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Hydrology and Earth System Sciences
Discussions
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Interactive comment on "Analysis of an extreme rainfall-runoff event at the Landscape Evolution Observatory by means of a three-dimensional physically-based hydrologic model" *by* G.-Y. Niu et al.

G.-Y. Niu et al.

niug@email.arizona.edu

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In this work, the physics based model Cathy is used to investigate the response of an artificial hillslope to the application of a uniform rainfall input. The artificial hillslope (named LEO) is built by using a homogeneous soil. Based on the supposedly well known soil properties and on earlier modelling applications, the rainfall was applied uniformly in space and time to bring the hillslope to a hydrologic steady-state. However, the hillslope never reached the predicted steady-state but instead developed saturation

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excess overland flow. The work aims to understand why did the observed hydrological response differ so significantly from the predicted response. The answer offered by the authors is that the experiment itself triggered some form of heterogeneity in the soil hydraulic conductivity of the seepage face. Indeed, when this heterogeneity is included in the model building, the model is shown to be able to accurately reproduce the hydrologic response. The topic is very interesting, in that it shows the hydrological implications of processes which introduce heterogeneity in a supposedly homogeneous environment. The objectives are of interest for the readers of HESS and the writing is good. Nevertheless, the paper lacks focus and a clear story line and suffers from structure.

R: Thanks for the comments and for your time in reviewing the paper.

Lack of focus and a clear story line: The title is misleading. The 'investigation of an extreme rainfall-runoff event' is evidently not the central focus of this paper. The introduction reserves too room for the general description of the LEO experiment, whereas too few is dedicated to establish a link between one main objective of LEO (examination of co-evolution of the physical and biological system) and the incipient heterogeneity which is tested by the field-numerical experiment. There are essentially no conclusions, in the sense that the implications of the obtained results are not even addressed.

R: We have changed the title, revised the introduction and conclusion, and added a discussion section.

Problems with structure: The main problem with the structure of the work is that it poses a very nice question assisted with a formidable experimental structure, and ends up with an answer which is just barely supported by the multiple monitoring means. The authors should use internal data (at least soil moisture data and soil hydraulic data at the seepage face) to add experimental foundation to the numerical simulations, and to reduce equifinality in the answers they are able to offer. Moreover, the authors should at least address what is the main implication of this field-numerical experiments. In

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my opinion, this can be stated as follows: during the observed event, the hydraulic properties of part of the hillslope evolved from one value to another. The numerical model cannot reproduce this behavior: it is based on use of static values for the hydraulic properties. This is interesting, because it is a process likely occurring in many intense events, and very often forgotten both by experimentalists and modellers. The discussion of the results should include consideration of this implication.

R: We have taken care to revise the paper throughout to make clearer the context and objectives of our study and the wider implications of our findings. On the issue of using soil moisture data, see our response to the previous reviewers.

Considering the general interesting topic I think that the work might be publishable after moderate revisions. In the following I will try to outline, where and how the manuscript can be improved.

R: We really appreciate the outline, which we followed closely.

Title: The title should focus on the main problem addressed by the work, which is not the investigation of an extreme rainfall-runoff event.

R: We changed the title to “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”

Abstract: The abstract should make clear the meaning of the ‘saturated soil compactation near the seepage face’. This is apparently due to the transport of fine sediments during subsurface saturated flow prior the onset of overland flow. Moreover, the abstract should make clear how the heterogeneous model is built. The sentence starting with “We varied the saturated: : :” is central for this, but it is definitely hard to understand.

R: We significantly revised the abstract following the suggestions: “Heterogeneity may have developed during the first experiment at one of Biosphere 2 Landscape Evolution

Observatory (LEO) hillslopes. The LEO hillslopes are carefully compacted with homogeneous soil to a depth of 1m. The experiment, driven by an intense rainfall event, produced predominantly seepage face water outflow, but also generated overland flow that caused erosion of the superficial soil and formation of a small channel. In this paper, we explore the hypothesis of incipient heterogeneity development in LEO and its effect on overland flow generation using a three-dimensional physically-based hydrological model. The model simulations consider spatially varying saturated hydraulic conductivity (Ksat), as well as uncertainty in Ksat and other soil parameters. Our null hypothesis is that the soil is hydraulically homogeneous, while the alternative hypothesis is that the soil has developed some heterogeneity in the downstream direction due to transport of fine sediments driven by saturated subsurface flow. The heterogeneous case is modeled by assigning a different saturated conductivity at the LEO seepage face (Ksat,sf). A range of values is used for Ksat, Ksat,sf, soil porosity, and pore size distribution, resulting in more than 20,000 simulations. It is found that the best runs under the heterogeneous soil hypothesis produce smaller errors than those under the null hypothesis, and that the heterogeneous runs yield a higher probability of best model performance than the homogeneous runs. These results support the alternative hypothesis of localized incipient heterogeneity of the LEO soil, which facilitated generation of overland flow."

Introduction: After a short general description of LEO and of its aims, the introduction should describe only the facilities used for the described experiment and the relevant links to the general aims of LEO. This is not the case, and this is where the Introduction must be improved. For instance, the introduction describes the first experiment as a sequence of two artificial rain applications (P4 L18-20), with the second rain application being labeled with deuterium. It announces also that chemical analysis should inform about water transit times. Since the second rain event and the chemical analysis was never executed (or at least is not part of this work), this only adds confusion to the description of the experiment. Even more important: the reader cannot understand from the Introduction if the incipient heterogeneity tested with the field and numerical experiment is a documentation of an already started co-evolution of the system, or it is just due to an accident. Owing to lack of clarity on this, the reader cannot understand why it is important to understand the reasons for the mismatch between predicted and observed hillslope's behavior and which are the potential lessons to learn.

R: We revised the introduction following the suggestions, starting with heterogeneity issues in catchment hydrology: "Landscape heterogeneity is ubiquitous at various spatial scales, it may evolve over time, and it induces process complexity that still hasn't been properly addressed in catchment hydrology. As such, predictions of the Earth system response to natural and anthropogenic forcing are currently highly uncertain (Sivapalan 2005; McDonnell et al., 2007; Troch et al., 2009). To develop a unified theory of catchment hydrology, hydrologists should ask questions of "why" the heterogeneity exists rather than traditional questions of "what" heterogeneity exists (McDonnell et al., 2007). This requires an improved understanding of the intimately coupled processes of hydrology, geomorphology, ecology, pedology, and biogeochemistry (McDonnell et al., 2007; Troch et al., 2009)."

The first LEO Experiment: This text doesn't include information on the hydraulic behavior of the seepage face. Part of this information is instead reported at P14, L18-27, almost at the end of the paper. This last text should be moved into the description of the first LEO Experiment, to provide ground to the choice to decrease the saturated hydraulic conductivity for the seepage elements of the computational mesh.

R: Agreed. We moved this paragraph to "The first LEO experiment" section: "Shortly after the experiment we removed the gravel to a depth of 72 cm and determined the fraction of fines per volume of gravel to be about 2%, which may or may not represent a significant reduction in hydraulic conductivity of the seepage face, considering also that precise measurements could not be made over the entire seepage face. In addition we observed some of the holes in the plate to be clogged with fines but were unable to test the effect of this clogging on the hydraulic conductivity of the seepage face."

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Also, at P7, L8, it is stated that "total mass change, total seepage flow, and soil moisture at 496 locations were recorded every 15 min during the experiment". However, the authors only use total mass change and total seepage flow in the analysis. They should make clear why the use of soil moisture data is considered inessential to better clarify the hydrological functioning of the hillsope. Otherways, they should use these data to shed light on the comparison between observed behaviours and model results.

R: As mentioned in previous points, examination of the soil moisture data has been included in another paper submitted to HESS-D, and further analyses of LEO experiments data using internal data is ongoing.

Model setup: a figure with the description of the mesh organization should be reported to help the reader to understand how the Homogeneous and the Heterogeneous model simulations were built. This distinction is key to understand the model results; however it is left to three mere lines (P9 L 2-4) where the unclear term Ksat,sf is reported. This variable is never defined in the text. Also, it is difficult to locate the mesh grids where the conductivity was modified.

R: We revised Figure 3 to add the seepage face nodes where Ksat,sf was modified in the heterogeneous case, and Ksat,sf is now properly defined (including in the Abstract).

Modelling results: as reported above, one key implication of this work is that during the observed event, the hydraulic properties of part of the hillslope evolved from one value to another. The numerical model cannot reproduce this behavior: it is based on use of static values for the hydraulic properties. The discussion of the results should include consideration of this implication. In the current text, this is done only at P10 L16.

R: We do not of course know whether the heterogeneity developed gradually or suddenly, but very good model results were obtained with the hypothesis of localized heterogeneity. In the new Discussion section we provide the following impetus to further development of coupled Earth system models: "In this modeling study we assume that all soil parameter values vary horizontally and are static during the modeling period.

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Evolution of heterogeneity due to coupled water and sediment transport processes, which may occur in particular under intense rainfall conditions, is beyond the ability of state-of-the-art hydrological models and requires more attention in ongoing efforts to develop coupled Earth system models. Likewise, soil erosion models that consider only surface processes (e.g., Hofer et al., 2012) are also inadequate to this task."

Moreover, at P13 L2-4 the authors report: "With the large conductivity of the LEO soil (e.g., Ksat = 1.4x10-4 ms-1 upslope of the seepage face for the optimal M4_Hetero simulation), the overland flow generation mechanism is saturation-excess". This key statement should be supported by use of soil moisture data.

R: We added the sentence "This saturation-excess runoff generation process was confirmed by a detailed analysis of the 496 soil moisture sensors (Gevaert et al., 2014)."

Discussion and conclusion: This section falls short and fail to discuss the implications of this work. Here the authors really need to extend the discussion identifying pathways for future work. Why is the work relevant to the analysis of co-evolution? What moves it beyond the status quo in the analysis of events which are able to modify the constituent soil properties? Why should someone cite this work? I expect more from a HESS paper.

R: We have added a new Discussion section: "Unlike other artificial large-scale hillslopes such as Hydrohill in China (Kendall et al., 2001) and Chicken Creek in Germany (Gerwin et al., 2009; Hofer et al., 2011), LEO was built with homogenous soil and with a focus on evolving heterogeneity from a "time-zero" homogenous condition through co-evolution of the soil-water-biota system over a time scale of years (Hopp et al., 2009; Dontsova et al., 2009). Development of catchment morphology and soil catena driven by hydrological processes through soil erosion and deposition may be one of the major causes that induce heterogeneity and that in turn exert strong feedbacks on hydrological processes (e.g., Beven et al., 1988; Sivapalan, 2005; McDonnell et al., 2007; Troch et al., 2009). At LEO it was not expected that soil heterogeneity would develop

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in such a short time period during an intense rainfall event that induced significant subsurface saturated flow. This is one of the main reasons that our pre-experiment model predictions failed to produce overland flow.

A thorough investigation of the fine particles at the seepage face or upslope is not feasible as this would alter the soil structure of LEO-1. The physically-based hydrological model used in this study allowed us to make a probabilistic assessment of the incipient heterogeneity hypothesis while considering uncertainties in soil parameters. Under heterogeneous conditions the model produced better results for seepage flow and total water storage, as well as overland flow that is comparable to estimates from a water budget analysis. It was not our intention to improve the modeling accuracy through parameter calibration but to test the hypothesis of incipient heterogeneity development.

The model we used in this study solves the Richards equation based on Darcy-Buckingham theory, resolving matrix flow and not macropore flow. There are many modeling studies that use percolation theory and other approaches to simulate hydrologic connectivity of macropores to form preferential flow pathways and threshold-like hydrological responses (e.g., Lehmann et al., 2007; Hofer et al., 2011). At this early stage of LEO, with complete absence of organic matter and vegetation roots, we do not anticipate macropore-related processes to be dominant. Macropores might possibly exist around the sensors, although in this case subsurface flow would be enhanced and would very likely have prevented generation of overland flow.

In this modeling study we assume that all soil parameter values vary horizontally and are static during the modeling period. Evolution of heterogeneity due to coupled water and sediment transport processes, which may occur in particular under intense rainfall conditions, is beyond the ability of state-of-the-art hydrological models and requires more attention in ongoing efforts to develop coupled Earth system models. Likewise, soil erosion models that consider only surface processes (e.g., Hofer et al., 2012) are also inadequate to this task."

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And the paper now concludes with:

"... This modeling study of the first LEO experiment suggests an important role of coupled water and sediment transport processes in the evolution of subsurface heterogeneity and on overland flow generation."

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 10, 12615, 2013.