.*, 1995)].

In both sectors of the plain, the fluvial dynamics of the Tagliamento River has influenced the geometric characteristics and the lithological distribution of the underground water resources. The river originates in the Mauria Mountain (1195 m), which is 175 km long and has a catchment area of about 2871 km^2 (ABN, 1997). In the upper catchment basin, the average annual precipitation during the period 1961-1990 was about 3000 mm. Rainfall is mainly concentrated in heavy and erosive showers determining the torrential regime typical of the river. During the period 18-6 ka BP, the river occupied the western sector of the middle and lower catchment area and formed the San Vito alluvial fan (Fantin, 1990; Fig. 2). In contrast, based on the historical documentation and the interpretation of the LANDSAT TM5 image, four ancient riverbeds have been documented (A, B, C and D in Fig. 2) between the Roman period and the 16th century (Fig. 2; Rinaldi, 1870; Averone, 1911; Fantin, 1990; Castellarin, 1990; Spaliviero, 2003). During the 14th century, the middle Tagliamento was flowing more to the west compared to its present position.

One of the most important aquifer systems of Europe develops in the subsurface of the selected area. It extends from the region of Friuli to Lombardy all along a morphological belt that separates the Prealps from the Po River and the Venetian-Friuli plains. Based on the stratigraphic data [Consorzio di Bonifica Pianura Veneta tra Livenza e Tagliamento, (2001); Pordenone Province database; Friuli-Venezia Giulia Region database; private well], it is possible to define the geometric characteristics of the aquifers developed along the western sector of the Tagliamento River to a depth of 500 m. The investigation depth is strongly limited by the distribution of private and public boreholes whose maximum depth is 120 m, north of the springs alignment; in the area of Torrate, about 200 m south of the springs and 400-600 m towards the delta of the Tagliamento River (Fig. 3).

In general, the hydrogeological conceptual model is different if it is either north or south of the springs line. In the northern sector, it consists of an unconfined undifferentiated aquifer (A), made of ca. 20 to 120 m coarse-grained gravel/sandy material (Fig. 3, hydrogeological section A). The major supply of this aquifer body is through vertical infiltration of rainfall and lateral infiltration from the Tagliamento River bed. The lateral infiltration from the Tagliamento River is about 1.5 m^3/s·km; while the average annual precipitation for the period 1961–1990 varies from 1700 mm in the Spilimbergo area to 1000 m in southern sector of the Bevazzana area (ABN, 1997).

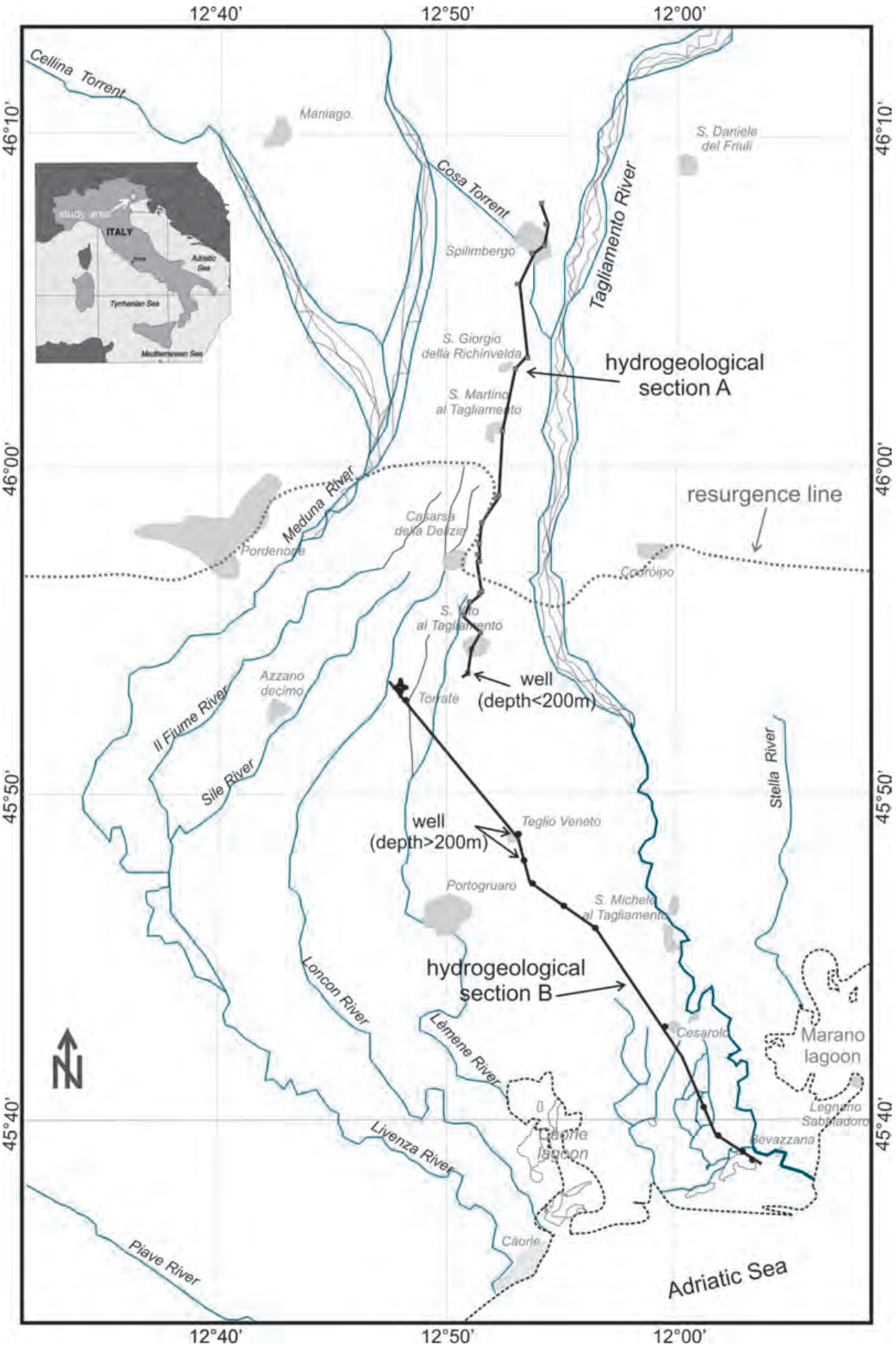

Fig. 1 - The major hydrographic features of the investigated area, west of the Tagliamento River, northeastern Italy.

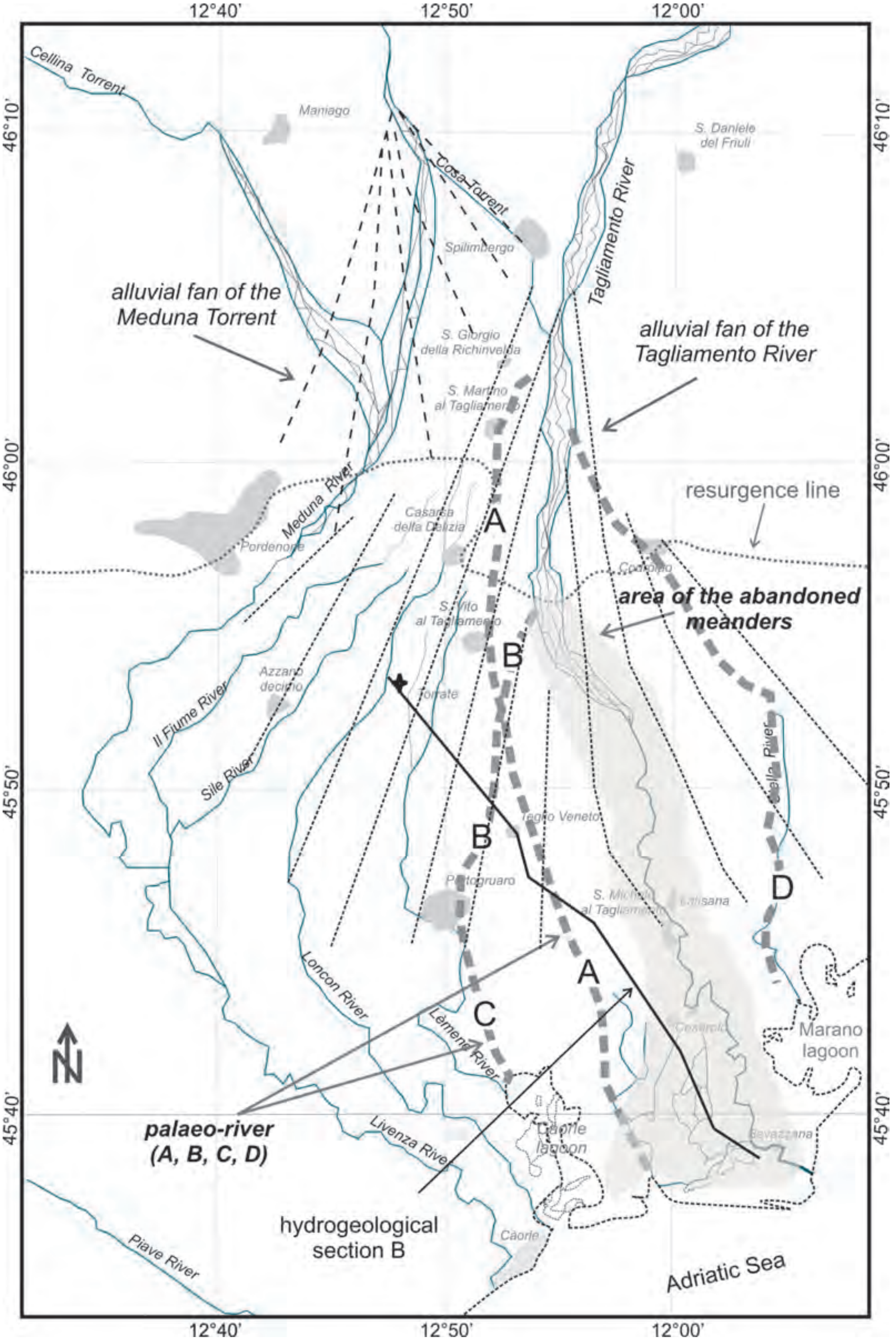

Fig. 2 - Simplified geomorfological map of the investigated area [modified from Spaliviero, (2003)]. Palaeorivers referred to in the text are labelled with capital letters.

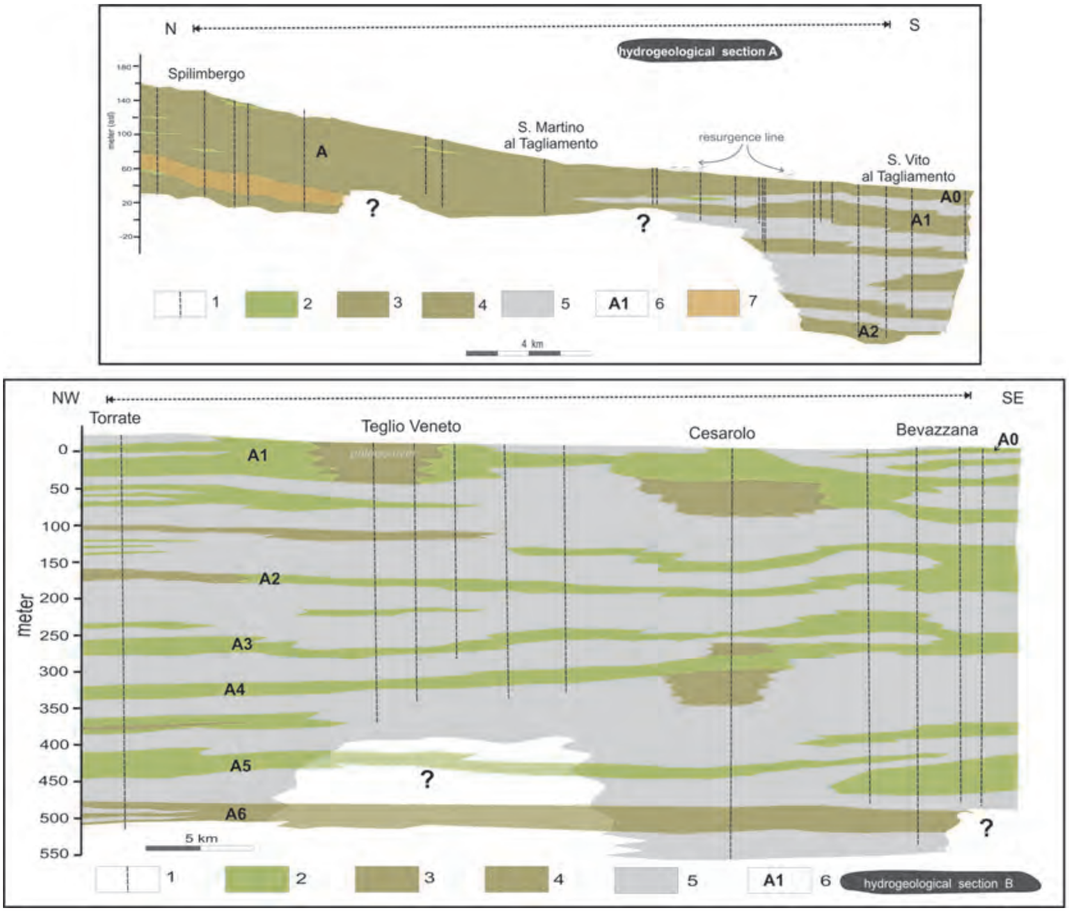

Fig. 3 - Interpretative hydrogeological section (1) borehole; (2) sand; (3) gravel; (4) sandy-gravel; (5) clay; (6) aquifer system (for location, see Fig. 1).

From the spatial distribution of the groundwater depth and using a geostatistical methodological approach for the interpretation of the point data (Kriging method), the groundwater depth varies in the southern sector from 17 m (San Giorgio della Richinvelda) to 0 m, as one approaches the springs line (Fig. 4). As a consequence of its high permeability, this unconfined aquifer body is very vulnerable to surface pollution.

By contrast, south of the resurgence line, lies a multi-aquifer system, made up of one unconfined body which, with increasing depth changes into several confined aquifer bodies of variable thickness and hydraulic permeability, consisting mainly of sandy/gravel material. In particular, up to a depth of 500 m from the surface, it is possible to recognize an unconfined aquifer (A0), a partially confined-locally unconfined aquifer (A1) and five confined aquifer systems (A2, A3, A4, A5, A6) consisting mainly of sandy materials (Fig. 3 hydrological section B).

The unconfined aquifer (A0) develops in the alluvial deposits of the Tagliamento River. The geometric characteristics of this aquifer system is strongly influenced by the dynamics of the flooding events of the Tagliamento River and it is characterised by a prevalent sand granulometry

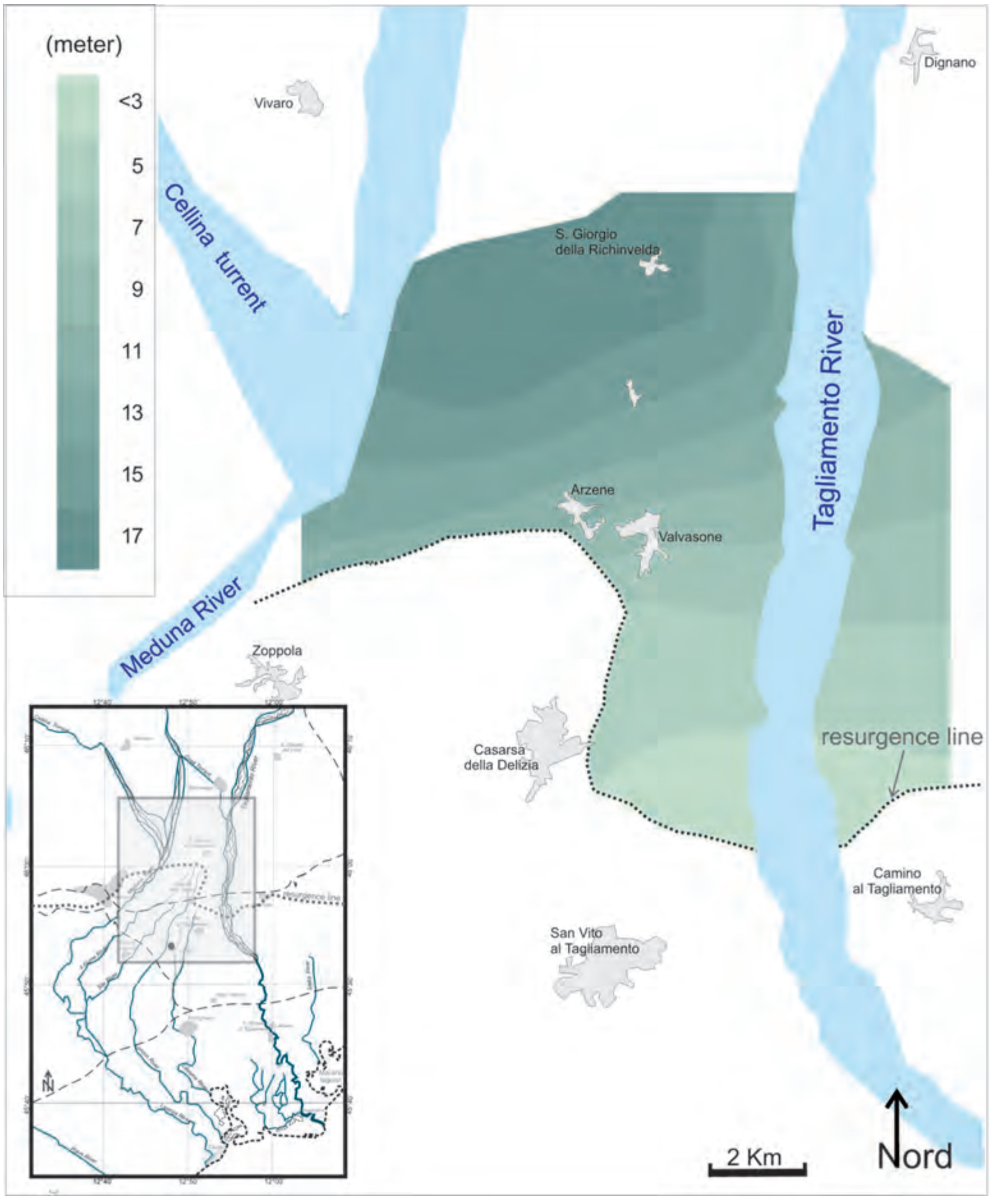

Fig. 4 - Water depth distribution of the unconfined undifferentiated aquifer system A (October, 2005).

alternating with mud and silty lenses, and locally, peat levels. Due to its reduced production capacity it is rarely exploited.

The other confined aquifer systems show a significant lateral anisotropy which is strongly influenced by the geological and geomorphological evolution of the area.

The aquifer system A1, between the spring line and the area of Torrate, is generally artesian with a natural rise of the water to 3.5 m above the field surface. It is mainly of variable sand granulometry, 40 m thick and commonly exploited for aqueduct purposes. Pumping tests in the

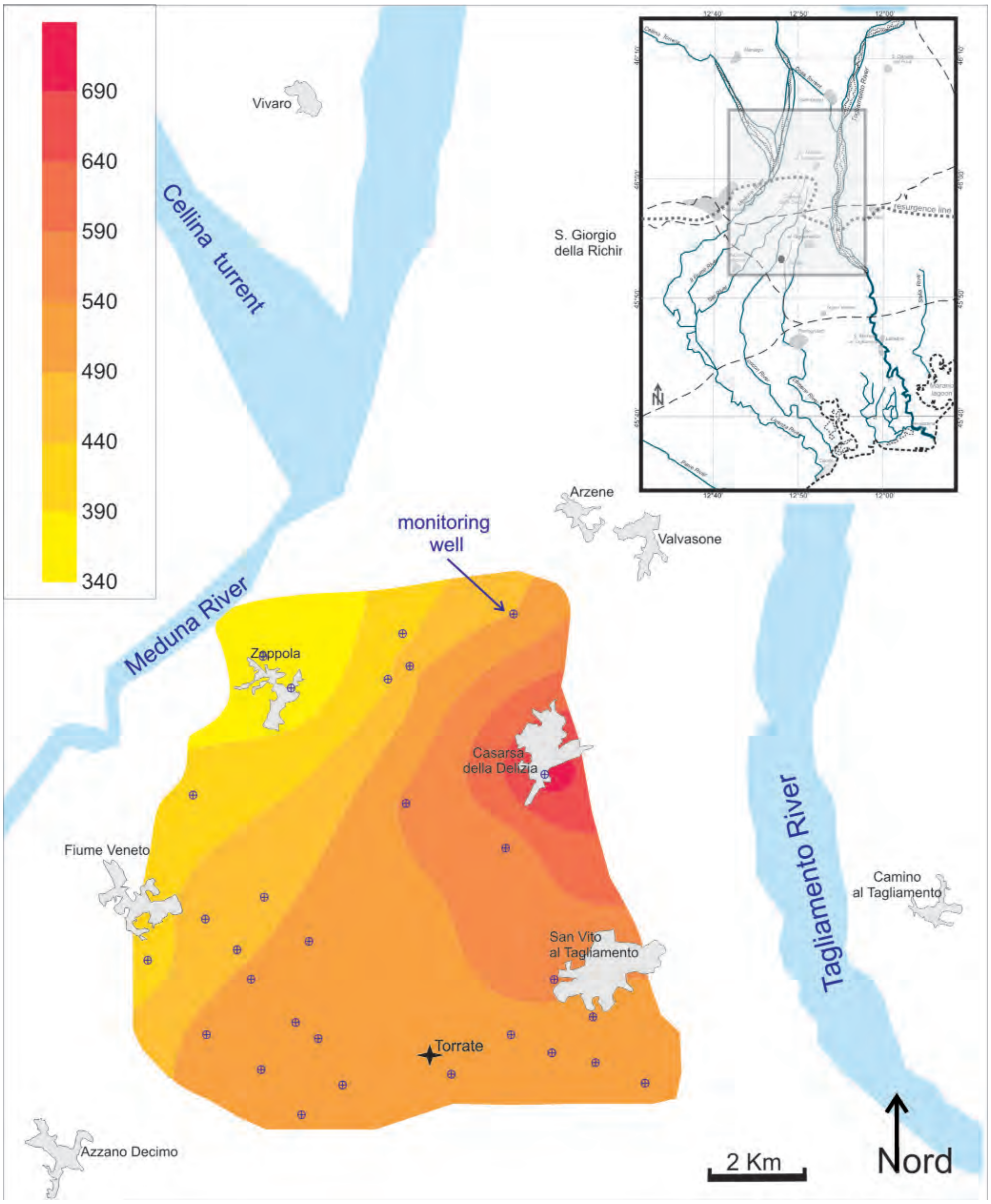

Fig. 5 - Distribution of the electrical conductivity (in microS/cm at 20 °C; October, 2005) within the first confined aquifer system (A1).

Torrate area document hydraulic conductivity values of about $5 \cdot 10^{-4}$ m/s, indicating the presence of a ‘good’ aquifer system with pervious relative permeability. Also, the electrical conductivity of this aquifer system in the Torrate area shows a seasonal variation of between 450 and 550 μS/cm.

South of Teglio Veneto, a 50 m thick gravel body represented by the Tagliamento palaeo-river bed (Fig. 3; palaeo-river A in the Fig. 2) is connected to the sandy aquifer and consequently:

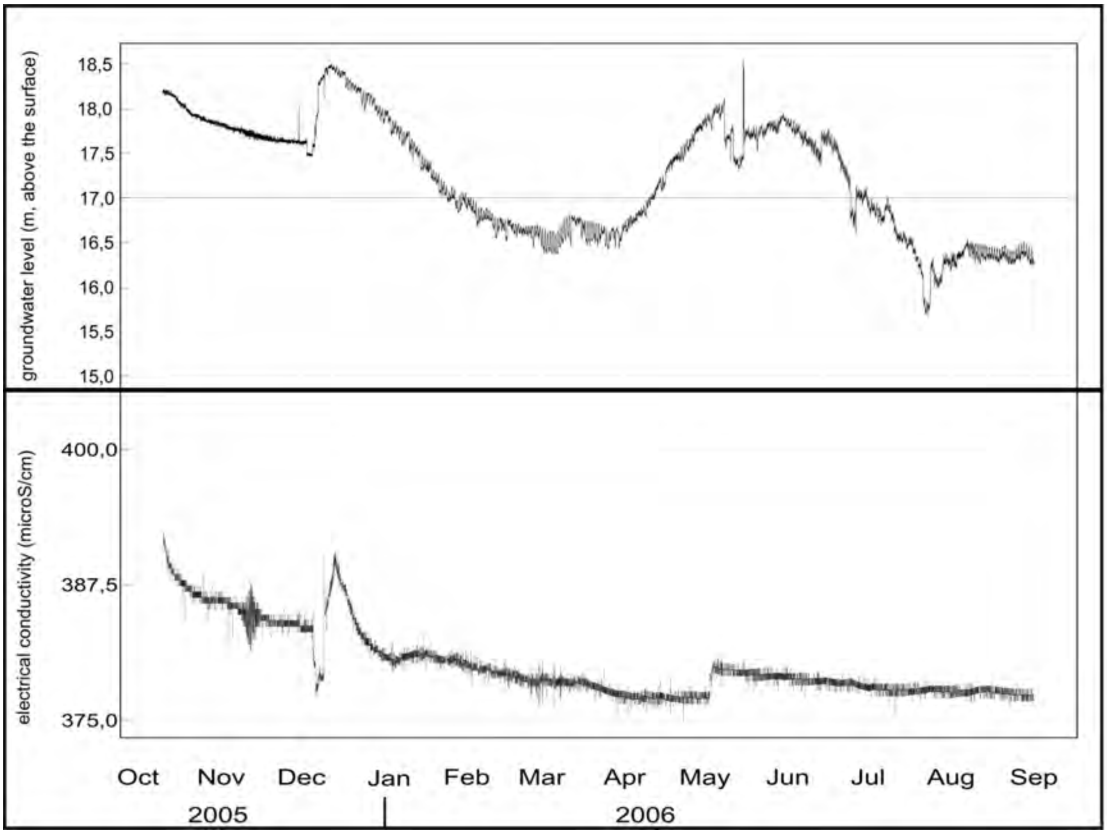

Fig. 6 - Time variation of the groundwater level (in metres) and of the electrical conductivity (in μS/cm at 20 °C) within the A2 aquifer system in the Torrate area.

a) the aquifer changes from artesian to unconfined;
b) the increase of the intrinsic vulnerability to surficial pollution sources; in the areas where the aquifer is connected to the palaeo-river bed, the electrical conductivity reaches a value of 700 μS/cm, which is much higher than the mean value of 480 μS/cm measured in the central sector of the investigated area (Fig. 5).

Close to the delta of the Tagliamento River, in the area of Bevazzana, the top of aquifer A1 progressively deepens (up to ca. 35 m), while the occurrence of a progressively thickening clay-rich lense (up to 30 m thick) split the sand body in a lower and upper subunits.

The top of the aquifer system A2 is at 180 m from the surface in the area of Torrate, and ca. 120 m, towards the delta of the Tagliamento River. From the granulometric point of view, the aquifer mainly consists of gravelly material, up to the Torrate area, while in the southern sector the sandy component prevails.

In the artesian aquifer system A2 the piezometric level is about 15.5 m above the surface. Continuous monitoring of the piezometric level and of the chemico-physical parameters in the area of Torrate (CAMI project) allowed us to emphasize that (Fig. 6):
a) during the hydrological cycle, the piezometric level shows oscillations of 1.5-2 m, with

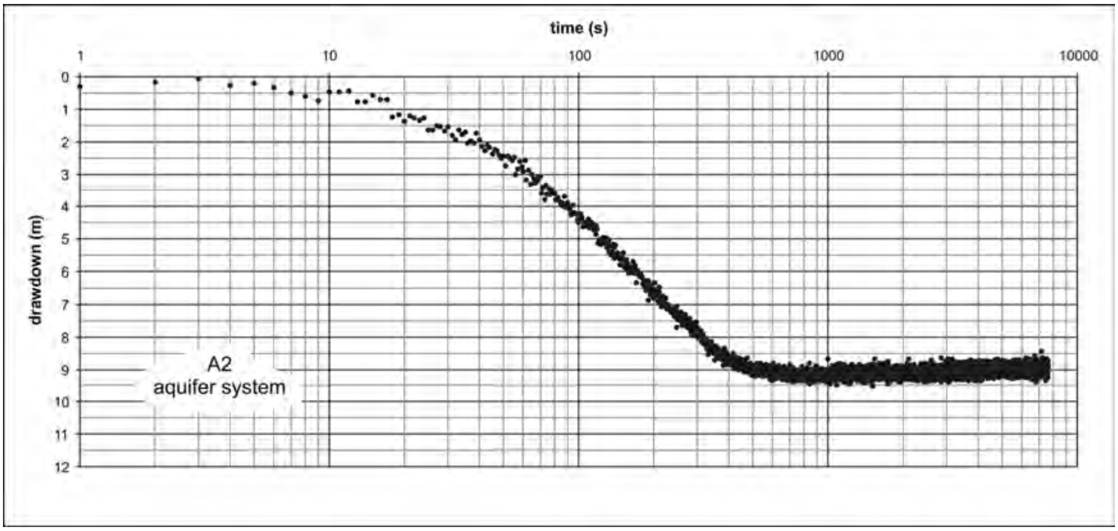

Fig. 7 - Drawdown of the piezometric level (in metres) during the pumping test in the A2 aquifer system within the Torrate area.

minimum values during the summer period, while the recharge occurs during the winter and spring months;

b) the water have a mean electrical conductivity of about 380 μS/cm, thus documenting the good geochemical characteristics of this aquifer system, while the pH and the temperature are 7.7 e 13.5° C, respectively.

The hydraulic conductivity of aquifer A2 presents variations between $4 \cdot 10^{-4}$ m/s (Fig. 7), in the area of Torrate, and $3 \cdot 10^{-5}$ m/s, in the area of Teglio Veneto.

The aquifer system A3 has a depth ranging between 220 and 280 m from the surface. Its thickness varies from 15 to 7 m, while the hydraulic conductivity is about $2.7 \cdot 10^{-5}$ m/s (Teglio Veneto). This aquifer is mainly sandy, frequently alternating with clay-rich lenses in the area of Torrate, but it pinches out in the area of Bevazzana. The electrical conductivity of aquifer A4, measured in the area of Torrate is 334 μS/cm, while in the area of Bevazzana it reaches 650 μS/cm. The temperature changes from 15.8 °C at Torrate, to 18 °C in the area of San Michele al Tagliamento and to 25 °C at Bevazzana. Such high temperatures (25 °C) are likely caused by mixing phenomena between warm fluids, coming from the Mesozoic carbonate reservoir on a large structural high of Cesarolo-Lignano (at an estimated temperature of 50-60 °C at a 1000 m depth), and the low-temperature aquifer (Dal Pra and Stella, 1978; Barnaba, 1990; Calore *et al.*, 1995; Nicolich and Squarci, 1995; Carella and Sommaruga, 2000). Finally, the pH values are around 7.7.

Aquifer A4 is hydraulically separated from the overlying system by a clay-rich layer, whose thickness varies between 27 m (Torrate area) and 7 m (Cesarolo area). Due to the local thinning of the argillaceous layer, interconnection phenomena with the overlying A3 aquifer are likely to occur. The granulometric composition is highly heterogeneous and changes from sand to muddy sand or gravels, therefore showing important local variations of the permeability.

The top of aquifer A5 is at a depth of 430 m from the surface. In the northern sector, it consists of gravels with alternating argillaceous lenses, while to the south it is mainly sandy-gravel.

The top of aquifer A6 is at a depth of about 480 m from the surface and it consists mainly of gravel deposits alternating with argilla-rich lenses. The geometrical characteristics of this aquifer are not well defined, but from the lithostratigraphic sections its southward lateral extension is quite evident. The electrical conductivity varies between 296 μS/cm (Torrate aqueduct field) and 1000 μS/cm (Bevazzana, area). The temperature oscillates between 18.9 °C (Torrate) and 29 °C (Teglio Veneto) and reaches 44 °C in the southern sector, due to the mixing phenomena of the fresh aquifer water with the deep geochemical fluid. Finally, the pH of the aquifer is 7.8 in the area of Torrate.

At present, in the area of Torrate aquifers A1 and A2 are exploited by the aqueducts, while in the southern sector, the depth of the boreholes strongly increases in its search for high-temperature water.

3. Conclusion

The Low Friuli Plain is characterised by a thick Quaternary sedimentary body. Lithostratigraphical correlations and hydrogeological investigations reveal the existence of an unconfined aquifer system, north of the springs line, and a southern confined multiaquifer system formed by six artesian aquifer systems. The definition of the geometrical parameters of the aquifers, of their hydraulic and hydrogeochemical characteristics up to a deph of ca. 500 m, will allow the Authorities responsible for the territorial planning to formulate appropriate policies for the protection, management and use of the ground- and undergroundwater resources.

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