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REPLY

Response to comment by Jozsef Szilagyi on ''Using numerical modelling to evaluate the capillary fringe groundwater ridging hypothesis of streamflow generation'' (Journal of Hydrology 316 (2006) 141–162)

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The comment by Szilagyi is a welcome addition to the debate surrounding the link between the hypothesis of groundwater ridging and streamflow generation. Indeed, since the first paper by Abdul and Gillham (1984), many comments and replies on this topic have followed in the journal literature (e.g., Zaltsberg, 1986 vs. Gillham and Abdul, 1986; McDonnell and Buttle, 1998 vs. Jayatilaka and Gillham, 1998). Questions regarding how water gets into streams during rainfall and snowmelt events, and what the geographic sources are of runoff, continue to challenge analytical description at the catchment scale. Despite widespread acceptance of the groundwater ridging hypothesis of streamflow generation (and in particular the mobilization of high pre-event water contributions to the stream during storm rainfall), there is little evidence for such a phenomenon outside of the particular environments and test cases for which it has been quantified. Our work, described in Cloke et al. (2006), was an attempt to use a flow and transport modelling tool to test a number of hypotheses concerning the capillary-fringe groundwater ridging mechanism. We aimed to identify those combinations of soil type, antecedent moisture, riparian volume, slope and rainfall intensity that might result in groundwater ridging being a dominant runoff mechanism. We found that in only a limited number of cases was groundwater ridging a possible explanation for high proportions of pre-event water.

Szilagyi (submitted) has identified a number of issues associated with our numerical experiments of groundwater ridging. In terms of the generality of our findings, we agree with Szilagyi that the results of our numerical experiments should be used with caution when looking at generalized responses of natural riparian zones, and that it is wise not to draw definite conclusions from our numerical experiments. However, we clearly stated this in several places in the Cloke et al. (2006) paper and we strongly advocated further testing in more realistic settings, e.g., Cloke et al. (2006, p. 151): ''It should be noted that these simulations are only an extension of the original Abdul and Gilham experiment, and thus can only be a first step towards generalization. These

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Table 1 Comparison of the riparian zone parameters of Cloke et al. (2006, Table 3) and Szilagyi (submitted)

Setup parameter	Closest equivalent riparian characteristic value from Cloke et al. (2006)	Szilagyi (submitted)
Initial water table depth compared to stream channel	Near surface (approximately 10% if slope depth from surface)	0 m (water table and stream equivalent)
Rainfall intensity	1.0×10^{-4} m s^{-1} (high)	Variable with sine curve maximum of 2.464×10^{-5} m s^{-1}
Slope of riparian zone	4° (low)	2.86°
Saturated hydraulic conductivity of sand	1.0×10^{-4} m s^{-1} (high)	1.76×10^{-4} m s^{-1}
Capillary fringe height for sand	0.002 m (low)	0.00395 m
Maximum PEZ reached	4 (50–75%)	''Fast baseflow response''

experiments should therefore not be interpreted to represent the whole range of conditions found in nature.'' We reiterate that the main point of the Cloke et al. (2006) paper was to evaluate the groundwater ridging hypothesis in relation to the Abdul and Gillham (1984) experiment, which is often used by hillslope hydrologists as the main proof of concept of the operation of the mechanism. The results of our numerical experiments show that for many riparian zones based on the Abdul and Gilham model, capillary fringe groundwater ridging does not produce the high proportions of pre-event water observed in the field.

We appreciate the simulations completed by Szilagyi in his comment but would argue that they are tangential to the research presented in Cloke et al. (2006). In the Szilagyi example, there are no estimates of the proportions of pre-event water discharged to the stream, and his example relies instead on estimates of the flux of subsurface and surface waters. This could be misleading for certain cases where, for example, ''old'' (pre-event) water exfiltrates and becomes overland flow, or where infiltrated ''new'' (event) water reaches the stream via the subsurface. We used a random walk particle method to overcome this specific problem, allowing us to tag water parcels as ''new'' or ''old'' water. We hope that similar techniques will become more widely used in modelling exercises, so that modelling results can give estimates of pre-event and event water ratios in runoff hydrographs, and can be compared directly with field experiments.

Szilagyi states that it is the ''presence of sharp gradients in the hydraulic head near the stream bank'' that is the driving force behind the elevated subsurface discharge. We argue that this has always been an important part of how the groundwater ridging mechanism has been thought to operate, however, in the Abdul and Gillham laboratory experiment, the ridge needed to reach the surface to allow any discharge. In the cases where there is a connection between the stream and groundwater through the channel bank, then the ridge would not necessarily have to reach the surface in order to create discharge. However, the occurrence of this ridging in space and time needs to be investigated alongside the influence of the capillary fringe and, of course, the proportion of pre-event water discharged to the stream. The work that we presented in Cloke et al. (2006) is a first substantial step to pin down the spaces of operation of this mechanism.

We agree that a direct connection between the stream and the groundwater may alter the proportions of pre-event water discharged. This is a very valuable point, and certainly worth exploring in detail. We acknowledge that we did not explicitly include this in the list of those features of natural riparian environments that we had not covered (e.g., Cloke et al., 2006, p. 159, section 4). Whilst we agree that a set of simulations where the groundwater and stream are directly connected could be very useful in furthering our understanding of the mechanisms of pre-event water discharge, we do not view the Szilagyi example as being very helpful in this regard as it gives no explanation for the particular numerical example that has been chosen to illustrate his case. It is therefore difficult for us to evaluate the results of his example within the framework that we described in Cloke et al. (2006). One particular issue with the example presented by Szilagyi is his representation of a river with a vertical seepage. We argue that the water level in the river is still fixed and will not react to rainfall input (very similar to the computer simulations performed by Sklash and Farvolden, 1979), and this may not be a realistic assumption, especially for smaller upstream reaches and intense rainfall events.

The domain used by Szilagyi in his example had a slope of only 1%, which is less than the minimum slope that we tested in Cloke et al. (2006), and less than the ~7–16% observed by Abdul and Gillham (1989). We would argue that a set of numerical experiments based on slopes greater than 1% (or indeed a range of slopes) would be a better basis for testing the groundwater ridging mechanism further.

In Table 1, we have compared Szilagyi's simulations with the nearest equivalent results from our simulations (see table 11 in Cloke et al., 2006), and it is clear that our PEZ value of 4 matches Szilagyi's observation of high elevations of subsurface water in the stream. Therefore, we see no conflict between the two simulation examples, and can conclude that although a further set of simulations would enhance our understanding of this hydrological process, the example given by Szilagyi seems to be responding in a similar manner to the simulations in Cloke et al. (2006).

We thank Szilagyi for his comments. Resolving streamflow generation processes and coupled flow and transport is one of the key priorities in hydrological research, and we strongly advocate further work on this problem.

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