Effects of differential hillslope-scale water retention characteristics on rainfall-runoff response at the Landscape Evolution Observatory

Daniël B. van den Heuvel
University of Twente
d.b.vandenheuvel@student.utwente.nl

ABSTRACT

To be able to collect the reliable data necessary for understanding and modeling various Earth system processes in real catchments, controlled experiments are being conducted at the Landscape Evolution Observatory (LEO) within Biosphere2, The University of Arizona. Rainfall experiments have revealed differences in hydrological response between two landscapes within LEO, despite the landscapes' identical design and equipment. In an attempt to discover where the observed differences stem from, we use a full 3D hydrological model (CATchment HYdrology, CATHY) to show the effect of soil water retention on the rainfall-runoff response of these two hillslopes.

Keywords

Rainfall-runoff response, landscape evolution, soil water retention, soil characteristics, hydrological 3D modeling, Biosphere2

INTRODUCTION

In an endeavor to be able to explain the influence of earth system processes on landscape evolution, the University of Arizona broke ground in 2007 on a large-scale interdisciplinary research project, the Landscape Evolution Observatory (LEO), located within Biosphere2. The project's goal is to understand how different interacting coupled earth system processes associated with hydrology, ecology, geochemistry and geomorphology determine the evolution of landscapes over time. LEO consists of three landscapes (hillslopes) that are identical in shape, soil, environment and technical equipment. The project is unique in its field due to its fully controlled environment, abundant presence of measuring equipment and hillslope-size scale. An artist impression of LEO within Biosphere2 is shown in Figure 1.

Similar projects include the artificial catchment "Chicken Creek" (Gerwin et al., 2009) and the TERENO program (Zacharias et al., 2011), both located in Germany. Although these projects also seek to improve understanding of coupled processes in catchments, they take place at different spatial scales. Moreover, these projects lack the observational capacity and control of LEO as they take place at larger scales and are not located within controlled environments.

Rainfall experiments conducted simultaneously on LEO's central and west hillslopes (LEO-C and LEO-W) in 2015 revealed substantial differences between the two hillslopes' hydrological response. More specifically, LEO-C seems to discharge water much faster than LEO-W. The existence of this difference is concerning, as the slopes were assumed to be fully identical in geometry, soil composition and technical equipment installed.

The study presented here aims to elucidate why these two identically designed and built hillslopes differ substantially in rainfall-runoff response. To this end, behavioral models of these two landscapes are set-up with CATchment HYdrology (CATHY). Since measurements and tests have proven that the landscapes' geometries are identical and the measuring equipment functions properly, this work focuses on the role of the soil's water retention parameters α^{-1} (related to the capillary fringe) and n (related to the soil packing) (Van Genuchten, 1980) and the saturated hydraulic conductivity K_s. In this work we simulate the hydrological behavior of both landscapes in CATHY using variations of these three soil parameters. We then compare the best simulations with observations from both landscapes in an attempt to explain the differences in rainfall-runoff response. We consider only the central and west landscapes because similar rainfall experiments were conducted almost simultaneously on these landscapes, ensuring good comparability.

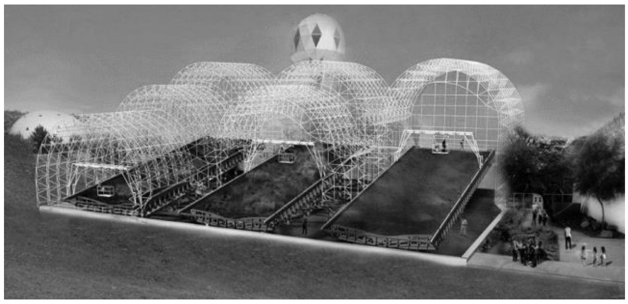

Figure 1: Artist impression of the LEO project, showing the three convergent landscapes within Biosphere2

MATERIALS AND METHODOLOGY

Physical model

The LEO landscapes measure 30 m by 11.15 m. The average slope is 10° and the shape of each landscape is convergent. Crushed basalt tephra from the same crushed rock was used as a homogeneous soil layer of 1 m thickness. There was no vegetation on the soil during the experiments. The basalt tephra is expected to evolve into structured soil over the course of multiple rainfall experiments, but we assumed no geochemical of primary minerals would happen during the first experiments. The bottom ends of each landscape feature a 0.5 m wide section of gravel bordering a plastic plate with 2 mm diameter holes drilled in it. The seepage face is located at the interface between the tephra and gravel.

Artificial rainfall can be applied to the landscapes using 14 sprinkler heads installed above each slope. These sprinklers are equally distributed in space, are positioned approximately 3 m above the soil surface and have a maximum rainfall capacity of 48 mm h^{-1}.

Rainfall experiments

Long-lasting rainfall experiments were conducted on the central landscape on 11 May 2015 between 07:30 and 19:30 Local Time (LT) and on the west landscape on 18 May 2015 between 07:00 and 19:00 LT. Both rainfall events had a constant intensity of approximately 12 mm h^{-1}. Prior to these events, test runs had been carried out to bring the hillslopes to similar initial wetness conditions and to test all equipment installed. Both landscapes were equally wet at the start of the experiment with water storage values of approximately 105 mm. This value was derived from soil moisture content measurements taken before the experiments were executed. On both landscapes 134 mm of artificial rainfall was applied and no overland flows occurred.

Data acquisition and processing

The landscapes sit in a controlled environment, ensuring constant values of other relevant parameters, such as temperature, air humidity and pressure. Each landscape is equipped with over 1,800 subsurface sensors and samplers. For measurement purposes, sensors are installed at five depth levels throughout each landscape. This ensures high spatial resolution in the horizontal and vertical directions. Each landscape contains 496 Decagon 5TM sensors that measure the volumetric soil water content (SWC). These are co-located with Decagon MPS-2 sensors measuring the soil's matric potential (MP). Moreover, landscape discharge is measured by NovaLynx 26-2501-A tipping buckets and magnetic flow meters (SeaMetrics PE102 Flow Meter). The former are most reliable during low discharge regimes (< 0.11 ℓ min^{-1}) while the latter yield minimum relative errors at higher discharges (> 0.11 ℓ min^{-1}).

SWC values were retrieved from each landscape during the 12-hour experiment and during a long period of 220 hours thereafter. For each depth at which SWC sensors are installed, the average value of all available sensor readings was calculated. These averages were then weighted by the vertical distance between the sensors at the different soil depths to obtain the landscape water storage.

Landscape discharge rates over the same 232-hour time period were also retrieved. In the first 12-hour portion of the experiment during which rainfall was still being applied, we used data from the NovaLynx tipping buckets because discharge was below the 0.11 ℓ min^{-1} threshold during this period. Data from the PE102 Flow Meters were used for the remainder of the experiment, after rainfall ceased and discharge started to increase.

We also observed SWC and MP during and after the experiment to compare observations with simulated soil water retention curves (MP plotted against SWC).

Hydrological model

We used the full 3D hydrological model CATHY to obtain simulations of the landscape experiments that had been conducted. Because no overland flow occurred during the rainfall experiments, only the subsurface module of CATHY was used in this study. This module is based on solving the 3D Richards equation (Richards, 1931). For comparability, CATHY was set up in a similar fashion as described by Niu et al. (2014) where each slope is discretized into a grid of 60 × 24 cells and 8 vertical layers. Also, time steps are variable, depending on the number of iterations necessary to reach convergence, whereas the spatial grid does not vary.

In order to find which soil parameters differ the most among the two landscapes and thus could be responsible for the different landscape responses, approximately 1,000 CATHY simulations were obtained for each landscape. Values of the Van Genuchten parameters α^{-1} and n, and K_s were varied each time within broad ranges. Each simulation was conducted with a randomized set of parameters, assuming soil homogeneity.

For each simulation, model efficiency was calculated. We decided to use an efficiency coefficient based on the Nash-Sutcliffe Efficiency coefficient (NSE) (Nash & Sutcliffe, 1970) and the more recent Kling-Gupta Efficiency coefficient (KGE) (Gupta et al., 2009). These coefficients are respectively expressed as follows:

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Y_m^t - Y_o^t)^2}{\sum_{t=1}^{T}(Y_o^t - \bar{Y}_o)^2} \quad [1]$$

where NSE is the Nash-Sutcliffe Efficiency coefficient [–], $Y_m{}^t$ is the modeled value of quantity Y at time t [T] and $Y_o{}^t$ is the observed value of quantity Y at time t, and:

$$KGE = 1 - \sqrt{(R-1)^2 + \left(\frac{\sigma_m}{\sigma_o} - 1\right)^2 + \left(\frac{\bar{Y}_m}{\bar{Y}_o}\right)^2} \quad [2]$$

where KGE is the Kling-Gupta Efficiency coefficient [–], R is the correlation between the observed and modeled series of quantity Y [–] and σ is the standard deviation of the modeled and observed values.

CATHY's performance in simulating both storage and discharge is taken into account using a single expression for CATHY's model efficiency coefficient E [–]:

$$E = \frac{1}{4}\left(NSE_Q + NSE_S + KGE_Q + KGE_S\right) \quad [3]$$

where subscript Q denotes the time series of the discharge for each landscape and subscript S denotes the time series of the storage for each landscape.

The top 2% of simulations in terms of model efficiency coefficient E were retained as behavioral, meaning that we considered these simulations sufficiently fit to draw conclusions from them. This resulted in 20 sets of the parameters α^{-1}, n and K_s for each landscape. These were used to set up ranges of each soil parameter for which CATHY is considered behavioral.

Furthermore, we used the soil parameter values that yield maximum model performance to obtain simulations of the slopes' storage and discharge over time and soil water retention curves. Here a porosity value of 0.395 for both landscapes as previously reported by Pangle et al. (2015) was assumed and the residual soil moisture content was set to zero. We compared these simulations to observations in order to draw conclusions as to the influence of soil parameters on the landscapes' hydrological response.

RESULTS

Optimal parameter ranges resulting from the CATHY calibration are shown in Table 1, which also includes the model efficiency coefficients. Especially the value of the Van Genuchten parameter α^{-1} is remarkably different in both landscapes while differences in the parameters n and K_s are smaller. Judging by the high model efficiency coefficient, model performance was excellent. Figure 2a shows both landscapes' observed and simulated water storage as function of time. Figure 2b depicts the landscapes' observed and simulated discharge as a function

Table 1: CATHY calibration results

	LEO-C (range)	LEO-C (optimal)	LEO-W (range)	LEO-W (optimal)
α^{-1} (m)	[−0.257; −0.137]	−0.197	[−0.573; −0.370]	−0.444
n (–)	[1.73; 2.09]	1.88	[1.97; 2.60]	2.25
K_s (10^{-4} m s^{-1})	[1.64; 1.99]	1.79	[1.05; 1.37]	1.19
Average E	0.956	0.965	0.930	0.941

of time. Storage in both landscapes increased steadily and at the same pace for the duration of the rainfall event (0-12 h). However, shortly after the rainfall had stopped, the storage dynamics between the central and west slope started to differ considerably. This behavior is reflected by the model as simulations match well with observations (E of 0.965 and 0.941 respectively for LEO-C and LEO-W). Both landscapes' storage decreased due to the discharge of water through their seepage faces, but LEO-C lost water much faster. This observation is echoed by the discharge rates. As rainfall stopped, discharge from both landscapes continued to increase, but the west landscape discharged water at a much slower pace than the central landscape.

Figure 3 depicts the observed and simulated soil water retention curves for both landscapes. While the curves are similar in shape, the west slope's soil observed higher matric potential values under identical wetness conditions, both in observations and in simulations. Also, the hysteresis between the wetting phase (during the rain experiment; upper observation series) and the drying phase (post-experiment; lower observation series) is clearly visible. Model performance is generally acceptable, except under wetter conditions (SWC > 0.15). This was caused by MP sensor saturation during wet conditions which could not be resolved.

DISCUSSION AND CONCLUSION

This research has shown that there exists a clear difference in the hydrological response of LEO's central and west landscapes. LEO-W retains artificial rainfall applied to the slope much longer than LEO-C. As a result, post-experiment discharge rates of LEO-W are up to two times lower than those of LEO-C. Simulations of the same experiments on both landscapes conducted with CATHY yield very similar results.

Moreover, observed soil water retention curves of both landscapes indicate a substantial difference in soil water characteristics among the two landscapes. Simulations using the optimal parameter set resulting from CATHY calibration match reasonably well with observations. Especially the value of α^{-1} differs among the two landscapes, which supports our hypothesis that the soil water retention characteristics are responsible for the observed difference in hydrological response. The value of α^{-1} is related to the capillary fringe of the landscapes' soil. We were unable to find the precise cause of the difference in capillary fringe between the landscapes in the context of this research. However, we have formulated the hypothesis that the soil in LEO-W may contain more fine pores. This may have led to structurally lower discharge during and after experiments causing the landscape to retain more water compared to the central landscape. As the soil drains, differences in absolute MP between the landscapes become substantial. This difference in soil water retention characteristic is reflected by the strong difference in observed and modeled values for the parameter α^{-1}.

It is important to realize that many conclusions drawn from this research are based on just one experiment. Most results obtained during this research seem to be in accordance with each other and explain the difference in observations, but analysis of a larger number of experiments may further support the conclusions drawn here.

Furthermore, it is necessary to acknowledge that the results gathered and discussed in this research rely on some model idealizations. For instance, the Van Genuchten model has been assumed throughout this research. Although renowned in its field, the Van Genuchten model is highly empirical and features idealizations to simplify the

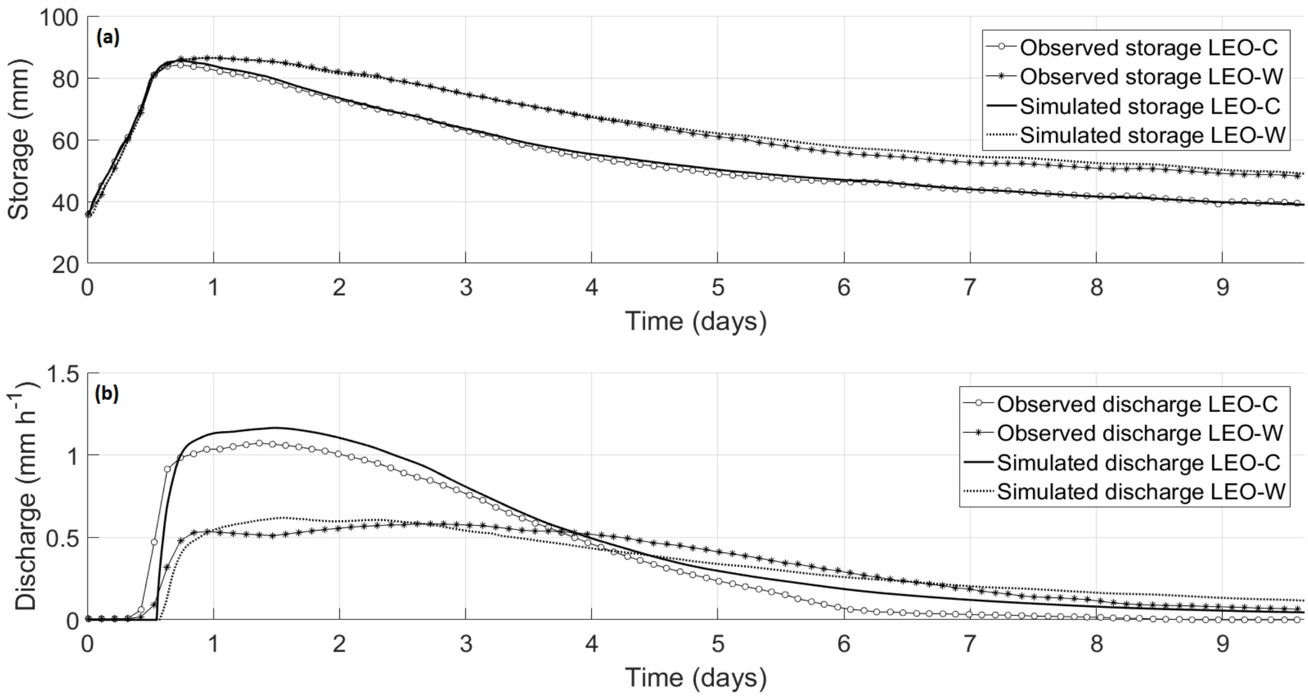

Figure 2: Timeseries of observed and simulated water storage (a) and discharge (b) of LEO-C and LEO-W over the course of the rainfall experiments. Rainfall was stopped after 12 hours.

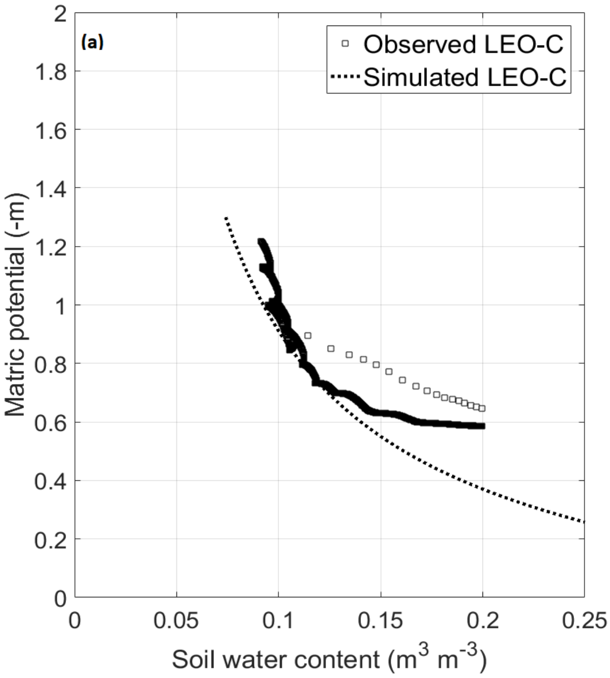

Figure 3: Observed and simulated soil water retention curves in LEO-C (a) and LEO-W (b). Note that observations are so close together during the wetting phase that they may appear as a line.

equations involved.

In addition, this work underlines the profound effects of soil water retention characteristics on landscapes' hydrological response. Despite a controlled environment and intensive instrumentation, simulated water retention characteristics were not entirely in accordance with observations. Prediction of catchment behavior using water retention characteristics will therefore continue to be challenging as real-world sites are not fully controlled and as heavy-instrumented. However, CATHY model performance was good throughout this research, which is promising for the role of 3D hydrological modeling in future studies.

ROLE OF THE STUDENT

Daniël van den Heuvel conducted an internship at the University of Arizona in 2016 to obtain his Bachelor's degree at the University of Twente. He was supervised by dr. Troch and visited the Biosphere2 facility multiple times. Dr. Booij was Daniël's supervisor and examiner from the University of Twente and provided much help and feedback prior to and during the internship.

Actual experiments had already been conducted before the internship took place and preliminary analysis of the results yielded considerable differences in hydrological response between the two landscapes. Dr. Troch determined the approximate assignment to investigate these differences and suggested to focus on soil characteristics. He also provided relevant data, a working version of CATHY and much feedback on intermediate results. Daniël came up with the described methodology, conducted the analysis of experiment data, adapted CATHY to fit its purpose here to obtain simulations and processed all the results to draw some conclusions as to the observed difference in hydrological response. He also delivered a presentation summarizing the results in front of an audience of local scientific staff to discuss tentative conclusions and raise further research ideas.

REFERENCES

1. Gerwin, W., Raab, T., Biemelt, D., Bens, O., & Hüttl, R. F. (2009). The artificial water catchment "Chicken Creek" as an observatory for critical zone processes and structures. *Hydrology and Earth System Sciences Discussions, 6(2)*, 1769–1795.
2. Gupta, H. V., Kling, H., Yilmaz, K. K., & Martinez, G. F. (2009). Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *Journal of Hydrology, 377(1–2)*, 80–91.
3. Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I — A discussion of principles. *Journal of Hydrology, 10(3)*, 282–290.
4. Niu, G. Y., Pasetto, D., Scudeler, C., Paniconi, C., Putti, M., Troch, P. A., … Zeng, X. (2014). Incipient subsurface heterogeneity and its effect on overland flow generation - Insight from a modeling study of the first experiment at the Biosphere 2 Landscape Evolution Observatory. *Hydrology and Earth System Sciences, 18(5)*, 1873–1883.
5. Pangle, L. A., DeLong, S. B., Abramson, N., Adams, J., Barron-Gafford, G. A., Breshears, D. D., … Zeng, X. (2015). The Landscape Evolution Observatory: A large-scale controllable infrastructure to study coupled Earth-surface processes. *Geomorphology, 244*, 190–203.
6. Richards, L. A. (1931). Capillary conduction of liquids through porous mediums. *Journal of Applied Physics, 1(5)*, 318–333.
7. Van Genuchten, M. T. (1980). A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Science Society of America Journal, 44(5)*, 892–898.
8. Zacharias, S., Bogena, H., Samaniego, L., Mauder, M., Fuß, R., Pütz, T., … Vereecken, H. (2011). A Network of Terrestrial Environmental Observatories in Germany. *Vadose Zone Journal, 10(3)*, 955-973.