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Discussions

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

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Thank you very much for this constructive and critical reaction to the opinion paper. This is much appreciated. Being written as an opinion paper, it is exactly the intention of the paper to trigger reactions by the community, in the hope that we can address one of the biggest riddles in hydrology that I have been struggling with. The riddle that I tried to solve is why so many catchments demonstrate linear behaviour. Indeed, as Berghuijs indicates, there are quite a number of catchments that are not linear, but have a power of n=2 (corresponding with b=1.5 in the dQ/dt versus Q plots). This power of 2 is in some agreement with the Boussinesq equation for a sloped aquifer with an impermeable basement (Verhoest and Troch, 2000). However, the fact remains that many catchments demonstrate linear reservoir behaviour, and we don't know where

this comes from. Probably the reason lies in the conditions for the Boussinesq equation to apply. It depends on how permeable the underlying aquifer is, and how strong the slope is. And maybe these two characteristics are correlated. An impermeable foundation deflects the streamlines, whereby the groundwater flow at the start of the streamlines is not purely vertical.

1. Is the catchment's groundwater reservoir linear?

Berghuijs states that many catchments do not perform like linear reservoirs, but then on the other hand, many do. As was indicated by Ye et al. (2014), a substantial number of catchments have a power (n) between 0.8 and 1.3. They showed that this power depends strongly on slope (the more sloped, the less linear) and on the aridity index (higher aridity, more linear). These two indicators may be correlated, because sloped terrains in the west of the USA and in the Rocky mountains are seldom dry. A strongly sloping catchment with a poorly permeable base rock is indeed likely to function according to the Boussinesq equation (e.g. Verhoest and Troch, 2000). But catchments that are more similar to the situation sketch in the opinion paper (Figure 2) with a deep freatic aquifer and –as a result –a dominant vertical flow direction above the level of the nearest open water, appear to function as linear reservoirs.

By the way, looking more closely at the figures in Brutsaert and Nieber (1977), lines with b=1 would fit almost as well to Figs. 4, 5, 6 and 7 of that paper. Only Figs. 2 and 3 have a clearly identifiable steeper slope with $1<b<3/2$. But b=3/2 is clearly on the high side. In general the lines drawn in these figures are suggestive.

I agree with Berghuijs that adding up two exponential equations does not generally result in another exponential function. There are two conditions where it does: when the time scales of the two catchments are the same; and when one catchment is generating much more flow than the other. But this is of course not a satisfactory answer. A more interesting possibility would be that the two catchments influence each other, and that they work in tandem. In a drainage network, a fractal-like network, the groundwater is drained in a complex three-dimensional pattern, whereby it is not unthinkable that two neighbouring drainage basins interact during low flow. Streamlines are likely to bend off as the water levels in the drainage network subside. How this exactly works, is not easy to figure out, but the fact that we see linear reservoir behaviour also in composite catchments, indicates that some interaction is taking place. So, to be honest, I don't know the answer to the question, but I do know that there is an interesting riddle to be solved.

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

Beghuijs raises the question whether Darcy's law is the right equation to use if it is assumed that groundwater flow is preferential. This is a misunderstanding. The idea is that Darcy's flow only applies for the groundwater to reach the preferential drainage network. The analogy with the blood vessel system is that recharge to the soil and the groundwater level is preferential (like the artery system) and that the drainage network to the stream is also preferential (as the veins). But in between the flow is Darcyan. The drainage network does not extend all the way to the water table, but only starts a certain distance W away from the groundwater table. Over that distance the flow is Darcyan, until the point where it accesses the drainage network. The consequence of using both the linear reservoir and Darcy's equation is that the resistance to entering the network is the same all over the domain of integration.

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

This is a very interesting point. It is reasonable to assume that the drainage network far away from the open water is not as well established as the network closer to the stream. Thus the distance W to entering the network is longer. The larger head is then offset against a longer travel distance for the Darcyan flow.

4. Is resistance constant?

But clearly closer to the stream, the travel distance is smaller. However we also know that closer to the stream the soils are less permeable, with a lower conductance. Also, as Berghuijs correctly observes, there is a lot of heterogeneity in the groundwater system. But maybe what some define as heterogeneity is in fact the manifestation of patterns, where in some parts the conductance seems very high (if there are veins) and in some places the conductance is low (relatively dead pockets). Of course, the sketch in Figure 2 is just a simple impression of how it might look. In reality the system of preferential drainage will be difficult to map and in reality may look capricious. The essential assumption here is that if the linear reservoir applies to systems without an impermeable base rock, then the resistance to entering the preferential drainage network should be constant.

5. Is groundwater recharge vertical?

The assumption is that between the freatic water table and the zero head level of the nearest drainage (the dashed line in Figure 2), the flow is predominantly vertical. Of course in the semi-circular picture of Figure 2 there is a substantial horizontal component, but this part is concentrated in the deeper part of the freatic system, where there is a preferential network and the Darcyan flow is no longer dominant. I do agree that in a situation with an impermeable foundation (without a preferential drainage structure) the flow would be partly, or even mostly, horizontal. That would be a situation in agreement with the paper of Brutsaert and Nieber (1977), which indicates a quadratic power (n=2 and b=1.5). I would expect that also in such catchments a preferential flow system is present, but because of the substantial horizontal component a quadratic power relation applies.

6. "Residence time"

I do agree that the term "residence time" is not correct. I shall make sure that in the final paper this term is not used in places where the time scale of the linear reservoir is meant.

Again, thank you very much for raising these very valid points and for opening the discussion, which I appreciate enormously.

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