Response to Referee 2

This is an interesting and generally well written paper that investigates possible effects of preferential flow on slope stability using numerical experiments. Relating hydrological processes and slope stability is a relevant topic that is within the scope of HESS. Existing literature on the topic is limited, and especially quantitative studies are rare.

Some points of the study need clarification, and a few missing points needs to be addressed. These are detailed in the following, and in the specific comments below. Finally, minor technical corrections should be made.

Answer 1: We thank the reviewer for his valuable comments. The quantification of the influence of preferential flow on hillslope hydrology and landslide-triggering is exactly the objective of this preliminary analysis.

One issue I have to point out is that basic parts of the present paper have also been published as "Shao, W., T. Bogaard, and M. Bakker (2014), How to Use COMSOL Multiphysics for Coupled Dual-permeability Hydrological and Slope Stability Modeling, Procedia Earth and Planetary Science, 9(0), 83-90." This work is sort of a proceedings publication and publicly available, but is not mentioned in the present manuscript. Clear differences between the two works are that the proceedings paper presents benchmark tests of the model for both hydrological and slope stability calculations, while the present manuscript reports much more details on the modelling results and includes two different rainfall and two different cohesion scenarios. So I do not think that this has to be considered prior publication according to the HESS policy, although this finally has to be decided by the editor. In any case, the authors should ensure that they avoid copyright issues. The copyright for the proceedings paper is at Elsevier B.V. and the content is licensed under the CC BY-NC-ND license, so the work at least has to be cited if (unchanged) contents are reused in another paper. Apart from that, I would suggest to include reference to the proceedings paper anyway to point out the benchmark simulations, and further expand on this previous work.

Answer 2: The reviewer is correct; we forgot to include a reference to our own (!) short technical paper, which describes the development and implementation in COMSOL of a Hydro-mechanical model and its benchmarking. The current paper focuses on the process understanding and quantification of influence of preferential flow on the slope stability using the same model. We will refer to our previous work for a description of the implementation and benchmarking of our model.

For the present manuscript, I would suggest streamlining the argumentation, and discussing in greater detail the influence of the chosen model setup and scenarios. These include the role of flow paths arrangement, which has not been discussed, or the role of time-variable rainfall, as the rainfall input dynamics in the study were highly idealised. From the hydrology side, the presentation of the results related to infiltration excess after longer rainfall period should be revisited.
The model setup consists of two soil layers with very contrasting hydraulic properties, but with the same mechanical properties, which seems an acceptable choice for a start, but also deserves discussion. A parameter sensitivity study, as suggested by Reviewer 1, would be excellent, although easily going beyond scope of the paper. If it is done, it should ideally also include other mechanical properties like the angle of internal friction.

Answer 3: The model setup is indeed an idealised 2D slope geometry, parameter set, and initial and boundary conditions. The objective of this paper is using a numerical model to evaluate how preferential flow influences the slope stability. This paper provides two examples of different hydrology patterns driven by two types of rainfall events for further analyses. For the low-intensity rainfall case, preferential flow has a positive effect on the slope stability as it drains the water from the matrix domain, reducing the body load and pore water pressure. For the high-intensity rainfall case, preferential flow has a negative effect on the slope stability as the majority of rainfall infiltrates into the preferential flow domain, resulting in a higher water pressure and consequently a larger failure area. In the paper, we state that the rainfall intensity and amount is crucial for hillslope hydrology, and is related to the hydraulic properties of the matrix and preferential domains. The issue related to infiltration-excess flow will be gives detail in answer 30. A complete sensitivity analysis for all parameters (including the rainfall) are indeed beyond the scope of this paper.

The selection of cited papers sometimes appears to be made with the intention to include some less-often cited, recent work, which is a credit to the authors. The literature review on the relationships of preferential flow and slope stability, however, could be made a bit more comprehensive. A quick selection of papers you might want to consider additionally:

- Pierson, T. C. (1983), Soil pipes and slope stability, Quarterly Journal of Engineering Geology, 16(1), 1-11.
- van Asch, T. W. J., J. Buma, and L. P. H. van Beek (1999), A view on some hydrological triggering systems in landslides, Geomorphology, 30(1-2), 25-32.
- Wienhöfer, J., F. Lindenmaier, and E. Zehe (2011), Challenges in Understanding

the Hydrologic Controls on the Mobility of Slow-Moving Landslides, Vadose Zone J., 10(2), 496-511.

• Ghestem, M., R. C. Sidle, and A. Stokes (2011), The Influence of Plant Root Systems on Subsurface Flow: Implications for Slope Stability, Bioscience, 61(11), 869-879.

• Handwerger, A. L., J. J. Roering, and D. A. Schmidt (2013), Controls on the seasonal deformation of slow-moving landslides, Earth and Planetary Science Letters, 377, 239-247.

• Wilson, G. V., and G. A. Fox (2013), Pore-Water Pressures Associated with Clogging of Soil Pipes: Numerical Analysis of Laboratory Experiments, Soil Sci. Soc. Am. J., 77(4), 1168-1181.

Answer 04: The suggested papers are highly-relevant to our research. We will include the selected paper in our manuscript in the appropriate sections.

13056, ll. 15f: “positive effect on slope stability as it drains the water from the matrix domain: : :” – Pore-pressure in the matrix domain was not considered in the stability calculations. This reasoning should be revised.

Answer 5: We will rephrase as follows: “preferential flow has a positive effect on drainage and resulting in a smaller failure area.”

13057, l.7: What is “the empirical infiltration model”? Maybe I missed that, or perhaps you might like to consider “an empirical infiltration model”.

Answer 6: We meant “conceptual models” and will fix that in the revised document.

13057, ll. 10-11: Meaning of the cited reference is not clear; the factor-of-safety concept is much older and treated in many textbooks.

Answer 7: The references are meant as two examples, and will rewrite the sentence to reflect that.

13057, l. 12: Please describe the limitations that are important for your study, and pick that up in the discussion.

Answer 8: The limitation of this study is that only a liner-elastic model is used to calculate the stress field for slope stability analysis, the plastic deformation was not considered. Therefore the model can only used to quantify the failure area and time, but can not simulate a correct slope deformation after the failure.

13057, ll. 17-28: Perhaps you could put the COMSOL software used in this study into this picture.

Answer 9: We thank the reviewer for his suggestion, but the COMSOL software does not provide an easily-implemented function for slope stability. The coupling of the hydrological module and the linear elastic module is achieved by scripting the function in the model interface to extend the function of the original software.

13057, l. 28: Not clear why pedotransfer functions are mentioned here. The Beven and Germann citation is not needed twice.

Answer 10: Correct. Change was made.

13058, ll. 20f: "Field studies have shown that preferential flow is one of the major mechanisms: : :" Only one study is cited - are there more studies? Does any study really show that preferential flow is the major mechanism for landsliding? In contrast, I rather would say that there are some studies that suggest an important role of preferential flow, and these need to be cited in the paper.

Answer 11: It is very difficult to prove that the preferential flow is a major triggering mechanism of landslides. Preferential flow will cause rapid water-table build-up and may trigger landslides, as suggested by many researchers, but it is rarely quantified. The difficulty of quantifying the influence of preferential flow on hydrology and landslides is exactly the motivation of our current paper. We added the following reference to give additional examples of 'some studies':

Hencher, S. R. (2010), Preferential flow paths through soil and rock and their association with landslides. Hydrol. Process., 24: 1610–1630. doi: 10.1002/hyp.7721

Uchida, T., Kosugi, K.i. and Mizuyama, T. (2001) Effects of pipeflow on hydrological process and its relation to landslide: a review of pipeflow studies in forested headwater catchments. Hydrological Processes 15(11), 2151-2174.

Uchida, T. (2004) Clarifying the role of pipe flow on shallow landslide initiation. Hydrological Processes 18(2), 375-378.

13058, l. 22: Please explain why you consider soil pipes being "minor" flow paths.

Answer 12: Minor refers to the volumetric flux relative to other preferential flow paths. We will delete the "minor" to avoid misunderstanding, as that is not part of our argument here.

13058, ll. 23f: "clearly associated" with slope failure: I do not think that statement is tenable, nor supported by the cited references, since it would mean everywhere where preferential flow occurs, also slope failure occurs. Please also check the references, the Krzeminska et al. and Debieche et al. studies were not conducted in forested areas.

Answer 13: Correct. We rephrase the sentence to "In hillslopes, the preferential flow paths, such as soil pipes and macropores, have been associated with slope stability".

13058, ll. 28f: The given references are not suitable – both are review articles on preferential flow, and neither of them is treating the relation to landslides or slope stability. Please insert suitable references.

Answer 14: We will replace the references by the following:

Hencher, S. R. (2010), Preferential flow paths through soil and rock and their association with landslides. Hydrol. Process., 24: 1610–1630. doi: 10.1002/hyp.7721

Uchida, T. (2004) Clarifying the role of pipe flow on shallow landslide initiation. Hydrological Processes 18(2), 375-378.

13059, ll. 6f: What is the "empirical model"? Did all cited references use the same model? Were Vrugt et al. mainly concerned with preferential flow modelling?

Answer 15: Vrugt's paper is not directly related to preferential flow modelling and will be removed. We will change "empirical model" to "conceptual models" (see Answer 6 above) as it refers to different conceptual models to simulate the preferential flow on a catchment scale.

13059, l. 21: Perhaps you might like to cite Shao et al. (2014) here (Shao, W., T. Bogaard, and M. Bakker (2014), How to Use COMSOL Multiphysics for Coupled Dualpermeability Hydrological and Slope Stability Modeling, Procedia Earth and Planetary Science, 9(0), 83-90)

Answer 16: Done

13061, ll. 10f: Please consider moving the definition of the water exchange coefficient from the discussion section here; or rather specify that it was used as a fitting parameter in your study.

Answer 17: We prefer to leave the discussion on the values of the exchange parameter used in different studies in the Discussion section. We added below Eq. 6 that the water exchange is governed by the product of alpha_w and K_a.

13061, ll. 11-14: Would it not be more correct if the water exchange between the two domains would be limited by the lower value of the hydraulic conductivities?

Answer 18: The product of the water exchange coefficient and the relative hydraulic conductivity controls the water exchange between the two domains (see Answer 17, where we emphasize that again in the paper). Our work adopts a parameter combination that has been used in other studies, as discussed in section 5.2. Althernatively, as the authors suggest, the lower value of the hydraulic conductivity could be used, but then the water exchange coefficient needs to be raised such that their product remains in the reasonable range (see Table 2). This is discussed in detail in Section 5.2.

13062, l. 6: Should it not be $i = i_f + i_m$ with $i_f = w_f i$ and $i_m = w_m i$?

Answer 19: i_f and i_m are fluxes per unit area, so that the total flux into the dual permeability domain is obtained by multiplying the fluxes with their respective area fractions (the area fractions are the same as the volume fractions).

13062, l. 13: How is infiltration capacity specified in your model?

Answer 20: The infiltration capacity of each domain is the product of saturated hydraulic conductivity and pressure head gradient for each domain. A sentence will be added to clarify this.

13063, ll. 3f: Bishop's equation has not been mentioned before.

Answer 21: The reference to "Bishop's equation" is removed, as it is not important here. The comment about air pressure is also removed, as this is common in soil mechanics. A reference is added for Equation 15

13063, l. 5: As I understand, your model calculates pressure head in the unsaturated zone directly. Why is the reduction by effective saturation needed?

Answer 22: The reduction by the effective saturation is used to calculate the shear strength in unsaturated soils that are influenced by soil water suction. Under unsaturated conditions, the soil pores are not fully filled with water, thus, the suction stress needs to be reduced (Eq. 15). A detailed theory of using effective saturation for this we refer to Lu et al 2010.

13063, ll. 9-17: Please explain in more detail the difference between the "local factor of safety" and the traditional factor of safety. To me, both appear the same.

Answer 23: The Factor of safety (FS) is typically defined as the ratio of the available shear strength to the shear stress required for equilibrium along a prescribed failure surface. The "local factor of safety" is defined by Lu et al. (2012), "The FS at each point within a hillslope is called the local factor of safety (LFS) and is defined as the ratio of the Coulomb stress at the current state of stress to the Coulomb stress of the potential failure state under the Mohr-Coulomb criterion". We follow the local factor safety approach, applying the Mohr-Coulomb failure criterion to the principle stress field (calculated with the linear-elastic model) to calculate the distribution of the "factor of safety"

13063, l. 17: Do you mean "first and third effective PRINCIPAL stress"?
Answer 24: Yes, correction will be made.

13064, l. 13: What possible boundary effects did you encounter, or could you think of? Please consider including this in the discussion section.
Answer 25: The influence of "no flow" or "roller" boundary conditions on the area of interest. The computational area is significant larger than the area of interest to reduce the effect of the chosen boundary conditions. Changed to: 'to reduce the effect of the specified boundary conditions along the model boundary (to be discussed in the following) on the area of interest' .

13064, l. 21: Maybe consider explaining what a "roller boundary" is. 13064, ll. 22-26: Please specify also the time discretization and perhaps information on the numerical solver.
Answer 26: An explanation of a roller boundary is already given in the paper (e.g., only vertical displacements along vertical boundaries). The time discretization depends on the convergence of the numerical solution, which is automatically adjusted by the software, in our case could be in a range of few seconds to few hours. A sentence was added at the end of section 2.

13065, ll.14-17: I do not fully understand the Bogner et al. reference. Do you mean that this is an assumption in your study, or a general fact?
Answer 27: The paper (Bogner et al.,2013) is not manifests a general fact, we refer to Bogner et al., as they report that the deeper soil has a low density of macropores, and we will write (e.g. Bogner et al., 2013).

13065, l. 26: What is meant by "non-unique parameter set"? I would expect to get two parameter sets, one for each domain.
Answer 28: It is very difficult to determine unique parameter sets for dual-permeability models due to equifinality, as discussed in the cited papers.

13066, l. 19: Maybe consider replacing "seepage outflow" by "return flow"

Answer 29: We use this word to describe that the flow occurs along the specified seepage boundary condition. The reviewer is correct that in hydrology this is sometimes called "return flow", but we think it may be confusing to use that terminology here.

13066, ll. 25f: As I understand, rainfall rates were constant in your simulations. Why then should rainfall rate exceed infiltration capacity after a while? Or is it saturation excess, which is not a function of rainfall, but infiltration and redistribution? Please differentiate.
Answer 30: Infiltration capacity is the capability of a certain boundary for infiltration (see also Answer 20. The reviewer is right, in our case the saturation excessed overland flow occurs due to the wetting on the upper part of soil.

13067, l. 12: Please specify "all three boundaries".
Answer 31: We will specify them as "the left, right, and bottom boundaries".

13067, l. 17: Are there different groundwater levels for the upper and lower layers in your model?
Answer 32: Yes, as evidenced by the perched groundwater table in, e.g., Figure 7.

13069, l. 20ff: This exchange from matrix to macropores is quite astonishing. Is this realistic? What drives these flows?
Answer 33: The water exchange is driven by the head difference between the preferential flow domain and the matrix domain, see Eq. 6.

13072, ll. 7-9: Prior to this study – remember Shao et al. 2014; also the Krzeminska et al study was in this direction. Maybe you are willing to relax the rather strong statements "systematic" and "fully coupled", which both are not exactly to the point, since not a wide range of scenarios was analysed, and the influence of slope movement on flow phenomena was not included.
Answer 34: Correct. The statement is relaxed.

13072, ll. 15-17: Please discuss how explicit representation of flow paths could possibly change your findings.
Answer 35. It is difficult to speculate on how an explicit representation of preferential flow will change our findings, and we are not comfortable doing so without carrying out the analysis. Such a study requires a lot of (numerical) works and a separate paper.

13072, l. 17: “Several field studies”, but just one is mentioned. 13072, l. 27: Why does the slope has to be forested? How is the influence of trees considered in your study?

Answer 36: Indeed, we do not focus on forest slope but on hillslope in general, we removed the “forest”. We will add also other field study reference::

Verachtert, E., Van Den Eeckhaut, M., Poesen, J. and Deckers, J. (2013), Spatial interaction between collapsed pipes and landslides in hilly regions with loess-derived soils. Earth Surf. Process. Landforms, 38: 826–835. doi: 10.1002/esp.3325

Uchida, T. (2004) Clarifying the role of pipe flow on shallow landslide initiation. Hydrological Processes 18(2), 375-378.

13073, l. 16: Also the pressure difference determines the water exchange.

Answer 37: Correct. Sentence is modified.

13075, l. 3: Was the Lanni et al. study really concerned with preferential flow?

Answer 38: We replaced the reference by Laine-Kaulio’s paper.

13075, l. 6: Consider replacing “hazard assessment” with “slope stability”.

Answer 39: Done

13075, l. 7-8: Please include available studies on the effect of preferential flow on slope stability in this discussion.

Answer 40: We will cite the relevant reference.

13075, l. 12: If the complexity is due to the rainfall characteristics, why did you not chose more realistic rainfall scenarios? How would intermittent rainfall change your results?

Answer 41: Use of rainfall scenarios that have the same characteristics as measured rainfall scenarios is indeed a good idea for a sensitivity study. As, discussed earlier (Answer 03), in this paper we investigate the relevant processes, which in our opinion could be done with two rainfall events and two sets of cohesion parameters.

13075, ll. 16-18: Meaning of “bimodal response” not clear, please explain in further detail and add references. Which effects could not be modelled, for example, with a single bi-modal soil hydraulic parameterisation?

Answer 42: We see the confusion in using the term “Bimodal response”. We will rephrase the sentences as “the different response from the matrix as compared to the preferential flow domain”.

13075, ll. 20-22: But of course it is also very difficult to correctly parameterise a single-permeability model, given the commonly unknown, heterogeneous structure of the subsurface above the scale of a representative elementary volume.

Answer 43: We agree that the difficulty of parameterization exists for both the single-permeability model and dual-permeability models, as the natural soil system is always heterogeneous, but the Reviewer probably agrees that it is easier to parameterize a single permeability model than a dual permeability model.

13088, Table 1: Please include the values for cohesion.

Answer 44: Done

13057, l. 28: Start a new paragraph.

13069, l. 15: Reword – maybe "pressure difference between domains causes ..."

13072, l. 22: "Numerical simulationS" ("require", "are")

13074, ll. 14f: K_{sa} -> K_a ? (also Table 2)

13074, l. 21: Van der Spek : : : showed

13075, l.22: "A coupled"

13075, ll. 23f: Reword "consequent slope failure area"

13092, Figure 3 : "Left BOttom seepage"; Maybe consider replacing "Surface seepage" by "Return flow"

13097, Figure 8 caption: Check: "Positive values (blue) : : : negative values (blue)"

Answer 45: All editorial changes listed above are included in the revised paper.