Southwestern Intermittent and Ephemeral Stream Connectivity

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SOUTHWESTERN INTERMITTENT AND EPHEMERAL STREAM CONNECTIVITY[1]

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ABSTRACT: Ephemeral and intermittent streams are abundant in the arid and semiarid landscapes of the Western and Southwestern United States (U.S.). Connectivity of ephemeral and intermittent streams to the relatively few perennial reaches through runoff is a major driver of the ecohydrology of the region. These streams supply water, sediment, nutrients, and biota to downstream reaches and rivers. In addition, they provide runoff to recharge alluvial and regional groundwater aquifers that support baseflow in perennial mainstem stream reaches over extended periods when little or no precipitation occurs. Episodic runoff, as well as groundwater inflow to surface water in streams support limited naturally occurring riparian communities. This paper provides an overview and comprehensive examination of factors affecting the hydrologic, chemical, and ecological connectivity of ephemeral and intermittent streams on perennial or intermittent rivers in the arid and semiarid Southwestern U.S. Connectivity as influenced and moderated through the physical landscape, climate, and human impacts to downstream waters or rivers is presented first at the broader Southwestern scale, and secondly drawing on a specific and more detailed example of the San Pedro Basin due to its history of extensive observations and research in the basin. A wide array of evidence clearly illustrates hydrologic, chemical, and ecological connectivity of ephemeral and intermittent streams throughout stream networks.

(KEY TERMS: surface water hydrology; arid lands; rivers/streams; ephemeral streams; connectivity; surface water/groundwater interactions; recharge.)

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INTRODUCTION

Ephemeral and intermittent streams are abundant in the Southwestern United States (U.S.) (Figure 1). Based on the National Hydrography Dataset (NHD), 94%, 89%, 88%, and 79% of the streams in Arizona, Nevada, New Mexico, and Utah, respectively, are intermittent or ephemeral (NHD 2008). Hydrological, biological, and chemical connectivity of ephemeral and intermittent streams to the relatively few perennial reaches through flows and floods is a major driver of the dynamic hydrology and ecology of the region (Levick et al. 2008). These streams supply water, sediment, nutrients, and biota to mainstem rivers. In addition, they are a primary source of recharge to alluvial aquifers and regional groundwater aquifers (Goodrich et al. 2004; Coes and Pool

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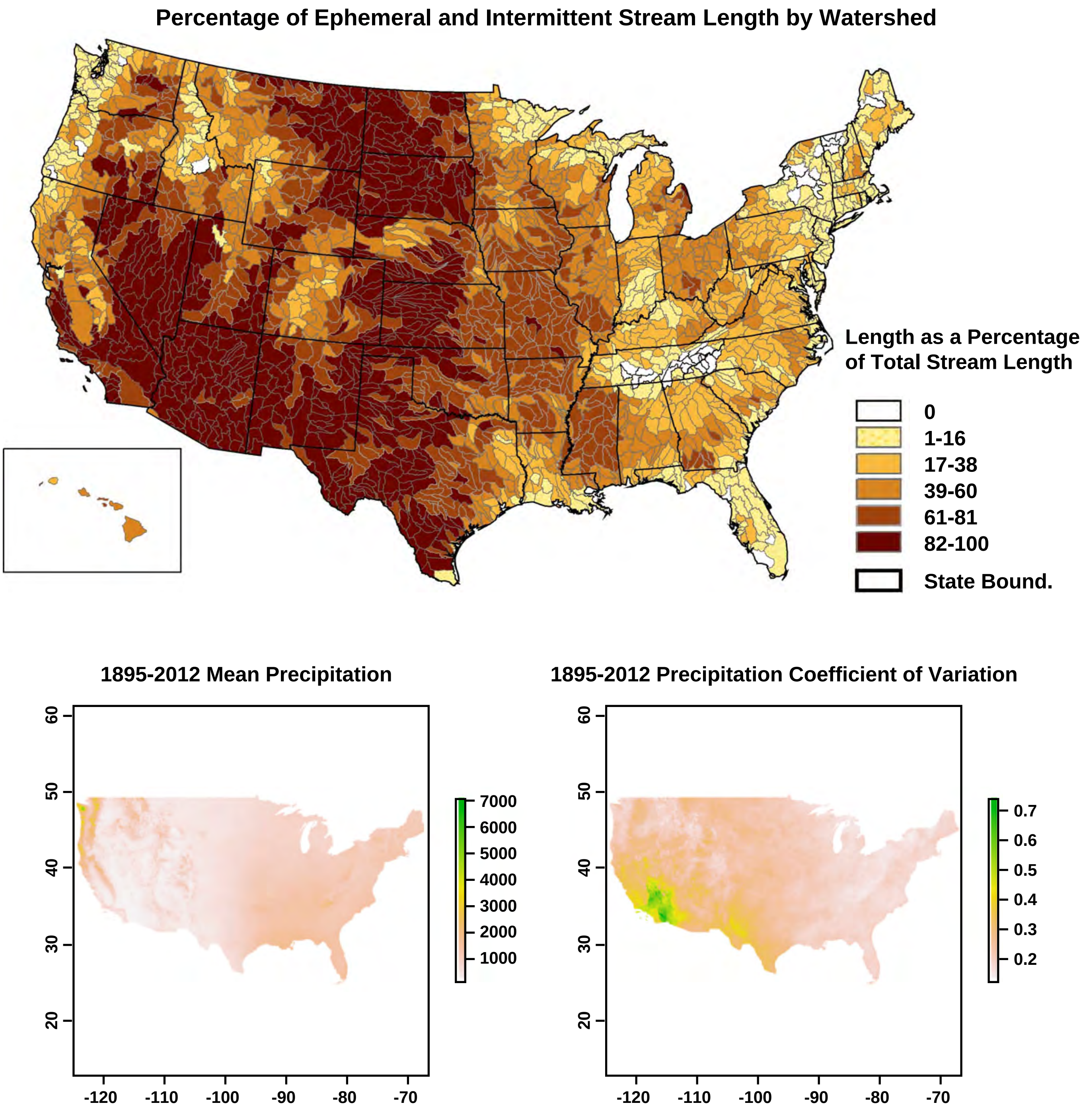


FIGURE 1. Upper: Percentage of ephemeral and intermittent streams relative to total stream length excluding Alaska based on data from the National Hydrography Dataset (NHD) at medium resolution. Lower: Maps of mean precipitation (left) and its coefficient of variation (right) of annual precipitation from 1895 to 2012. The value ranges in the key were devised to reveal underlying groupings and patterns in the data displayed on the upper map. One mile is equal to 1.61 km. Source data: NHD from Reach Address Database (RAD) v2.0 at 1:1,000,000 scale using eight-digit Hydrologic Unit Code (HUC) watersheds. Note that the NHD might not accurately reflect the total extent of ephemeral or intermittent streams, as it does not include stream segments less than 1.6 km (1 mile) long.

2005) that support baseflow in perennial reaches over extended periods (sometimes months) when little or no precipitation occurs. This baseflow and shallow groundwater support the limited naturally occurring, vibrant, and diverse riparian communities in the region. Equally important to these communities are the irregular flood flows, including the sediment and nutrients they transport from ephemeral tributaries (Brooks and Lemon 2007; Meixner et al. 2007).

For this paper we employ the following definitions (USEPA 2015):

> *Ephemeral*: A stream or portion of a stream which flows briefly in direct response to precipitation in the immediate vicinity, and whose channel is at all times above the groundwater reservoir.
>
> *Intermittent*: A river or stream where portions flow continuously only at certain times of the year, for example when it receives water from a spring, groundwater source or from a surface source, such as melting snow (i.e., seasonal). At low flow there may be dry segments alternating with flowing segments.
>
> *Perennial:* A river or portion of a stream that flows year round, is considered a permanent stream, and for which baseflow is maintained by groundwater discharge to the streambed due to the groundwater elevation adjacent to the stream typically being higher than the elevation of the streambed.
>
> *Headwater*: The low order, small stream at the top of a watershed, when viewed at the 1:100,000 map or image scale; may be perennial, intermittent, or ephemeral (Nadeau and Rains 2007).

Leibowitz et al. (2018) lay out a conceptual framework for evaluating the connectivity of streams to downstream waters. A basic premise of this framework is that "a river is the time-integrated result of all waters contributing to it, and connectivity is the property that spatially integrates the individual components of the watershed." If the landscape is treated as an integrated system, the connections between the upland and headwaters contributing to the river must also be part of the overall connectivity to the river network. Leibowitz et al. (2018) go on to build this framework by defining the components of a river system, its hydrology, the influence on, and connectivity of, streams and wetlands to downstream waters. They note that the "hydrological, chemical, and biological connectivity of river systems is determined by characteristics of the physical landscape, climate, and the biota, as well as human impacts."

This paper focuses on the connectivity or the degree that river systems are joined by various transport mechanisms of ephemeral and intermittent streams in the arid and semiarid Southwestern U.S. (USEPA 2015). We follow the framework of Leibowitz et al. (2018) in providing a comprehensive examination of the landscape (surface and subsurface), climate, biota, and human impacts on hydrologic, biological, and chemical connectivity of ephemeral and intermittent streams. We attempt to address the questions of: (1) What evidence is there of ephemeral and intermittent stream connectivity to downstream waters? and (2) What factors noted above impact and affect this connectivity? The first portion of the paper examines these aspects and effects on connectivity at a broader geographic scale across the Southwest. The second portion of the paper focuses geographically on the San Pedro River Basin (Sonora and Arizona), due to the wealth of long-term interdisciplinary research conducted within this basin. An overall synthesis then provides key conclusions on ephemeral and intermittent stream connectivity and factors that affect and impact it.

CONNECTIVITY OF SOUTHWESTERN EPHEMERAL AND INTERMITTENT STREAMS

Southwestern Climatic Characteristics

Precipitation in the Southwest is characterized by low annual amounts and high variable precipitation where potential evapotranspiration exceeds precipitation. This pattern has a profound effect on streamflow characteristics. In summer, precipitation is strongly influenced by atmospheric moisture flowing from the Gulf of Mexico and the Gulf of California (Mexican monsoon), where local heating triggers high-intensity air-mass thunderstorms, causing localized flash flooding. In fall, tropical depressions, often remnants of hurricanes, can bring infrequent but long-duration heavy rainfall events; such storms are responsible for many of the larger floods in the region (Webb and Betancourt 1992). Cyclonic storms from the Pacific Ocean, resulting in large frontal systems, dominate winter precipitation in the form of snow in higher elevations and typically as low-intensity rainfall in lower elevations (Blinn and Poff 2005). The relationship of mean annual precipitation and its variability to percent of ephemeral and intermittent stream length by watershed are illustrated in Figure 1.

Physical Connectivity via Surface Water and Subsurface Recharge

Understanding the unique characteristics of Southwestern American rivers is necessary to evaluate the connectivity and influence of ephemeral and intermittent streams on these rivers (Levick et al. 2008). Southwestern rivers differ in many ways from rivers in the humid eastern U.S. or in the Midwest and West. Besides being defined as ephemeral, intermittent, or perennial, the flow permanence of Southwestern rivers can be described in terms of temporal flow continuity (i.e., continuous flow at a specific location through time), and flow connectivity (i.e., continuous flow across space and time — Jaeger and Olden 2012). Fritz et al. (2018) note that the very existence of a continuous bed and bank stream channel structure, as commonly observed in the Southwest, "makes these fluvial units physically contiguous…." This results in connectivity from headwaters to downstream waters over sufficient periods of time to integrate the effects of numerous, but intermittent flood flows, that may propagate different distances downstream. It is also important to understand the spatiotemporal patterns of flow permanence and the influence of meteorological, geologic, and land cover controls on Southwestern river systems (Costigan et al. 2016).

Besides being defined in terms of flow permanence, Southwestern rivers can be divided into two main types based on location on the landscape, particularly in the Basin and Range, Sonoran Desert, and Mexican Highland geologic province. The first type comprises rivers in the mountainous upper basins that receive more precipitation, often as snow, and the second type comprises those rivers located in the arid or semiarid plateau regions and valley plains dominated by ephemeral streams (Blinn and Poff 2005).

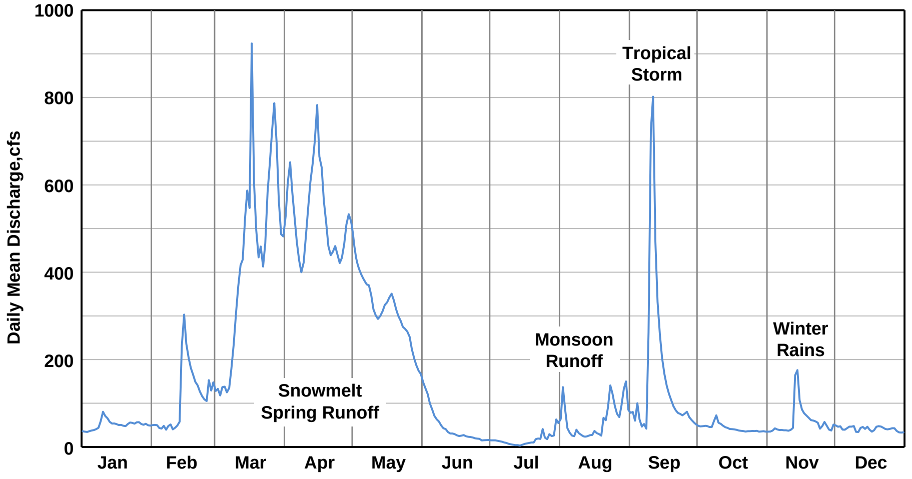
The Pecos River basin in eastern New Mexico and Western Texas includes part of the southern Rocky Mountains in the north, and grasslands, irrigated farmlands, deserts, and deep canyons in the southern lower reaches of the river. Precipitation occurs as snow in the mountains and summer monsoonal rainfall in the lower river valley. Based on hydrogen and oxygen isotope composition of river water, Yuan and Miyamoto (2008) separated the river basin into three subbasins: (1) the upper basin, (2) the middle basin, and (3) the lower basin. Snowmelt dominates the mountainous upper basin. The river in the topographically gentle middle basin had mixed sources of water. Up to ~85% of streamflow in the lower basin was derived from local freshwater sources, mainly monsoonal rainfall. This finding is consistent with significant contributions of flow from ephemeral tributary streams.

Figure 2 contrasts the 2003 calendar year hydrograph from the White River near the Fort Apache U.S. Geological Survey (USGS) gaging station (Figure 2a) in east-central Arizona, and the San Pedro River USGS gage near Tombstone, in southeastern Arizona (Figure 2b). Although the two gaging stations are only separated by roughly 220 km and differ in elevation by less than 200 m, the watershed contributing to the White River is substantially larger and is higher in elevation than the San Pedro watershed, resulting in long-duration spring runoff from snowmelt. Monsoon-generated, short-duration runoff dominates the San Pedro watershed but monsoonal influence also is apparent in the White River hydrograph. Runoff generated from late monsoon precipitation in September caused a major increase in discharge in the White River and a minor increase in the San Pedro River.

Abrupt changes in streamflow connectivity (i.e., a change from perennial to intermittent or ephemeral and back again) can result from underlying geology. Streams with abrupt changes can be referred to as interrupted streams (Meinzer 1923; Hall and Steidl 2007), although they are more typically referred to as intermittent. A constriction and rise in bedrock geology can force regional groundwater to the surface resulting in perennial flow while streamflow encountering highly fractured bedrock or a highly porous karst system can virtually disappear over very short distances. Another relatively abrupt transition affecting connectivity in arid and semiarid stream hydrology and morphology occurs where steep mountain slopes transition into lower valley slopes. At this transition, watersheds with high sediment transport out of the mountainous portion often form alluvial fans. The stream channel system above the transition is typically dendritic, and below the transition the channel system often becomes a diffusive set of shallow braided channels. Runoff across alluvial fans typically becomes less concentrated or confined to a single channel but more diffuse turning into broad sections of sheet flow (Parker et al. 1998). The diffuse runoff is more likely to infiltrate into the alluvial fan resulting in lost spatial connectivity. Very large flows may be required for runoff to cross the alluvial fan and connect to downstream waters.

Dominant hydrologic flowpaths vary with location within Southwestern river basins. After climate and weather, recharge and infiltration mechanisms are the next most important factors determining the occurrence and connectivity of ephemeral, intermittent, and perennial stream reaches. Recharge mechanisms in arid watersheds are comparable to those in more mesic and hydric watersheds but vary significantly in magnitude. Recharge over longer time scales (months to centuries) is essential to replenishing regional groundwater and near-stream alluvial aquifers, which in turn are essential to maintaining baseflow in perennial streams. Primary recharge mechanisms include mountain block recharge, mountain front recharge, diffuse hillslope or interchannel recharge, and ephemeral channel recharge.

Mountain locations with deeper soils or those consisting of fractured rock will have higher infiltration capacities, less frequent occurrences of overland flow, and serve as recharge areas for regional groundwater (Wilson and Guan 2004; Blasch and Bryson 2007; Wahi et al. 2008). Mountain locations with shallow soils and more consolidated rock will shed stormflow and shallow groundwater off the mountain block onto


(a) WHITE RIVER NEAR FORT APACHE

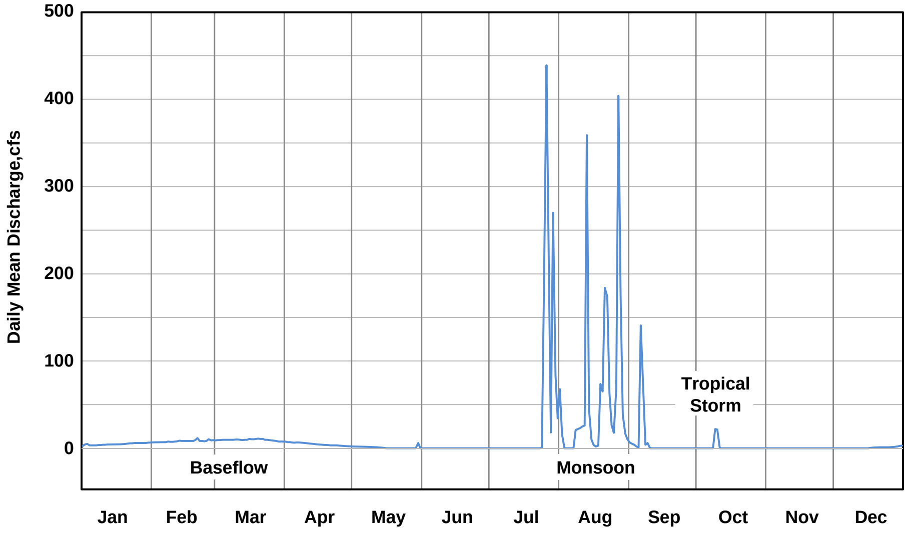

(b) SAN PEDRO RIVER NEAR TOMBSTONE

FIGURE 2. 2003 calendar year hydrographs from (a) the White River near Fort Apache, Arizona, and (b) the San Pedro River near Tombstone, Arizona illustrating the distinct differences in watershed response from a high-elevation basin with substantial snowmelt (a) as compared to a monsoon-dominated basin (b).

the valley, which often consists of deep alluvium. This transition area is where mountain front recharge typically occurs. High-elevation perennial streams often become intermittent or ephemeral at this transition, with their downstream disappearance of surface flow dependent on the flow rates coming off the mountain block and the permeability of the valley alluvium. During periods of high flow, they can reconnect with other perennial downstream reaches maintained by groundwater flow (Blinn and Poff 2005; Blasch and Bryson 2007; Yuan and Miyamoto 2008).

In the lower basin valley as water flows through dry ephemeral channels, it infiltrates into the channel bottom and sides (i.e., channel transmission losses occur) where channel substrate is porous. If restricting soil or geologic layers underlying the channel do not substantially inhibit downward motion, channel transmission losses will recharge either the regional or alluvial groundwater (Tang et al. 2001; Constantz et al. 2002; Harrington et al. 2002; Goodrich et al. 2004; Coes and Pool 2005; Blasch and Bryson 2007). In this influent stream environment typical of many Southwestern streams, the volume of transmission water losses in ephemeral channels increases as watershed size increases, resulting in a losing stream environment as opposed to a gaining stream environment encountered in wetter hydroclimatic regimes (Goodrich et al. 1997). Typically, as drainage area increases, the alluvium under and next to the stream begins to serve as important shallow aquifers that receive and store streamflow infiltration during hydrologic events, and sustains baseflow and riparian communities between storms (Stromberg et al. 2005; Baillie et al. 2007; Dickinson et al. 2010).

Scanlon et al. (2006) conducted a global synthesis of over 100 recharge studies in semiarid and arid regions. In their review, the chloride mass balance technique was widely used to estimate recharge. They found that "average recharge rates estimated over large areas (40–374,000 km^2) range from 0.2 to 35 mm year^{-1}, representing 0.1% to 5% of long-term average annual precipitation. Extreme local variability in recharge, with rates up to ~720 m year^{-1}, results from focused recharge beneath ephemeral streams and lakes and preferential flow mostly in fractured systems." There is substantial evidence that groundwater recharge in hot arid and semiarid areas will occur only where water is concentrated and focused, such as in channels, depressions, or areas of high infiltration such as karst areas (Brahana and Hollyday 1988; Hughes and Sami 1992; Sharma and Murthy 1995; Scanlon et al. 1997; Scott et al. 2000; Constantz et al. 2002; Coes and Pool 2005). This contrasts to infiltrated precipitation in upland hillslopes and interchannel areas where infiltration and runoff rarely reaches the groundwater table as recharge due to high potential evapotranspiration, the adaptation of xeric plants to use available soil moisture efficiently, and upward temperature gradients that transport water vapor upward in thick vadose zones.

Chemical and isotopic tracers have confirmed that ephemeral streams are cumulatively important areas for floodwaters to recharge groundwater aquifers in desert regions (Tang et al. 2001). In a synthesis of research into groundwater recharge in the Southwestern and Western U.S., Phillips et al. (2004) conclude that: (1) desert vegetation effectively eliminates diffuse recharge in the interchannel areas of the basin floor, (2) ephemeral channel recharge can be very important in wet years and greatly dominates recharge in basin-floor environments, and (3) environmental tracers are now available to "fingerprint the sources and amounts of groundwater recharge at the basin scale." Although ephemeral and intermittent channel transmission losses represent disruptions of surface connectivity between streams and downstream waters, such losses indicate vertical hydrologic connections that reduce downstream flooding and recharge the groundwater aquifers that eventually contribute to flow in downstream waters (Izbicki 2007).

Biological Importance and Connectivity

Ephemeral and intermittent streams perform many of the same functions in a watershed as do perennial streams. In arid and semiarid regions, riparian areas, including those near ephemeral and intermittent streams, support the vast majority of wildlife species, are the predominant sites of woody vegetation including trees, and surround what are often the only available surface water sources, even if they are available only for limited periods. These riparian areas occupy a small percentage of the overall landscape but they host a disproportionately greater percentage of the biodiversity than the areas surrounding them (Goodrich et al. 2000; Stromberg et al. 2005). Ephemeral and intermittent stream channels are easily recognizable by their dense corridors of vegetation that strongly contrast with the more sparsely vegetated uplands (Figure 3). In contrast to the nearby uplands, these connected stream corridors and their associated vegetation communities provide structural elements of food, cover, nesting and breeding habitat, predator protection, and movement/migration corridors for organisms. These corridor vegetation communities moderate soil and air temperatures, stabilize channel banks, provide seed banking, trap silt and fine sediment that favor the establishment of diverse floral and faunal species, and dissipate stream energy (Levick et al. 2008). The resulting microclimates in and around ephemeral and intermittent stream vegetation corridors are used extensively by fauna.

The expansion and contraction of flowing waters within Southwestern streams results in reaches that have flow or residual pools of water surrounded by reaches without water, and is common in dryland rivers across the globe (Stanley et al. 1997; Arthington et al. 2005; Bunn et al. 2006). The isolated pools in intermittent streams often serve as refuges for fish (Labbe and Fausch 2000) and aquatic invertebrates (Cañedo-Argüelles et al. 2015) to survive during dry periods.

Both passive and active biological connections exist in intermittent and ephemeral stream networks. Passive connections involve the transport of organisms and organic matter driven by water flow; these connections thus depend on hydrologic connectivity. Pulse or episodic flows in intermittent and ephemeral streams influence plant diversity and patterns both spatially and temporally, create seed beds (Stromberg and Tellman 2009) and contribute to overall riparian diversity in the long term (Katz et al. 2011). Active connections do not depend on flowing water; instead, dispersal of organisms and organic matter occurs throughout the stream network through walking, flying, or hitchhiking on mobile organisms. These organism-mediated connections form the basis of bidirectional biological connectivity between headwater streams and downstream waters. Movement can be both longitudinal along the stream network and lateral (Schlosser 1991; Fausch et al. 2002).

Meyer et al. (2007) noted the importance of headwater streams, including ephemeral and intermittent

FIGURE 3. Aerial photograph showing the dense corridors of vegetation lining ephemeral stream channels in southeastern Arizona. Image accessed from Google Earth from May 2005 imagery.

streams, as vital parts of the biological integrity of U.S. waterways. Summer monsoons in the Southwest coincide with periods when herpetofauna such as snakes and amphibians are most active; the episodic flows provide a generally continuous aquatic corridor during flow for their dispersal. The translocation and dispersal of species enables genetic interchange between subpopulations that are often isolated for most of the year and recolonization of sites when subpopulations are lost due to drought or disturbance.

Several studies found that native fishes and invertebrates are well adapted to the variable flow regimes common in rivers of the Southwest (John 1964; Meffe 1984) and are heavily influenced by ephemeral tributary streams (Turner and List 2007). Minckley and Meffre (1987) and Poff et al. (1997) went on to note that the dynamic flow regime in the arid Southwest is a competitive factor for native species over exotics adapted to lake and pond conditions. Rinne and Miller (2006) compared fish assemblage data in the Gila River (New Mexico and Arizona) and the Verde River (Arizona) over seven to 12 years. They found that variable streamflow and higher flow volumes favor native fish species over nonnatives.

The floral species in xeroriparian areas that lack a shallow groundwater system are moderated by the frequency and magnitude of runoff events. Nonetheless, they give rise to a vegetative community distinct from the surrounding uplands. Common tree species in these areas include subtropical legumes such as mesquite (*Prosopis* spp.), catclaw acacia (*Acacia greggii*), ironwood (*Olneya tesota*), and blue palo verde (*Cercidium floridum*). Mesquite has been identified as the key provider of food for numerous migrating birds (Van Riper and Cole 2004). Netleaf hackberry (*Celtis reticulata*) and Arizona sycamore (*Platanus wrightii*) have been identified as providing exceptional cover for nesting birds on intermittent streams (Powell and Steidl 2002).

Large ephemeral stream channels with shallow groundwater zones support a wider variety of floral including phreatophytic trees, such as Fremont cottonwood (*Populus fremontii*), Arizona sycamore (*P. wrightii*), and Arizona ash (*Fraxinus velutina*). These channels also contain distinctive shrubs, such as willow (*Salix* spp.), seepwillow (*Baccharis* spp.), burrobrush (*Ambrosia monogyra*), saltcedar (*Tamarix ramosissima*), and dense stands of sacaton grass (*Sporobolus* spp.).

Sediment, Chemical, and Nutrient Connectivity

Ephemeral desert streams can exhibit high sediment export efficiency by having higher bed load per unit stream power than that of forested perennial streams (Laronne and Reid 1993). Despite infrequent flows of short duration, flood waves (bores) in ephemeral desert streams can carry substantial amounts of sediment downstream (Hassan 1990). The transport distance associated with these floods, however, often is insufficient to link them directly to perennial rivers. Only the largest events can flush sediment completely through ephemeral tributaries (Lane et al. 1997). Lekach et al. (1992) found that more than 90% of the bed-load yield originated from the mid-watershed channels during larger runoff events from an arid watershed in Israel.

Fine bed and bank sediments slow infiltration; in many semiarid and arid streams, bed sediments become finer in the downstream direction because flow competence and stream power declines due to channel transmission losses (Dunkerley 1992; Shaw and Cooper 2008) and decreasing stream reach slopes (Flint 1974). Because fine sediments can become concentrated in channels following moderate flows, higher flows that scour out fine sediments or submerge more permeable floodplains have higher infiltration rates (Lange 2005).

Studies of radionuclide (e.g., plutonium, thorium, uranium) released from military and energy applications since the beginning of the nuclear age in ephemeral and intermittent stream networks provide convincing evidence for long-distance sediment and chemical connections in these systems (Fritz et al. 2018). Like many metals, radionuclides adsorb readily to fine sediment; thus, the fate and transport of radionuclides in sediment generally mirrors that of fine sediment. Radioactive releases from the Los Alamos test site and aboveground nuclear weapons testing in New Mexico and Nevada, ephemeral and intermittent portions of the Upper Rio Grande Basin provide a natural laboratory for tracing the fate and transport of radionuclides from ephemeral headwaters (Graf 1994; Reneau et al. 2004). More specifically, Graf (1994) found that the mean annual bed-load contribution of plutonium from the Los Alamos Canyon subwatershed of the Rio Grande (0.4% of the Rio Grande drainage area at its confluence) was almost seven times that of the main stem and was attributed to sporadic intense storms mobilizing substantial sediment that were out of phase with flooding on the Upper Rio Grande.

Ephemeral and intermittent streams can contribute water and nutrients to perennial streams even in the absence of direct aboveground flow. Surface runoff into these streams brings nutrients that may be stored and transferred to groundwater reserves (Fisher and Grimm 1985; Belnap et al. 2005), or in hyporheic zones, where there is substantial biogeochemical cycling of nutrients and trace elements, which are essential to aquatic life (Valett et al. 1994; Boulton et al. 1998; Hibbs 2008). Dry riverbeds tightly retain organic matter and nutrients (Wagener et al. 1998) until flow pulses initiate biogeochemical processes by stimulating microbial activity, cycling nutrients and organic matter, and transport these resources to downstream areas where they are available to the adjacent riparian zone (Larned et al. 2010) and are an important source of nutrients to plants and wildlife (Fisher and Grimm 1985).

Human Alterations Impact

Anthropogenic uses and activities on arid and semiarid landscapes can have significant effects — both good and bad — on downstream waters and on the overall health of watersheds. Human alteration to arid and semiarid watersheds includes livestock grazing, land clearing, mining, timber harvesting, groundwater withdrawal, streamflow diversion for water supply and irrigation, channelization, urbanization, agriculture, roads and road construction, off-road vehicle use, camping, hiking, and vegetation conversion (Levick et al. 2008). Historically, riparian habitats represented about 1% of the landscape in the West, and within the past 100 years, an estimated 95% of this habitat has been lost due to a wide variety of land-use practices such as river channelization, unmanaged livestock grazing, agricultural clearing, water impoundments, and urbanization (Krueper 1995). Reservoir construction, irrigation withdrawals, and the cumulative impacts of groundwater pumping have converted many historical, perennially flowing reaches into intermittently flowing reaches (Blinn and Poff 2005).

Climate change likely will have increasing influence on streams and their connectivity in the Southwest. Most climate models predict increased warming and drying, intensification of droughts, and increased variability of precipitation for the region (Seager et al. 2007). Jaeger et al. (2014) simulated streamflow response to projected climate change in the Verde River Basin, Arizona, to evaluate changes in flow continuity over time and flow connectivity over space. Their simulations projected an increase in days with no flow and a decrease in flowing portions of the river resulting in decreased hydrologic connectivity. Projected reductions in snowpack will also result in shorter periods of longitudinal stream connectivity in intermittent streams, as snowmelt will occur more rapidly and earlier in the year in a warmer climate.

Riparian areas near mainly perennial streams, but also in many intermittent streams, historically have been attractive for human development, leading to their alteration on a scale similar to that of wetlands degradation nationally (National Research Council, 2002). This situation is especially true in arid and semiarid regions because riparian areas typically are indicative of water availability either as surface water or as shallow groundwater. Arid and semiarid riparian areas in regions are greener and cooler than most upland areas, resulting in increased property values for homes located in and near riparian corridors (Colby and Wishart 2002). However, riparian areas are more sensitive to development impacts than in wetter regions because of their limited geographical extent, drier hydrologic characteristics, and fragile nature (e.g., erodible soils). The following subsections present some of the types of human-caused impacts on ephemeral and intermittent streams and their associated riparian areas.

Land Development. Land development includes urban, suburban, and exurban development but is referred to here collectively as urban development. Before the 2008 recession, the Southwest was one of the fastest growing regions of the U.S., having an increase in population of ~1,500% during the period from 1900 to 1990. In contrast, the population of the country as a whole grew by just 225% during that period (Chourre and Wright 1997). Typical urban development significantly changes the hydrologic characteristics of a watershed by covering uplands with impervious surfaces, and infilling and/or channelization, or armoring of headwater streams (Figure 4). Alteration of the natural stream network disrupts natural flow patterns and sediment transport and storage, resulting in downstream flooding and changes to the clarity and quality of the downstream flows and receiving waters. These effects can damage downstream water supplies and habitat.

The impact of urbanization increases as the percentage of impermeable surface increases. Various studies have shown that semiarid stream systems become irreparably impaired once the impervious surfaces within the watershed exceed about 10% and experience dramatic morphological changes once those surfaces exceed about 20% (Schueler 1994; Miltner et al. 2004). As the amount of impervious surface increases, runoff increases and infiltration decreases (Kennedy et al. 2013), starting a chain of events that includes flooding, erosion, stream channel alteration, increases in human-caused pollutants, and ecological damage. Floods become more severe and more frequent, and peak flows and runoff volumes will be many times greater than in natural basins. The greater volume and intensity of flooding causes increased erosion and sediment transport downstream.

To accommodate the increased flow and sediment load, streams in urbanized areas tend to become deeper and straighter over time. The resulting bank erosion can destroy established streamside habitat and tree cover, leading to higher temperatures, sedimentation, and disruption of wildlife corridors. Storm sewers and lined drainages increase the rate of water delivery to the downstream channel network. Improperly constructed and maintained roads, especially unpaved roads, can alter hillslope drainage, and change baseflow and precipitation–runoff relationships, causing erosion and sedimentation in streams (USDA 2002). The primary geomorphic consequence of these hydrologic changes is the erosional entrenchment of nearby channels and associated transportation of the excavated sediment downstream, causing a significant increase in sediment load. Sediment is of particular concern in arid and semiarid regions because many other pollutants tend to adhere to eroded soil particles. Additional pollutants from urban runoff can include pathogens, nutrients, toxic contaminants, sediment, and debris. Consequently, urban areas require stormwater management plans both during and after construction to control runoff and offsite pollution.

Streams are channelized in urbanizing areas to protect private property and control streambank erosion. Channelization typically straightens and steepens the stream resulting in increased flow velocity and sediment movement. While increasing connectivity, these changes transfer flooding and bank erosion downstream of hardened areas. Channelized reaches greatly reduce out-of-bank flow disrupting water, sediment, organic matter, and nutrient enrichment of the floodplain (National Research Council 2002).

Habitat fragmentation is a common consequence of urbanization (Figure 4) (Hilty et al. 2006). New developments can alter large areas of land, removing natural drainage systems and wildlife habitat, and replacing them with houses and roads. Altering, bisecting, or channelizing streams effectively can eliminate the main biological functions of the stream channel by disrupting vegetation communities and hydrologic function. Habitat and stream fragmentation reduces wildlife diversity and abundance and might cause sensitive species to disappear (England and Laudenslayer 1995).

Land Use. In addition to urbanization, agriculture (livestock and crops) and mining, including sand and gravel operations, are major land uses in the desert Southwest. Livestock grazing is one of the more common uses of rural land in the Southwest. Late 1800s estimates of cattle numbers in Arizona

FIGURE 4. Aerial photograph showing the small community of Vail, southeast of Tucson, Arizona, built among ephemeral tributaries to Cienega Creek, a perennial stream. Photograph: L. Levick/Aerial flight courtesy of Lighthawk.

and New Mexico exceeded 1.5 and 2 million, respectively. During this period, the region experienced both significant droughts and floods. During drought, the resulting desiccation of the uplands drove cattle to the riparian areas, which were heavily damaged as a result. When the rains returned to the denuded landscape, erosive processes were greatly enhanced contributing to a relatively widespread period of channel downcutting, forming deep arroyos and lowering groundwater levels (Schumm and Hadley 1957; Hastings 1959; Graf and Lecce 1988).

In modern grazing-land management, livestock are provided with watering sources away from streams when possible, but frequently they must depend on the streams for water. Livestock management efforts attempt to avoid overuse of an area, but because water is scarce in arid environments, cattle and wildlife tend to linger near water sources. Where not properly managed, cattle can remain too long in a riparian area and trample streambanks, eat the riparian vegetation to the ground, contaminate the water with wastes, and compact the soil (Levick et al. 2008). Several literature sources have stressed that the cumulative impacts of unmanaged livestock in Southwestern riparian ecosystems for the past several hundred years probably have been the single most important factor in riparian ecosystem degradation (Wagner 1978; Ohmart 1995).

Mining is another activity that historically has played a large role in the economy and land use in the Southwest. Some of the largest copper and gold mines in the world are found in this region, and some cover many thousands of hectares. Mining not only dewaters the area but it also removes vegetation and soil and changes the topography, severely affecting the watershed and altering the hydrology. Instream and floodplain gravel mining can alter channel dimensions, increase sediment yield, and increase fine sediment loading and deposition that can reduce infiltration into ephemeral channels (Bull and Scott 1974).

Cultivated agriculture has had a long history in the Southwestern deserts, and areas such as the Central Valley in California provide much of the country's food supply. Most crops, however, must be irrigated due to low annual rainfall. Impacts to local hydrology from agricultural activities include: (1) increased salinity caused by clearing of native vegetation that raises the groundwater reservoir; (2) reduced flows from groundwater pumping or stream diversions for irrigation; (3) increased nutrients and turbidity from the use of fertilizers that run off into the streams across the land surface or through the soil, causing excessive algal growth; and (4) fish, aquatic invertebrate, and bird kills from pesticides and trace metals (e.g., selenium), that run off into the streams or leach into the groundwater (Levick et al. 2008).

Due to the abundant solar resources in the arid and semiarid Southwest, numerous, large-scale solar energy projects are envisioned or already under development. O'Connor et al. (2014) note that development of solar energy zones will significantly affect ephemeral channel systems. They developed a scoring system to conduct ephemeral stream assessments using publicly available geospatial data and high-resolution aerial imagery.

Water Resources Impacts. Rapid growth in the Southwest can be sustained only with reliable water supplies. Lack of surface water flows has placed increased reliance on groundwater for human, industrial, and agricultural uses. The percentage of water use from groundwater is 40% in Arizona (Arizona Water Facts. Accessed January 2018 http://www.arizonawaterfacts.com/water-your-facts), 78% in New Mexico (New Mexico Environmental Department. Accessed January 2018, https://www.env.nm.gov/water/), and 30%–60% depending on drought conditions in California (Water Education Foundation. Accessed January 2018, http://www.watereducation.org/all-california-water-sources). When groundwater pumping is sufficiently large or prolonged, it can lower water-table levels in regional and alluvial aquifers. If these aquifers are a primary source of water for sustaining surface water flow in perennial or intermittent streams and if the drop in aquifer water levels is large enough, the pumping can effectively dewater these stream reaches, severing longitudinal and vertical connectivity (Winter and Rosenberry 1998; Scanlon et al. 2012). Perennial and intermittent streams effectively become ephemeral streams, and the habitat supported by reliable surface flow or shallow groundwater is lost (Stromberg et al. 1996).

Until the Central Arizona Project brought Colorado River water to Tucson in the early 1990s, Tucson's domestic water supply was solely provided by groundwater. As groundwater pumping increased to supply the growing population, the aquifer water level dropped by more than 25 m and the high-quality riparian habitat was completely altered, as all phreatophytic vegetation died out. Water-level declines and the resulting impact to the riparian system are illustrated via repeat photography of the Santa Cruz River south of Tucson from 1942 and 1989 (Figure 5). Tucson's population in 1940 was roughly 36,000 and increased to ~405,000 by 1990. The growing population of Tucson also resulted in proportional increases in discharge of treated effluent. Streamflow augmentation can occur in human-dominated watersheds in the form of treated municipal and industrial wastewater effluent discharges. Streams that would dry without these discharges are effluent-dependent streams, whereas those that receive most, but not all, of their flow from effluent are effluent-dominated streams (Brooks et al. 2006). Portions of the Santa Cruz River downstream of the treatment plant outfalls are now effluent-dependent perennial stream reaches. Depending on the level of treatment, effluent can have various effects on the stream ecosystem (Brooks et al. 2006). Without careful water management and reuse (Bischel et al. 2013), the benefits of baseflow augmentation can be overshadowed by potential risks, such as increased contaminant and pathogen exposures (Treese et al. 2009; Jackson and Pringle 2010; Bateman et al. 2015). Streams draining human-dominated areas also can acquire baseflow from groundwater recharged by over-irrigation and leaky infrastructure (Lerner 1986; Roach et al. 2008; Townsend-Small et al. 2013).

Dams and retention or detention basins frequently are used to store water or as flood-control devices in the Southwest. However, they disrupt natural surface flow and sediment transport, interfere with natural geomorphic processes, alter water temperatures, and fragment the connectivity of natural stream systems both upstream and downstream of the structure (Williams and Wolman 1984). Upstream locations might experience flooding, whereas downstream locations may be dewatered and become starved of sediment.

CONNECTIVITY IN THE SAN PEDRO RIVER BASIN

Basin Characteristics

Because of a rich research and long-term monitoring history, the San Pedro Basin in southeastern Arizona represents an excellent example of the

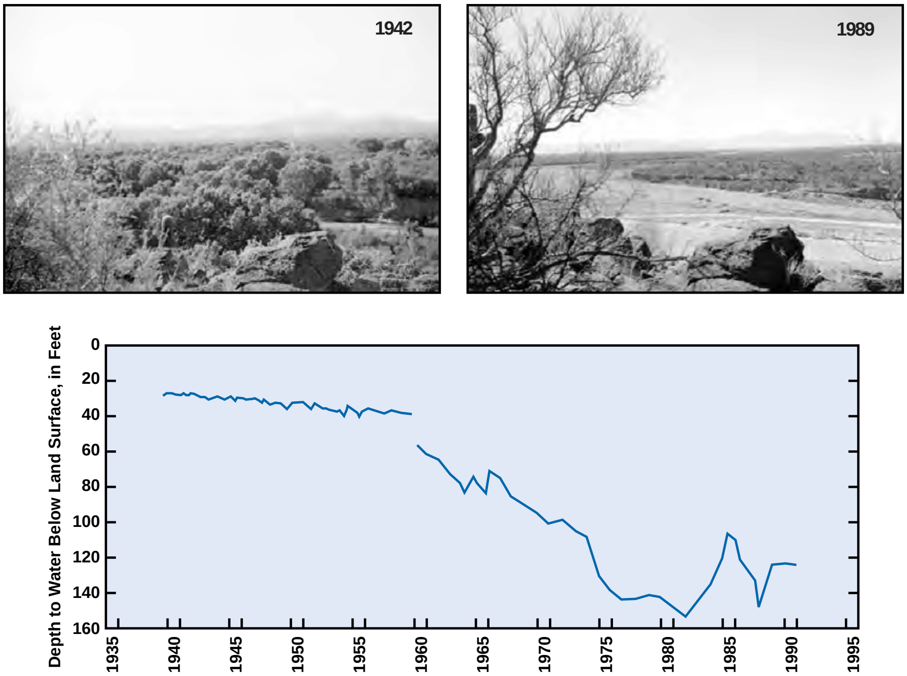


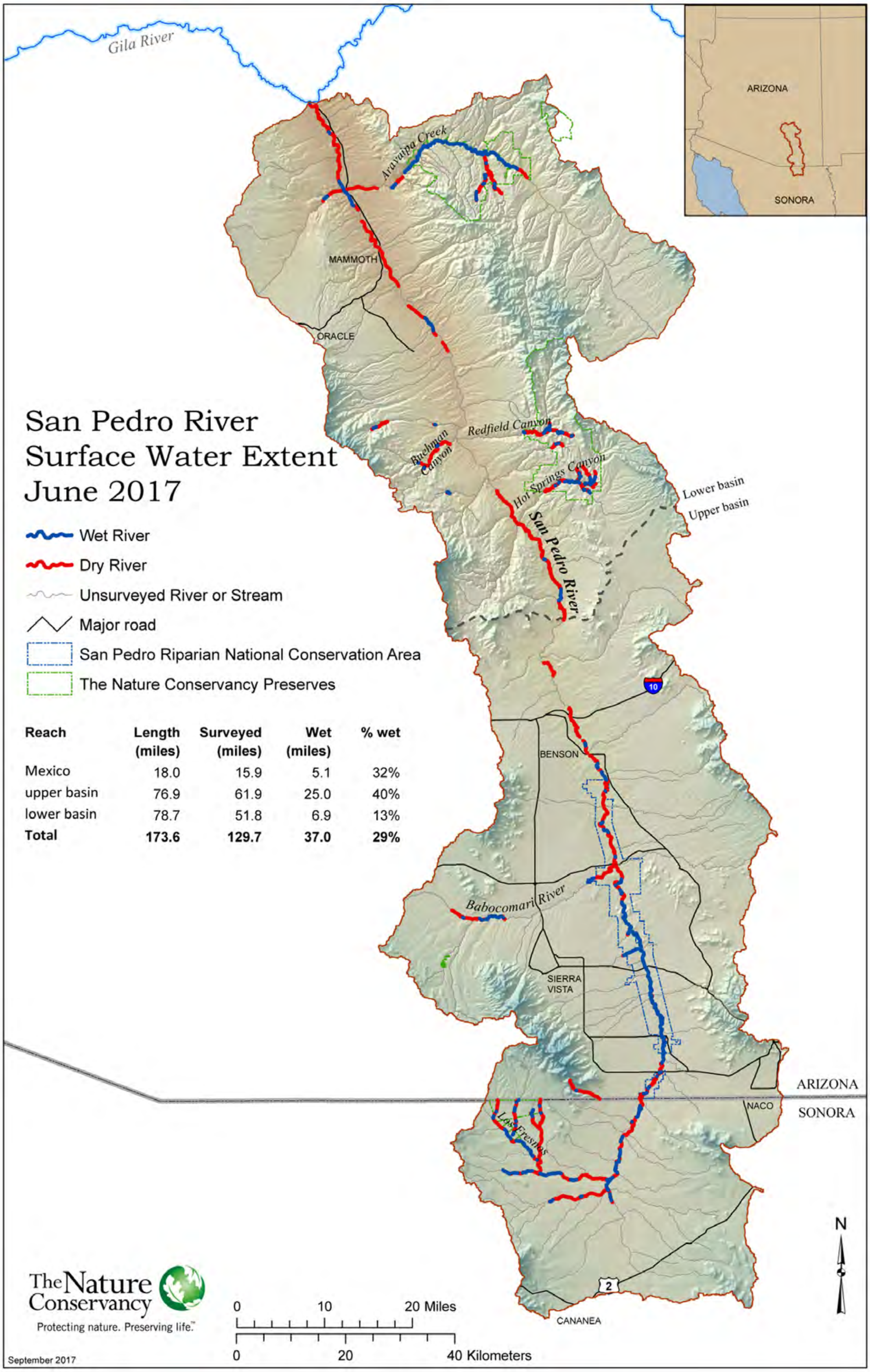
FIGURE 5. Change in riparian vegetation along the Santa Cruz River, Tucson, Arizona, as the result of water-level declines in the regional aquifer. Photographs of the Santa Cruz River looking south from Tucson, Arizona, provided by Robert H. Webb, U.S. Geological Survey, Anderson and Woosley (2005).

hydrologic behavior and connectivity of Southwestern rivers (Goodrich et al. 2000; Stromberg and Tellman 2009). It is important to note that the San Pedro River main stem is not typical of the majority of Southwestern rivers because of its relatively long intermittent and perennial reaches. The San Pedro River originates in Sonora, Mexico, flowing undammed north to its confluence with the Gila River near Winkelman, Arizona for a total of 279 km (173.6 miles). The San Pedro River is the only significant un-impounded river in Arizona and the last remaining stream in southern Arizona with long perennial reaches (Figure 6) (Kennedy and Gungle 2010). Most tributaries to the river are ephemeral at their confluence with the main stem. The river basin, located in the Basin and Range Province, whose elevation ranges from 2,000 to 2,900 m, has a valley that is generally 30–50 km wide, comprised of sedimentary fill deposits.

The San Pedro River Basin including Mexico consists of 94% nonperennial reaches (ephemeral and intermittent), 5.3% artificial paths (canals, diversions, pipeline, connectors), and 0.7% perennial reaches as derived from the USGS High Resolution NHD (USGS 2006). The percentage of stream types is not static but varies from year to year. The Nature Conservancy and its partners have annually mapped the wet and dry reaches along the San Pedro main stem and several large tributary streams since 1999 (Turner and Richter 2011). The wet–dry mapping is conducted on the third Saturday in June, historically the time of lowest streamflow, prior to the onset of the monsoon. From 1999 to 2006, the wet–dry mapping was confined to 50 miles of stream reach (80.5 km) within the San Pedro National Riparian Conservation Area (SPRNCA). From 2007 to 2017, the wet–dry mapping was expanded into the entire basin with an average of 130.3 miles (210 km). The dynamic nature and interannual variability of the wet vs. dry reaches is illustrated in Table 1. The percentage of wet reaches within the SPRNCA (Table 1 — top) ranged from 36% to 76% and for the basin it ranged from 25% to 45%.

Annual precipitation within the basin ranges from 300 to 750 mm with highest amounts occurring in the mountains. Vegetation includes desert scrub, grasslands, oak woodland savannah, mesquite woodland, riparian forest, coniferous forest, and agriculture (Kepner et al. 2000; Kepner et al. 2004). Shrub or scrub and grasses typical of Southwestern semiarid landscapes (Goodrich et al. 1997) dominate the valley floor vegetation.

The hydrogeology of the San Pedro River Basin is typical of many alluvial basins in the Southwest (Dickinson et al. 2010). Groundwater flows through the basin-fill aquifer (regional aquifer) from recharge areas near the mountains and beneath ephemeral tributaries to perennial reaches of the San Pedro River (Wahi et al. 2008; Dickinson et al. 2010). A narrow band of highly permeable stream alluvium is incised



Reach	Length (miles)	Surveyed (miles)	Wet (miles)	% wet
Mexico	18.0	15.9	5.1	32%
upper basin	76.9	61.9	25.0	40%
lower basin	78.7	51.8	6.9	13%
Total	**173.6**	**129.7**	**37.0**	**29%**

FIGURE 6. San Pedro River Basin map showing major physiographic features and wet and dry reaches at the time of approximate annual low-flows (June 2017) (Source: http://azconservation.org/downloads/san_pedro_wet_dry_mapping, accessed January 2018).

TABLE 1. Wet–dry mapping results in the San Pedro National Riparian Conservation Area (SPRNCA) only (top); wet–dry mapping for the whole San Pedro Basin (bottom). Most surveys conducted the third weekend in June of each year.

	Surveyed		**Wet**		
Year	**Miles**	**Kilometers**	**Miles**	**Kilometers**	**% Wet**
Wet–dry results — SPRNCA only					
1999	50	80.47	27	43.45	54
2000	50	80.47	25	40.23	50
2001	50	80.47	38	61.15	76
2002	50	80.47	27	43.45	54
2003	50	80.47	28.5	45.87	57
2004	50	80.47	23	37.01	46
2005	50	80.47	18	28.97	36
2006	50	80.47	24	38.62	48
Average	50.0	80.47	26.3	42.35	52.6
Wet–dry results					
2007	120.44	193.83	47.05	75.72	39
2008	120.1	193.28	43	69.20	36
2009	118.7	191.03	53.4	85.94	45
2010	131.8	212.11	49.2	79.18	37
2011	134.5	216.46	44	70.81	33
2012	131.2	211.15	37.5	60.35	29
2013	143.7	231.26	46.5	74.83	32
2014	133.1	214.20	33.6	54.07	25
2015	138.5	222.89	60.1	96.72	43
2016	131.3	211.31	49.5	79.66	38
2017	129.7	208.73	37	59.55	29
Average	130.3	209.66	45.5	73.28	35.1

Source: http://azconservation.org/downloads/san_pedro_wet_dry_mapping, accessed January 2018 (1 mile = 1.61 km).

into the basin-fill along the major stream channels. The stream and floodplain alluvium is an important alluvial aquifer that receives discharge from the basin-fill aquifer and streamflow via streambank infiltration occurring during high stream stages.

This bank and alluvial aquifer storage supports riparian vegetation during periods lacking runoff (Leenhouts et al. 2006; Dickinson et al. 2010). The San Pedro River network with associated shallow alluvial aquifers (main stem and portions of some tributaries) supports extensive riparian vegetation communities (Stromberg et al. 2005) that provide habitat for more than 350 species of birds, 80 species of mammals, and 40 species of reptiles and amphibians (Kennedy and Gungle 2010). Alluvial aquifers also are zones of extensive hyporheic exchange (Stanford and Ward 1988; Fernald et al. 2001).

Physical Connectivity via Surface Water and Subsurface Recharge

The U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) operates the Walnut Gulch Experimental Watershed (WGEW) located near Tombstone, Arizona. The WGEW is a subbasin of the San Pedro River Basin and is entirely ephemeral (Figure 7). A great deal of research into semiarid region hydrology has been conducted at the WGEW since it was established in the mid-1950s. It is one of the most intensively instrumented semiarid experimental watersheds in the world with nearly 100 years of abiotic and biotic data (Moran et al. 2008). The network of over 125 gaged rainfall and runoff stations has been continuously collecting precipitation and runoff data for over 55 years. Given the substantial knowledge base and long-term database, it is ideally situated to more quantitatively illustrate the connectivity of ephemeral tributaries to downstream perennial and intermittent reaches of the main stem of the San Pedro.

Long-term WGEW observations indicate that approximately two-thirds of the annual precipitation on the watershed occur as high-intensity, convective thunderstorms of limited aerial extent (Goodrich et al. 1997). Winter rains (and occasional snows) are generally low-intensity events associated with slow-moving cold fronts and are typically of greater aerial extent than summer rains. Runoff is generated almost exclusively from convective storms during the summer monsoon season via infiltration excess that produces overland flow.

Overland runoff generation and associated ephemeral streamflow is common in the WGEW and numerous tributaries along the main stem of the San Pedro River. However, because most of these tributaries traverse a thick vadose zone with relatively large depths to the water table, runoff response as a function of drainage becomes more nonlinear as drainage area increases in contrast with runoff in more mesic regions. Goodrich et al. (1997) examined the linearity of runoff response in the WGEW using hundreds of hydrologic events in different-sized catchments. They found that watershed response as measured by runoff volume (V) and peak runoff rate (Q_p) becomes more nonlinear with increasing drainage area. In other words, rainfall inputs into the watershed are attenuated to a greater degree as drainage area increases before becoming runoff (e.g., V and Q_p decrease with increasing drainage area). Goodrich et al. (1997) found a critical watershed area threshold of ~36–60 ha. Beyond this drainage area there is a marked increase in the nonlinearity of basin response. They concluded there were two key reasons for this threshold. Beyond the threshold area, the spatial variability and limited spatial extent of runoff-producing precipitation, and the loss of runoff by infiltration into the bed of ephemeral channels (transmission losses) become dominant factors in runoff response. This relationship is very different from the commonly observed relationships in humid streams of

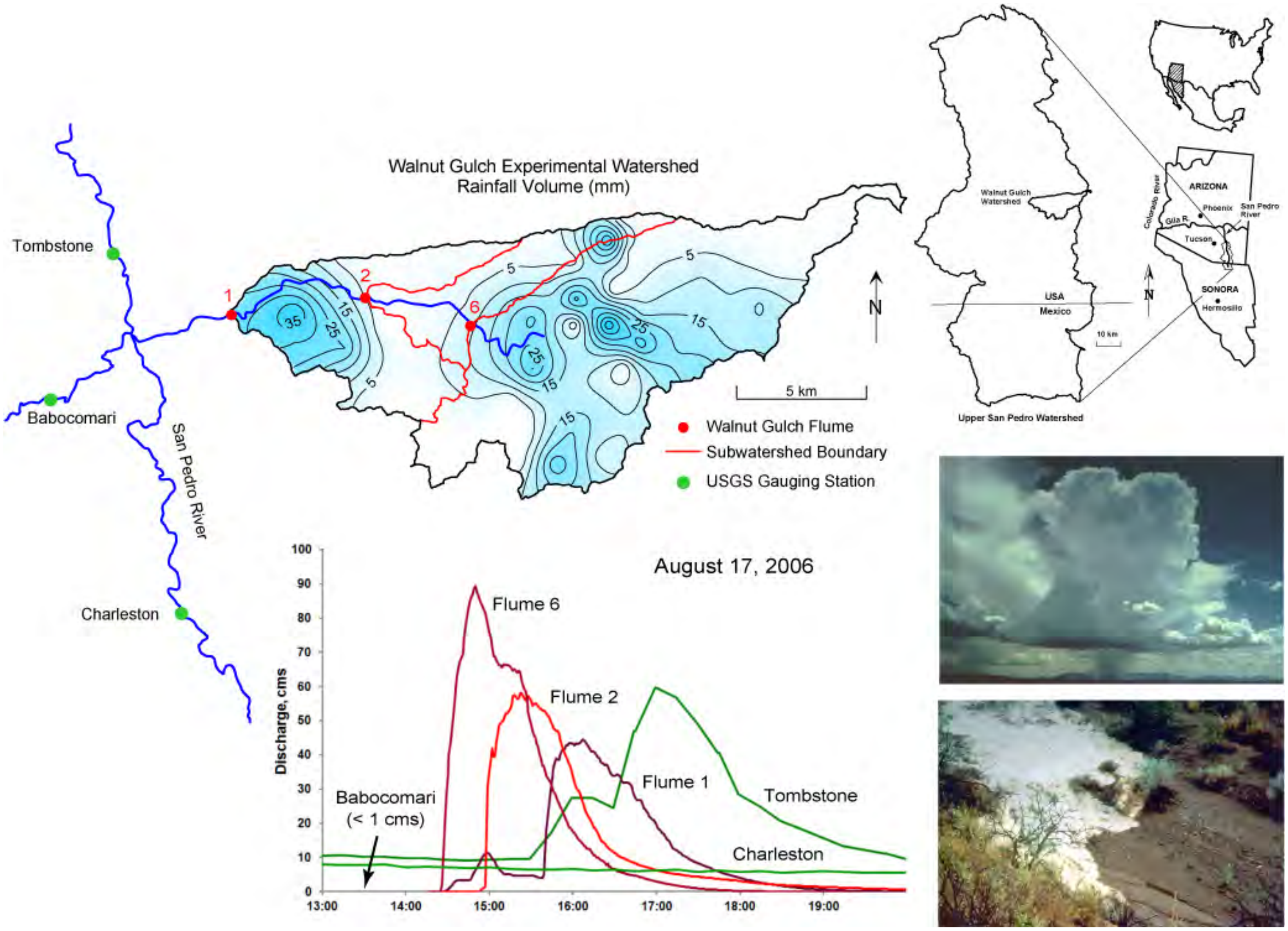


FIGURE 7. Storm rainfall and downstream hydrographs with decreasing runoff volume and peak rate due to channel transmission losses as measured in the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) Walnut Gulch Experimental Watershed (WGEW) and the impact of this storm runoff on the San Pedro River in southeastern Arizona. Inset photos show a typical air-mass thunderstorm and the front of surface flow progressing down an ephemeral channel.

the Midwest and eastern U.S., where runoff generally is proportional to watershed area and V and Q_p per unit area increase with increasing drainage area.

As an example, during a large rainstorm on August 17, 2006, most of the precipitation from multiple air-mass thunderstorm cells occurred over relatively localized areas in the upper and lower portions of the WGEW (Figure 7). As overland flow occurred and became concentrated in the ephemeral tributary network, streamflow dramatically diminished as the runoff hydrograph traveled downstream through the channel network. However, a substantial amount of runoff from this storm traversed the ephemeral Walnut Gulch tributary and connected to the main stem of the San Pedro River, augmenting the flow as measured at the USGS Tombstone stream gage. Runoff in Walnut Gulch (149 km^2 drainage area) and many arid and semiarid streams is characterized by short-duration, highly episodic flows. The longitudinal extent of the effects of these flows on downstream waters is a function of the flow magnitude, its duration, the depth, conductivity, and antecedent moisture conditions of the ephemeral channel substrate that the runoff flows across, and the depth to groundwater. For example, in 2006 there were 23 runoff flows measured at Walnut Gulch Flume 1 (the outlet of the WGEW). The average volume, Q_p, and duration of these runoff events were 31,460 m^3, 7.23 m^3/s, and 239 min, respectively. Four of the 23 runoff events recorded at Flume 1 were estimated to have measurable impacts on flows measured at the downstream USGS Tombstone stream gage (4,510 km^2) on the San Pedro River (including the event shown in Figure 7).

In the San Pedro Basin, a detailed study comparing methods to estimate ephemeral channel recharge in the highly instrumented WGEW for the channel

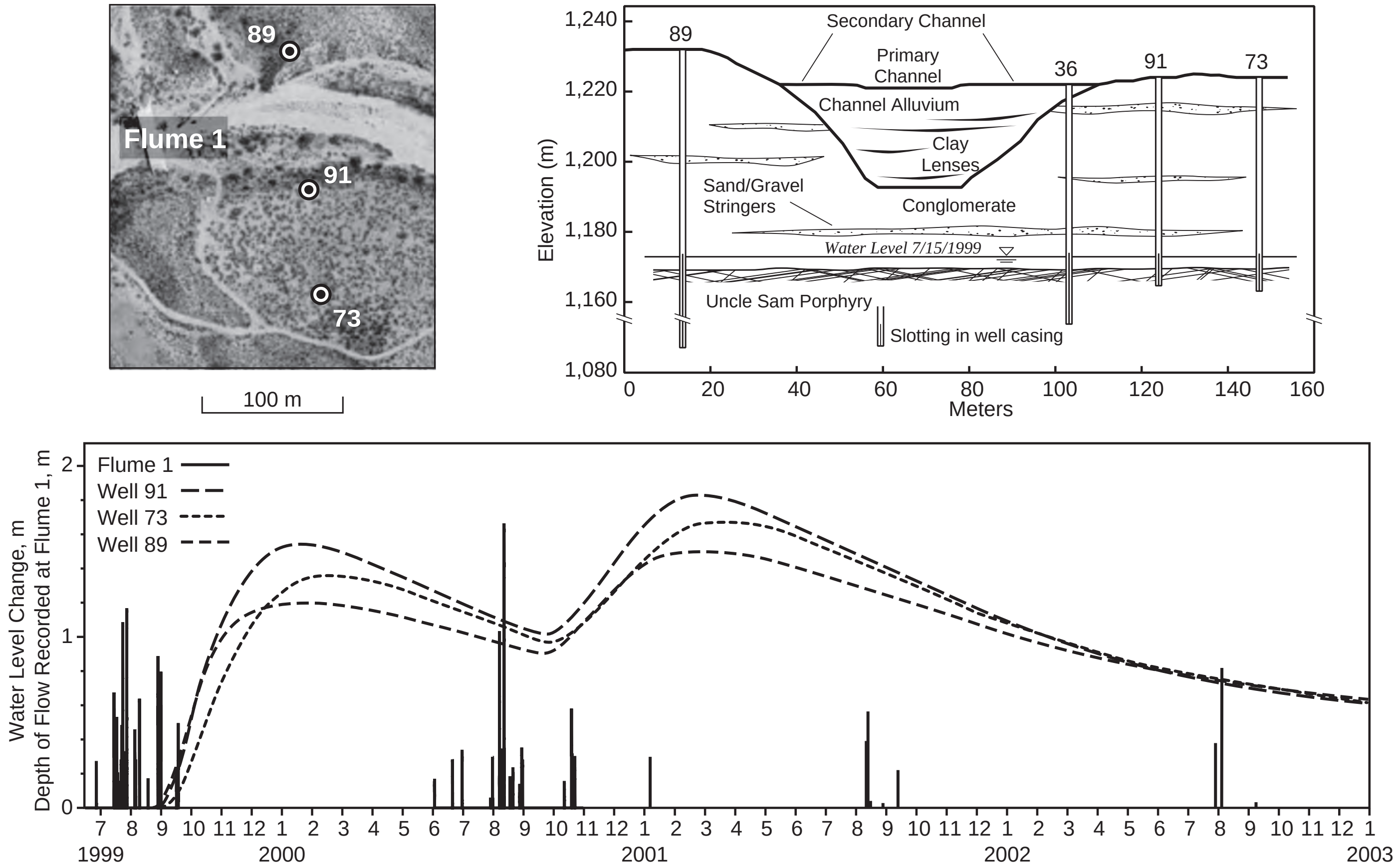


FIGURE 8. Upper left: WGEW — Flume 1 with upstream deep well locations; upper right: vertical cross section and stratigraphy aligned with deep wells; lower: 1999 to 2003. Surface runoff flow depth at Flume 1 (m): solid vertical lines in lower figure, and water level change in deep wells (m): dashed lines in lower figure.

reach between Flumes 1 and 2 (see Figures 7 and 8) was conducted by Goodrich et al. (2004). The methods included: (1) water balance, (2) a groundwater mounding model, (3) microgravity changes, (4) chloride concentration changes, and (5) temperature transport modeling. Observations from this study are illustrated in Figure 8. The lower portion of this figure illustrates the changes in deep groundwater levels due to multiple runoff events during the 1999 to 2002 monsoon (months 6 through 8) as well as associated microgravity changes. The deep wells just upstream of Flume 1 (wells 91, 73, and 89) responded roughly a month after the onset of significant monsoon runoff events with water levels continuing to increase for roughly six months. A rough scaling of ephemeral channel recharge volumes during the 1999 and 2000 monsoon seasons (~580,000 m^3) to the entire basin shows that these estimates would constitute roughly 15%–40% of all water recharged annually into the regional aquifer as derived from a calibrated groundwater model estimate (Pool and Dickinson 2007). During the dry monsoon seasons of 2001 and 2002, there was limited ephemeral streamflow and no increase in deep groundwater levels. This not only illustrates the high interannual variability of ephemeral channel recharge but also that a threshold volume of channel infiltration is needed to overcome low unsaturated conductivities in the thick vadose zone before deep aquifer recharge can occur. Coes and Pool (2005) conducted deep borehole measurements and analysis at 16 other interchannel and channel locations and confirmed there was little or no evidence of deep recharge from upland and interchannel basin locations as discussed above across the broader Southwest by Phillips et al. (2004).

The influence of stormflows and recharge from ephemeral tributary streams extends to the San Pedro River main stem. Using geochemical tracers (chloride, sulfate, and stable isotopes of hydrogen and oxygen in water), Baillie et al. (2007) found two main sources of water in the alluvial aquifer for the upper San Pedro River: (1) the regional groundwater recharged along the Huachuca Mountains (mountain block, mountain front) to the west; and (2) the local channel recharge from monsoon floodwaters. The importance of alluvial aquifer recharge and bank storage drainage in maintaining baseflow from monsoon floodwaters is illustrated in Table 1 (top) between the 2000 and 2001 wet–dry mapping. On October 23, 2000, the ninth largest recorded flood (since 1916) occurred at the Charleston gage on the San Pedro (daily Q_p = 242 m^3/s). Between that flood and the wet–dry mapping in mid-June of 2001 there were no runoff events with a daily $Q_\mathrm{p} > 13.5$ m^3/s. Note the percentage of wet area in the June 2001 mapping increased 26% over the 2000 value indicating that the June 2001 baseflow was elevated and sustained by the large October 2000 runoff event occurring almost seven months prior.

Biological Importance and Connectivity

Recent studies that looked at aquatic invertebrates in perennial and intermittent reaches in the San Pedro River Basin (Bogan et al. 2013; Cañedo-Argüelles et al. 2015) have concluded that perennial refuges and pools are important for their survival, and that flow connectivity strongly influences dispersal and long-term viability of these organisms. Bogan et al. (2013) also noted that while "perennial headwaters supported the highest diversity of invertebrates, intermittent reaches supported a number of unique or locally rare species and as such contribute to regional species diversity and should be included in conservation planning."

Mims et al. (2015) found that "aquatic connectivity had the strongest relationship with genetic connectivity across species when landscape drivers were combined with topography" for the species of dryland amphibians they studied in the San Pedro River Basin. Recent nonnative invasion and a corresponding decline in native fish species diversity were observed in the lower reaches of Aravaipa Creek, a tributary of the San Pedro River, which historically was only rarely connected to the main stem (Eby et al. 2003).

A major study was undertaken within the SPRNCA to quantify the hydrologic requirements of, and consumptive groundwater use by, riparian vegetation (Leenhouts et al. 2006). A key objective of that study was to develop relations between the streamflow regime and its connectivity to riparian vegetation composition, structure, and diversity within the SPRNCA. Instrumentation was installed to measure surface and groundwater hydrology variables over 14 stream reaches from 2001 to 2003. For each reach, herbaceous and woody species were sampled in plots within three alluvial zones (floodplain, postentrenchment alluvial and preentrenchment alluvium).

These data were analyzed at the site level, across alluvial zones, using Pearson product-moment correlation analysis to determine the importance of site hydrology on vegetation biomass, structure, and richness. The hydrologic metrics with the most explanatory power were: (1) streamflow permanence (the percentage of days in a year when surface water was present), (2) the mean floodplain depth to groundwater, and (3) the maximum annual floodplain groundwater fluctuation. Streamflow permanence was the most important of the three.

Three riparian condition classes (wet, intermediate, and dry) were then developed to provide a quantitative, multimetric rating system for riparian ecosystem functioning condition for each reach with associated ranges of the three hydrologic metrics noted above. This provided a riparian condition class map of the SPRNCA at the time of the study. Spatial and temporal changes in the riparian condition can then be predicted by monitoring the hydrologic metric over time. Using this framework, Brand et al. (2010) then related changes in ground/surface water and riparian vegetation reflected in the condition classes to types and abundances of breeding and migratory birds.

Sediment, Chemical, and Nutrient Connectivity

Ephemeral tributary stormflows are also sources of sediment and alluvium for the mainstem San Pedro River. Only the largest, less frequent events can flush sediment completely through ephemeral tributaries (Lane et al. 1997). For example, a reach-scale study in the WGEW estimated sand transport distances of only 401–734 m in nine floods over two consecutive years (Powell et al. 2007). Over longer time spans the episodic nature of flow in ephemeral and intermittent channels transfers sediment in a stepwise manner, depositing sediment some distance downstream and then moving it farther downstream by subsequent events. The frequency, timing, and predictability of stream runoff and therefore sediment transport vary widely with significant seasonal, annual, and interannual variations that depend on elevation, climate, channel substrate, geology, and the presence of shallow groundwater. Over longer time spans, however, sediment will continue to move downstream and affect downstream waters (Brooks and Lemon 2007).

Seasonal variability in chemical and nutrient connectivity was also observed in the San Pedro River. Differences in dissolved organic nitrogen concentration were detected among three segments of the river during the dry season, but during the wet monsoon season, stream water was well mixed. In this state the system was hydrologically connected, and no differences in dissolved organic nitrogen concentration were detected over a 95-km reach of the San Pedro (Brooks and Lemon 2007). These seasonal differences occur because nitrogen accumulates locally at varying levels during drier periods but is mixed and transported downstream during large, infrequent storm events, making nitrogen concentrations more longitudinally uniform (Fisher et al. 2001).

Ephemeral tributary stormflows heavily influence the nutrient and biogeochemical status of the San Pedro River. Synoptic sampling by Brooks and Lemon (2007) on the San Pedro reach noted above was performed to identify the effects of regional hydrology and land use on dissolved carbon and nitrogen concentrations. They found that, during the summer monsoon season, baseflow increased five- to 10-fold, and dissolved organic matter and inorganic nitrogen increased two- to 10-fold. The fluorescence index of water samples indicated a large input of terrestrial solutes with the onset of monsoon runoff inflows, and values of both chloride and oxygen isotope tracers indicated that stream water and alluvial groundwater were well mixed along the entire 95-km reach. Meixner et al. (2007) used chloride tracer samples and mixing analyses to examine sources of San Pedro River water during summer floods in 2001 (wet year) and 2002 (dry year). Results of mixing models indicated that both a groundwater-soil water end-member and a precipitation end-member (indicative of overland and ephemeral flow) contributed to the floods. During the first floods of each year, nitrate and dissolved organic carbon increased dramatically in the river, whereas dissolved organic nitrogen did not exhibit increases in 2001 but did in 2002.

In summary, numerous studies have shown that ephemeral and intermittent tributary streams have strong physical and chemical connections to the San Pedro River. The extensive riparian plant communities along the mainstem San Pedro River depend on the availability of water in the alluvial aquifer along the river, including water and nutrients derived from ephemeral stream stormflows (Stromberg et al. 2005; Baillie et al. 2007). These riparian areas, in turn, strongly influence river attributes through stream shading, channel stabilization, nutrient cycling, inputs of invertebrates and other organisms, and inputs of detritus, wood, and other materials (Gregory et al. 1991; National Research Council 2002; Naiman et al. 2005).

Human Alternations Impacts

The San Pedro Basin is experiencing many of the land development, land use, and water resource extractive impacts discussed in the broader section on connectivity of Southwestern ephemeral and intermittent streams above. The most pressing issue impacting the viability of the perennial and intermittent reaches of the SPRNCA is the overpumping of the regional groundwater aquifer for domestic, municipal, and military needs. Concerted efforts by member organizations belonging to the Upper San Pedro Partnership (Richter et al. 2009; *uspp.us/*) have been undertaken to reduce the annual groundwater deficit. Actions include the retirement of agricultural pumping, incentives and code changes to upgrade indoor and outdoor water fixtures, turf replacement by xeriscaping, passive recharge of treated municipal effluent near the river to build up a groundwater mound to block the effects of the groundwater cone of depression, removal of invasive phreatophytic vegetation, and wholesale upgrades and changes across the entire water infrastructure of the local military base.

As noted above, the effects of urbanization and adding impervious area increase local runoff that would otherwise infiltrate and be lost to plant transpiration or evaporation (Kennedy et al. 2013). This “new,” manageable, urban enhanced runoff water resource is being harnessed in and around Sierra Vista, the largest city in the basin, and is being directed to constructed recharge facilities to further reduce the effects of groundwater overpumping. Gungle et al. (2016) conducted a comprehensive review of these efforts using 14 indicators to assess the sustainability of groundwater use in the basin. They include measures of the surface hydrologic connectivity of the San Pedro using annual wet–dry mapping; surface–subsurface connectivity using stream and alluvial groundwater levels and gradients; and tracking the riparian condition classes in stream reaches using the biohydrologic metrics discussed above. These efforts have reduced the annual water budget deficit by nearly 50%.

SOUTHWESTERN INTERMITTENT AND EPHEMERAL STREAMS: SYNTHESIS AND IMPLICATIONS

Ephemeral and intermittent streams and their tributaries in the American Southwest provide a wide range of functions that are critical to the health and stability of arid and semiarid watersheds and ecosystems. Most importantly, they provide hydrologic and biological connectivity within a basin, linking ephemeral, intermittent, and perennial stream segments. This linkage and the corridor of connectivity facilitate the movement of water, sediment, nutrients, debris, fish, wildlife, and plant propagules throughout the watershed. The relatively more vegetated stream corridors connected to downstream perennial reaches provide wildlife habitat and a cooler, more humid environment than the surrounding uplands. During ephemeral and intermittent streamflow, energy dissipates as part of natural fluvial adjustment, and sediment, organic matter, and debris are transported.

Rivers of the arid and semiarid Southwest are products of a highly variable and dynamic environment. The variability of the hydrologic regime in these streams is the key determinant of spatial and temporal distribution of plant community structure and the types of plants and wildlife present. Some of the major ways in which ephemeral streams are connected with and influence perennial waters are as follows:

- Flows from ephemeral streams are a major driver of the dynamic hydrology of Southwestern rivers. Ephemeral tributary streamflows are especially important drivers of downstream floods during the monsoon season;
- Ephemeral tributary streams supply water to mainstem river alluvial aquifers; these alluvial aquifers help sustain river baseflows;
- Ephemeral streams export sediment to rivers during major hydrologic events; the sediment contributes to materials that comprise alluvial aquifers and shapes the fluvial geomorphology of rivers;
- Ephemeral tributaries export nutrients to mainstem rivers during hydrologic flow events; nutrients occur in many forms and contribute to river productivity;
- Ephemeral and intermittent streams and their associated vegetation communities provide structural elements of food, cover, nesting and breeding habitat, and movement/migration corridors for organisms;
- Water, sediment, and nutrients exported to the river from ephemeral tributaries support riparian communities of mainstem rivers; the riparian communities profoundly influence river attributes through shading and allochthonous inputs of organic matter, detritus, wood, and invertebrates to the river;
- Regional groundwater aquifers are in part recharged through infiltration of water to the streambed of ephemeral stream channels during wet years; the regional aquifer supplies a varying but critical portion of baseflow for perennial river reaches illustrating subsurface connectivity;
- Fishes and invertebrates native to mainstem rivers are adapted to the variable flow regimes that ephemeral tributary streams strongly influence. Ephemeral flows mitigate invasion by introduced species.

ACKNOWLEDGMENTS

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DISCLOSURE

Former JAWRA Editor Kenneth J. Lanfear served as acting editor in chief for all articles in this featured collection. Parker J. Wigington, Jr., an author on some of the collection papers and who was JAWRA editor in chief at the time the collection was submitted, had no role in the review or editorial decisions for any part of the collection.

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