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## REPLY

# 3 Response to comment by Jozsef Szilagyi on 4 “Using numerical modelling to evaluate the 5 capillary fringe groundwater ridging 6 hypothesis of streamflow generation” 7 (Journal of Hydrology 316 (2006) 141–162)

8 H.L. Cloke <sup>a,\*</sup>, J.-P. Renaud <sup>b</sup>, J.J. McDonnell <sup>c</sup>, M.G. Anderson <sup>b</sup>

9 <sup>a</sup> Department of Geography, King's College London, Strand, London WC2R 2LS, UK

10 <sup>b</sup> School of Geographical Sciences, University of Bristol, University Road, Bristol BS8 1SS, UK

11 <sup>c</sup> Department of Forest Engineering, Oregon State University, Corvallis, OR, USA

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14 The comment by Szilagyi is a welcome addition to the de-  
15 bate surrounding the link between the hypothesis of  
16 groundwater ridging and streamflow generation. Indeed,  
17 since the first paper by Abdul and Gillham (1984), many  
18 comments and replies on this topic have followed in the  
19 journal literature (e.g., Zaltsberg, 1986 vs. Gillham and  
20 Abdul, 1986; McDonnell and Buttle, 1998 vs. Jayatilaka  
21 and Gillham, 1998). Questions regarding how water gets  
22 into streams during rainfall and snowmelt events, and  
23 what the geographic sources are of runoff, continue to  
24 challenge analytical description at the catchment scale.  
25 Despite widespread acceptance of the groundwater ridging  
26 hypothesis of streamflow generation (and in particular the  
27 mobilization of high pre-event water contributions to the  
28 stream during storm rainfall), there is little evidence for  
29 such a phenomenon outside of the particular environments  
30 and test cases for which it has been quantified. Our work,  
31 described in Cloke et al. (2006), was an attempt to use a  
32 flow and transport modelling tool to test a number of  
33 hypotheses concerning the capillary-fringe groundwater

ridging mechanism. We aimed to identify those combina- 34  
tions of soil type, antecedent moisture, riparian volume, 35  
slope and rainfall intensity that might result in groundwa- 36  
ter ridging being a dominant runoff mechanism. We found 37  
that in only a limited number of cases was groundwater 38  
ridging a possible explanation for high proportions of 39  
pre-event water. 40

Szilagyi (submitted) has identified a number of issues 41  
associated with our numerical experiments of groundwa- 42  
ter ridging. In terms of the generality of our findings, 43  
we agree with Szilagyi that the results of our numerical 44  
experiments should be used with caution when looking 45  
at generalized responses of natural riparian zones, and 46  
that it is wise not to draw definite conclusions from our 47  
numerical experiments. However, we clearly stated this 48  
in several places in the Cloke et al. (2006) paper and 49  
we strongly advocated further testing in more realistic 50  
settings, e.g., Cloke et al. (2006, p. 151): “It should be 51  
noted that these simulations are only an extension of 52  
the original Abdul and Gilham experiment, and thus can 53  
only be a first step towards generalization. These experi- 54  
ments should therefore not be interpreted to represent 55  
the whole range of conditions found in nature.” We 56

\* Corresponding author. Tel.: +44 20 7848 2604.

E-mail address: [hannah.cloke@kcl.ac.uk](mailto:hannah.cloke@kcl.ac.uk) (H.L. Cloke).

**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	$1.0 \times 10^{-4} \text{ m s}^{-1}$ (high)	Variable with sine curve maximum of $2.464 \times 10^{-5} \text{ m s}^{-1}$
Slope of riparian zone	4° (low)	2.86°
Saturated hydraulic conductivity of sand	$1.0 \times 10^{-4} \text{ m s}^{-1}$ (high)	$1.76 \times 10^{-4} \text{ m s}^{-1}$
Capillary fringe height for sand	0.002 m (low)	0.00395 m
Maximum PEZ reached	4 (50–75%)	“Fast baseflow response”

57 reiterate that the main point of the Cloke et al. (2006)  
58 paper was to evaluate the groundwater ridging hypothesis  
59 in relation to the Abdul and Gillham (1984) experiment,  
60 which is often used by hillslope hydrologists as the main  
61 proof of concept of the operation of the mechanism.  
62 The results of our numerical experiments show that for  
63 many riparian zones based on the Abdul and Gilham  
64 model, capillary fringe groundwater ridging does not pro-  
65 duce the high proportions of pre-event water observed in  
66 the field.

67 We appreciate the simulations completed by Szilagyi in  
68 his comment but would argue that they are tangential to  
69 the research presented in Cloke et al. (2006). In the Szilagyi  
70 example, there are no estimates of the proportions of  
71 pre-event water discharged to the stream, and his example  
72 relies instead on estimates of the flux of subsurface and sur-  
73 face waters. This could be misleading for certain cases  
74 where, for example, “old” (pre-event) water exfiltrates  
75 and becomes overland flow, or where infiltrated “new”  
76 (event) water reaches the stream via the subsurface. We  
77 used a random walk particle method to overcome this spe-  
78 cific problem, allowing us to tag water parcels as “new”  
79 or “old” water. We hope that similar techniques will be-  
80 come more widely used in modelling exercises, so that mod-  
81 elling results can give estimates of pre-event and event  
82 water ratios in runoff hydrographs, and can be compared di-  
83 rectly with field experiments.

84 Szilagyi states that it is the “presence of sharp gradients  
85 in the hydraulic head near the stream bank” that is the driv-  
86 ing force behind the elevated subsurface discharge. We ar-  
87 gue that this has always been an important part of how the  
88 groundwater ridging mechanism has been thought to oper-  
89 ate, however, in the Abdul and Gillham laboratory experi-  
90 ment, the ridge needed to reach the surface to allow any  
91 discharge. In the cases where there is a connection between  
92 the stream and groundwater through the channel bank, then  
93 the ridge would not necessarily have to reach the surface in  
94 order to create discharge. However, the occurrence of this  
95 ridging in space and time needs to be investigated alongside  
96 the influence of the capillary fringe and, of course, the pro-  
97 portion of pre-event water discharged to the stream. The  
98 work that we presented in Cloke et al. (2006) is a first sub-  
99 stantial step to pin down the spaces of operation of this  
100 mechanism.

101 We agree that a direct connection between the stream  
102 and the groundwater may alter the proportions of pre-event  
103 water discharged. This is a very valuable point, and cer-

tainly 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 dis-  
charge, we do not view the Szilagyi example as being very  
helpful in this regard as it gives no explanation for the par-  
ticular numerical example that has been chosen to illustrate  
his case. It is therefore difficult for us to evaluate the re-  
sults 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 Farv-  
olden, 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 great-  
er 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 pro-  
cess, 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 stream-  
flow 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.

**Uncited reference**

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