Hydrology and Earth System Sciences Discussions

Interactive comment on "A critical assessment of simple recharge models: application to the UK Chalk" *by* A. M. Ireson and A. P. Butler

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We are grateful to Anonymous Referee #1 for an extremely thorough and constructive review. On reflection, we feel that the reviewer has raised an important point about focus and clarity. In the original manuscript we presented a "benchmark" detailed model to simulate a continuous groundwater recharge signal, which we then we tried to reproduce using two simple modeling approaches. In a revised manuscript, we will remove the first of these simple modeling approaches, namely "emulation by linear models", from the paper altogether. Whilst this analysis does present some novel and important findings, these are somewhat peripheral to the overall focus and conclusions of the manuscript. Removing this section will also address the reviewers concerns about

Chapter 3.1. The revised paper will be considerably shorter and more focused.

Below we provide a response to each of the reviewer's specific comments, all of which will be addressed in a revision. Each response references the page/line numbers associated with the reviewer's comments. Overall, we feel we have been able to address the reviewer's comments largely by cutting large parts of text, reworking parts of the text for clarity, including additional references suggested by the reviewer, inclusion of a new table listing the parameters, and minor modifications to existing tables/figures. However, there are two broad points raised by the reviewer that we wish to challenge in this response.

The first of these concerns a clarification of our overall objective in this paper. In the reviewers opening paragraph, they provide a number of useful references. However, we would like to point out that our paper is neither a pure "virtual experiment", (Weiler and McDonnell, 2005), but nor is it a pure exercise in fitting a model to field observations (such as Fenicia et al., 2006, 2008). It could be considered a hybrid of these approaches. The objective of the paper is to perform an assessment of simple recharge models, as applied to the UK Chalk. The challenge we face in seeking to do this is to quantify groundwater recharge. As this cannot be directly measured (as opposed to catchment runoff, which was the focus in Fenicia et al., 2006, 2008), we need an alternative approach. Groundwater level hydrographs are a locally integrated response to recharge. However, to extract recharge fluxes from these data requires a model. The hillslope model presented in our paper represents probably the most detailed physically-based representation of the controls on water storage and movement in unsaturated chalk. It was built on the knowledge we obtained from a highly detailed dataset of near-surface unsaturated zone data as report in Ireson et al. (2009b). This model describes the system as a fractured-porous medium and characterizes the vertical heterogeneity in the near-surface, which, as we show in this paper, plays a crucial role in the conversion of rainfall to groundwater recharge. In fitting the model to the groundwater level data we only modified one of the 17 parameters, the fracture satu-

rated hydraulic conductivity. This was entirely reasonable as this parameter is poorly identified under unsaturated conditions (which was the case in Ireson et al. (2009)) but very well identified under saturated conditions, as we have here. The only other modification to the model was the introduction of a constant flux at the upstream boundary to account for the complexity of time the varying groundwater divide that occurs in this catchment. As shown in Figure 2 in the paper, this model is able to produce, what we considered to be, a reasonable representation of the time varying behaviour of groundwater levels at 3 borehole locations lying along a dry valley. It also allows the recharge flux at the water to be extracted from the model, thereby providing us with a proxy dataset for testing the simple model. The assessment was then to explore the performance of a simplified conceptual model representation of infiltration in the near-surface (and very similar to the UZ representation presented in Fenicia et al., 2006). We should also point out that as explained in Mathias et al (2006) the infiltration capacity of these Chalk grasslands is so high that there is essentially no overland (or as represented in Fenicia et al (2006) Fast Reacting) flow. Furthermore, as we are dealing with a grassland, the effect of interception loss is very small and therefore was neglected in our model. Our aim, therefore, was to provide a critical assessment the performance of these recharge models, which do not account for capillary rise within the chalk matrix, storage in the deep Chalk unsaturated zone, or the vertical heterogeneity in the near-surface hydraulic properties of the unsaturated rock/soil. We show that the inclusion of a preferential (or by-pass) flow component can lead to a convincing simulation of the water table, but that this mechanism is in fact compensating for slow drainage rather than actual bypass, or fracture flow.

The second point relates to the reviewers comment "That there is no relationship between storage and flux is not reasonable and should be discussed carefully" and then later in the review "It is not quit [sic] reasonable that there is no relationship between recharge and unsaturated soil storage. [...] matrix recharge should have a correlation to storage." These statements are incorrect. In Richards' equation models, the flux is driven by a gradient in the state variable (i.e. Darcy's law), not the magnitude

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of the state. It does not necessarily follow that there should be a relationship, linear or otherwise, between the state and the flux. There often is no relationship, and this can be shown using a simple, Richards' equation model for a single porous medium. We provide an easily reproducible demonstration of this point in the Appendix in this response. For the particular case described in the paper, the system is much more complicated, with a deep unsaturated zone, fracture flow and significant evaporation processes (i.e. bi-directional vertical flow). Fig 5 showed clearly that there is no simple relationship between the recharge flux and the storage in the matrix, and we do not find this result unexpected or surprising. This is why finding a simple model that can reproduce the detailed model is extremely challenging. Whilst we have removed the detailed analysis of unsaturated zone storage versus recharge from the paper (section 3.1 and Figure 5 in the original manuscript), this is to improve the focus of the paper and not a concession that this analysis was flawed.

Specific reviewer comments:

The following modifications are being implemented in a revised manuscript, to be resubmitted shortly.

P12066, L13: reference corrected

P12066, L17-26: Text modified to clarify Compton is lower boundary.

P12066, L23-26: We modified the text to clarify that only 4 monitoring wells are used in our study. However, we didn't remove reference to East Ilsley altogether, as it will be useful for future researchers to know that this site lies on our transect.

P12067, L8-10: We will include further information about hydraulic properties of the Chalk layers and vegetation cover.

P12067, L12 & P12076, L17: We wrote ODE 15S in capital letters

P12069, L5-7: We included reference to the paper by Diersch and Perrochet. We were careful to check for numerical errors in our model, and in particular we checked for

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mass conservation. We have found using ODE 15S for the temporal integration of the pressure head form of Richards' equation to be highly effective. We added the following text at the end of Section 2.2: "The numerical solutions were found to be numerically stable and mass conservative. More efficient techniques maybe available (e.g. Diersch and Perrochet, 1999) but for the current problem, this simple approach was effective."

P12070, L2-12: We do not consider preferential flow and fracture flow to be the same thing, as discussed in the citations given here. We've clarified this in the text. In our view it is necessary to consider two forms of fracture flow: preferential and non-preferential. This distinction has been discussed and justified elsewhere (Ireson et al., 2011, 2012). Essentially, non-preferential fracture flow occurs when the matrix and fractures respond in equilibrium and thus the equivalent continuum approach is justified. Terminology is of course subjective and debatable – we hope that we have provided an adequate definition/explanation of our use of terminology here, so that even if there is not a universal consensus on this, our approach is at least transparent.

P12070, L13: The review is correct – a table of parameter values, definitions and units will be included in a revision of the paper.

P12071, L16-17: We have modified the description of the upslope boundary condition in this paragraph for clarity.

P12072, L4-11: This paragraph has been shortened considerably.

P12072, L23-24: We added "Land cover is grassland over the hillslope, and interception is considered to be negligible compared with errors in the rainfall and potential evaporation measurements."

P12073, L15: See above comment.

P12074, L12: We do not think an RMSE or Nash value is particularly useful – looking at Fig 2. is the best way to judge the model performance.

P12075, L25-27-P12076, L1-2: Here we describe the premise of the modeling. Now

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that the first emulation approach has been removed from the paper, this confusion is avoided. Text in this section has been more generally reworded for clarity.

P12076, L17: In this section we aren't talking about either emulation method (Rushton or Duffy as the reviewer puts it). We are testing the premise that the unsaturated zone and saturated zone can be decoupled, by driving a 1D Boussinesq model of the saturated zone with the recharge fluxes extracted from the 2D Richards' equation model. This was explained on P12076, L7, and we have modified the text here for clarity. We also only use one emulation method in the revised manuscript, so this should be clear.

P12077, L13-15:.We have now removed this section altogether, and removed Fig 5 and 6. However, we note that the reviewer is incorrect to state that the "matrix recharge should have a correlation to the storage", which is a point we address in the Appendix in this response.

P12077, L17: This was done using the integral balance method, as a function of time. The text has been modified for clarity as per the previous comment.

P12078, L18-20: We modified the caption of Fig. 7 to clarify that this is the conventional recharge model (i.e. that used in emulation approach 2). The reviewer has misinterpreted the figure – there is only one store. This was unclear, so we've replaced the figure with a more conventional bucket with a threshold discharge level which more clearly illustrates the functionality. We have included "I" in Table 2. In Fig 7 we modified M to SMDA and in Table 2 we modified MA and MP to SMDA and SMDP. This was made consistent throughout the text notably in Equations 20-25.

P12080, L25-P12081, L4: Since we don't have a separate discussion section, and wish to keep the conclusions brief, we prefer to leave this text here. We take the point about bucket models vs soil physics, but here we're performing a critical comparison of the two, not a direct comparison. We have modified the text to use only SMD now (see previous comment).

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P12082, L25-P12083, L13: We have removed this paragraph altogether, since this was a summary rather than "conclusion".

P12085, L7: We agree with this comment and have removed "or under a changed climate".

Fig 1: Agreed. Modifications to this figure will be made for clarity.

Fig 3: It is important to be able to make a direct comparison between precipitation and the recharge flux, both in pattern and magnitude, so placing them on different axes would be unhelpful. Therefore, we have not changed this Figure.

Fig 8c): We've corrected these typos. The same errors appeared in Fig 10c) and have been corrected there too.

References

Diersch, H. J. G., Perrochet. P., 1999. On the primary variable switching technique for simulating unsaturated-saturated flows. Adv. Wat. Res. 23, 271–301.

Fenicia, F., Savenije, H.H.G., Matgen, P., Pfister, L., 2006. Is the groundwater reservoir linear? Learning from data in hydrological modeling, Hydrol. Earth Syst. Sci., 10, 139–150.

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Mathias, S.A., Butler, A.P., Jackson, B.M. and Wheater, H.S., 2006. Transient simulations of flow and transport in the Chalk unsaturated zone. J Hydrol, 330, p 10-28.

Weiler, M. and McDonnell, J.J., 2004. Virtual experiments: a new approach for improving process conceptualization in hillslope hydrology, J. Hydrol., 285, 3-18.

APPENDIX: Flux-storage relationships in Richards' equation

In response to the reviewers comment that it is "unreasonable" that there is not a relationship between the flux out of a soil column and the storage within that column, a simple numerical experiment is presented here. It should be easy to replicate this simulation using any Richards' equation solver (e.g. Hydrus 1D which is freely available). We have also included the MATLAB script which was used to solve this problem below (see supplementary zip file). We consider a 500 cm soil column, with van Genuchten parameters as follows: thetaR=0; thetaS=0.35; alpha=0.1 cm-1; n=1.4; Ks=2 cm/d; neta=0.5. At base of the soil column is a fixed water table. At the top, an infiltration flux alternates between 1 mm/d and 0 mm/d, switching every 25 days over a 100 day simulation. The simulation result is shown in the attached Figure. The discharge flux is clearly not uniquely related, linearly or non-linearly to the storage. In fact here it is cyclic, due to the periodic boundary conditions. This is a very simplified example, but it makes the point adequately. When evaporation processes are also operating, as in the model in the paper, there will be upward and downward fluxes in different parts of the unsaturated zone. It should then be clear that there is no reason to believe that there would be a relationship between storage and discharge from the base. This is perhaps a useful demonstration, because it shows clearly that Richards' equation models behave unlike linear or non-linear stores that are commonly used in hydrological models.

Please also note the supplement to this comment:
http://www.hydrol-earth-syst-sci-discuss.net/9/C6306/2013/hessd-9-C6306-2013-supplement.zip

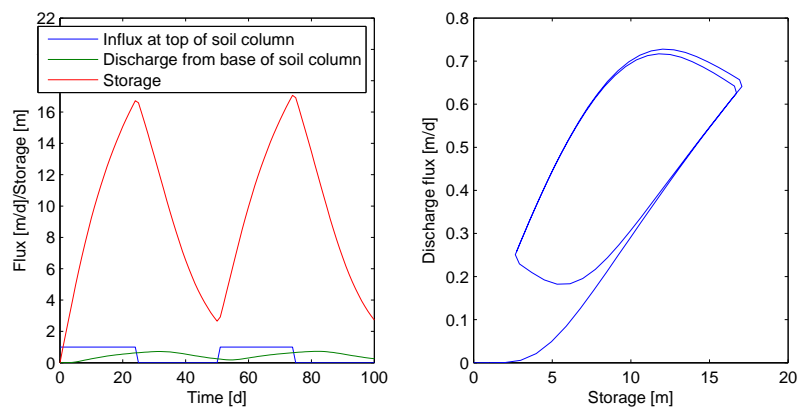Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 9, 12061, 2012.

Fig. 1. Illustrative relationship between unsaturated zone storage and recharge