Experimental and modelling studies of infiltration

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Introduction and motivation

This presentation describes of a study of infiltration in the unsaturated soil with the objective of estimating the recharge to a phreatic aquifer.

In particular the study area is at the border of the city of Milano (Northern Italy), which draws water for both domestic and industrial purposes from groundwater resources located beneath the urban area. The rate of water pumping from the aquifer system has been varying during the XX century, depending upon the number of inhabitants and the development of industrial activities. This caused variations with time of the depth of the water table below the ground surface and in turn some emergencies: the two most prominent episodes correspond to the middle '70s, when the water table in the city centre was about 30 m below the undisturbed natural conditions, and to the last decade, when the water table has raised at a rate of approximately 1 m/year and caused infiltrations in deep constructions (garages and building foundations, the underground railways, etc.).

We have developed four ground water flow models at different scales, which share some characteristics: they are based on quasi-3D approximation (horizontal flow in the aquifers and vertical flow in the aquitards), conservative finite-differences schemes for regular grid with square cells in the horizontal plane and are implemented with proprietary computer codes. The four models are:

1) `Espin` (Ponzini et al., 1989), which models ground water flow at a well field of the municipal Water Works, considers the traditional aquifer (100 m thickness) and has a grid spacing equal to 50 m.
2) `ModMil` (Giudici et al., 2000), which models ground water flow in an area of about 400 km² and includes the municipality of Milan; in the area more than 600 public wells

and more than 400 private wells are drilled. The model considers the traditional aquifer and has a grid spacing equal to 500 m.

3) `modLambro` (Romano et al., 2002), which models an area of about 20 km², at the margin of the city area, includes a park area and is crossed by the Lambro river and includes four pumping stations of the municipal Water Works. It considers both the traditional and the deep aquifers (thickness of almost 200 m) and has a grid spacing equal to 100 m. Since the physical boundaries of the aquifer system are far from the modelled area, the results of `ModMil` are used to fix the boundary conditions of `modLambro`.
4) `ProvMI`, which is the extension of `ModMil` toward North, up to the morenic hills. It models the traditional aquifer and has a grid spacing is equal to 1500 m.

Among the problems that were studied for the development of these models, I recall some numerical problems, related to the behaviour of the phreatic aquifer under conditions of strong exploitation (Valota et al., 2002). Model calibration and validation for `ModMil` has been performed with a two-stage process, i.e., using some of the available data for model calibration and the remaining data for model validation.

It is of paramount importance the estimation of the source terms, which can be summarized in the following list (Giudici et al., 2001):

1. abstraction from public wells for domestic use and from private wells for industrial or agricultural use,
2. abstraction from topographic sources;
3. drainage/recharge from rivers and natural or artificial channels;
4. recharge from rain infiltration;
5. recharge from losses from the aqueduct and sewage networks;
6. recharge from infiltration of water used for irrigation.

The location of the abstraction wells is in general well known, and estimates of the water abstraction rates at point 1 are available; some data for point 2 are also available, whereas estimates of location and strength of points from 3 to 6 of the previous list are very uncertain and depend on water infiltration through unsaturated soil.

Research description

The following sections summarize some of the results obtained with the research program "The contribution of geophysics to hydrogeological risk assessment: exploration, monitoring and modelling", which involved the Universities of Milano, Modena e Reggio Emilia and Padova.

Figure 1 shows the study area and the location of the three sites where experimental studies have been performed.

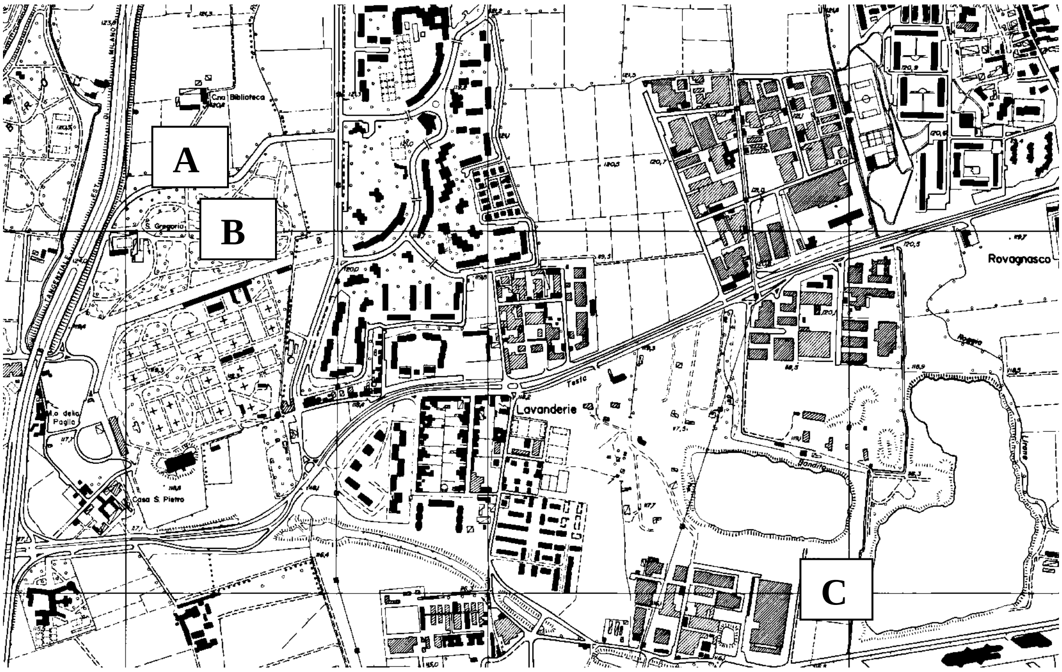

Figure 1 – Map of the study area, with represented the three areas where experiments have been conducted (site A – Lambro pumping station; site B – Lambro Park; site C – artificial mining lake)

In particular at site B we have acquired a high-resolution seismic profile and geoelectrical tomography. The results are in good agreement with those obtained from stratigraphic logs of the wells drilled in the area and showed some further heterogeneous features. Instead, a magnetotelluric sounding has not provided good results, because, as expected, anthropogenic noise was too strong.

The electrical tomography performed in area C has provided interesting results, showing that the lake and the phreatic aquifer have a good hydraulic contact. This is a very important information for ground water model development.

In the following section some of the monitoring data are resumed.

Monitoring

At site C, we performed a statistical analysis of piezometric head and rainfall rates. In particular we have shown that the piezometric head sampled with an approximately monthly rate are correlated with the cumulated rainfall for a period of time longer than 90 days before the date of measurement of the piezometric head, whereas it is not correlated with the cumulated rainfall for a period shorter than 30 days. In other words, the monthly sampling of piezometric head does not allow us to study the effect of a rain event on the piezometric head, whereas it is correlated with the seasonal behaviour of rainfall.

At site A, a hydrometeorological station has been installed, which collected meteorological and soil data from 20 June 2001 to 5 November 2002. In particular the meteorological data were collected with instruments installed on a 12-meters-high telescopic pole to measure the following quantities: atmospheric pressure (at an height of 2 m), air temperature and moisture (0.1, 2 & 6 m), wind velocity and direction (10 m), short wavelength incident radiation (2 m), net radiation at short and long wavelength (2 m), rainfall and evaporation at soil. Horizontally buried TDR probes to measure soil water content were installed at depths of 5.5, 17, 33, 52 and 76 cm; soil temperature was monitored with PT100 thermometers at four different depths (6, 15, 32, 50 cm). Finally from 28 June to 27 July 2002 capillary pressure was monitored with four tensiometers (2 at a depth of 32 cm, 1 at 80 cm, and 1 at 90 cm).

The studied soil consists of a natural soil, which has been altered during building works and mixed with building residuals. Therefore, this is a very common soil in urban areas where natural soils are modified during building or civil engineering works.

Figure 2 shows the data collected by the TDR probes at 5.5 and 76 cm and by the rainfall gauge. The sampling period was 30 minutes.

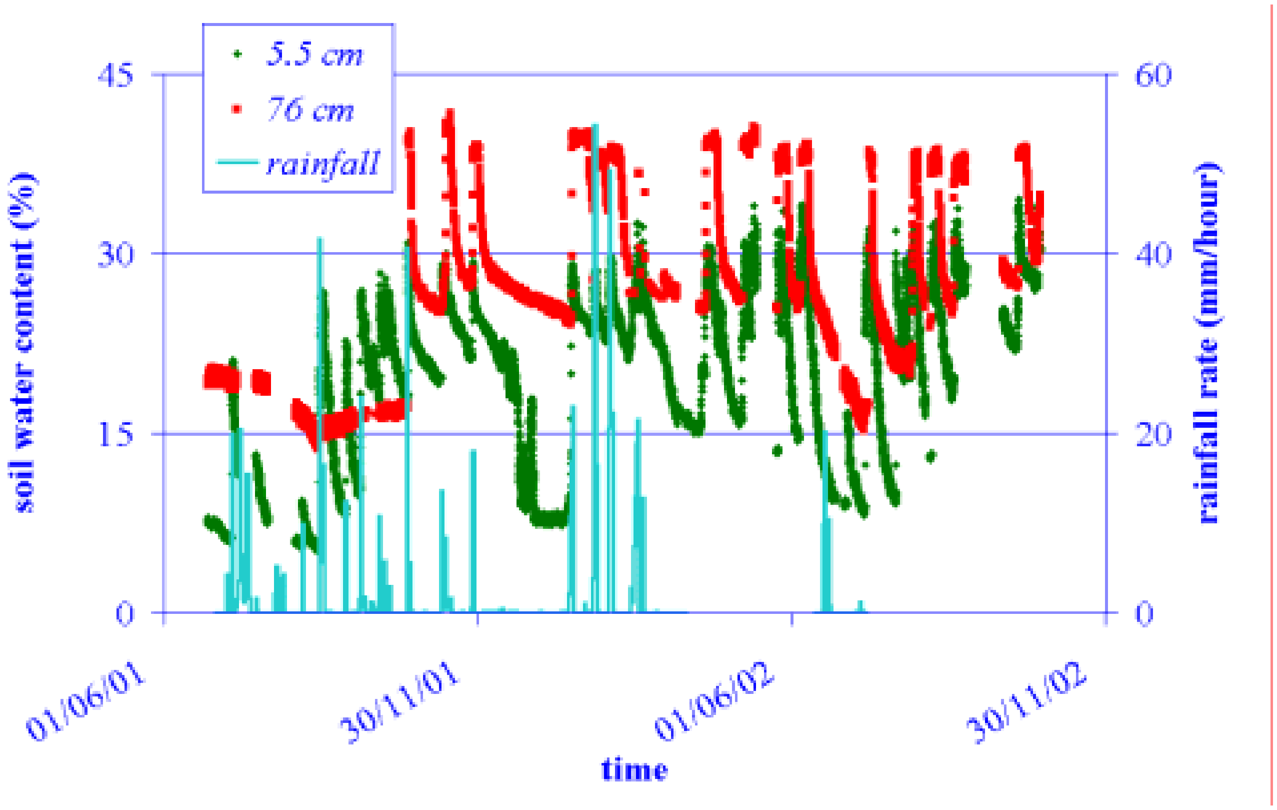

Figure 2 – Soil water content and rainfall rate modeled at site A.

We stress a couple of features apparent from the time series.

The decrease of soil water content observed for the shallow probe during December 2001-January 2002 is not due to a real decrease of this physical quantity, but is due to partial frozen of soil water in a period when soil temperature was close to 0°C for quite a long period.

A daily oscillation is observed in the time series of soil water content at almost any depth and for almost the whole monitoring period. This is correlated with daily temperature variations, which affect not only the electrical permittivity of soil and water, but also the behaviour of the data acquisition unit. Laboratory experiments have shown that a change of 1°C induces a variation of soil water content of about 0.1%.

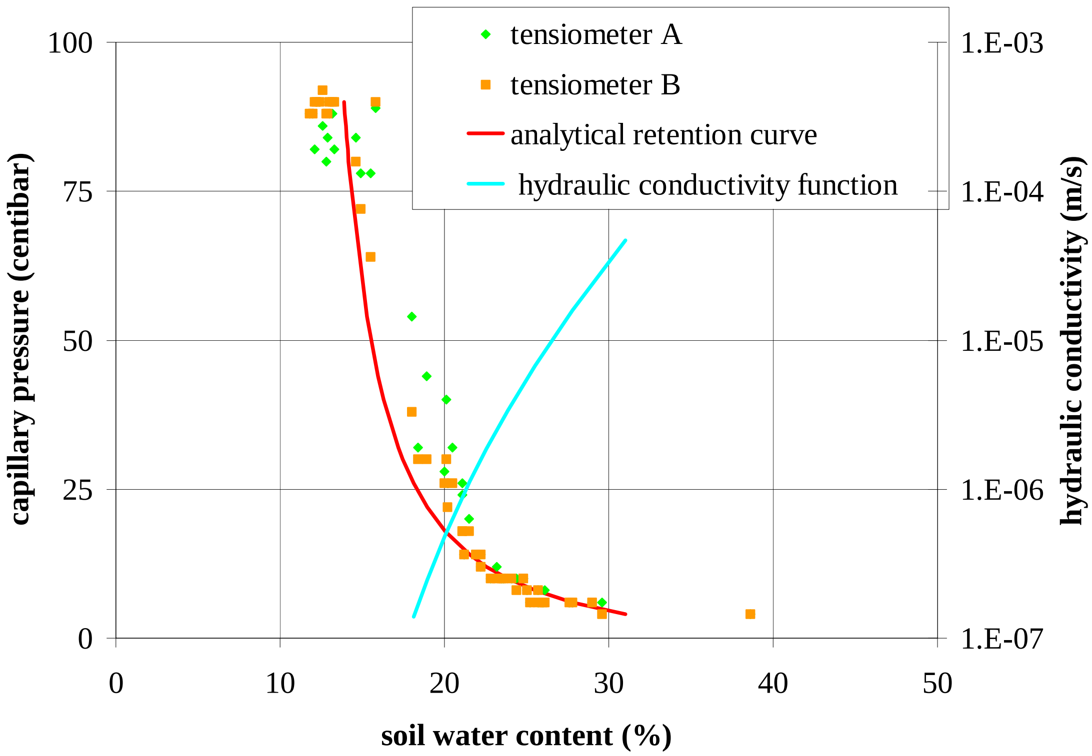

Figure 3 – Characteristic curve of the soil.

Modelling

An unsaturated flow model has been developed with the following characteristics:

- 1-D vertical single phase flow;
- finite-differences conservative scheme;
- discretisation grid step 0.1 m;
- time step 60 s;

- Dirichlet boundary conditions at the upper boundary at a depth of 0.35 m, where water content is fixed from experimental data, and at the lower boundary at a depth of 13.95 m, which approximately corresponds to the depth of the water table at the site;
- retention and conductivity curve from observations;
- initial condition as solution of stationary unsaturated flow.

The response of the model to variations of the top boundary condition strongly depends on the initial condition and, as a consequence, infiltration strongly depends not only on rainfall, but also on soil condition before the rain event.

Synthetic models show that if we have a periodic boundary condition at the top boundary, the behaviour is periodic after few cycles; this result is not trivial for a non linear model. It offers a possible suggestion to impose initial conditions, e.g. obtaining them from the response to periodical (annual, seasonal or daily) boundary conditions.

Summary and perspectives

The application of geophysical exploration techniques, in particular seismic and geoelectrical prospecting, have been very useful to complete the data and information on the hydrogeological structure obtained from stratigraphic logs.

Meteorological and soil data collected at site A are a time series which is very interesting and promising for further processing, which is going to provide important information on water infiltration in the soil found at site A of the study area. For this we are improving modelling of unsaturated media, not only with numerical models, but also with analytical models, and taking into account not only the water mass balance, but also the energy budget and exchanges between water, soil, atmosphere and vegetation.

Another important perspective comes from some measurements of the soil characteristic curve which are going to be performed on soil samples with the Richard’s apparatus.

Acknowledgement

The work described in this communication was partly supported by the Italian Ministry for University and Scientific and technological research (Progetto di Ricerca di Interesse Nazionale “The contribution of geophysics to hydrogeological risk assessment: exploration, monitoring and modelling”).

The research program was developed with the participation of the University of Milano (M. Giudici, E. Romano, M. Manera, C. Sisti, G. Ponzini), the University of Modena and Reggio Emilia (S. Pugnaghi, M. Menziani, M. De Leva, L. Lombroso, R. Santangelo, S. Vincenzi - ISDGM CNR) and the University of Padova (A. Zaja, R. Francese, G. Fardin, G. Girardi, N. Praticelli).

Some of the data were provided by or collected with the cooperation of the following companies or institutions: Comune di Milano (R. Airoldi), INERTI Holding spa (M. Noris, M. Carini), Provincia di Milano (C. Arduini, F. Di Palma), Università di Milano - Istituto di Fisica Generale Applicata (M. Maugeri, L. Buffoni), University of Alberta, Edmonton, CA (D. Schmitt, M. Lazorek).

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