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# *Interactive comment on* "Opinion paper: Linking Darcy's equation to the linear reservoir" *by* Hubert H. G. Savenije

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This is a thought provoking opinion paper by Hubert Savenije (H.S.) concerning how Darcy's law relates to the linear reservoir concept. The response by Wouter Berghuijs (W.B.) provides a useful basis for discussing a number of the assumptions made in the paper, and while I agree with most of the points raised in that response, I have a few other thoughts to add to the discussion. I've used the same numbered points used by W.B. to maintain the flow of the discussion:

1. Is the catchment's groundwater reservoir linear?

I agree with W.B. that empirically, linear reservoir responses may not often be observed and that theoretically, there are many reasons why a groundwater will not give a linear



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response (e.g. see refs in W.B.'s comment). However, there are sound reasons why groundwater may sometimes behave like a linear reservoir and these have already been linked in the literature to Darcy's law via the linearised Bousinesq equation (e.g. various cases shown by Brutsaert (2005)). Most simply, where groundwater flow is predominantly horizontal (with characteristic length, L) the groundwater hydraulic response time is found to be proportional to Lˆ2/D, with D being the hydraulic diffusivity (e.g. Erskine & Papaioannou (1997)). I think though that this type of linear reservoir concept and response time formulation is only valid for small and/or highly hydraulically diffuse situations (Cuthbert 2014), although it may also occur in 2-D radially convergent or divergent settings, not just for 1-D flow (Cuthbert 2014).

The result given in the opinion paper that 'K = rg.n' is thus rather different to that given in previous literature. The given formulation of the response time is still dependent on the hydraulic properties (porosity – which is implicitly assumed equal to specific yield in the paper - and hydraulic conductivity). However, here it is related to the length scale of the flow domain (vertically) as opposed to the square of the characteristic length (horizontally). This difference follows from the assumption in the paper that groundwater will drain vertically to the nearest preferential flow pathway and that the head variation varies linearly over this flow path. It appears to be mathematically equivalent to equating the catchment drainage response to a 'falling head permeameter'.

(As a minor aside, perhaps it would be better to call the response time something like 'Tau' in the paper rather than K which is normally reserved for hydraulic conductivity, to avoid confusion?)

2. Is upscaling Darcy flow a logical choice in describing subsurface drainage networks?

The key question here is how the preferential flow network relates hydraulically to the rest of the connected subsurface porosity. Does it behave like an 'equivalent porous media'? Or does it exhibit explicit features expected of a dual porosity system? Both these concepts are mature in the hydrogeological literature and should be brought into the discussion. . .

3. Are areas far away from the stream contributing more to total groundwater flow reaching the streams?

W.B. comments here “By assuming a constant resistance for the entire catchment, it implies that areas further away from the stream disproportionally contribute to GW flow to stream? (since they will have a bigger head difference with the stream)”.

I’m not sure I agree here. If the resistance is the same everywhere and the preferential flow paths have a much greater hydraulic conductivity than the rest of the subsurface, then surely the result will be that the ‘water table’ has almost no slope – there is no need for the heads further away from the stream to be significantly higher than the head in the stream? If there is a significant difference between the water table gradient and the piezometric profile in the preferential flow zone as shown in Figure 2, then there must also be a component of horizontal flow occurring in the ‘non-preferential’ zone? This rather undermines the conceptual model? I think the conceptual model and Figure 2 needs more thought.

In essence I would expect the hydraulic response at the stream to be a complex interaction between the hydraulic response in the higher and lower permeability zones depending on their relative hydraulic conductivity and the vertical and horizontal length scales in question.

An interesting study with similarities to the proposed conceptual model (i.e. highly conductive preferential flow pathways extending through the subsurface from a drainage point into the catchment) has been studied by Swanson & Bahr (2004). They found that the L^2/D relationship still holds in such a case, at least for the range of parameters studied, even though the head distribution is modified by the presence of the preferential pathway.

4. Is resistance constant?

My comment on point 2 above is relevant here – whether this is reasonable depends on the scale of the heterogeneity versus the scale of the catchment observations.

5. Is groundwater recharge vertical?

The terminology in the paper is confusing here. 'Recharge' is not the same as 'drainage' or 'groundwater flow'. I think the paper is suggesting that groundwater flow is predominantly vertical through the bulk of the subsurface but predominantly horizontal through the preferential pathways - the direction of the recharge arriving through the unsaturated zone to the water table doesn't seem relevant to the argument?

6. The paper talks about "residence time", but this term may confuse part of the community

I totally agree with W.B. that this is adding unnecessary confusion. The "characteristic time-scale of the linear reservoir" is a hydraulic response time (timescale of a pressure wave propagation) which is a completely different concept to residence time (related to the velocity of water molecules).

Summary

In summary, I would suggest that there are a whole range of conceptual models (and related mathematics) which can link Darcy's law to the linear reservoir equation. The one presented in this opinion piece may be amongst them. However I would encourage thinking along the lines of there being a continuum of catchment hydraulic responses ranging from those where multi-porosity is explicitly exhibited in the groundwater discharge response (which may be most similar to the idea presented here) and those for which the discharge response looks more like an equivalent porous medium consistent with previous research on this. While we may be able to imagine end members for this continuum and find real examples in nature, I imagine most catchments will exhibit and integrate both behaviours at the same time at the typical spatial scale sampled by a stream flow gauge.



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Apologies if I've misunderstood any of the points presented in the paper by H.S. or the comment by W.B., but I hope my comments are of some use in the ongoing discussion of this theme.

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