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COMMENTARY
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Where Is the Bottom of a Watershed?

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Key Points:
- Methods for defining the bottom of a watershed vary greatly across the hydrologic community
- Improved communication and collaborative efforts between the catchment hydrology and hydrogeology communities are needed

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Abstract Watersheds have served as one of our most basic units of organization in hydrology for over 300 years (Dooge, 1988, https://doi.org/10.1080/02626668809491223; McDonnell, 2017, https://doi.org/10.1038/ngeo2964; Perrault, 1674, https://www.abebooks.com/first-edition/lorigine-fontaines-Perrault-Pierre-Petit-Imprimeur/21599664536/bd). With growing interest in groundwater-surface water interactions and subsurface flow paths, hydrologists are increasingly looking deeper. But the dialog between surface water hydrologists and groundwater hydrologists is still embryonic, and many basic questions are yet to be posed, let alone answered. One key question is: where is the bottom of a watershed? Knowing where to draw the bottom boundary has not yet been fully addressed in the literature, and how to define the watershed "bottom" is a fraught question. There is large variability across physical and conceptual models regarding how to implement a watershed bottom, and what counts as "deep" varies markedly in different communities. In this commentary, we seek to initiate a dialog on existing approaches to defining the bottom of the watershed. We briefly review the current literature describing how different communities typically frame the answer of just how deep we should look and identify situations where deep flow paths are key to developing realistic conceptual models of watershed systems. We then review the common conceptual approaches used to delineate the watershed lower boundary. Finally, we highlight opportunities to trigger this potential research area at the interface of catchment hydrology and hydrogeology.

1. On the Definition of Deep

Studies have demonstrated that groundwater is an important control on runoff generation (Buttle, 1994; Konikow & Leake, 2014; Tetzlaff et al., 2014; Zimmer & McGlynn, 2017), solute fluxes (Kirchner & Neal, 2013), transit time distributions (Hale & McDonnell, 2016; Maxwell et al., 2016; McGuire & McDonnell, 2006; Soulsby et al., 2006; Visser et al., 2019), ecohydrological processes (Fan, 2015; Horton et al., 2001; Koirala et al., 2017; Laio et al., 2009), and the behavior of earth system models (Clark et al., 2015; Krakauer et al., 2014). At the watershed (or catchment, used interchangeably here to refer to drainage basins) scale, nested local to regional groundwater flow paths emerge naturally from topography, and groundwater discharge is often a mix of shallow and deep flow paths (Figure 1). Yet the bulk of the effort to understand and represent groundwater interactions is limited to the shallowest part of the groundwater system. Catchment and land surface models commonly extend 2–3 m into the soil column and may exclude "deeper" storage or rely on a lumped approach to groundwater storage (Clark et al., 2015; Fan et al., 2019; Sellers et al., 1996). Recent critical zone (CZ) research extends deeper, generally looking tens of meters into the subsurface, while integrated groundwater-surface water models tend to cover tens to hundreds of meter depth (Figure 1).

Although 100 m may sound deep as viewed by a catchment hydrologist, this is still less than the extent of many deep groundwater systems. Modern groundwater, as defined by the presence of tritium, is typically found at depths extending to 250 m (Gleeson et al., 2016). Similarly, active circulation of groundwater in mountain aquifers has been noted in the upper 100–200 m (Gleeson & Manning, 2008; Manning & Caine, 2007; Markovich, Manning, et al., 2019). We routinely pump groundwater for human usage from depths exceeding 100 m (Ferguson, McIntosh, Perrone, et al., 2018), and there are many examples of highly productive agricultural regions that rely on deep groundwater systems (e.g., Scanlon et al., 2012).

Looking deeper, Pleistocene meteoric recharge has been found in both sedimentary and crystalline environments at depths of up to 1,000 m (McIntosh et al., 2012). More recent work has characterized most

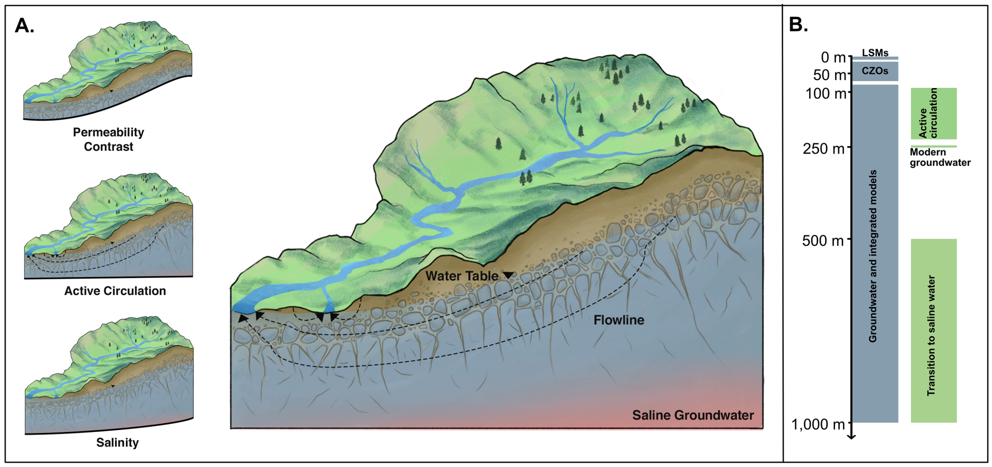

Figure 1. Conceptual model of watershed boundaries and examples of maximum depth extents for modeling applications (blue) and observations (green). (a) A conceptual watershed model with insets illustrating three common approaches to defining a bottom boundary described in section 3. (b) Maximum depth extent for most Land Surface Models (LMS), Critical Zone Observatory (CZO) models and observations, and groundwater and integrated hydrologic models in relation to groundwater age and salinity.

groundwater at depths >250 m as pre-Holocene in age (Jasechko et al., 2017). Groundwater discharge from these deep regional flow systems has been noted in the Colorado Plateau (Crossey et al., 2006) and the Western Canada Sedimentary Basin (Grasby & Betcher, 2002). Below a few thousand meters, most groundwaters are essentially stagnant over periods of millions of years due to a combination of low permeability (Ingebritsen & Manning, 1999; Warr et al., 2018) and negative buoyancy (Ferguson, McIntosh, Grasby, et al., 2018). The transition from fresh to saline groundwater generally occurs between 500 and 1,000 m (Ferguson, McIntosh, Perrone, et al., 2018). Nevertheless, deeper exceptions to these generalizations exist, particularly in mountainous regions where thermal springs with meteoric origins have circulation depths of up to 5,000 m (Ferguson & Grasby, 2011; Grasby & Hutcheon, 2001).

2. On the Importance of Going Deep

The fact that we can often observe modern groundwater hundreds of meters deep does not necessarily mean that every watershed study needs to extend to these depths. What defines a reasonable watershed bottom boundary will vary depending on the research questions, hydrogeologic setting, scale, available observations and computational resources (Ameli et al., 2018). As a first step, we advocate simply a critical assessment of whether "deep" flow paths (in this case referring to paths that extend deeper than one's current conceptual model) are potentially relevant in a particular place or to a given research question. To illustrate the potential importance of including deep flowpaths, we identify three cases where deep flow paths are key to developing a realistic conceptual model.

First, in places where deep flow paths contribute significantly to the catchment water balance, excluding these flow paths may lead to an incorrect formulation of the water balance or a fundamentally flawed conceptual model. Across larger river basins, Schaller and Fan (2009) and Fan (2019) challenged the commonly held view that catchments are closed systems, finding instead that many are regional groundwater importers or exporters. Similarly, multiple CZOs and other experimental sites operating at headwater scales have found that groundwater in fractured bedrock aquifers commonly contributes to streamflow (Brantley et al., 2017; Jin et al., 2011; Markovich, Dahlke, et al., 2019; McIntosh et al., 2017; Payn et al., 2012; White et al., 2019). Key to this discussion is the recent recognition that even at well-studied sites, we are only beginning to detect that our "shallow views" on the hydrologic cycle may miss large fluxes of water or oversimplify our conceptual models of these systems. A recent study at the well-studied Maimai catchment in New Zealand exemplifies this by demonstrating that deep groundwater, recharged in first-order catchments, subsidizes flows to their parent watersheds (Ameli et al., 2018). This finding was all the more surprising considering the super-humid climate, steep topography, and low permeability bedrock—characteristics that are generally cited in shallow flowpath conceptualizations (Gleeson et al., 2011; Gleeson & Manning, 2008). A recent review by Fan (2019) suggests that such subsidies may be important in a range of watersheds settings.

Analysis of deep flow paths should not be limited to the natural interactions. Deep flow paths may be increasingly important where groundwater pumping and management operations are accessing groundwater, and connecting groundwater to the surface water budget through irrigation or other uses. Across the United States there is a trend of increasing well depth as wells are being drilled deeper to counter water scarcity (Perrone & Jasechko, 2019). This pumping represents a critical water supply for human activities but can have adverse environmental impacts. While it is well established that groundwater pumping can result in some stream capture (Konikow & Leake, 2014), recent, large-scale modeling efforts have helped quantify the total impact that widespread groundwater pumping can have on the surface water budget (Condon & Maxwell, 2019; Konikow & Leake, 2014). Current human activities at depth may spell unknown future impacts for surface water quantity and quality. However, the treatment of hydrostratigraphy in many large-scale watershed models remains simplistic and further work is needed to evaluate water quality at depth and the effects of pumping in deeper wells. Konikow and Leake (2014) note that deeper confined aquifers are less likely to result in capture of streamflow than pumping in shallower unconfined aquifers.

Second, even when deeper flowpaths contribute minimally to bulk discharge, they can still account for a disproportionate amount of solute fluxes. Rumsey et al. (2017) estimated that groundwater discharge to the Upper Colorado River accounted for 89% of the dissolved load in the river despite baseflow accounting for less than 44% of discharge at most gauges. While there was no attempt to determine the relative importance of groundwater and solute contributions from different depths in that study, the increase in salinity with depth typically observed in groundwater systems emphasizes the need to characterize deeper flowpaths to understand concentration-discharge (C-Q) relationships (Bluth & Kump, 1994; Grasby et al., 1999; Wymore et al., 2017). A deeper bottom boundary may also be necessary to capture legacy contamination. Van Meter et al. (2017) found that much of the nitrate in the Mississippi watershed was delivered as groundwater discharge. The depth of flowpaths was not explicitly explored in that study, but other regional studies in North America have found elevated nitrate concentrations to depths of up to 50 m (Mitchell et al., 2003; Nolan & Hitt, 2006; Rudolph et al., 2015).

Finally, deep flow paths are critical for characterizing the shape, and particularly the tails, of water residence time distributions (RTDs) and the transit time distributions (TTDs) of streamwater. While streamflow can be disproportionately fed by young (<3 months old) flowpaths (Berghuijs & Kirchner, 2017; Jasechko et al., 2016), analysis of transit times during low flow periods has shown the opposite—that substantially older flowpaths feed rivers during these times (>20 years; Gabrielli et al., 2018; Rademacher et al., 2005). Similarly, Maxwell et al. (2016) showed that topographically controlled groundwater systems can result in a larger diversity in subsurface flow paths and that groundwater configuration can control RTD shape. These shapes are linked to plant available water and streamflow generation. Exploring how Earth's CZ shapes deep groundwater flow pathways, groundwater RTD, and stream TTD remains a fundamental challenge in the hydrologic sciences (Brooks et al., 2015).

3. Where to Draw the Line

So how to "draw the line" on the bottom watershed boundary? Figure 1a shows several basic conceptual approaches that could be used to delineate the watershed lower boundary—each unique, but not mutually exclusive. Also, we note that these characterizations of the bottom boundary do not take into account the approach of land surface models, surface water models, and conceptual rainfall runoff models that generally impose a bottom boundary at the land surface or the bottom of the soil column. Here we focus on the approaches to defining a lower boundary based on subsurface processes.

1. *Depth to low conductivity boundary:* Perhaps the most straightforward conceptualization of the bottom boundary of the watershed is a low conductivity unit that can be treated as a no-flow boundary. As described in one standard groundwater textbook, "the lower boundary is a real boundary; it represents the base of the surficial soil, which is underlain by a soil or rock formation with a conductivity several orders of magnitude lower" (Freeze & Cherry, 1979). It is common practice in catchment models to specify a soil depth and assume that the soil column terminates within unfractured bedrock that does not contribute to streamflow. Notwithstanding, field hydrologists have been evaluating this

conceptualization for some time, with some acknowledging this conceptual model as a hindrance to furthering the field of catchment science (Payn et al., 2012; Tromp-van Meerveld & Weiler, 2008; Zimmer & McGlynn, 2017). Groundwater hydrologists generally look deeper using hydrostratigraphy, geologic history, and/or geochemistry to identify no-flow boundaries based on permeability contrasts. Groundwater models commonly place a no-flow boundary condition at the point where the lower geologic unit is more than 2 orders of magnitude less permeable, assuming that the lower permeability unit will carry 1% of the flow of the overlying unit if thickness and hydraulic gradients are equal (Anderson et al., 2015). It is also interesting to note that the same 2-order-of-magnitude contrast has been used to define the soil-bedrock interface condition to induce lateral flow at the hillslope scale (Hopp & McDonnell, 2009).Many research watersheds are located in fractured rock settings. Identifying low conductivity boundaries in these systems is a challenge. At depths beyond surface weathering controls on bedrock (Holbrook et al., 2014; St. Clair et al., 2015), fractures become less dense due to compaction, metamorphism, and/or mineralization (Saar & Manga, 2004). This transition is commonly treated as the boundary between active and inactive groundwater flow (Mayo et al., 2003), and studies have placed this boundary at roughly 100–200 m, most often in fractured granitic bedrock (Welch & Allen, 2014). However, this boundary is highly heterogeneous within and between systems, owing to bedrock type and tectonic stress. Observations of this boundary are often limited by the small number of boreholes completed in this low conductivity zone.

2. *Active circulation depth:* The bottom boundary does not necessarily need to correspond with a geologic boundary. Indeed, nested flow systems can occur purely as a result of topography (Toth, 1963). An alternate approach is to define the bottom based on the flowpaths that are relevant to the question being asked. From a hydrogeological perspective, the active circulation depth encompasses all flowpaths that originate and terminate either at the ground surface or a surface water body. Such flowpaths often occur at much greater depths than those considered in catchment-scale studies. Alternatively, catchment hydrologists may define active circulation depth as "active zones," akin to CZ approaches, which encompass soil and groundwater stores that contribute water or solutes to the surface on timescales relevant to annual fluxes (McNamara et al., 2011) or active storage that contributes to streamflow and recession (Pfister et al., 2017).Notably, CZ conceptualizations can fall into either of the above definitions. The CZ community often defines the lower system boundary as the bottom of groundwater (Brantley et al., 2007; Council, 2001; Grant & Dietrich, 2017), but where that bottom resides or what it represents is poorly defined. Groundwater that drains seasonally from soil and saprolite and contributes to streamflow is most often considered in CZ conceptual models (Brantley et al., 2007), while groundwater movement through deeper, unweathered bedrock is often assumed to be negligible and excluded from catchment water balances (Kirchner, 2009). Thus, the extent of the CZ (and "groundwater") has been defined as the depth to unweathered bedrock, or depth to the regional water table, or sometimes as deep as actively circulating groundwater (Keller, 2019).
3. *Depth to saline water:* The bottom boundary of the watershed can also be delineated as the bottom of the freshwater system. One rule of thumb used in the groundwater community is to define the freshwater bottom as that having total dissolved solids less than 3,000 mg/L (Hem, 1959), which varies in depth depending on the aquifer of interest (Ferguson, McIntosh, Perrone, et al., 2018).

4. Observing the Bottom of a Watershed

While defining the watershed bottom boundary is one thing, "seeing it" is quite another. Defining a lower watershed boundary in real systems is complicated by lack of deep subsurface data and often complex hydrostratigraphy. In major aquifer systems the frequency of observations allows for higher confidence in subsurface configuration; however, in most catchment studies existing observations are not sufficient for observational guidance on what constitutes the system base. In many catchment hydrology studies, depth to bedrock is observed by hand-auger well installation to a "refusal" depth or by excavating soil pits down to bedrock across headwater catchments (Jencso et al., 2009; Zimmer & McGlynn, 2017). In the CZOs, deep (tens of meters) drilling campaigns and installation of bedrock monitoring wells have helped characterize deeper groundwater stores and the dynamic hydraulic connections to streamflow (White et al., 2019). Still, there are only a few deep groundwater monitoring wells in CZOs with maximum depths greater than ~50 m (Küsel et al., 2016).

More recently, hydrogeophysical methods have been used to estimate deep CZ hydrostratigraphy, fracture density, and water content distribution (Flinchum et al., 2018; Holbrook et al., 2014; Parsekian et al., 2015; St. Clair et al., 2015) as well as depth to bedrock (Lane et al., 2008), or to the "base-of-aquifer" (Abraham et al., 2012) in various hydrological settings. Above ground, advances in airborne geophysics and other geophysical methods have great promise for advancing our ability image the CZ across spatial scales (Parsekian et al., 2015; Seyfried et al., 2018), as do developments with ground-based gravitometers and other new measurement and sensing devices (Tauro et al., 2018). Many hundreds of kilometers up, data collected from the Gravity Recovery and Climate Experiment (GRACE) has expanded perspectives on how much water catchments can store, although this approach cannot provide depth specific information by itself (Alley & Konikow, 2015).

Gridded hydrogeology datasets may also provide useful information in data sparse regions. Recent efforts provide global maps of lithological classes and their hydrologic properties (e.g., permeability and porosity; Gleeson et al., 2011; Gleeson et al., 2014; Hartmann & Moosdorf, 2012). These datasets offer unprecedented information on subsurface properties below the soil but still introduce some challenges and uncertainties. For example, they focus on depth-averaged near surface (roughly 100 m) properties, and they do not provide information on hydrostratigraphy. Previous maps of depth to bedrock focused on shallow bedrock (less than 2 m; Miller & White, 1998), though new global products are now emerging that estimate the total depth to bedrock extending tens to hundreds of meters (Pelletier et al., 2016; Shangguan et al., 2017).

5. Summary and Vision for Moving Forward

This commentary highlights the disparate treatment of the watershed bottom across the hydrologic community. Though there are several paths forward, the first step may simply be a (vertical) shift in the depth we consider when building our conceptual models. We see three key opportunities to improve our representations and understanding of this fundamental watershed characteristic:

1. Actually "observing" the bottom of a watershed remains a major challenge, but an important need. To this end, we need more observations at depth to characterize the vertical distribution of permeability. For example, CZ and other catchment studies often have too few wells below the interface of weathered and unweathered bedrock to adequately capture spatial variability of deep groundwater. There have been some advances in small borehole installation that have allowed for important discoveries related to residence time and active circulation depths in fractured rock systems (Gabrielli & McDonnell, 2012), but these generally extend to only 10 m or so. Additional deep well drilling and greater application of geophysical methods (e.g., White et al., 2019) are needed to provide spatial characterization of hydrostratigraphy down to 100–200 m. New 3-D gridded datasets that make use of existing permeability data and data from a range of other sources are needed to improve modeling efforts at large scales.
2. We need new tools to characterize deep flow paths as well as the vertical storage and release of deep groundwater. The stable isotopes of hydrogen and oxygen have been workhorse tracers in water studies for decades. However, variability in flowpath lengths can be masked by similar isotopic signatures, and the tails of TTD may be truncated with these methods (Stewart et al., 2010). Collecting stable isotope data for both streamflow and precipitation with high frequency (e.g., von Freyberg et al., 2017) has led to insights in catchment response and is a novel area of development (Kirchner, 2019). Across the board, we advocate for additional tracer studies as well as the implementation of novel tracers, such as synthetic DNA (Dahlke et al., 2015), and tracers representing longer transit times, such as Argon-39 (Loosli, 1983) to inform this important question.
3. Finally, we acknowledge that perfect information of subsurface architecture and permeability is probably unobtainable, especially outside heavily instrumented catchments. This means that we will always need to rely on numerical models of the subsurface. Within these numerical investigations, we need additional research to evaluate the sensitivity of simulated results to bottom boundary conceptualization and to characterize the systems and questions most sensitive to our representation and spatial configuration of the bottom. This is vital for large-scale land surface and earth systems models where we are still iterating how best to represent the subsurface (Clark et al., 2015; Fan et al., 2019). We therefore advocate additional modeling and observational work across a more diverse set of systems, including catchments in distinct climates (e.g., Tetzlaff et al., 2015), those with complex CZs (e.g., Buss et al., 2013; Hahm et al., 2019; Shi et al., 2013; Zimmer & McGlynn, 2017), and those

experiencing human stressors and management (e.g., Bhaskar & Welty, 2015; Condon & Maxwell, 2019; McDonnell et al., 2018; Perrone & Jasechko, 2017; White et al., 2019).

Above all, we need to critically interrogate our existing conceptual models of watershed systems and allow for more dialog on what the bottom of a watershed truly represents. Such interrogations may bring rethinking the water balance alongside our basic definition of watersheds into closer focus, accelerating the potential for a new conceptual model of catchments to emerge. By improving our conceptualizations of this lower boundary, we are likely to bring hydrogeology and hydrology into closer contact, creating opportunities for the coevolution of knowledge and refining our perceptions of watershed functioning from a lateral as well as vertical lens—redefining watershed hydrology from the bottom-up.

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