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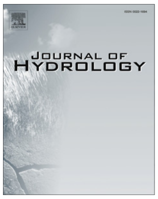

Rain and channel flow supplements to subsurface water beneath hyper-arid ephemeral stream channels

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SUMMARY

In hyper-arid regions, ephemeral stream channels are important sources of subsurface recharge and water supply for riparian vegetation, but few studies have documented the subsurface water content dynamics of these systems. This study examines ephemeral channels in the hyper-arid western Sonoran Desert, USA to determine how frequently water recharges the alluvial fill and identify variables that affect the depth and persistence of recharge. Precipitation, stream stage, and subsurface water content measurements were collected over a three-year study at six channels with varying contributing areas and thicknesses of alluvial fill. All channels contain coarse alluvium composed primarily of sands and gravels, and some locations also have localized layers of fine sediment at 2–3 m depth. Rain alone contributed 300–400 mm of water input to these channels over three years, but water content responses were only detected for 36% of the rain events at 10 cm depth, indicating that much of the rain water was either quickly evaporated or taken up by plants. Pulses of water from rain events were detected only in the top meter of alluvium. The sites each experienced $\leqslant$5 brief flow events, which caused transient saturation that usually lasted only a few hours longer than flow. These events were the only apparent source of water to depths >1 m, and water from flow events quickly percolated past the deepest measurement depths (0.5–3 m). Sustained saturation in the shallow subsurface only developed where there was a near-surface layer of finer consolidated sediments that impeded deep percolation.

1. Introduction

Hyper-arid regions are those where the mean annual precipitation is less than 5% of the mean annual potential evapotranspiration (Safriel et al., 2005). The most geographically extensive hyper-arid region crosses the Sahara Desert in Africa and the Arabian peninsula. Other smaller areas of hyper-aridity are found along the western coasts of South America and South Africa, in the rain shadow north of the Himalaya in Asia, and a small portion of southwestern North America near the Gulf of California (Middleton and Thomas, 1997). Because these regions are so dry, channels draining them are ephemeral, flowing only after large rains. Flow events are so rare in these environments that few studies document their characteristics. In hyper-arid channels in Israel, streams only flow around 0–6 times per year (Reid et al., 1998; Greenbaum et al., 2000; Shentsis, 2003; Shentsis and Rosenthal, 2003; Dahan et al., 2007). In the hyper-arid to arid Mohave Desert of North America reported stream flow frequencies range from 8 events in a nearly 100 year record to several times a year (Enzel and Wells, 1997; Izbicki et al., 2000). Hyper-arid stream networks often have higher flow frequency in headwater reaches, as transmission losses reduce flow downstream (Enzel and Wells, 1997; Tooth, 2000; Yair and Kossovsky, 2002). Flow occurrence in hyper-arid regions is even less frequent than in arid and semi-arid regions, where streams may flow for two weeks up to multiple months per year (Knighton and Nanson, 1994; Constantz and Thomas, 1997; Blasch et al., 2006; Jarihani et al., 2015).

Abbreviations: D_f, duration of flow; D_s, duration of saturation; MI_x, maximum storm intensity for an x-minute time interval; P, storm precipitation depth; S_p, flow event peak stage; VWC, volumetric water content.

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In both hyper-arid and arid regions, ephemeral stream channels are important sources of recharge (Renard et al., 1964), and they are hot spots of biodiversity relative to surrounding uplands (Noy-Meir, 1973; McAuliffe, 1999). Both rain and episodic flow events contribute water to the subsurface along ephemeral stream corridors, so subsurface water contents beneath ephemeral streams can be substantially higher and more variable than in surrounding uplands (Stonestrom et al., 2004). Riparian vegetation along these channels relies on water supplied by streamflow events (Kolb et al., 1997; Snyder and Williams, 2000; Gazal et al., 2006; Shaw, 2015). Plants have extensive root systems capable of accessing both shallow and deep water sources, so they can tolerate prolonged drought periods (Turner et al., 1995; Gibson, 1996). Flow events are clearly a crucial ecosystem water supply in hyper-arid regions, but few primary datasets document how frequently water recharges the subsurface and how long this water persists between recharge events. This information is important for understanding hyper-arid riparian ecosystems and their sensitivity to change. The objectives of this study are to (1) document the depth and timing of subsurface water content responses to rain and flow events in six hyper-arid ephemeral stream reaches, and (2) identify variables affecting the depth and timing of subsurface recharge.

2. Study site

The study area is in southern Arizona, USA in the hyper-arid section of the Sonoran Desert. Mean annual precipitation in this area is only 94 mm at the U.S. Army Yuma Proving Ground (YPG) weather station, ranging from 79 to 163 mm at other nearby long-term weather stations. This is one of the hottest parts of North America, with a mean annual temperature of 31 °C and mean annual pan evaporation around 2500 mm. The majority of precipitation is from frontal or cutoff low pressure systems during the winter (November–February) and the North American monsoon during summer (June–September). Dissipating tropical cyclones can also contribute precipitation in September–October (Pool, 2005). At the YPG weather station, the months of highest precipitation on average are December–February and August–September. Runoff is generated by infiltration excess overland flow and is most frequently observed in small headwater catchments with relatively impermeable bedrock or desert pavement land cover (Faulconer, 2015). Winter storms rarely generate streamflow except in headwater channels that lack alluvial fill. Downstream alluvium-filled channels typically flow only during the summer after intense rains from convective storms (Faulconer, 2015). This flow pattern is similar to the slightly wetter Walnut Gulch area in Arizona (mean annual precipitation 280 mm), where most channel flow is during the summer, and winter flow events are only reported in small (<0.1 km^2) catchments (Diskin and Lane, 1972).

Study sites are nested within two watersheds, Mohave Wash and Yuma Wash (Fig. 1). Six channel sections were selected for subsurface water content monitoring following the geomorphic channel classification of Sutfin et al. (2014), who identified five channel types in this region. Headwater channels were classified as either bedrock or piedmont channels, which do not have alluvium stored in the channel bed. Higher order ephemeral channels all contain stored alluvium, and these are the channel types examined here (Table 1). The smallest of these channel types is bedrock with alluvium, which is bounded on either side by bedrock but has coarse alluvium within the channel bed. Bedrock with alluvium channels are single-threaded, confined channels. The monitoring location at Mohave bedrock with alluvium drains a contributing area of 0.9 km^2 and is confined by bedrock along the bed and bank on the east side and by an elevated point bar and alluvial terrace on the west side (Fig. 2). The monitoring location at Yuma bedrock with alluvium drains 2.2 km^2 and is a straight gravel-bedded section of channel confined on both sides by bedrock. Incised alluvium channels are single-threaded and confined on either side by older alluvium. The Mohave incised alluvium site drains 170 km^2 and is a confined reach of a channel that is otherwise braided above and below the monitored section. Yuma incised alluvium drains 3.6 km^2 and is fully confined on either side by steep banks of alluvium. The largest main channels in each study watershed are braided channels, which are multi-threaded and the widest of the study channels (>100 m; Table 1). All sites are mixed sand- and gravel-bed channels with median bed surface grain size between fine and medium gravel (Sutfin et al., 2014). Levees are not present at any of the sites.

Riparian vegetation is mainly shrubs and trees along the channel banks and on islands between channel threads in the braided reaches. Common woody plant species include *Olneya tesota* (desert iron wood), *Parkinsonia microphyllum* (foothills palo verde), *Acacia greggii* (catclaw acacia), *Encelia farinose* (brittlebush) *Ambrosia dumosa* (white bursage), and *Larraea tridentada* (creosote bush) (Sutfin et al., 2014; Shreve and Wiggins, 1964). Vegetation is also present in localized patches (<10 m^2) on the channel beds within braided reaches.

3. Methods

3.1. Instrumentation

To document how subsurface water in ephemeral channels responds to rain and surface flow events, we set up a network of precipitation, stream stage, and subsurface water content sensors in bedrock with alluvium, incised alluvium, and braided channel types in both Mohave and Yuma Wash (Fig. 2). Each monitoring location had a Texas Electronics TE525 tipping bucket rain gauge for recording precipitation and an In-Situ Inc. Rugged TROLL 100 pressure transducer for recording streamflow stage. The pressure transducers were un-vented and corrected for barometric pressure fluctuations using In-Situ BaroTROLL loggers installed in each watershed. To track subsurface responses to rain and channel flow, Delta-T Devices Ltd. SM300 soil moisture and temperature sensors were installed in hand-dug pits at depths of 10, 20, and 50 cm at all study sites. At incised alluvium and braided sites, deeper trenches were also dug with a backhoe, and sensors were installed at greater depths (Table 2). For all sites except Yuma bedrock with alluvium, which is bounded entirely by bedrock, additional SM300 or SM150 water content sensors were installed in the vegetated floodplain outside the main channel at depths of 10, 20, and/or 50 cm. At bedrock with alluvium and incised alluvium sites, these floodplain sensors were located 3–8 m from the main channel bed. At braided sites, floodplain sensors were in vegetated islands 50–70 m from the in-channel monitoring locations. Most sensors were manually inserted horizontally into an undisturbed face of the pit or trench, and the holes were backfilled with the excavated material. In a few deep locations, installing sensors in an undisturbed face was infeasible because of cementation between grains of alluvium. In these cases, we backfilled alluvial material around the sensors, attempting to maintain similar bulk density to the in situ materials. Most rain and water content sensors except those in the deep subsurface and flood plains (Table 2) were installed in early 2011 and remained in place until May 2014, giving approximately 3 years of record. Stage sensors were installed in late 2011 and early 2012. All sensors recorded data in 15 min time steps.

3.2. Data analysis

We divided rain gauge records into discrete rain events using a minimum inter-event time of 7 h. To ensure that each event