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HILLSLOPE CONTROLS ON THE HYDROLOGIC RESPONSE FROM A COUPLED SURFACE/SUBSURFACE MODEL

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Summary. A coupled surface/subsurface model is applied to an instrumented study basin located in Northern Italy, where detailed observations of streamflow, atmospheric forcing, water table levels, soil moisture, as well as a characterization of hydrogeological properties exist. The model is based on a three-dimensional Richards equation solver describing variably saturated flow in porous media and is used to test the extent to which a Richards-like unsaturated flow dynamics can explain the observed hillslope response. Simulations show the model ability, for validation periods distinct from calibration ones, to satisfactorily capture discharge hydrographs over long time scales and across different seasons.

1 INTRODUCTION

One of the crucial themes in hydrological processes is how much of the observed hillslope-scale complexity and heterogeneity needs to be included in any predictive hydrological model at the watershed scale. The detailed understanding of hillslope dynamics is of fundamental theoretical and practical importance in hydrology, and has been investigated by use of analytical and theoretical approaches, numerical models with various degrees of simplification, and field experiments.

Several factors potentially exert an important influence on hillslope response and streamflow generation. Among others, of primary interest in the present work are the following phenomena: effects of bedrock topography [1]; existence of threshold values in subsurface stormflow [3]; dependence on soil-water retention curves [4]; the importance of macroporosities, pipe-flow and role of pre-event water versus event water [5, 6, 7]; role of groundwater flow [7, 2]. Even at a larger basin scale saturated groundwater flow has been recognized [8] as one of the major contributors to streamflow generation processes. Altogether, all this experimental evidence suggests that physically based simulation models of hillslope response must be able to simulate many different phenomena, from subsurface flow, to nonlinear infiltration and redistribution in the vadose zone, to possibly nonlinear interactions between surface and subsurface.

However, it seems necessary to study in detail acting mechanisms and their role in the behavior of streamflow generation processes. The lack of an exhaustive and generally accepted theoretical framework suggests that it is crucial to observe and understand the role of water transport mechanisms at the hillslope scale by coupling physically-based, fully-distributed, surface-subsurface flow models with detailed experimental setups.

For these purposes, an experimental site has been instrumented for the hydrologic monitoring of a headwater catchment located in Northern Italy. The site has been heavily characterized in terms of subsurface hydrogeological properties by means of geophysical surveys and geognostic methods. A detailed numerical model, coupling surface and subsurface flow, has been applied to calibrate some events registered at the study site. The results evidence the hydrologic processes dominating flow generation at the experimental site but also highlight the limitations in describing all the relevant phenomena without a proper site characterization, both in terms of hydrological process understanding and accurate subsurface characterization. In our site we were able to recognize the importance of some of these issues. For example, numerical experiments under different scenarios highlight the relative role of the shallow vegetated layer and the control of the riparian vegetation zone on the streamflow dynamics.

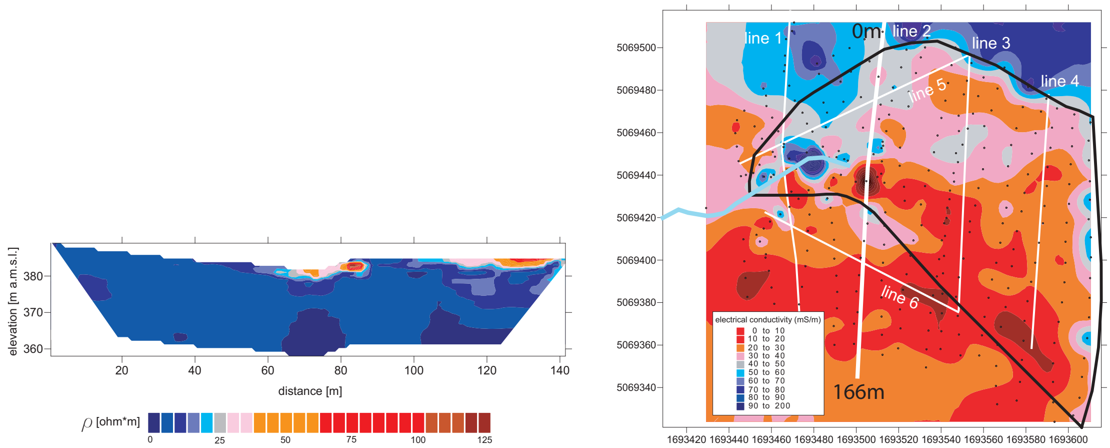
2 THE MODEL

The model used for the numerical experiments couples the diffusive wave equation and the Richards equation respectively to describe surface flow propagation throughout a hillslope and stream channel network identified using terrain topography and hydraulic geometry concepts and variably saturated flow in the subsurface porous media [10]:

$$\frac{\partial Q}{\partial t} + c_k \frac{\partial Q}{\partial s} = D_h \frac{\partial^2 Q}{\partial s^2} + c_k q_s \tag{1}$$

$$S_w S_s \frac{\partial \psi}{\partial t} + \phi \frac{\partial S_w}{\partial t} = \vec{\nabla} \cdot [K_s K_r (\vec{\nabla}\psi + \vec{\eta_z}] + q_{ss} \tag{2}$$

where s is the longitudinal coordinate used to describe the channel network [L], Q is the surface discharge $[L^3/T]$, c_k is the kinematic celerity $[L/T]$, D_h is the hydraulic diffusivity $[L^2/T]$, and q_s is the inflow (positive) or outflow (negative) rate from the subsurface to the surface $[L^3/LT]$. In the subsurface flow equation (2), $S_w = \theta/\theta_s$ is water saturation [-], θ is the volumetric moisture content [-], θ_s is the saturated moisture content (generally equal to the porosity Φ), S_s is the aquifer specific storage $[L^{-1}]$, ψ is pressure head [L], t is time [T], $\vec{\nabla}$ is the gradient operator $[L^{-1}]$, K_s is the saturated hydraulic conductivity $[L/T]$, $K_r(\psi)$ is the relative hydraulic conductivity [-], $\vec{\eta_z} = (0, 0, 1)'$, z is the vertical coordinate



(a) ERT Line 2, dipole-dipole acquisition (date: 18-09-08). Right side of the image (=left hydrographic side) shows shallow drier layers. Scale is in resistivity (Ωm)

(b) Average electrical conductivity on the first 75 cm by means of Electromagnetometer (date: 19-06-09).

Figure 1: *Results from Geophysical surveys: ERT (a) point out heterogeneity in electrical resistivity between the two catchment sides. Analogous results given from Electromagnetometer measurement (b) in terms of electrical conductivity (resistivity reciprocal).*

upward [L], and q_{ss} is the source (positive) or sink (negative) terms $[L^3/L^3T]$. The surface–subsurface flow coupling is handled by a boundary condition switching algorithm that define appropriate exchange fluxes q_{ss} and q_s based on mass-balance considerations [10].

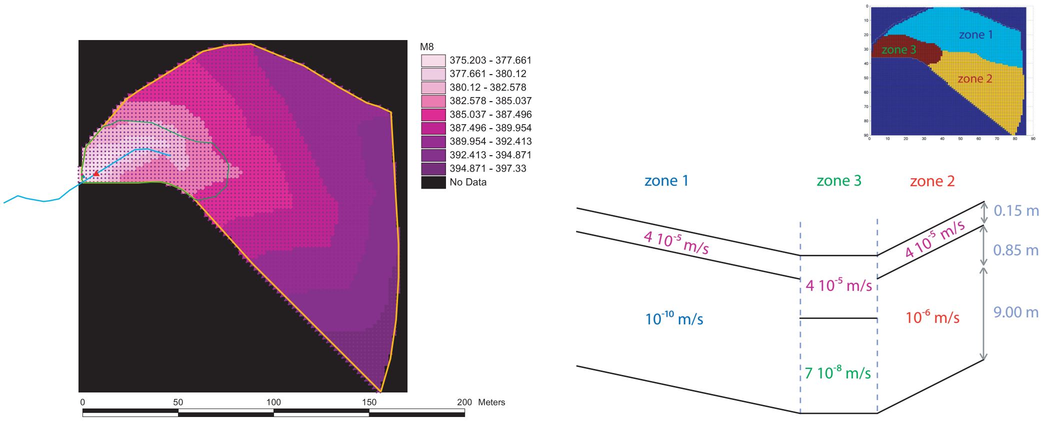
Both the 3D subsurface flow and 1D surface flow equations are solved using classical numerical formulations, i.e., Galerkin finite elements for the subsurface and a finite difference explicit in time Muskingum-Cunge algorithm for the surface. More details on both subsurface and surface flow solvers, and their relative features can be found in [10, 9].

3 STRUCTURAL CHARACTERIZATION

The study hillslope is located near the town of Carrè (Vicenza, North-Eastern Italy) in the pre-alpine hill region named *Bregonze*. The area of interest is the headwater portion of an hydrological catchment drained by an ephemeral stream and is characterized by a very limited size (about 15,700 m^2) and moderate slopes (390 to 375 m a.m.s.l.). Next to the stream slopes increase up to 100% and self-vegetation exists.

The Bregonze basin experimental project is in progress since September 2007, with tensiometers and shallow piezometers installed in a transect close to the stream and a V-notch weir placed immediately upstream, where discharges are registered. A pluviometer collects hourly rainfall data. Phreatic water table and capillary tension measurements are also collected hourly by a datalogger connected to the probes.

Several geotechnical investigations were performed in order to obtain informations on the physical properties of the soil showing its silty-clay nature. Several geophysical meth-



(a) Digital Elevation Model (DEM) identifying the study area. The green line represents vegetation limit.

(b) A sketch of the section in the domain, including permeabilities.

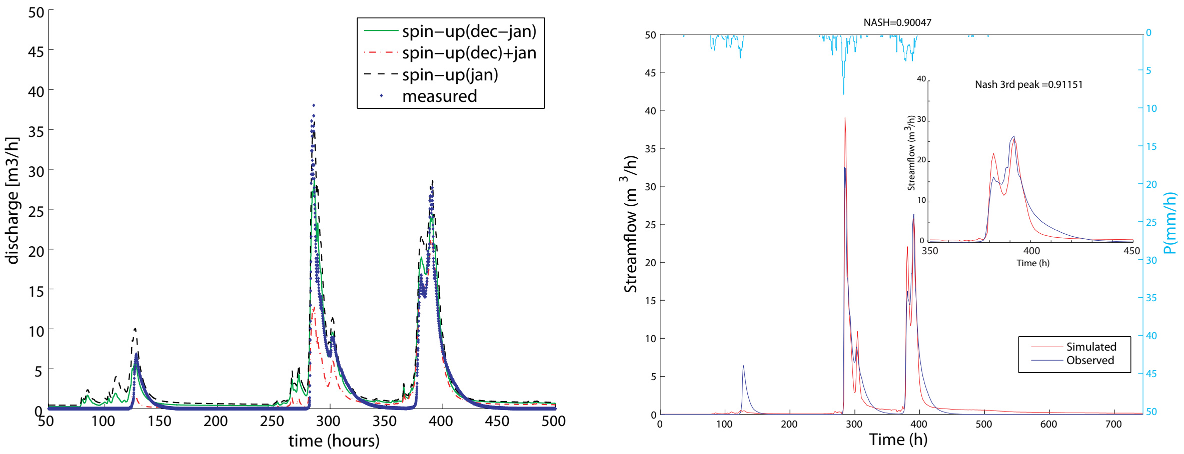
Figure 2: *The domain used in simulations.*

ods (Electrical Resistivity Tomography, Seismic Refraction, Electromagnetometer) were used to gain more accurate and reliable informations on the subsurface structure. Examples of these studies are shown in Figure 1. ERT surveys results clearly distinguish the site heterogeneities, whereby the Southern area (right side in Figure 1(a)) shows a clearly more resistive trend in the first 1-2 m of soil[11]. The general presence of low electrical resistivity is an indication of a substantial clay fraction and is evidence of low hydraulic conductivity. Borehole K_s determinations have confirmed these results, and allowed us to constrain to quantitative estimates the geophysical investigations.

4 MODEL APPLICATION

The domain for the simulations and the Digital Elevation Model (DEM, 2 meter resolution) used in the model is shown in Figure 2(a). The surface triangulation obtained from the DEM was then replicated vertically 8 times to form 7 layers, yielding a three-dimensional mesh of 164850 tetrahedral elements and 32808 nodes, encompassing a total soil thickness of 10 meters (Figure 2(b)). The base of the domain and the lateral faces are assumed impermeable. A shallow soil layer of 15 cm is present on the hillslopes while a thicker 1 meter deep riparian zone has been reconstructed. Three homogeneous zones can be identified in terms of hydraulic conductivity. Figure 2(b) summarizes the setup. Porosity ϕ is assumed equal to 0.50 for all the domain. The storage coefficient S_s is considered fixed equal to 10^{-5} m^{-1}, consistent with clayey soil. Moisture retention curves have been obtained from granulometric properties by means of the database Rosetta [12]. Rainfall rates available from rain gage measurements and potential evapotranspiration estimated by the FAO-Penman-Monteith formula are applied at the surface of the domain.

Initial conditions for calibration simulations, in terms of pressure head at the nodes of the domain, have been obtained by means of a spin-up technique. The approach proceeds



(a) Example of different spin-up applications. By repeating the whole December-January period; simulating January after 5 December loops; by repeating the only January month.

(b) Reference calibration for the event of January 2008. Efficiency equals 0.90 for the whole month, 0.91 for the last event (detail).

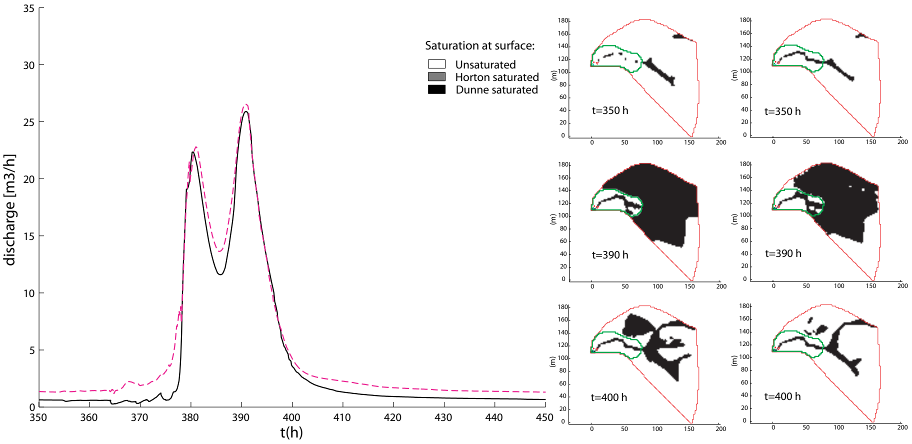
Figure 3: *Results from simulations.*

by using atmospheric forcing recorded in the months preceeding the period of interest, and duplicating this forcing period several times until the solution reaches a "visually accurate" dynamic equilibrium. This periodic condition is supposed to be independent from the initial condition, but is dependent on the calibration parameters, and must be thus performed for each realization of the calibration process. Figure 3(a) shows different spin-up scenarios, and the final calibrated simulation for the month of January 2008. The results show the importance of a well chosen spin-up period, that possibly includes several wet periods. It can be seen, in fact, that spin-up based on the month of December, a dry month) do not yield initial conditions consistent with the following events.

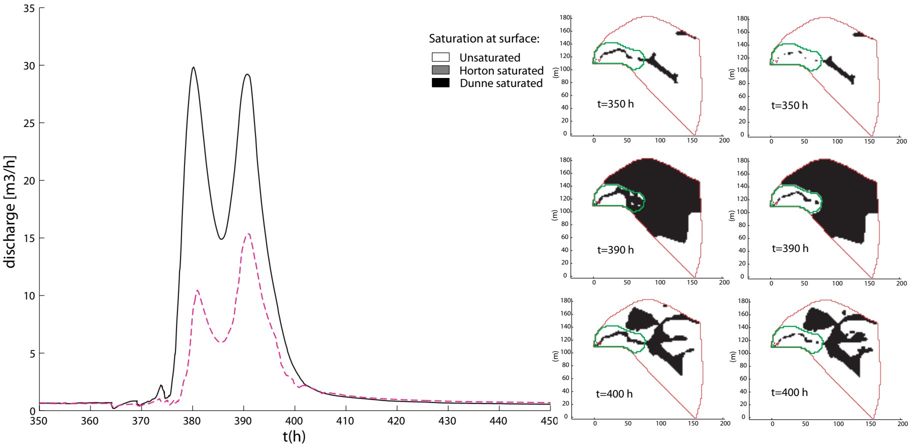
The calibration results for the period of January 2008 produces a satisfactory result in terms of hydrograph reproduced by the model, giving an efficiency coefficient (Nash-Sutcliffe parameter on hourly volumes) of 0.90 (Figure 3(b)). These results show that the model used can be effectively calibrated to reproduce (in pure validation mode) the observed hydrograph. We would like to emphasize here that the aid of geohpysics was essential in alleviating the problem of nonuniqueness during the calibration process, and only a few parameters needed to be changed to obtain the shown calibration.

5 PROCESSES OBSERVATION

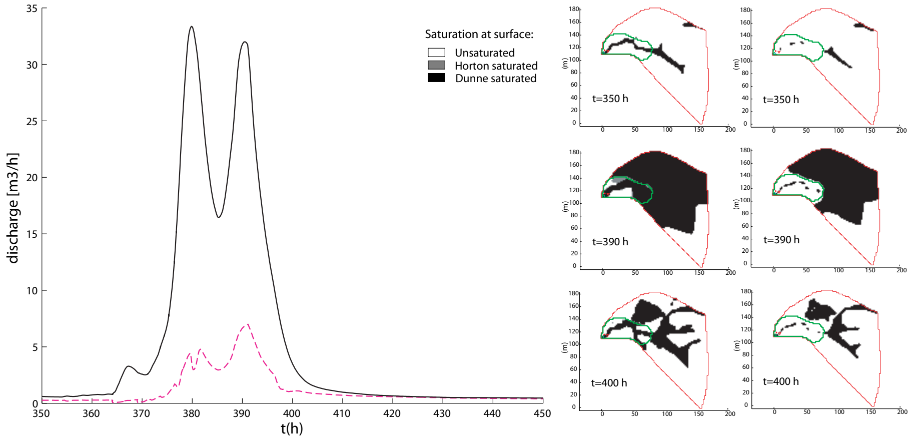
The calibration run was assumed as a reference calibration for further numerical experimention on different scenarios. We thus evaluate the effects of different physical characteristics (permeabilities, soil thickness in hillslope and riparian zone) on the hydrologic response given by the model, with the aim of identifying the role of the most relevant physical phenomena acting at this scale. We qualitatively look at the dynamics



(a) Variation in hillslope soil thickness: from 15 cm (black line, left saturations) to 50 cm (pink dashed line, right saturations).



(b) Variation in riparian zone soil permeabilities: from 2 $\cdot 10^{-5} m/s$ (black line, left saturations) to 8 $\cdot 10^{-5} m/s$ (pink dashed line, right saturations).



(c) Variation in riparian zone soil thickness: from 15 cm (black line, left saturations) to 2 m (pink dashed line, right saturations).

Figure 4: *Simulation details pointing out the role of some hydrological processes. Discharges and saturation patterns.*

of surface saturation distribution patterns, a feature we believe to be of high influence in the streamflow generation mechanism.

The results of some of the scenarios we analyzed are shown in Figure 4. An increased soil thickness in the hillslopes, from 15 to 50 centimeters, show an increase of the base flow accompanied by a surface saturation decrease, because of the increased soil infiltration capacity (Figure 4(a)). Higher hydraulic conductivities in the riparian zone imply higher infiltration and thus lower discharge peaks, as seen in Figure 4(b). Contrasting to this, decreasing the soil thickness in the riparian zone, from 1 meter to 50 and then 15 cm, yield an increase in discharge peaks, because of the lower storage volume capacity, with surface nodes showing higher saturation. On the contrary, increasing the riparian soil thickness up to 2 m causes infiltration to drastically increase, with a consequent decrease in peak discharge. These effects are summarized in Figure 4(c), and alltogether show the importance of accurate soil and subsoil characterization for a proper definition and calibration of detailed physically based models. We would like to emphasized the role of the dynamic of saturated areas in determining the outlet discharges. Future field studies will be aimed at evaluated dynamically the extent of these areas to determine their control on the physical process of interest and the possibility of using these values to drive and further constrain simulation models.

6 CONCLUSIONS

The study of a small hydrographic catchment in the pre-alpine zone near Vicenza, North-Eastern Italy, has firstly evidenced the need for detailed pedologic and geologic information of the soil and subsoil structure characterization for the accurate calibration of numerical models.

Simulations for some events registered at the monitored catchment have shown the relative importance of water transport processes at the hillslope scale. It emerges relevant roles are played by the processes taking place in the riparian zone, which influence storage dynamics, and by water re-infiltration and surface runoff in saturated areas of the hillslope surface, which exert a control on the water arrival times at the outlet. The first consideration strengthen the fact that biological processes strongly influence the determination of geo-pedologic structure of a hillslope, conditioning the response to precipitation events. The importance of flow re-infiltration processes is very interesting even from a modellistic point of view, and can be used to guide the development of future modeling tools.

REFERENCES

[1] Freer, J. E., J. J. McDonnell, K. J. Beven, N. E. Peters, D. A. Burns, R. P. Hooper, B. T. Aulenbach, C. Kendall. The role of bedrock topography on subsurface stormflow. *Water Resources Research*, **38**, 1269, DOI: 10.1029/2001WR000872, (2002).

[2] Katsura, S., K. Kosugi, T. Mizutani, S. Okunaka, T. Mizuyama. Effects of bedrock

groundwater on spatial and temporal variations in soil mantle groundwater in a steep granitic headwater catchment. *Water Resources Research*, **44**, W09430, doi:10.1029/2007WR006610, (2008).

[3] Tromp-van Meerveld H. J., J. J. McDonnell. Threshold relations in subsurface stormflow: 1. A 147-storm analysis of the Panola hillslope. *Water Resources Research*, **42**(2): W02410. DOI: 10.1029/2004WR003778, (2006).

[4] Torres, R., W. E. Dietrich, D. R. Montgomery, S. P. Anderson, and K. Loague. Unsaturated Zone Processes and the Hydrologic Response of a Steep, Unchanneled Catchment. *Water Resources Research*, **34**(8), 1865-1879, (1998).

[5] Anderson, S. P., W. E. Dietrich, D. R. Montgomery, R. Torres, M. E. Conrad, K. Loague. Subsurface flow paths in a steep, unchanneled catchment. *Water Resources Research*,**33**, 2637-2653, (1997).

[6] Montgomery, D. R., W. E. Dietrich, R. Torres, S. P. Anderson, J. T. Heffner, K. Loague. Hydrologic response of a steep, unchanneled valley to natural and applied rainfall. *Water Resources Research*, **33**, 91109, (1997).

[7] Uchida, T., Y. Asano, T. Mizuyama, and J.J. McDonnell. Role of upslope soil pore pressure on lateral subsurface storm flow dynamics. *Water Resources Research*, **40**(12), W12401, doi:10.1029/2003WR002139, (2004).

[8] Wörman, A., A. I. Packman, L. Marklund, J. W. Harvey, S. H. Stone. Fractal topography and subsurface water flows from fluvial bedforms to the continental shield. Geophysical Research Letters, vol. **34**, L07402, doi: 10.1029/2007GL029426, (2007).

[9] Paniconi, C. and Putti, M.. A comparison of Picard and Newton iteration in the numerical solution of multidimensional variably saturated flow problems. *Water Resour. Res.*, **30**(12), 3357-3374, (1994).

[10] Camporese, M., 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 Resources Research*, 10.1029/2008WR007536, in press, (2009).

[11] Rossi, M., G. Vignoli, G. Cassiani, and R. Deiana *Non invasive characterization of small mountain catchment for hydrological purposes*, Near Surface 2009 - Dublin (2009).

[12] Schaap, M. G., F. J. Leij, M. T. van Genuchten. A bootstrap-neural network approach to predict soil hydraulic parameters, Characterization and Measurements of the Hydraulic Properties of Unsaturated Porous Media, pp. 1237-1250, University of California, Riverside, CA, (1999).