Giornale di Geologia Applicata 3 (2006) 59-67, doi: 10.1474/GGA.2006-03.0-08.0101

The confined aquifer system of Friuli Plain (North Eastern Italy): analysis of sustainable groundwater use

Grazia Martelli[1], Cristina Granati[2]

Dipartimento di Georisorse e Territorio Via Cotonificio, 114 – 33100 Udine, grazia.martelli@uniud.it, cristina.granati@uniud.it

ABSTRACT: The hydrogeological characteristics of the Friuli Plain are derived from the depositional processes which occurred in the Upper Pleistocene. The fluctuations in the dynamics of the plain's hydrographic network connected with climatic events of Quaternary glaciations, led to a subdivision of the area into two distinct sectors: *High Plain*, formed by coarse-grained detrital sediments, prevalently gravels, irregularly cemented in conglomerate horizons; *Low Plain*, characterised by prevalently sandy deposits intercalated with pelitic horizons. A reconstruction of the aquifer layers present in the Low Friuli Plain, enabled three aquifer systems to be identified: (1) a confined aquifer system, formed by 8 variously branched superimposed artesian aquifers at average depths of between 20 and over 500 m below sea level (bsl); (2) a transitional aquifer system, comprising two confined layers at average depths of between 27.2 m above sea level (asl) and 12.2 m bsl; (3) an unconfined shallow system, developing intermittently at average depths of between 44 m asl and 18 m bsl. The groundwater of the Low Friuli Plain is exploited by means of a dense network of water-wells for drinking, agricultural, industrial and trout breeding purposes. The total quantity of groundwater drawn from the Low Plain has been estimated to be approximately $701 \cdot 10^6$ m^3 annually, 75% of which derives from the confined system. On the basis of these data a study was carried out to evaluate the sustainability of current levels of exploitation of the confined aquifer system of the Low Friuli Plain.

Key Terms: Alluvial plain, Aquifer systems, Groundwater abstraction, Groundwater sustainability, Friuli Plain
Termini chiave: Pianure alluvionali, Sistemi acquiferi, Prelievi, Sfruttamento sostenibile

Preliminary statement

The Friuli alluvial plain (North-East Italy) has a hydrogeological structure that allows identification of two distinct sectors with different characteristics (Fig. 1): the High Plain consists of a lateral succession of alluvial fans (Tagliamento, Torre, Natisone and Isonzo rivers) formed by coarse-grained fluvial sediments, prevalently gravel, which contain an unconfined aquifer principally fed by recharge from rainfall and surface waters; the Low Plain extends from the spring line to the coastline and it is formed by alternance of wide and continuous clay and silty-clay layers and sand or gravel layers, containing a multistrata artesian aquifer system; these aquifers, variously branched, may be found over 420 m bsl.

The unconfined aquifer of the High Plain constitutes a reservoir with a remarkable capacity for absorption and storage of water, that partly outflows at the spring line and partly feeds the artesian aquifers of the Low Plain.

While the hydrogeological characteristics of the High Plain are well known from scientific papers by many authors and water quality, water table depth and wells discharge are monitored, the hydrogeological knowledge of the Low Plain is scarce. Nevertheless the aquifers of the low plain are intensively exploited by means of a dense network of artesian wells for domestic, drinking, agricultural, industrial, livestock and trout breeding use. The exact number of active wells isn't known, but recent estimates suggest more than 30.000 wells to be present in the territory. The large amount of wells is due besides to ancient traditions being integrant part of a keen popular colture, even to the present lack of public supply system in some town, where the wells represent the only source of water supply. From an estimation of the annual groundwater extraction drawn from the Low Plain based on a sample of water-wells, results a volume of about $701 \cdot 10^6$ m^3. This amount is remarkable referring to a population of about 120,000.

Traditionally, water research well drilling is managed without support of technical documentation or quantitative measurements related to crossed strata characteristics in spite of the large wells discharge and depth.

The analysis of the considerable amount of collected data (over 20,000 water-wells in the last 10 years) showed the widespread fragmentary character and the shortage of technical and hydrogeological information.

Data about discharge rates concern only 2% of collected wells, lithostratigraphic data concern about 5% of collected wells. Notwithstanding the modest quality of the collected data, it has been possible to gain some relevant result with regard to the hydrogeology of the Friuli Plain: an evaluation of groundwater sustainability in the exploitation of the confined aquifer system. A reconstruction of the aquifer layers in the Low Friuli Plain was utilized (Martelli et alii, 2003; Martelli et alii, 2004) and the hydraulic gradients were calculated on the basis of measurement carried out on 80 water – wells.

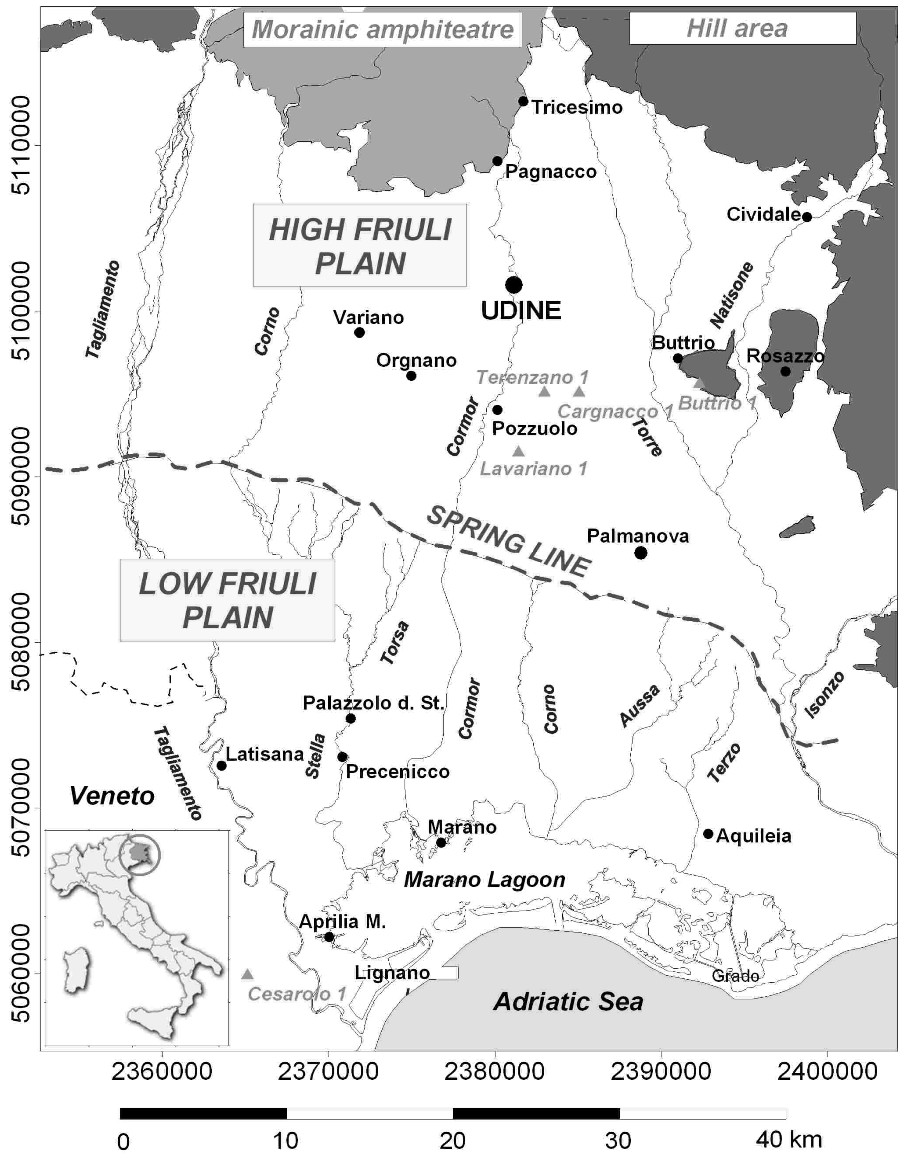

Fig.1 - The Friuli Plain between the Tagliamento river to the W and the Natisone river to the E. The AGIP boreholes are evidenced by triangle

Geological characteristics of the Friuli alluvial plain

The Friuli Plain is divided into two distinct sectors (Comel, 1958; Vecchia *et alii*, 1968):

- the High Plain, formed by coarse-grained detrital sediments, prevalently gravels, irregularly cemented in conglomerate horizons and intercalated with sand and less frequently with clay layers. These deposits are a consequence of the rapid progradation of an alluvial fan system formed in the Upper Pleistocene as a result of the LGM (Last Glacial Maximum - between 20 ka and 18 ka BP) (Orombelli & Ravazzi, 1996; Florineth & Schluchter, 1998);
- the Low Plain, characterised by sand and clay deposits intercalated with gravel horizons which become increasingly less frequent and are present at ever increasing depths as one moves southward. These sediments are partly of fluvioglacial origin and partly of marine, lagoon and marshy origin.

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

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

Studies achieved on the basis of geophysical surveys carried out by the AGIP Group in the Low Friuli Plain allowed the reconstruction of the Quaternary base to be extended over the entire area (Cavallin & Martinis, 1980; Calore *et alii*, 1995). The bathymetric maps show a thickening of the Quaternary deposits proceeding from NE (250 m in the vicinity of Palmanova) to SW (over 500 m to the W of Lignano).

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

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

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

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

During the LGM, four main fluvioglacial currents developed in the High Friuli Plain. These correspond with the present courses of the Torre, Cormor, Corno and Tagliamento rivers. As these fluvioglacial currents flow towards the Adriatic Sea, their speed and force progressively decrease and this has led to the deposit of coarse-grained alluvium and sandy-clayey sediments in the northern (High Plain) and in the southern (Low Plain) areas of the Friuli Plain respectively.

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

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

The presence of marshy areas within the alluvial plain (Marocco, 1989, 1991) is testified by peaty horizons of varying ages identified in the vicinity of Aquileia (21,700 ± 580 years BP), Aprilia Marittima (28,100 ± 250 years BP) and Marano (20,200 ± 270 years BP) at 6.3 m bsl, 29.7 m bsl and 23 m bsl respectively.

Radiometric datings (^{14}C) carried out at boreholes drilled to a depth of approximately 30 m in the Marano Lagoon (Marocco, 1989) established the age of deep continental deposits (present at a depth of 23 m) to be 20,200 ± 270 years BP, superimposed lagoon deposits (at 10.05 m) to be 5,540 ± 225 years BP and coastal sediments (at 2.60 m) to be 1,400 ± 290 years BP.

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

After the LGM, the Low Friuli Plain (Marocco, 1989,

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

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

In the Holocene, the Tagliamento river, probably together with the Corno river, formed the western sector of the Friuli Plain to the point of the eastern boundary represented by the Stella river (Boschian, 1993; Bondesan & Fontana, 1999).

The fluvioglacial deposits of the Cormor river formed the plain on the E of the Stella river. To the E of the Cormor river, the Aussa-Corno hydrographic network flows over the remains of the wide, late-glacial alluvial plain, the river bed traces of which are represented by gravelly-sandy fluvial ridges stretching N to S, while the ancient overflow area, traversed by the present spring rivers, is characterised by the presence of both fine-grained sediments and buried river-beds (Bondesan *et alii*, 1995).

Hydrogeological characteristics

The Friuli Plain in the Province of Udine (fig.1) is bordered by the Tagliamento river to the West, by the hydrographic system of the Torre and Natisone rivers to the East, by the morainal amphitheatre of the Tagliamento to the North, and by the Adriatic Sea to the South.

The progressive transformation, moving southward, of the alluvial sediments from a homogeneous structure of highly permeable gravel deposits to a differentiated structure with superimposed sand, gravel and clay layers, determines the transition of an unconfined aquifer to a multilayered aquifer system (Stefanini & Cucchi, 1977; Granati *et alii*, 2001; Martelli & Roda, 1998; Martelli *et alii*, 2003). A similar structure can be identified throughout the Po Plain and Veneto Plain (Regione Emilia-Romagna, ENI-AGIP, 1998; Antonelli et alii, 1986).

It is along this transitional stretch between the two aquifer systems that part of the High Plain's groundwater surfaces, giving rise to the area of springs which extends approximately 100 km in an EW direction and feeds the Low Plain's hydrographical network (Fig. 1). This series of springs develops beyond the Friuli region as an almost continuous element on the left of the Po river as far as the Mondovì area, to the S of Turin (Feruglio, 1925; Antonelli & Stefanini, 1982; Dal Prà *et alii*, 1989; Martinis *et alii*, 1976; Peloso et alii, 1989).

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

The aquifer system of the Low Friuli Plain

A reconstruction of the aquifer layers in the Low Friuli Plain (Martelli et alii, 2003; Martelli et alii, 2004); revealed the existence of three aquifer systems:

- a confined aquifer system, composed of eight artesian layers located from 19 to over 500 m bsl;
- a transitional aquifer system consisting of two confined layers located at average depths of between 27.2 m asl and 12.2 m bsl; this displays different characteristics from those of the confined system, from which it has been separated;
- an unconfined aquifer system located at average depth of between 44 m asl and 18 m bsl.

Confined Aquifer System

This is characterised by the presence of eight artesian layers (A, B, C, D, E, F, G, H), most of which are subdivided into sub-layers. Table 1 summarizes the thickness and the average depth of each layer and respective sub-layers. The calculated thickness and depths of layer H are purely indicative due to fact that data were only available for the depth of the top. Observations arising from an analysis of this data are as follows:

- the average depth of layer A increases in a southward direction to 80.3 m bsl and the thickness reaches a maximum of 58.3 m near the spring line in correspondence with the hydrographic systems of the Aussa-Corno and Terzo rivers; two zones, which roughly correspond with the present water-courses of the Terzo and Stella rivers, are characterised by a thickness of between 25 and 50 m which increases moving westward to the Tagliamento river;
- the greatest average depths (112.4 m bsl) of layer B are identified in the hydrographic system of the Stella and Torsa rivers; the thickness (average value of 14.5 m) is at its greatest in the western section of the Stella river and in correspondence with the Corno river; Observations arising from an analysis of this data are as follows:
- the average depth of layer A increases in a southward direction until 80.3 m bsl and the thickness reaches a maximum of 58.3 m near the spring line in correspondence with the hydrographic systems of the Aussa-Corno and Terzo rivers; two zones, which roughly correspond with the present water-courses of the Terzo and Stella rivers, are characterised by a thickness of between 25 and 50 m which increases moving westward to the Tagliamento river;
- the greatest average depths (112.4 m bsl) of layer B are

identified in the hydrographic system of the Stella and Torsa rivers; the thickness (average value of 14.5 m) is at its greatest in the western section of the Stella river and in correspondence with the Corno river; the average depth of layer C is at its greatest in the vicinity of the spring line along the upper Stella river (148.3 m bsl), in the western sector of the area between the Tagliamento and Stella rivers, and on the right of the middle Corno river; the greatest thickness of 37 m is found along the middle watercourse of the Corno river in the east side;

- layer D is located at consistent depths (max 170 m bsl) along the middle watercourse of the Stella river towards the Tagliamento river and has an average thickness of 10.6 m; in the area between the Stella and Aussa rivers, the thickness of the layer is modest (approximately 4 m), but the average depth reaches 179.3 m bsl; the greatest thickness is to be found in the area between the Tagliamento and Stella rivers and in the Marano Lagoon in correspondence with a NE-SW axis;
- layer E is located at the average depth of 215.8 m bsl and is present in the area between the Stella and Cormor rivers; the thickness (average value of 17.9 m) is greatest in the vicinity of the spring line in correspondence with the upper Stella river system;
- the greatest average depth (261.8 m bsl) of layer F is located along the lower Tagliamento river; the thickness reaches a value of 40.3 m in the vicinity of the Tagliamento river.

Table 1. The confined system: summary of data relating to depth and thickness.

LAYER	N°	THICKNESS (m)			AVERAGE DEPTH (m bsl)	
		min	max	med	min	max
A	152	1.2	58.3	29.7	19.4	80.3
A_1	46	1.2	20.0	10.6	19.4	34.8
A_2	82	2.0	37.0	19.5	38.5	63.9
A_3	88	1.5	27.0	14.3	62.0	80.3
B	102	1.5	27.4	14.5	80.1	112.4
B_1	61	2.0	21.5	11.8	80.1	91.7
B_2	44	1.5	20.0	10.8	91.5	104.2
B_3	9	4.5	11.3	7.9	106.9	112.4
C	57	2.8	37.0	19.9	114.6	148.3
C_1	15	3.0	11.0	7.0	114.6	122.3
C_2	21	2.0	19.0	10.5	125.8	137.2
C_3	20	4.0	21.0	12.5	140.7	148.3
D	76	1.1	20.0	10.6	152.5	179.3
D_1	57	1.1	18.5	9.8	152.5	168.5
D_2	22	3.5	15.0	9.3	165.8	179.3
E	40	3.7	32.0	17.9	181.5	215.8
E_1	7	4.0	15.0	9.5	181.5	190.9
E_2	11	4.0	16.0	10.0	193.3	206.6
E_3	21	3.7	13.2	8.5	211.2	215.8
F	52	1.5	40.3	20.9	219.5	261.8
F_1	11	4.3	20.9	12.6	219.5	230.5
F_2	23	1.5	11.0	6.3	232.2	241.1
F_3	13	4.0	11.0	7.5	244.8	255.1
F_4	4	7.7	11.0	9.4	258.2	261.8
G	3	9.0	12.7	10.9	267.3	276.4
H	22	2.7	62.0	32.4	303.3	553.0

Transitional Aquifer System

This is particularly developed in the NW sector and represents the transition of the unconfined aquifer of the High Plain to the confined system of the Low Plain. On the basis of data obtained from 11 water-wells, it was possible to identify two confined layers (S_1, S_2), at average depths of between 27.2 m asl and 12.2 m bsl. These are determined by the appearance of superficial clayey horizons near the spring line. The average thickness and depth of each layer are indicated in Table 2.

Table 2. The transitional system: summary of data relating to depth and thickness.

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

Unconfined Aquifer System

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

Evaluation of annual groundwater abstraction in the Low Friuli Plain

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

An evaluation of the annual volume of groundwater drawn from the Low Plain aquifers was carried out based on a sample of 11,864 water-wells, only 605 of which were provided with discharge data. With regard to the remaining 11,259 water-wells, extraction values were estimated using analogical criteria: a discharge rate of 0.78 l/s, equivalent to the average extraction from documented wells of the same use, was applied to domestic water-wells, most of which are continuously active. A discharge rate of 0.35 l/s was applied to agricultural wells which are actively used for a period of three months per year. As regards industrial wells, a discharge rate of 0.7 l/s was applied, based on the assumption that these flow continuously 24 hours a day. A discharge rate of 3.1 l/s and 0.78 l/s were applied respectively to trout breeding wells and those for livestock use. A discharge rate of 0.78 l/s was applied to non defined use wells (Granati *et alii*, 2000).

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

Table 3. Summary of extraction rates.

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

In order to estimate extraction levels from the confined aquifer system, 567 water-wells supplied with depth and discharge data were examined. Each well is attributed to an aquifer layer (confined or unconfined) according to depth and the stratigraphic data available. The known extraction rate is estimated at $394 \cdot 10^6$ m^3/year, 25% of which comes from the unconfined aquifer system. The same percentage was applied in analogy to the total groundwater volume in order to evaluate extraction rates from the confined aquifer system. Results revealed a total extraction rate of $526 \cdot 10^6$ m^3/year, of which $294 \cdot 10^6$ m^3/year - approximately 56% - represents the known extraction rate, while $232 \cdot 10^6$ m^3/year represents the estimated extraction rate. The latter was distributed among the confined layers in proportion to known extraction rates (Table 4).

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

Table 4. Summary of extraction rates from the confined aquifer system

Layers	Known extraction (Mm^3/y)	Estimated extraction (Mm^3/y)	Total extraction (Mm^3/y)
A	154	122	276
B	93	7	167
C	10	8	18
D	14	11	25
E	9	7	16
F	9	7	16
G	1	1	2
H	3	2	5
Total	293	232	525

Groundwater sustainability in the exploitation of the confined aquifer system

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

Table 5. Hydraulic conductivity calculated from available data.

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

Table 6. Hydraulic conductivity values in the Low Friuli Plain (Osservatorio Geofisico Sperimentale di Trieste, 1988)

Municipality	Gravel (depth, m bsl)	Sand (depth, m bsl)	K (m/s)
Talmassons	21.5-22.0		$3.9\cdot10^{-5}$
Codroipo	28.0-28.5		$7.1\cdot10^{-5}$
S.Giorgio di Nogaro		42.0-42.5	$8.3\cdot10^{-6}$
Talmassons	46.0-46.5		$3.1\cdot10^{-5}$
Gonars	51.0-51.5		$5.0\cdot10^{-5}$
Codroipo	61.0-61.5		$4.2\cdot10^{-5}$
Latisana		77.5-78.0	$7.2\cdot10^{-6}$
Gonars	91.0-91.5		$2.9\cdot10^{-5}$
Talmassons	91.0-91.5		$2.8\cdot10^{-5}$
S.Giorgio di Nogaro		116.0-116.5	$7.4\cdot10^{-6}$
Latisana		192.5-193.0	$5.4\cdot10^{-5}$
S.Giorgio di Nogaro		219.5-220.0	$3.4\cdot10^{-6}$
S.Giorgio di Nogaro		263.0-263.5	$4.3\cdot10^{-6}$
Latisana		268.0-268.5	$8.4\cdot10^{-5}$
Latisana		315.5-316.0	$6.6\cdot10^{-5}$
S.Giorgio di Nogaro		341.5-342.0	$5.5\cdot10^{-6}$
S.Giorgio di Nogaro		390.0-390.5	$7.7\cdot10^{-6}$

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

In particular, the hydraulic gradients (Table 5) for layers A, B, C, D, F, were calculated on the basis of measurements of groundwater levels obtained from a sample of 80 water-wells appertaining to these aquifers: the values ranging from 0.00082 to 0.002. The similar value for the layer B, C, D, suggests a possible hydraulic continuity between the different aquifer layers and that therefore the silty-clayey levels act as be aquitards. The cross-sectional flow area used for the calculation, 43,700 m long, is located in correspondence with the spring line between the Tagliamento and Torre rivers. As a result, the hydraulic conductivity values of aquifers A and B, are particularly high, ranging between $6.8{\cdot}10^{-3}$ and $4.6{\cdot}10^{-3}$ m/s, thus indicating that exploitation rates are at border-line level with aquifer capacity. These hydraulic conductivity values were compared with data obtained from both falling-head permeameter tests carried out in samples coming from boreholes of the Low Friuli Plain (Osservatorio Geofisico Sperimentale di Trieste, 1988) (Table 6) and pumping tests (Table 7) carried out in the Mestre area (Antonelli, 1994). It can be observed that the estimated hydraulic conductivity values (Table 5) are somewhat higher than those measured in the Low Friuli Plain and in the Veneto Plain.

The confined aquifers of the Mestre subsoil are prevalently in sands, while the confined aquifer system of the area studied here is characterised by both sand and gravel. In particular, the lithology of layers A and B is predominantly gravelly in the northern sector of the Low Plain and prevalently sandy in the southern sector. Layers C corresponds principally to sand horizons, while layers D and F are characterised by both lithologies.

Conclusions

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

Table 7. Hydraulic conductivity values in the Mestre area of the Veneto Plain (Antonelli, 2004).

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

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

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

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

References

Antonioli F. & Vai G.B. (2004) – Climex Maps Italy. Explanatory notes. 32nd International Geological Congress Florence Italy, Bologna, 80 pp.

Antonelli R. (1986) – Primi risultati di ricerche idrogeologiche sulla ricarica naturale delle falde nell'alta pianura alluvionale del fiume Piave. Mem. Sc. Geol., 38: 393-413, 13 figg., 1 tab., Padova.

Antonelli R. (2004) – personal communications

Antonelli R. & Stefanini S. (1982) – Nuovi contributi idrogeologici ed idrochimici sugli acquiferi dell'alta pianura veronese. Mem. Sc. Geol., 35: 35-67, Padova.

Bondesan A. & Fontana A. (1999) – La geomorfologia della bassa pianura friulana sud-occidentale. Proceedings of "Le Pianure. Conoscenza e salvaguardia: il contributo delle scienze della terra", 8-11 November 1999, Ferrara: 206-207, Bologna.

Bondesan A., Castiglioni G.B., Elmi C., Gabbianelli G., Marocco R., Pirazzoli P.A., Tomasin A. (1995) – Coastal Areas at Risk from Storm Surges and Sea – Level Rise in Northeastern Italy. Journal of Coastal Research, 11(4): 1354-1379. Fort Lauderdale (Florida).

Boschian G. (1993) – Paleoidrografia della bassa pianura friulana tra i fiumi Tagliamento e Stella. Il Quaternario, 6 (1): 49-58, 2 figg., Roma.

Calore C., Della Vedova B., Grassi S., Marson I., Nicolich R. & Squarci P. (1995) – A hydrothermal system along the coastal area of Friuli-Venezia Giulia region (NE Italy). Transactions of "Geothermal Resources Council - World Geothermal Congress", May 1995, Firenze, 2: 1269-1274, Firenze.

Cavallin A., Lauzi S., Marchetti M. & Padovan N. (1987) – Carta geomorfologica della Pianura Friulana ad est del F.Tagliamento e a sud dell'anfiteatro morenico. Proceeding of "Riun. Ricercatori Geologia", Milano.

Cavallin A. & Martinis B. (1980) – I movimenti recenti ed attuali della regione friulana. In Alto, Cr. SAF, 42, Udine.

Comel A. (1955) – Monografia sui terreni della pianura friulana. II. Genesi della pianura centrale connessa all'antico sistema fluvioglaciale del Tagliamento. Nuovi Ann. Ist. Chim. Agr. Sperim. Gorizia, 6, pp.217, Gorizia.

Comel A. (1958) – Note illustrative della Carta Geologica delle Tre Venezie. Foglio 40 Palmanova. Uff. Idrogr. Del Magistrato alle Acque, Sez. Geolog., 50 pp., 2 tabb., Padova.

Correggiari A., Roveri M. & Trincardi F. (1996) – Late Pleistocene and Holocene evolution of the North Adriatic Sea. Il Quaternario, 9 (2): 697-704, Roma.

Dal Prà A., Fabbri P. & Bellenghi G. (1989) – Esempi di sfruttamento delle falde artesiane nella media pianura veneta in aree non servite da acquedotti pubblici. Modalità di utilizzazione, quantità dei prelievi, vantaggi ed effetti negativi. Mem. Sc. Geol., 41: 115-130, 18 figg., Padova.

Dal Prà A., Fabbri P. & Pollastri L. (1989) – Caratteri idrogeologici della zona di San Polo e Ormelle in sinistra Piave nella pianura trevigiana. Mem. Sc. Geol., 41: 459-478, 18 figg., 5 tabb., Padova.

Feruglio E. (1925) – La zona delle risorgive del basso Friuli fra il Tagliamento e la Torre. Ann. Staz. Chim. Agr. Sperim. Udine, ser.3, 1 , pp.346, 24 figg., 10 tavv., 1 carta geol. 1:50.000, Udine.

Feruglio E. (1936) – Sedimenti marini nel sottosuolo della bassa pianura friulana. Boll. Soc. Geol. It., 55: 129-138, 1 tav., Roma.

Florineth D. & Schluchter C. (2000) – Alpine Evidence for Atmospheric Circulation Patterns in Europe during the Last Glacial Maximum. Quaternary Research, 54: 295-308, Washington.

Gambolati G. (1998) – CENAS. Coastline Evolution of the Upper Adriatic Sea due to Sea Level

Rise and Natural and Anthropogenic Land Subsidence. Kluver Academic Publishers. Netherlands, 344 pp.

Granati C., Martelli G. & Roda C. (2000) - Valutazione preliminare del volume di acqua estratta annualmente in Provincia di Udine dal sottosuolo della Bassa Pianura Friulana. IGEA, 15: 13-26, Torino.

Granati C., Martelli G. & Roda C. (2001) - Characterisation of the Artesian Aquifers in the Friuli Plain (NE Italy) by Means of Low-Quality Hydrological Data. Journal of Conference - EUG XI – Strasbourg – 8/12 April 2001: 48, Cambridge.

Marocco R. (1988) – Considerazioni sedimentologiche sui sondaggi S19 e S20 (delta del F.Tagliamento). Gortania, Atti Museo Friul. Storia Nat., 10: 101-120, 4 figg., Udine.

Marocco R. (1989) – Evoluzione quaternaria della laguna di Marano (Friuli-Venezia Giulia). Il Quaternario, 2 (2): 125-137, 3 figg., 4 tabb., Roma.

Marocco R. (1991) – Evoluzione tardopleisto cenica-olocenica del delta del F. Tagliamento e delle lagune di Marano e Grado (Golfo di Trieste). Il Quaternario, 4 (1b): 223-232, 4 figg., 1 tab., Roma.

Martelli G.& Roda C. (1998) - L'acquifero della Bassa Pianura Friulana in Comune di S. Giorgio di Nogaro. Quaderni di Geologia Applicata, 5 (1): 15-38, Bologna.

Martelli G., Granati C. & Roda C. (2003) - Distribution of coarse-grained sediments in the Friuli alluvial plain (Northern Italy) from the surface till the depth of 50 metres. Quaderni di Geologia Applicata - Serie Aiga, 2 (1): 131-146, Bologna.

Martelli G., Granati C. & Rossi S. (2004) – The multistrata aquifer system in the Low Friuli Plain (NE Italy). Proceedings of International Symposium on Earth System Sciences, 267-274, Istanbul.

Martinis B., Pozzi R., Cavallin A. & Mancuso M. (1976) – Indagine sugli acquiferi della Lombardia centro-settentrionale. Quaderni IRSA, 28 (4): 97-134, Roma.

Mosetti F. (1983) – Sintesi sull'idrologia del Friuli-Venezia Giulia. Quaderni ETP, 6, 159 pp., Udine.

Orombelli G. & Ravazzi C. (1996) – The late glacial and early Holocene: chronology and paleoclimate. Il Quaternario, 9 (2): 439-444, Roma.

Osservatorio Geofisico Sperimentale di Trieste (1988) – Studio idrogeologico e geofisico della bassa pianura friulana ubicata a Sud della linea delle risorgive e compresa tra il Torrente Cormor e il Golfo di Panzano. Rapporto preliminare; allegato n.2; allegato n.4. Trieste.

Peloso G.F. & Cotta Ramusino S. (1989) – Idrogeologia della pianura bronese-stradellina (Oltrepò pavese): caratteristiche dei corpi idrici sotterranei e considerazioni sul loro sfruttamento. Atti Tic. Sc. Terra, 32: 125-162, 17 figg., 12 tabb., Pavia.

Regione Emilia-Romagna, ENI-AGIP (1998) – Riserve idriche sotterranee della Regione Emilia-Romagna. Edited by G. Di Dio, S.EL.CA, 120 pp., Firenze.

Stefanini S. (1978) – La falda freatica nell'Alta Pianura friulana. Quaderni IRSA, 34 (14): 343-360, Roma.

Stefanini S. & Cucchi F. (1977) – Gli acquiferi nel sottosuolo della provincia di Udine (Friuli-Venezia Giulia). Quaderni IRSA, 34 (6): 131-147, CNR P/368, Roma.

Vecchia O., De Wrachien D. & Magini A. (1968) – Le acque sotterranee nella Pianura Friulana Orientale. Tip. Ambrosini, 149 pp., 11 figg., Penne.

Venturini S. (1987) – Nuovi dati sul Tortoniano del sottosuolo della pianura friulana. Gortania, Atti Museo Friul. Storia Nat., 9: 5-16, 5 figg., Udine.