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Hydrology and Earth System Sciences
Discussions

# *Interactive comment on* "A hydrological framework for persistent river pools in semi-arid environments" *by* Sarah A. Bourke et al.

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Thank you to the reviewer for taking the time to review our paper and give useful and constructive comments. We appreciate the feedback and constructive criticism, which has identified important aspects to be improved and will help us to refine and clarify the value and contribution of the paper. The major criticism of this reviewer is that classification systems for springs exist; almost all persistent pools are springs; therefore this paper is redundant. The reviewer is indeed correct that multiple classifications for springs do exist and we have referred to and cited some of these. However we disagree that the literature on springs forms a suitable and comprehensive framework for the study of persistent river pools. It is our experience that persistent river pools display hydrological characteristics that span streams and lakes as well as ground-



water springs. Streams and lakes have been treated distinctly to groundwater springs within existing literature with concepts around gaining and losing streams, through-flow lakes, and hyporheic exchange have been well documented by experts in surface water – groundwater interaction (see Winter 1998 USGS Circular 1139 for a summary). Separately, there is an established body of work around mechanisms for spring discharge with multiple classifications to choose from. Spring classifications can be based on geological mechanism, hydrochemical properties, landscape setting, or a combination of all three, leading to broad categories such as thermal or artesian, as well as nuanced distinctions based on detailed geological structures (Alfaro 1994). For the purposes of understanding persistent river pools, this array of categories is both overly complex and incomplete.

To demonstrate, we examine the reviewers' suggestion that one of the pool types in this paper is a limnocrene spring after Springer (2009). We assume in this comment the reviewer is referring to what we have called through-flow pools. Springer (2009) presents a classification of springs based on their "sphere of influence", which is the setting into which the groundwater flows. A "limnocrene spring" is simply any groundwater that discharges to a pool, as distinct from say a "cave spring", which emerges into a cave. On this basis, one might consider all persistent pools that are not perched as limnocrene springs. However, the schema also articulates 'helocrene springs" which are associated with wetlands and "rheocrene springs" that emerge into stream channels. These also seem to be potentially fitting labels for persistent river pools, which does one choose? As an aid for the reader Springer (2009) includes a number of conceptual diagrams of their generalized spring types, similar in intent to the cross-section diagrams presented in our manuscript. Looking at the diagram of a limnocrene (Fig 1j) the reader is presented with a pool that is fed by groundwater that sourced from an aquifer that is karstic limestone or fractured (the watertable has stepwise changes) adjacent to and beneath the unconsolidated alluvium that the pool sits within. The groundwater flows from the limestone up a fault under pressure into the pool, and the alluvium directly below the pool is represented as unsaturated. So there are two issues with the using this category to describe our through-flow pools. Firstly, the diagram is hydraulically inaccurate; a low-permeability confining layer between the limestone and the pool would be required for the alluvium for the groundwater to be under sufficient pressure to maintain a pool while the alluvium remains unsaturated, but no such layer is shown. Secondly, this diagram does not represent the hydraulic characteristics of through-flow pools, which are windows into the water level in the saturated zone within the modern creek channel. If the alluvium were not saturated to the level of the base of the pool then these types of pools would not exist. So the diagram is both inaccurate and inappropriate for the types of pools we have identified as through-flow pools.

A more appropriate conceptualization for the hydrology of the pools we have called through-flow pools, is that of through-flow lakes, which are widely documented within the literature on surface water – groundwater interactions (e.g. Fig 16C in Winter 1998). The hydrology of these lakes provides an excellent analogue for persistent river pools that are fed by water from within the alluvium of the river channel. Unlike spring categorizations (which focus geological controls and the point of groundwater outflow), the key features of this conceptualisation are that that 1) the surface water is connected to the underlying aquifer and represents a window to the water table and 2) that water enters the lakes (or pool) on the up-gradient side (the capture zone) and leaves the lake (or pool) on the down-gradient side (the release zone) (Townley and Trefry, 2000). The lake thus provides something of a "short circuit" for regional groundwater flow. The hydraulic mechanism is effectively identical to our through-flow pools; the pool is connected to a highly conductive saturated zone within the alluvium and the water level reflects the water table within the alluvium. Water within the alluvium is flowing in the down-gradient direction, but some portion of this subsurface water will use the pool as a kind of "short-circuit" to make its way downstream.

A comprehensive understanding of the hydrological attributes of persistent river pools, and the mechanisms that support them, therefore requires drawing on concepts from both surface water groundwater interactions, and spring hydrogeology. While numer-



ous classifications of spring systems have been published, these are commonly complex classification systems with multiple types of springs (often ten or more) that are neither designed for, nor easily applied to persistent river pools in a useful manner. Furthermore, these classifications do not include the full suite of mechanisms supporting the persistence of river pools. Similarly, as this reviewer notes, the methods required to understand the hydrology of persistent river pools are drawn from multiple strands of the literature and are not routinely deployed in tandem during studies of flowing streams, permanent lakes or groundwater springs. As such, there is a need for a comprehensive framework specific to persistent river pools that is inclusive enough to incorporate the range of pools encountered, but also simple enough so as to be useful for hydrologists, ecologists and water managers alike. We believe that is what we have presented in this manuscript. This context has clearly not been clearly articulated sufficiently in the existing manuscript and we look forward to improving this aspect of the paper in a revised submission.

Having established the need for this paper, we readily accept that it would benefit from a more robust treatment of existing literature as recommended by all three commentators thus far. We believe that the generalized diagrams presented in the current manuscript are vital templates that provide the framework that others site-specific data can sit within (see also comments by Rau et al in support of these diagrams). However, we are willing and able to include more site-specific data in the revised manuscript as both reviewers have suggested. We do not propose to include full case studies of individual pools as this would make the manuscript too long, but we can certainly see the value of including water level data demonstrating perched conditions as opposed to a through-flow pool, for example.

Thanks again for taking the time to provide a constructive review, it is much appreciated and we look forward to updating the manuscript to address your concerns and criticisms.

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