Groundwater

Issue Paper/

The Importance of Groundwater in Critical Zone Science

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Abstract

The critical zone (CZ)—from treetops to groundwater—is an increasingly studied part of the earth system, where scientists study interactions between water, air, rock, soil, and life. Groundwater is both a boundary and an essential store in this integrated system, but is often not well considered in part because of the difficulty in accessing it and its slow movement relative to other parts of the system. Here, we describe some fundamental areas where groundwater hydrology is of fundamental importance to CZ science, including sustaining streamflow and vegetation, reacting with minerals to produce dissolved solutes and regolith, and influencing energy fluxes across the land-atmosphere interface. As the timing and type of precipitation change with climate, groundwater may play an even more important role in CZ processes as a sustainable water source for plants and streamflow. Many open questions also exist about the role of CZ processes on groundwater. Many data streams are needed and important to quantifying the integrated response of the CZ to groundwater and vice versa, but long-term data records are often incomplete or discontinued due to limited funding. We argue that the long timescales of processes that involve groundwater necessitate data collection efforts beyond typical federal funding timespans. Sustaining monitoring networks and developing new ones aimed at testing hypotheses related to slow-moving, groundwater-controlled CZ processes should be a scientific priority, and here we outline some open questions that we hope will motivate groundwater scientists to get involved in CZ science.

Introduction

Critical zone (CZ) science is an interdisciplinary field of research—including geology, hydrology, ecology, atmospheric science, and landscape evolution, among others— that is becoming an increasingly popular way of thinking about the shallow earth system (e.g., Waldron 2020). The first CZ Observatories were funded more than 15 years ago (Anderson et al. 2008), and since that time, many researchers have defined themselves as CZ scientists and defined questions beyond the disciplinarity of traditional earth or environmental science fields (e.g., Sullivan et al. 2017). Some of the earliest definitions of the CZ describe it as the piece of the earth from the top of vegetation to the "base of active groundwater" (Anderson et al. 2008), opening the question: what is "active" groundwater, how does it affect CZ systems, and what are roles for groundwater scientists in CZ science? While the term "groundwater" is sometimes confusingly used within the hydrology community, we here use the term to mean saturated systems, as opposed to the vadose zone (e.g., Woessner and Poeter 2020). Here, we argue that groundwater is an integral part of the hydrogeochemical system in Earth's CZs: it sustains streamflow during periods of low precipitation, is accessible by deep vegetation, reacts with minerals to produce dissolved solutes and regolith, and can influence energy fluxes across the land-atmosphere interface (Figure 1). Many data streams, from stream gages to vegetation maps, provide important

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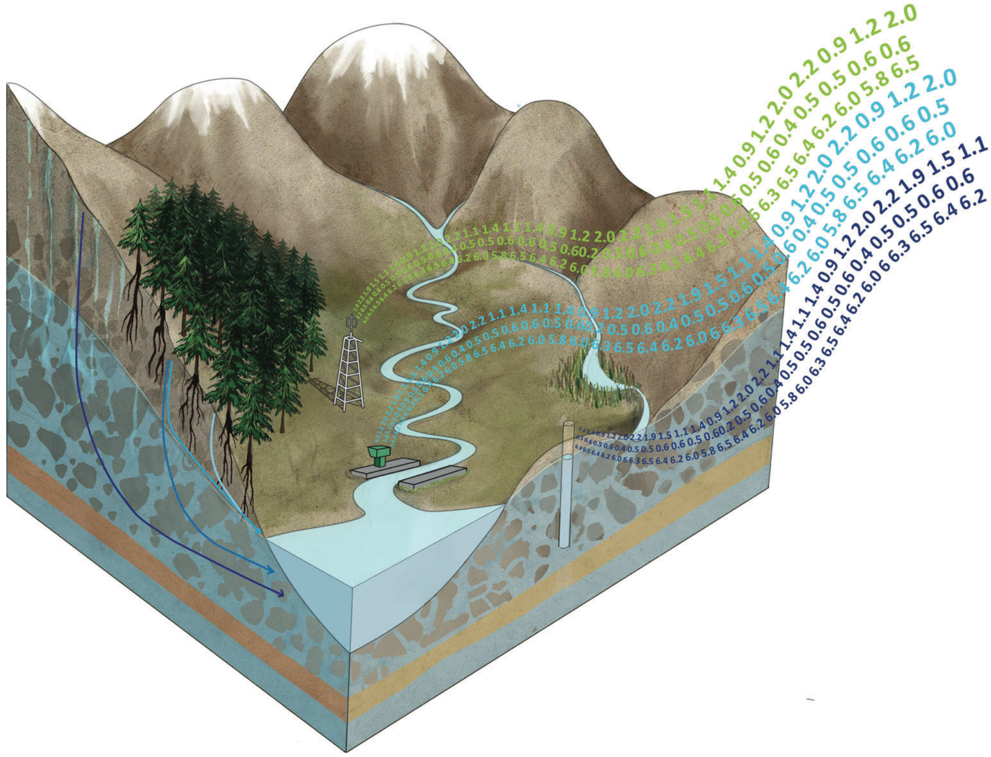

Figure 1. Groundwater is a fundamental, slow-moving part of the critical zone (CZ) that affects and is affected by comparatively short-timescale CZ systems such as streamflow, vegetation, and energy fluxes across the land-atmosphere interface, as well as longer-term processes like weathering. Data streams from multiple sensing platforms, from eddy flux towers, stream gages, and wellbores, provide important clues to the role of groundwater in CZ processes.

clues to the role of groundwater in CZ processes and help us to understand the integrated response of the CZ to climate change. While many of the examples here focus on temperate to humid areas, we note that there is a role for groundwater in arid CZ systems as well, for instance, as a stable water source for plants in riparian corridors or perched groundwater systems (e.g., Yin et al. 2015). Groundwater fluxes in arid regions are also thought to be less affected by climate change than humid systems (Cuthbert et al. 2019), which may mean CZ systems are more stable in drier regions under a changing climate.

One might wonder if groundwater is too deep to affect or be affected by many CZ systems, and what "deep" means is open to interpretation, depending on processes of interest (Condon et al., 2020b). Numerical models have been used to define the "depth of active flow" in the CZ, where water is actively moving. In some systems, this depth may be quite shallow (Reed et al. 2007; Amvrosiadi et al. 2017). Of course, accessing the subsurface beyond the top meter or two in the field is often difficult (e.g., Parsekian et al. 2015), which makes it difficult to measure groundwater broadly over the landscape, and may lead some to neglect its role in CZ processes or to have the data to integrate into models around its importance. Some work, however, has outlined the importance of shallow groundwater in the CZ from the hillslope to global scales (e.g., Shi et al. 2013; Fan 2015). The global-scale depth-to-groundwater observations compiled by Fan et al. (2013) show that as much as a third of the global land area is underlain by shallow groundwater, and that it is common worldwide for the depth of groundwater to be <5 m below land surface—which is shallow enough to be within reach of some plants' roots (e.g., Canadell et al. 1996) and to contribute to land-energy fluxes (e.g., Maxwell and Condon 2016). Weathering in shallow groundwater is also an important contributor of solutes in systems where a portion of stream water is derived from groundwater and opens pore space for water infiltration into the groundwater system. We argue that groundwater is consequently important to both short- and long-time scale CZ processes and look to outline some of these systems where groundwater plays a key role, with the hope of motivating other groundwater scientists to work in CZ science. Below, we briefly outline the role of groundwater in wetland systems, sustaining streamflow, ecosystems, land surface fluxes, and weathering, and note where groundwater hydrologists could contribute to open questions in CZ science.

A Driver of Wetlands

Groundwater connections to many wetlands have been long recognized (Winter and Rosenberry 1995; Van der Kamp and Hayashi 1998). Miguez-Macho and Fan (2012) highlight how wetlands are driven not only by precipitation but the presence of groundwater broadly. Wetlands also impact groundwater; vegetation and microtopography in wetlands drive interactions between surface- and groundwater, and can create biogeochemical hotspots just like in river systems due to gradients in organic matter and dissolved oxygen. If a wetland interacts with regional groundwater, there may be other electron acceptors such as nitrate or sulfate that facilitate oxidation of organic carbon (e.g., Alewell et al. 2008). Consequently, predicting wetland dynamics is key to predicting carbon cycling (e.g., Trettin and Jurgensen 2003) and consequently climate (e.g., Erwin 2009). Wetlands have high evapotranspiration (ET) rates, which thus affect surface water and energy balances. From a CZ perspective, some open questions around how the mixing of long residence-time groundwater and the shorter-term surface water affect wetland chemistry, including prediction of algal blooms (Brookfield et al. 2021) as well as the role of wetlands in buffering sea level rise and storm surges (Liu et al. 2021).

Surface Water–Groundwater Interaction

Like with wetlands, it has long been recognized that many streams are sustained by groundwater (e.g., Winter et al. 1998), and that there is a two-way communication between groundwater and surface water. Fan et al. (2013)'s depth-to-water table map demonstrates that groundwater is shallow in topographic lows under all climate types, which suggests that groundwater may be a source of water in topographic depressions regardless of precipitation. In some systems, groundwater emanating from springs has a profound impact on surface-water chemistry and flows (e.g., Crossey et al. 2006).

From a CZ perspective, baseflow matters for maintaining healthy riparian vegetation (e.g., Webb and Leake 2006), which in turn controls stream-channel and bank stability and sediment transport (e.g., Trimble 2004; Salant et al. 2008; Estrany et al. 2009; Duvert et al. 2011). Groundwater is also key to lowering stream temperatures (e.g., Meisner et al. 1988; Loheide and Gorelick 2006), which can be important for fish refugia (e.g., Power et al. 1999). Groundwater contributions to streamflow may become even more important as climate change and other perturbations drive changes in near-surface hydrological processes that lead to increased groundwater stores, such as decreases in ET driven by widespread tree death (Bearup et al. 2014). We note that the CZ response to climate change includes water quality as well as quantity, and groundwater may provide more consistent water chemistry to streams that is less impacted by modern anthropogenic activities than surface water; conversely, surface water carries dissolved oxygen into groundwater that drives redox reactions and mitigates dissolved metal contributions of groundwaters to streams (e.g., Hoagland et al., 2020). Because of these exchanges, groundwater-surface water mixing affects both stream and groundwater quality (e.g., Gburek and Folmar 1999; Cantafio and Ryan 2014), including metal immobilization (e.g., Gandy et al. 2007) and nutrient uptake (e.g., Boulton et al. 1998). Many open questions about groundwater-surface water systems remain, including how the hyporheic zone controls fate and transport of contaminants (e.g., Wallis et al. 2020), how agricultural systems impact baseflow contributions (e.g., Frisbee et al. 2017) and how a changing climate may affect water quality through baseflow contributions and groundwater-surface water interaction (e.g., Chunn et al. 2019).

Groundwater Effects on Plant Growth and Survival

Plants are a key component of the CZ system by driving transpiration, increasing the weathering of rock to soil, and influencing biogeochemical cycling of carbon and nutrients. Groundwater is less well coupled to large fluctuations in precipitation than streams or vadose zone water, providing a sustained water source for vegetation even beyond riparian areas (e.g., Dawson and Pate 1996; Elliott et al. 2006; Jobbágy et al. 2011; Fan 2015; McLaughlin et al. 2017; Harmon et al. 2020), allowing plants to thrive in dry times by buffering against plant stress (Condon et al. 2020a). Groundwater can not only provide a water supply during dry times but can also decrease plant yield during wet conditions by enhancing oxygen stress (Zipper et al. 2015).

Groundwater also drives the rooting depths of plants (Lewis and Burgy 1964; Schenk and Jackson 2002), with root growth following declining water tables (e.g., Stromberg et al. 1996; Naumburg et al. 2005). Of course, trees may affect groundwater quantity and quality, too, using groundwater supplies that might otherwise available for other uses, through phytoremediation (Vangronsveld et al. 2009) and by exuding water and solutes from their roots that change local chemistry (Williams and de Vries 2020). Exudates add organic carbon, sugars, and amino acids, among other substances (Olanrewaju et al. 2019) and can affect mobilization of materials adsorbed on soil surfaces, although whether that is a large enough signal to affect groundwater stores is an open question. Direct measurements of groundwater-transpiration fluxes over large regions have been outlined as important data needed to quantify patterns and dynamics of ecosystems (National Research Council 2012), and many open questions about ties between groundwater and plant-water use—including when and where they are connected—exist.

Land Surface Fluxes

Energy and water balances are important to the CZ in terms of controlling weather and climate and predicting weathering and ecosystem productivity. Shallow groundwater can control energy and water balances by affecting soil moisture (e.g., Kollet and Maxwell 2008; Soylu et al. 2011; Miguez-Macho and Fan 2012; Hain et al. 2015), and can determine the susceptibility of regions to changes in climate (e.g., Maxwell and Kollet 2008). Adding groundwater to land-surface models improves estimates of precipitation partitioning and matching water level and storage observations at multiple scales (e.g., Niu et al. 2007; Huang et al. 2019). While it is well recognized that climate will change components of the water cycle such as recharge (e.g., Konikow 2011; Cuthbert et al. 2019), the impact of climate change on groundwater and its effects on land-atmosphere feedbacks and buffering of the climate system remains an important area of research (e.g., Wu et al. 2020). These changes likely determine the thickness of the CZ, which remains a complex property to estimate; defined in part by vegetation height and depth to the bottom of groundwater, it is likely controlled by the humidity index and the effective energy and mass transfer into the CZ (Xu and Liu 2017).

Weathering

Weathering is tightly coupled to near-surface processes with influences from vegetation, climate, and erosion. As dilute, reactive fluids infiltrate into the subsurface and dissolve minerals, solute concentrations increase and eventually the fluid reaches chemical saturation with respect to dissolving minerals in the underlying bedrock and weathering ceases. The zone over which saturation indices increase from far from saturation with respect to dissolving minerals ($SI < 0$) to saturated ($SI = 0$) is termed the weathering front. The rate of advance and thickness of this weathering front in the subsurface is a function of the rate of water infiltration and the dissolution rate of minerals (e.g., Lichtner 1988; White et al. 1996), while the position of the weathering front relative to the water table is driven by erosion rates and infiltration rates (Lebedeva and Brantley 2020). It has largely been assumed that this weathering front is positioned above the water table and most rock weathering occurs in the vadose zone (e.g., Hilley et al. 2010; Goodfellow et al. 2011). But weathering at the water table (e.g., Wan et al. 2019) and deep weathering—or weathering below the water table (e.g., Ollier 1988)—have long been observed and are important processes for generating saprolite-hosted aquifers used for drinking water (e.g., Taylor 2001). The position of weathering fronts relative to the water table changes as the water table raises and lowers seasonally or in response to changes in climate, and its position relative to the water table varies with landscape position within a single watershed (Gu et al. 2020). The fraction of weathering derived solutes attributed to groundwater can therefore change as the position of the weathering front changes relative to the water table (e.g., Todd et al. 2012). In some systems, weathering drives the opening of porosity and disaggregation of rock leading to nested reaction fronts and driving deeper infiltration of fluids that ultimately become groundwater (Brantley et al. 2013). Weathering in karst systems, in particular, is an important process for creating subsurface pathways for groundwater flow (e.g. Kaufmann and Braun 2000). Weathering is also a product of biology, including vegetation and microbes; for example, roots searching for deeper water sources have large feedbacks to rock weathering (Hasenmueller et al. 2017), and many questions remain about the coupling of root systems to rock weathering.

Weathering also drives the geochemistry of surface water. Groundwater residence times are longer than shallower flowpaths through the vadose zone. These longer residence times can allow for more weathering and generation of solutes, and solute concentrations in streams are often highest when groundwater dominates stream discharge. For example, in a steep, rapidly eroding, mountain watershed in Taiwan, deep groundwater contributes 16% of the total river discharge but 40% of cation-weathering flux carried by the river (Calmels et al. 2011). In the upper Colorado River watershed, USA, 89% of dissolved solutes is attributed to groundwater contributions to the river, with weathering of sedimentary rocks by groundwater being an important source of solutes (Rumsey et al. 2017). The year-round contribution of groundwater to streamflow can also be an important, persistent, source of trace elements produced by chemical weathering (King and Pett-Ridge 2018). Groundwater geochemistry can, therefore, impact water quality and ecosystems downgradient, all the way to the ocean (Sawyer et al. 2016). Questions remain about the timescales over which weathering reactions respond to perturbations in the water table driven by climate or land-use and the role of weathering below the water table on disaggregating rock and solute generation. These questions cannot be answered without a better understanding of the relationship between weathering profiles and water tables and the solute contribution of groundwater to stream flows under varying conditions.

Conclusions and Recommendations

As we outline here, groundwater is key to a myriad of CZ processes. That said, the movement of groundwater is slow compared to surface-water or atmospheric-water systems. Quantifying changes to the many groundwater-controlled processes we have highlighted above and developing the requisite, testable perceptual models needed to capture our understanding of process across systems (e.g., Wagener et al. 2021) requires long-term data records. For example, hydrograph-separation analysis to determine the fractional groundwater contribution to streamflow requires multiple years of hydrological and geochemical data from groundwater and surface waters (e.g., Bearup et al. 2014). Because of the relative languor of groundwater and the long-term effects of climate, groundwater science is one of many environmental sciences that would benefit from long-term funding for measurements.

While we both support hypothesis-driven science, the three-year timescale of many federal grants often does not allow groundwater to be a major player in the systems that we measure, or it is assumed static. Of course, groundwater can be considered as an important part of the CZ system through numerical modeling, but we are not going to learn something new about the world system from models unhindered by data. Field-based hydrologic research is notably on the decline, at least in catchment hydrology (Burt and McDonnell 2015), although one can imagine that pattern is not different within hydrogeology. Long-term measurements have historically been provided to the hydrogeologic community by the USGS; however, in recent years, cuts to their operating budget and changes in priority have affected their ability to maintain many of their groundwater and surface water data stations (e.g., stream gages as listed at https://water.usgs.gov/networks/fundingstability/), some of which have been collecting data for a century. Additionally, the USGS has seen the closure or refocusing of some important programs collecting long-term groundwater data such as the Toxic Substances Hydrology Program, the National Water-Quality Assessment Program (NAWQA), and the Water, Energy, and Biogeochemical Budgets (WEBB) Program. Long-term groundwater data—both quality or quantity—are invaluable in the identification of changing water resources with climate change, and continued collection should be a priority to hydrologic scientists, especially in sensitive or important water systems. Collecting groundwater data co-located with other data, such as stream water quality and quantity, vegetation index, sap flow measurements, soil moisture, pore water chemistry, and meteorological observations among others, provides opportunities to ask and answer questions related to the role of groundwater in CZ processes. New mechanisms are needed to promote and fund long-term data collection with the express goal of providing the scientific community the observations needed to ground-truth models and identify temporal trends. While the National Science Foundation has provided 5-year, renewable grants to study CZ science to date, these time scales are still too short to look at climate records. If the USGS is not able to collect these data, who can? We do not have an answer, but know we need to look beyond the walls of academia, with its (generally) short-term projects, to collect continuous, high-quality data over decadal scales.

That said, academia has a clear role to play here as well. We need to motivate the next generation of scientists to participate in the generation of new information about the earth system via data collection. Partnerships within the hydrologic community could establish regional monitoring networks centered around systems of importance or potential perturbations, while also strengthening relationships between institutions; the previous CZ Observatories, at some level, served in this role for the broader CZ community. These sorts of data, if collected near and made accessible to undergraduate institutions, could also be used to promote collaborative science between primarily undergraduate serving institutions and universities that grant research-based graduate degrees and get the next generation of hydrogeologists interested in CZ science and data collection.

There is an important and perhaps underutilized role for hydrogeologists in CZ science. Many key processes in the CZ are underpinned by groundwater hydrology, and we hope that the readership of Groundwater sees this paper as a call to join in on research in this area. For those interested in how to get involved, we bring your attention to three National Science Foundation-funded Research Coordination Networks, specifically developed to enhance inclusion in CZ science: one focused on early-career researchers (https://sites.google.com/view/czrcn; @joinCZscience on Twitter), one on carbonate CZs (https://carbonatecriticalzone.research.ufl.edu/), and one on reactive transport modeling (https://www.mines.edu/reactivetransporthub/), as well as nine newly funded Critical Zone Collaborative Network Clusters (https://czo-archive.criticalzone.org/national/news/story/critical-zone-collaborative-network/; https://www.criticalzone.org/), many of which are looking for new collaborators [Correction added after first online publication on November 20, 2021. https://cznet.clearpeak.net in text has been changed to https://www.criticalzone.org/].

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Authors' Note

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