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REDUCING MODELING UNCERTAINTY IN NATURAL AQUIFERS: THE EXPERIMENTAL SITE OF SETTOLO (ITALY)

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Summary. The uncertainties characterizing the description of hydraulic properties of aquifers and modeling of flow and transport processes, together with measurement errors, can be successfully dealt with by stochastic approaches, which allow the interpretation and the prediction of these processes in natural heterogeneous formations. However, the practical application of these approaches still encounters many difficulties, mainly due to the need for a detailed hydrogeological characterization of the site and to the unsuitability of the models, sometimes related to simplistic schematizations when describing in random terms the aquifer properties. Such circumstances emerge clearly in the real case of Settolo, an alluvial phreatic aquifer in a piedmont area of Northeastern Italy, where the uncertainties related to the variability of the geological structures crossed by paleo-riverbeds, to the interactions between watercourses and the aquifer, and to the recharge linked to precipitation and evapotranspiration must be challenged for an effective protection and/or a sustainable exploitation of the water resource. In order to face these challenges, a careful site characterization is in progress, with a number of different measurements and scales involved. The experimental site has an area of about 6 km^2, with an average aquifer thickness of about 40 m. We present here the data recorded at Settolo in the first months of monitoring activities and some results of a modeling approach consisting of a coupled surface-subsurface hydrological model integrated with an ensemble Kalman filter assimilation algorithm. The objective of this preliminary study is to show how the assimilation of variables that are relatively easy to collect in the field (e.g., only water table depth), in conjunction with other measurements (e.g., geophysical characterization of the subsurface formations), can help to quantify and reduce the uncertainty inherently affecting real applications of hydrological models.

1 INTRODUCTION

Studies dealing with natural heterogeneous aquifers have recently been boosted by the diffusion of theories that describe hydraulic properties of porous media (porosity, hydraulic conductivity, transmissivity, storativity, etc.) as random variables[1]. According to these studies, the uncertainty characterizing the description of hydraulic properties, together with that due to measurement errors and the one implied in the process modeling, can be successfully dealt with by stochastic approaches, which allow the interpretation and the prediction of flow and transport phenomena in natural heterogeneous formations. Though these theoretical developments were validated by comparison with several field experiments, the practical application still encounters many difficulties, mainly due to i) the need for a precise hydrogeological characterization of the area under study and ii) the unsuitability of the mathematical models, sometimes related to strict requirements for the domain geometry, boundary conditions, and the stochastic description of the aquifer properties.

An aspect that is often neglected by the stochastic theories is the non-homogeneity of the flow field caused by the boundary conditions. These may be strongly influenced by the interactions between surface and subsurface waters, typical examples including water bodies such as rivers or lakes lying close to the aquifer and infiltration from and evapotranspiration to the ground surface, which may play an important role depending on the pedological characteristics of the soil. Such situations are common in piedmont areas, where shallow phreatic aquifers are often exploited for irrigation or domestic purposes. In the latter case, a particular attention must be paid for preserving also the quality of the water resource, hence not only from the point of view of quantitative flow problems, but also concerning the aspect of contaminant transport and dispersion processes. These are strongly influenced by the interactions between surface water and groundwater and are characterized by a flow field definitely non-homogeneous, also because the distributions of the hydraulic properties are spatially non-stationary and some of them manifest a hierarchic structure. The lack of statistical homogeneity of the flow field is thus mainly related to i) the spatial variability of the hydraulic property means, due to the principal geologic differentiations of the aquifer, and ii) to the time fluctuations of the water table, linked to the hydrological forcing (precipitation and evapotranspiration), to the watercourse levels, and the possible presence of pumping wells. These factors can be assessed by using coupled models of surface and subsurface flow, whose importance has been recently recognized by many authors[2], together with data assimilation techniques[3], which allow to integrate into the model information coming from measurements relative to both subsurface processes (e.g., water table level and water content) and surface processes (e.g., streamflow and stream level), estimating at the same time the related uncertainty. Correlated variations of the hydraulic properties and their implications on transport processes are necessarily neglected at the scale of the coupled surface-subsurface model, i.e., the catchment scale, but can be subsequently analyzed in a smaller subdomain area, whose boundary conditions can be derived from the larger scale model.

This paper presents an application of a coupled model of surface–subsurface flow and data assimilation to an experimental site located in Northern Italy, where a shallow phreatic aquifer strongly interconnected with a nearby river has being monitored since summer 2009. We report the first data recorded in the site and the preliminary results of the modeling activity, demonstrating how data assimilation can be usefully employed to quantify and possibly reduce the uncertainty inherently characterizing real world problems.

2 MATERIALS AND METHODS

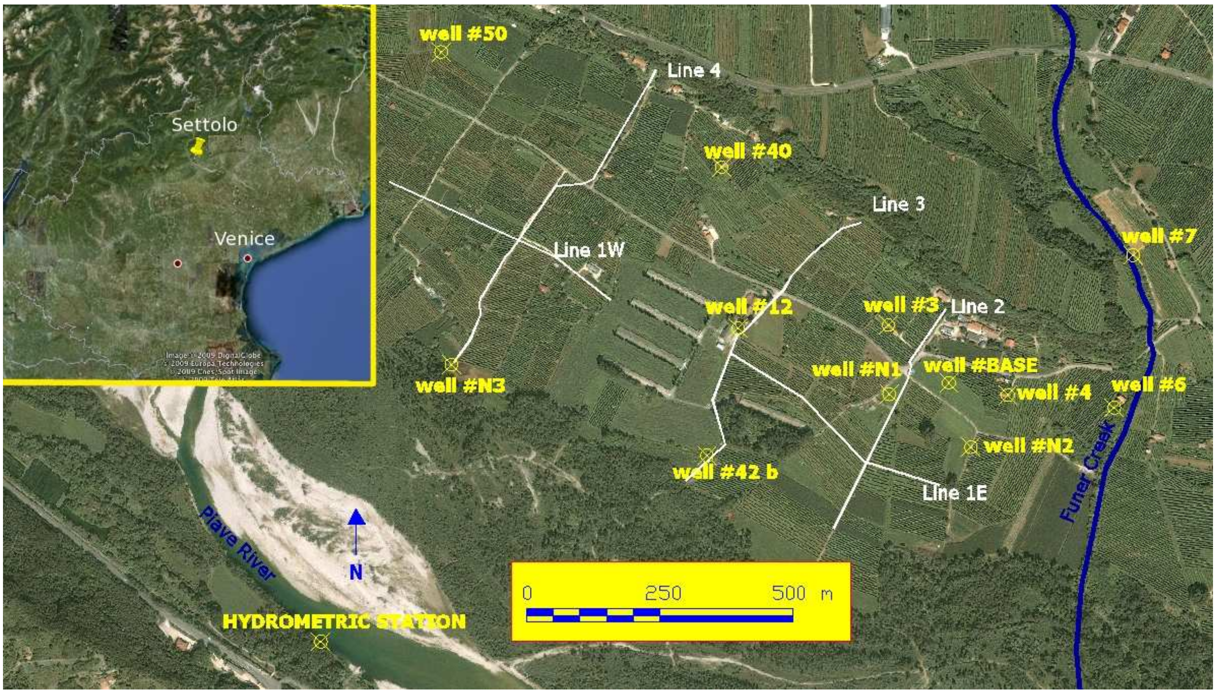

Figure 1: Location of the experimental site within the Veneto region in Northeastern Italy (top left inset) and map of the study area with the installed monitoring network and five lines along which surface electric resistivity tomography has been carried out.

2.1 The study area

The study area is located along the left bank of the Piave River, near Valdobbiadene, in the upper Treviso province (Figure 1), and has an extension of approximately 6 km^2. This is an important recharge area, as the river leaves its mountain catchment and feeds the underlain unconfined aquifer. For this reason, Alto Trevigiano Servizi s.r.l., the agency that manages the water distribution system for most of the Treviso province (49 municipalities, with a population of 310,000 and a water demand of 33,000,000 m^3 in the year 2004), has a great interest in the aquifer and has already installed a production well with a maximum capacity of 200 l/s. However, the aquifer is vulnerable to contamination events, due to its large (average) hydraulic conductivity and shallow phreatic surface, hence there is a strong need for a detailed characterization and monitoring of the area.

2.2 Monitoring network and other measurements

Figure 1 shows the location of the devices deployed for the monitoring of the study area. The monitoring network includes: a hydrometric station for the measurement of the Piave River water level, located on the right bank and remotely transmitting data to the Alto Trevigiano Servizi s.r.l. every 15 minutes; a flowmeter and a pressure transducer for the measurement of the pumping rate and water table level at the water distribution agency production well ("BASE"), also remotely transmitting data to the agency every 15 minutes; other pressure transducers with dataloggers recording every 10 minutes in 11 observation wells, chosen among the several private wells located in the area or drilled on purpose. The choice of the observation well locations has been made on the basis of two objectives: i) to collect information about the water table around the BASE well in order to use such information as validation data for the setup of a catchment-scale model of coupled surface and subsurface flow (wells #50, N3, 42b, N2, 6, and 7); ii) to perform a series of pumping tests using BASE as the pumping well and wells #4, N2, N1, 3, and 12 as observation wells. Surface ERT (Electrical Resistivity Tomography) has been carried out along five lines (Figure 1) to better characterize the aquifer depth and to point out possible heterogeneities. The results (not shown here) indicate that the range of variation for the aquifer thickness can be estimated from 20 m up to more than 60 m. Moreover, the geology appears to be complicated by the presence of several Piave paleo-riverbeds, which can represent important preferential paths in case of a contamination event.

2.3 Modeling approach

The distributed, physically-based CATHY model[4] integrates land surface and subsurface flow processes. The three-dimensional Richards equation is used for variably saturated flow in porous media, whereas a path-based one-dimensional diffusion wave equation is used for hillslope (rivulet) and stream channel flow, with a different parameterization for these two elements of surface runoff. The exchange fluxes, coupling terms between the surface and subsurface, are computed via a boundary condition switching procedure as the balance between atmospheric forcing (rainfall and potential evaporation) and the amount of water that can actually infiltrate or exfiltrate the soil. A sequential data assimilation scheme, the ensemble Kalman filter[5], allows model predictions to be updated with spatio-temporal observation data of surface and subsurface state variables.

3 RESULTS

3.1 Model setup

Topographic data used for the Settolo area was obtained from the Veneto Regional Authority with a resolution of 5 m. These data were processed in a geographic information system to coarsen the digital elevation model (DEM) to a resolution of 20 m, from which the surface and subsurface discretizations for the model implementation were derived.

Average hydraulic conductivities for the domain were assigned on the basis of pumping test results, for the southern part of the catchment, and of soil and geological maps, as regards the upstream hilly part of the watershed. The model domain has been subdivided in two geological units, one representing the downstream aquifer near the river and one for the upstream hillslope zone of recharge. We assigned a high saturated hydraulic conductivity ($K_s = 4.43 \times 10^2$ m/d) to the former portion, while a much less permeable soil was set to the latter ($K_s = 8.64 \times 10^{-1}$ m/d). Porosity ϕ, specific storage coefficient S_s, and van Genuchten's retention curve parameters α, n, and Θ_r were considered homogeneous and set to 0.30, 1.0×10^{-3} m^{-1}, 2.79 m^{-1}, 1.60, and 0.032, respectively. No calibration was performed on the chosen parameters.

A base parallel to the soil surface was used for the bottom of the study area, with a total of 15 layers used for the vertical discretization. The thinnest layer (0.26 m) was that closest to the surface, needed to capture the interactions between surface water and groundwater, including rainfall-runoff-infiltration partitioning. The layers were progressively coarsened with depth, to a maximum thickness of 15 m for layer 15.

In passing from the DEM-based discretization of the catchment surface (13,112 cells in total) to the finite element discretization of the subsurface, each group of 9 cells was divided into two triangles. The 3,072 triangles (connected by 1,657 cell corners or nodes) were then projected vertically to the 15 layers, with each pair of subtended triangles giving rise to 3 tetrahedra. The subsurface domain was thus discretized into 138,240 tetrahedral elements and 26,512 grid points or nodes.

Boundary conditions assigned to the discretized domain representing the catchment were no-flow across its base and its lateral boundaries, except for the southwest boundary, characterized by Dirichlet boundary conditions with pressure head imposed on the basis of the Piave River levels recorded at the hydrometric station, and a small portion of the boundary in correspondence of the well #7, in which pressure heads deduced from the water table measurements were imposed. Atmospheric forcing (measured rainfall and estimated potential evaporation), subject to boundary condition switching[4], was imposed over the surface and the measured pumping rate was enforced at the nodes corresponding to the "BASE" well. Initial conditions for the model were obtained starting from a partially saturated domain and simulating a spin-up period of 6 months, consisting of three cycles of forcing data measured in June and July 2009. We then simulated a three-month period, from August to October 2009, the first two months without assimilation and the third month assimilating pressure head data derived from the collected water table levels.

3.2 Simulation results

Figure 2 shows the comparison between measured and simulated water table at the observation wells in August and September 2009. Except for well #50, there is a constant overestimation of the water table levels and the simulated dynamics is slightly slower than that exhibited by the measured data. These inconsistencies are due to the various sources of uncertainty affecting the model setup, i.e., initial conditions, boundary conditions, and parameter values.

To take into account these uncertainties and assess the possibility to reduce them, October 2009 was simulated assimilating pressure head data for observation wells #3, 4, 6, 12, 40, 42b, and 50, with a daily interval, according to the technique described in Camporese et al.[5]. All ensemble Kalman filter methods are affected by a deteriorating quality of the analyzed covariance matrix during the real-time assimilation of observations[6]. Due to this effect, known as filter inbreeding, late updates can show numerical and non-physical

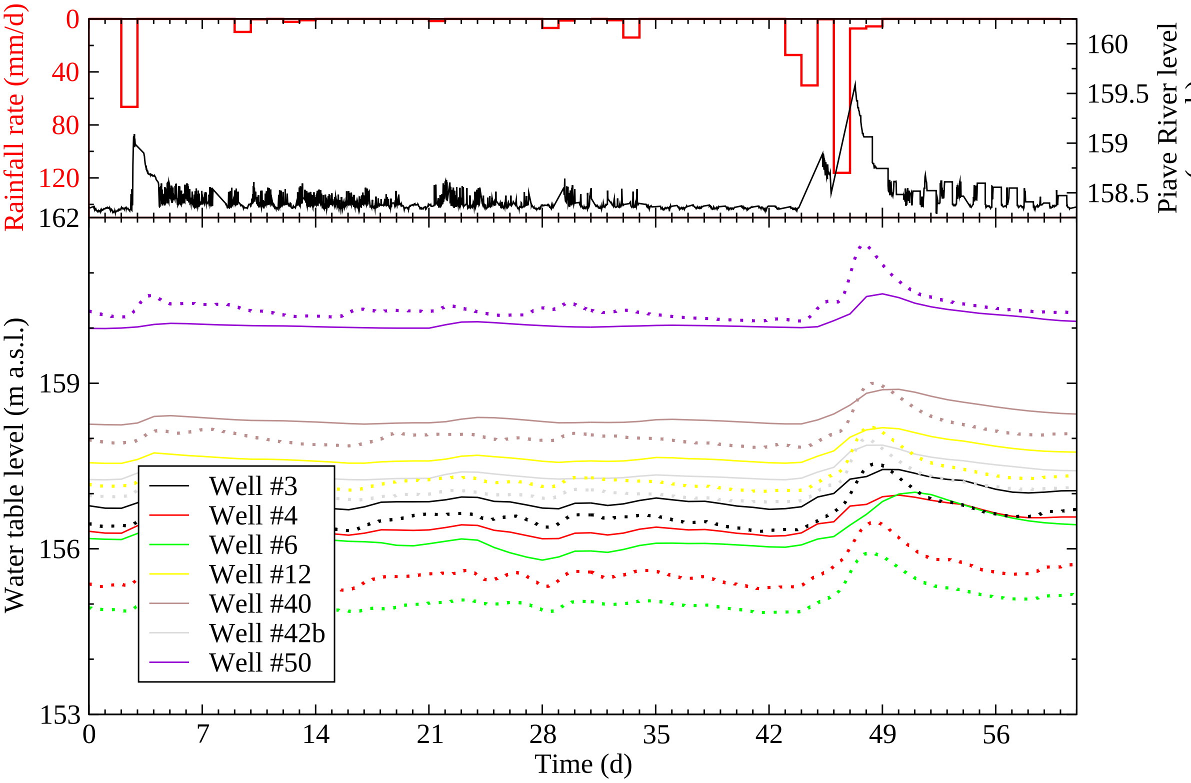

Figure 2: Measured rainfall rate and Piave River levels (top) and comparison between measured (dotted lines) and simulated (solid lines) water table levels at the observation wells in August and September 2009 (bottom).

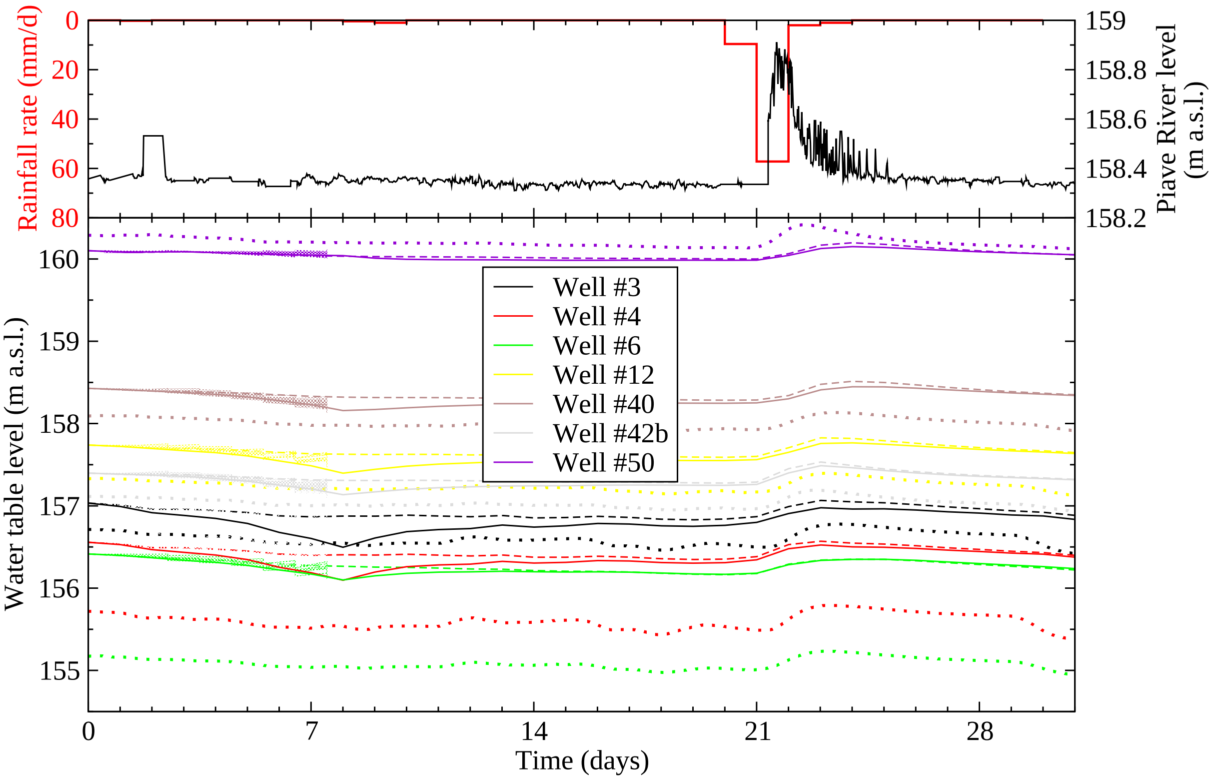

Figure 3: Measured rainfall rate and Piave River levels (top) and comparison between measured (dotted lines), simulated with data assimilation (solid lines), and simulated without data assimilation (dashed lines) water table levels at the observation wells in October 2009 (bottom). The ensemble of realizations for each simulated well is also shown by light colored lines.

artifacts that can affect the convergence of the numerical solver. Thus, only the first week of the simulation was subject to assimilation, while for the rest of the simulated period the system was left free to evolve as controlled by the forcing dynamics. Most of the uncertainty in this simulation was assigned to the saturated hydraulic conductivity. Figure 3 shows the comparison between observed and simulated water table levels, with and without data assimilation. The system state, and hence the water table level, is corrected at each assimilation. Note that the wells located close to the boundaries of the domain (e.g., well #50) are constrained by the boundary conditions and thus exhibit a smaller variability than the ones in the middle (e.g., well #3). As a consequence, the capability of the assimilation scheme to update the water table is greatly reduced. After the last update, the system state tends again to the dynamics as simulated without data assimilation. This is a symptom of a bias in the soil properties, which should be corrected in order to better reproduce the measured dynamics.

4 CONCLUSIONS

A series of models operating at different scales will be used to reproduce the processes of flow and transport in an experimental aquifer located in Northeastern Italy. As a first step, a catchment-scale coupled model of surface/subsurface flow is being used for a preliminary assessment of the mean hydraulic parameters at the larger scale and especially for clarifying the role of the Piave River and the upstream hills as sources of recharge for the aquifer. To this aim, a three-month simulation was performed to assess the capability of an ensemble Kalman filter data assimilation technique to improve the prediction of the water table dynamics. The assimilation of water table observations allowed to reduce the uncertainty of the system state and to correct the water table time evolution. However, in the absence of other compensatory information on the soil properties, the model diverged from the measured system as soon as data assimilation ceased. This denotes the need for a better evaluation of the hydraulic properties, in particular the mean and spatial variability of the saturated hydraulic conductivity, for instance using data assimilation to update the parameters together with the system state.

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REFERENCES

[1] Y. Rubin. *Applied stochastic hydrogeology*, Oxford University Press, (2003).

[2] A. Furman. Modeling coupled surface-subsurface flow processes: A review. *Vadose Zone J.*, **7(2)**, 741–756, (2008).

[3] D. McLaughlin. An integrated approach to hydrologic data assimilation: interpolation, smoothing, and filtering. *Adv. Water Resour.*, **25**, 1275–1286, (2002).

[4] M. Camporese, C. Paniconi, M. Putti, and S. Orlandini. Surface–subsurface flow modeling with path-based runoff routing, boundary condition-based coupling, and assimilation of multisource observation data. *Water Resour. Res.*, **46**, W02512, doi:10.1029/2008WR007536, (2010).

[5] M. Camporese, C. Paniconi, M. Putti, and P. Salandin. Ensemble Kalman filter data assimilation for a process-based catchment scale model of surface and subsurface flow. *Water Resour. Res.*. **45**, W10421, doi:10.1029/2008WR007031, (2009).

[6] H.J. Franssen and W. Kinzelbach. Real-time groundwater flow modeling with the Ensemble Kalman Filter: Joint estimation of states and parameters and the filter inbreeding problem. *Water Resour. Res.*. **44**, W09408, doi:10.1029/2007WR006505, (2008).