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The Ecological and Hydrological Significance of Ephemeral and Intermittent Streams in the Arid and Semi-arid American Southwest

by

Lainie R. Levick, David C. Goodrich, Mariano Hernandez
USDA-ARS
Southwest Watershed Research Center
Tucson, Arizona

Julia Fonseca
Pima County
Office of Conservation Science and Environmental Policy
Tucson, Arizona

Darius J. Semmens
USGS – Rocky Mountain Geographic Science Center
Denver, Colorado

Juliet Stromberg, Melanie Tluczek
Arizona State University
Tempe, Arizona

Robert A. Leidy, Melissa Scianni
USEPA, Office of Water, Region IX
San Francisco, California

D. Phillip Guertin
University of Arizona
Tucson, Arizona

William G. Kepner
USEPA, ORD, NERL
Las Vegas, Nevada

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Abstract

This report represents a state-of-the-art synthesis of current knowledge of the ecology and hydrology of ephemeral (dry washes) and intermittent streams in the American Southwest, and may have important bearing on establishing nexus to traditional navigable waters (TNW) and defining connectivity relative to the Clean Water Act. Ephemeral and intermittent streams make up approximately 59% of all streams in the United States (excluding Alaska), and over 81% in the arid and semi-arid Southwest (Arizona, New Mexico, Nevada, Utah, Colorado and California) according to the U.S. Geological Survey National Hydrography Dataset. They are often the headwaters or major tributaries of perennial streams in the Southwest. This comprehensive review of the present scientific understanding of the ecology and hydrology of ephemeral and intermittent streams will help place them in a watershed context, thereby highlighting their importance in maintaining water quality, overall watershed function or health, and provisioning of the essential human and biological requirements of clean water. Ephemeral and intermittent streams provide the same ecological and hydrological functions as perennial streams by moving water, nutrients, and sediment throughout the watershed. When functioning properly, these streams provide landscape hydrologic connections; stream energy dissipation during high-water flows to reduce erosion and improve water quality; surface and subsurface water storage and exchange; ground-water recharge and discharge; sediment transport, storage, and deposition to aid in floodplain maintenance and development; nutrient storage and cycling; wildlife habitat and migration corridors; support for vegetation communities to help stabilize stream banks and provide wildlife services; and water supply and water-quality filtering. They provide a wide array of ecological functions including forage, cover, nesting, and movement corridors for wildlife. Because of the relatively higher moisture content in arid and semi-arid region streams, vegetation and wildlife abundance and diversity in and near them is proportionally higher than in the surrounding uplands. In the rapidly developing southwest, land management decisions must employ a watershed-scale approach that addresses overall watershed function and water quality. Ephemeral and intermittent stream systems comprise a large portion of southwestern watersheds, and contribute to the hydrological, biogeochemical, and ecological health of a watershed. Given their importance and vast extent, it is concluded that an individual ephemeral or intermittent stream segment should not be examined in isolation. Consideration of the cumulative impacts from anthropogenic uses on these streams is critical in watershed-based assessments and land management decisions to maintain overall watershed health and water quality.

Table of Contents

Acknowledgements ii
Abstract iii
Table of Contents v
List of Tables vii
List of Figures viii
1. Introduction 1
2. Location of Ephemeral and Intermittent Streams 2
3. Definitions 6
4. The Watershed Context 7
5. Characteristics, Functions, and Ecosystem Significance 9
a. Hydrologic Features 13
i. Variability of arid and semi-arid region flows and floods 15
ii. Types of arid and semi-arid region floods 17
iii. Transmission losses 18
iv. Ground-water recharge 22
v. Landscape and hydrologic connections 24
vi. Energy dissipation 26
vii. Sediment mobilization, storage, transport, and deposition 26
b. Geomorphic Characteristics 28
i. Channel-forming processes 31
ii. Geomorphic response to land management 34
iii. Map scale in determining channel network and stream order 35
c. Biogeochemical Functions 36
i. Cycling of elements and compounds 36
ii. Detention of imported elements and compounds 37
iii. Particulate detention 38
iv. Organic carbon export 39
d. Plant Community Support 40
i. Physiognomy, density, and species composition. 41
ii. Primary productivity and plant water sources 43
iii. Temporal and spatial patterns of species diversity 44
iv. Influences of vegetation on ecosystem processes. 45
v. Vegetation and channel morphology. 46
vi. Vegetation and geochemical cycles 47
e. Faunal Support and Habitat 47

i. Spatial structure, connectivity, and corridors in wildlife habitat....48
ii. Physical habitat features....49
iii. Vegetative habitat features....50
iv. Hydrological habitat features....52
v. Faunal abundance and distribution....52

f. Synthesis of Functions....64

6. Anthropogenic Impacts on Ephemeral and Intermittent Streams and Riparian Areas....65

a. Land Development....66

b. Land Uses....69

c. Water Resources Impacts....70

d. Climate Change....71

7. Discussion....71

a. Clean Water Act Context....71

b. Ecosystem Goods and Services....72

c. Management Principles....74

d. Research Recommendations....75

8. Conclusions....76

9. Literature Cited....77

List of Tables

Table 1. List of wildlife species that use riverine soil exposures in Pima County, Arizona (source: Julia Fonseca, Pima County Office of Conservation Science and Environmental Policy, 2008)..... 50

List of Figures

Figure 1. Illustration of the locations of present day drylands and their categories. (Millennium Ecosystem Assessment, 2005a). 3

Figure 2. Map showing the San Pedro River Watershed's current and historical perennial reaches (courtesy of The Nature Conservancy, Arizona). 4

Figure 3. Map of the Southwestern U.S. showing the National Hydrography Dataset (NHD) intermittent/ephemeral (red) and perennial (blue) streams. 5

Figure 4. Diagram of the four interacting zones of a desert stream ecosystem: the surface stream, hyporheic, parafluvial and riparian zones (from Holmes et al. 1994). 7

Figure 5. Diagram showing connectivity of landscape-level processes and attributes important for ecosystem monitoring (from Miller, 2005). 9

Figure 6. Photograph showing ground-water dependent cottonwood trees (*Populus fremontii*) lining an intermittent stream. 10

Figure 7. Map of the conterminous U.S. showing Bailey's Ecoregions with the dry domain outlined in red. 12

Figure 8. Map of the conterminous U.S. with EPA Level II Ecoregions showing most of Nevada, Arizona, Utah, and New Mexico in the North American Deserts classification. 12

Figure 9. Photographs of an ephemeral stream, same location with flow (left), and dry (right), Tucson, Arizona. 13

Figure 10. Maps showing average annual precipitation amounts, 1961-1990 (left), and locations of ephemeral/intermittent (red) and perennial (blue) streams (right). 14

Figure 11. Maps showing percent of average annual precipitation, July and August (left) and percent of average annual precipitation, October through March (right), for comparison, Western Regional Climate Center, http://www.wrcc.dri.edu/precip.html. 15

Figure 12. Photograph of a flash flood in an ephemeral channel, Southern Arizona. 18

Figure 13. Example hydrograph showing typical rapid rise to peak discharge and long recession curve of a flash flood. 18

Figure 14. Map of the Walnut Gulch Experimental Watershed (WGEW), Tombstone, Arizona, showing major stream network, flumes and sub-watershed boundaries. 19

Figure 15. Hydrograph, location map, and photograph of rainfall-runoff event August 27, 1982, illustrating ephemeral stream channel transmission losses as measured within the WGEW (Goodrich et al., 1997). 21

Figure 16. Photographs of Flume 1 at WGEW, dry (left) and with flow (right). 21

Figure 17. Diagrams of well levels and flow depths at the WGEW. 23

Figure 18. Photograph of ephemeral and intermittent stream channels connecting to a perennial reach of Cienega Creek, southeast of Tucson, Arizona. (Photograph: Lainie Levick/Aerial flight courtesy of Lighthawk, www.lighthawk.org). 25

Figure 19. Photographs of an ephemeral stream, same location during flow (left), and dry (right), Tucson, Arizona. 26

Figure 20. Photographs from an unusually large flood event in an ephemeral stream that damaged roads and bridges, and flooded nearby homes, Tucson, Arizona, July 31, 2006. 27

Figure 21. Photograph of sediment-laden floodwaters in an ephemeral stream, Walnut Gulch, Arizona. (Photograph: USDA-ARS/SWRC). 28

Figure 22. Photograph showing an ephemeral braided stream system, Yuma Wash, southwest Arizona. (Photograph: Susan Howe, Colorado State University). 29

Figure 23. Relation of bankfull channel width to drainage area for different climatic environments (after Wolman and Gerson, 1978). 30

Figure 24. Photograph of a typical wide, flat, and sandy ephemeral stream channel, Martinez Wash, Arizona. (Photograph: William Kepner, USEPA/ORD) 31

Figure 25. Photograph of a small arroyo or incised channel, southern Colorado. 33

Figure 26. Diagram of digitized stream channels on a subwatershed at WGEW (from Miller et al., 1999a). 35

Figure 27. Photograph showing dense corridor of vegetation lining an ephemeral wash, Agua Fria River, north of Phoenix, AZ. (Photograph: William Kepner, USEPA/ORD). 40

Figure 28. Photograph showing riparian vegetation along a desert stream, western Arizona. 42

Figure 29. Photograph of native palms (*Washingtonia filifera*) in Castle Creek, AZ. (Photograph: William Kepner, USEPA/ORD). 43

Figure 30. Photograph of annual plant species in an ephemeral streambed following spring rains, southern Arizona. 45

Figure 31. Photograph of vegetation growing in an ephemeral channel bed, Arizona. (Photograph: Lainie Levick/Aerial flight courtesy of Lighthawk, www.lighthawk.org). 46

Figure 32. Photograph of diverse riparian vegetation, Badger Springs Wash, Arizona. 51

Figure 33. Graph of herpetofauna species by taxonomic group and by habitat type, from BLM surveys in Arizona, 1977-1981 (Jones, 1988). 54

Figure 34. Graph of lizard abundance by habitat type at Organ Pipe Cactus National Monument, Arizona, 1989-1990 (from Rosen and Lowe, 1996). 55

Figure 35. Photographs of amphibians that inhabit and breed in ephemeral and intermittent streams (clockwise from top left): Canyon tree frog (*Hyla arenicolor*), lowland leopard frog (*Rana yavapaiensis*), red spotted toad (*Bufo punctatus*), Sonoran desert toad (*Bufo alvarius*, photograph: Shea Burns, USDA-ARS), Egg strand of Sonoran desert toad (photograph: Shea Burns, USDA-ARS). 56

Figure 36. Photograph of a desert mule deer (*Odocoileus hemionus*), Arizona. 59

Figure 37. Illustrations of caddisfly larva (www.scientificillustrator.com) (left), and caddisfly adult (www.nps.gov) (right). 61

Figure 38. Diagram of a conceptual model of the delivery of invertebrates, sloughed algae and detritus from headwater streams, intermittent and permanent first-order fishless streams to larger fish-bearing streams, illustrating the dependence of downstream reaches on upstream processes (from Cummins and Wilzbach, 2005). 63

Figure 39. Photographs of the Rillito River, Tucson, Arizona, dry (left) and with flow (right). 65

Figure 40. Aerial photograph showing ephemeral tributaries to Cienega Creek, a perennial stream, flowing through the small community of Vail, southeast of Tucson, Arizona.... 67

Figure 41. Photograph of the Santa Cruz River, Tucson, Arizona, during summer monsoon flows. (Photograph: unknown). 74

1. Introduction

This report addresses the hydrological and ecological significance of ephemeral and intermittent streams in the arid and semi-arid Southwestern United States (U.S.) for the purpose of illustrating their connection and value to perennial stream systems and other "waters of the United States" as protected under the Federal Water Pollution Control Act, otherwise known as the Clean Water Act (CWA). The CWA was established to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters." Its goal is to prevent pollution of waters of the U.S., and to ensure that our citizens have safe, clean water. Although originally enacted in 1948, the act was revised and expanded in 1972, with nearly annual amendments since then.

In recent years, there have been numerous discussions as to whether ephemeral and intermittent streams are "waters of the United States" under the Act, and if the act applies to those streams. From 33CFR, Part 328.3, the definition of "waters of the United States," as it applies to the jurisdictional limits of the authority of the Corps of Engineers under the CWA, includes (in part):

> (1) All waters which are currently used, or were used in the past, or may be susceptible to use in interstate or foreign commerce, including all waters which are subject to the ebb and flow of the tide;
>
> (2) All interstate waters including interstate wetlands;
>
> (3) All other waters such as intrastate lakes, rivers, streams (including intermittent streams), mudflats, sandflats, wetlands, sloughs, prairie potholes, wet meadows, playa lakes, or natural ponds, the use, degradation or destruction of which could affect interstate or foreign commerce including any such waters:
>
> > (i) Which are or could be used by interstate or foreign travelers for recreational or other purposes; or
> > (ii) From which fish or shellfish are or could be taken and sold in interstate or foreign commerce; or
> > (iii) Which are used or could be used for industrial purposes by industries in interstate commerce;
>
> (4) All impoundments of waters otherwise defined as waters of the United States under this definition;
>
> (5) Tributaries of waters identified in paragraph (s) (1) through (4) of this section (from http://www.usace.army.mil/cw/cecwo/reg/33cfr328.htm).

This definition specifically includes intermittent streams (paragraph 3), and tributaries of any waters identified in the definition (paragraph 5). From these definitions ephemeral and intermittent streams appear to qualify for protection under the CWA; however, there have been some recent court cases that have complicated interpretation of this law. Nadeau and Rains (2007) discussed the Supreme Court decisions of June 2006, concerning the determination of jurisdiction under the CWA, and the implication that non-navigable, isolated, intrastate waters need a "significant nexus" to navigable waters to be jurisdictional under the CWA (see also Leibowitz et al., 2008). Although "significant nexus" has not been defined, the goal of the CWA is to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters" (33 U.S.C. 1251). Nadeau and Rains (2007) therefore, consider a "significant nexus" to exist if a headwater stream contributes to the chemical, physical, or biological integrity of navigable water.

Ephemeral and intermittent streams are the defining characteristic of many watersheds in dry, arid and semi-arid regions, and serve a critical role in the protection and maintenance of water resources, human health, and the environment. This report is a compilation of information that describes the significance of ephemeral and intermittent streams to the hydrology, biogeochemistry, flora and fauna of arid and semi-arid region watersheds. This comprehensive review of the present scientific understanding of the ecology and hydrology of ephemeral and intermittent streams will help place them in a watershed context, thereby highlighting their importance in maintaining water quality, overall watershed health, and provisioning of the essential human and biological requirements of clean water. Individual ephemeral or intermittent stream segments should not be examined in isolation. Given their vast extent and the accumulation of impacts to them over large areas in the rapidly developing southwest, a landscape or watershed-scale approach should be employed that considers the cumulative effects on overall watershed function.

The geographic scope of this report is the arid and semi-arid regions of the conterminous U.S. as defined by the Bailey's and EPA/Omernik ecoregion classifications (see Figures 7 and 8), but focuses on the states of California, Arizona, Nevada, New Mexico, Utah and Colorado. The application of this report is for the EPA Region 9 states of Arizona, California and Nevada. This report does not address management, policy, or regulatory issues.

2. Location of Ephemeral and Intermittent Streams

Ephemeral and intermittent streams are found across the Earth's land surface in arid and semi-arid regions that are commonly referred to as "drylands." Approximately one-third of the Earth's land surfaces are classified as arid or semi-arid (Whitford, 2002; Millennium Ecosystem Assessment, 2005a), including most of the Western U.S. (Figure 1).

These lands are characterized by low and highly variable annual precipitation, where evapotranspiration exceeds precipitation. It is because of these dry conditions, which result in great contrast between the moist riparian areas and adjacent dry upland communities, that arid and semi-arid region streams are so important. Riparian ecosystems occupy very small portions of the landscape in arid and semi-arid regions, yet they exert substantial influence on

hydrologic, geomorphic, and ecological processes (Shaw and Cooper, 2008), and typically support the great majority of biodiversity in these regions.

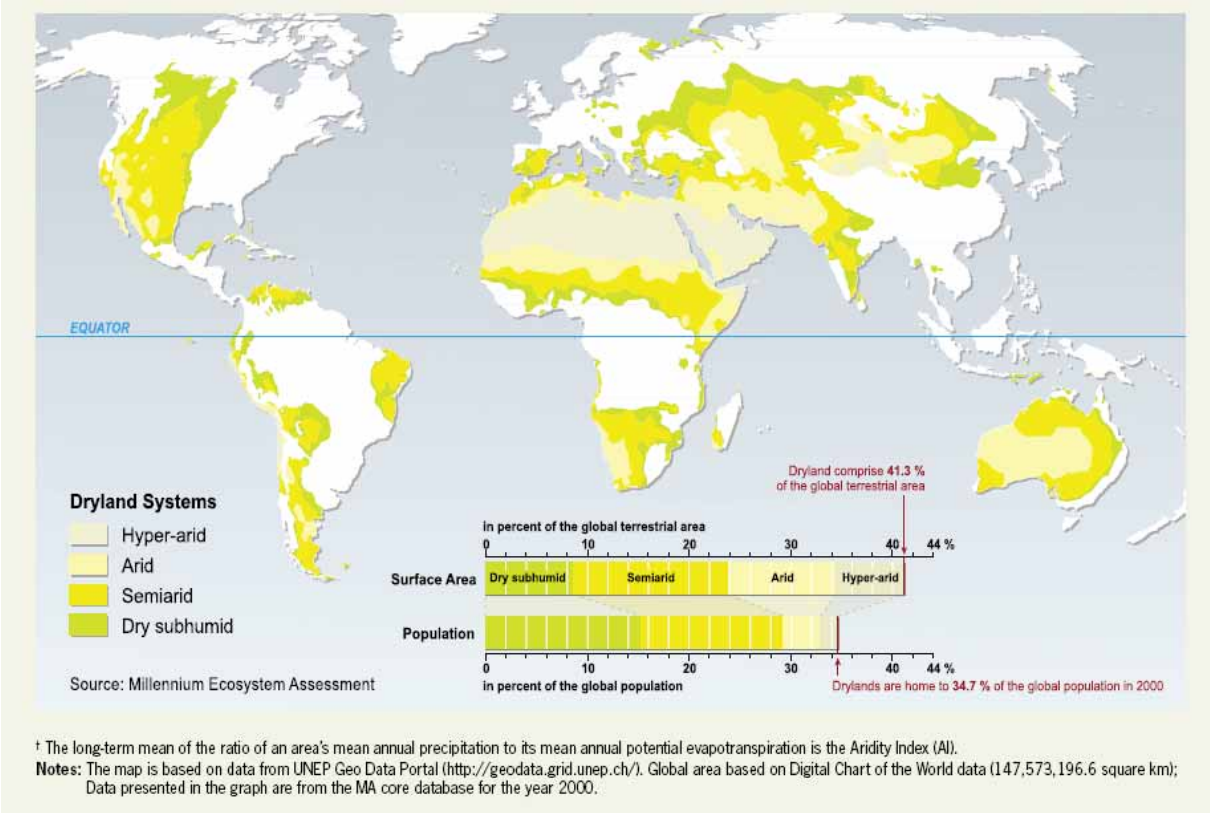

Figure 1. Illustration of the locations of present day drylands and their categories. (Millennium Ecosystem Assessment, 2005a)

Some southwestern landscapes confound typical notions of where water is to be found. The recent CWA discussions generally assume that perennial streams receive water from ephemeral tributaries. But, a person dying of thirst in the Cabeza Prieta National Wildlife Refuge in southwestern Arizona will find surface water in the mountains, not in the valley floor streams. In the San Pedro Valley of southeastern Arizona, perennial and intermittent stream reaches commonly are found in the tributaries, as well as along the main stem San Pedro River (Figure 2). In the Mojave Desert of southern California, some mountain streams are physically isolated from downstream hydrologic systems. Water from these mountain streams takes hundreds or thousands of years to move into and through the regional aquifer and discharge into valley floor streams, springs and wetlands (Izbicki, 2007).

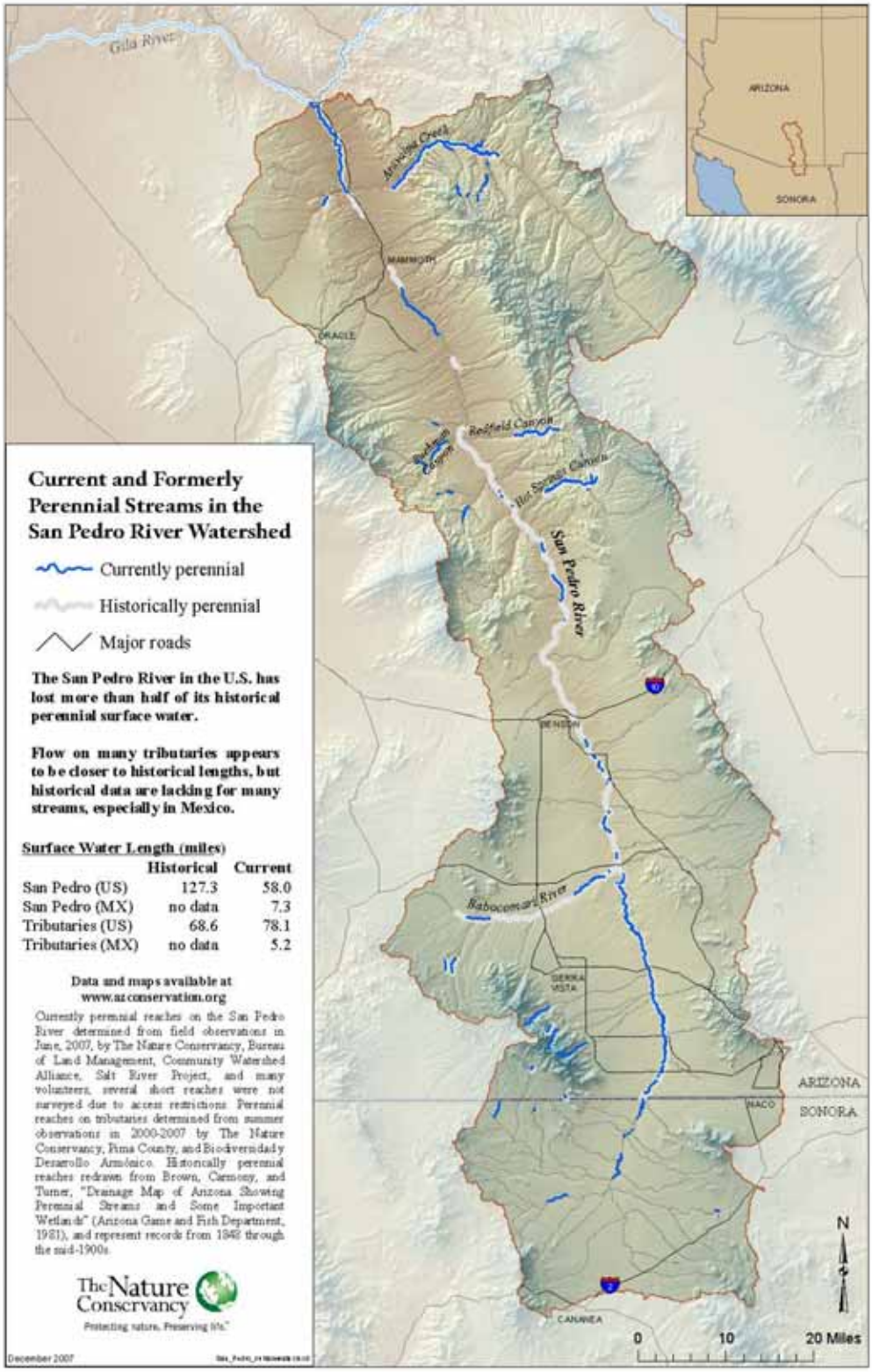

Figure 2. Map showing the San Pedro River Watershed's current and historical perennial reaches (courtesy of The Nature Conservancy, Arizona).

The U.S. EPA, using the National Hydrography Dataset (NHD) (USGS, 2006), has estimated that 59 percent of the streams in the U.S. (excluding Alaska) are ephemeral or intermittent (U.S. EPA, 2005). The NHD combines ephemeral and intermittent streams in its mapping, and identifies them as streams, which contain water for only part of the year. The NHD also identifies start reaches as those that have no other streams flowing into them (at the 1:100,000 scale). These reaches can thus be considered headwater or first-order streams (Nadeau and Rains, 2007).

Among the six states being addressed in this report, Arizona has the greatest percentage, 94 percent, of ephemeral and intermittent streams, whereas California has the least, 66 percent. However, it is not just states in the arid Southwest that contain high percentages of non-perennial streams. For example, 86 percent of South Dakota's streams are ephemeral or intermittent, 81 percent in Kansas, and 84 percent in North Dakota. The percentages of ephemeral/intermittent streams from the NHD for the six Southwestern states that are the subjects of this report are tabulated in Figure 3, and are illustrated using the NHD stream map (National Hydrography Dataset, http://nhd.usgs.gov/).

Arizona	94%
Nevada	89%
New Mexico	88%
Utah	79%
Colorado	68%
California	66%

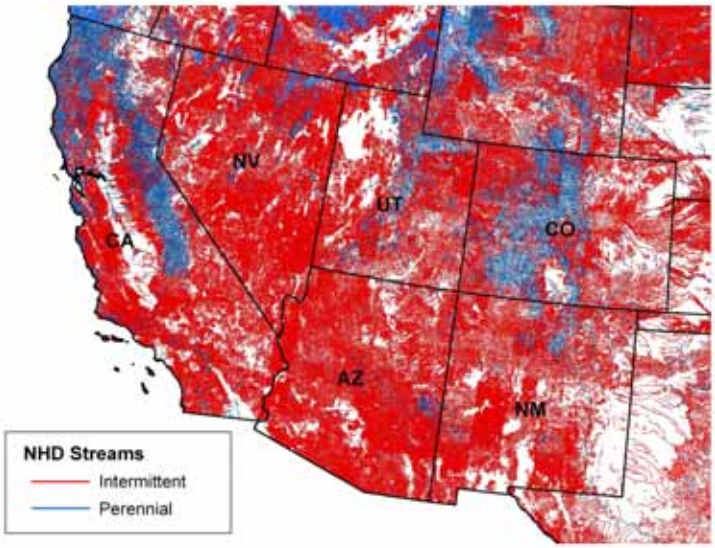

Figure 3. Map of the Southwestern U.S. showing the National Hydrography Dataset (NHD) intermittent/ephemeral (red) and perennial (blue) streams.

It should be noted that the NHD may not accurately reflect the total extent of ephemeral or intermittent streams; it does not include stream segments less than one mile in length, combines intermittent and ephemeral streams, and is based on 1:100,000 scale topographic maps. Washes (dry streambeds that contain water only during or after a local rainstorm or heavy snowmelt) in the arid Southwest are not consistently demarcated. The NHD dataset contains information on naturally occurring and constructed bodies of water, paths through which water flows, and related entities (USGS, 2006), and calculates the percent of streams that are ephemeral or intermittent relative to total stream length using total kilometers of linear streams in watersheds that are totally or partially contained within each state boundary. Watersheds are at the 8-digit Hydrologic Unit Code (HUC) level (U.S. EPA, 2005).

3. Definitions

In humid parts of the world, where precipitation exceeds evapotranspiration, water is plentiful, and rivers will typically flow ceaselessly except in times of exceptional drought or human diversion. In arid and semi-arid regions, flows have a beginning and an ending in time and space, and there are various classification systems for categorizing the permanency of stream flows, or hydrologic continuum.

For this report, we classify streams by the following definitions:

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 ground-water reservoir.

Intermittent: A stream where portions flow continuously only at certain times of the year, for example when it receives water from a spring, ground-water 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 stream or portion of a stream that flows year-round, is considered a permanent stream, and for which baseflow is maintained by ground-water discharge to the streambed due to the ground-water 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).

In addition, for this report we clarify the definition of *Riparian area* or *riparian zone* as: the strip of vegetation along an ephemeral, intermittent, or perennial stream, which is of distinct composition and density from the surrounding uplands (see Section 5.d.i Plant physiognomy, density and species composition for further discussion).

Many seemingly perennial reaches of a stream are separated by ephemeral or intermittent segments of flow, as a result of differences in geology along the river. This variation of flow is common enough in the Southwest that hydrologists use the terms *interrupted* or *spatially intermittent* to describe the spatial segmentation of a river into reaches that are ephemeral, intermittent, or perennial.

The active channel of a desert stream is defined by the *hyporheic zone,* the zone between the surface stream and alluvial ground water, and the *parafluvial zone,* the part of the active channel without surface water (Figure 4). A desert stream ecosystem is composed of four interacting subsystems: the riparian zone, the surface stream, the hyporheic and the parafluvial zones (Holmes et al., 1994). Stream ecologists are becoming increasingly aware of the importance of what happens below the channel bed (Boulton et al., 1998) and in these interacting zones (Holmes et al. 1994).

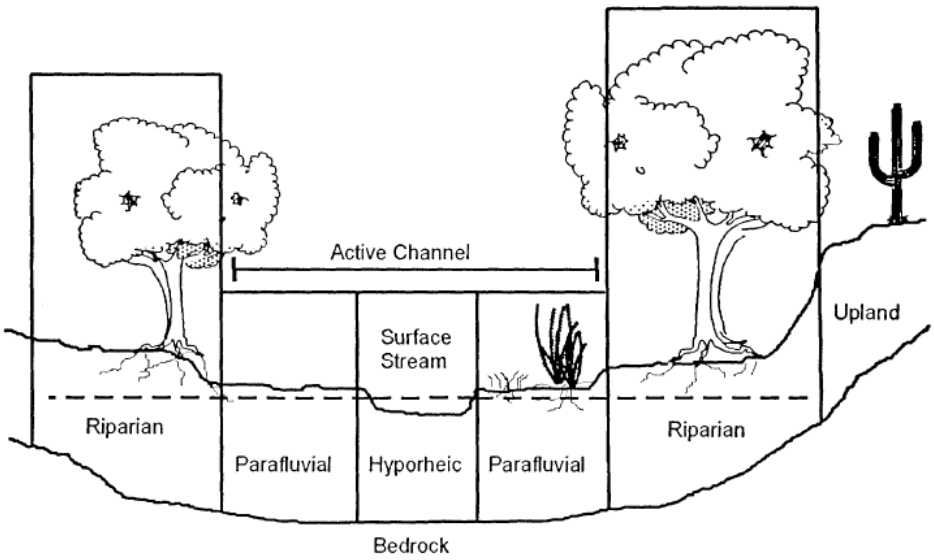

Figure 4. Diagram of the four interacting zones of a desert stream ecosystem: the surface stream, hyporheic, parafluvial and riparian zones (from Holmes et al. 1994).

The hyporheic zone is important to the physical, chemical, and biological integrity of the above-ground portion of the stream. A stream reach that lacks water at all times on the surface may continue to have a thriving hyporheic zone. Water in the hyporheic zone may be discharged into perennial or intermittent reaches of flow downstream. During hyporheic flow, ground water and stream water mix in the beds and banks of ephemeral, intermittent, and perennial streams and sometimes in a larger region surrounding the stream channel. In these zones, there is substantial biogeochemical cycling of nutrients and trace elements that are essential to aquatic life (Valett et al., 1994; Boulton et al., 1998; Hibbs, 2008). The parafluvial zone can be extensive in some systems, and the potential for surface-subsurface exchange is high; however, less is known about these processes than in the hyporheic zone (Holmes et al., 1994).

4. The Watershed Context

Watersheds gradually are becoming regarded as the most appropriate spatial unit for land management, and especially for water-resource management. Managing from a watershed context is more effective than focusing on a specific site, such as an individual ephemeral or intermittent stream segment, because actions by humans, wildlife, and nature can have widespread effects, crossing political boundaries and impacting downstream water quality and ecosystem health. The accumulation of impacts over large areas in the rapidly developing southwest suggests a landscape or watershed-scale approach that considers the cumulative effects on overall watershed function.

Ephemeral and intermittent stream channels are often but not always the smallest channels in the watershed, and often represent the headwaters of a stream. Given their large extent, these streams are important sources of sediment, water, nutrients, seeds, and organic matter for

downstream systems and provide habitat for many species (Gomi et al., 2002) and their inclusion is important in watershed-based assessments (Gandolfi and Bischetti, 1997; Miller et al., 1999b).

An understanding of the key ecological and hydrological functions that watersheds perform is required for effective land and water quality management. These watershed functions, outlined by Black (1997), include:

(1) the collection of water from rainfall, snowmelt, and storage that becomes runoff,
(2) the storage of various amounts of water and sediment,
(3) the discharge of water as runoff, and the transport of sediment,
(4) providing diverse sites and pathways along which chemical reactions take place, and
(5) providing habitat for flora and fauna.

The two integrative watershed responses to these five functions are hydrologic energy attenuation, and the regulated movement or flushing of water through the system which controls the movement of chemicals. Depending on the flow regime, the movement of water affects the concentration or load of materials in suspension or solution in the aquatic environment. Black (1997) referred to this link between hydrology and water quality to demonstrate the importance of considering the entire watershed in the protection of water resources.

Miller (2005) discussed the connectivity of ecosystems in a landscape, and the importance of managing at that scale, noting how the condition of one part of a landscape can affect other portions. Figure 5 illustrates how ecosystem processes, organisms, resources, and disturbances interact across a landscape. In arid and semi-arid regions, ephemeral and intermittent streams provide much of the ecological and hydrological connectivity in a landscape. Although lacking perennial flow, they may constitute a large percentage of the stream network in a watershed, and are connected to the larger stream system.

The disturbance or loss of ephemeral and intermittent streams has dramatic physical, biological, and chemical impacts, which are evident from the uplands to the riparian areas and stream courses of the watershed. Barnett et al. (2002) noted that the condition of upland areas is integral to hydrologic function. The amount of precipitation which immediately runs off the land surface, and that which infiltrates into the soil to either be used for plant growth or to recharge ground water, is dependent on this critical interface. For example, when precipitation falls on the land its fate is affected by the soil and vegetation, which in turn are affected by land uses, both historical and current.

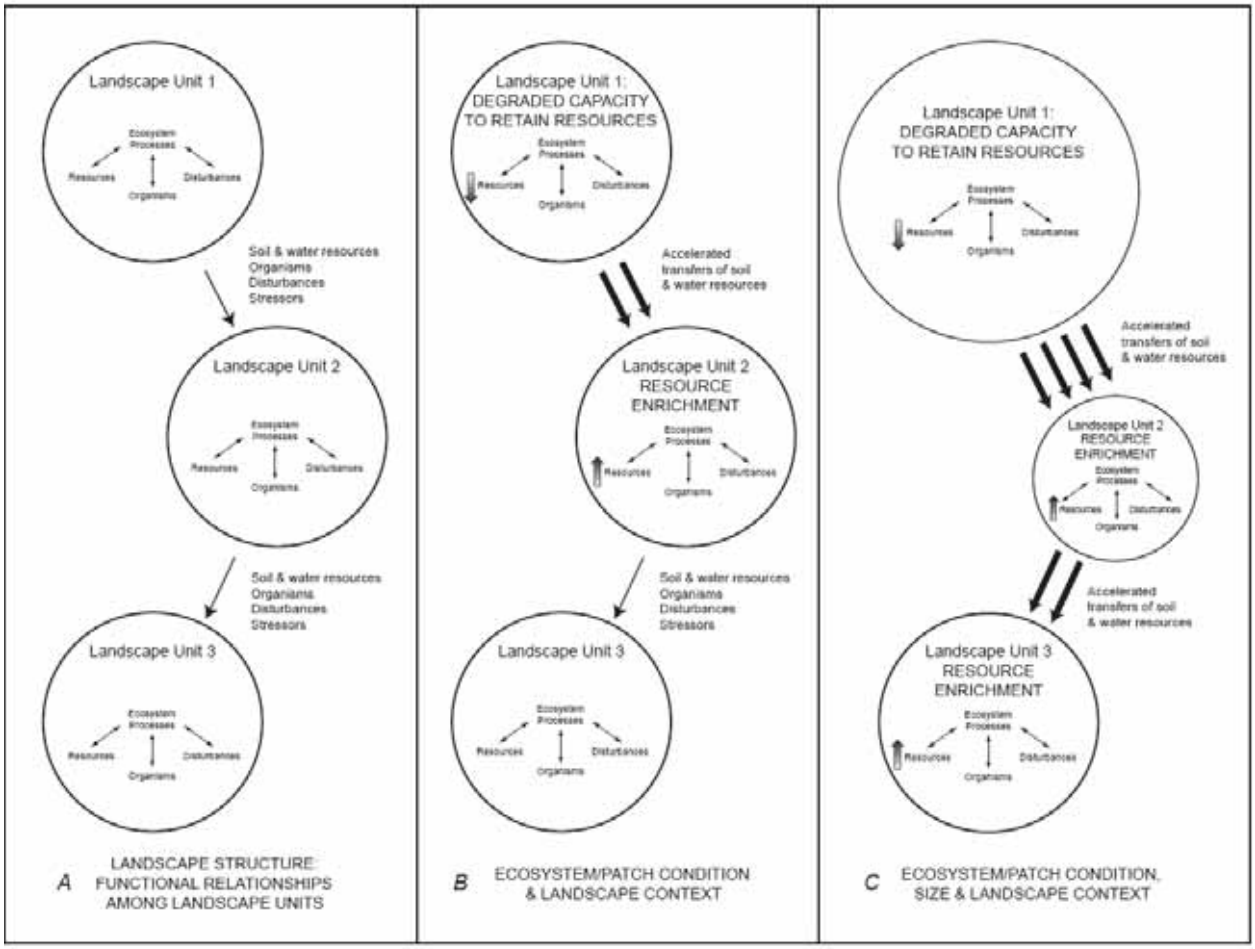

Figure 5. Diagram showing connectivity of landscape-level processes and attributes important for ecosystem monitoring (from Miller, 2005). In box *A*, landscape units are functionally connected by flows of soil and water resources, organisms, disturbances, and stressors. In box *B*, degraded conditions in Unit 1 are shown to cause resource enrichment in Unit 2, illustrating the importance of landscape context. In box *C*, degraded conditions in Unit 1 are propagated to Unit 3 due to increased size of Unit 1 and decreased size of Unit 2.

5. Characteristics, Functions, and Ecosystem Significance

Ephemeral and intermittent streams in arid and semi-arid regions have distinctly different characteristics from perennial streams that are in wetter, more humid (mesic to hydric) environments. These complex systems have developed in a climatic regime of wide fluctuations of precipitation, ranging from drought to flood. Anthropogenic uses, such as urbanization, superimposed on that climatic regime can exacerbate or ameliorate their effects on soils and vegetation, and may affect hydrologic and ecological functions throughout the watershed. Stability and resiliency to disturbance are important for ecological integrity, but because of the deficiency of water, terrestrial arid and semi-arid region ecosystems do not recover quickly from human-imposed disturbance, although desert streams recover more quickly than the uplands.

While hydrologists generally reject the popular concept of an "underground river," the sediment below the channel does convey water. For some streams, in current climatic regimes, there may not be a perennial or intermittent reach, but water may always be present below the ground and accessible to a rich assemblage of plant and animal life. This is illustrated in Figure 6, the San Pedro River, Arizona, an intermittent stream, bordered by a ground-water-dependent cottonwood forest.

Figure 6. Photograph showing ground-water dependent cottonwood trees (*Populus fremontii*) lining an intermittent stream.

Ephemeral or intermittent stream reaches can be headwater reaches or the main stem. Some watersheds consist of only ephemeral or intermittent streams. Generally, these systems occur in arid and semi-arid regions, and their locations can be described using climatic factors, latitude, continental position, and elevation. These features combine to form the world's ecoclimatic zones, which are referred to as an ecosystem region or ecoregion.

The classification of ecoregions provides a method of characterizing the ecological areas of the U.S., and allows for the rich mosaic of environmental conditions to be placed in context with one another, enabling their connections to be better understood. Ecoregion classifications indicate areas of similar environmental characteristics, which can serve as a spatial framework for the research, assessment, management, and monitoring of ecosystems and ecosystem components, and can help us to understand the ecosystems in which ephemeral and intermittent streams occur. This is useful for proper understanding and management of our environmental resources, including water (Commission for Environmental Cooperation, 1997).

Both Bailey's Ecoregions (Bailey, 1976) and the EPA Ecological Regions of North America (Commission for Environmental Cooperation, 1997), based on Omernik and others, place the

Southwestern states mainly in dry, desert, or semi-arid classifications. The essential feature of these classifications is that annual losses of water through evaporation at the earth's surface exceed annual water gains from precipitation.

Bailey's Ecoregion classification is based largely on forest and climatic factors. This classification system designates four domains: polar, humid temperate, humid tropical, and dry. The first three are based on humidity and thermal characteristics; however, the fourth, the dry domain, is based solely on moisture, and is defined as those locations where annual losses of water through evaporation at the earth's surface exceed annual water gains from precipitation. Five of the six states considered in this report lie wholly within the dry domain: Arizona, Nevada, Colorado, Utah, and New Mexico. The deserts of Southern California are also within the dry domain, whereas the rest of the state is within the humid temperate domain (Figure 7). The dry domain includes the arid desert and the semi-arid steppe, and represents seven Divisions encompassing a wide diversity in terrain, vegetation structure and composition, climatic regime, hydrologic regime, and ecosystem function. However, the dominant characteristics are variable rainfall and high evapotranspiration.

The EPA Ecological Regions Classification is based on Omernik, who was one of the first to take a more holistic approach by including physical and biotic characteristics (Commission for Environmental Cooperation, 1997). This classification defines four levels of ecological regions that represent increasingly detailed local characteristics. Level II, which is most similar to Bailey's Divisions, is illustrated in Figure 8. Most of the Southwestern states fall into the warm or cold desert ecoregion, the southern semi-arid highlands, or temperate sierras. These areas are described as having an arid to semi-arid climate, with marked seasonal temperature extremes. This aridity is the result of the rain shadows of the Sierra Nevada, Cascade Mountains and Sierra Madre ranges as they intercept the wet winter air masses brought by the westerly and easterly winds.

Both the Bailey's and EPA Ecoregion classifications illustrate the extent of arid and semi-arid regions in the Southwestern U.S. and provide a framework for understanding the unique conditions found in this region where most watersheds are dominated by ephemeral and intermittent streams.

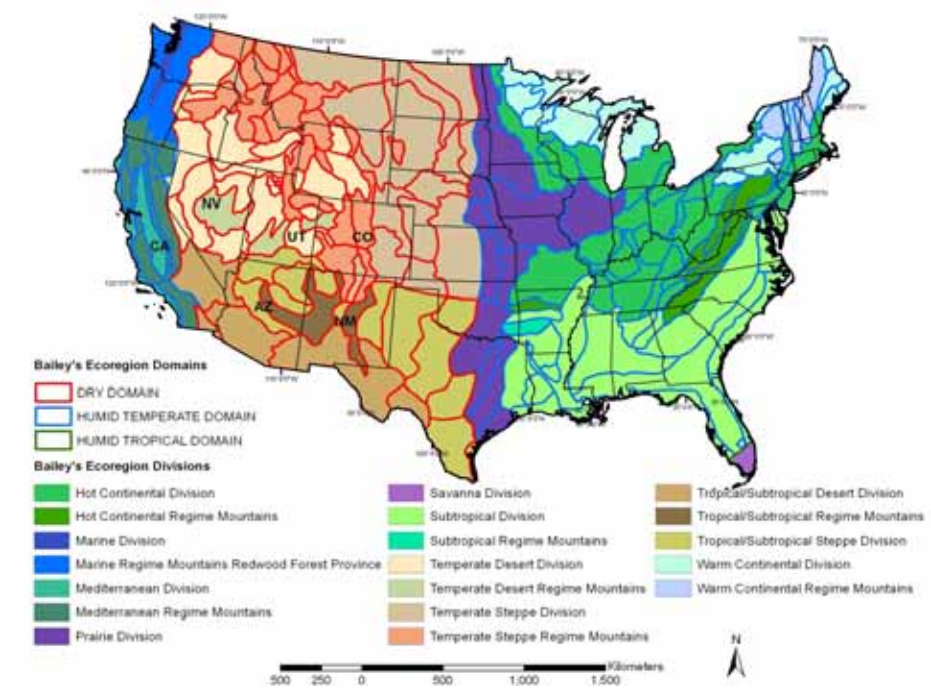

Figure 7. Map of the conterminous U.S. showing Bailey's Ecoregions with the dry domain outlined in red.

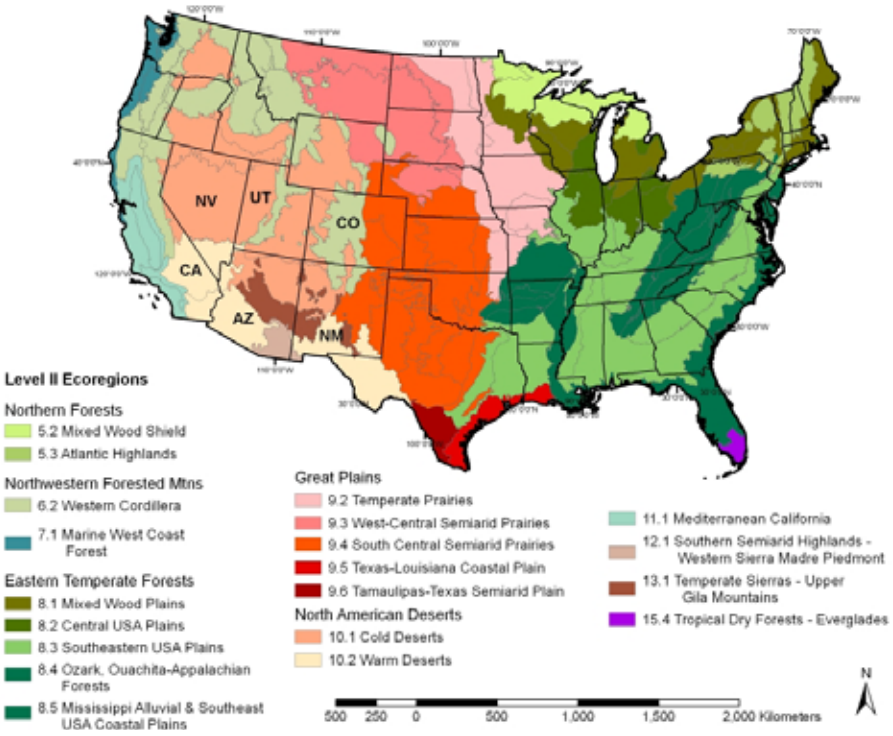

Figure 8. Map of the conterminous U.S. with EPA Level II Ecoregions showing most of Nevada, Arizona, Utah, and New Mexico in the North American Deserts classification.

a. Hydrologic Features

Ephemeral streams are unique in that they lack permanent flow except in response to rainfall events. Intermittent streams flow continuously only in places where it receives water from a ground-water source or from seasonal runoff. Nevertheless, they perform the same critical hydrologic functions as perennial streams: they move water, sediment, nutrients, and debris through the stream network and provide connectivity within the watershed. These streams experience extreme and rapid variations in flood regime (Figure 9), and as a consequence rarely reach process-form equilibrium where flow conditions change too rapidly for bedforms to develop a form matching that flow, so sedimentary structures can give a misleading picture of the flow that occurred (North, 2005).

Although arid and semi-arid region streams perform the same functions as perennial streams, their hydrology and sediment transport characteristics cannot be reliably predicted by extrapolation from humid regions (Scott, 2006; McMahon, 1979). This is due to a much higher degree of spatial and temporal variability in hydrologic processes and also in the resulting erosion and sedimentation processes than in humid regions. Desert environments typically produce more runoff and erosion per unit area than in temperate regions for a given intensity of rainfall due to sparse vegetation cover and poorly developed soils with little organic matter (Thornes, 1994).

Figure 9. Photographs of an ephemeral stream, same location with flow (left), and dry (right), Tucson, Arizona.

The variability of flood magnitudes is much greater for ephemeral stream channel flows as compared to that of perennial stream systems. For example, Graf (1988) reported that in a humid region in Pennsylvania, the 50-year return flood event is roughly 2.5 times the mean annual flow, whereas the 50-year return flow for the Gila River in Arizona is about 280 times the mean annual flow. Although this may also be a function of differences in base-flow, the difference is still significant. Some studies have noted that many of our watersheds in the Western States (up to 90 percent in Arizona, for example) yield less than 12.7 mm of runoff

per unit area, per year, but the vast extent of these arid and semi-arid watersheds makes their total runoff production significant, and their proper management important (Renard, 1970). Osterkamp and Friedman (2000) compared runoff and extreme rainfalls of semi-arid areas with those of other climatic areas in the conterminous U.S. They found that the magnitudes of intense precipitation in semi-arid areas are generally less than in humid areas, but peaks of infrequent floods are typically larger, with many of the greatest recorded unit flood flows occurring in drainage basins of less than 1,000 km^2.

Most of the Southwest receives less than 500 mm of rainfall per year, and a correlation can be seen between locations with low average annual rainfall amounts and locations with ephemeral or intermittent stream flow. Figure 10 shows maps of the average annual precipitation for the Western U.S. for 1961-1990, and the locations of perennial and ephemeral/intermittent streams from the NHD dataset for comparison. Because of the low rainfall amounts, most stream reaches in the Southwest are ephemeral or intermittent.

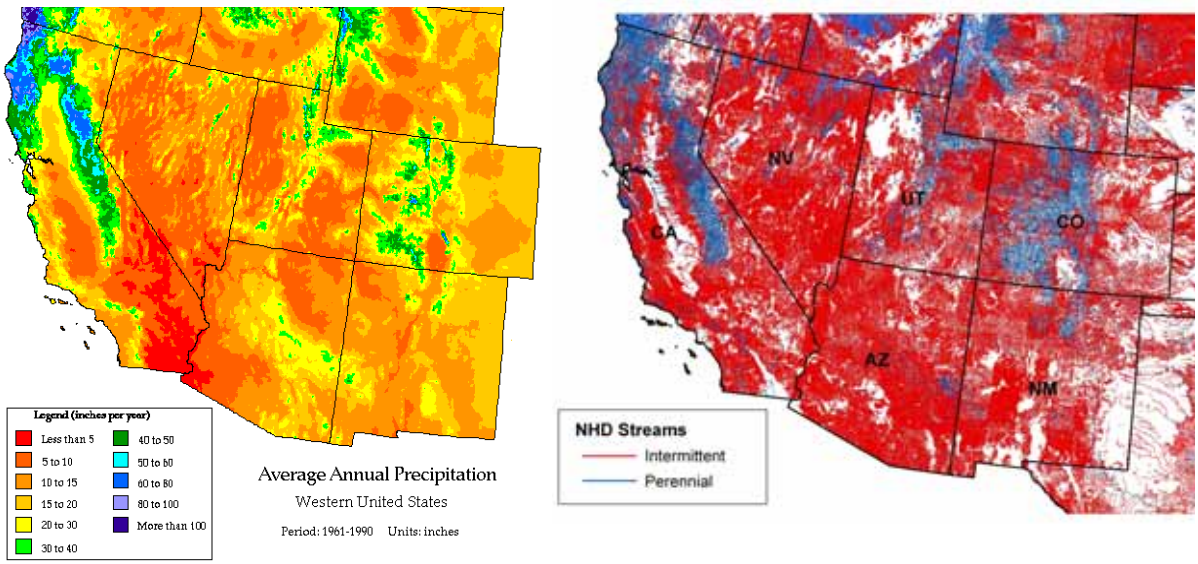

Figure 10. Maps showing average annual precipitation amounts, 1961-1990 (left), and locations of ephemeral/intermittent (red) and perennial (blue) streams (right). (Western Regional Climate Center, http://www.wrcc.dri.edu/precip.html, and National Hydrography Dataset (NHD), http://nhd.usgs.gov/. For NHD see also "Concepts and Contents" at http://nhd.usgs.gov/chapter1/chp1_data_users_guide.pdf).

Rainfall patterns in arid and semi-arid regions influence when streamflow is most likely. The Great Basin and Mojave Deserts have wet winters and relatively dry summers with sporadic thunderstorms. The Chihuahuan Desert receives rainfall primarily during the summer. The Sonoran Desert receives rainfall in both winter and summer (England and Laudenslayer, 1995). Most streamflow events in a large portion of the Sonoran and Chihuahuan Deserts (southern Arizona and New Mexico) occur during the summer monsoon (July through September) from high-intensity, short-duration rainfall events which typically occur as air-mass thunderstorms resulting from convective heating of moisture-laden air masses (Gochis et

al., 2006). This warm-season monsoonal rainfall results from a seasonal reversal of atmospheric circulation that transports moisture from the Gulf of Mexico and/or the Gulf of California (Hereford et al., 2002). Longer duration rainfall events with embedded high-intensity thunderstorms are often the result of dissipating tropical depressions that are common in the fall and sometimes in the winter (Webb and Betancourt, 1992; Gochis et al., 2006), while the lower-intensity events are typical of cool-season precipitation caused by frontal systems originating in the eastern North Pacific Ocean (Hereford et al., 2003).

Significant streamflow events in ephemeral stream channels occur infrequently from low-intensity cool-season precipitation unless there has been regular rainfall for several months and the soil is saturated. Still less frequently (for example, approximately 3 to 5 percent of the annual rainfall in southern Arizona, on average), runoff and streamflow occurs from the remnants of hurricanes and tropical depressions which track north from lower latitudes. The influence of both the summer monsoon and increases in precipitation from tropical depressions decreases northward.

Most of New Mexico and large portions of Arizona and Colorado receive between 30 to 50 percent of their annual precipitation during just two months, July and August, when the monsoon thunderstorms occur. Figure 11 shows maps of the percent of average annual precipitation occurring during the summer season (July and August), and during the 6 months of the cool season (October through March) for a comparison.

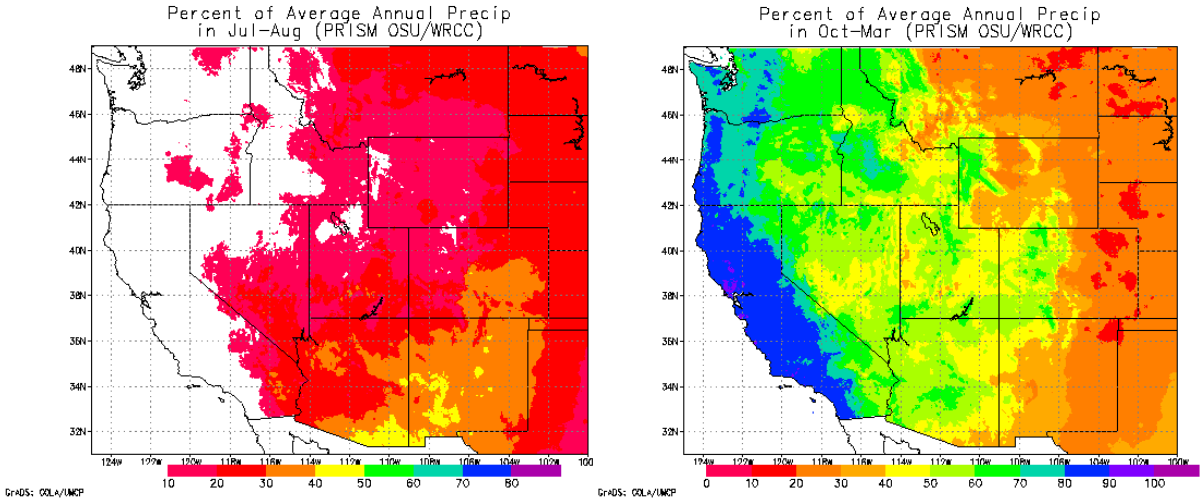

Figure 11. Maps showing percent of average annual precipitation, July and August (left) and percent of average annual precipitation, October through March (right), for comparison, Western Regional Climate Center, http://www.wrcc.dri.edu/precip.html.

i. Variability of arid and semi-arid region flows and floods

Many aspects of arid and semi-arid region floods are highly distinctive. The low annual precipitation in these regions inevitably means low annual runoff, with interannual variability of runoff increasing as annual totals decrease (McMahon, 1979; Rodier, 1985). In North American arid lands, the variability of mean annual runoff is about double that for the

continental area as a whole (McMahon, 1979). In addition, given the spatially variable patterns of precipitation and runoff in arid and semi-arid regions, for any given watershed size there is a large range in annual runoff totals (Reid and Frostick, 1997), and basin response can only be extrapolated to a very limited extent (De Boer, 1992). This implies that watershed area usually cannot be used as a reliable surrogate measure of runoff in arid and semi-arid regions. Goodrich et al. (1997) found that watershed rainfall-runoff response becomes more non-linear with increasing watershed size due to the increasing importance of ephemeral stream channel transmission losses and partial area storm coverage.

With the exception of perennial, mainly allogenic rivers (those that originate and are fed from outside of the area, where precipitation and runoff are sufficient to generate flow), most arid and semi-arid region rivers are characterized by long periods without flow. For example, in the Negev Desert in Israel, Reid et al. (1998) conducted flow duration analysis and found that ephemeral stream channels are hydrologically active only 2 percent of the time, or about seven days per year, and that overbank flow can be expected for only 0.03 percent of the time – about three hours per year. Because of infrequent flows, process studies in arid and semi-arid region channels are dominated by the analysis of flood events (Graf, 1988). In the general fluvial literature, a flood is usually defined in relation to a humid region event (i.e., the near or complete exceedance of bankfull). Nevertheless, several authors (e.g. Leopold and Miller, 1956; Schumm and Lichty, 1963; Hedman and Osterkamp, 1982; Bourke and Pickup, 1999) have referred to the variable size of floods, as this can be important for processes of sediment transport and channel change.

Floods caused by distinctly different climatic processes commonly have distinctly different magnitude and frequency relations. Many studies have examined the nature of these differences by separating flood data for a station into two or more populations on the basis of the climatic causes of the floods (U.S. Army Corps of Engineers, 1958; Elliott et al., 1982; Jarrett and Costa, 1982; Waylen and Woo, 1982; Hirschboeck, 1987). Results of these studies for different regions have indicated that floods caused only by snowmelt, by rain on snow, and only by rain, form distinct populations; floods caused by rain on snow or only by rain tend to have larger magnitudes than do floods caused only by snowmelt. In parts of the arid Southwest, floods caused by precipitation from frontal passages in the winter tend to be larger than floods caused by precipitation from convectional storms in the summer. In the Southwest and Northeast, floods caused by precipitation from tropical cyclones tend to have greater magnitudes than do floods caused by precipitation from storms other than tropical cyclones. Floods caused by precipitation from tropical cyclones commonly include the peak flow of record (USGS, 1997).

Variability of flow is a natural continuum in arid and semi-arid regions, and is affected by climatic and ecological conditions. For example, the peak water demands of a dense riparian forest for transpiration in dry regions can deplete a stream channel of its flow for several hours during a hot summer day. A stream can run continuously for several years, and then go dry, making it difficult to classify the stream as perennial or ephemeral. Increasingly accurate and precise methods of monitoring and measurement, which may now detect these natural phenomena, might change a stream classification, without the river itself changing. Stanley et al. (1997) noted that desert streams are “spatially dynamic ecosystems that undergo cycles of expansion, contraction, and fragmentation; that conventionally hydrologic measurements of

water velocity or volume passing a fixed point represent only one aspect of hydrologic dynamism…"

ii. Types of arid and semi-arid region floods

As well as varying in size, floods in arid and semi-arid regions vary from entirely channeled, to largely unchanneled (Olsen, 1987). In the American Southwest, for example, partly channeled floods occur during major events when river banks are overtopped and flood waters diffuse across vast, low-gradient plains (Hedman and Osterkamp, 1982). Graf (1988) described numerous instances of sheet floods from piedmont settings as examples of unchanneled floods.

Channeled floods in arid and semi-arid region rivers may occur as flash floods, single-peak events, multiple-peak events and seasonal floods (Graf, 1988). The highly variable stream flow in ephemeral and intermittent systems most often occurs as a flash flood, lasting only minutes or hours, or persisting for days or weeks depending on the climatic regime and the nature of the watershed contributing area. Flash floods may occur any time of the year in response to a short-duration high-intensity precipitation event, and after the watershed has received enough precipitation to generate runoff (Figure 12).

Most commentaries on arid and semi-arid region river floods refer to the characteristics of flash flood hydrographs (charts showing change in flow over time), which are typically produced by convectional precipitation in small (< 100 km^2) watersheds. Due to high runoff coefficients and the dominance of Hortonian overland flow in runoff generation, these hydrographs are characterized by steep rising and receding limbs and a short time base (Reid, 1994; Dick et al., 1997). For a simple individual flow event generated by a discrete storm, the rapid rise to peak discharge (almost instantaneous) is followed by the recession portion of the hydrograph. The duration of recession is generally much longer than the time required to reach peak flow, and the resulting flood wave shape is such that almost the entire hydrograph is the recession curve (Figure 13). The recession curve of an ephemeral stream hydrograph has two properties of interest: (1) flow ceases after some period of time, causing the flow to be of finite duration, and (2) the shape of the curve can be compared to an exponential decay reference curve (Chow et al., 1988).

Figure 12. Photograph of a flash flood in an ephemeral channel, Southern Arizona. (Photograph: USDA-ARS/SWRC)

Less well documented are the single and multiple-peak floods generated by tropical storms or frontal systems, or the floods associated with seasonal snowmelt or rainfall. Knighton and Nanson (1997) considered that in moving from single-peak to multiple-peak to seasonal floods there is a corresponding reduction in the steepness of the rising limb of the hydrograph and a broadening of the time base of the floods.

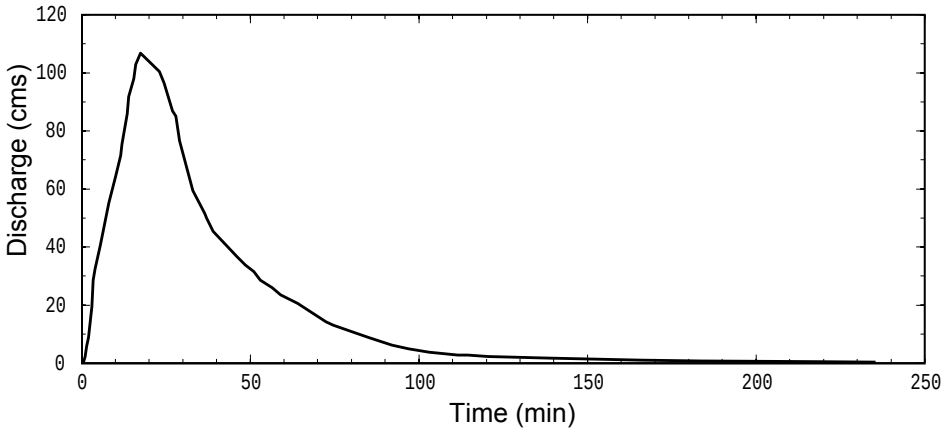

Figure 13. Example hydrograph showing typical rapid rise to peak discharge and long recession curve of a flash flood.

iii. Transmission losses

In a spatial as well as a temporal sense, streamflow in arid and semi-arid region rivers exhibit unique characteristics. Regardless of the source of water, flows in arid and semi-arid region rivers are generally influent, or subject to downstream volume decreases. These decreasing flow volumes principally are due to transmission losses resulting from infiltration of

streamflow into the unconsolidated alluvium forming channel boundaries, losses resulting from overbank flooding, and evaporation of floodwaters (Babcock and Cushing, 1942; Keppel and Renard, 1962; Sharp and Saxton, 1962; Lane, 1983; Goodrich et al. 1997; Cataldo et al., 2004). Transmission losses are also an important source of water for ground-water recharge (see next section).

Downstream volume decreases are sometimes negligible along small, alluvial or bedrock channels, but for larger alluvial channels they can be of great importance, with many flows failing to travel the full length of the channel (Keppel and Renard, 1962; Aldridge, 1970), leaving the lower parts of the watershed dry.

The nature of the rainfall event can affect downstream reductions in flow. When precipitation is widespread, tributary contributions can increase downstream flows even while losses are still large. For spatially localized events, however, in combination with hydrograph attenuation, and in the absence of appreciable tributary inflows in the lower parts of the watershed, transmission losses can produce significant downstream decreases in total flow volume, flood peak, and flow frequencies (Keppel and Renard, 1962; Lane, 1983; Goodrich et al., 1997; Knighton and Nanson, 1997).

A great deal of research on semi-arid region hydrology has been conducted at the USDA-ARS Walnut Gulch Experimental Watershed (WGEW) near Tombstone, Arizona (Figure 14). The WGEW is one of the most intensively instrumented semi-arid experimental watersheds in the world with nearly 100 years of abiotic and biotic data (Moran et al., 2008). The network of over 125 gauging stations has been continuously collecting precipitation and runoff data for over 50 years.

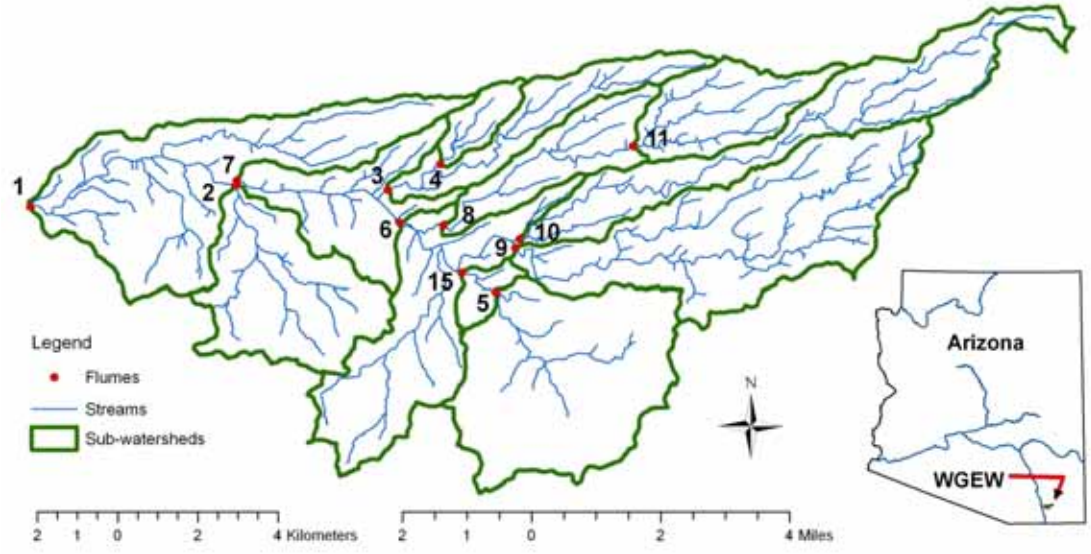

Figure 14. Map of the Walnut Gulch Experimental Watershed (WGEW), Tombstone, Arizona, showing major stream network, flumes and sub-watershed boundaries.

An example of the magnitude of transmission losses within the WGEW is presented in Figure 15. This figure shows the August 27, 1982, storm event that was isolated in Sub-watershed 6 and recorded at Raingage 56 on the upper 95 km^2 of the watershed (although not all of that precipitation produced runoff). The spatial pattern of total storm precipitation depth depicted by the isolines in Figure 15 is interpolated from the WGEW rain gauge network. The temporal distribution of rainfall intensity observed at Raingage 56 is illustrated in the upper right portion of the figure. The runoff measured at Flume 6 was 246,000 m^3, with a peak discharge of 107 m^3/s. Runoff traversing the 10.86 km of dry streambed from Flume 6 to Flume 1 experienced significant infiltration losses. As a result, 90,800 m^3 of water was absorbed in the channel alluvium, and total peak discharge was reduced by 52 m^3/s. Photographs of Flume 1 with and without flow are shown in Figure 16.

The magnitudes and rates of transmission losses for streamflow or flood events in a given arid and semi-arid region river are often highly variable, as both depend on a complex of interrelated factors, including the characteristics of the storm (e.g., size, position of the storm track, location in relation to the drainage network), the hydrograph (e.g., flow volume and duration), and the channel (e.g., width of the wetted perimeter, porosity and initial moisture content of the channel bed, stratigraphy of the channel fill) (Knighton and Nanson, 1997; Reid and Frostick, 1997; Lekach et al., 1998). Cataldo et al. (2004) reviewed about three dozen approaches for predicting transmission losses in ephemeral streams in the U.S., and concluded that approaches that combine differential equations and regression analyses that consider physical processes and statistical methods have the most promise.

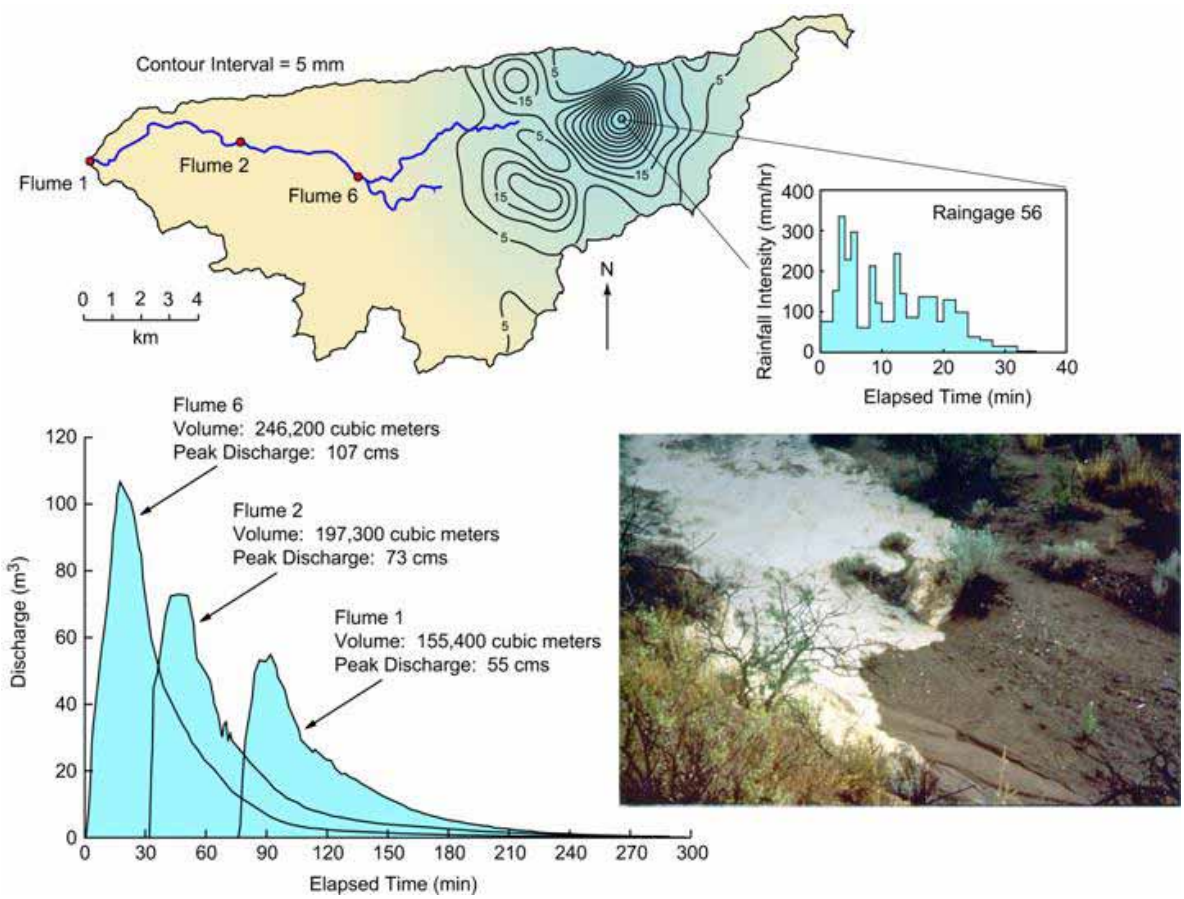

Figure 15. Hydrograph, location map, and photograph of rainfall-runoff event August 27, 1982, illustrating ephemeral stream channel transmission losses as measured within the WGEW (Goodrich et al., 1997).

Figure 16. Photographs of Flume 1 at WGEW, dry (left) and with flow (right). (Photographs: USDA/ARS-Southwest Watershed Research Center, Tucson, Arizona)

iv. Ground-water recharge

Ground-water recharge in arid and semi-arid regions has generally been viewed as the sum of several different distinct pathways including mountain-block recharge, mountain-front recharge, spatially distributed recharge, and ephemeral stream channel recharge. Recent research has expanded this view to include the mediating role of vegetation (i.e. water use by vegetation), and the greater role of ephemeral stream channel recharge in basin floors.

"Mountain-front recharge" refers to the contribution from mountain precipitation to recharge of aquifers in adjacent basins. It includes recharge from the mountain block system and stream channels, and is considered to be the most significant form of ground-water recharge in arid and semi-arid regions, with ephemeral stream channel recharge providing a significant portion in these climates (Goodrich et al., 2004; Coes and Pool, 2005). Basin floor or spatially distributed recharge in arid and semi-arid regions plays a lesser role in the overall recharge volume due to high evaporation rates, low rainfall, and high water use by desert vegetation (Coes and Pool, 2005).

Advances such as environmental tracers and geographic information systems (GIS) based ground-water models have improved our understanding of recharge processes (Phillips et al., 2004; Hogan et al, 2004). However, an accurate representation of ground-water recharge is difficult since it cannot be measured directly on a basin scale, in addition to other reasons, including the extremely small recharge rates and recharge mechanisms that vary greatly in time and space throughout a watershed. The methods used in humid regions, such as a water balance approach, are not applicable in arid and semi-arid regions because these extremely small amounts of recharge are within the measurement error, and potential evapotranspiration exceeds precipitation (Hogan et al., 2004; Phillips et al., 2004). Also, channel transmission losses are more significant in most ephemeral and intermittent channels than in humid region perennial streams, as noted in the previous section. Therefore, methods for calculating recharge are indirect, and subject to cumulative measurement errors. In addition, the annual variability of precipitation in arid and semi-arid regions makes it difficult to apply recharge models, which simulate the direct recharge to the aquifer from infiltration of precipitation. Goodrich et al. (2004) noted that ephemeral stream channel transmission losses play an important role in ground-water surface-water dynamics in numerous arid and semi-arid regions and are potentially significant sources of recharge at the basin scale. However, identification of the processes driving these dynamics is difficult. Specifically, it is difficult to obtain data on the proportion of transmission losses that become deep ground-water recharge instead of being lost to near-channel evapotranspiration (ET) and wetted channel evaporation.

This issue was addressed via coordinated field research and modeling within the WGEW. A variety of methods were used to estimate ephemeral stream channel recharge, including ground water, surface water, chemical, isotopic, tree sap flux, micrometeorological techniques, and changes in microgravity. Changes in microgravity reflect the gravitational pull of the Earth and indicate the presence of subsurface density variations such as those produced by voids or cavities. A cavity usually has a lower density than the surrounding

materials and may be filled with water or sediment, resulting in a very small reduction in the pull of the Earth's gravity (Styles et al., 2006).

Figure 17 illustrates the changes in deep ground-water levels due to multiple runoff events during the 1999 and 2000 monsoon as well as associated microgravity changes. During the relatively wet 1999 and 2000 monsoon seasons the channel recharge estimated from these methods differed by a factor of about 2.9. A rough scaling of these rates to the entire basin shows that these estimates would constitute roughly 15 percent at the low end of the range and 40 percent at the high end, respectively, of all water recharged annually into the regional aquifer as derived from a calibrated ground-water model estimate (Goodrich et al., 2004). However, in 2001 and 2002 no discernable ephemeral stream channel recharge in the intensely studied reach was detected due to weak monsoon seasons, illustrating that ground-water recharge in ephemeral stream channels can be significant in some years and negligible in others.

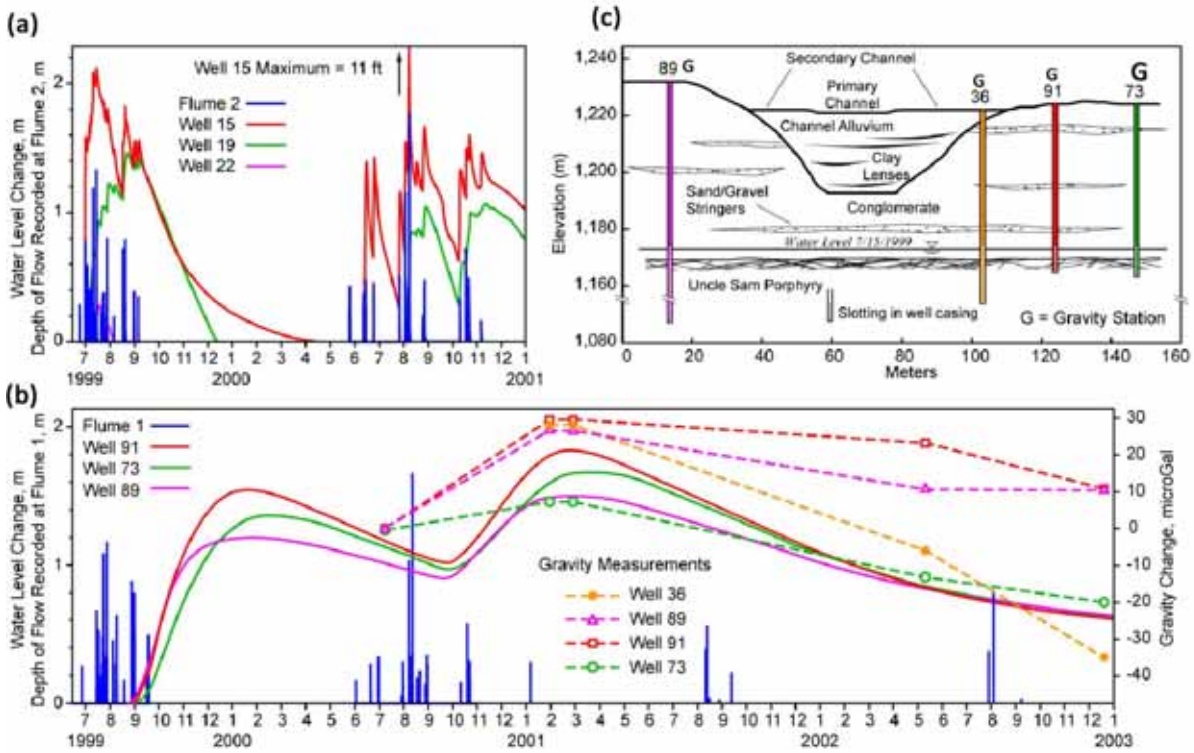

Figure 17. Diagrams of well levels and flow depths at the WGEW. Diagram (a) at top left shows Flume 2 well level changes (m) and flow depths (m), diagram (b) at bottom shows Flume 1 well level changes (m), flow depths (m) and gravity measurements, and diagram (c) on upper right shows a cross section of well transect above Flume 1 (from Goodrich et al., 2004).

Other studies have also noted the importance of locally recharged monsoon floodwater derived from ephemeral stream channels for maintaining river flow. Using a suite of geochemical tracers and a two end-member mixing model, Baillie et al. (2007) found that locally recharged monsoon floodwaters is one of the dominant water sources in the main stem

of the spatially intermittent San Pedro River, with these waters comprising 60 to 85 percent of riparian ground water in losing reaches of the main stem and 10 to 40 percent in gaining reaches. Baseflows in the perennial reaches also contained a significant component of monsoon floodwater: 80 percent at the upstream segment, decreasing to 55 percent after several gaining reaches (Baillie et al., 2007). Various other methods of tracers are described in Cook and Herczeg (1999). Coes and Pool (2005) looked at recharge in the same basin and found that ephemeral stream channel recharge occurs during both summer and winter streamflow events.

v. Landscape and hydrologic connections

Watersheds and their surrounding ecosystems are linked by the flow of water. In a watershed context, landscape hydrologic connectivity refers to the maintenance of natural hydraulic connections of surface and subsurface flow between source, headwater, or contributing areas and downstream/down gradient receiving waters. Nadeau and Rains (2007) defined it as "the hydrologically mediated transfer of mass, momentum, energy, or organisms within or between compartments of the hydrologic cycle." In arid land streams, this hydrologic connection occurs episodically during flood pulses, yet still provides a substantial amount of the mass, momentum, energy and organisms delivered to downstream perennial waters, as well as to ground-water recharge.

Freeman et al. (2007) stated that, "The hydrologic connectivity of small headwater streams to navigable waters is clear and unambiguous to ecologists. Every important aspect of the river ecosystem, the river geomorphic system, and the river chemical system begins in headwater streams." Kennedy (1977) discussed the interactions of stream-riparian-vegetation-energy-nutrients-water production-aquatic life and terrestrial life, noting that the key to wise management of aquatic ecosystems is wise management of the watershed.

As headwater streams occur upstream from, and may ultimately discharge into higher order perennial streams, they connect landscape processes through their influence on the supply, transport, and fate of water and solutes in the watershed (Alexander et al., 2007; Leibowitz et al., 2008).

Shaw and Cooper (2008) noted that biotic patterns within ephemeral stream networks are controlled directly by interactions of hydrologic and geomorphic regimes, and indirectly by watershed and stream-network properties. In their study of riparian vegetation and watershed linkages in ephemeral stream systems, they classified channels into three types based on physical properties and plant community types. Their classification system described functional linkages among watersheds, stream reaches, and riparian plant ecology, indicating a strong landscape connection between processes in the upper watershed and the lower watershed. For example, they found that streamflow and ground water regimes in regional flood plain rivers were driven by climatic patterns from distant portions of the upper watershed and were relatively insensitive to local rainfall.

Figure 18. Photograph of ephemeral and intermittent stream channels connecting to a perennial reach of Cienega Creek, southeast of Tucson, Arizona. (Photograph: Lainie Levick/Aerial flight courtesy of Lighthawk, www.lighthawk.org)

Delivery of water to a stream is dependent largely on the timing, duration, and amount of water that falls on the surface and subsequently runs off, which is dependent on soil type, and condition of the watershed and buffer. The importance of hydrologic connectivity in arid environments relates closely to the delivery of water, sediment, nutrients, compounds, etc. to downstream areas. Small tributaries generally have land-dominated hydrographs as opposed to stream-flow dominated, because they mainly drain adjacent land surfaces. Numerous observed runoff events originating in the uplands of ephemeral tributaries at the WGEW have reached the San Pedro River as evidenced by corresponding hydrograph observations at the USGS Tombstone gaging station just downstream of the confluence of Walnut Gulch and the San Pedro River. Instrumenting additional watersheds would add to the understanding of these arid and semi-arid systems.

Although observed runoff events are more meaningful than simulated results, nevertheless, models are useful in understanding a hydrologic system. In a hydrologic modeling study of ephemeral tributaries to the San Pedro River, Levick et al. (2006) determined that simulated flows from the uplands would reach the San Pedro. Using the AGWA/KINEROS model, they looked at runoff and sediment yield using three design storms: 2-year 1-hour, 5-year 1-hour, and 10-year 1-hour. They determined that under predevelopment conditions, even the 2-year-1-hour design storm event (18.47 mm) was enough to fill the void spaces in channel-bed sediment, overcome transmission losses, and cause a small but measurable flow at the watershed outlet, demonstrating a hydrologic connection from the ephemeral tributaries to the San Pedro River, nearly ten miles downstream. The simulations showed that larger storm events yielded more flow, as did post-development simulations where impermeable surfaces in the watershed increased. For more information on the AGWA/KINEROS model, go to http://www.tucson.ars.ag.gov/agwa.

Figure 19. Photographs of an ephemeral stream, same location during flow (left), and dry (right), Tucson, Arizona.

vi. Energy dissipation

Energy dissipation refers to the transformation and/or reduction in the amount of kinetic energy of flowing water, which is a function of channel roughness, channel morphology, and buffer and landscape vegetation. Stream energy dissipation is important for the prevention of channel erosion and scour, and increased sediment loads that can degrade water quality.

Water flowing in stream channels is subject to two key forces: (1) gravity that moves the water downslope and (2) friction between the water and channel boundaries that resists the downslope movement. These two forces determine, to a large degree, the ability of the water to modify the channel geometry and transport debris. In addition, channel roughness, slope, and depth determine the velocity of the flowing water (Leopold et al., 1964; Wakelin-King and Webb, 2007). Channel slopes in the Southwest are often large so when flows do occur they have high velocities and consequently significant energy and stream power.

Dissipation of energy in channels can occur due to vegetation, curvature (stream sinuosity), obstructions (rocks, debris, dams), and the size, character and configuration of material in the bed and banks. Flow hydraulics and roughness coefficients in some arid and semi-arid channels are strongly influenced by vegetation, which frequently grows on the normally dry channel beds to exploit moisture contained in subsurface sediment.

vii. Sediment mobilization, storage, transport, and deposition

As noted previously, although ephemeral streams do not flow at all times, they still perform the major functions of a stream: the transportation of water, nutrients, and sediment. Unlike perennial streams that continuously move sediment through the watershed, sediment movement in non-perennial stream channels generally occurs as a pulse in response to runoff generated by the short duration, high intensity thunderstorms that are typical of arid and semi-arid regions. These thunderstorms can result in flash floods and yield rapidly rising runoff

hydrographs. The associated high velocity turbulent flash flows contain heavy sediment loads and push large amounts of coarse sediment through the system. In addition, sediment is moved from the uplands and hillslopes into the channels from overland flow. Figure 20 shows photographs from an unusually large flood event in Tucson, Arizona, that moved large quantities of rock and debris through the channel. The rock and debris plugged up the bridge, causing the floodwaters to leave the channel, damaging the roadway and flooding nearby homes.

Figure 20. Photographs from an unusually large flood event in an ephemeral stream that damaged roads and bridges, and flooded nearby homes, Tucson, Arizona, July 31, 2006.

Channels in arid and semi-arid regions tend to have deep sediments that are mostly sands and gravels, with widely scattered shrubs that are resistant to violent flood waters. However, the unconsolidated alluvium can easily be mobilized during flows, unlike the clay bedded or armored channels in more humid regions. These deep sediments cause large transmission losses in the downstream direction, resulting in reductions in both flow volume and velocity over the length of the stream, and subsequent deposition of bed load materials and coarser suspended sediments in the downstream segments (Whitford, 2002).

Storm water is often completely absorbed in the channel network before reaching the outlet. Transmission losses and decreasing discharge in the downstream direction thus promote the stepwise movement, deposition and storage of sediment within ephemeral stream networks (Renard, 1975). The effect is a pulsing style of sediment movement that doesn't always reach the watershed outlet, but is instead remobilized during the next flow and redistributed within the watershed's channel network (Leopold et al., 1964; Thornes, 1977; DeBano et al., 1995).

Ephemeral and intermittent channels contain a wide range of sediment size, with the larger material remaining essentially at rest although a significant portion is available for transport (Renard and Laursen, 1975). These channels are typically transport-limited systems as opposed to detachment limited. The large flows that can move great quantities of sediment are relatively infrequent in arid and semi-arid regions; however the sediment moved by the smaller more frequent flows can add up to a considerable amount (Nichols, 2006).

As a result of decreased flow rates in the downstream direction, more silts and fines are deposited in the channel, which can be advantageous to biotic communities. A study of

ephemeral rivers in the Namib Desert (Jacobson et al., 2000a) found that "Organic carbon, nitrogen and phosphorous were correlated with silt content, and silt deposition patterns influence patters of moisture availability and plant rooting, creating and maintaining micro-habitats for various organisms." Jacobson concluded that "…alluviation patterns associated with the hydrologic regime strongly influence the structure, productivity, and spatial distribution of biotic communities in ephemeral river ecosystems."

Because the small, uppermost channels of a drainage network are important in determining the amount of sediment transported downstream during storm events, their removal will increase sedimentation rates in downstream channels (Meyer and Wallace, 2000). This increased sediment load can have negative effects on channel stability, fish, invertebrates, and overall stream productivity. However, when small or headwater streams are replaced with paved or lined floodways during land development, sediment production may decrease, causing an increase in downstream erosion as sediment starved waters move through the watershed. Figure 21 is a photograph of sediment-laden floodwaters.

Figure 21. Photograph of sediment-laden floodwaters in an ephemeral stream, Walnut Gulch, Arizona. (Photograph: USDA-ARS/SWRC)

Sediment deposition can have varying effects. For example, sediment deposited during flow events can encourage plant germination (i.e. Cottonwood, *Populus fremontii*) by providing seed beds and scarifying seeds, but it also can inhibit the growth of seedlings or some types of vegetation, such as non-native saltcedar (*Tamarix ramosissima*). This can be beneficial in some instances where stream restoration efforts are occurring. However, some aquatic species can be adversely affected by excessive sediment, which can interfere with reproduction and feeding.

<u>b. Geomorphic Characteristics</u>

The variability in time and space of fluvial processes is particularly characteristic of arid and semi-arid area rivers (Tooth, 2000a), yet the role of rivers in shaping desert landscapes has

generally been underestimated by geomorphologists. As a result, there is inadequate information on geomorphic processes and forms in arid and semi-arid regions. This is important because fluvial processes are a cause of so many problems in desert areas (Reid and Frostick, 1989), and also because the geomorphology and hydraulic-geometry relationships of ephemeral and intermittent streams are very different from humid area perennial streams (Graf, 1988; Reid and Frostick, 1989; Thornes, 1994; Tooth, 2000a; Bull and Kirkby, 2002).

Although one of the most universally recognized traits of arid and semi-arid ephemeral stream channels is their enormous variability in form, several broad generalizations have been used to characterize them:

- They are often closely spaced, resulting in a high drainage density.
- They have high width-to-depth ratios.
- They are likely to be braided (Figure 22).
- They have low sinuosity relative to their humid counterparts.

Closely spaced channels and a high drainage density are generally due to high erosion rates and limited runoff, which produce high sediment concentrations in arid and semi-arid region channelized flows (Reid and Frostick, 1997; Bull and Kirkby, 2002). In headwater areas, this may lead to gullying and/or badland development until such time as shrinking contributing area, stabilizing vegetation, and/or surface armoring moderate erosion from rain splash and surface flows. High width-to-depth ratios, braided channels and low sinuosity are often the result of high sediment concentrations and coarse grain sizes (Bull and Kirkby, 2002).

Figure 22. Photograph showing an ephemeral braided stream system, Yuma Wash, southwest Arizona. (Photograph: Susan Howe, Colorado State University)

In most arid and semi-arid river cross sections, depth increases with discharge somewhat faster than does width (Leopold and Maddock, 1953). The width of channels increases much more rapidly in the downstream direction (Breschta and Platts, 1986) than is observed in humid regions, resulting in wide channels in the lower reaches. Wolman and Gerson (1978) compiled data from different arid and semi-arid regions and found that channel widths increased rapidly up to a drainage area of about 50 km^2 (Figure 23). As drainage area increased beyond about 50 km^2, channel widths asymptotically approached a value between 100 and 200 m. It is likely that this stabilization of channel width for larger drainage areas is due to the fact that transmission losses from flows with such a high wetted perimeter compensate for any addition of tributary water (Reid and Frostick, 1997). In ephemeral stream channels with no significant tributary inputs, transmission losses can result in decreasing channel width and capacity in the downstream direction with some ultimately becoming unchannelized alluvial surfaces termed "floodouts" (Dunkerley, 1992; Tooth, 2000b).

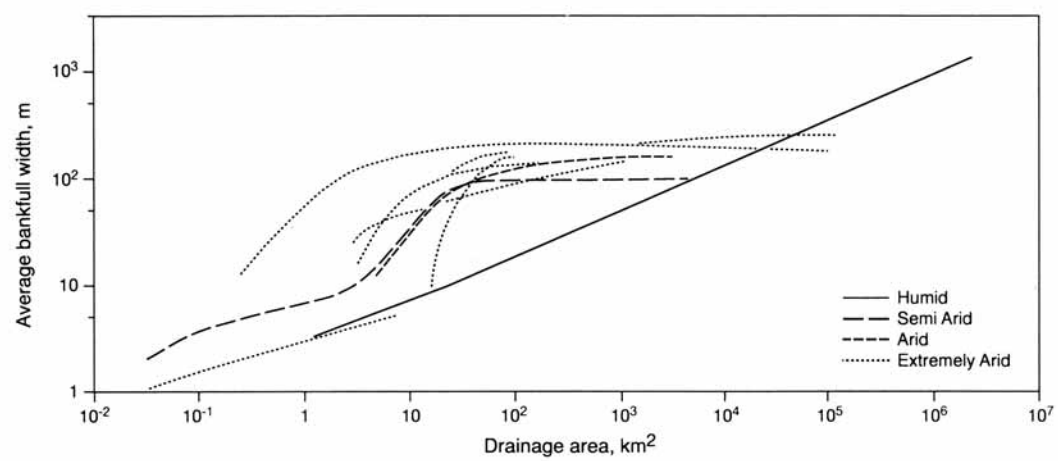

Figure 23. Relation of bankfull channel width to drainage area for different climatic environments (after Wolman and Gerson, 1978).

An oscillating pattern of narrow, incised reaches and wide, shallow reaches has also been observed in ephemeral stream channels (Schumm and Hadley, 1957; Bull, 1997; Pelletier and DeLong, 2004). The wavelength of these oscillations ranges from 15 m to over 10 km (Bull, 1997) and has been successfully modeled as a function of channel slope, width, and depth (Pelletier and DeLong, 2004). Alternating erosional and depositional reaches migrate progressively upstream, resulting in repeated episodes of incision and aggradation at any given point along the channel. Perturbation of these systems by natural or anthropogenic causes can result in the development of continuous incised channels, or arroyos, as described in the next section.

In addition to their pronounced widths, the lower reaches of ephemeral streams are noted for having particularly flat bed topography; the beds of single-thread streams are often near horizontal and planar (Reid and Frostick, 1997) (Figure 24). Channel bars, where present, are also often flat-topped and rise only 10-20 cm above the thalweg (Leopold et al., 1966; Frostick and Reid, 1977, 1979). Bed flatness and channel width are likely related through

flow depth; wide, shallow flows suppress the secondary current cells that encourage the development of bars (Reid and Frostick, 1997). Rapidly receding flows can destroy or modify bedforms such as ripples, dunes, and antidunes that may develop at greater flow depths. Bedforms in streams are created when water currents carry loose grains across the horizontal surface of unconsolidated sediments. The size and shape of bedforms are determined by the flow velocity, direction, and consistency.

Figure 24. Photograph of a typical wide, flat, and sandy ephemeral stream channel, Martinez Wash, Arizona. (Photograph: William Kepner, USEPA/ORD)

i. Channel-forming processes

Fluvial processes are significant agents of erosion and deposition in arid and semi-arid regions and thus, over time, desert rivers can be active land-forming agents (Frostick and Reid, 1987; Reid and Frostick, 1997). Low rainfall in desert regions results in weathering processes dominated by mechanical rather than chemical means. Clay production is thus inhibited and silt-sized fractions are predominant in the soils. The lack of bank-stabilizing clay in arid and semi-arid region ephemeral stream channels may partially explain why these channels typically have wide, shallow, low sinuosity geometries (Schumm, 1961; Scott, 2006). The sparseness of vegetation along some stream banks in arid areas can also contribute to channel widening tendencies (Miller, 1995; Reid and Frostick, 1997). Furthermore, channel-bed armoring is uncommon in desert streams because of the high supply of all sediment sizes, rapid recession of flash flood hydrographs, and extended periods of no flow (Reid and Laronne, 1995).

As event size increases sediment can be moved further downstream, but only the largest, least frequent events are capable of flushing sediment completely through the system and opening up (widening or incising) channels that have become progressively choked with vegetation and sediment. Indeed, Lekach et al. (1992) observed that more than 90 percent of the bed

load yield in an arid-region watershed originated from the mid-catchment channels during larger runoff events. High-magnitude, low-frequency floods thus control channel development, and their effects tend to be modified very slowly by smaller events. The result is a tapestry of highly varied, transient channel forms that are a reflection of the recent flood history rather than an equilibrium state. In addition, the variable flows in combination with sediment characteristics will influence the character of the flood plain (Nanson and Croke, 1992).

The morphology of ephemeral stream channels, in combination with transmission losses, is the result of cyclical patterns of infill and erosion. For example, the smaller, more frequent flows that transport sediment into the channel network can, over time, result in the infilling of channels and decreasing of channel width (e.g., Burkham, 1972), often in association with the growth of riparian vegetation (see section 5.d). In contrast, periods of low (base) flow in perennial steams are characterized by low sediment loads and can cause channel narrowing by cutting into deposits left during larger flows when ephemeral tributaries are active (e.g., Friedman et al.,1996). Dunkerley and Brown (1999) determined that smaller flows are disproportionately impacted by transmission losses than bank-full flows because flat-bottomed channels result in proportionately larger wetted perimeter for a given flow volume. In addition, a steep increase in transmission losses occurs as flows overtop their banks and spread out onto the flood plain, which further limits the potential work that can be accomplished by intermediate floods (Graf, 1983; Lange, 2005). Together these relationships encourage aggradation within the channel network. Over time, however, the threshold flow required to cause a major erosive event is reduced as fine sediment retards infiltration capacity (e.g., Dunkerley, 2008), channel width narrows and the growth of flood plain vegetation encourages the concentration of flow within the main channel. Both channel widening (e.g., Burkham, 1972; Friedman and Lee, 2002) and incision (e.g., Merritt and Wohl, 2003) have been observed when this threshold has inevitably been reached.

In the late 19th century, ephemeral stream channels throughout the American Southwest began to incise into alluvial valleys, creating deep continuous channels that are collectively referred to as arroyos. This arroyo formation episode was one of several periods of channel incision that are evidenced in the Holocene stratigraphic record, and separated by extended periods of aggradation (Cooke and Reeves, 1976). Arroyos are defined by Elliot et al. (1999) as large-scale, continuous, and persistent erosional features created when stream channels incise into their alluvial valleys (Figure 25). The term arroyo is usually used to refer to incised ephemeral stream channels in the American Southwest, but it is important to note that incised channels have also been formed on intermittent streams and have been observed in many regions throughout the world.

Arroyo development is commonly thought to result from a combination of three factors: anthropogenic disturbance, changing climatic conditions, and/or intrinsic geomorphic conditions. Land-use change associated with overgrazing, farming, and timber harvesting was one of the first explanations for arroyo development (e.g., Thornwaite et al., 1942; Antevs, 1952; Cooke and Reeves, 1976; Fanning, 1999). Reduced vegetation and infiltration rates associated with these anthropogenic activities were widespread in the late 1800s, and likely increased both runoff and erosion.

Figure 25. Photograph of a small arroyo or incised channel, southern Colorado.

A factor that is mentioned less frequently in the literature on cyclic incision episodes is the reason why it is observed primarily in ephemeral stream channels. Aside from obvious differences in their discharge regime, the fundamental difference between ephemeral and perennial streams is that ephemeral stream channels are characterized by sizeable transmission losses when they flow. Numerous authors have documented substantial transmission losses in ephemeral streams, frequently to such an extent that flows infiltrate completely before reaching the watershed outlet (Keppel and Renard, 1962; Aldridge, 1970). Schumm and Hadley (1957) suggested that deposition as a result of seepage-induced discharge reductions in the downstream direction eventually causes dismemberment of the drainage system by the sealing off of tributary channels. Resulting increased valley gradients cause the formation of discontinuous gullies and reintegration of the system by arroyo cutting in the fills. Successive episodes of erosion and deposition are then thus the logical course of events as gradients adjust to differential filling along the profile. This explanation is consistent with observations of alternative erosion and aggradation following a flood event in Yuma Wash, a tributary to the Colorado River in southwestern Arizona (Merritt and Wohl, 2003).

Combining these observations under conditions characterized by high transmission losses and decreasing downstream stream power, aggradation will prevail. These conditions are altered during the highest flows when transmission losses are less significant, and increased stream gradients from prior deposition allow streams to cut into the valley fill. Subsequent smaller flows will be contained within the enlarged channel area and subject to reduced transmission loss and increasing stream power in the downstream direction. As a result they will continue to widen and deepen the channel until such time as the downstream distribution of stream power is again decreasing. Whether it is one flood event or a series of events closely spaced

in time that is needed to upset aggraded conditions has still not been resolved, and is likely to vary depending on a suite of other site-specific hydrologic conditions.

ii. Geomorphic response to land management

It is difficult to assess the stability of stream systems that are widely characterized as being in a perpetual state of flux. A single cycle of incision and deposition can last decades to centuries, and numerous cycles would have to be analyzed before it could be decisively concluded that any persistent change was taking place. Despite this, however, enough is known about the functioning of hydrologic and geomorphic systems to make very broad generalizations about the downstream effects of climatic and/or management changes. For instance, if upland surfaces are armored with impervious pavement due to development then it is known that there will be increased runoff (particularly from smaller storms), but less sediment delivered to the channels. Over time it can be expected with some confidence that increased erosion will occur in channels downstream of the developed area, as numerous studies have shown (e.g., Booth, 1990; Chin and Gregory, 2001; Semmens, 2004).

The management of arid and semi-arid lands drained by ephemeral stream channels has a direct impact on the hydrology and geomorphology of the drainage network. Indeed ephemeral streams may be more sensitive to anthropogenic disturbance than perennial streams (Bull, 1997). Impervious surfaces increase the frequency and magnitude of flooding. Storm sewers and lined drainages increase the rate at which these waters are delivered to the channel network, and thus further increase peak flows (Center for Watershed Protection, 2003). The primary geomorphic consequence of these hydrologic changes is the erosional entrenchment of adjacent channels and associated transportation of the excavated sediment further downstream. Ultimately, as headwater streams equilibrate to the new flow regime and their importance as a sediment source declines, channel entrenchment will likely shift further and further downstream.

The cumulative effect of many entrenching channels is a significant increase in sediment load in downstream waters, which may partly explain why many TMDLs in the Southwest are written for sediment. *TMDL* stands for "Total Maximum Daily Load," and is a written, quantitative plan and analysis to determine the daily maximum amount of a pollutant that a waterbody can receive and still meet water quality standards, and includes an allocation of that amount to the pollutant's sources (http://www.epa.gov/owow/tmdl/intro.html). In EPA Region 9, twenty out of twenty-six TMDLs that have recently been completed include sediment as one of the pollutants (http://www.epa.gov/region09/water/tmdl/final.html).

In addition to changes in channel form and sediment yield, the geomorphic response to anthropogenic disturbance can also have significant consequences for riparian ecosystems and water supplies. As streams become entrenched, formerly rich biological communities on the flood plain can become hydrologically disconnected from ephemeral streamflow and transform into dry terraces. Additionally, as channels become narrower and unconsolidated alluvial bed material is removed, there is less capacity to absorb passing flows and for vegetation to establish.

iii. Map scale in determining channel network and stream order

Map scale can influence the identification of a stream channel network, which is often the basis for watershed, basin and regional scale assessments of hydrologic systems and surface processes. As mentioned earlier, ephemeral stream channels are oftentimes the smallest channels in a watershed, or headwater streams, and make up a significant portion of the total stream network, making them important in watershed-based assessments. However, because of map scale, they frequently will not be represented on a map.

In conducting a watershed assessment, map scale will influence the level of detail of the drainage network (Miller et al., 1999a). The most common source of drainage network data is from 1:24,000-scale U.S. Geological Survey (USGS) topographic maps (i.e. blue-line streams) and studies have found that USGS 1:24,000-scale maps may grossly underestimate the number and length of drainage networks (Schneider, 1961; Leopold et al., 1964; Mark, 1983; Heine et al., 2004).

Heine et al. (2004) reported that USGS 1:24,000-scale maps under-represented drainage networks by 64.6 percent in a study in Kansas. Mark (1983) found in a study in Kentucky on twenty-nine small watersheds that USGS 1:24,000-scale maps under-represented the number of source channels with an average of 2.15 channels per watershed.

Miller et al. (1999a) compared drainage density of digitized stream channels using different resolution aerial photographs and USGS maps, and found that drainage density decreased with decreasing scale while the underlying structure of the drainage pattern was retained (Figure 26).

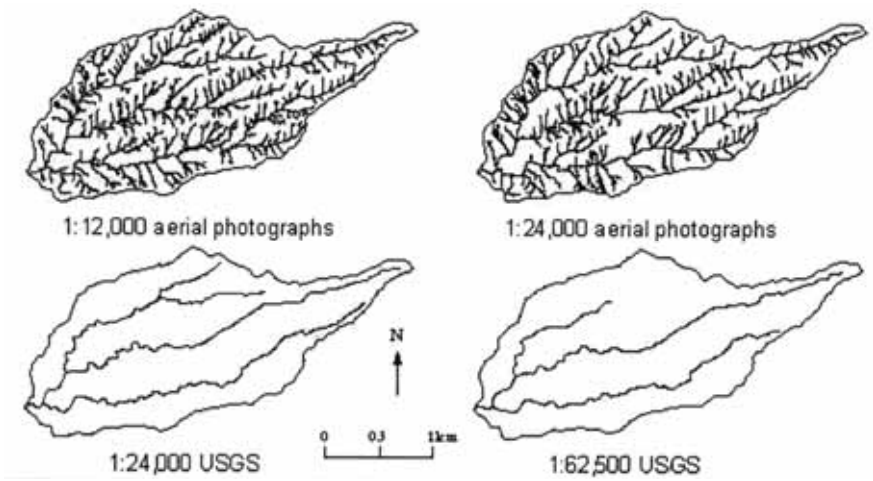

Figure 26. Diagram of digitized stream channels on a subwatershed at WGEW (from Miller et al., 1999a).

In a striking study of importance to arid and semi-arid environments, Leopold et al. (1964) examined the Arroyo de los Frijoles watershed near Santa Fe, New Mexico. Based on USGS 1:24,000-scale maps, the Arroyo de los Frijoles watershed had no identified stream channels;

however, after an examination of the contour patterns, the investigators found a potential drainage network with 258 first-order channels. A field study of one of the first-order channels revealed that its watershed actually contained 86 first-order ephemeral stream channels. The study by Leopold et al. (1964) illustrated that in arid and semi-arid environments even detailed examination of terrain data (i.e. contours or DEM) may still under-represent the number and length of ephemeral stream channels, making the use of "stream order" problematic.

c. Biogeochemical Functions

The biogeochemical functions of ephemeral and intermittent streams include cycling of elements and compounds, removal of imported elements and compounds, particulate detention, and organic matter transport. These functions influence water quality, sediment deposition, nutrient availability, and biotic functions. Biogeochemical features are affected directly and indirectly by land-use and land-cover change. Hydrologic modifications such as direct alteration of flow regime and hydrologic flow paths, and indirect alterations such as increased impervious cover in contributing areas of the watershed can cause biogeochemical changes. Elimination of the surface-water ground-water connection or disruption of the connection between a stream and its watershed by large-scale changes such as urban and suburban development also influence biogeochemical functions (Grimm et. al., 2004).

The spatial and temporal variability of rainfall in the arid Southwest affects the biogeochemical functions of ephemeral and intermittent streams. These systems are driven by pulse inputs of water, sediment, organic matter, and other materials during rain events. Periodic flows in ephemeral or intermittent channels have a strong influence on biogeochemistry by providing a connection between the channel and other landscape elements (Valett et al., 2005). This episodic connection can be very important for transmitting a substantial amount of material into downstream perennial waters (Nadeau and Rains, 2007) where it is an important component of perennial food webs (Jacobson et al., 2000b).

i. Cycling of elements and compounds

Cycling of elements and compounds refers to biotic and abiotic processes that cycle elements and convert compounds from one form to another (Lee et al., 2001, 2004) and is an essential ecosystem function performed by ephemeral and intermittent streams. Biotic processes include net primary production wherein plants and algae take up nutrients from the soil and water, and detritus turnover from which nutrients are released back into the ecosystem by microbial activity (Brinson et al., 1995).

Biogeochemical cycling primarily occurs through chemical transformation in response to redox potentials. These reduction and oxidation reactions are affected by the soil profile, wind inputs, and hydrologic input (Brinson et al., 1995). The recycling of elements and compounds is critical to maintaining their low concentrations in flowing water. As uptake and removal processes primarily occur at the water-sediment interface, physical characteristics such as channel depth and water velocity will affect nutrient recycling (Peterson et al., 2001). In addition, the amount of soil organic matter, coarse and fine woody

debris, and litter within the channel and soil profile will largely determine the ability of ephemeral and intermittent streams to perform certain biogeochemical functions (Lee et al., 2004). In hyporheic zones, there is substantial biogeochemical cycling of nutrients and trace elements, which are essential to aquatic life (Hibbs, 2008). Holmes et al. (1994) found that the parafluvial zone represents a significant source of nitrate to a nitrogen-limited stream ecosystem, which might be expected to contribute to ecosystem resilience following disturbance.

Alteration of channel characteristics (e.g., channel shape and depth) and organic matter input will affect the ability of streams to cycle materials. Because small streams have high surface-area to volume ratios, they are often able to take up and process nutrients at higher rates than larger perennial streams (Pinay et al., 2002), and are important for maintaining downstream water quality.

Water limitation in arid environments results in patchy, sparse vascular plant cover. As a result, algal and soil microbial activity is important for nutrient cycling in these environments (Belnap et al., 2005). Some dominant plant species such as mesquite (*Prosopis sp.)* living along ephemeral streams have nitrogen fixing bacteria associated with their roots, which can be an important influence on local nitrogen availability (Virginia et al., 1992).

Biological soil crusts, or cryptobiotic crusts, are a mixture of mosses, algae, microfungi, lichen and cyanobacteria that live on and just below desert soil surfaces. They are usually found in open, undisturbed areas where vegetation is sparse, for example in upland areas adjacent to ephemeral streams. These organic complexes help to stabilize desert soils, hold in soil moisture, fix carbon and nitrogen, and can stimulate plant growth (Belnap, 2003). In some soil types, biological soil crusts can increase infiltration rates. Biological soil crusts can determine the amount, location, and timing of water infiltration into desert soils, which, in turn, determines the type and size of microbial response. Nutrients resulting from this pulse then create a positive feedback as increases in microbial and plant biomass enhance future resource capture or, alternatively, may be lost to the atmosphere, deeper soils, or downslope patches (Belnap et al., 2005).

ii. Detention of imported elements and compounds

Headwater streams and wetlands are in a unique position to intercept nutrients and contaminants from upland environments before they reach larger perennial streams (Brinson, 1988). As water moves through small, shallow channels and comes in contact with sediment, vegetation, coarse and fine woody debris and soil organic matter, elements and compounds are removed from the water, either by direct uptake or by conversion into inactive forms. Important variables in assessing the capacity of ephemeral and intermittent streams to perform this function include the amount of vegetative cover and soil organic matter (Lee et al., 2004).

Nutrient uptake and removal occurs more rapidly in the small, uppermost channels in a watershed than in larger, downstream channels (Peterson et al., 2001). During intermediate storms, small headwater channels may serve as collection points for organic matter. Material accumulated during drier periods can be released downstream during large, infrequent storm

events (Fisher et al., 2001). In an Arizona watershed, Fisher and Grimm (1985) found that ephemeral streams retained between 50 percent and 90 percent of the nitrogen and phosphorous entering the stream during intermediate storm events. Several authors have hypothesized that headwater streams contribute significantly to downstream productivity (Freeman et al., 2007; Cummins and Wilzbach, 2005; Wipfli, 2005).

The temporally and spatially variable rainfall in the arid Southwest influences nitrogen processing and retention in small streams. Nitrogen cycling is dependent on soil moisture as some processes (e.g., nitrification) only occur in aerobic conditions while others (e.g., denitrification) only occur in anaerobic conditions (Pinay et al., 2002). Therefore, the degree of soil moisture will affect the end products of nitrogen processing, which will affect downstream waters. During high moisture condition (such as after a storm event), ephemeral streams may experience elevated rates of denitrification (Fisher et al., 2001; Rassam et al., 2006). Denitrification converts nitrogen to gaseous forms that can be lost to the air, thereby completely removing it from the system, which can be important in areas that receive excess nutrients from the watershed. Westerhoff and Anning (2000) found that ephemeral streams had higher total organic carbon (TOC) levels than perennial streams, suggesting that ephemeral streams are important for storing and processing organic material between large storm events. Because large amounts of material are only moved into larger streams during extreme rainfall events, much of the nutrient cycling may occur in the smaller streams.

iii. Particulate detention

Factors important in assessing the capacity of ephemeral and intermittent streams to retain particulates include floodway cross-sectional area, channel roughness, and sediment supply (Lee et al., 2004). Because headwater, ephemeral and intermittent streams comprise a large percentage of the total watershed channel distance, in combination they may have the capacity to store large amounts of sediment and particulates. When studying the seasonal dynamics of physical and chemical variables in perennial, intermittent and ephemeral streams, Dieterich and Anderson (1998) found that ephemeral streams were very effective in removing and storing suspended sediment from the water column. This stored particulate matter (e.g., sediment, plant fragments) can be released to downstream ecosystems during large storm events.

The amount of particulate retention will depend on the timing, duration, and amount of water received, as well as the characteristics of the stream channel and the integrity of the vegetative community around the stream (Brinson et al., 1995; Powell et al., 2007). Powell et al. (2007) found little net change in the removal and deposition of sediments in an Arizona ephemeral stream over a three-year period. However, individual storm events resulted in scour or fill depending on storm severity suggesting that ephemeral stream channels may undergo cycles of infill and erosion.

In the southwestern deserts, large amounts of sediment and other particulates are washed into small streams during storms due to compacted soils with low infiltration rates and sparse vegetation in the upland environment (Fisher and Minckley, 1978). Flow events that do not fully connect small streams to downstream waters will result in particulate matter accretion

and storage in the small stream. Sediment deposition in small streams can affect retention of organic material, for example by burying leaf litter (Brinson et al., 1995). Buried organic matter is processed and transformed in the stream sediments, thereby making it available for biological uptake (Richardson et al., 2005).

iv. Organic carbon export

Dissolved and particulate organic matter may be exported throughout the watershed through mechanisms such as erosion, flushing, displacement, and/or leaching (Lee et al., 2004). Organic carbon is the primary source of energy for microbial food webs and its export is critical to the productivity of down-gradient receiving waters (Allan, 1995; Wetzel, 2006). Variables involved in determining the capacity of ephemeral and intermittent streams to export carbon include the condition of the hydrologic connection to downstream reaches, shallow subsurface substrate permeability and porosity, soil organic matter content, shrub and herbaceous canopy coverage, amount and stage of decay of course litter, and coarse and fine woody debris (Lee et al., 2004).

Thoms et al. (2005) found that anabranch channels (channels that branch off the main river and rejoin it downstream) in Australia were important sources of organic carbon for main channels despite being connected only during flood events. Freeman et al. (2007) noted that headwater streams, which can make up most of the length in a river system, are the primary collectors and processors of terrestrially derived organic matter. For example, one study on the San Pedro River found that approximately 98 percent of nutrients came into the river during the summer monsoon thunderstorms from ephemeral tributaries, and that almost 60 percent of that input occurred as a flux of particulate matter (Brooks et al., 2007).

Organic material brought into and stored in small headwater streams, can be broken down and transformed into forms more readily available for use by biota in larger perennial streams (Richardson et al., 2005). This organic matter may originate from terrestrial sources or from algal growth within the stream channels. In arid and semi-arid environments, algae growth in the channel may be a more important source of organic carbon than terrestrial plants due to the low upland plant cover (Jones et al., 1996; Jacobson et al., 2000b). This was also confirmed by Brooks and Lemon (2007) who concluded that in the San Pedro River, high concentrations of organic matter, and especially high concentrations of nitrogen occurred with the inflow of monsoon runoff from lateral ephemeral tributaries.

The degree to which material will be transported out of streams depends on channel integrity and the condition of the downstream hydrologic connection. Organic matter may be transported in multiple ways including leaching, displacement, and flushing (Brinson et al. 1995). Surface runoff into headwater streams brings nutrients that may be stored and transferred to ground-water reserves (Fisher and Grimm, 1985; Belnap et al., 2005). The ground water containing nutrients may reemerge downstream in perennial waters or springs where they can be an important source of nutrients to plants and wildlife (Fisher and Grimm, 1985). Ephemeral and intermittent streams can contribute water and nutrients to perennial streams even in the absence of direct above ground flow.

d. Plant Community Support

Desert washes are easily recognizable by their dense corridor of vegetation that is in strong contrast to the more sparsely vegetated uplands (Figure 27). This corridor contributes to the disproportionately high biological diversity of desert environments relative to their total area (Warren and Anderson, 1985).

Vegetative communities along ephemeral and intermittent streams provide structural elements of food, cover, nesting and breeding habitat, and movement/migration corridors for wildlife that are not as available in the adjacent uplands. Functional services of these communities include moderating soil and air temperatures, stabilizing channel banks and interfluves, seed banking and trapping of silt and fine sediment favorable to the establishment of diverse floral and faunal species, and dissipating stream energy which aids in flood control (Howe et al., 2008).

In arid and semi-arid regions, plants have adapted to limited water, high temperatures, and high evaporation rates. These stresses are only partly alleviated in locations that concentrate water, whether they are perennial, ephemeral, or intermittent stream networks. Such areas are also subject to periodic disturbance from flood flows. Limited water and flood disturbance thus are key factors that structure the vegetation of ephemeral streams (Nilsen et al., 1984; Friedman and Lee, 2002).

Figure 27. Photograph showing dense corridor of vegetation lining an ephemeral wash, Agua Fria River, north of Phoenix, AZ. (Photograph: William Kepner, USEPA/ORD)

The factors affecting riparian vegetation in arid and semi-arid regions are not as well understood as in humid regions with perennial rivers. In turn, the influence of vegetation on ephemeral or intermittent stream systems is not well studied. It is, however, understood that the vegetative structure of desert landscapes reflects the effects of low rainfall. Regardless of low rainfall, even in the driest of deserts, there are productive patches (Whitford, 2002).

i. Physiognomy, density, and species composition

In ephemeral and intermittent streams, the structure and composition of the vegetation is related to the size of the stream and patterns of flow, although most of the diversity is comprised of herbaceous species (Bagstad et al., 2005). In their study of vegetation along the San Pedro River, Stromberg et al. (1996) found that depth to ground water and bottomland elevation and inundation frequency exerted the greatest influence on species composition, followed by soil texture, soil moisture holding capacity, light availability and site elevation. In another study along the San Pedro River, all annuals showed strong increases in richness and cover in the year following a large fall flood, while hydric perennials had a small net increase in richness, indicating that both disturbance and increased moisture conditions caused by floods, as well as moisture from seasonal rains, contribute to increased richness and cover of herbaceous plants in the bottomlands of the San Pedro River, a spatially intermittent desert river (Bagstad et al., 2005).

In regions with seasonal precipitation, depth to ground water is particularly important since ground water is closely coupled with stream flow to maintain water supply to riparian vegetation (Groeneveld and Griepentrog, 1985). As the hydrologic regime shifts from perennial to ephemeral, vegetation composition shifts towards more drought-tolerant species, vegetation cover declines, riparian woodlands give way to riparian shrublands, and canopy height and upper canopy vegetation volume decline (Leenhouts et al., 2006; Stromberg et al., 2007).

The composition of riparian vegetation along desert streams reflects the vegetation composition of its watershed. The plants growing along large ephemeral or intermittent stream channels or smaller ones below about 5,000 feet elevation include species that are obligately associated with riparian environments and ones that typify the surrounding desert uplands (Figure 28). The species composition of ephemeral and intermittent streams within the arid and semi-arid Southwestern U.S. thus varies widely depending on species composition of the watershed and floristic province, as well as with drainage size, climatic regime, latitude, longitude, elevation, aspect, and soil characteristics.

Figure 28. Photograph showing riparian vegetation along a desert stream, western Arizona.

Along small desert washes, vegetation composition and structure overlap considerably with those of the surrounding desert uplands (Bloss and Brotherson, 1979; Warren and Anderson, 1985) and consist primarily of small, xerophytic shrubs and trees. Stem and leaf succulents and perennial grasses often are present, and annual grasses and forbs become seasonally abundant during wet periods. Collectively, the drought-tolerant vegetation that borders ephemeral streams is referred to as xeroriparian vegetation (Johnson et al., 1984).

As water availability increases, the vegetation becomes increasingly distinct from the upland vegetation with respect to physiognomy and species composition. The vegetation becomes taller (Shreve and Wiggins, 1964) and tree canopy cover can increase (Sponseller and Fisher, 2006). Xeroriparian species are still present, but mesoriparian and hydroriparian species increase in abundance. Ephemeral streams with intermediate water availability support drought-tolerant shrubs such as wolfberry (*Lycium spp.*) or brickellbush (*Brickellia spp.*) and small-leaved trees such as acacia (*Acacia greggii*), blue palo verde (*Parkinsonia floridum*), or velvet mesquite (*Prosopis velutina*) (Hardy et al., 2004). Along intermittent and perennial streams, riparian scrublands include seepwillow or batamote (*Baccharis glutinosa*), broom (*Baccharis sarothroides* or *B. emoryi*), arroweed (*Pluchea sericea*), and tamarisk (*Tamarix chinensis*) (Brown et al., 1977). Broad-leaved trees with relatively high water needs (e.g., the mesoriparian species Arizona walnut (*Juglans major*), and the hydroriparian species Fremont cottonwood (*Populus fremontii*)) are typically sustained on large washes by floodwater stored in perched ground-water reservoirs.

The additional water availability in the bottomland and riparian zone of a perennial to intermittent stream in the Sonoran Desert results in greater plant diversity than the arid upland, as measured at temporal scales that capture seasonal variance in resource and disturbance pulses, and at spatial scales that capture the environmental heterogeneity of bottomlands. Although periodically limited by intense flood disturbance, diversity remains

high in bottomlands because of the combination of moderate resource levels (ground water, seasonal flood water) and persistent effects of flood disturbance (high spatial heterogeneity, absence of competitive exclusion), in concert with the same climatic factors that produce seasonally high diversity in the region (temporally variable pulses of rainfall) (Stromberg, 2006). For example, native palms (*Washingtonia filifera*) occur in only two locations in Arizona, both of which are washes (Figure 29).

Figure 29. Photograph of native palms (*Washingtonia filifera*) in Castle Creek, AZ. (Photograph: William Kepner, USEPA/ORD)

Vegetation structure also shifts as watershed size and flood intensity increase. On large, dry ephemeral streams with intense flood scour, species composition shifts towards pioneer species. For example, in Sonoran Desert washes, desert broom (*Baccharis sarothroides*), a pioneer xeroriparian shrub that produces prolific numbers of wind-dispersed seeds, was more abundant in washes as watershed size increased (Warren and Anderson, 1985). Other pioneer species include burrobush (*Ambrosia salsola*), a xeroriparian shrub that is adapted to disturbance through capacity for clonal growth, and desert willow (*Chilopsis linearis*), a drought-tolerant tree that produces wind-dispersed seeds. Zonation can occur between fluvial surfaces within an ephemeral-stream bottomland, with the pioneer species sometimes being more abundant in the active channel bed than on the stream banks or flood plain (Bloss and Brotherson, 1979).

ii. Primary productivity and plant water sources

Plant productivity in arid and semi-arid regions is often low for much of the year, punctuated by bursts of activity following rain and runoff events. For example, Smith et al. (1995) found that burrobush (*Ambrosia salsola*) is typically dormant (not actively transpiring) for most of the year in a desert wash setting.

Patterns of primary productivity and evapotranspiration vary depending on whether the main water source for the vegetation is direct precipitation, channel flow, or stored water

(Leenhouts et al., 2006; de Soyza et al., 2004). When stored water is accessible, productivity and evapotranspiration of plant species can be high for much of the growing season (Atchley et al., 1999). De Soyza et al. (2004) found that plants along an ephemeral stream channel responded more to channel flow than direct precipitation, indicating the importance of maintaining intact channel networks throughout a watershed.

Productivity patterns also vary seasonally depending on phenology, morphology, and physiological adaptations of the plant species. Some of the perennial plants that grow along desert washes are evergreen (e.g., creosote (*Larrea tridentata*)), and can maintain some level of productivity year-round. Others are summer drought-deciduous (e.g., desert lavender (*Hyptis emoryi*)), or winter cold-deciduous (e.g., desert ironwood (*Olneya tesota*)) (Nilsen et al., 1984).

iii. Temporal and spatial patterns of species diversity

Non-perennial streams with active flood regimes contain a high diversity of plant species that varies depending on the location within the watershed. The complex longitudinal gradients encompassing changes in flood intensity, climate, and water availability result in a wide range of biological conditions along the stream length (Lite et al., 2005; Shaw and Cooper, 2008).

During seasonal dry periods, plant species diversity levels along ephemeral stream channels typically are low, with values much lower than along perennial streams and also often lower than in adjacent uplands (Leitner, 1987). During seasonal wet periods, however, diversity levels along some ephemeral stream channels can equal that along perennial stream channels (Stromberg et al., in press).

Species type and composition are affected by flow regime. Stromberg et al. (2006) found that in the San Pedro River there is a sharp decline in the riverine marsh type as perennial flows become intermittent. As flows become more ephemeral, and the stream channel loses vegetation cover and widens, hydromesic pioneer forests (cottonwood-willow (*Populus fremontii-Salix gooddingii*)) give way to mesic pioneer shrublands (dominated by saltcedar *(Tamarix ramosissima)*, an introduced species) as tolerance levels for survivorship relative to ground-water depth and fluctuation are exceeded.

Species diversity varies with seasonal rain and stream flow patterns, and also varies on longer temporal scales. Following infrequent large winter floods, stream flow can be sustained for several months in ephemeral stream reaches of large rivers that drain humid mountains. During this period of sustained runoff, the ephemeral stream washes can support a high density and diversity of wetland (hydroriparian) plant species (Stromberg et al., in press). These “ephemeral wetland” communities develop with a recurrence interval of perhaps once per decade or more, depending on the flow regime of the particular stream.

Water from rainfall and flood flows can trigger a pulse of germination of annual and perennial plant species in ephemeral streambeds (Figure 30). Because the dry-season cover of the woody vegetation is low, and cover of bare soil is fairly high, the seasonal resource pulses can

result in very high diversity levels in comparison to those of the more densely vegetated perennial streams.

Figure 30. Photograph of annual plant species in an ephemeral streambed following spring rains, southern Arizona.

Ephemeral reaches of spatially intermittent rivers maintain diverse soil seed banks (Stromberg et al., in press). Many of the plant species that establish along ephemeral stream channels during water pulses arise from soil seed banks. Along a spatially intermittent stream in central Arizona, the soil seed banks of ephemeral stream reaches included a mixture of species adapted to xeric, mesic, and hydric conditions (Stromberg et al., in press). For example, viable seeds of the wetland taxa *Juncus* (rushes) were found in ephemeral stream reaches. In contrast, wetland species were not found in the soil seed bank of a smaller tributary that was ephemeral over its entire length.

iv. Influences of vegetation on ecosystem processes

Miller (2005: p. 18) noted that "the most important functions in dryland ecosystems are those that control the retention of water and nutrient resources because productivity and diversity cannot be sustained in systems that fail to retain these resources." Vegetation in ephemeral stream channels plays a key role in resource retention by protecting soils from wind and water erosion, slowing floodwater velocity, and moderating temperatures. Ephemeral stream vegetation also influences biogeochemical cycles by providing leaf litter, and food and cover for wildlife. In some cases, vegetation can intercept rainfall, preventing it from infiltrating into the soil, and influencing the local water balance and ecosystem processes (Owens et al., 2006; Miller, 2005). Vegetation structure and diversity determine wildlife species diversity and abundance, and if a portion of habitat on which a species depends is damaged or destroyed, the breeding population of that species could be lost (Anderson and Ohmart, 1977),

Changes in the abundance or composition of the plant community thus affect an array of ecosystem functions and processes. Plants that have the greatest effects on the structure and functioning of dryland ecosystems are small trees, shrubs, sub-shrubs and perennial grasses (Whitford, 2002).

v. Vegetation and channel morphology

Vegetation in arid and semi-arid regions is largely controlled by the availability of water, with flood disturbance and edaphic conditions further shaping plant distribution patterns. Depending on attributes of the particular stream, the highest density of vegetation may occur along the stream bank or within the channel bed (Figure 31). By providing channel and stream bank roughness through standing or downed material, vegetation can influence flow velocities, flow depths, bank and flood plain erosion, and sediment transport and deposition, and can be a major factor contributing both to channel stability and to channel instability (e.g., Heede, 1985). Vegetation along the stream bank stabilizes the soil through the reinforcing nature of their roots, and prevents erosion (Groeneveld and Griepentrog, 1985).

In ephemeral stream channels, vegetation may establish on sand bars, and subsequently initiate the formation of various depositional features such as small current shadows, bars, benches, ridges, or islands (Tooth and Nanson, 2000). Spatially extensive assemblages of any plant species have the potential to alter geomorphology and geomorphic processes through bioturbation, alteration of nutrient or fire cycles, and patterns of succession (Lovich, 1996).

Figure 31. Photograph of vegetation growing in an ephemeral channel bed, Arizona. (Photograph: Lainie Levick/Aerial flight courtesy of Lighthawk, www.lighthawk.org)

In humid climates, the spatial distribution of riparian vegetation is related through the flow and associated disturbance regimes to fluvial landforms that create establishment sites or stress the persistence of established vegetation (Hupp and Osterkamp, 1996). "In semi-arid

and arid areas, bare sites are relatively abundant but water-availability, particularly in the seedling establishment phase, is especially limiting. Thus, in dry climates, patterns of establishment may be strongly influenced by surface flow (floods), whereas ground-water levels my greatly influence persistence" (Hupp and Osterkamp, 1996, p. 293).

vi. Vegetation and geochemical cycles

The dominant plant species of many ephemeral streams are leguminous trees that harbor nitrogen-fixing bacterial symbionts. These trees influence geochemical cycles and local pools of nitrogen (Virginia et al., 1992). The levels of nitrogen-fixation are related in part to plant productivity, and vary temporally and spatially along gradients of water availability.

The trees and shrubs that grow along ephemeral streams vary in the degree to which they resorb nutrients in senescing leaves. The nitrogen-fixing honey mesquite (*Prosopis glandulosa*) had the greatest resorption in one multi-species study (Killingbeck and Whitford, 2001).

e. Faunal Support and Habitat

The riparian environments created by ephemeral and intermittent streams in the arid and semi-arid Southwest provide and maintain important habitat for wildlife, and are responsible for much of the biotic diversity, yet the scientific literature on this topic is limited. The following sections present the current understanding of the contribution of ephemeral and intermittent streams to the biotic integrity of southwestern watersheds.

Riparian systems are one of the rarest habitat types in North America. In the arid Southwest, about 80 percent of all animals use riparian resources and habitats at some life stage, and more than 50 percent of breeding bird species nest chiefly in riparian habitats (Krueper 1993). It has been estimated that over half of all wildlife species in Arizona depend on riparian areas (Arizona Riparian Council, 2004). Riparian habitat is the area between the stream channel and the upland terrestrial ecosystems. The strongest contrasts between these areas are found in arid and semi-arid lands where water is a limiting resource (e.g., Ceballos, 1985).

Because ephemeral and intermittent stream channels have a higher moisture content and more abundant vegetation than the surrounding areas, they are very important to wildlife. Frequently, these streams may retain the only available water in the area, with perennial segments or permanent pools interposed wherever hydrogeological conditions allow. These isolated perennial waters can support fauna not found in an otherwise ephemeral system.

The microclimates created in and around ephemeral and intermittent streams are utilized extensively by wildlife, and especially by less mobile species that cannot avoid the harsh desert environment by moving to more favorable microclimates. As a result, these areas generally support the greatest concentrations of wildlife, providing the primary habitat, predator protection, breeding and nesting sites, shade, movement corridors, migration stopover sites, and food sources.

The importance of streamside or riparian vegetation communities to wildlife is well recognized (Carothers, 1977), and is heightened in the arid and semi-arid Southwestern U.S. due to the high ambient temperatures and intense aridity outside of the riparian community.

i. Spatial structure, connectivity, and corridors in wildlife habitat

The spatial structure of wildlife habitat is described by patch size, number of patches, density and distribution, in addition to the geometric complexity of the patches (Johnson and Lowe, 1985). The term "connectivity" has been used to describe how spatial arrangement and quality of elements in the landscape affect movement of organisms among habitat patches. The term "corridor" refers to a connecting feature in the landscape, and "habitat corridor" generally refers to a linear strip of vegetated land that provides a continuous or near continuous pathway between two larger habitat blocks (Bennett, 1999). One of the key functions of intact and functional migration corridors is to link patches in the landscape.

Ephemeral and intermittent stream channels provide important wildlife movement corridors in arid and semi-arid regions because they contain continuous chains of vegetation that wildlife can utilize for cover and food. In addition, during the summer monsoon season small floods create a more-or-less continuous corridor of water that allows dispersal of herpetofauna such as garter snakes and amphibians, which are active during the summer. Winter rains do not serve the same function, since the cold temperatures prevent much activity in amphibians or reptiles. This dispersal mechanism allows genetic interchange between subpopulations that are isolated for most of the year, and allows recolonization of sites where subpopulations may be lost due to drought or disturbance.

Various authors (e.g. Meyer et al., 2007) have recognized the importance of small stream and headwater habitats, including those of ephemeral and intermittent streams, as vital parts of the biological integrity of U.S. waterways. The degradation of these habitats and loss of their connections to larger streams have negative consequences not only to the inhabitants of these streams, but also for the diversity of downstream and riparian ecosystems, and the biological integrity of the entire river network.

Habitat fragmentation caused by human activities can jeopardize the survival of wildlife species by diminishing their ability to access the resources they need, retain genetic diversity, and maintain reproductive capacity within a population; however, conservation biologists have debated these concepts because of lack of detailed information (Hilty et al., 2006). Recent studies are attempting to clarify this issue. For example, in their study of predator use of corridors in the northern California wine-growing region, Hilty et al. (2006) found that mammalian predator detection rates were 11 times higher in riparian areas than in vineyard locations. More research into this topic is needed.

As previously mentioned, nearly 81 percent of all streams in the six Southwestern states are ephemeral or intermittent (USGS, 2006) and in many watersheds most stream channel reaches are ephemeral or intermittent. From a strictly numerical standpoint, then, the degradation of ephemeral or intermittent streams diminishes ecosystem functions in most southwestern watersheds.

The structural components of wildlife habitat are considered below in terms of the physical, vegetative, and hydrological contributions that ephemeral and intermittent streams provide to the landscape. Habitat needs vary according to species, but this overview treats larger taxonomic groups more generally.

ii. Physical habitat features

The habitat provided by desert streams contracts and expands dramatically in size due to the extreme variations in flow, which can range from high-discharge floods to periods when surface flow is absent. This spatial variation in habitat or ecosystem size is a fundamental, defining feature of these streams (Stanley et al., 1997).

Regardless of whether it is perennial, a stream affects the substrate it flows upon, creating habitat for various species of wildlife. Some physical features of wildlife habitat along ephemeral and intermittent streams include the deposits of river material (sediment and debris), the exposure of rock and subsurface soil layers by erosion, the provision of shade through topographic relief, the creation of microclimatic zones, and the sequestration of moisture and nutrients in alluvium.

River bank material provides shelter for numerous species of wildlife in the arid Southwest, including reptiles, amphibians, birds, mammals and invertebrates. Bank shelters are created through the action of water, wind, and gravity, independent of whether the river contains water year-round. In fact, dry wash embankments are notoriously full of small caves and crevices critical in the life of desert animals such as the desert tortoise (*Gopherus agassizii*) (Van Devender, 2002). These shelters not only provide refuge from predators, but also critical protection from extreme heat and aridity. Table 1 lists species observed to use riverine soil exposures in the Pima County, Arizona, area, and includes bats, birds, snakes, lizards, mammals, insects and amphibians.

Stream alluvium is often looser than the soils or colluvium of surrounding uplands, which enhances the potential for exploitation by specialized sand-burrowing species of wildlife. Woody debris swept in from the watershed collects in the flood plain and stream channel as flood wrack (brush piles), creating additional complex, high-value shelters. If the stream incision is deep enough, it may create a cooler canyon environment in which heat and moisture loss are retarded.

Table 1. List of wildlife species that use riverine soil exposures in Pima County, Arizona (source: Julia Fonseca, Pima County Office of Conservation Science and Environmental Policy, 2008).

Species	Soil exposure use
Townsend's Big-eared Bat	Roost, maternity roost
Western Pipestrelle	Year-round roost
Pallid Bat	Night roost
Myotis species	Roost, maternity roost
Mexican Long-tongued Bat	Roost, maternity roost
Lesser Long-nosed Bat	Roost
Burrowing Owl	Roost, nest
Barn Owl	Roost, nest
Great-horned Owl	Roost, nest
Common Raven	Nest
Rough-winged Swallow	Nest
Cliff Swallow	Nest
Black Phoebe	Nest
Say's Phoebe	Nest
Rock Wren	Nest
Green Kingfisher	Roost
Belted Kingfisher	Roost, nest
Western Diamondback Rattlesnake	Shelter, foraging
Mojave Rattlesnake	Shelter
Sonoran Desert Toad	Shelter
White-throated Woodrat	Nest
Rock Squirrel	Den
Desert Tortoise	Shelter, den
Desert Spiny Lizard	Shelter
Clark's Spiny Lizard	Shelter
Coyote	Den
Kit Fox	Den
Mud-dauber Wasp	Hive
Ringtail Cat	Den
Striped and Hog-nosed Skunks	Den
Kissing Bugs	Foraging
Javelina	Day camp
Raccoons	Foraging, shelter

iii. Vegetative habitat features

The abundance and diversity of riparian vegetation, as compared to uplands, is a critical wildlife habitat feature of arid and semi-arid region streams (Figure 32). Each of the plant

communities found along these streams offers distinct and notable habitat features to wildlife, summarized in Brown (2004).

Major washes with shallow ground-water zones are typically lined with phreatophytic trees including Fremont cottonwood (*Populus fremontii*), Arizona sycamore (*Platanus wrightii*), Arizona ash (*Fraxinus velutina*), distinctive shrubs such as willow (*Salix ssp*), seepwillow (*Baccharis ssp*), burrobrush (*Ambrosia monogyra*), and saltcedar (*Tamarix ramosissima*), or dense grass stands of sacaton (*Sporobolus ssp*). A special case is presented by those southwestern ephemeral streams carrying discharge of treated municipal sewage or other effluent.

Figure 32. Photograph of diverse riparian vegetation, Badger Springs Wash, Arizona.

Ephemeral and intermittent streams which lack a shallow ground-water system or effluent discharge nonetheless give rise to a distinctive vegetative habitat from the surrounding uplands, often referred to as xeroriparian habitat. Tree canopy of ephemeral streams generally includes subtropical legumes such as mesquite (*Prosopis ssp*), catclaw acacia (*Acacia greggii*), ironwood (*Olneya tesota*), and blue palo verde (*Cercidium floridum*). Netleaf hackberry (*Celtis reticulatata*) and Arizona sycamore (*Platanus wrightii*) have been identified as providing exceptional cover for nesting birds on intermittent streams (Powell and Steidl, 2002), and mesquite has been identified as the key provisioner of food for many migrating birds (Van Riper and Cole, 2004).

Krausman et al. (1985) found that xeroriparian vegetation provides forage, thermal cover, and travel zones. For example, deer in their Arizona study sites were much more dependent on xeroriparian systems than were deer in west Texas. In arid parts of western Arizona, many birds such as red-tailed hawks (*Buteo jamaicensis*), and Gila woodpeckers (*Melanerpes uropygialis*), can become dependent on ephemeral streams for nesting sites, as this is where large trees occur due to the increased moisture (Johnson and Lowe, 1985).

iv. Hydrological habitat features

Channel flow is a visually prominent aspect of the hydrological character of a stream, but it is seldom the only hydrological habitat feature of biological significance. A stream may also possess moist banks fed by capillary flow from ground water, which offer sites for turtle or insect reproduction. A hyporheic (subsurface) zone of flow with a distinct invertebrate fauna may underlie a dry streambed. Flooding, erosion, or man-made excavations can give rise to in-channel or off-channel pools where amphibians breed. Springs, which may exist within the stream channel or in the flood plain, can offer distinct chemical compositions or thermal refugia from the main stream. Stream diversion and irrigation systems may spread the river's flow into fields via irrigation canals lined with cottonwoods and willows, altering habitat conditions in both the aquatic and riparian communities. Together, these natural or man-made hydrological features provide a wide variety of important habitat conditions for aquatic and terrestrial organisms.

Stream corridors naturally guide the movement of wildlife. Movement is essential to wildlife survival, whether it be the day-to-day movements of individuals seeking food, shelter, or mates, dispersal of offspring (e.g., seeds, fledglings) to new areas, gene flow, migration to avoid seasonally unfavorable conditions, recolonization of unoccupied habitat after environmental disturbances, or shifting of a species' geographic range in response to global climate change (Beier et al., 2006).

v. Faunal abundance and distribution

Fauna using ephemeral or intermittent waters include fish, mammals, amphibians, reptiles, birds, and invertebrates. Most desert species have developed adaptations to the water-limited conditions of arid and semi-arid regions, allowing them to survive under adverse environmental conditions (Ward and Associates, 1973; Louw and Seely, 1982; Williams, 2006). The natural flow regime in arid lands is a key factor favoring native species over exotics that are adapted to lake and pond conditions (Minckley and Meffe, 1987; Poff et al., 1997). However, the variability of climate and flow regime, which influences species' abundance and diversity, makes evaluation difficult unless surveys are conducted over a period of years in different community types (Anderson et al., 1977; Boulton and Lake, 1992).

Habitat studies seldom partition the various microhabitats that water creates for wildlife, and do not often attempt to separate the natural continuum of flow conditions that exist in a given area into perennial and non-perennial components, particularly since such conditions may exist along the same stream at the same time. The following sections describe in greater detail wildlife uses and benefits of ephemeral and intermittent streams in arid and semi-arid lands, including the collective contributions that water itself makes to faunal composition of southwestern streams. Since habitat values differ among taxonomic groups, the discussion is grouped taxonomically.

Reptiles and Amphibians

Reptiles and amphibians are diverse and abundant in arid and semi-arid regions, and have a variety of physiological and behavioral adaptations that enable them to conserve energy and moisture during harsh conditions of high temperature or low humidity and survive in dry environments. These adaptations include behavioral heat avoidance involving going underground, becoming nocturnal or subterranean, reducing activity levels, developing resistance to dehydration, developing the ability to absorb water through their skin, developing the ability to use temporary waters for breeding, and having rapid larval and egg development. In addition, most arid and semi-arid region reptiles can withstand high levels of electrolyte levels in their body fluids, and have relatively impervious skin which reduces water loss (Stebbins, 1995).

Many researchers have noted that the high diversity of plants and the associated microhabitats in desert riparian systems provides preferred habitat for herpetofauna. Some herpetofauna prefer desert washes to other types of desert habitats, and have the highest number of habitat specific species than other desert habitat types (Jakle and Gatz, 1985). However, the data have been limited until recently. For example, at the Symposium on the Management of Amphibians, Reptiles, and Small Mammals in North America (U.S. Department of Agriculture, 1988), many of the presenters noted the lack of data on amphibians, reptiles and small mammals, possibly due to the difficulty in surveying them because of their small size and secretive habits, or because they have historically not been considered important.

Many, indeed most species of snakes and lizards preferentially utilize xeroriparian habitat because of the dense cover provided by the shrub, vine and groundcover layers of annual and perennial plants. Jones (1988) reported on an extensive survey by the BLM from 1977 through 1981 on Arizona's herpetofauna. This was one of the most comprehensive inventories of herpetological communities ever conducted in North America with 27,885 array-nights in 16 habitat types over a five-year period, on approximately 3,441.296 ha (8.5 million acres) of public land. It was also an important effort to associate herpetofauna with ecosystems. For the Mixed Riparian Scrub (also called xeroriparian) habitat type, the results indicated a high number of species and species diversity for snakes, amphibians, and lizards relative to the other habitat types. Figure 33 is a graph of the number of species (turtles, amphibians, snakes, and lizards) for each habitat type. Mixed Riparian Scrub (xeroriparian) is represented by the "MR" habitat type.

In their study of the herpetofauna at Organ Pipe Cactus National Monument, Arizona, Rosen and Lowe (1996) also found that xeroriparian habitat was preferred by lizard species and certain snake species and hypothesized that it was due to higher prey abundance, higher relative humidity, and the presence of denser vegetation for cover. During drought peaks, almost every non-riparian-dependent snake species used the xeroriparian habitat as refugia, although those that normally used that habitat type had a higher survival rate. They also found that lizard species were most abundant in mesquite woodland or bosque and xeroriparian habitats (see Figure 34). At Organ Pipe Cactus National Monument, mesquite

woodland is restricted to ephemeral and intermittent streams, and therefore constitutes a special type of xeroriparian habitat.

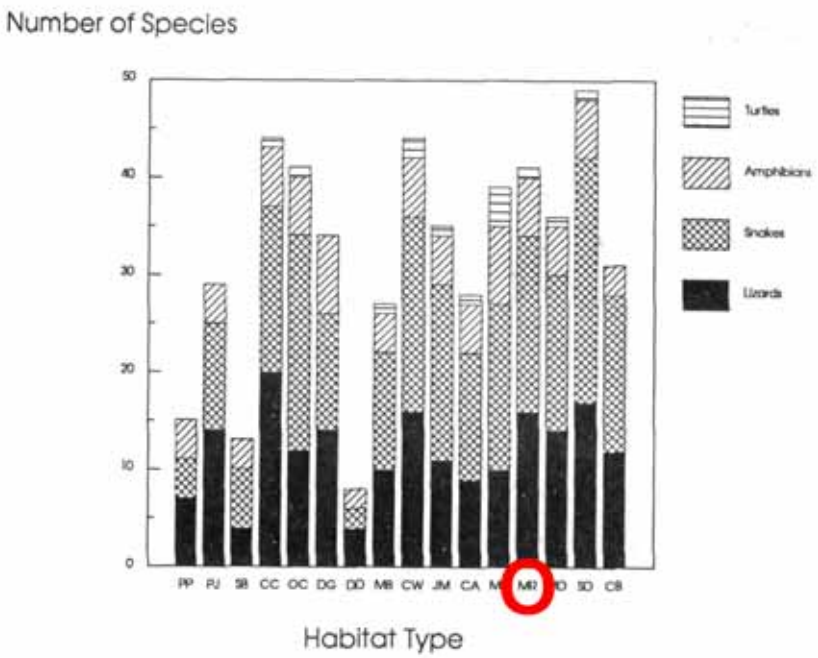

Figure 33. Graph of herpetofauna species by taxonomic group and by habitat type, from BLM surveys in Arizona, 1977-1981 (Jones, 1988). "MR" represents Mixed Riparian Scrub (xeroriparian) habitat type.

Rosen (2005), in his review of the herpetofauna of the 126-mile San Pedro River looked at the riparian herpetofauna assemblages in three reaches of the river from the Mexican border to the confluence with the Gila River. He looked at historic and current records and found a large number of species that occurred in the lower (mainly ephemeral) reach of the river that were not found in other reaches, although many species occurred in all reaches.

Baxter (1988) noted that in the Mojave Desert, washes are important habitat for the desert tortoise (*Gopherus agassizii*) although their burrows tended to be in the uplands. Because desert washes contain a highly diverse plant community, they were probably important foraging locations. McArthur and Sanderson (1992) studied plant associations in arroyos and uplands in southeastern Utah in relation to use by desert tortoise. They found that the arroyos with more shrubs and a rougher topography were good den sites and provided more succulent forage than uplands. In Arizona Upland Sonoran desertscrub, the desert tortoise is absent from the valleys, and occurs only along major upper and middle bajada washes and on rock slopes (Van Devender, 2002).

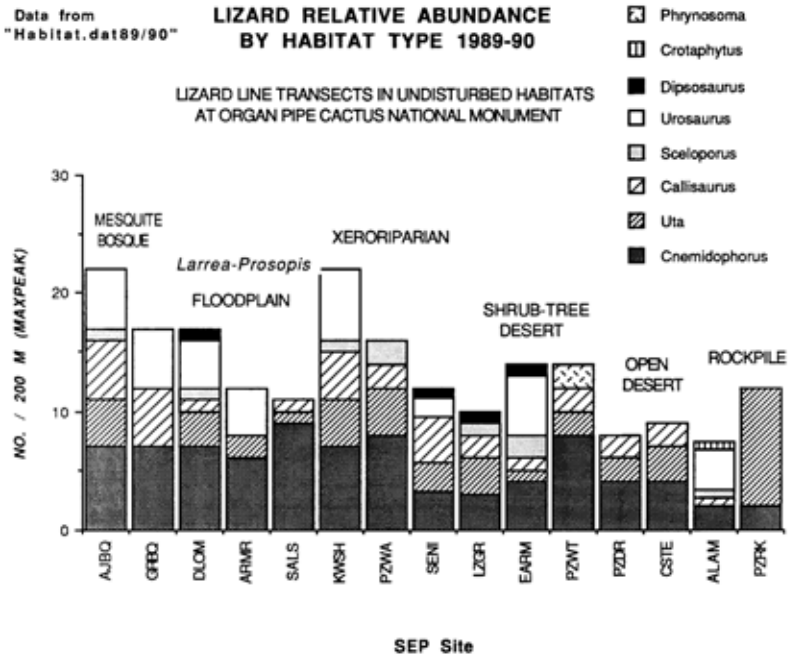

Figure 34. Graph of lizard abundance by habitat type at Organ Pipe Cactus National Monument, Arizona, 1989-1990 (from Rosen and Lowe, 1996). MAXPEAK is maximum peak value observed for all runs of transects within a habitat type at a site. SEP is the Sensitive Ecosystems Program.

Lowe (1985) discussed the obligate riparian turtle, snake, and amphibian species in riparian ecosystems in southern Arizona and adjacent Sonora, Mexico, and their local population extinctions. Many reptiles and amphibians depend on permanent springs, seeps, and ephemeral streams for their survival. Although these species are widely distributed throughout the region, their narrow ecological distributions and low densities make them extremely vulnerable to habitat degradation. Impacts to water quality and quantity, such as acid rain, ground-water pumping, and pollution, are the main threats.

Amphibians are not physiologically well adapted to dry desert conditions; however, they have developed several behavioral adaptations that allow them to survive there, including the ability to avoid the heat and dryness by burrowing underground for extended periods. Species that do not require permanent water may emerge from underground only after rainfall events (e.g., Couch's spadefoot (*Scaphiopus couchi)*). Some amphibians are also very tolerant of dehydration and can survive a water loss equivalent to about 40 percent of their body weight. They handle dehydration by decreasing the rate of urinary water loss and increasing the rate of water absorption through the skin. For example, some amphibians can extract water from moist soil (Mayhew, 1995).

The vast majority of amphibians spend at least part of their life cycle in water, but frequently only for breeding. At the Rincon Mountain Unit of Saguaro National Park near Tucson, Arizona, lowland leopard frogs (*Rana yavapaiensis*) depend on bedrock pools in ephemeral streams that retain water year round for breeding habitat (Parker, 2006). Other amphibian

species, such as the red spotted toad (*Bufo punctatus*), are found only in arid ecosystems (Mayhew, 1995). The canyon tree frog (*Hyla arenicolor*) is found along temporary, intermittent, and permanent streams, springs, and tinajas in rocky desert canyons in much of the Southwest, and uses the temporary pools during summer rains for breeding (Arizona-Sonora Desert Museum, 2007; Arizona Game and Fish Department, 2002). Photographs of some of these species are shown in Figure 35.

In a study of all known occurrences of the California red-legged frog (*Rana aurora draytonii*) in the Central Valley of California (n=143), approximately 64 percent were found in intermittent streams as opposed to perennial streams (Hayes and Jennings, 1988). Six amphibian taxa were captured on ephemeral streams in three southwestern sites by URS Corporation, an environmental consulting firm (2006), including salamanders, frogs, and toads. Tadpoles were commonly observed in longer-lived ephemeral pools.

Figure 35. Photographs of amphibians that inhabit and breed in ephemeral and intermittent streams (clockwise from top left): Canyon tree frog (*Hyla arenicolor*), lowland leopard frog (*Rana yavapaiensis*), red spotted toad (*Bufo punctatus*), Sonoran desert toad (*Bufo alvarius*, photograph: Shea Burns, USDA-ARS), Egg strand of Sonoran desert toad (photograph: Shea Burns, USDA-ARS).

Rosen and Lowe (1996) in their study of herpetofauna at Organ Pipe Cactus National Monument noted that anurans (toads and frogs) are closely tied to permanent or temporary

surface water that lasts long enough to allow their eggs to hatch and produce tadpoles. They found that anurans bred successfully in temporary pools in major washes and ephemeral springs. As little as 7.5 days may be required for the Couch's spadefoot (*Scaphiopus couchi*) to go from egg to toadlet, with a longer period required for the true toads (genus *Bufo*).

Upland desertscrub offers essentially no breeding habitat to the diverse array of summer-breeding toads and frogs characteristic of southwestern deserts and grasslands. The key natural environments for their breeding are the riparian flats along major valley washes, where scour holes in the silts and clays hold floodwaters long enough for tadpole development.

Birds

Birds, more than any other animal group, are highly dependent upon riparian and xeroriparian vegetation in arid and semi-arid lands even though they have the ability to migrate seasonally to find favorable climates. This is thought to be due to the vegetative structure, diversity and productivity of riparian areas as compared to surrounding uplands (Johnson et al., 1977; Ohmart and Anderson, 1982; Johnson and Haight, 1985; England and Laudenslayer, 1995; Kirkpatrick et al., 2007). In the Lower Colorado River Valley subdivision of the Sonoran Desert, dry washes occupy less than 5 percent of the area, but support 90 percent of its bird life (Dimmitt, 2000).

Some birds are particularly adapted to the hot, dry conditions found in deserts: they excrete waste in the form of a semi-solid, requiring one-tenth the water used by mammals; some have a nasal salt gland to excrete excess salts; they have higher body temperatures than most mammals and can tolerate a wide range of body temperatures; and they can store body heat during the day to be released in the cooler evening hours (England and Laudenslayer, 1995).

Kirkpatrick et al. (2007) looked at seventeen sites in southern Arizona (5 sites that had perennial flowing surface water, 9 sites that had intermittent surface water, and 3 sites that had ephemeral surface water) for avian abundance and species richness along riparian areas as compared to uplands. He found that avian species richness and abundance were substantially higher than in the surrounding uplands, even for the dry, ephemeral sites. This was attributed to the riparian vegetation. No association was evident between species richness and abundance in association with surface water at the community level; however, there was a positive association with the volume of velvet mesquite, which provides food sources (high densities of insects and other arthropods).

A study by Stevens et al. (1977) on seven paired sites (riparian and adjacent upland) in Arizona found that the importance of riparian habitat to migrant passerines is substantial. They found that the parameters influencing the use of riparian habitats included: specific habitat preferences of the bird (stop-over habitat selection); floral components (niche diversity and vegetation species composition); location of habitat (island situations and accessibility); and quality of the adjacent habitat (including the amount of grazing and other forms of impact).

Higher bird species richness was found in dry wash systems according to a study of bird use of desert habitats by the California BLM on sixty-six study plots. They found approximately 1.5 times as many breeding species (Kubik and Remsen, 1977; Tomoff, 1977; Daniels and Boyd, 1979a, 1979b) and about twice as many wintering species (Daniels, 1979a, 1979b; Henderson, 1979; Remsen et al., 1976; Tomoff, 1979a, 1979b, 1979c) in the dry washes. This demonstrated that these systems supported a greater diversity of species than did the more common desert scrub possessing overstory vegetation structure.

Skagen et al. (1998) compared migrating birds use of riparian corridors versus isolated oases in the San Pedro River and found that "Small, isolated oases [riverine vegetation isolated from similar vegetation patches] hosted more avian species than the corridor sites, and the relative abundance of most migrating birds did not differ between sites relative to size-connectivity." They concluded that the protection of both the small patches and the more extensive riparian corridors that link these patches is imperative, given the overall habitat limitation in western landscapes. They noted that these areas are critical in providing migration stopover areas, and therefore affect the breeding success of northern bird populations.

Ohmart and Zisner (1993) conducted an extensive literature review of riparian habitat in Arizona, which included perennial, intermittent, and ephemeral streams. They found that nearly every species of bird in Arizona was found in riparian habitats either for breeding, foraging, migration or wintering. This included fifty-seven ducks, geese, and waterfowl; twelve hawks, falcons, and eagles; forty-two shorebirds (breeding habitat); one quail; and seventy-eight songbirds and other birds.

Few studies attempt to separate the effects of water from vegetation on species diversity. In their survey of southwestern streams, Kirkpatrick et al. (2007) found a relationship between the abundance of four bird species (Black Phoebe (*Sayornis nigricans*), Wilson's warbler (*Wilsonia pusilla*), common yellowthroat (*Geothlypis trichas*), and song sparrow (*Melospiza melodia*)), and presence and extent of surface water. They were unable to determine whether the association with surface water might be caused by other factors, such as a higher arthropod biomass along "wet" streams (which included intermittent and perennial sites). The majority of bird richness or abundance was not explained by the presence of water, but was positively correlated with mesquite volume.

A study conducted by the Point Reyes Bird Observatory (PRBO, 2007) during conditions of extreme drought identified 120 bird species using dry washes in western Arizona, including twenty-five breeding species. Skagen et al. (2005) looked at the geography of spring bird migration through riparian habitats in the Southwest and found that all riparian habitat types were used to some degree.

Mammals

A wide variety of mammals inhabits the arid and semi-arid Southwest. Most have adapted to the harsh conditions and lack of water in one or more of the following ways: heat evasion (daily or seasonal estivation, diurnal or nocturnal behavior, or seasonal migration), water conservation, water storage, dehydration tolerance, heat tolerance, and heat dissipation (open-

mouthed gaping, or long appendages such as long ears). Many mammals burrow underground during the hottest part of the day to avoid the heat and increase water conservation.

Nearly all mammals must be able to find free water, making them dependent upon riparian areas to some degree where they can utilize temporary and permanent pools found in ephemeral or intermittent streams. However, some small mammals in desert environments, such as the heteromyid rodents, utilize riparian areas but never drink free water, having evolved to meet their water requirements through the metabolism of carbohydrates, an efficient renal system that concentrates urine, lack of sweat glands, and nocturnal habits (Kepner, 1978; Frank, 1988).

Mammals utilize dry washes in many ways. Krausman et al. (1985) determined that xeroriparian washes and their associated vegetation were an important component of desert mule deer (*Odocoileus hemionus*) habitat in Arizona (Figure 36). They noted that the greater plant densities and diversity in washes allowed deer to find the forage and cover they require. They also found that in central Arizona deer used washes 42 percent of the time in winter, increasing to 83 percent in summer. In the arid and hot King Valley, Arizona, desert mule deer used washes 99 percent of the time. Deer in these areas used washes for forage, cover, travel lanes, and birth sites.

Figure 36. Photograph of a desert mule deer (*Odocoileus hemionus*), Arizona.

Bellantoni and Krausman (1991), and Ragotzkie and Bailey (1991) found that female mule deer especially used xeroriparian or dry wash habitat for foraging during early summer. They suggested that in the Southwest, xeroriparian areas provide thermal cover, forage, and travel corridors for mule deer, and that these areas are most important during the hot, dry period of early summer. In addition, the increased stresses on female mule deer during pregnancy could increase this habitat selection. Other large ungulates, such as Desert bighorn sheep (*Ovis Canadensis*) utilize scattered isolated pools in desert washes (Jones, 1986).

Various authors have noted that collared peccaries (*Tayassu tajacu*) in Arizona used dry washes during certain times of the year for loafing and resting (Bigler, 1974; Bellantoni and Krausman, 1993), or as bedding sites and corridors (Ticer et al., 1998). Bellantoni and Krausman (1991) found that both mule deer (*Odocoileus hemionus*) and peccaries used dry washes for bedding.

When evaluating potential jaguar (*Panthera onca*) habitat, Hatten et al. (2003) found that riparian areas and major wash complexes, mountain ranges, and associated canyons are potentially suitable geographic features. Jaguars occupy a wide range of altitudes as long as food, water, and cover are available. Perennial and intermittent water sources within 20 km were considered important to dispersing jaguars in an arid environment. They noted that any sources of water, even ephemeral ones, may be important because they are usually associated with well-defined channels that serve as travel corridors, and contain riparian vegetation, a cooler microclimate, and higher prey abundance. Beier (1995) looked at juvenile cougar dispersal from their maternal home range in three corridors, including a desert arroyo, in southern California. The study found that the cougar used all three corridors even though few drainages had perennial water; however, seeps and springs were distributed throughout the area.

A variety of other small mammals utilize dry wash habitats and xeroriparian areas, including the Mesquite mouse (*Peromyscus merriami*) (Kingsley, 2006) and a wide variety of other rodents (Jorgensen et al., 1995; Kepner, 1978). Duncan (1990) found that spotted ground squirrels (*Spermophilus spilosoma*) often use dry, sandy washes for their burrows. Jorgensen et al. (1995) studied an arroyo in New Mexico to determine rodent use of the wash area (sandy bottom), terraces, and shoulders (stream banks). They found that the terraces and shoulders were used much more than the wash, and that most animals traveled parallel to the arroyo as opposed to perpendicular to it. This behavior may be due to the high vegetation density along arroyos that offers predator protection.

In Ohmart and Zisner's (1993) extensive literature review of wildlife usage of riparian areas in Arizona, they compiled a list of fifty-five mammals that use riparian areas in any way for breeding, foraging, cover or migration. They noted the importance of riparian areas to birds, bats and large mammals such as elk and deer for migration corridors, and that continuity of these areas was important for population expansion and genetic diversity in small vertebrates. They found that only a few mammals in Arizona, such as the river otter, beaver, muskrat, or water shrew, were truly tied to aquatic habitats. These species were unlikely to be found on non-perennial streams, with the exception of effluent-dependent ephemeral streams. For instance, beaver have reoccupied part of the Salt and Gila River systems near the 91st Avenue waste water treatment plant in Phoenix, Arizona.

Invertebrates

The abundant invertebrates associated with ephemeral, intermittent, and headwater tributaries are important contributions to the biological integrity of river networks. Invertebrates constitute a major portion of the faunal diversity of the earth, and the emergence of aquatic invertebrates from streams is a significant part of the food chain. For instance, Fisher (1991)

reported that flycatchers used a large portion of the insect biomass emerging from Sycamore Creek, Arizona, an intermittent stream.

Ephemeral streams contain rich assemblages of both invertebrates and macroinvertebrates. Kingsley (1998) conducted an extensive survey of the invertebrates at Organ Pipe Cactus National Monument, Arizona, and found a very high species richness in the wash habitats in the Ajo Mountains and Aguajita Wash. He noted that this was to be expected due to the diversity of microhabitats. This study described each of the nearly 1,000 taxa surveyed.

Many invertebrates require a hydrologic connection for their spatial dispersal, even if the connection is ephemeral or intermittent (Nadeau and Rains, 2007). Whiles and Goldowitz (2005) looked at macroinvertebrates in wetlands across a hydrologic gradient from ephemeral to perennial. Although this study was conducted in Nebraska, the results were interesting in that they showed the highest taxon richness and diversity at the intermittent sites. In northern California, Del Rosario and Resh (2000) compared invertebrates in the hyporheic zones of intermittent and perennial streams, and found that intermittent streams had lower densities, similar richness, but higher species diversity than perennial streams.

Intermittent streams in the Southwest provide food sources for the high numbers of macroinvertebrates found there. Disturbances caused by intermittent flows may actually facilitate high food quality and consequently high levels of insect production in warm-temperate desert streams (Fisher and Gray, 1983; Jackson and Fisher, 1986; Grimm and Fisher, 1989; Huryn and Wallace, 2000). For example, in Arizona, macroinvertebrate biomass in Sycamore Creek tends to decline following extended periods without disturbance (e.g., more than 60 to 80 days) because of reduced food quality resulting from cyclical coprophagy (the consumption of feces) (Grimm and Fisher, 1989; Huryn and Wallace, 2000).

Many invertebrates require standing water for part of their life cycle. For example, the caddisfly (*Limnophilus sp.*) requires water only for the egg, larva, and pupae stages of its life cycle; the adult is terrestrial (Erman and Nagano, 1992) (Figure 37). Other species live in sediment, either in encysted form, or within the hyporheic zone. Graham (2002) studied temporary pools in watercourses in Wupatki National Monument, Arizona. He found 22 taxa of aquatic macroinvertebrates and two taxa of amphibians. Ward and Associates (1973) noted that the life cycles of these species are triggered by specific temperature and/or water conditions, and they may remain dormant or aestivate during unfavorable or stress periods. Invertebrate species using ephemeral streams are generally good dispersers, either being swept in from the upland, moving in from the air, or colonizing from hydrologically separate perennial sources, including backwaters, pools, and off-channel ponds (URS Corporation, 2006).

Figure 37. Illustrations of caddisfly larva (www.scientificillustrator.com) (left), and caddisfly adult (www.nps.gov) (right).

Some crustaceans (Phylum Arthropoda, Class Crustacea, e.g., tadpole and fairy shrimp) are able to survive in temporary waters in ephemeral stream channels. Fairy shrimp can complete its life cycle, going from egg to egg, in seven days during summer, and two weeks during winter. As cysts, these creatures are able to dry with the mud and rehydrate later when water returns, hatching 24 to 36 hours after hydration (Carpelan, 1995).

URS Corporation (2006) sampled several ephemeral streams in Arizona, Colorado, and New Mexico during July and August of 2006. Most microinvertebrates were terrestrial, but eighty-six aquatic taxa, including copepods, ostracods, and cladocerans were detected. Seventy-seven aquatic macroinvertebrate taxa occurred in streams with known or likely upstream sources of colonizers, and thirty-five taxa occurred in those without. Macroinvertebrate taxa had a high degree of dissimilarity, either between study watersheds or within them (URS Corporation, 2006).

However, in general it is difficult to understand the dynamics of these communities in intermittent or ephemeral streams due to the irregular nature of the hydrologic regime and their high sensitivity to climatic fluctuations. Boulton and Lake (1992) suggested studying a number of sites over a period spanning several complete cycles of flow to assess adequately these complex interactions. Adams (2000) found that he was able to develop baseline biological conditions for water-quality assessment prior to urban development by sampling macroinvertebrates in ephemeral streams during periods of flow.

A typical conceptual model of the movement of invertebrates through a stream network is exemplified by Cummins and Wilzbach (2005), with headwater intermittent stream reaches responsible for delivery of invertebrates, sloughed algae, and detritus to the downstream perennial stream reaches (Figure 38). Although their research looked at whether fish were present as a criterion for inclusion in management plans, they noted that downstream reaches are always highly dependent on upstream processes, and that successful stream management should include the entire watershed.

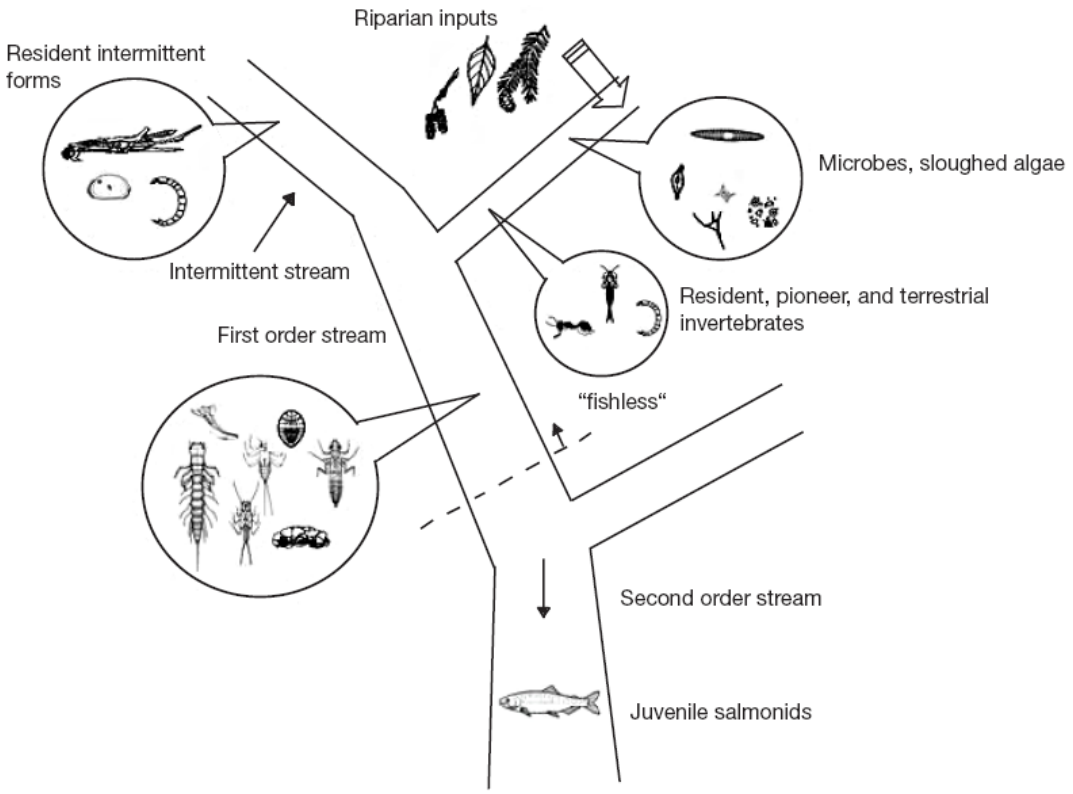

Figure 38. Diagram of a conceptual model of the delivery of invertebrates, sloughed algae and detritus from headwater streams, intermittent and permanent first-order fishless streams to larger fish-bearing streams, illustrating the dependence of downstream reaches on upstream processes (from Cummins and Wilzbach, 2005).

Fish

Native and non-native fish are abundant in perennial streams in the Southwest deserts. For example, seventy-five native fish species have been recorded in Arizona and New Mexico, many of them listed as endangered, although some have been lost due to habitat loss (Hubbard, 1977). Surprisingly, many species of fish, both native and non-native, can be found in isolated perennial pools in otherwise ephemeral or intermittent streams. For example, four fish taxa were collected during a one year study on ephemeral streams in southern Arizona by URS Corporation (2006), including two native species and two non-native species.

Native desert fish are adapted to the harsh and variable conditions of the desert. Pupfish (*Cyprinodon sp.*) can withstand the high temperatures, alkalinity, and salinity of small desert pools (Pister, 1995). Lema (2008) looked at environmental factors influencing phenotypic development of the seven species of pupfish inhabiting the fresh water pools, saline marshes, and small streams in the Death Valley system.

Although pupfish require permanent water, a few of the hardiest desert fish species can survive in areas that periodically go nearly dry, such as in intermittent streams. Longfin dace

(*Agosia chrysogaster*), for example, survive relatively high water temperatures and low water quality and quantity, and have been found alive in moist algal mats where there was not enough water to swim (Hulen, 2007; Rinne and Minckley, 1991). Longfin dace have the most widespread distribution of any native fish in the Southwest, and can disperse rapidly once flow returns (Rinne and Minckley, 1991). The Gila topminnow (*Poeciliopsis occidentalis occidentalis*) also withstands low flows, high temperatures and poor water quality of intermittent desert streams (Arizona Game and Fish Department, 2001).

Although ephemeral streams only temporarily support fish, they indirectly support fish populations by helping to deliver required nutrients and other materials to the perennial segments. Cummins and Wilzbach (2005) noted that ephemeral and intermittent streams are important suppliers of invertebrates and detritus to permanently flowing, receiving streams that support juvenile salmonids. They also acknowledged the connection between headwater streams and downstream perennial waters by noting that it is critical to maintain riparian cover in the headwater systems to prevent increased temperatures of the downstream delivery of water that would interfere with juvenile salmonids.

Intermittent streams are important to some fish species. Erman and Hawthorne (1976) found that trout production in California was dependent on intermittent streams. Over a four-year period, 39-47 percent of rainbow trout recruits in Sagehen Creek, California, came from an intermittent tributary that flowed only four months each year. Loggins et al. (1996) found that five native migratory cyprinid fishes were spawning in intermittent tributaries of the Sacramento River: Sacramento pikeminnow (*Ptychocheilus grandis*), hardhead (*Mylopharodon conocephalus*), hitch (*Lavinia exilicauda*), speckled dace (*Rhinichthys osculus*) and Sacramento sucker (*Catostomus occidentalis*).

Populations of native desert fishes are rapidly dwindling due to destruction of aquatic habitats from urbanization, channelization, land-use change, over grazing, ground-water pumping, dams, water diversions, and pollution (Rinne and Minckley, 1991).

f. Synthesis of Functions

Ephemeral and intermittent streams and tributaries provide a wide range of functions that are critical to the health and stability of arid and semi-arid watersheds and ecosystems in the American Southwest. Most importantly, they provide hydrologic connectivity within a basin, linking ephemeral, intermittent, and perennial stream segments, thereby facilitating the movement of water, sediment, nutrients, debris, fish, wildlife, and plant propagules throughout the watershed. They provide wildlife habitat and connectivity to perennial reaches by providing a relatively more vegetated and moister environment than do the surrounding uplands. The processes that occur during ephemeral and intermittent stream flow include dissipation of energy as part of natural fluvial adjustment, and the movement of sediment and debris.

Ephemeral and intermittent streams are responsible for a large portion of basin ground-water recharge in arid and semi-arid regions through channel infiltration and transmission losses. These stream systems contribute to the biogeochemical functions of the watershed by storing,

cycling, transforming, and transporting elements and compounds. Ephemeral and intermittent streams support a wide diversity of plant species, and serve as seed banks for these species. Because vegetation is more dense than in surrounding uplands, ephemeral and intermittent streams provide habitat, migration pathways, stop-over places, breeding locations, nesting sites, food, cover, water, and resting areas for mammals, birds, invertebrates, fish, reptiles and amphibians. In arid and semi-arid regions, the variability of the hydrological regime is the key determinant of both plant community structure in time and space and the types of plants and wildlife present.

Figure 39. Photographs of the Rillito River, Tucson, Arizona, dry (left) and with flow (right).

6. Anthropogenic Impacts on Ephemeral and Intermittent streams and Riparian Areas

Anthropogenic uses and activities on the landscape can have significant impacts – both good and bad – on water quality and the health of a watershed. Human-related disturbances are numerous and include livestock grazing, land clearing, mining, timber harvesting, ground-water withdrawal, stream flow diversion, channelization, urbanization, agriculture, roads and road construction, off-road vehicle use, camping, hiking, and vegetation conversion. Biological stressors include habitat loss, alteration, effluent discharge, and degradation from decline in water quality, and changes in channel and flow characteristics (Pima County, 2000).

The CWA has regulated many of these uses, but recent changes to the act have weakened or eliminated that enforcement. While many land owners voluntarily employ best management practices for water quality protection, not all do. However, in arid and semi-arid areas, where water is limited and systems do not recover quickly, it is especially important to employ best management practices for water quality protection whenever possible.

As noted earlier, ephemeral and intermittent streams and the adjacent riparian areas perform many of the same functions in a watershed as perennial streams. Especially in arid regions of the country, riparian areas 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. These features have made riparian areas attractive for human development, leading to their alteration on a scale similar to that of wetlands degradation nationally (National Research Council, 2002). This is especially true in arid and semi-arid regions because riparian areas are typically greener and cooler than other places. However, riparian areas in arid and semi-arid regions are more sensitive to development impacts than in wetter areas because of their limited geographical extent, drier hydrologic characteristics, and fragile nature (e.g., erodible soils).

In general, human-induced changes to natural hydrological regimes in desert streams reduce temporal and spatial heterogeneity of plant habitats, resulting in the loss of biodiversity and homogenization of plant community composition and structure. Given the ecological importance of plant communities in desert rivers (e.g., for channel bank stabilization and wildlife habitat), there may be significant secondary impacts as well. There is some evidence to suggest that restoration of natural hydrological regimes in ephemeral streams may be partly sufficient to reverse such deleterious changes in plant communities (see for example, Stromberg, 2001).

In the past, riparian habitats represented about 1 percent of the landscape in the West, and it has been estimated that within the past one hundred years, 95 percent of this habitat has been destroyed due to a wide variety of land use practices such as river channelization, unmanaged livestock utilization, agricultural clearing, water impoundments and urbanization (Krueper, 1995). Given the vast extent of ephemeral and intermittent streams and the accumulation of impacts to them over large areas in the rapidly developing southwest, a landscape or watershed-scale approach should be employed that considers the cumulative effects on overall watershed function. This section presents some of the types of human caused impacts on ephemeral and intermittent streams and their associated riparian areas.

a. Land Development

The ecological and hydrological value of ephemeral and intermittent streams has been under appreciated, especially with respect to land conversion and development. Land development includes urban, suburban and exurban development, but is referred to here as urban development.

The Southwest is one of the fastest growing regions of the U.S., having an increase in population of approximately 1,500 percent over the last ninety years. In contrast, the population of the country as a whole has grown by just 225 percent. Arizona and Nevada have grown the most with population increases of 2,880 percent and 2,840 percent, respectively. Most of the growth in Nevada has been in Las Vegas, with Clark County having a 90-year growth rate of 22,480 percent, growing from 3,284 people in 1900 to 741,459 people in 1990. Maricopa County (Phoenix), Arizona, had a one hundred year growth rate of 10,275 percent, with most of that growth occurring between 1960 and 1990 (Chourre and Wright, 1997).

Assuming that the significant trend in population growth in the Southwestern U.S. over the last ninety years continues, it is necessary to develop plans to manage and protect streams and riparian areas that consider cumulative impacts across a watershed. Water and natural resources need to be managed to accommodate future growth, and economies need to be examined to ensure a healthy environment (Chourre and Wright, 1997).

Urban development has the potential to change significantly the hydrologic characteristics of a watershed by covering uplands with impervious surfaces, and removal, channelization or armoring of small or headwater streams. Disruption of the natural stream network interferes with or destroys natural flow patterns and sediment-transport functions, resulting in downstream flooding and changes to the clarity and chemistry of the downstream flows. This can damage wildlife habitat and downstream water supplies for humans (National Wildlife Federation, 2007). Many land-preservation efforts have focused on upland areas, allowing the lowland bottomlands to continue being developed and degraded, although these areas support a rich biota (Rosen et al. 2005). In other areas, the bottomlands are protected from degradation, but not the uplands. Figure 40 shows a network of ephemeral streams that flows through a small community southeast of Tucson, Arizona, to Cienega Creek, a protected perennial stream.

Figure 40. Aerial photograph showing ephemeral tributaries to Cienega Creek, a perennial stream, flowing through the small community of Vail, southeast of Tucson, Arizona. (Photograph: Lainie Levick/Aerial flight courtesy of Lighthawk, www.lighthawk.org)

The influence of impermeable surfaces associated with urbanization increases as the percentage of impermeable surface increases. Various studies have shown that semi-arid stream systems become irreparably impaired once the impervious surfaces within the watershed exceed about 10 percent, and experience dramatic morphological changes once that

percentage exceeds about 20 percent (Coleman et al., 2005; Miltner et al., 2003; Schueler, 1994).

As the amount of impervious surface increases, runoff increases and infiltration decreases, starting a chain of events that includes flooding, erosion, stream channel alteration, increases in man-made pollutants, and ecological damage. Floods will become more severe and more frequent, and peak flows will be many times greater than in natural basins. The greater volume and intensity of flooding will cause increased erosion and sedimentation downstream. To facilitate the increased flow and sediment load, streams in urbanized areas tend to become deeper and straighter over time. The resulting bank erosion destroys valuable streamside or riparian habitat and tree cover, leading to higher temperatures, sedimentation, and disruption of habitat. Ground-water recharge will also be reduced as rainfall runoff leaves the watershed more rapidly than before (University of Connecticut, 1994).

Storm sewers and lined drainages increase the rate at which water is delivered to the channel network, and thus further increases peak flows and erosion. Sedimentation is increased during construction and road building for new urban areas. Improperly constructed and maintained roads, especially dirt roads, can cause alterations to hillslope drainage, and alter baseflow and precipitation-runoff relationships, resulting in erosion and sedimentation into the streams (USDA, 2002). The primary geomorphic consequence of these hydrologic changes is the erosional entrenchment of adjacent channels and associated transportation of the excavated sediment downstream, causing a significant increase in sediment load. Urban areas require storm water management plans both during and after construction to control polluted runoff.

Water-quality impacts from urbanization include nonpoint source pollution, considered to be the single largest water quality threat in the U.S. Pollutants include pathogens, nutrients, toxic contaminants, sediment, and debris. Sediment is of particular concern because many other pollutants tend to adhere to eroded soil particles. These changes to a stream system's form and function result in degraded systems no longer capable of providing good drainage, healthy habitat, or natural pollutant processing (University of Connecticut, 1994).

Stream channelization is often applied in urbanizing areas to protect private property and control stream bank erosion. However, channelization straightens and steepens the stream, resulting in increased flow velocity and sediment movement. It also reduces moisture content along the stream banks by reducing out of bank flows which disrupts water, sediment, organic matter and nutrient enrichment of the flood plain (National Research Council, 2002). In addition, removal of vegetation as part of the channelization process degrades wildlife habitat.

Many authors have noted that habitat fragmentation is one of the consequences of urbanization (University of Connecticut, 1999; Aurambout, 2003; 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 can effectively eliminate the main biological functions of the stream channel by disrupting vegetation communities and hydrologic function. Habitat fragmentation reduces wildlife diversity and abundance, and may cause sensitive species to disappear (University of

Connecticut, 1999). A study by the California BLM that inventoried sixty-six study plots for bird use of desert habitats noted the heavy recreational uses of washes, and the related disturbance to wildlife and habitat degradation (England and Laudenslayer, 1995).

b. Land Uses

Besides urbanization, agriculture (livestock and crops) and mining are other major land uses in the desert southwest. Livestock grazing is one of the more common uses of rural land in the Southwest, and has historically been a large part of the economy. It occurs primarily on state or federal land, but also on private land. In many areas livestock are provided with watering sources, but frequently they must depend on the streams for water. Livestock management plans attempt to avoid overuse of an area, but because water is scarce in arid environments, cattle and wildlife tend to linger near water sources. When they are not properly managed, and remain too long in a riparian area, cattle can trample stream banks, eat the riparian vegetation to the ground, contaminate the water with wastes, and compact the soil. In addition, livestock grazing can introduce exotic plant species from hay or feed brought in from outside the area. Non-native plants may out-compete native species, causing disruption of natural ecosystem functions. (Pima County, 2000).

It has been estimated that by the late 1800's over one and one half million cattle were in Arizona, with another two million in New Mexico. Around that time the Southwest was experiencing its typical climatic pattern of drought and unpredictable rainfall patterns. 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 took over and down cutting began, forming deep arroyos and lowering the ground-water reservoir. Marshes and riparian vegetation disappeared (Rinne and Minckley, 1991; Krueper, 1995).

A study by Siekert et al. (1985) on grazing impacts on ephemeral streams in Wyoming found that seasonal grazing had an impact on channel morphology. Specifically, spring grazing had no effect, but summer and fall grazing resulted in increased channel cross sections. These impacts in and along a stream channel can cause reduced stream bank stability, decreased ground-water recharge, water quality degradation, increased erosion and sedimentation, removal of vegetation, increased flood risk due to reduced vegetation cover, and dispersal of exotic plants. Many sources have stressed that the cumulative impacts of unmanaged livestock in southwestern riparian ecosystems for the past several hundred years has probably been the single most important factor in riparian ecosystem degradation (e.g., Krueper, 1995; Wagner, 1978; Ohmart, 1995).

Reducing damage to riparian vegetation from over-grazing by livestock is important in arid and semi-arid regions. Riparian vegetation helps stabilize stream banks, reduce water temperatures and evaporation through shading, and provides food and habitat for wildlife. Although in the past it was thought that removal of stream bank vegetation would increase stream flow, recent studies have shown that in some places open water has higher annual water losses from evaporation than riparian trees from evapotranspiration (Leenhouts et al., 2006).

Mining is another activity that historically has had a large place in the economy and land use in the American Southwest. Some of the largest copper and gold mines in the world are found here, and some cover many thousands of hectares. However, mining can cause major impacts on riparian areas both adjacent and downstream by altering the local hydrology. Mining not only dewaters the area, it removes vegetation and soil and changes the topography, severely impacting the watershed. Instream and flood plain gravel mining can cause alteration to the channel dimensions and increase sediment yield. Mining can also decrease water quality by leaching heavy metals and toxic chemicals into the surface and ground water (Ecosystem Restoration Web site, accessed Sept. 12, 2008, http://ecorestoration.montana.edu/mineland/guide/problem/impacts/default.htm)

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. However, most crops must be irrigated due to the low annual rainfall. Impacts to local hydrology from agricultural activities include:

- Increased salinity caused by clearing of native vegetation which raises the ground-water reservoir;
- Reduced flows from ground-water pumping or stream diversions for irrigation;
- 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 algae growth;
- Fish, aquatic invertebrate and bird kills from pesticides that run off into the streams or leach into the ground water.

(from South Australia Environmental Protection Authority Web site, http://www.epa.sa.gov.au/water_impact.html, accessed August 7, 2008)

c. Water Resources Impacts

The Southwest has experienced rapid growth over the past several decades, straining the already limited water resources. Lack of surface water flows has placed increased reliance on ground water for domestic, industrial, and agricultural uses. Ground-water pumping creates a chain reaction of events that impact the local and regional ecology.

Ground-water pumping lowers the ground-water reservoir killing near-channel vegetation whose roots no longer reach the aquifer, or desiccates the subsurface to the point that flow frequently is reduced (Stromberg et al., 1996). As riparian vegetation dies, stream banks become unstable due to the loss of the reinforcing nature of the plant roots, resulting in bank erosion (Groeneveld and Griepentrog, 1985). Lowering of the ground-water reservoir helps the invasion of exotic and drought tolerant species. Alteration and degradation of riparian vegetation can adversely affect wildlife species and human uses of those areas.

Dams and retention or detention basins are frequently used in the Southwest to store water or as flood-control devices. They disrupt natural surface flow and sediment transport, interfere with natural geomorphic processes, alter water temperatures, and fragment the natural stream systems both upstream and downstream of the structure. Upstream locations may experience

flooding, whereas downstream locations may be dewatered and become sediment starved. As a result, both vegetation and wildlife communities are altered.

Ephemeral and intermittent streams in the Southwest are often the recipients of effluent from waste water treatment plants. Depending on the level of treatment, effluent can have various effects on the stream ecosystem. For example, Walker et al. (2005) compared four effluent dominated waters in Arizona and found that aquatic macroinvertebrates were most affected by the levels of nitrogenous species, especially un-ionized ammonia, and mean diel dissolved oxygen. Specifically, diversity decreased with increasing levels of nitrogen.

As human population in the desert Southwest continues to grow, water resources will become even more stressed. Ground-water pumping has long been an important source of water in these areas; however, ground-water depletion, ground surface subsidence and impacts to riparian areas are becoming more common. Further research and understanding of the surface-water ground-water interactions is needed for better management of these resources (Phillips et al., 2004; Newman et al., 2006).

d. Climate Change

Most climate models predict severe changes for the southwest U.S., including increased warming and drying, intensification of droughts, and increased variability of precipitation. These changes will result in less runoff, reduced snow packs, changes in streamflow patterns, longer and hotter growing seasons, shifts in vegetation growth patterns, and changes in wildfire regimes (CIRMOUNT Committee, 2006; Betancourt, 2007). The Intergovernmental Panel on Climate Change (IPCC) model simulations suggest that the hydrologic cycle will become more vigorous, with the possibility of greater droughts and/or floods in some regions and reduced occurrences of these phenomena in other areas (Thompson, 1997). Most of these impacts are already occurring to varying degrees, but acceleration over the next century will make management of land and water resources more complex.

7. Discussion

a. Clean Water Act Context

The goal of the CWA is to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters," and to prevent pollution of those waters. Historically, desert washes have been considered to be jurisdictional under the CWA (for example, 408 F.3d 1113 Save Our Sonoran, Inc. v. Flowers). However, as a result of the Supreme Court decision in the consolidated cases *Rapanos v. United States* and *Carabell v. United States* ("Rapanos," 2004), the definition of the Nation's waters or waters of the United States jurisdictional under the CWA has required additional clarification, specifically with respect to tributaries that are "not relatively permanent" (i.e. ephemeral or intermittent streams). Recent guidance from the U.S. EPA and Army Corps of Engineers (U.S. Environmental Protection Agency, 2007) requires that a "significant nexus" exist between a non-relatively permanent tributary and a traditional navigable water of the United States for the tributary to be jurisdictional under the

CWA. This significant nexus evaluation must consider flow characteristics and functions of the tributary to determine if it has a significant effect on the chemical, physical, and biological integrity of downstream traditional navigable waters.
We believe that the information presented in this report shows that ephemeral and intermittent streams in the arid and semi-arid Southwestern U.S. are ecologically and hydrologically connected to downstream waters, and have a significant effect on the chemical, physical, and biological integrity of those waters.

Connectivity in non-perennial streams, however, can be difficult to demonstrate owing to a lack of data. Stream gages and water quality monitoring sites tend to be in perennial reaches, for example. Most ecological studies on wildlife or vegetation have been conducted in wetter environments or in the uplands. Nevertheless, hydrologic models suggest that in arid and semi-arid region watersheds flow in small tributaries does reach the perennial stream courses (see for example Levick et al., 2006). Other studies have shown that non-perennial streams contribute nutrients, seed sources, or spawning areas necessary for biological and aquatic health in downstream perennial waters (see for example Erman and Hawthorne, 1976; Howe et al., 2008).

b. Ecosystem Goods and Services

Many sources recognize that the ecosystem goods and services provided by natural systems are critical to the healthy functioning of the natural environment. They also recognize the significant contribution of these goods and services to human welfare and well-being, both directly and indirectly, and therefore the contribution to the overall social and economic value of the natural environment.

Ephemeral and intermittent streams are integral parts of a watershed, and their condition affects the health of the entire ecosystem. Healthy ecosystems perform a diverse array of functions that provide goods and services to society. In this context, “goods” refers to materials that can be sold (e.g., drinking water, tourism, or timber), whereas “services” provide value but cannot be sold (biodiversity, wildlife habitat, or nutrient cycling) (Whiting, 2000; Wilson et al., 2004)

The Millennium Ecosystem Assessment (2005b) reviewed the consequences of ecosystem change on human well-being. Their multi-year study, published in 2005, presents a state-of-the-art scientific appraisal of the condition and trends in the world’s ecosystems and the services they provide, as well as the scientific basis for action to conserve and use them wisely. The report defines *well-being* as including “the basic material needs for a good life, the experience of freedom, health, personal security, and good social relations, which together, provide the conditions for physical, social, psychological, and spiritual fulfillment.”

From the Millennium Ecosystem Assessment (2005b):

> Human well-being is supported by ecosystem services, which refers to the benefits received by people from an ecosystem. These may include:

- *provisioning services* such as food, water, timber, fiber, and genetic resources;
- *regulating services* such as the regulation of climate, floods, disease, and water quality;
- *cultural services* such as recreational, aesthetic, and spiritual benefits; and
- *supporting services* such as soil formation, pollination, and nutrient cycling.

Ecosystems also have value for human well-being through the cultural services they provide, through, for example, totemic species, sacred groves, trees, scenic landscapes, geological formations, or rivers and lakes. These attributes and functions of ecosystems influence the aesthetic, recreational, educational, cultural, and spiritual aspects of human experience. Many changes to these ecosystems, through processes of disruption, contamination, depletion, and extinction, therefore have negative impacts on cultural life and human experience.

In most cultures and regions, people generally prefer the aesthetics of natural environments over built-up or urban ones. For example, real estate values tend to be higher near protected open space, and reflect the willingness of people to pay for this amenity (Wilson et. al., 2004). The benefits provided by nature have inspired art, music and clothing throughout human history. Development and degradation of natural areas have reduced these benefits. The use of natural areas for recreation and tourism is growing as populations increase. Nature travel continues to increase, as does nature tourism, or eco-tourism.

The previous sections of this report demonstrate that ephemeral and intermittent streams provide all of these ecosystem services, and therefore support overall human well being in the arid and semi-arid Southwest. One of the strongest points made in the Millennium Ecosystem Assessment was the powerful impact of ecosystem degradation on people with lower incomes, especially in developing countries. Lower income people depend more on natural areas for well-being than more affluent people because they are less able to replace the ecosystem services with purchased goods.

Although the Millennium Ecosystem Assessment report (2005b) did not address specific ecosystems, such as ephemeral and intermittent stream systems, it did make a strong case for the value of local ecosystems to the cultural diversity and cultural identity of a society. People have historically identified with their environment for their sense of culture and value systems. This is especially true in arid and semi-arid areas where water is a major concern that receives significant attention and focus. Areas where water concentrates are cherished and valued, whether or not permanent water is present. Desert cultures have traditionally based their lives around water, rainy seasons and the times when the rivers flowed. This is still true in the desert today: whenever it rains enough to cause the ephemeral streams to flow, people flock to the rivers to watch the water (Figure 41).

Figure 41. Photograph of the Santa Cruz River, Tucson, Arizona, during summer monsoon flows. (Photograph: unknown)

c. Management Principles

Ecologically responsible land management attempts to meet economic and social objectives while maintaining environmental health. It requires a landscape or watershed-scale approach that considers cumulative impacts to ensure that all physical, biological, and chemical components function together. For example, both the upland areas of a watershed and the riparian or stream course areas must be in a healthy functioning condition for the entire watershed to be healthy and to supply clean water for human and ecosystem use, and in many cases, food and fiber production.

Landscape or watershed health can be described as a measure of the balance of anthropogenic uses and ecological function or integrity (Jones et al., 2002). Ecological integrity is the condition in which the productivity of resources and ecological values, including diversity, are resilient to disturbance and maintained for the long term (Reynolds, 1995). It involves maintaining biodiversity, biological productivity, and ecosystem processes. Important aspects of ecosystem integrity include energy flow through the food web, water and nutrient cycles, disturbance/recovery cycles, biotic diversity, evolutionary processes, and human influences. These characteristics and processes function at various rates and across multiple scales. Maintaining ecosystems requires maintaining these processes; it is not sufficient to only preserve the individual pieces (Institute for River Ecosystems, 1997).

The management of arid and semi-arid lands has a direct impact on the hydrology and geomorphology of the drainage network, in addition to wildlife habitat. Bull (1977) noted that ephemeral streams are much more sensitive to climate or anthropogenic disturbance than are perennial streams. Nadeau and Rains (2007) discussed a management approach that considers how hydrological and ecological systems function at various temporal and spatial

scales. They described a watershed management approach that uses an integrated set of tools (federal, state, tribal, local) and programs (voluntary and regulatory), includes all stakeholders, and applies an iterative planning or adaptive management process to address strategically priority water resource goals.

In arid and semi-arid regions, the functions of ephemeral and intermittent streams must be recognized and appreciated to protect and manage them properly; they must not be relegated to second-class status as compared to wetter systems elsewhere in the U.S. Ephemeral and intermittent streams should not be considered in isolation from the entire watershed. Given their vast extent and the accumulation of impacts to them over large areas in the rapidly developing southwest, a landscape or watershed-scale approach should be employed that considers the cumulative effects on overall watershed function. Ecosystem protection would be meaningless and ineffective if these supporting waterways were significantly degraded.

d. Research Recommendations

Many of the underlying physical, ecological, and biological processes and linkages in arid and semi-arid region systems are not well understood or documented. This general lack of information specific to ephemeral and intermittent streams in the arid and semi-arid Southwest leaves a wide range of research opportunities. For example, linking knowledge of past hydrological and channel changes to present-day changes in arid and semi-arid region streams should be a key research priority (Tooth, 2000a).

Nadeau and Rains (2007) noted the need for long term, large-scale monitoring and research that are integrated across spatial and temporal scales to help provide the theoretical and empirical foundations necessary to identify problems and problem sources. For example, more research is needed to determine and classify the suites of flora and faunal species dependent on ephemeral and intermittent streams, and their preferred habitat types. Instrumenting more arid and semi-arid region watersheds with precipitation and stream flow gages would greatly advance the understanding of these systems.

The protection of intact sites and the establishment of “representative” sites would provide reference areas for future studies and comparisons with impacted areas. Predictive models are needed to understand the consequences of alternative management actions on hydrological, ecological, economic and social systems.

Regarding wildlife, a better understanding of the species that inhabit these systems will aid in our understanding of the significance of arid and semi-arid region streams to wildlife. For example, baseline inventories are needed to determine species composition, abundance, and distribution as compared to adjacent upland or perennial areas. Specific ecological information is needed for critical target species, such as habitat requirements and current population numbers and distribution.

Much still needs to be learned about the ecological and hydrological interactions on ephemeral and intermittent streams due to variability and the often highly episodic occurrence of extreme events in these systems. There are unique challenges for work on these desert

rivers. Sometimes the environments are inhospitable, but arguably the greatest challenge is trying to use short-term projects to understand arid and semi-arid region streams whose variable behavior sometimes demands years of data more than are needed on a mesic river. As noted, ephemeral and intermittent streams constitute the vast majority of drainage ways in the Southwest and they play an integral role in overall watershed function. Future research is needed for both the long-term monitoring of these systems over a range of conditions, and on developing modeling tools that can be applied to large temporal and spatial scales.

8. Conclusions

When functioning properly, arid and semi-arid region streams provide many of the same services as perennial streams that affect water quality and ecosystem health. These services include landscape hydrologic connections; surface and subsurface water storage and exchange; ground-water recharge and discharge; sediment transport, storage, and deposition; flood plain development; nutrient cycling; wildlife habitat including movement and migration corridors; support for vegetation communities that help stabilize stream banks and provide wildlife services; water supply and water quality filtering or cleansing; and stream energy dissipation associated with high-water flows that reduces erosion and improves water quality (USFWS, 1993; BLM, 1998). In addition, riparian areas associated with ephemeral and intermittent streams help mitigate and control water pollution by removing pollutants and sediment from surface runoff (Sonoran Institute, 2007). Thus, these streams play a significant role in the physical, biological, and chemical integrity of an ecosystem and must be afforded the same importance as other wetter systems in the U.S. in land management decisions.

Effective management of water resources in arid and semi-arid environments requires awareness of the interdependencies of hydrologic, biogeochemical and ecological processes, and collaboration between ecologists and hydrologists. Stream channel characteristics are based on upland watershed and channel conditions, and physical characteristics such as the hydrology of the system-driven biological values. Non-perennial streams with active flood regimes contain a high diversity of plant species that varies depending on the location within the watershed. The complex longitudinal gradients along arid and semi-arid region streams encompassing changes in flood intensity, climate, and water availability, result in a wide range of biological conditions along its length. Therefore, to protect water quality and riparian habitat, a watershed-based approach to land management must be taken, involving all stakeholders and applying best management practices. Newman et al. (2006) suggest establishing a monitoring network in water-limited environments to facilitate this collaboration, from the experimental design phase, through interpretation and modeling.

In the rapidly developing southwest, land management decisions must employ a watershed-scale approach that addresses overall watershed function and water quality. As shown in this report, ephemeral and intermittent stream systems comprise a large portion of southwestern watersheds, and contribute to the hydrological, biogeochemical, and ecological health of a watershed. Given their importance and vast extent, consideration of the cumulative impacts from anthropogenic uses on these streams is critical in watershed-based assessments and land management decisions to maintain overall watershed health and water quality.

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