

Quantitative hydrogeological studies of the Treviso alluvial plain, NE Italy

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Abstract

The alluvial plain of Treviso (NE Italy) is one of the most important aquifers in the Veneto Region. Numerous hydrogeological studies of this unconfined groundwater system of the Venetian Plain provided qualitative and semi-quantitative data for its structural and hydrodynamic assessment. The unconfined aquifer changes from high plain southwards to multi-layered confined or semi-confined aquifers. The transition zone corresponds to a band 2–5 km wide where characteristic plain springs emerge with maximum discharge along a line known as the *fontanili* line. Important groundwater resources are exploited by widespread industry and agriculture, and also for public water supply including some large towns outside of study area. In recent years some test sites at which the knowledge of hydrodynamic parameters of the aquifer were improved, have been established in the study area. These, together with already available data (geometry, boundary conditions, recharge-discharge process, flow nets) allowed a water balance and a 2-D finite difference groundwater flow model to be constructed. A first calibration gave reasonable results. This flow model could be developed further to provide a tool for managing groundwater resources including chemical water quality when combined with chemical transport models.

Keywords: Treviso (NE of Italy), porous media, groundwater protection, water budget, numerical modelling

The high alluvial plain of Treviso (NE Italy) is one of the most important aquifer systems of the Veneto Region. There are considerable water resources in the gravelly and sandy strata, with a high vertical and lateral continuity down to the bedrock. These resources are of good quality, due to very active recharge mainly from massive leakage of two main rivers the Brenta and Piave, to the west and east respectively (Fig. 1). In the specific study area about 250 000 people live in 17 municipalities, including the town of Treviso.

There are nine public drinking-water plants, each being a multiple well system, as well as many thousands of domestic, industrial and agricultural wells, with an estimated combined production of about 110 ×

10³ m³/day. Immediately south of the studied area approximately 520 × 10³ m³/day of drinking-water are extracted to supply Treviso, Mestre and Venice.

In the last twenty years, because of intensive agriculture and the spread of industrial activity, general deterioration of groundwater quality standards as hardness and conductivity increase, began to be observed by ARPA (Regional Agency Environmental Protection) in some plain areas, where the most relevant recharge processes take place. More recently, some cases of pollution (nitrates, pesticides, organic chemicals) have been observed north of Treviso (Antonelli & Dal Prà 1991; Zangheri 1995; Antonelli *et al.* 2000).

In this hydrogeological system of regional relevance, classical numerical methods have been applied using previously acquired hydrogeologic parameters. The aim of this research is to devise a finite difference flow model, to which a mathematical model of groundwater quality may later be related. The final target is to give decision-makers an indispensable instrument for groundwater management and control.

Description of site

Geological and hydrogeological scheme of conceptual model

The Montello anticline defines the northern boundary to the hydrogeologic domain of the alluvial plain (Fig. 1). It marks the southern edge of the Pre-Alps and is composed of the Upper Miocene conglomerates and Late Miocene calcarenites with low permeability. The river Piave defines the study area to the east and cuts its own coarse, permeable alluvial deposits, allowing part of its discharge to reach the underlying free aquifer. As there is no natural hydrogeological boundary, the lines joining Montebelluna-Barcon and Barcon-Istrana-Treviso have been assumed as the outer limits respectively west and SW.

The southern boundary corresponds to the plain spring-line (*fontanili zone*).

The whole high and middle plain of Treviso is a well-defined alluvial unit, mostly formed of the ancient riverbeds of the Palaeo-Piave, which flowed much further west than it does nowadays. The low plain starts to the south of lower boundary of plain springs and extends to the Adriatic coast line (Figs. 2 & 3).

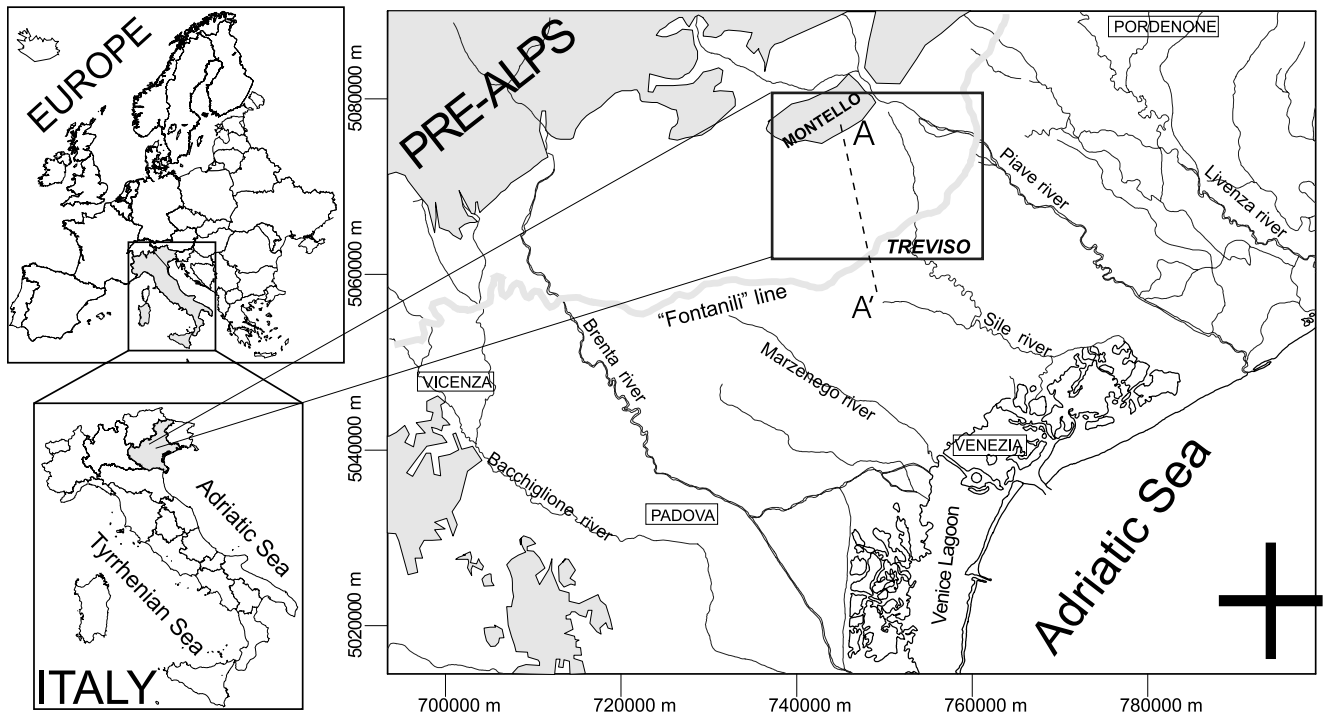


Fig. 1. Geographical sketch of NE Italy; trace of geological cross-section (A-A') of Figure 3. Study area rectangle near Treviso

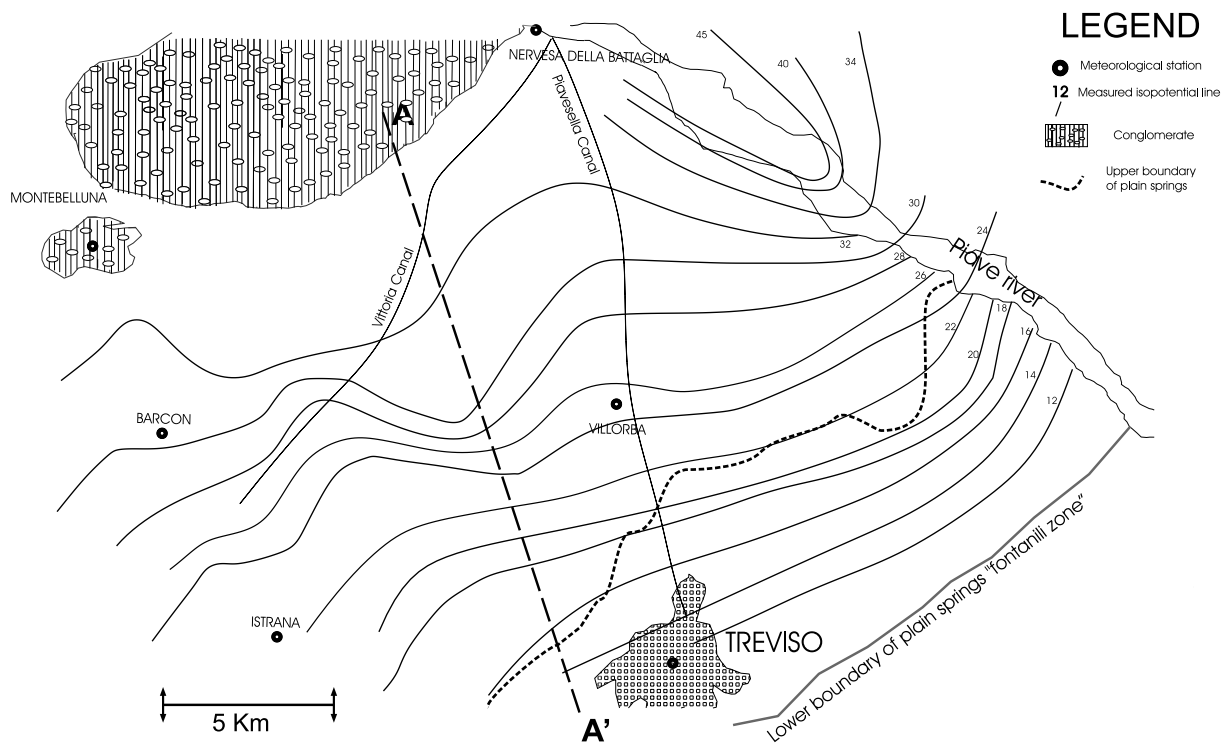


Fig. 2. Measured isopotential contour lines of study area.

During and after the Würm glacial period, the Piave channels formed large alluvial fans which were overlapped and laterally penetrated by fans from adjacent rivers. As shown in Figure 3, the entire plain from the piedmont belt in the north to about 15 km south, thus consists of an undifferentiated accumulation of gravel with sand, sometimes interbedded with

clay layers. In the distal part of this fan, the alluvial body is made up of alternating layers of gravel, sand, silt and clay, the fine-grained deposits being of lagoonal or marine origin. At variable depths between 50 and 150 m, the Riss-Würm conglomerate is interbedded within this sediment (Venzo 1977; Surian *et al.* 1993).

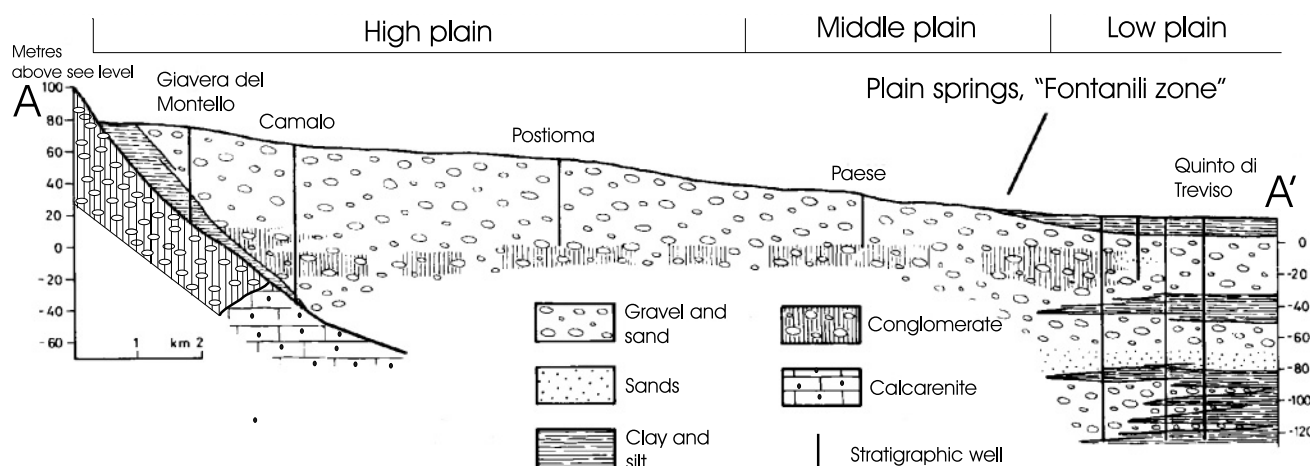


Fig. 3. Hydrogeological cross-section.

A large unconfined aquifer is located in this alluvial cover, extending southwards from the Pre-Alps as the 'high plain' where water table is at maximum depth, to a 'middle plain' band 2–5 km wide and several kilometres long, where the water table, being very shallow, intersects the topographic surface. In this band, numerous characteristic plain springs emerge (Figs. 2 & 3), which are called *fontanili*. This natural drainage system supplies numerous perennial stream-flows (Fig. 1) e.g. river Sile ($5\text{--}6 \text{ m}^3 \text{ s}^{-1}$).

The relatively homogeneous unconfined hydrogeological unit changes into a multi-layered confined or semi-confined aquifer system south of the *fontanili* zone. Impervious or semi-pervious layers which may be more than 10 m thick, are interbedded with sand and gravel. The thickness of this aquifer system increases progressively towards the Adriatic Sea.

Many public wells of different depths (100–200 m) were drilled in the southern part of the study area and screened in multilayered aquifer system in order to supply the cities of Venice, Mestre and Treviso (about 400 000 people) with drinking- water.

Hydrological and hydrogeological parameters

Data from previous researches

In the last twenty years, many regional and local scale hydrogeological studies have been carried out in this area and, although they were collected over a long period of time, have yielded many representative experimental data over a wide area.

Conventional pumping tests with observation boreholes, single-borehole tests and slug injection tests conducted throughout the area have given values of hydraulic conductivity from $k=12.9 \text{ m/day}$ to 596 m/day and transmissivity from $T=1 \times 10^3 \text{ m}^2/\text{day}$ to $1.2 \times 10^4 \text{ m}^2/\text{day}$ (Antonelli 1986; Antonelli *et al.* 1995;

Callegari *et al.* 1989). Hydraulic tests were executed in partially penetrating wells. The maximum thickness of the homogeneous unconfined aquifer is not yet well known, but it may be estimated around 250–300 m, according to data from some deep exploratory wells in the area.

New experimental data

At two test sites, ten new production wells and monitoring piezometers were drilled a few kilometres north of Treviso, in order to supplement data from existing wells (Fig. 4). This was done in order to verify the most important hydrogeological parameters (transmissivity, hydraulic gradient, flow velocity, kinematic porosity). An average transmissivity value of $T=1 \times 10^4 \text{ m}^2/\text{day}$ was obtained. Six total porosity tests were carried out at the bottom of gravel quarries (15–20 m depth) and four others in smaller excavation pits (2–3 m depth). The adopted method consisted of determining the difference between the volume of the small hand-made pits (V_p), filling these after proofing by water, and the volume of the excavated alluvium obtained by immersion (V_s). They yielded a range of values of $15\% \pm 5$.

Regional water balance

Some preliminary notes

Several steady-state flow nets of regional groundwater flow, developed on the basis of piezometric measurements, provided good field evidence of the groundwater recharge-discharge process at the selected boundaries of the hydrogeological domain. These were interpreted quantitatively in order to set up the hydrogeological budget for the watershed in question.

In this phase of model planning, a steady-state water balance was considered sufficient, assuming that the entire basin was a black-box, with its components

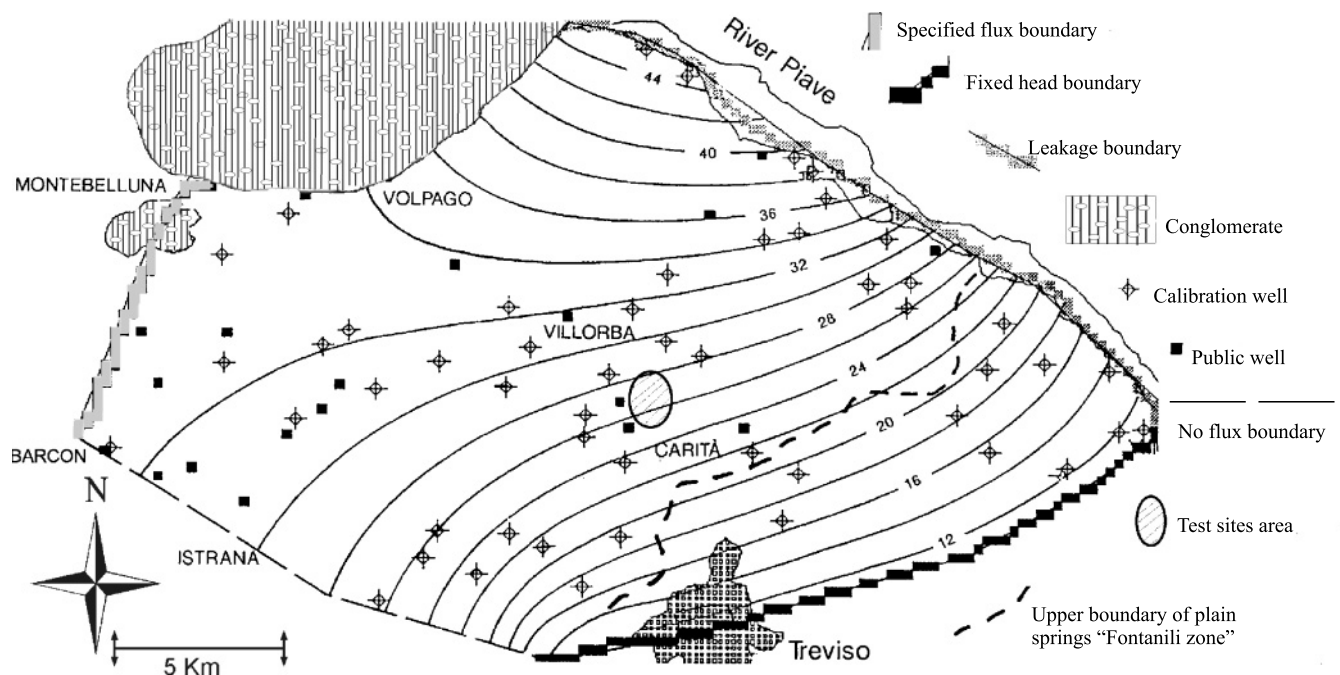


Fig. 4. Boundary conditions, simulated head distribution and observation-calibration wells.

lumped together according to the theory of systems analysis (De Marsily 1986). As a consequence some recharge and discharge components of the hydrologic cycle were treated by an approach which masks the importance of time-dependent effects, e.g. the incoming river Piave and irrigation canals, which lose water to the subsurface system as they traverse the recharge area.

Recharge components

Annual precipitation was interpolated from 5 meteorological stations well distributed on the plain. Data recorded over the last 16 years were compared with those of another series over a period of more than 20 years in order to verify the variance of data.

In the study area, the average rainfall computed by the Thiessen method is 1071 mm/a. Using the Turc formula corrected by average monthly rainfall (Turc 1954), an effective infiltration recharge of about 450 mm/a was estimated. The application of other common methods based on empirical correlations between evapotranspiration and climatic factors, i.e. Blaney & Criddle (1950), Thornthwaite (1948), did not, for the purposes of this paper, give significantly different values.

Leakage from the Piave river along the whole eastern boundary of the watershed was estimated by 10 differential flow rate measurements at each of 5 cross-sections along the river at different seasonal conditions. A recharge of $1.7\text{--}1.8 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-1}$ was calculated, considering an average river flow rate of $50 \text{ m}^3 \text{ s}^{-1}$ (D'alpaos & Dal Prà 1978).

Irrigation over an area of 250 km^2 is one of the most important components of groundwater recharge. An

average flow rate of $10 \text{ m}^3 \text{ s}^{-1}$ (Regional Irrigation Agency) in the hydrologic year is taken by irrigation plants. Considering the field capacity of the soil, especially of gravely-sandy kind, its mean depth (0.5–1.0) and ground-cover conditions, Public Reclamations Companies estimated that about 55–60% of the irrigation water volume is lost to the aquifers by net infiltration.

A constant discharge of about $15 \text{ m}^3 \text{ s}^{-1}$ throughout the year flows into two main irrigation canals. Their leakage was calculated by the same method as applied to the Piave (Dal Prà *et al.* 1996) producing recharge rates to the free aquifer from the Vittoria and Piavesella canals of $0.3 \text{ m}^3 \text{ s}^{-1}$ and $0.2 \text{ m}^3 \text{ s}^{-1}$ respectively.

The inflow rate through the specified flux boundary (Montebelluna-Barcon line) into the aquifer was estimated at $0.8 \text{ m}^3 \text{ s}^{-1}$ (Fig. 4), by applying the flow net method developed in different seasons and assuming at the northern side of the plain an aquifer cross-section 200 m deep, with average values of hydraulic gradient and hydraulic conductivity.

Discharge components

In a flat basin, it is considered an acceptable approximation to estimate surface run-off as nil.

The total natural discharge of the shallow aquifer along the *fontanili* spring line was measured by flow-meter at $20 \text{ m}^3 \text{ s}^{-1}$ (Antonelli & Dal Prà 1980). In the discharge area extending from Treviso to the Piave, the measured flow net shows an upward-flow component (Fig. 2).

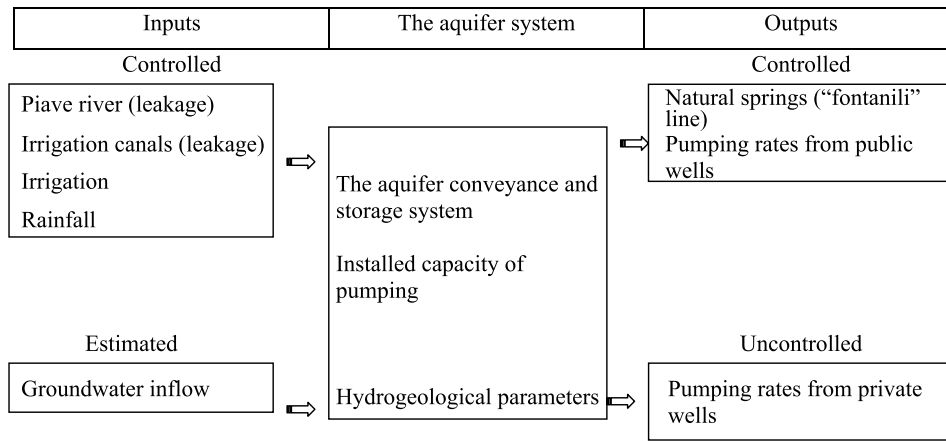


Fig. 5. Scheme of aquifer system.

Table 1. Water budget data; mean values per year.

Inflow (+)	(m ³ s ⁻¹)	Outflow(-)	(m ³ s ⁻¹)
Piave River (leakage)	14.5	Flow through natural spring line 'Fontanili line'	20.0
Precipitation	6.2	Public wells	0.6
Irrigation	6.0	Private wells in High Plain	1.3
Leakage from irrigation canals	0.2	Well in multi-layer aquifer system of "middle Plain"	6.1
Groundwater flow from N-W boundary	1.1		
Total	(+) 28.0	Total	(-) 28.0

The total groundwater exploited by public wells located both inside and immediately south of the hydrogeological domain was evaluated with reasonable approximation from recorded data (Bullo & Dal Prà 1994). It is more difficult to make a reliable estimation of flow rate withdrawn from private wells because of their very large number and lack of records. An average flow rate of $1.3 \text{ m}^3 \text{ s}^{-1}$ was estimated by applying a statistical approach to some rural, urban and industrial sample areas.

A simplified concept of the behaviour of the aquifer is shown in Fig. 5. Table 1 lists all these calculated or estimated values of the water balance components with the following comments:

- So far, the calculated result, with an accuracy of $0.1 \text{ m}^3 \text{ s}^{-1}$, is acceptable although it is recognized that some budget parameter values are from limited data collection;
- until now, groundwater production supplying private demand may be underestimated by a factor of about 1.5;
- the groundwater inflow rate obtained along the NW boundary by isopotential maps may have been overestimated, because of decreasing hydraulic conductivity in the deeper parts of the aquifer.

Mathematical model

Choice of mathematical model and its boundary conditions

As the aim of this study was to check the water balance and reliability of experimental data from field investigations, a two-dimensional steady-state groundwater flow model was applied. The ASM, a 2-D groundwater flow and transport model (Chiang *et al.* 1998), was used for the numerical solution of the flow equation. The ASM uses a block centred finite difference scheme. The reason for applying it was that its very user-friendly pre- and post-processing tools, greatly facilitate modelling processes.

The assumptions used to simplify the real system were as follows.

- The conglomerates of the Montello hill, with relatively low permeability, define the north boundary; thus it is assumed that there is no significant groundwater recharge ($< 0.1 \text{ m}^3 \text{ s}^{-1}$) and that the boundary is of no-flow type.
- The Piave has a symmetric hydraulic interaction with the free aquifer, supplying or draining it, and is considered a 'leakage boundary'. The problem of the high gradients near Nervesa to the north (Fig. 2) was overcome by achieving homogeneous

decreasing distribution of the highly localized leakage values along the course of the river, from north to south.

- (iii) There is a constant discharge from the unconfined aquifer at the *fontanili* springs (lower boundary) and a prescribed head boundary is therefore considered appropriate. The isopotential line, 11 m above sea level, was thus chosen, characterized by small variations (some decimetres) in the water-table over the average hydrologic year.
- (iv) The west boundary is divided into two parts, of which one corresponds to an isopotential line at 35 m a.s.l. and is considered a specified flux boundary. The second part of the west boundary, drawn at right angles to the isopotential lines, is considered a no-flow boundary (Fig. 4).

A finite difference grid with 9424 square cells with a constant cell size of 250 m over an area of about 590 km² was selected for the flow model. There are 124 cells in the 'x' direction (west to east) and 76 in the 'y' direction. The number of inactive cells is 4100. This discretisation gives a clear-cut idea of the groundwater flow field in the entire area.

Calibration of the model

In this preliminary phase it appeared sufficient to achieve the identification or calibration model that is the process of determining the various coefficient and parameter values. This process (inverse problem) is based on a comparison between predicted and observed response in the form of field values (Bear 1982).

A homogeneous distribution of the transmissivity value of $T=2.5 \times 10^3 \text{ m}^2/\text{day}$, deduced by harmonic mean, was assigned to the whole study area to guarantee the uniqueness of the solution. Therefore only the inflows and outflows of the aquifer have been calibrated.

The inflows are: the leakage from the river Piave and irrigation canals, the groundwater flow from the western boundary and the recharge by precipitation and irrigation.

The outflows are: the discharges by pumping wells and the outflow from the southern boundary (*fontanili* zone) (Table 1).

The calibration was partly undertaken by trial and error, partly using an automatic calibration procedure (AMS modulus based on the Marquard-Lovemberg method), considering that the calculated parameters matched the measured ones fairly well. The diagram of Figure 6 demonstrates that the calculated heads are in a good agreement with the ones measured at the observation wells. Table 2 specifies some input and output data obtained by simulation and calibration modelling procedures that are in the same range as the experimental data. The error can be considered compatible with the aims to be pursued in this research.

Comparison of Calculated and Observed Heads

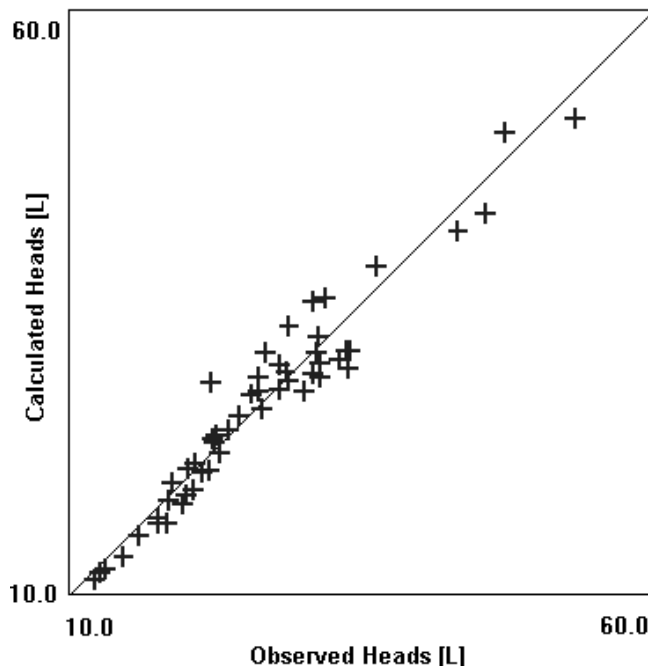


Fig. 6. Comparison of calculated and observed heads.

Conclusions

The Treviso plain is underlain by a major alluvial aquifer consisting of coarse-grained, fluvio-glacial sediment of uncertain thickness, probably up to 300 m. The northern limit of the study area, of approximately 400 km², was defined by the emerging bedrock (Upper and Late Miocene) and the southern limit by the spring zone, known as the '*fontanili* line' where fine-grained deposits start to become intercalated with the coarse material. The eastern limit was defined by a major river, the Piave, but the western limit had no specific hydrogeological boundary and was assumed partly as specified flux boundary, partly as no-flow boundary.

A successful attempt was made to construct a water balance for the aquifer by quantifying as far as possible the various recharge (rainfall, river leakage, canal leakage, irrigation seepage and ground water inflow) and discharge (spring and extraction) components. Some of this data was limited in detail and spread in time and could be subject to revision when more information becomes available.

A 2-D finite difference steady-state model was developed incorporating this water balance and assigning appropriate hydraulic condition to the hydrogeological boundaries (dynamic boundaries). The model also used existing data from various field experiments on aquifer properties.

The calibration of the model was reasonable and taken to show that the basic characteristics and

Table 2. Comparison between some input and output data in the model calibration process.

Boundary	Experimental data (m ³ s ⁻¹)	Simulated result (m ³ s ⁻¹)	Calibration result (m ³ s ⁻¹)
Piave River (leakage)	14.5	10.9	10.4
Specified flow from N–W (only Montebelluna area)	0.8	0.7	1.0
Outflow from the prescribed head (fontanili line)	11.5	7.8	7.8

behaviour of the groundwater system were understood and have been achieved at low cost.

The result are good enough to encourage further work on the sensitivity analysis of the model and also identify the need for further data from the field. The use of the hydrogeologic model could then be extended by adding appropriate chemical transport models to describing changes in groundwater chemistry, to produce a comprehensive tool to aid decision-making in groundwater management.

Acknowledgements. The review comments by P. Ackerer of Strasburg University and by E. Hoehn of EAWAG, Dübendorf, greatly improved the paper. Funding was provided by MURST 60% (University, Technology And Research Ministry), Grant Antonelli R.; I.R.P.I. - C.N.R. - G.N.D.C.I. (U. O. 4.3, 4 Grant Civita M.); Environment and Ecology Department of Treviso district.

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