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Hydrology and Earth System Sciences
Discussions

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

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I am very grateful to Dr Cuthbert for sharing his detailed reading and valuable thoughts and suggestions. Indeed, this opinion paper does not claim to have found the only explanation for linear (or non-linear) behaviour of groundwater drainage in catchments, but rather would like to present an alternative perspective and an alternative explanation for how the laboratory scale Darcy equation can be made to match with linear macro-scale behaviour. The conceptual connection, as presented in Figure 2, is the fact that in unconfined aquifers (without an impermeable base) streamlines start predominantly vertical. Also it requires an equally distributed resistance to entering the preferential drainage network. Equal resistance implies a constant proportion of W (the distance to entering the preferential drainage network) and Darcy's k (the conduc-

tance). As a result, W and k can both vary, but in a fixed proportion. One could imagine that parts of the catchment that are further removed from the drainage network have a larger head H, a larger W and maybe another k. But then the integration assuming the resistance as a constant cannot be made as simply. This is something to be further investigated. There may be more solutions of the integral of $v\mathrm{d}A$ that result in a linear reservoir while prescribing a certain relation between H, W and k. The essence, however, is that the groundwater system has structure and that approaching it purely from a Darcy perspective (the lab scale) denies the fact that all formation through which water flows have structure (except in most groundwater models).

I fully agree with the excellent summary presented by Dr Cuthbert under item 1. The Boussinesq approach still assumes that no structure is present in the groundwater body. In situations where water flows through an erodible or freely shaping material, there is always structure and there are always patterns. Most likely this has to do with systems evolving to a state of Maximum Power, as discussed and made plausible by Axel Kleidon (2016). Darcyan flow is reserved for lab experiments or for flow through a medium that has not yet evolved into a fractal-like structure due to exceedingly long morphological time scales.

I fully agree with Dr Cuthbert on item 2. The assumption is that the extremes of the groundwater system, near the phreatic table, can be described as an 'equivalent porous medium', even if there may be, and probably is, a dual porosity.

Regarding item 3, I already addressed this in my reply to Wouter Berghuijs. In addition to that, I don't think that a slope of the phreatic table implies a horizontal flow system. The flow and the streamlines are perpendicular to the equipotential lines and even in large aquifer systems, these streamlines start perpendicular to the phreatic table (unless there is substantial recharge, but this does not apply to the recession stage). It then essentially depends on the boundaries of the water body; whether there is an impermeable base, and how deep it is? Boussinesq-type solutions all assume an impermeable base, which forces streamline to be directed in the direction of the hillslope.

I agree that there may be 'a more complex interaction between the hydraulic response in the higher and lower permeability zones', as I indicated in the beginning of this reply. I also think that the region closer to the stream may have a lower conductance, offsetting the shorter drainage length and thus maintaining a constant resistance.

Thank you for drawing the attention to the article by Swanson and Bahr (2004). This is indeed a very interesting analytical study, strengthening the notion that subsurface structures are present even in catchments with relatively small hydraulic gradients.

On item 5, I fully agree that the term recharge is not correct. I intended the flow in the upper part of the streamlines. The recharge through the unsaturated zone is not relevant to the argument. I shall adjust the text accordingly.

I also agree that the term 'residence time' is not correct and confusing. It shall be replaced. The variable K is indeed the hydraulic response time of wave propagation, which is much shorter than the residence time of individual water particles.

I also agree with the well-worded summary. I would like to add, that in view of the long morphological time scales of groundwater systems, which function at geological time scales, even longer than the morphological time scales of surface drainage systems, we cannot assume that a complete subsurface drainage network is always present. If further we assume that this network makes use of cracks and fissure present in the base rock, but further, most likely, expands and develops by minerals going into solution, than these networks never stop to develop, while refining and expanding the fractal structure. In relatively young catchments such structures may not yet have been developed to the full extent. I think it is an interesting venue of research to study the expansion of such networks as a function of the mineral composition of the groundwater feeding the stream network.

Reference:

Kleidon, A. (2016). Thermodynamic foundations of the Earth system. Cambridge University Press.

Swanson, S. K., Bahr, J. M. (2004). Analytical and numerical models to explain steady rates of spring flow. Groundwater, 42(5), 747-759.

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