Response to Interactive comment on "Hillslope hydrology under glass: confronting fundamental questions of soil-water-biota co-evolution at Biosphere 2" by L. Hopp et al.

Our responses to every comment (printed in normal) are given (*printed in italic*) on the following pages. <u>Revisions to the manuscript in response to comments from the reviewer are underlined.</u>

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1. General comments

The paper presents the hydrologic studies for designing three experimental hillslopes at Biosphere 2. The ongoing research program at Biosphere 2 is unique for many aspects. The long-term experiments in controlled environmental conditions are proposed to provide significant advances in eco-hydrology. Initial design efforts for this type of experiments deserve to be published in specific papers.

This paper illustrates:

- the main design criteria followed by the authors to ensure that the experimental hillslopes will be capable of answering the key scientific questions;
- the application of different models as design tools;
- the application of a 3-D numerical model for simulating the response of the recommended design hillslope to different climatic regimes.

I found many parts of the paper interesting, in particular those discussing the general design criteria (Section 2.1) and the difficult tradeoffs in the hillslope hydrologic design (Section 4.1).

However, I have some reservations about the design approach employed. I also think that the paper structure does not help the reader in understanding the overall design process.

I report these specific comments below, starting with the analysis of the paper contents and structure.

We highly appreciate the reviewer's comments on paper structure. They were very helpful in making the organization of the paper more consistent. Corresponding changes to the manuscript are indicated below in the specific comments section.

2. Specific comments

2.1 About the paper structure

I think that the paper should better introduce the main research questions that are going to be addressed in Biopshere 2 experiments or at least those research questions that are more relevant for the following hillslope design process. This would help the reader in understanding what are the main hydrological processes being investigated and what are the corresponding spatial and temporal scales of interest. Some research questions are just briefly presented in the introduction (page 4414 lines 14-16). Surprisingly, research questions are also presented in the discussion section, after the hillslope design has been already presented (page 4435 lines 9-21).

The goal of our manuscript is to illustrate the spatial design of the hillslope experiment, i.e. the physical design of the hillslopes themselves. Our research questions that are covered by the paper are listed at the end of the introduction: key design criteria, model results to support design, testing of three different semiarid climates. The overarching research questions of the B2 hillslope experiment are not focus of this paper but were addressed in a recent publication by Huxman et al. (EOS, 2009). They are briefly mentioned in the introduction to illustrate the overall experimental goals. The questions in the discussion, section 4.3, are open research questions with respect to the evolution of the hillslope hydrology in the course of the experiment. They cannot be answered at this point but they outline the main topics of interest and will be used to formulate specific hypotheses that can be tested with the hillslopes. <u>We have added text to the introduction to clarify this point. We have also added text to the modeling section (2.3) listing the main hydrological processes that we expect in the hillslopes.</u>

The paper should then illustrate the main hillslope features that are going to be designed. These are listed at the end of Section 2.1 "Design criteria" (page 4420 lines 15-17), while I think that they should presented before the design criteria are illustrated.

We do not agree that the hillslope features that are primarily addressed in the paper (slope angle, soil depth, soil texture) should be presented before the design criteria are outlined. Those hillslope features result from the design criteria. <u>We did restructure section 2, though, to more clearly illustrate the design process.</u> We first present the design criteria (2.1) and then explain which hillslope features were decided before the actual design modeling because of technical and philosophical considerations. This left three hillslope features (or parameters) that were addressed with the modeling. The modeling is explained in the following section (2.3).

The design study focuses on the identification of the following hillslope features: 1) hillslope surface topography; 2) subsurface topography; 3) permeability of the base; 4) overall slope; 5) soil depth and 6) soil hydraulic properties.
The first three hillslope features have been chosen by pragmatic decisions according to some general design criteria:
- hillslope surface (1) topography is designed with a zero order basin geometry, this to enhance spatial variability in the eco-hydrological processes;
- subsurface topography (2) has been designed equal to the surface topography (i.e. uniform soil depth);
- base (3) has been designed as impervious.

These pragmatic decisions are presented in the Section 2.2 "Modelling approach" (page 4421 lines 1-17). However, I think that these should not be considered as part of the "modelling approach", which has been followed only for designing the other three hillslope features. These pragmatic decisions should be discussed in a preceding section, as preliminary constraints for the following hillslope design.

We agree that the original presentation of design criteria, a priori decisions and modeling work may not have been very clear. We therefore followed the suggestion of the reviewer and <u>*restructured section 2.2 (now called “A priori design decisions”) and 2.3 (Modeling approach).*</u>

Hydrologic models have been employed as design tools in order to identify the most suitable combination of the remaining three hillslope features (see points 4-6 listed above), given the following design objectives:
- avoiding the occurrence of overland flow in order to minimise surface soil erosion;
- ensuring that the soil water dynamics during the dry season will not lead to desiccation of the vegetation.

The Authors apply two types of models with increasing level of numerical complexity:
- the first is a combination of a model simulating the vertical infiltration and flow dynamics in the unsaturated zone and a model simulating the saturated flow through the hillslope;
- the second is Hydrus-3D, which solves the Richards’ equation in the threedimensional hillslope domain.

The first model is employed essentially to identify the most suitable soil type after evaluating the hillslope response with several sets of model parameters derived by combining 12 soil types, four soil depths, two time-series of potential evaporation and various average mean surface slopes. The second model is employed to indentify the most suitable soil depth and surface slope.

I found this part of the paper difficult to read. Section 2.2.2 "Hydrus-3D modeling" anticipates some of the first model results which are discussed in the following section. Figure 4 is mentioned before Figure 3.
I think that this part of the paper could be structured in a better way. I would illustrate the design rainfall pattern in a separate figure, since the small graphics in Figure 4 are unclear. It could be important to discuss the maximum average rainfall intensities for different time intervals in order to understand the simulated surface and subsurface hillslope responses. I would also present the first model setup and the corresponding model results prior discussing Hydrus-3D setup and results.

As suggested by the reviewer we now present the initial modeling methods and results first (2.3.1) followed by the HYDRUS modeling approach and results (2.3.2).

Tables summarising the model parameterisations could be helpful for the readers.

2.2 About the design approach
I do not think that the selection of the "climatic properties" could be deferred, as stated by the authors (page 4420 lines 21-22).
It is difficult to draw some design conclusions by running relatively complex models with just a half year generated rainfall time-series and two different potential evapotranspiration time-series, without verifying that the statistics of these time-series are representative of the extreme conditions that are going to be applied to the experimental hillslopes. This approach could lead to identify just a small part of the parametric space that could fit the actual design objectives. In the worst case, the model simulations could provide just a partial view of the actual issues that could be faced during the experiments.

The first step in any hydrologic design study is to characterise the design climatic forcing, such as: the maximum average rainfall intensities within different time intervals, the mean extent of the inter-storm periods, the temporal extent of the dry periods, the maximum average (reference) potential evapotranspiration rate during the dry periods.

We do not know what the reviewer refers to with “extreme conditions that are going to be applied to the experimental hillslopes”. It was decided that the climates that will be applied to the hillslopes will be representative for semiarid climates (design criteria B1). The exact climate scenario has not been decided yet and will most likely be varied in the course of the experiment. The rainfall distribution that was used in the design modeling (section 2) was representative for a semiarid Sky Island Forest. It was generated based on statistics of mean intensities, storm duration and interstorm periods. The climate that was used for testing the importance of timing of rainfall and radiation input (section 3) was based on actual measured climatic data from the Lucky Hills Site in Arizona, USA (section 3). In both cases, the general hillslope *hydrological behavior was similar. This means we did use representative climates and could show that the proposed hillslope design conforms to design criteria B1-B5. We expect that these design criteria are still met even if the exact applied climate will be somewhat different (but still representative for semiarid). <u>We now provide more information on statistics of the design modeling rainfall scenario at the beginning of section 2.3.</u>*

Then the hillslope features (or better, their constraints or limiting values) should be designed by evaluating separately the most relevant hydrologic processes at the corresponding characteristic time-scales, with the design climatic conditions, possibly by using simpler design models, specific for each process analysed, as it is normally done in applied hydrology.

The hillslope features that were primarily investigated with the design modeling were soil depth, slope angle and soil texture. The first two were mostly decided based upon engineering and stability considerations – the weight of the hillslope structure would become too high if soil depth exceeded 1 m, and steeper slopes could lead to mass wasting which would destroy the experiment. So the main hillslope feature to be determined was the soil texture. Relevant hydrological processes that we expect in the hillslopes are infiltration, unsaturated flow and saturated (or near-saturated) lateral subsurface flow. The models we used are capable of simulating these processes and loamy sand was identified as a soil texture likely to promote the desired design criteria. The soil hydraulic properties of the parent material (crushed basalt) will likely somewhat differ from the database values we used in the modeling. Through control of rainfall intensities erosion and surface runoff will be minimized. We are of the opinion that our modeling accounted for the relevant hydrological processes in the hillslopes in an adequate way. <u>We added text to the beginning of section 2.3 detailing the relevant hydrological processes we expect.</u>

For instance, the maximum rainfall intensities could be employed to indentify the minimum value required for the saturated hydraulic conductivity in order to avoid any infiltration excess runoff. Similarly, rainfall intensities at small time scales could be employed for evaluating the maximum splash erosion rates for different physical soil properties and different surface slopes, since splash erosion could be also a problem as stated by the Authors.

During the design workshops we took a different approach. We first identified a soil texture that will likely support our design criteria (especially B1-B5). The selected parent material will be ground to a particle size distribution typical for loamy sand and hydraulic properties of this parent material will be determined. Based on the results, the applied rainfall intensities will be controlled such that they do not exceed the infiltration capacity of the soil. Most likely splash erosion and some soil movement cannot be completely avoided but minimizing these processes will be top priority.

Small time-scale design rainfall could be also employed to evaluate the maximum overland flow rate for a given saturated area extent and thus for evaluating the maximum expected soil erosion in case overland flow is generated by saturation excess mechanism, again for different surface soil properties and surface slopes.

In order to not risk mass wasting and excessive gullying of the hillslopes overland flow (whether as infiltration excess or saturation excess) needs to be minimized by control of rainfall intensities. Once the exact hydraulic properties of the crushed basalt are determined, simulations may be run again to investigate the specific hydrologic behavior of the parent material and to determine a maximum rainfall intensity that will most likely not cause overland flow.

As reported also by the Authors (Figure 4), the subsurface flow response as well as the most relevant features of the surface soil moisture patterns at the peak discharge, are not sensitive to the rainfall variability at small time scales. Thus from a design perspective, in order to identify further constraints to some hillslope features (such as the hydraulic conductivity at high soil pressure heads, the soil depth and the slope), it could be more effective to compare the simulated hillslope subsurface responses with design rainfalls at large time scales, corresponding for instance to the maximum average rainfall intensity at seasonal scale, for given initial conditions at the beginning of the rainy season.

Similarly, in order to identify constraints to the soil hydraulic properties (hydraulic conductivity and soil water retention) at small soil pressure heads, it could be more effective to evaluate the pressure head dynamics with design dry seasons, corresponding for instance to the maximum average potential evapotranspiration rates and the maximum duration of the dry season, for given initial conditions at the beginning of the dry season.

Soil depth and slope angle were mostly decided based on technical and engineering constraints. More important than adjusting the hydraulic conductivity to potential rainfall events was for the B2 scientists to find a soil texture that will conform to the design criteria. Rainfall rates can then, due to the fully controllable climate in the B2 biomes, be adjusted so that the generation of surface runoff is minimized.

I also have some doubts about the choice of the 12 sets of soil hydraulic parameters. It should be considered that soil types are affected by the climatic conditions. Thus once semi-arid climatic conditions have been selected, only those soil types potentially occurring in semi-arid areas should be evaluated. I also think that it is not technically correct to employ soil hydraulic parameters derived by averaging parameters values suggested for given textural classes. These are parameters of soil hydraulic functions that are fitted to measured values. Averaging directly the parameters is not the same as averaging the corresponding water retention and hydraulic conductivity functions. The risk of using average parameters for given textural classes is to get "unrealistic" soil hydraulic properties. This is probably the type of issue that lead the Authors to change the hydraulic parameters with values corresponding to "potential soil materials" (see page 4428 lines 25-29 and page 4429 line 1). In fact, it would have been more effective to explore the soil parameter space by considering just the soil types that could be employed for Biosphere 2 and representative of semi-arid areas.

It is certainly true that particular soil types do tend to arise in particular climates. Indeed the Biosphere 2 experiments are aimed at understanding the mechanisms by which this occurs. However, the same is not true of soil texture. Clay, sandy and silty soils can all be found in all climatic regions. For example, Hedricks' Arizona Soils (College of Agriculture, University of Arizona, Tucson, Arizona, 1985), lists a range of soil textures, from the deep, fine textured soils of the White House-Caralampi Association, to the coarse Superstition-Rosita Association. Since the initial modeling was aimed at exploring the parameter space of possible designs for further evaluation, we see no reason why we should have excluded any particular soil textural class a priori.
Regarding the reviewer's concern about using class averages, the Rosetta texture class values on which the numbers are based are derived from the first in a series of five pedotransfer functions derived from an extended dataset. They are intended to be the best estimate of soil hydraulic properties where information is limited. We have found no references in the literature suggesting that they are "unrealistic", though if the reviewer knows of any, we would happily include a reference to it and a caveat in the text suggesting that this may be an issue.
Our statement on p. 4428, l. 28-29 and p. 4429, l. 1 reflects the chronological progress of the hillslope design. At the time of the climate testing modeling described in section 3 basalt had been identified in the meantime as a parent material with favorable mineralogical composition and geochemical properties. Subsequently, preliminary soil hydraulic tests had been run on crushed basalt samples that indicated that the crushing and grinding of basalt would lead to grain size distributions with slightly different soil hydraulic parameters, typical for finer-grained soils than loamy sand. With the adjusted parameters, we were still in the range of loamy sand to sandy loam soils and thus did not see this issue as a concern. It will not be possible to produce an exact grain size distribution by grinding, and we expect some deviation from model hydraulic parameters in the final parent material to be used on the hillslopes. However, we do not expect that this deviation will lead to fundamentally different hydrological behavior.

2.3 Further specific comments
Beside the hillslope experiments, monolith or small plots experiments on, such as infiltration and evaporation tests, could provide important reference data for interpreting the results on the large hillslopes and for a better characterisation of the soil hydraulic properties.

These are valuable suggestions. The soil hydraulic behavior of the parent material will be tested thoroughly before the application on the hillslope to derive reference parameters.

3. Technical corrections
Page 4420 line 16-17: I think that the sentence ". . ..6) soil texture (i.e. hydraulic properties)" is not technically correct. Soil texture alone cannot be representative of the soil hydraulic properties, since other soil properties could affect the soil water retention and the soil hydraulic conductivity. "Soil properties" could be more appropriate than "soil texture".

We agree that in naturally evolved soils soil hydraulic properties are not determined by texture only but also e.g. by structure (aggregation, macropores, cracks etc.), organic matter, clay coating of pores or hydrophobicity. The soil material that will be used in the experiment, however, will consist of crushed rock and will initially not contain organic matter. Thus, in the initial stages of the experiment, soil hydraulic properties will be determined by texture and bulk density only. In the course of the experiment we expect the soil hydraulic properties to change reflecting an increasing degree of heterogeneity.

Figure 3. The variables "Rs" and "Rw" are mentioned in the figure caption and in the manuscript text, but are not indicated in the graphic.

Figure 3 was revised.

Figure 3. Why not showing the results for the 10 degree mean slope angle as in Figure 4? This would help in comparing the results of the two different models.

Our goal was not to compare the results of the two different models. We used the models in a two-stage approach, i.e. consecutively, with different objectives: the parsimonious model to constrain the parameter space, particularly with respect to soil texture, and the more complex model to explore spatial patterns and temporal dynamics of soil moisture on a few hillslope realizations. Therefore, we did not show results from the two modeling efforts in one plot.

Figure 5. In the figure caption, "Figure 2" should be written instead of "Fig. 1".

This was corrected.