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21st Century Hydrological Modeling for Optimizing Ancient Water Harvesting Techniques

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ABSTRACT

In order to increase dryland crop productivity, water harvesting techniques (WHT) have received renewed attention, leading to their massive implementation in marginal drylands. However, versatile tools to evaluate their efficiency under a wide range of conditions are often lacking. For two case studies in the arid and semi-arid central-northern zone of Chile, a fully coupled 3D surface-subsurface hydrological model based on the Richards' and the Saint Venant equations was used to evaluate and improve existing water harvesting techniques using infiltration trenches (locally called 'zanjas'). The model was parameterized with detailed runoff and soil-water content data collected during simulated rainfall from a 6 x 2 m experimental plot including a catchment area and infiltration trench at the arid site. Using seven responsive parameters identified by a global sensitivity analysis, surface and subsurface flow processes were calibrated simultaneously. The calibrated model accurately reproduced observed soil moisture contents (R^2 = 0.92) and runoff amounts (R^2 = 0.97), and represented the overflowing infiltration trench, which is a clear improvement over existing frameworks. A comparative analysis with a natural slope demonstrated that the trench was efficient in capturing runoff under high rainfall intensities, such as the one simulated, resulting in a significant decrease (46%) of runoff. However, when extended to natural rainfall seasons, runoff water harvesting was insufficient in dry, normal and wet years, while only under very wet conditions, 55% of the potential runoff effectively harvested and stored in the soil profile. As such, this test case shows the importance of correct water harvesting design to become an effective tool in dryland management, taking both soil physical and climatic constraints into account. The model was further tested on a much larger scale at two ~3 ha large watersheds at the semi-arid site, one with infiltration trenches and one without. Good agreement was observed between measured and simulated runoff at the watershed outlet.

INTRODUCTION

In arid and semi-arid regions, deficiency in water availability for plant growth is often a serious problem, which can lead to desertification. Precipitation often comes in the form of short bursts of high intensity rainfall, causing rapid saturation of the uncovered soil surface and promoting soil erosion, flash floods and mud flows in extreme cases. In Andean arid and semi-arid lands, a range of small-scale solutions for these conditions were implemented by a large number of indigenous communities, as extensively documented by Denevan (2001). These technologies were designed to improve the crop environment, increase labour efficiency, enhance sustainability, improve productivity, and to minimize risks from unpredictable climatic conditions. Today, many of these practices are still in use. Pandey et al. (2003) reported that throughout past civilizations, climate changes resulting in droughts were often followed by an increase in the use of water harvesting techniques (WHT), indicating that WHT can partly alleviate the negative climatic conditions. They also stated that traditional systems would become more efficient if scientific attempts would be combined.

Recent developments in soil hydrology allow the use of complex distributed models to describe hydrological processes at the field scale. These advances make it now feasible to use these complex models to evaluate and improve ancient WHT. The work presented here describes a method to evaluate the water balance of infiltration trenches for water harvesting, using a fully coupled surface-subsurface process-based hydrological model. We will demonstrate how the model was parameterized with detailed runoff and soil-water content data collected during simulated rainfall from a 6 x 2 m experimental plot including a catchment area and infiltration trench (i.e., the WHT under study), and how it was used to evaluate existing WHT. We also illustrate that the model shows good performance when applied on a much larger scale at two ~3 ha large watersheds, one with infiltration trenches and one without.

MATERIALS AND METHODS

Study site and data collection

Field experiments were performed in Chile at two locations, on a sandy loam hillslope in the greater Elqui Valley, characterised by an arid Mediterranean climate (P=99 mm, ETo=1500 mm) and in two watersheds with loamy soil in the semi-arid Metropolitan Region (P=560 mm, ETo=1220 mm) (Fig. 1).

On the arid hillslope, a field plot of 6 x 2 m was selected and consisted of an infiltration trench with its impluvium. Twenty two 30-cm long Time Domain Reflectometry (TDR) probes, connected to a TDR100 device and datalogger were installed horizontally at a depth between 7 and 45 cm below the soil surface. A rainfall event with an intensity of 120 mm h^{-1} was simulated for 20 minutes using a rainfall simulator similar to the one described by Verbist et al. (2003).

During the simulated 20-min long rainfall event, the advance of the wetting front was monitored with the TDR probes and soil-water content was further monitored after the rainfall event until no significant changes were observed for a 24 hour period, which

Figure 1. Hillslope with impluvium and infiltration trench in the Elqui Valley (left) and watersheds with (front) and without (back) infiltration trenches in the Metropolitan Region (right)

was 4 days from the start of the rainfall simulation. Runoff discharge exiting the parcel was guided by a funnel through a 1 m long plastic tube and was measured continuously at 196 minute intervals using calibrated beakers of 700 cm^3.

After the rainfall simulations, soil texture, bulk density and the soil water retention characteristic curve were determined on twenty five undisturbed soil samples taken using standard sharpened steel 100 cm^3 Kopecky rings at various depths (0-5 cm, 15-20 cm, 25-30 cm and 35-40 cm) at 1 m interval distances along the slope. Soil texture was determined with the pipette method, whereas organic matter measurements were based on the Walkley and Black method.

Infiltration measurements were performed at the selected field plot to quantify the field unsaturated and saturated hydraulic conductivity (Ksat). As a concurrent study, six different measurement methods for Ksat were applied: the pressure infiltrometer, the single and double ring method, the inverse auger hole method, the tension infiltrometer and the rainfall simulator. Methods used to derive Ksat values from the measured infiltration rates can be found in Verbist et al. (2009, 2010b).

A comparable procedure was followed in the ~3 ha larger managed (with WHT) and unmanaged (without WHT) watersheds in the Metropolitan Region, but with soil sampling and infiltration measurements taken at, respectively, five and two locations along three transects. Infiltration measurements were carried out using a tension infiltrometer at the surface and Guelph permeameter for deeper layers. Four 30-min rainfall simulations were conducted on 1 x 1 m plots, during which water content was measured with four TDR probes installed at a 5 cm depth and 20 cm apart, and runoff as above. At the outlet of both watersheds, runoff discharge was recorded with a limnigraph with a V-shaped weir.

Model setup and parameterization

We used the HydroGeoSPhere (HGS) code which is a fully-integrated process-based numerical model capable of simulating surface-subsurface water flow in a three dimensional framework. Transient overland flow is described in 2D by the diffusion wave approximation of the Saint-Venant equation, while the 3D variably saturated form of the Richards' equation governs flow processes in the subsurface (Sudicky et al. 2008).

Based on detailed measurements of the geometry of the slope and trench, a 2D grid was first generated using Grid Builder (McLaren 2007). In order to more accurately represent field conditions, a variable grid density was chosen with small grid elements forming the trench area and larger grid elements shaping the catchment area. The 3D grid was then generated by extending the 2D grid to greater depths. As an illustration, Fig. 2 shows the 2D grid at the 3 ha watershed, with a refinement near the river and infiltration trenches, and a 3D visualisation of the surface elevation (based on a DEM and kriging) in which the trenches are clearly detectable.

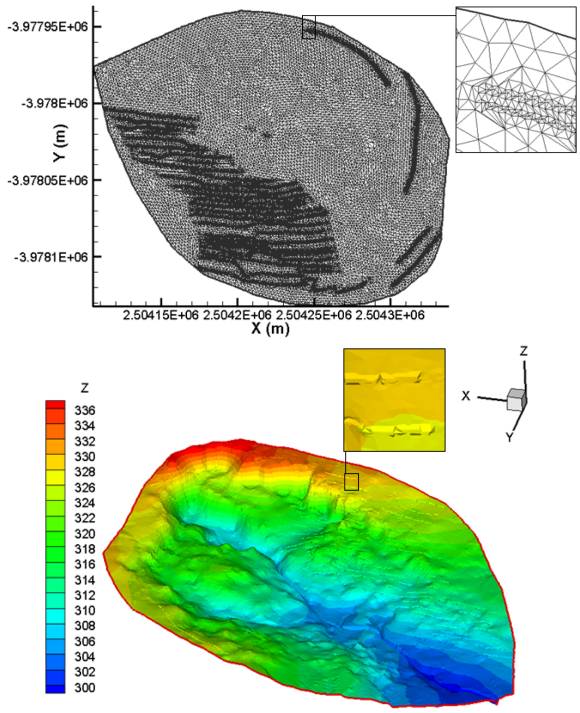

Figure 2. 2D grid at the 3 ha watershed, with a refinement near the river and infiltration trenches (top) and 3D visualisation of the surface elevation (in m) (bottom). Small windows illustrate the trenches.

Since the hydraulic properties were found not to significantly differ with depth at both sites, the profiles were regarded as homogeneous. One set of ten parameters, including five van Genuchten-Mualem parameters, saturated hydraulic conductivity, two Manning coefficients (x and y direction) and two so-called coupling lengths between the surface and subsurface domain (one for the impluvium and one in the sealed trench) was considered for model parameterization per site. The measured hydraulic parameters were used as initial estimates. Because of the parameter interaction that typically occurs in a highly-parameterized non-linear model such as the one used, a variance-based global sensitivity analysis (GSA) was applied on the arid hillslope (small catchment) dataset (rather than a local sensitivity analysis or one-at-a-time approach). GSA looks at both the first order sensitivities as well as the total order sensitivities starting from the model output variance. We used Jansens' estimator which applies a quasi-random sequence generator. A total of 5000 model runs were performed with HGS, in which runs were separated in ten separate sections and using the parallel HGS version (Park et al. 2010) to solve the model on 16 computer cores (Intel Xeon L5420 2.5GHz) simultaneously, which could reduce the calculation time significantly (Verbist et al. 2012).

Since prior studies on inverse modelling of unsaturated flow identified the need to supply at least two different data types to calibrate unsaturated flow models uniquely (e.g. Wöhling and Vrugt 2011), two different model outputs, i.e., runoff hydrographs and soil-water content time series were used in the inversion process to parameterize HGS with PEST (Doherty 2010). We are currently employing DREAM (Laloy and Vrugt 2012) to assess whether the parameterization process can be improved and to include uncertainty estimates.

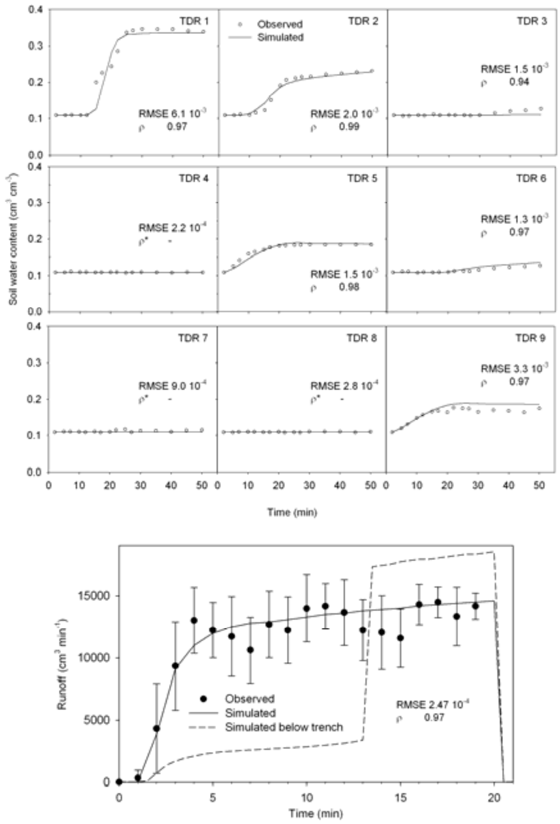

Figure 3. Observed and simulated change in soil water content for nine TDR-probes inserted under the impluvium and trench (top) and in runoff (bottom) with time

RESULTS AND DISCUSSION

Hillslope study

Model setup and performance

GSA showed that the model was not sensitive to the longitudinal and lateral Manning surface friction coefficients, and Mualem's pore connectivity parameter. PEST was then executed in parameter estimation mode and required 149 model runs to calibrate the model, resulting in a weighted Pearson correlation coefficient of 0.97. Overall, the optimized parameter values showed rather small confidence intervals as required for a well-posed model solution. The optimized values of saturated hydraulic conductivity Ksat and the van Genuchten parameters θs and α were close to the initial value estimates and fell within the confidence interval of the measured values, similar to the findings of Köhne et al. (2011). The coupling length values for the impluvium and trench were very different, since the free variation of both parameters compensated for the differences in infiltration rates between both sections. Figure 3 shows the good match between observed and simulated water contents and runoff. The simulated runoff downslope of the trench (after 14 minutes; dashed line) perfectly matched the observed overtopping. This is an important feature of the model, since it allows representing interaction of water harvesting techniques in complex design schemes. As such, a better understanding of the behaviour and effectiveness of these WHT on irregular terrains becomes feasible.

Evaluation of WHT efficiency

To evaluate rainwater harvesting efficiency, the calibrated model was used to simulate runoff and redistribution of soil water for a slope with and without a trench under the same simulated rainfall conditions (Fig. 4). Visually, large differences in water content (expressed as degree of saturation) are apparent between both cases. When looking at the cross section along the slope at the middle position (y = 1 m), the water harvesting capacity of the trench becomes clear, with increased water storage in the soil domain surrounding the trench, when compared to the unaltered slope. The very local effect of water storage in infiltration trenches was also observed by Makurira et al. (2009).

For a total rainfall amount of 36.94 mm applied during the rainfall simulations, 63% was lost by runoff when no trench was present (23.2 mm), whereas only 12.5 mm of runoff was generated in the case with the trench. This decrease in runoff by 46% means that, for the simulated rainfall, 10.7 mm (29%) of additional runoff water infiltrated in the soil profile when a trench was present. However, when extending the evaluation of the WHT's efficiency to natural rainfall conditions occurring in the area of interest, the model demonstrated that for dry, normal and wet years (22, 58 and 102 mm, resp.), the volumetric differences of the water balance components between both cases were very small. Actual transpiration and soil evaporation were clearly driven by precipitation constraints, increasing from dry to wet. The observed precipitation in those years was indeed below the minimum precipitation for optimal microcatchment runoff water harvesting, which has been estimated to lie between an annual precipitation

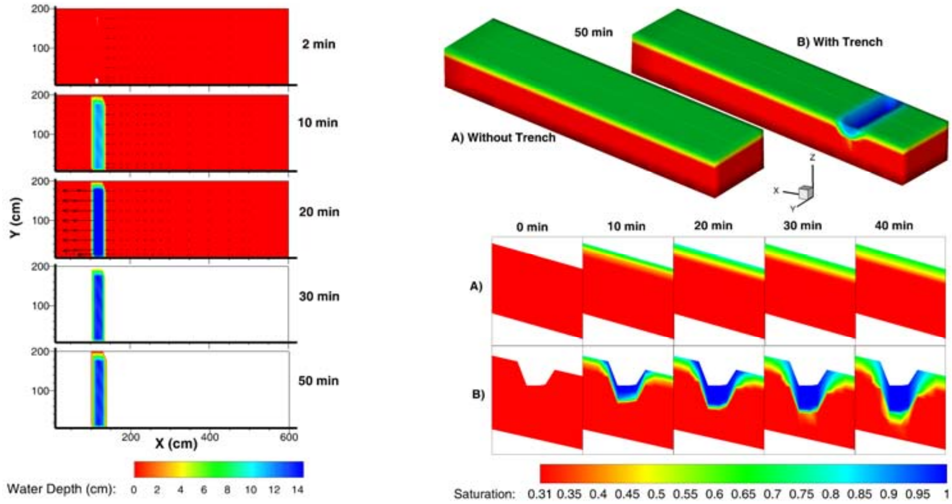

Figure 4. Left panel: 2D representation of the simulated water depth at the soil surface and in the trench at times 0-50 min. Vectors indicate the overland flow direction and velocity at the node level. Note that the colour scale starts at a water depth of $1x10^{-5}$ cm. A white colour thus means a zero water depth and no overland flow. Right panel: 3D representation of the simulated soil water content expressed as saturation degree a) without and b) with water harvesting trench at time 50 min. The lower part shows a vertical 2D slice of the soil domain at y = 1 m and at time 0-40 min.

amount of 100 mm (Boers and Benasher, 1982) up to 250 mm (Chritchley and Siegert, 1991). Only under extremely wet conditions did differences in the water balance components become apparent. In the wettest year on record (1940-2008), 1987 with 407 mm annual rainfall due to a strong El Niño signal (Verbist et al. 2010a), the WHT resulted in a reduction in runoff of 65%. However, soil moisture only increased by 9%, as a large part of the infiltrating water was lost to deep drainage (+189%). This means that although infiltration trenches have a great potential to harvest water, they were not efficient under the climatic and soil conditions prevailing in this arid study area.

Watershed study

After calibrating HGS for the semi-arid watersheds of interest, model runs were produced for several years. Figure 5 shows a reasonable agreement between observed and simulated runoff at the watershed outlet (3 to 15 October 1997, with 1997 being a wet year). Although in the case of the watershed with WHT, which has an extremely complex microtopography because of the presence of hundreds of trenches, the agreement was lower than for the watershed without WHT, the general runoff pattern was well captured.

Simulations for dry, normal and wet years (144, 438 and 893 mm, resp.) showed that the presence of WHT in the watershed reduced runoff by 14 to 23%. To further improve their efficiency, different design scenarios should be developed.

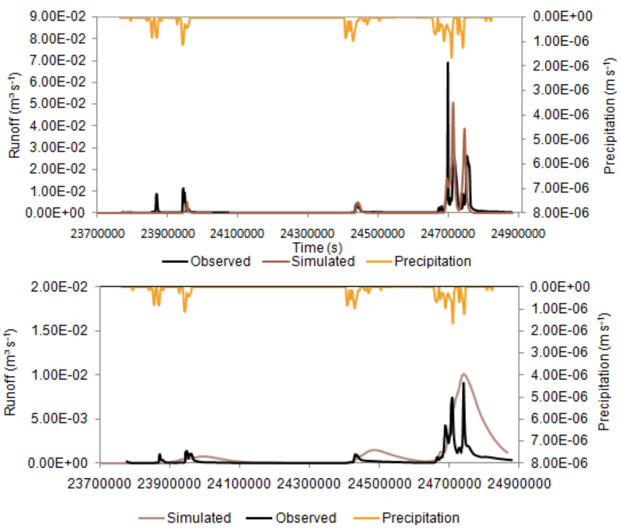

Figure 5. Observed and simulated runoff at the watershed outlet with (top) and without (bottom) infiltration trenches (3 to 15 October 1997)

CONCLUSIONS

We conducted a small-scale experiment on an arid hillslope (6 x 2 m) in which water content and runoff were measured during simulated rainfall to parameterize a fully-coupled surface/subsurface process-based hydrological model. The model proved to be most sensitive to saturated hydraulic conductivity, van Genuchten parameters and coupling length between the surface and subsurface domain. After optimizing the model parameters, we found very good agreement between observed and measured water contents and runoff. The model was then used to evaluate the efficiency of existing WHT (infiltration trenches) in the arid area of interest. The model results demonstrated that the WHT was not efficient in reducing runoff and capturing water for dry, normal and wet years. Only under extremely wet years, such as El Niño years, were marked differences in water balance components observed. Such findings are not surprising and could have been concluded from other more empirical approaches. However, the advantage of our approach is that we have a versatile tool at hand that enables improving the design of the

WHT by evaluating multiple scenarios and that it provides much better insights on how soil hydrology is affected by such techniques.

The model was also applied in a semi-arid region at a much larger scale (~3 ha), in a watershed with and without WHT. Runoff at the watershed outlet was reasonably well predicted even in the case of the watershed with WHT, which had an extremely complex microtopography because of the presence of hundreds of trenches. Under the climate and soil conditions prevailing at the semi-arid site, the WHT seemed to be more efficient. Scenarios with different designs can be carried out to further improve the WHT's efficiency. Moreover, the model seems very appropriate to evaluate the upstream and downstream hydrological impact of WHT at the watershed scale. Harvesting water upstream can deprive downstream water users. Analyzing the potential and the implications of upscaling of water harvesting on a watershed and/or community scale is thus of primary importance.

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REFERENCES

Boers, T. M., and Benasher, J. (1982). A review of rainwater harvesting. *Agric. Water Manage.*, 5, 145-158.

Chritchley, W., and Siegert, K. (1991). W*ater harvesting: a manual for the design and construction of water harvesting schemes for plant production*. FAO, Rome, Italy.

Denevan, W. M. (2001). *Cultivated Landscapes of Native Amazonia and the Andes*. Oxford University Press

Doherty, J. (2010). *PEST, Model-Independent Parameter Estimation User Manual*. 5th Edition, 705 Watermark Numerical Computing, Oxley, Australia.

Köhne, J., Wöhling, T., Pot, V., Benoit, P., Leguedois, S., Le Bissonnais, Y. and Šimůnek, J. (2011). Coupled simulation of surface runoff and soil water flow using multi-objective parameter estimation. *J. Hydrol*., 403,141-156.

Laloy, E. and Vrugt, J. A. (2012). High-dimensional posterior exploration of hydrologic models using multiple-try DREAM((ZS)) and high-performance computing. W*ater Resourc. Res.*, 48, W01526.

Makurira, H., Savenije, H. H. G., Uhlenbrook, S., Rockström, J. and Senzanje, A. (2009). Investigating the water balance of on-farm techniques for improved crop productivity in rainfed systems: A case study of Makanya catchment, Tanzania. Ph*ys. Chem. Earth*, 34, 93-98.

McLaren, R. G. (2007). Grid Builder. A pre-processor for 2-D, triangular element, finite element programs. Groundwater Simulations Group, University of Waterloo, CA.

Pandey, D. N., Gupta, A. K. and Anderson, D. M. (2003). Rainwater harvesting as an adaptation to climate change. *Current Science,* 85, 46-59.

Park, Y., Hwang, H. and Sudicky, E. A. (2010). A parallel computational framework for integrated surface-subsurface flow and transport simulations. American Geophysical Union, Fall Meeting 2010, abstract #H41F-1132.

Sudicky, E., Jones, J., Park, Y.-J, Brookfield, A. and Colautti, D. (2008). Simulating complex flow and transport dynamics in an integrated surface-subsurface modeling framework. *Geoscienc. J.*, 12, 107-122.

Verbist, K., Schiettecatte, W. and Gabriels D. (2003). Usability of rainfall simulation experiments to assess soil erosion under natural rainfall. In '25 years of assessment of erosion' (Eds D. Gabriels, W. M. Cornelis) Ghent, Belgium. pp. 269-276.

Verbist, K., Baetens, J. M., Cornelis, W. M., Gabriels, D., Torres, C. and Soto, G. (2009) Hydraulic conductivity as influenced by stoniness in degraded drylands of Chile. *Soil Sci. Soc. Am. J.,* 73, 471-484.

Verbist, K., Robertson, A., Cornelis, W. M. and Gabriels, D. (2010a). Seasonal predictability of daily rainfall characteristics in central-northern Chile for dry-land management. *J. Applied Meteorol. Climatol.*, 49, 1938-1955.

Verbist, K., Torfs, S., Cornelis, W. M., Oyarzún, R., Soto, G. and Gabriels, D. (2010b). Comparison of single- and double-ring infiltrometer methods on stony soils. *Vadose Zone J*., 8, 462–475.

Verbist, K., Cornelis, W. M., Pierreux, S., McLaren, R., Gabriels, D. (2012). Parameterizing a coupled surface-subsurface 3D soil hydrological model to evaluate the efficiency of a runoff water harvesting technique. *Vadose Zone J*. Sub judice.

Wöhling, T. and Vrugt, J. A. (2011). Multiresponse multilayer vadose zone model calibration using Markov chain Monte Carlo simulation and field water retention data. *Water Resour. Res.*, 47, W04510.