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Simulating the transition of a semi-arid rainfed catchment towards irrigation agriculture

A.J. Pérez [a], R. Abrahão [b], J. Causapé [c], O.A. Cirpka [a], C.M. Bürger [a,*]

[a] Center for Applied Geoscience, University of Tübingen, Sigwartstr. 10, 72076 Tübingen, Germany
[b] University of Zaragoza, Pedro Cerbuna 12, 50009 Zaragoza, Spain
[c] Instituto Geologico y Minero de España (IGME), C/ Manuel Lasala N 44, 9B, 50006 Zaragoza, Spain

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SUMMARY

We investigate the effects of land-use change in the semi-arid Lerma basin (Ebro valley, Spain), which underwent a transition from rainfed towards irrigation agriculture. For four consecutive years, this transition of formerly uncultivated land to irrigated farmland was intensively monitored. We use the calibrated and validated, physics-based, 3-D fully-coupled model HydroGeoSphere to study the hydrological effects of the change for this unique site, where spatio-temporal data on cropping patterns, irrigation and fertilizer amounts, and the associated catchment response are available with comparatively high resolution. Validation results show that the physics-based model can simulate and predict the impact of the land-use transformation and irrigation on surface and subsurface flow dynamics with high accuracy. Sensitivity and correlation analyses about the calibrated model parameter vector indicate that the set of van Genuchten parameter values and hydraulic conductivities is identifiable and locally unique for the parameter zonation that was defined using information on lithological units and texture data. In order to indicate changes in the runoff generation process and catchment functioning, we analyze the evolution of the total stream length and the average infiltration capacity provided by the model. The results show that irrigation agriculture has raised the base level of the water table of the Lerma aquifer causing new portions of the drainage network to become perennial. Furthermore, we introduce an approximate infiltration capacity, analyze its evolution and study its effect on Hortonian overland flow. Due to the physics-based nature of the model we can obtain values for exfiltrating fluxes directly from the model and show that both, the approximate infiltration capacity curve and the contribution of exfiltration to stream flow are consistent in indicating a shift from Hortonian towards Dunne flow runoff generating processes triggered by the land-use change.

1. Introduction

In the last century, irrigated agriculture has expanded around the world by 480% (from 47.3 MHa in 1900 to 276.3 MHa in 2000). Nowadays it represents 18% (≈280 MHa) of the global croplands and projections – focusing exclusively on developing countries – claim a further increase of 20% (up to a total of ≈330 MHa) by 2030 (Scanlon et al., 2007). In semi-arid areas, irrigation fosters crop productivity and allows for intensification and diversification of agriculture. As a backdrop, irrigation consumes 90% of global freshwater (Shiklomanov, 2000) and degrades water quality by flushing nutrients into soils and aquifers.

In the central Ebro valley (northern Spain), agriculture represents the main use of water and the majority of agricultural production relies on irrigation. The immense amount of water needed is supplied by a well-structured man-made channel network, which is fed by reservoirs located up to 100 km north in the higher Pyrenees. In recent years, the total irrigation amount has increased constantly, which has led to increased efforts to study the effectiveness of irrigation practices. Spanish researchers have begun to monitor larger irrigation districts in detail. Studies in the Bardenas irrigation district, (i.e. Causapé et al., 2004; Causapé et al., 2006) suggest that the intensification of irrigation has caused a considerable increase in nitrate within the drainage network. This may put the sustainability of these agricultural practices at risk. Despite the ongoing efforts, more comprehensive studies to improve the understanding of the impact of irrigation and land-use change on the surface–subsurface flow dynamics are still missing. One way to gain better insight in the latter could be by detailed modeling, where flow and transport processes are quantitatively described to a level consistent with available data series. Considering the ongoing land-use change where hydrosystems are forced by increasingly large amounts of irrigation water and cropping area expansion, we chose a physics-

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* Corresponding author. Tel.: +49 7071 29 73173; fax: +49 7071 29 50 59.
E-mail address: claudius.buerger@uni-tuebingen.de (C.M. Bürger).

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based, fully-coupled model to study the transition of a semi-arid rainfed catchment towards irrigation agriculture in detail.

By a physics-based model we refer to a model of coupled partial differential equations derived from the principles of conserving mass and momentum of water. In particular these are the shallow-water equations for flow at the land-surface and in streams and the Richards equation for flow in the subsurface. Parameters appearing in the equations have a physical meaning at a particular scale and may be measured at this scale. However, in the transition to larger scales, parameters attributed to more coarsely defined units become effective values which cannot directly be measured, but must be obtained by model calibration where details of the unresolved variability needed for rigorous upscaling are missing. Still, the principles of conserving mass and momentum hold and the relevant flow processes are directly represented in a spatially distributed way.

Fully-coupled surface–subsurface flow modeling approaches were first introduced by Freeze and Harlan (1969), who presented a blueprint for a physics-based mathematical model of a complete hydrological system. Since then, many studies have used this concept to simulate rainfall-runoff relationships. VanderKwaak and Loague (2001) applied the Integrated Hydrology Model (InHM) (VanderKwaak, 1999) to the R-5 catchment ($\approx$0.1 km^2). In particular, they simulated two "Horton type" rainfall events (i.e. rainfall rates are greater than the infiltration capacity of the soil) with duration of 1.6 and 1.9 h. To evaluate the goodness-of-fit, simulated hydrographs at the outlet were compared to the observed hydrographs by calculating the root mean squared error. The subsurface response could not be evaluated as the data set of the R-5 catchment did not include hydraulic heads in the unsaturated or saturated zones. Despite the "Horton type" forcing of the system, they found that both, Horton and Dunne (i.e. saturation excess overland flow) streamflow generation processes, are important for the R-5 catchment. The Dunne mechanism dominates along the channel axis, while the Horton mechanism is dominant in areas of low permeability. Using InHM the authors could track dynamic wetting and drying histories of partial-source (a single streamflow generation process dominant) and variable-source areas (where both mechanisms play a role).

Panday and Huyakorn (2004) presented a physics-based spatially-distributed model with additional capabilities to account for agricultural features at the catchment scale, namely the *storage exclusion* based on the definition of an obstruction height term and the *depression storage* related to rill heights. They successfully tested their implementation on the so-called tilted V-catchment by direct comparison to solutions obtained with two traditional hydrological simulation codes: HSPF (Bicknell et al., 1993) and HEC-1 (US Army Corps of Engineers, USACE).

Kollet and Maxwell (2006) presented an alternative coupling approach where overland flow is simulated as a free-surface boundary condition of the physics-based model. It is based on the assumption of pressure continuity across the surface–subsurface interface. This approach was used by Maxwell and Kollet (2008) to quantify the effect of subsurface heterogeneity on Hortonian runoff generation and to identify settings where groundwater flow dynamics directly feed back to the land-surface-atmosphere energy exchange (Maxwell et al., 2007; Ferguson and Maxwell, 2011).

Studying lake-groundwater interaction in a glacial outwash terrain (area = $\approx$4 km^2; Boreal Plains of northern Alberta, Canada), Smerdon et al. (2007) reported a successful application of a physics-based model at the watershed scale. They found that, due to the transition from the frozen to the thawed state of riparian peat in summer, a seasonal time-dependence of saturated hydraulic conductivity and storage coefficient had to be incorporated in their model.

Kolditz et al. (2007) presented a regional hydrologic soil model (RHSM) and applied it to simulate groundwater recharge patterns at a regional scale for the Beerze-Reusel drainage basin (Netherlands). This investigation evolved into the proposal of an object-oriented concept for the numerical simulation of multi-field problems in coupled hydrosystems, the so-called *compartment approach* (Kolditz et al., 2008).

Li et al. (2008) studied the hydrological response of the Duffin creek watershed (area = $\approx$286.6 km^2) honoring eight different hydrostratigraphic subsurface units with the physics-based, surface–subsurface model HydroGeosphere (Therrien et al., 2008). Subsurface hydraulic head observations, taken during a reference period, were used to constrain the initial condition for the simulated three-dimensional hydrological response driven by daily precipitation as measured from April to December of the years 1986 and 1987. Calibrating seasonally variable parameters controlling evapotranspiration (based on Hargreaves and Samani (1985), Kristensen and Jensen (1975)) for the year 1986, they found that their simulated stream-flow matched the measured one for 1987 at four different gauging stations within the catchment reasonably well. The subsurface response was not assessed due to the lack of concurrent hydraulic head time-series data.

Considering both, surface and subsurface hydrological response at the watershed scale, Jones et al. (2008) applied the physics-based InHM model to simulate the response of the Laurel Creek watershed (Ontario,CA) (area = 75 km^2) to two discrete rainfall events with 420 and 900 h duration. Their results show moderate agreement in simulated and measured runoff as well as subsurface hydraulic heads, and demonstrate the dynamic nature of the interaction occurring between the surface and the subsurface hydrological regimes. Their overall conclusion is that fully-coupled, surface/variably-saturated subsurface models are applicable at the watershed scale and possibly at larger scales. Nevertheless, they emphasize the need for more studies with more comprehensive data in order to improve the state of the art of coupled surface–subsurface modeling.

Despite the above mentioned successful applications of physics-based models, objections to these types of models are widely discussed in the hydrological literature. Apart from the question of parameter identifiability, uniqueness, and the need for effective parameter values at larger scales, (e.g. Beven, 1993; Beven, 2001, 2002), the range of validity of Richards' equation has been posed as a problem of physics-based models: Downer and Ogden (2004), Vogel and Ippisch (2008), among others, have pointed out that consistency with the assumptions underlying Richards equation requires a high spatial resolution that also depends on soil type and the scale of heterogeneities. Recent work of Kollet et al. (2010) has shown, however, that such a refined resolution is possible even at catchment scale by the use of high-performance computing. In this study, we see Richards' equation as an effective law leading to appropriate system behavior rather than a fundamental soil-physical law.

An important reason for the use of a physics-based model lies in the nature of the hydrosystem under consideration. The Lerma basin ($\approx$7.0 km^2 in size), located at the south-eastern part of the Arba catchment, see Fig. 1 is a semi-arid, formerly fallow land, whose transformation into an irrigation agriculture catchment was closely monitored by Spanish researchers. Since October 2005, predefined plots were gradually opened to local farmers for cropping and irrigation agriculture. In conjunction with the transformation, irrigation water amounts, crop pattern, and fertilizer application were documented plot-wise and stream-discharge measured in 15-min intervals at the basin outlet. The amount of irrigated water is gauged at irrigation hydrants located at each plot and the logged data regularly checked for plausibility. Nitrate concentrations and electrical conductivity were measured at first in daily intervals