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CHAPTER 1
Defining Arizona's Riparian Areas and Their Importance to the Landscape

By George Zaimes

Importance of riparian areas

Riparian areas of the southwestern United States have been receiving more attention in recent years. Much of the increased attention can be attributed to the fact that riparian areas occur near water, an important resource that cannot be underestimated particularly in the southwest. The greater water availability in riparian areas relative to adjacent terrestrial uplands promotes greater vegetative and wildlife diversity. Riparian areas are called "ribbons of life," since they are considered the most productive habitats in North America (Johnson et al., 1977; Chaney et al., 1990). The close proximity to water also means that changes made to riparian areas have direct impacts on water quality.

In the arid western United States, riparian areas are estimated to be less than 2% of the total land area (Ffolliott et al., 2004). Some estimate the acreages of riparian areas in Arizona are only 113,000 hectares, with 40,750 hecatres along the Gila River alone (Pase and Layser, 1977). This is only 0.4% of Arizona's total area, a percentage that is much smaller than the estimated average for the arid western United States. The small percentage of riparian areas in Arizona is in line with the name of our state, "little spring," in the language of the Pima Indians. Despite their small area, Patten (1998) points out that the role of riparian areas is disproportionate to their size, particularly in the semi-arid regions of North America. This is mainly due to the many functions and values of riparian areas. Although many use the terms "function" and "value" interchangeably, they differ (Walbridge, 1993). Brinson (1993) described functions as the ecological, hydrological or other phenomenon that contributes to self-maintenance. In contrast, value is defined as something of worth, desirable or useful to humans (Mitsch and Gosselink, 1986).

Riparian areas support more productive and diverse vegetation assemblages and serve more ecological functions than their terrestrial upland counterparts. These areas provide important links between terrestrial upland and aquatic ecosystems (Elmore, 1992; Osborne and Kovacic, 1993). Their most important functions are to (Schultz et al., 2000):

1) support animal habitat and enhance fish habitat
2) filtrate and retain sediments and nutrients from terrestrial upland runoff or out-of-bank floods
3) reduce chemical inputs from terrestrial uplands by immobilization, storage and transformation
4) stabilize stream banks and build-up new stream banks
5) store water and recharge subsurface aquifers and
6) reduce floodwater runoff.

A large percentage of wildlife depends on riparian areas for foraging, nesting or cover during part or their entire life cycle. This is even more true for the southwestern United States where riparian areas are recognized as critical areas (DeBano and Schmidt, 2004). In Arizona, eighty percent of all vertebrates spend some portion of their life cycle in riparian areas (Hubbard, 1977). In addition riparian vegetation can provide food, cover or regulate stream temperature (by shade), three important factors that can impact the survival of native fish populations.

Higher vegetation density in riparian areas compared to adjacent uplands reduces runoff velocity either from overland flows or out-of-bank floods and effectively removes sediments and nutrients (Correll, 1997). The higher stem densities of riparian vegetation increase their sediment trapping capacity that allows the buildup of soil. As a result, these areas can develop stream banks and floodplains faster and more efficiently. Higher vegetation density also leads to more microbial activity resulting in an increase of the assimilation, immobilization, storage and transformation of chemicals and nutrients (Schultz et al., 2000). Because riparian areas slow and spread flood waters that crest over the banks, more water infiltrates in the soil, recharges groundwater and extends stream baseflow (Wissmar and Swanson, 1990; Elmore, 1992). In the southwest under specific conditions, researchers have found that water losses from evapotranspiration of riparian vegetation can reduce water in streams (Gatewood et al., 1950).

The root densities of the woody plants, shrubs, grasses or sedges of the riparian vegetation are also higher compared to the terrestrial upland vegetation (Baker, 2002). The dense root system is an important characteristic of the riparian vegetation. The higher root density allows for better protection of stream banks, reducing erosion and increasing infiltration rates. Increased infiltration rates in the riparian areas can lead to a significant decrease of overland flow or out-of-bank flooding runoff volumes (Schultz et al., 2000). These riparian vegetation characteristics allow the stream and riparian system to better withstand disturbances from high water flow events than those with upland vegetation.

Riparian areas are very important because of their multiple use values (Clary and Booth, 1993). Riparian vegetation decreases the sediments, nutrients and chemicals that would reach the stream otherwise. As a result, these areas can improve water quality, particularly by reducing non-point source pollutants. Non-point source pollution is the pollution that cannot be traced back to a single origin or source (eg. a sewer pipe is point source pollution). It occurs when rainfall, snowmelt, or irrigation runs over land or through the ground, picks up pollutants, and deposits them into rivers, lakes, and coastal waters or introduces them into ground water. The public's value of water quality protection was recognized by the Clean Water Act of 1972 (amended 1977) and the subsequent development of the Total Maximum Daily Loads (TMDL) program to regulate water pollution that is maintained by United States Environmental Protection Agency (USEPA).

The Endangered Species Act of 1973 (amended in 1988) was passed to conserve threatened and endangered species. It lists and monitors all the threatened and endangered species. Seventy percent of threatened and endangered vertebrates in Arizona depend on riparian habitat (Johnson, 1989). Domestic livestock are also attracted to these areas because of the high forage abundance (Pinchak et al., 1991) and water availability (Ames, 1977). Today, ranching still accounts for a significant portion of the agricultural economy of Arizona (approximately 25%) (Ruyle et al., 2000). The many aesthetic values of riparian areas add to the complexity of their management. Riparian areas are considered prime areas for recreational activities such as hiking, horse-back riding, cycling, fishing, hunting, swimming, rafting, boating, canoeing, bird and wildlife watching, picnicking, camping and off-road vehicular travel with ATV's (Ffolliott et al., 2004).

The high number of users and diverse perception regarding the importance and proper use of riparian areas makes managing these areas complex and a nationwide top priority. In addition, large percentages of riparian areas are considered in degraded and non-functional conditions and in need of restoration (Ffolliott et al., 2004; NRC, 2002). Riparian area destruction has varied throughout regions of the United States. Estimates of the percentage of riparian areas that have been altered in the United States ranges from 70-90%, making them among the most drastically altered ecosystems (Brinson et al., 1981).

Defining riparian areas

Historical perspectives

Before trying to define riparian areas, let's look at the origin of the word "riparian" and the early use of the term. The term riparian is derived from the Latin word *riparius* that means stream bank. The term "riparian" was initially used in the United States in the early 1800's as a legal term (Ortega Klett, 2002). It described a landowner's property adjacent to a stream or river. To resolve conflict over water use and diversion between individual mills (both agricultural and industrial) the Doctrine of Riparian Rights was formulated and is still used in the eastern United States (Baker, 2002; Ortega Klett, 2002). According to this Doctrine, landowners adjacent to a water body have the right to use some of that water, as long as they do not interfere with the navigation of the waterway or do not reduce the quantity or quality of the water for downstream users. The western United States has the Doctrine of Prior Appropriation that is also known as "first in time, first in right." According to this Doctrine, the first user of the water has the first right to the water regardless of whether the land is adjacent to the water source (Chang, 2003; Ortega Klett, 2002). Ownership of the water is transferred with the deed or the title to the property and remains with it as long as the water continues to be put to beneficial use once every five years (Chang, 2003; Ortega Klett, 2002). The term beneficial use refers to agricultural, industrial or household. In some cases, though, ecological purposes such as maintaining a natural body of water and the wildlife that depends on it are being deemed recently as beneficial use.

It is unclear when scientists first adopted the term "riparian" to describe the areas adjacent to streams, rivers, and lakes. This term started appearing in the scientific literature in the 1970's (Baker, 2002). In this 30-35 year period, our understanding of the importance of ecological and hydrological processes in riparian areas has increased (Baker, 2002). Although we have a better understanding of the importance of riparian areas, there is no universal definition accepted by the scientific and/or regulatory community. It is very important to understand that riparian definitions are not static and often reflect the political demands for these areas, not just their dynamic temporal, physical, and biological environments.

Environmental Attributes

Riparian communities are not biomes (Dimmitt, 2000). Biomes are major ecological community types, such as tropical forests, grasslands, deserts etc., which are determined primarily by climatic factors. However all biomes have riparian areas, so you can find riparian areas in a wide range of climatic, hydrologic and ecological environments. Different latitudes and altitudes can support very different riparian communities primarily because of changes in precipitation and temperature (Cartron et al., 2000; Szaro, 1989). In Arizona, you can find riparian areas in high elevation montane forests through intermediate-elevation woodlands to low-elevation shrublands and desert grasslands biomes (Ffolliott et al., 2004). Riparian areas are ecosystems. An ecosystem is a functional system that includes organisms, such as the plants and animals (biotic part), and their immediate environment (abiotic part) (Whittaker, 1975). The organisms interact with each other and with their environment. The organisms and the environment of each ecosystem are unique and differ significantly from the other ecosystems.

Similar to wetland ecosystems, the three main characteristics that define riparian area ecosystems are hydrology, soils and vegetation. These areas have water-soil-vegetation habitats that reflect the influence of additional moisture as compared to their adjacent terrestrial uplands (Ffolliott et al., 2004). Aquatic ecosystems are in water either year-round or for long periods of time. Terrestrial ecosystems are on land. Riparian areas are not as dry as upland terrestrial ecosystems but not as wet as aquatic ecosystems. These areas are the transition zones or ecotones and have characteristics of both aquatic and upland terrestrial ecosystems. This is reflected with the presence of a larger number and more diverse species. Another characteristic of an ecotone is the active interactions that take place between two or more of its adjacent ecosystems, and leads to the appearance of mechanisms that do not exist in either of the adjacent ecosystems (Holland, 1988).

Riparian areas require higher moisture levels in the soil compared to the upland terrestrial ecosystems. From a hydrology standpoint, functioning riparian areas are defined by their ability to store and move water and sediment. The greater water storage capacity of riparian areas and their close proximity to water bodies results in greater soil moisture content and drives distinct plant communities as compared to adjacent terrestrial uplands. It is also important to note that riparian areas are very dynamic and disturbance-driven (Cartron et al., 2000) which leads to rapid changes in riparian vegetation composition and condition depending on the weather conditions and disturbances of a particular year

(Larsen et al., 1997). All riparian ecosystems are dependent on disturbances, primarily flooding, to regenerate some of their vegetation communities (eg. cottonwood) (Baker, 2002). The frequent disturbances in these areas also influence soils that are typically undeveloped and spatially variable compared to upland soils.

Riparian areas are also found in a variety of geomorphologic environments (Ffolliott et al., 2004). These areas occur from high mountains with narrow and deep ravines or canyons, to lowland floodplains in wide areas with streams exhibiting large meanders. The geomorphic setting can have a major impact on the type of vegetation present in the riparian area. Differences in vegetation, geomorphic conditions, and geologic settings have led to a wide variety of terms used to denote riparian areas. These include riparian buffer zones, cottonwood floodplains, alluvial floodplains, floodplain forests, bosque woodlands, cienegas, and meadows.

Significant differences in water availability due to precipitation between the eastern and western United States has led to major differences in these regions' riparian areas (Figure 1). In the eastern United States, precipitation is much greater and riparian areas can maintain more lush vegetation than the arid regions of the western United States. Because of the higher precipitation received in the eastern United States, even the terrestrial upland ecosystems can maintain lush vegetation. As a result, it is difficult to define the boundaries between riparian areas and terrestrial uplands in the eastern United States. In contrast, in most of the western United States and particularly in the southwest, the transition between riparian and upland terrestrial systems is easily identifiable. This distinction is abrupt because the surrounding terrestrial habitat is much drier than the riparian area (Figure 2). Riparian areas in the arid western United States have different plant composition but are also more lush than their adjacent uplands. Another important difference between the eastern and western United States that influences riparian areas are the pathways that water follows to reach streams. In the eastern United States, more water infiltrates the soil resulting in more subsurface flow reaching the stream and thus more soil moisture (Figure 1). In the western United States, there is more overland flow reaching the stream (Figure 1).

Definitions

Ideally, there should be a riparian area definition and classification system compatible with the current wetlands classification system (NRC, 2002). The structure, functions, and values of wetlands systems have been intensively investigated for many more decades than those of riparian areas. The relatively young age of the term "riparian area," the many different disciplines involved, and the high variability of riparian areas throughout the United States are the primary reasons why a precise and universally accepted definition of these areas is not currently available.

Riparian areas are studied by experts in various scientific disciplines such as plant ecology, hydrology, fisheries, wildlife, geology, geomorphology, forestry, soil science, range science, biology, entomology, and even engineering. This has created a variety of confusing and often contradicting definitions and terms for riparian areas (Bennett et al., 1989; Gregory et al., 1991). Typically, no single definition satisfies more then two-three disciplines (Baker, 2002). Each discipline has a tendency to emphasize on its own aspects and variable, for example a soil scientist emphasize on the soils properties found in the riparian areas. Definitions also range from simple descriptions, such as "associated with water courses" (Dick-Peddie and Hubbard, 1977), to technical and detailed descriptions (Table 1). In addition to purely scientific definitions, we have regulatory definitions or definitions for specific management objectives (Table 1). The simplest definition of a riparian area is a transitional zone between aquatic and terrestrial upland environments.

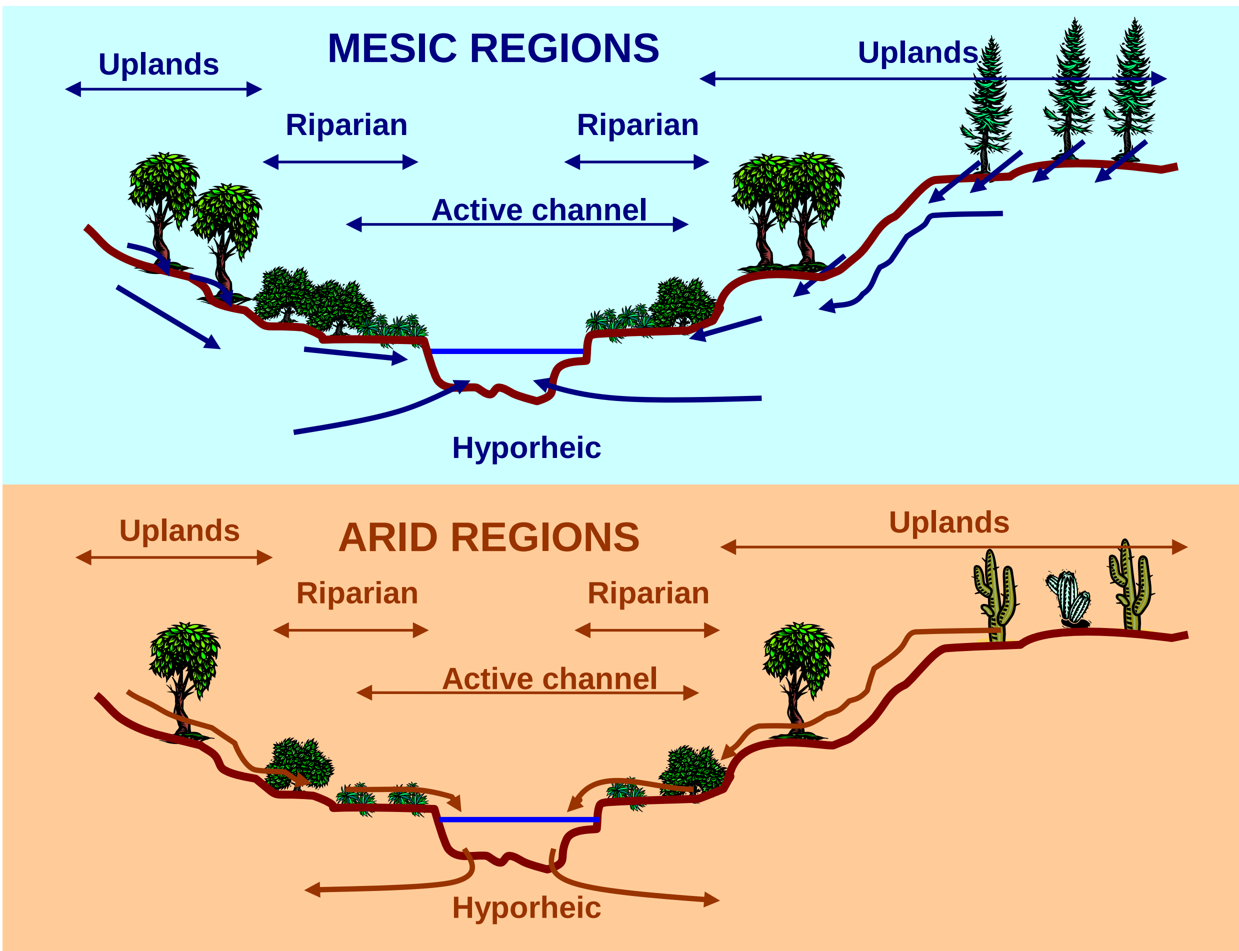


Figure 1. Differences in the pathways that water follows to reach the stream (illustration by G. Zaimes; based on Marti et al., 2000) in both mesic (humid) and arid (dry) regions. These differences can significantly influence riparian areas. In the eastern United States, also known as the mesic region, most of the water from precipitation primarily infiltrates into soil before reaching the stream. In contrast, in the western United States, also known as the arid, semi-arid region, most of the water from precipitation moves across the soil surface as overland flow before reaching the stream. The hyporheic zone is the zone in the stream bed substrate that exchanges water with the stream.

Figure 2. Distinct changes in vegetation density and species between riparian and upland terrestrial areas in Arizona (photos courtesy of G. Zaimes). Riparian areas have much more lush vegetation.

Despite the many differing definitions for riparian areas (Table 1), all include certain common points. The common points are that these areas are (Schultz et al., 2000):

1) adjacent to a body of water and dependent on perennial and intermittent water
2) without clearly defined boundaries
3) transitional zones between aquatic and terrestrial ecosystems and
4) linear in nature

Table 1. Riparian area definitions from various agencies, organizations and scientific publications.

	RIPARIAN DEFINITIONS
Merriam-Webster Dictionary (online)	"Riparian - Relating to or living or located on the bank of a natural watercourse (such as a river) or sometimes of a lake or tidewater."
<u>United States Agencies</u>	
U.S. Department of Agriculture Natural Resource Conservation Service (USDA-NRCS, 2005)	"Riparian areas are ecosystems that occur along watercourses or water bodies. They are distinctly different from the surrounding lands because of unique soil and vegetation characteristics that are strongly influenced by free or unbound water in the soil. Riparian ecosystems occupy the transitional area between the terrestrial and aquatic ecosystems. Typical examples would include floodplains, streambanks, and lake shores."
U.S. Forest Service (USFS, 2000)	"Riparian areas are geographically delineated areas, with distinctive resource values and characteristics that are comprised of the aquatic and riparian ecosystems, floodplains, and wetlands. They include all areas within a horizontal distance of 100 feet from the edge of perennial streams or other water bodies…. A riparian ecosystem is a transition between the aquatic ecosystem and the adjacent terrestrial ecosystem and is identified by soil characteristics and distinctive vegetation communities that require free and unbound water."
Bureau of Land Management (BLM, 1999)	"A riparian area is an area of land directly influenced by permanent water. It has visible vegetation or physical characteristics reflective of permanent water influence. Lake shores and stream banks are typical riparian areas. Excluded are such sites as ephemeral streams or washes that do not exhibit the presence of vegetation dependent upon free water in the soil."

U.S. Fish and Wildlife Service (FWS, 1998)	"Riparian areas are plant communities contiguous to and affected by surface and sub-surface hydrologic features of perennial or intermittent lotic and lentic water bodies (rivers, streams, lakes, or drainage ways). Riparian areas have one or both of the following characteristics: (1) distinctively different vegetative species than adjacent areas, and (2) species similar to adjacent areas but exhibiting more vigorous or robust growth forms. Riparian areas are usually transitional between wetlands and upland."
U.S. Environmental Protection Agency (EPA) and National Oceanic and Atmospheric Administration (NOAA) Coastal Zone Management Act (EPA, 1993)	"Riparian areas are vegetated ecosystems along a water body through which energy, materials and water pass. Riparian areas characteristically have a high water table and are subject to periodic flooding and influence from the adjacent waterbody. These systems encompass wetlands, uplands, or some combinations of these two land forms. They will not in all cases have all the characteristics necessary for them to be classified as wetlands."
Society for Range Management and Bureau of Land Management (Anderson, 1987)	"A riparian area is a distinct ecological site or combination of sites in which soil moisture is sufficiently in excess of that available locally, due to run-on or subsurface seepage, so as to result in an existing or potential soil-vegetation complex that depicts the influence of that extra soil moisture. Riparian areas may be associated with lakes, reservoirs, estuaries, springs, bogs, wet meadows, muskegs and intermittent and perennial streams. The distinctive soil-vegetation complex is the differentiating criteria."
<u>Arizona Agencies and Organizations</u>	
Tonto National Forest (Grove, 2005)	"Riparian areas - Land areas which are directly influenced by water. Usually have visible vegetative or physical characteristics showing this water influence. Streamsides, lake borders, or marshes are typical riparian areas." The definition is from the glossaries of both the Tonto National Forest Plan (1985) and its Environmental Impact Statement (EIS).
Arizona Riparian Council (ARC, 1994)	"Riparian is defined as vegetation, habitats, or ecosystems that are associated with bodies of water (streams or lakes) or are dependent on the existence of perennial, intermittent or ephemeral surface or subsurface water drainage."
<u>Scientific Publications</u>	
Lowrance et al., (1985)	"Riparian areas - Complex assemblage of plants and other organisms in an environment adjacent to water. Without definite boundaries, it may include streambanks, floodplain, and wetlands, ... forming a transitional zone between upland and aquatic habitat. Mainly linear in shape and extent, they are characterized by laterally flowing water that rises and falls at least once within a growing season."
Ilhardt et al., (2000)	"Riparian areas - Functionally defined as three-dimensional ecotones of interaction that include terrestrial and aquatic ecosystems, that extend down into the groundwater, up to above the canopy, outward across the floodplain, up the near slopes that drain to the water, laterally into the terrestrial ecosystem, and along the water course at a variable width."
National Research Council (NRC, 2002)	"Riparian areas - Transitional between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes, and biota. They are areas through which surface and subsurface hydrology connect waterbodies with their adjacent uplands. They include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems (i.e., a zone of influence). Riparian areas are adjacent to perennial, intermittent, and ephemeral streams, lakes, and estuarine–marine shorelines."
Ffolliott et al., (2004)	"Riparian areas - Situated in the interfaces between terrestrial and aquatic ecosystems, located along the banks of rivers and perennial, intermittent and ephemeral streams and around the edges of lakes, ponds, springs bogs and meadows."

Operational Definition	
Chattahoochee-Oconee National Forests (2004)	"Riparian areas - Associated with the aquatic ecosystem and that portion of the terrestrial ecosystem that is substantially affected by the presence of surface and ground water. Consists of perennial streams, natural ponds, lakes, wetlands, and adjacent lands with soils, vegetation and landform indicative of high soil moisture or frequent flooding. Have variable widths that are determined by ecologically significant boundaries rather than arbitrary distances. The extent of riparian areas is determined on-the-ground using features of soil, landform and vegetation. No one feature is used alone to delineate these ecosystems. Characteristics include: *Soils* - soils with poor drainage or a high water table during the growing season. *Landform* **-** the 100-year floodplain [relatively flat areas including the area subject to 1 percent (100 year recurrence) or greater chance of flooding in any given year]. *Vegetation* **-** the presence of hydrophytic (water-loving) vegetation, classified as obligates or facultative riparian species."

Future of riparian areas in Arizona

Riparian areas will continue to be a valued commodity for many diverse uses. As urban growth continues in the southwestern United States, so does the demand for water. The significant increase of the urban population compared to the rural population is a very important trend in the state of Arizona. Urban and rural communities have different opinions and perceptions regarding the values of riparian areas (Kennedy et al., 1995). Higher urban populations within the state have led to a significant increase in environmental and recreation-oriented values for riparian areas on public and state lands. Rural communities also have environmental concerns but view riparian areas for commodity and economic development. An example of a traditionally rural economic activity is cattle grazing in riparian areas in the southwest. This land-use practice is threatened by shrinking private land due to urbanization and the uncertainty of permits and leases of public and state land, respectively (Ruyle et al., 2000). The main reason is because riparian grazing is under pressure because some researchers consider grazing the main reason for the degradation of riparian areas (Ohmart, 1996; Belsky et al., 1999).

The National Research Council (2002) recommended that the restoration of riparian areas be a national goal with protection of these areas as a major focus. In addition, the lack of information on the status and trends of riparian areas requires an extensive and detailed assessment of these areas. Thompson et al. (2002) said that successful and effective conservation and restoration of riparian areas in arid and semi-arid regions depends on knowing the quality and quantity of the riparian areas. The many important functions, diverse users, and management implications, also require a unified characterization and definition of "riparian areas" that will satisfy all interested parties (Baker, 2002). As Anderson (1987) stated, "The definition of 'riparian area' is basic to riparian management; we first have to agree on what riparian is before we can manage it."

References

Anderson, E.W. 1987. Riparian area definition - A viewpoint. Rangelands 9:70.
Ames, C.R. 1977. Wildlife conflicts in riparian management: Grazing. In: Importance and management of riparian habitat. USDA Forest Service General Report RM-43. Ft. Collins, CO. pp. 39-51.
Arizona Riparian Council (ARC). 1994. Riparian. Fact Sheet. Available at: http://azriparian.asu.edu/newsletters/Fact11994.pdf (Accessed on 08-15-05).
Baker, T.T. 2002. What is a riparian area? Cooperative Extension Service Animal Resources Department. New Mexico State University. Las Cruces, NM. Available at: http://cahe.nmsu.edu/riparian/WHTRIPAREA.htm (Accessed on 08-12-05).
Bennett, P.S., M.R. Kunzmann, R.R. Johnson. 1989. Relative nature of wetlands: riparian and vegetational considerations. In: Abell, D.L. (tech. cord.), Proceedings of the California riparian systems conference: protection, management, and restoration for the 1990's. USDA Forest Service General Technical Report PSW-110. Berkeley, CA. pp. 140-142.
Belsky, A.J., A. Matzke, and S. Uselman. 1999. Survey of livestock influences on stream and riparian ecosystems in the Western United States. Journal of Soil and Water Conservation 54:419-431.
Brinson, M.M. 1993. Changes in the functioning of wetlands along environmental gradients. Wetlands 13:65-74.
Brinson, M.M., B.L. Swift, R.C. Plantico, and J.S. Barclay. 1981. Riparian ecosystems: their ecology and status. FWS/OBS-81/17, Office of Biological Services, U.S. Fish and Wildlife Service, Department of Interior. Washington, DC.
Bureau of Land Management (BLM). 1999. Draft environmental impact statement for riparian and aquatic habitat management. Las Cruces, NM.
Cartron, J-L.E., S.H. Stoleson, P.L.L. Stoleson and D.W. Shaw. 2000. Riparian areas. In: Jemison, R. and C. Raish (eds.), Livestock Management in the American Southwest: Ecology, Society and Economics. Elsevier Science. Amsterdam, Netherlands. pp. 281-328.
Chaney, E., W. Elmore, and W.S. Platt. 1990. Livestock grazing on western riparian areas. U.S. Environmental Protection Agency. Washington, DC.
Chang, C. 2003. Forest Hydrology: An Introduction to Water and Forests. CRC Press, Boca Raton, FL.
Chattahoochee-Oconee National Forests. 2004. Land and resource management Plan. Management Bulletin R8-MB 113 A. USDA Forest Service. Atlanta, GA. Available at http://www.fs.fed.us/conf/200401-plan/1-P-intro.pdf (Accessed on 08-15-05).
Clary, W.P and G.D. Booth. 1993. Early season utilization of mountain meadow pastures. Journal of Range Management 46:493-497.
Correll, D.L. 1997. Buffer zones and water quality protection: General principles. In: Hancock, N.E. et al. (eds.), Buffer zones: Their processes and potential in water protection. Quest Environmental. Hertfordshire, England.

DeBano, L.F. and L.J. Schmidt. 2004. Definitions and classifications. In: Baker M.B. Jr. et al., (eds.) Riparian areas of the Southwestern United States Hydrology Ecology and Management. CRC Press. Boca Raton, FL. pp. 11-27.

Dick-Peddie, W.A. and J.P. Hubbard. 1977. Classification of riparian habitat in the Southwest. In: Johnson, R.R. and D.A. Jones (tech. cords.), Importance, Preservation and Management of Riparian Habitat: a Symposium. USDA Forest Service. General Technical Report RM-43. Tucson, AZ. pp. 85-90.

Dimmitt, M.A. 2000. Biomes and Communities of the Sonoran Desert. In: Phillips, S.J., and P. Wentworth Comus (eds.), A Natural History of the Sonoran Desert. University of California Press. Berkeley and Los Angeles, CA. pp. 3-18.

Environmental Protection Agency (EPA). 1993. Guidance specifying management measures for sources of nonpoint pollution in coastal waters. United States Environmental Protection Agency. Washington, DC.

Elmore, W. 1992. Riparian responses to grazing practices. In: R.J. Naiman (ed.) Watershed management. Springler-Verlag. New York, NY. pp. 442-457.

Ffolliott, P.F., M.B. Baker, Jr., L.F. DeBano, and D.G. Neary. 2004. Introduction. In: Baker M.B. et al. (eds.), Riparian areas of the Southwestern United States: Hydrology, ecology and management. CRC Press. Boca Raton, FL. pp. 1-9.

Fish and Wildlife Service (FWS). 1998. A system for mapping riparian areas in the western U. S. U.S. Fish and Wildlife Service, Department of Interior. Washington, DC.

Gatewood, J.S., J.W. Robinson, B.R. Colby, J.D. Hem, and L.C. Halpenny. 1950. Use of water by bottomland vegetation in the Lower Safford Valley, Arizona. US Geological Survey Water-Supply Paper 1103. US Government Printing Office. Washington, DC.

Gregory, S.V., F.J. Swanson, W.A. McKee, and K.W. Cummins. 1991. An ecosystem perspective of riparian zones. BioScience 41:540-551.

Grove, J. 2005. Email personal communication (February, 2005).

Holland, M.M. (compiler). 1988. SCOPE/MAB technical consultations on landscape boundaries: report of a SCOPE/MAB workshop on ecotones. Biology International (Special Issue):17:1-163.

Hubbard, J.P. 1977. Importance of riparian ecosystems: biotic considerations. In: Johnson, R.R. and D.A. Jones (eds.), Importance, preservation and management of riparian habitat: a symposium. USDA Forest Service General Technical Report RM-43. Ft. Collins, CO. pp. 14-18.

Illhardt, B.L., E.S. Verry, and B.J. Palik. 2000. Defining riparian areas. In: Verry, E.S. et al. (eds.), Riparian management in forests of the continental eastern United States. Lewis Publishers. New York, NY. pp. 23-42.

Johnson, A.S. 1989. The thin green line: riparian corridors and endangered species in Arizona and New Mexico. In: Mackintosh, G. (ed.), In defense of wildlife: preserving communities and corridors. Defenders of Wildlife. Washington, DC. pp. 35-46.

Johnson, R.R., L.T. Haight, and J.M. Simpson. 1977. Endangered species vs. endangered habitats: a concept. In: Johnson, R.R. and D.A. Jones (eds.) Importance, preservation and management of riparian habitat: a symposium. USDA Forest Service General Technical Report RM-43. Ft. Collins, CO. pp. 68-79.

Kennedy, J.J., B.L. Fox, and T.D. Osen. 1995. Changing social values and images of public rangeland management. Rangelands 17:127-132.

Larsen, R.E., W.C. Krueger, M.R. George, M.R. Barrington, J.C. Buckhouse, and D.E. Johnson. 1997. Viewpoint: livestock influences on riparian zones and fish habitat: literature classification. Journal of Range Management 51:661-664.

Lowrance, R.R., R. Leonard, and J. Sheridan. 1985. Managing riparian ecosystems to control nonpoint pollution. Journal of Soil and Water Conservation 40:87-91.

Mariam-Webster online dictionary.
Available at: http://www.m-w.com/ (Accessed on 08-08-2005).

Marti, E., S.G. Fisher, J.D. Schade and N.B. Grimm. 2000. Flood frequency and stream-riparian linkages in arid lands. In: Jones, J.B. and P.J. Mulholland (eds.), Streams and Ground Water. Academic Press. New York, NY. pp. 111-136.

Mitsch, W. J. and J. G. Gosselink. 1993. Wetlands, 2nd edition. Van Nostrand Reinhold. New York, NY.

National Research Council (NRC). 2002. Riparian areas: functions and strategies for management. National Academy of Science. Washington, DC.

Ortega Klett, C.T. 2002. New Mexico Water Rights. 2nd Update. New Mexico Water Resources Research Institute. New Mexico State. Las Cruces, NM.

Osborne, L.L. and D.A. Kovacic. 1993. Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwater Biology 29:243-258.

Ohmart, R.D. 1996. Historical and present impacts of livestock grazing on fish and wildlife resources in western riparian habitats. In: Krausman, P.R. (ed.), Rangeland wildlife. The Society for Range Management, Denver, CO. pp. 245-279.

Pase, C.P. and E.F. Layser. 1977. Classification of riparian habitat in the southwest. In: R.R. Johnson and D.A. Jones (tech. coord.). Importance, Preservation and Management of Riparian Habitat: a Symposium. USDA Forest Service General Technical Report RM-43. Tucson, AZ. pp. 5-9.

Patten, D.T. 1998. Riparian ecosystems of semi-arid North America: diversity and human impacts. Wetlands 18:498-512.

Pinchak, W.E., M.A. Smith, R.H. Hart, and J.W. Waggoner Jr. 1991. Beef cattle grazing distribution patterns on foothill range. Journal of Range Management 44:267-275.

Rowe, P.B. 1963. Streamflow increases after removing woodland–riparian vegetation from a southern California watershed. Journal of Forestry 61:365–370.

Ruyle, G.B., R. Tronstad, D.W. Hadley, P. Heilman, and D.A. King. 2000. Commercial livestock operations in Arizona. In: Jemison, R. and C. Raish (eds.), Livestock Management in the American Southwest: Ecology, Society and Economics. Elsevier Science, Amsterdam, Netherlands. pp. 379-417.

Schultz, R.C., J.P. Colletti, T.M. Isenhart, C.O. Marquez, W.W. Simpkins, and C.J. Ball. 2000. Riparian Forest Buffer Practices. In Garett, H.E., et al. (eds.), North American Agroforestry: An integrated science and practice. American Society of Agronomy, Inc. Madison, WI. pp. 189-281.

Szaro, R.C. 1989. Riparian forest and scrubland community types of Arizona and New Mexico. Desert Plants 9:70-138.

Thompson, B.C., P.L. Matusik-Rowan, and K.G. Boykin. 2002. Prioritizing conservation potential of arid-land montane natural springs and associated riparian areas. Journal of Arid Environments 50:527-547.

Tiner, R.W. 1996. Wetland definitions and classifications in the United States. In: Fretwell, J.D. et al. (compilers), National Water Summary on Wetland Resources. US Geological Survey. Water-Supply Paper 2425. Reston, VA. pp. 27-34.

United States Forest Service (USFS). 2000. Forest Service Manual, Title 2500, Watershed and Air Management. Section 2526.06. USDA Forest Service. Washington, DC.

United States Department of Agriculture Natural Resource Conservation Service (USDA-NRCS). 2005. Riparian area and recognition, part 411. In Ecological Sites Title 110. General Manual.
Available at: http://policy.nrcs.usda.gov/scripts/lpsiis.dll/GM/GM_190_411.htm
(Accessed on 08-15-05)

Walbridge, M.R. 1993. Functions and values of forested wetlands in the Southern United States. Journal of Forestry 91: 15-19.

Whittaker, R.H. 1975. Communities and ecosystems. MacMillan. New York, NY.

Wissmar, R.C. and F.J. Swanson. 1990. Landscape disturbance and lotic ecotones. In: Naiman, R.J. and H. Decamps (eds.), The ecology and management of aquatic-terrestrial ecotones. Unesco and the Parthenon Publishing Group. Paris, France. pp. 65-89.

CHAPTER 2
Characterization of Riparian Areas

By George Zaimes, Mary Nichols and Douglas Green

Introduction

To better understand riparian areas it is necessary to identify their main characteristics. These characteristics can be distinguished at very broad scales (regional) or on narrow scales (local) by looking at specific attributes. Underlying geology can be used to characterize riparian areas at a regional scale. Riparian areas are also influenced by local water, soil, and vegetation characteristics. This chapter summarizes the hydrologic and biological processes that typify riparian areas. Finally, it is useful to characterize, differentiate and identify specific landscape areas, in this case riparian areas, in the context of their adjacent landscape areas.

Regions of Arizona

Arizona can be divided into three physiographic regions (provinces), with underlying geology as the primary determinant of the landscape features (Chronic, 1983). The deserts of southern Arizona are part of the "Basin and Range" region. The mountainous region in central Arizona is in the "Central Highland" and most of northern Arizona is part of the "Colorado Plateau" region. Within each region, there are a broad range in characteristics of drainage networks and riparian areas, which are generally controlled by the underlying geology and topography.

The Basin and Range region is characterized by numerous mountain ranges separated by broad valleys at lower elevations. Runoff coming from the mountain ranges forms alluvial fans at these valleys at the base of the mountains. The decreasing slope in the broader valley bottoms slows the runoff velocities of flows leaving the mountain ranges, causing sediment loads to be deposited. Very large alluvial fans, termed "bajadas," are prominent features in southern Arizona. In addition, these low-lying valleys of the watersheds have also been filled with deep sediment (valley fills). Drainage networks have and are developing over both the alluvial fans and valley fills. Although they are generally dry, the stream channels that make up the drainage network can appear as ribbons of green vegetation crossing the landscape. Rivers, such as the Lower San Pedro, flow through low-lying valley bottoms.

Figure 1. The three main regions of Arizona:
a) Basin and Range
b) Central Highlands and
c) Colorado Plateau,
(illustration by A. Thwaits)

The Central Highlands (or transitional zone) region receives relatively high rainfall compared to other

Arizona regions. Many small streams and lakes characterize this region. The stream channels that drain through small valleys are relatively steep. Many of the mountains are also surrounded by small alluvial fans that lead to low-lying valleys.

The Colorado Plateau contains flat-topped mesas, cliffs, multi-colored badlands carved by water, forests, and wind-swept deserts. The prominent geologic feature of this region is the Grand Canyon, through which the Colorado River flows. This region contains many temporary flowing channels that flow only in response to summer thunderstorm rainfall.

Riparian Lentic and Lotic Systems

Water from the adjacent waterbody is the key element that differentiates riparian areas from adjacent terrestrial upland areas. These water bodies can be natural waterbodies such as streams, rivers and lakes, or man-made waterbodies such as ditches, canals, ponds, and reservoirs. When riparian areas are along the banks of moving water (streams and rivers) they are called *lotic* systems (Pieczynska, 1990). In contrast, if the water is stationary (lakes, and ponds) these riparian areas are called *lentic* systems (Wissmar and Swanson, 1990). In this chapter emphasis will be given to lotic systems.

Types of Streams and Rivers

The types of streams and rivers based on stream flow characteristics are perennial, intermittent and ephemeral (Figure 2). The definitions for these stream/river types are not universally accepted but typically include the following characteristics (Hewlett, 1982; Art, 1993; Comín and Williams, 1994; Baker, 2002):

Perennial streams/rivers have flow in the stream channel throughout the year and substantial flow inputs from ground water. Stream flows can vary widely from year to year and may even dry up during severe droughts, but the ground water level is always near the surface. Perennial streams are found in both mesic (humid) and arid (dry) regions.

Intermittent streams/rivers are also connected to ground water, but flow in the stream channel typically occurs only for a couple of weeks or months each year. The ground water is immediately below the streambed even when there is no flow in the channel. In many cases the flowing or drying of these streams can be predicted by seasonal precipitation or snowmelt patterns. Typically, these streams are associated with arid and semiarid climates, but are also common in humid regions. Streams can be *spatially intermittent* when water appears above the streambed in some places, while it remains below the streambed in other places. In other cases, streams can be *temporally intermittent*. In this case, water appears above the streambed only after a rainfall or snowmelt event. These rainfall and snowmelt events recharge the stream and water typically rises above the streambed in part because the ground water is close to the streambed surface.

Ephemeral streams/rivers only flow for a few hours or days, in response to rainfall or snowmelt events that are of sufficient magnitude to produce overland flow.

The streambed of ephemeral streams is generally well above the water table. Intermittent and ephemeral streams are often confused with each other particularly in the arid and semiarid western United States. The primary distinguishing factor that is unique to ephemeral streams is the minimal to nonexistent ground water inputs and connectivity to the stream water. In the arid southwest, washes and arroyos are typically ephemeral streams.

Types of Lotic Riparian Areas

Based on these different types of streams/rivers (Figure 2), Johnson et al. (1984) suggested the following classifications for riparian areas:

Hydroriparian areas are associated with perennial or intermittent water. The soils are hydric (defined in riparian soils section) or have substrates that are never dry or dry for only a short period. The vegetation, when present, consists primarily of obligate and preferential riparian plants (defined in the following riparian vegetation section).

Mesoriparian areas are associated with intermittent streams or high-elevation ephemeral streams. The soils are non-hydric and have substrates that are seasonally dry. Vegetation may not always be present. When present, it consists of a mixture of preferential, facultative riparian and non-riparian plants (defined in the following riparian vegetation section).

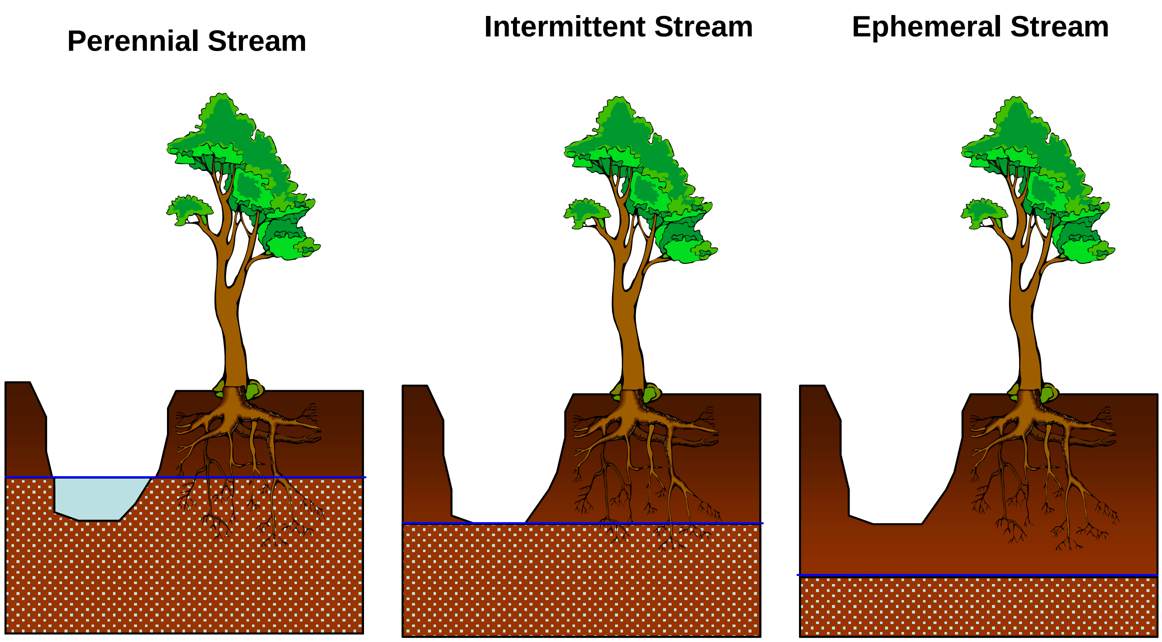


Figure 2. Perennial, intermittent and ephemeral streams/rivers. In perennial and intermittent streams/rivers, ground water contributes consistently to the adjacent vegetation (illustration by G. Zaimes; based on Baker, 2002). In ephemeral streams/rivers ground water does not contribute to adjacent vegetation. Water for the adjacent vegetation originates from excess local rainfall or snowmelt events. The blue line represents the top surface of the ground water level (water table) while the light blue dots represents soils saturated with water.

Xeroriparian areas are typically associated with ephemeral streams/rivers. Soils are also non-hydric and dry most of the year. The average annual soil moisture is higher than surrounding uplands and is enhanced by storage and accumulation of water in the stream channel and banks from excess local rainfall or snowmelt events. As a result, the soil moisture for vegetation is not consistent year around. In contrast, in hydroriparian and mesoriparian areas, ground water provides consistent moisture to vegetation in addition to any circumstantial surface moisture from excess local rainfall or snowmelt events. Vegetation in xeroriparian areas is much denser than adjacent terrestrial uplands, but species are typically facultative riparian and non-riparian plants (defined in the following riparian vegetation section).

Areas along Ephemeral Streams: Are they Riparian?

Regarding the definition of riparian areas, ephemeral streams/rivers are a main point of disagreement among scientists. Some scientists define areas adjacent to ephemeral streams/rivers as riparian (called xeroriparian), while others do not. The main argument for those who do not consider areas adjacent to ephemeral streams/rivers as riparian is that these areas do not have the potential to perform the entire spectrum of the riparian ecological functions (Baker, 2002). In contrast, areas adjacent to perennial and intermittent streams have the potential to serve the entire spectrum of riparian ecological functions. Water flows down ephemeral streams/rivers only occasionally, and the water table is sufficiently lower than the root zone of the vegetation (Figure 2). In "true" riparian areas, soil moisture is seldom a limiting factor for the vegetation even when surface water might not be present. In most cases, vegetation in areas adjacent to ephemeral streams/rivers grows in greater densities than adjacent terrestrial uplands because of the periodic excess water from overland flow that concentrates in these areas.

The main argument for including areas adjacent to ephemeral streams/rivers, like dry washes of deserts, in the definition of riparian areas is that these areas have "many" of the characteristic ecological functions that define hydroriparian and mesoriparian areas. These areas are frequently disturbed and unstable, similar to riparian areas adjacent to intermittent and perennial streams/rivers. The water, soil and nutrients deposited in these areas have been harvested and removed from the other parts of the watershed. Although plant species may not differ from the upland species, typically the plant density along the ephemeral streams/rivers is much higher. Areas adjacent to ephemeral streams also serve as corridors that disperse plants and serve as animal transportation routes similar to areas adjacent to perennial and intermittent streams.

In the southwestern United States, streams that originate in the lower elevations of the region are typically intermittent or ephemeral. Water flows in the stream channel, during winter or spring only after large frontal storms and during summer after infrequent convectional storms (DeBano and Baker, 1999). Although stream flow is not year around, the ground water is near the streambed surface and these areas can support riparian vegetation. Streams in higher elevations of the region typically receive much higher precipitation, have stream flow for longer periods and can maintain perennial flow

(Ffolliott et al., 2004). In many cases, flow in the stream channel might also be due to impervious geologic surfaces (eg. bedrock) near the streambed.

Riparian Soils

Soils are the unconsolidated mineral and organic material on the earth's surface and the natural medium for the growth of plants. Soils are thought to be a product of five factors: climate, parent material, organisms, relief (topography), and time (Buol et al., 2003; Gardiner and Miller, 2004).

In general, because of their position within the landscape, riparian soils are recipients of sediments and other materials from the watershed and are also important regulators and transformers of energy and materials between terrestrial and aquatic ecosystems (Naiman and Decamps, 1997; Hill and Cardaci, 2004). Riparian soils share many characteristics with their terrestrial upland counterparts, but they also differ in several ways.

One of these differences is related to frequent flood events and associated depositional and erosional processes. Because of the continuous influences of these processes, riparian soils have higher spatial diversity, are typically younger and lack well-developed soil horizons relative to their terrestrial upland counterparts. Riparian soils are also strongly affected by their position in the landscape. For example, on outside stream bends, erosional processes typically dominate, while along inside stream bends, depositional processes dominate. This can affect the size and diameter of material in these locations.

Although depositional and erosional processes significantly influence riparian soils, their geomorphic setting can also have significant control on their texture. The geomorphic setting influences the size of parent material and depositional mode. Low-gradient broad valley settings are usually fine textured with small areas of coarse textured deposits (Platts et al., 1987; Malanson, 1997). In contrast, parent materials of high-gradient narrow V-shaped settings, or alluvial fans/terraces at mountain fronts tend to be coarse textured, reflecting higher stream power (Platts et al., 1987; Malanson, 1997).

In broad valley floodplains, stream flows can frequently exceed bankfull discharge capacity and stream water will flow onto the floodplain. Bankfull discharge is the quantity of water (discharge) that controls channel form and the distribution of materials in the channel. The rapid increase in cross sectional area along with the hydrologic roughness of the floodplain decreases stream velocities substantially and the stream sediment load settles as a layer on the surface (vertical accretion). The general characteristics of the vertically accreted soils are (Platts et al., 1987; Lewis et al., 2003):

1) distinct horizon boundaries with often sharply contrasting textures indicative of different flooding events,
2) organic matter that decreases irregularly with depth, and
3) presence of buried horizons.

In general, sediment diameter decreases with increasing distance from the channel's edge toward the uplands. However, the influence of the surface irregularities of the floodplain and effect of vegetation on flow velocity can also impact the diameter and amount of vertically accreted sediments causing heterogeneous depositional patterns across the floodplain (Platts et al., 1987; Huggenberger et al., 1998; Johannes and Gurnell, 2003).

As a stream channel meanders across its floodplain it undercuts and erodes channel banks. The newly derived parent materials are transported and deposited on downstream point bars (Lewis et al., 2003). This is called lateral accretion. These sediments are deposited in a more turbulent environment than the vertically accreted sediments. As a result, the characteristics of laterally accreted soils have:

1) thick horizons containing rock fragments,
2) organic matter content that decreases regularly or is homogenous with depth, and
3) no buried horizons (Platts et al., 1987; Lewis et al., 2003).

Overall, the extent of laterally accreted soils is more limited than vertically accreted soils. Finally, laterally accreted soils are rarely found in V-shaped canyons, due to the limited lateral movement of the stream in these geomorphic settings.

Through time the thalweg (deepest part of the channel) of the stream channel may shift its position. This can lead sites, that lateral accretion was dominant, to shift and have vertical accretion dominant. This results in soil profiles with evidence of both vertical and lateral accretion. *In situ* processes can also dominate soil formation, if the channel thalweg continues to shift away and/or lateral accretion increase the elevation of the site above the flood prone elevation. When this happens these soils begin to have characteristics of upland soils because the *in situ* processes tend to erase the evidence of both lateral and vertical deposition over time. Soils influenced by *in situ* process can be characterized by:

1) accumulation in the surface soil and regular decrease of organic matter with depth,
2) development of soil structure, and
3) dissolution and redistribution of carbonates, clays, and other materials.

Riparian soils on terrace positions of the floodplain most commonly show strong evidence of *in situ* development.

Another major difference of riparian soils compared to adjacent terrestrial uplands is that they generally tend to be wetter and are subject to fluctuating water tables that may reach the soil surface (USDA-NRCS, 2005). The degree of wetness of the soil depends on seasonal and yearly weather characteristics that determine the amount of water in the adjacent waterbody (USDA-NRCS, 2005). The moisture regime of riparian soils is also influenced by geomorphic position. Riparian soils on low gradient broad valley floodplains at elevations at or below low flow stage may be saturated in some part of the profile for a significant part of the year. In fine textured soils where hydraulic conductivity is low, saturation may lead to development of hydric soils that favor establishment of bulrushes (*Scirpus* L. spp.) and cattails (*Typha* L. spp.). These areas may contain soils similar to hydric wetland soils (Mitsch and Gosselink, 2000). Hydric soils are defined as soils that are formed under conditions of saturation and that are flooded long enough during the growing season to develop anaerobic conditions (USDA-NRCS, 2003). In most Arizona soils there are few and limited in extent hydric soils due to the significant ground water pumping. Coarse textured soils are rarely anaerobic due to hydraulic conductivities that are high enough to supply dissolved oxygen to meet biological demand.

Riparian Vegetation

Vegetation is an integral part of riparian areas. The composition and amount of vegetation in riparian areas differ from that in the terrestrial upland vegetation. These differences reflect the influence of water from the adjacent waterbody primarily in terms of increased soil moisture in the riparian areas. In Arizona, a few tree species dominate riparian vegetation (Lowe, 1964). These species include Fremont cottonwood (*Populus fremontii* S. Wats.), Goodding's willow (*Salix gooddingii* Ball), Arizona sycamore (*Platanus wrightii* S. Wats.), velvet ash (*Fraxinus velutina* Torr.), Arizona walnut (*Juglans major* (Torr.) Heller) red willow (*Salix laevigata* Bebb.), Arizona alder (*Alnus oblongifolia* Torr.) and boxelder (*Acer negundo* L.). Common herbaceous plants in riparian areas of the southwest include spike rushes (*Eleocharis* R. Br. spp.*)*, bulrushes, rushes (*Juncus* L. spp.), sedges (*Carex* L. spp.), flatsedges (*Cyperus* L. spp.) (McLaughlin, 2004).

Classification of plants by their presence in riparian areas

In order to identify the expected vegetation for riparian areas, plants have been categorized as obligate wetland, facultative riparian and upland (Johnson et al., 1984; McLaughlin, 2004). In this early classification, wetlands were not differentiated from riparian areas and in many cases these terms have been used interchangeably. Wetlands and riparian areas are not always the same (this is discussed in detail in the riparian areas versus adjacent areas section):

Obligate wetland species are found almost exclusively in wetlands. A synonymous term to obligate riparian is *phreatophytes* that means "water-loving" and refers to plants whose roots generally extend downward into the water table.

Facultative riparian species are commonly found in both terrestrial upland and riparian areas.

Upland species are rarely found in wetlands.

The main problem with this classification in the southwest is that species commonly found in uplands at high elevations are also found in riparian areas at low elevations (McLaughlin, 2004).

The United States Department of Agriculture, Natural Resource Conservation Service (USDA-NRCS) (2006) also uses a wetland classification that is a little more detailed. They have a huge database of plants of the United States online that provides information on the plants and also classifies them based on this classification at a nationwide level but also for the different regions. The classification includes the following categories:

Obligate wetland: Occurs almost always (estimated probability 99%) under natural conditions in wetlands.

Facultative wetland: Usually occurs in wetlands (estimated probability 67%-99%), but occasionally found in non-wetlands.

Facultative: Equally likely to occur in wetlands or non-wetlands (estimated probability 34%-66%).

Facultative Upland: Usually occurs in non-wetlands (estimated probability 67%-99%), but occasionally found on wetlands (estimated probability 1%-33%).

Obligate upland: Occurs almost always (estimated probability 99%) under natural conditions in non-wetlands in the regions specified.

Finally, Johnson et al. (1984) also has a classification with percentages but this classification uses occurrence in riparian areas. The categories are:

obligate riparian (91-100%),
preferential riparian (76-90%),
facultative riparian (26-75%) and
nonriparian (0-25%).

Classification of riparian plants by depth to water table

For the riparian areas of the San Pedro River in Southern Arizona, Stromberg et al. (1996) found a strong association between species distribution and depth to water table. The shorter the depth to water table needed for a species, the more dependent the species is to wetland conditions. Using the USDA-NRCS wetland classification, they concluded: Goodding's willow as obligate wetland, Fremont cottonwood and Arizona walnut as facultative wetland, velvet ash as facultative, and netleaf hackberry (*Celtis laevigata* Willd. var. reticulata (Torr.) L. Benson), Texas mulberry (*Morus microphylla* Buckl.) and mesquite (*Prosopis* L. spp.) as facultative. This classification indicates the dependence of species on wetland conditions and tolerance to drought. Goodding's willow was the most dependent on wetland conditions and the least tolerant to drought of these species. At the other side of the spectrum was netleaf hackberry, Texas mulberry and mesquite being the most drought tolerant and least dependent on wetland conditions compared to the other species.

Classification of riparian plants by elevation

Elevation can have a significant effect on riparian vegetation as a function of the changes in temperature and precipitation. DeBano and Baker (1999) classified riparian vegetation for the southwestern United States into three broad categories based on elevation:

1) The landscapes at elevations less than 1,000 m are deserts, with low precipitation, and higher air temperatures that results in higher rates of evapotranspiration and stream water temperatures. The riparian areas associated with perennial, intermittent and ephemeral streams and rivers have broad floodplains and terraced bottoms. Sparse vegetation can be found along the stream banks, with minimal vegetation in the stream channel. The vegetation consists of deep-rooted trees like saltcedar (*Tamarisk* L. spp), Arizona sycamore, Fremont cottonwood and

paloverde (*Parkinsonia* L. spp) and many herbaceous plants (*Carex* L. spp, *Juncus* L. spp, *Eleocharis* R. Br. spp, *Scirpus* L. spp). Large stands of willow (*Salix* L. spp), cottonwood (*Populus* L. spp) and mesquite dominated these areas before the European settlers. Examples of streams include Sycamore Creek in central Arizona and Santa Cruz and San Pedro Rivers in southern Arizona. Examples of large rivers include the Lower Colorado, and lower parts of the Gila, Salt and Verde River. Today, few of these large rivers have perennial flow with the invasive saltcedars and Russian olives (*Elaeagnus angustifolia* L.) replacing the mesquite bosques and large cottonwood and willow forests.

2) The next category is between 1,000-2,000 m with Fremont cottonwood, willows, Arizona sycamore, velvet ash and Arizona walnut as the prevalent tree species. In addition, the understory supports several herbaceous plants. This category supports the greatest number of plants and has the highest canopy cover as compared to the other elevation categories. The vegetation covers narrow strips along primarily intermittent and ephemeral streams because very few perennial streams remain in these elevations. Surrounding upland terrestrial vegetation are chaparral, pinyon-juniper (*Pinus edulis* Engelm. - *Juniperus* L. spp) and oak (*Quercus* L. spp) woodlands.
3) The last category of riparian areas is at elevations greater than 2,000 m. Characteristic woody species include willows, chokecherry (*Prunus virginiana* L.), boxelder (*Acer negundo* L.), Rocky Mountain maple (*Acer glabrum* Torr.) and various conifers along with herbaceous plants. The excessive perennial soil moisture can also support wetlands and mountain meadows. The terrestrial uplands support spruce-fir (*Picea* A. Dietr. spp – *Abies* P. Mill. spp), mixed conifer and pine (*Pinus* L. spp) forests and in some cases aspen (*Populus tremuloides* Michx.) stands.

Diversity and presence of riparian vegetation

Though few tree species typically dominate riparian areas, overall riparian areas have extremely high plant diversity compared to their upland terrestrial counterparts. Specifically, in southeastern California, southern Arizona and central and southern New Mexico, McLaughlin (2004) categorized 579 plants as obligate and preferential riparian species and 812 as facultative riparian species (based on Johnson et al. (1984) classification).

It is important to also note that the presence of riparian species does not always indicate the presence of a "true" riparian area. For example, a cottonwood planted adjacent to a well or stock pond may indicate greater moisture in the vicinity, but the tree will never serve the range of ecological functions typically associated with vegetation in a "true" riparian area (Baker, 2002).

Riparian areas versus adjacent areas

To better understand riparian areas, sometimes it is easier to point out the main differences from their adjacent areas. The boundary of permanent water is the simplest way to delineate riparian areas from the aquatic ecosystems (Figure 3). But the boundary of permanent water changes frequently and this leads to changes in the extent of the riparian and aquatic areas. Another way to differentiate riparian and aquatic areas is through the plant species that occupy them. Typically, riparian areas primarily support woody plants (trees and shrubs), and emergent herbaceous plant cover (grasses and forbs) (NRC, 2002). In contrast, aquatic systems support, in shallow waters bulrushes, cattails and arrowheads (*Sagittaria* L. spp.), and in deeper waters submerged aquatic plants such as pondweed (*Potamogeton* L. spp.), watermilfoil (*Myriophyllum* L. spp.), hornwort (*Ceratophyllum* L. spp.), waterweed (*Elodea* Michx.) and bladderwort (*Utricularia* L. spp.) (NRC, 2002).

Riparian areas have higher vegetation densities and different species compared to the adjacent terrestrial uplands (Figure 3). The main reason for differences in vegetation densities is that riparian areas and terrestrial uplands have different sources of water for their vegetation (NRC, 2002). In terrestrial uplands, precipitation is the primary source of water for the vegetation. In contrast, riparian areas receive water from uplands, in the form of overland flow, subsurface flow, and ground water recharge, and from aquatic systems, in the form of out-of-bank flows, infiltration into stream banks (bank storage) and hyporheic (the area below the stream bed) flow from upstream. The end result is that riparian areas have more sources and greater amounts of water as compared to adjacent uplands. In addition, riparian vegetation is adapted to frequent disturbances, primarily flooding. Terrestrial uplands do not experience these types of disturbances. These two factors make riparian vegetation distinct to upland vegetation.

Riparian areas are often used interchangeably with the term "wetlands," but these two terms are not necessarily synonymous (Ohmart and Anderson 1986). Delineation between wetland, riparian, and terrestrial upland areas is not always straightforward. Some of the main reasons for the difficulty in their delineation are seasonal and annual changes in flooding levels, soil moisture, and vegetation (Mitsch and Gosselink 1986). In many cases, this delineation can cause considerable disagreement among scientists. Based on definitions of riparian areas in the table from chapter 1 and the wetlands definitions in Table 1, riparian areas can be the same, more expansive, or more restrictive when compared to wetlands (NRC, 2002) (Figure 4). Riparian areas might be more expansive because they can include terrestrial areas that do not have saturated or inundated conditions near the surface for significant periods of time. These terrestrial areas are not considered wetlands (Figure 4). In contrast, wetlands can include settings that are not along streams and lakes. Wetlands can also include aquatic systems that are not considered riparian areas (Figure 4). In this case, riparian areas are more restrictive than wetlands.

Summary

Region, geology, topography and elevation can influence and result in different types of riparian areas. But the three main factors that characterize riparian areas are water, soil and vegetation. These factors influence riparian areas so significantly that they can be differentiated from their adjacent landscapes (terrestrial and aquatic areas). Riparian areas are close to different water sources (streams, rivers, lakes), have soils that are young and undeveloped with high spatial diversity because of frequent disturbances while their vegetation has different composition and/or density because of the excess water compared to the terrestrial uplands. Finally, although wetlands and riparian areas are used interchangeably by some this is not always true. In many cases areas considered wetlands are not riparian and vice versa.

Table 1. Wetland definitions from agencies and scientific publications.

	WETLAND DEFINITIONS
Mariam-Webster Dictionary (online)	Wetlands - Land or areas (as tidal flats or swamps) containing much more soil moisture.
U.S. Army Corps of Engineers (Environmental Laboratory, 1987)	"The term wetlands means those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted to life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs and similar areas."
U.S. Fish and Wildlife Service (Tiner, 1996)	"Wetland - 1) The soils or substrate is saturated or covered by shallow water at some time during the growing season. 2) The plants (halophytes) in these environments are adopted to grow in water or soil or substrate that is occasionally oxygen-deficient because of water saturation. 3) The hydric soils are saturated long enough during the growing season to produce oxygen-deficient conditions in the upper part of the soil occupied by plant roots."
National Research Council (NRC, 1995)	"A wetland is an ecosystem that depends on constant or recurrent, shallow inundation or saturation at or near the surface of the substrate. The minimum essentials characteristics of a wetland are recurrent, sustained inundation or saturation at or near the surface and the presence of physical, chemical and biological features reflective of recurrent, sustained inundation or saturation. Common diagnostic features of wetlands are hydric soils and hydrophilic vegetation. These features will be present except where specific physicochemical, biotic, or anthropogenic factors have removed them or prevented their development."

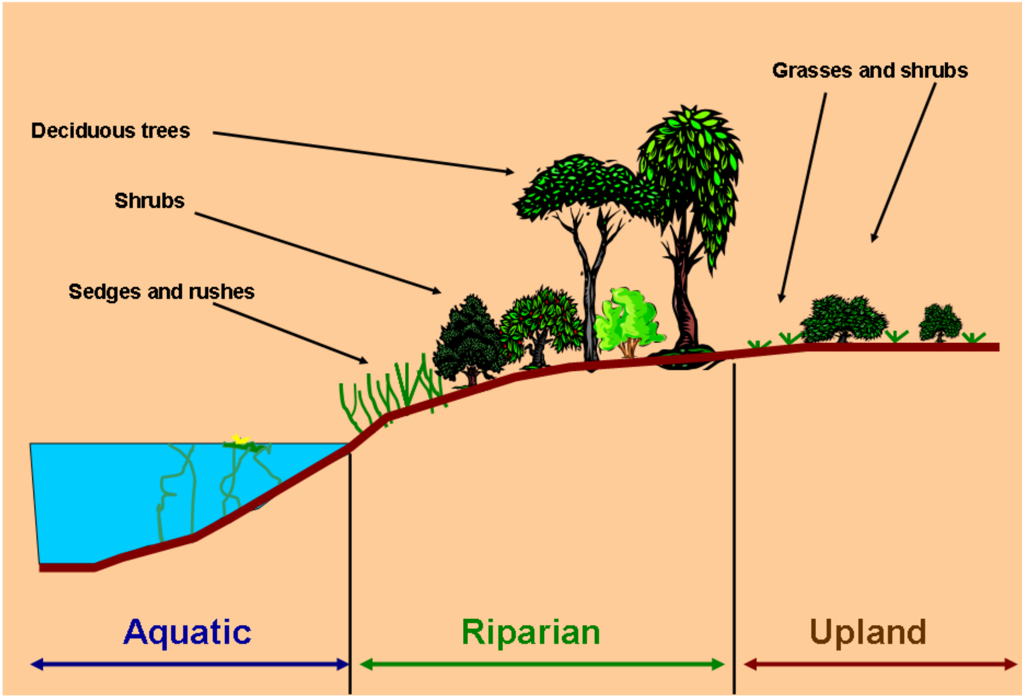


Figure 3. Delineating between aquatic, riparian, and upland areas (Illustration by G. Zaimes; based on BLM, 1991).

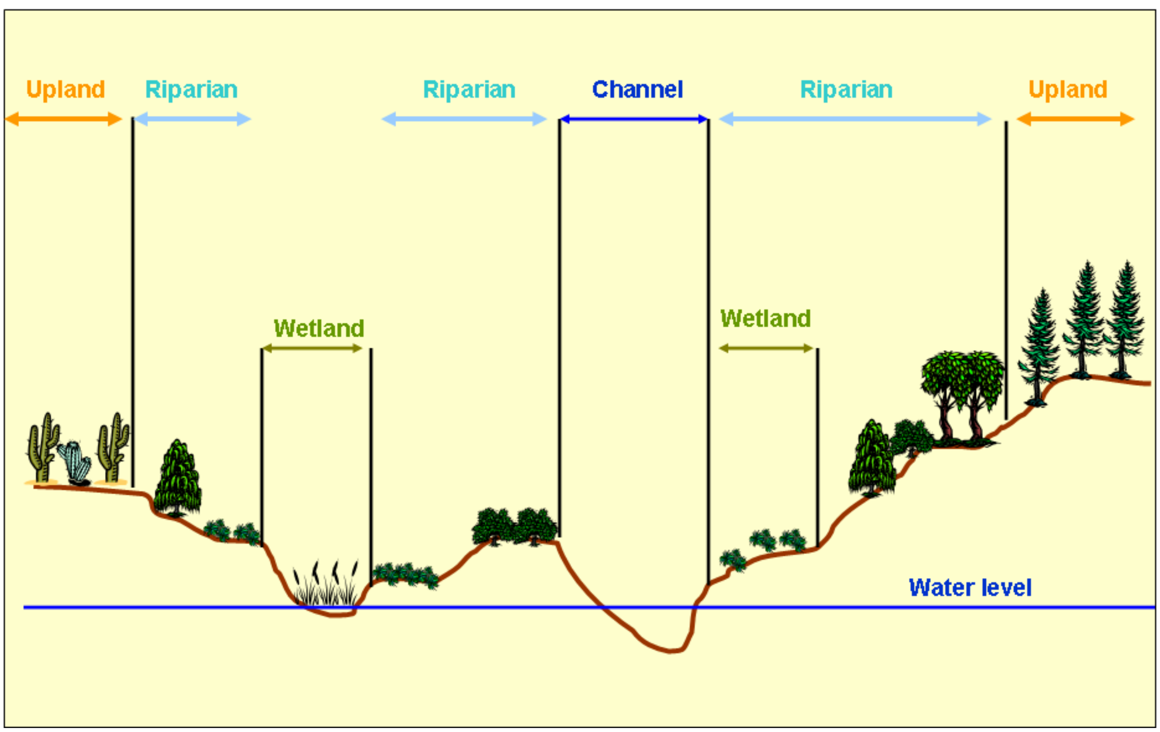


Figure 4. Delineating between riparian and wetlands areas (Illustration by G. Zaimes; modified from Minshall et al., 1989). As indicated in the graph riparian areas and wetlands do overlap in some cases while in other they do not.

References

Art, H.W. 1993. The dictionary of ecology and environmental science. Henry Holt and Co. New York, NY.

Baker, T.T.R. 2002. What is a riparian area? Cooperative Extension Service Animal Resources Department. New Mexico State University. Las Cruces, NM. Available at: http://cahe.nmsu.edu/riparian/WHTRIPAREA.htm (Accessed on 08-12-05).

Buol, S. W., R. J. Southhard, R. C. Graham, P. A. McDaniel. 2003. Soil genesis and classification 5th edition. Iowa State University Press. Ames, Iowa.

Bureau of Land Management (BLM). 1991. Riparian wetland initiative for the 1990's. United States Department of Interior Bureau of Land Management. Washington DC.

Chronic, H. 1983. Roadside Geology of Arizona. Mountain Press Publishing Company, Missoula, MT.

Comín , F.A. and W.D. Williams, 1994. Parched continents: our common future. In: R. Maralef (ed.), Limnology now: a paradigm of planetary problems. Elsevier Science. New York, NY. pp. 473-527.

DeBano, L.F. and M.B. Baker. 1999. Riparian Ecosystems in southwestern United States. In: Ffolliott, P.F. and A. Ortega Rubio (eds.), Ecology and Management of Forests, Woodlands and Shrublands in the Dryland Regions of the United States and Mexico. University of Arizona, Tucson, AZ, Centro de Investigationes Biologicas del Norte, SC. USDA Forest Service, Rocky Mountain Research Station. Fort Collins, CO. pp. 107-120.

Environmental Laboratory. 1987. U.S. Army Corp of engineers wetland delineation manual. U.S. Army Engineer Waterway Experiment Station. Technical Report Y-87-1. Vicksburg, MS.

Ffolliott, P.F., M.B. Baker, L.F. DeBano, and D.G. Neary. 2004. Introduction. In: Baker, M.B. et al. (eds.), Riparian areas of the Southwestern United States: Hydrology, ecology and management. CRC Press. Boca Raton, FL. pp. 1-9.

Gardiner, D. T. and R. W. Miller. 2004. Soils in our environment. Pearson Prentice Hall Inc., Upper Saddle River, NJ.

Hill, A. R. and M. Cardaci. 2004. Denitrification and organic carbon availability in riparian wetland soils and subsurface sediments. Soil Science Society of America Journal 68:320-325.

Hewlett, J.D. 1982. Principles of forest hydrology. University of Georgia Press. Athens, GA.

Huggenberger, P., E. Hoehn, R. Beschta, and W. Woessner. 1998. Abiotic aspects of channels and floodplains in riparian ecology. Freshwater Biology 40:407–425.

Johannes, S. and A. M. Gurnell. 2003. Spatial hydrogeomorphological influences on sediment and nutrient deposition in riparian zones: observations from the Garonne River, France. Geomorphology 49:1-23.

Johnson, R.R., S.W. Carothers, and J.M. Simpson. 1984. A riparian classification system. In: Warner, R.E and K.M. Hendrix (eds.), California riparian systems. University of California Press, Berkeley. pp. 375-382.

Lowe, C.H. 1964. The vertebrates of Arizona. The University of Arizona Press, Tucson, AZ.

Lewis, L., L. Clark, R. Krapf, M. Manning, J. Staats, T. Subirge, L. Townsend, and B. Ypsilantis. 2003. Riparian area management: Riparian wetland soils. Technical Reference 1737-19. Bureau of Land Management, Denver, CO. BLM/ST/ST-03/001+1737.

Malanson, G. P. 1997. Riparian landscapes. Cambridge University Press, New York, NY.

Mariam-Webster online dictionary.
Available at: http://www.m-w.com/ (Accessed on 08-08-2005).

McLaughlin, S.P. 2004. Riparian Flora. In: Baker, M.B. et al. (eds.), Riparian areas of the Southwestern United States Hydrology Ecology and Management. CRC Press. Boca Raton, FL. pp. 127-168.

Minshall, G.W., S.E. Jensen, and W.S. Platts. 1989. The ecology of stream and riparian habitats of the Great Basin region: a community profile. Biological Report 85(7.24). United States Department of Interior, Fish and Wildlife Service, National Wetlands Research Center, Slidell, LA.

Mitsch, W. J. and J. G. Gosselink. 2000. Wetlands. John Wiley & Sons, Inc., New York, NY.

Naiman, R. J. and H. Decamps. 1997. The ecology of interfaces-riparian zones. Annual Review of Ecology and Systematics 28:621–658.

National Research Council (NRC). 1995. Wetlands: Characteristics and boundaries. National Academy of Science. Washington, DC.

National Research Council (NRC). 2002. Riparian areas: Functions and strategies for management. National Academy of Science. Washington, DC.

Ohmart, R.D. and B.W. Anderson. 1986. Riparian habitats. In: Cooperrider, A.Y. et al. (eds.), Inventory and monitoring of wildlife habitat. U.S. Bureau of Land Management Service Center. Denver, CO. pp. 169-199.

Pieczynska, E. 1990. Lentic aquatic-terrestrial ecotones: their structure, functions and importance. In: Naiman, R.J. and H. Decamps (eds.), The ecology and management of aquatic-terrestrial ecotones. Unesco and the Parthenon Publishing Group, Paris, France. pp. 103-140.

Platts, W.S., C. Armour, G.D. Booth, M. Bryant, J.L. Bufford, P. Cuplin, S. Jensen, G. W. Lienkaemper, G.W. Minshall, S.B. Monsen, R.L. Nelson, J.R. Sedell, J.S. Tuhy. 1987. Methods for evaluating riparian habitats with applications to management. USDA Forest Service General Technical Report INT-221.

Stromberg, J.C., R. Tiller, and B. Richter. 1996. Effects of groundwater decline on riparian vegetation on riparian vegetation of semiarid regions: the San Pedro, Arizona. Ecological Applications 6:113-131.

Tiner, R.W. 1996. Wetland definitions and classifications in the United States. In: Fretwell, J. D. et al. (compilers), National Water Summary on Wetland Resources. Water-Supply Paper 2425. U.S. Geological Survey. Reston, VA. pp. 27-34.

United States Department of Agriculture Natural Resource Conservation Service (USDA-NRCS). 2006. Plants database.
Available at: http://plants.usda.gov/ (Assessed on 10-20-06)

United States Department of Agriculture Natural Resource Conservation Service (USDA-NRCS). 2005. Riparian Area and recognition part 411. In: Ecological Sites Title 110. General Manual.
Available at: http://policy.nrcs.usda.gov/scripts/lpsiis.dll/GM/GM_190_411.htm (Accessed on 08-15-05)

United States Department of Agriculture Natural Resource Conservation Service (USDA-NRCS). 2003. Field Indicators of Hydric Soils in the United States, Version 5.01. G. W. Hurt, P. M. Whited, and R. F. Pringle (eds.). USDA, NRCS in cooperation with the National Technical Committee for Hydric Soils, Fort Worth, TX.

Wissmar, R.C., and F.J. Swanson. 1990. Landscape disturbance and lotic ecotones. In: Naiman, R.J. and H. Decamps (eds.), The ecology and management of aquatic-terrestrial ecotones. Unesco and the Parthenon Publishing Group, Paris, France. pp. 65-89.

CHAPTER 3
Hydrologic processes in riparian areas

By Mary Nichols

Introduction

Water is taken for granted in many parts of the world where abundant, almost continually replenished supplies support people, livestock, and agriculture. But water is scarce in arid and semiarid regions, and this fact alone heightens attention to its sources, supply, distribution, and management. In Arizona, water supply will remain a dominant concern against a backdrop of increasing demand as ranching, agriculture, wildlife, increasing population, urbanization, expanding industry, and needs of downstream water users all compete for limited water resources.

This chapter provides general information describing the sources, distribution, and circulation of water on and below the earth's surface and in the atmosphere, with emphasis on Arizona. The science dealing with these topics is termed hydrology, and the processes that act to move water through the atmosphere and the earth are termed 'hydrologic processes.' Water is moved from the earth to the atmosphere as water vapor through evaporation and transpiration, water vapor condenses and falls as rain or snow, then travels laterally and downhill across the land surface, or infiltrates to underground aquifers, and travels laterally underground occasionally surfacing as springs and streamflow. The same water has been transferred around the globe since the origin of the earth. This cycle is termed the 'hydrologic cycle' (Figure 1). The hydrologic cycle is driven by the sun, which provides energy, and gravity, which keeps water moving vertically and horizontally. Hydrologic processes in Arizona are characterized by highly variable precipitation, runoff, and infiltration. This variability is seen across a range of spatial scales. For example, an individual rainstorm may cover a very local area. In contrast, regional droughts and large scale floods can affect large areas. In addition to the inherent variability in these processes, the effects of land use and management can have both direct and indirect effects on hydrologic processes.

Precipitation

Precipitation in Arizona, and throughout the southwest, exhibits some of the greatest variability within the US. Precipitation varies temporally at several scales:

1) daily in response to summer thunderstorms,
2) seasonally,
3) annually with drought and flood cycles, and
4) in response to larger scale atmospheric circulation patterns such as El Nino and La Nina.

Precipitation also varies spatially both across the landscape and with elevation. The amount of precipitation that falls is typically measured using a rain gauge. This provides a point measurement. Several point measurements collected through a network of rain gauges can be used to interpret the volume of precipitation over a region. Rain gauge

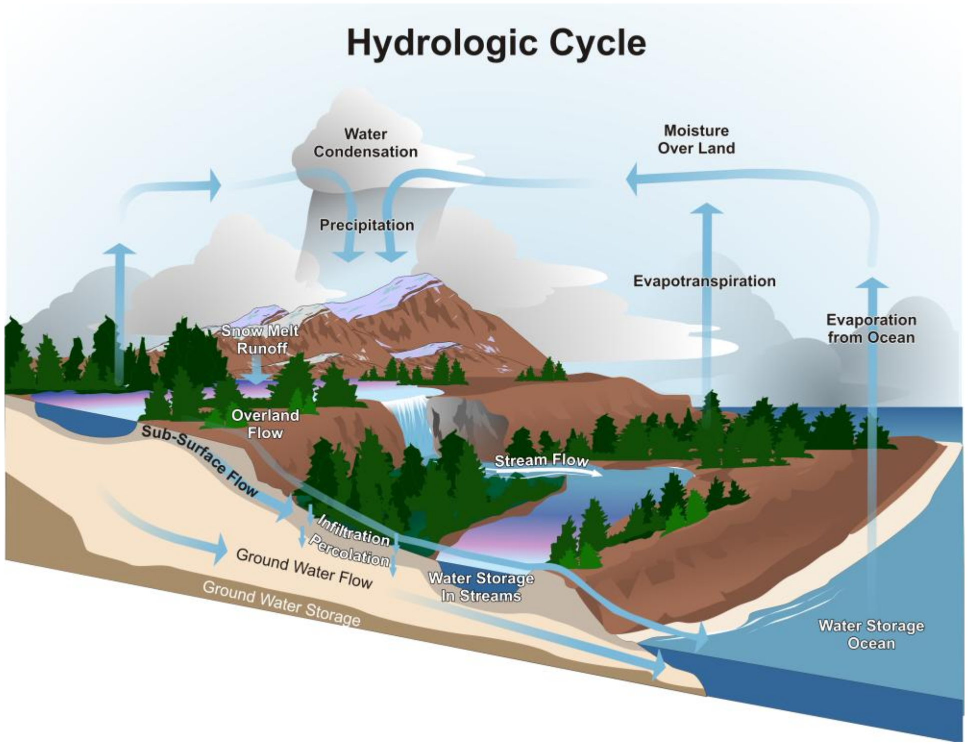


Figure 1. The hydrologic cycle is the movement of water between land, streams, oceans and the atmosphere. This cycle involves many numerous pathways and major storage units such as soils, aquifers, oceans, atmosphere and plants. Water is not created or destroyed (illustration by D. Cantrell).

technology spans a broad range from basic plastic graduated cylinders to tipping bucket gages and electronic weighing rain gauges. Traditional gauge measurements are complimented with data collected through new technologies such as radar.

Generally, precipitation is the result of four types of storms: convective storms, tropical storms, uplift near mountains, and frontal storms. In southeastern Arizona approximately 2/3 of the annual precipitation falls during the summer "monsoon season" that typically last from July through mid September. Thunderstorms deliver most of the monsoon rainfall in the southwestern United States. These storms result from convection that lifts moist air. This rising air cools, causing condensation and ultimately precipitation. Thunderstorms are typically characterized by extreme spatial variability, limited areal extent, and short durations (Osborn, 1982). Topography influences summer thunderstorms in areas where higher-elevation mountains cause elevated heating and enhanced convection (Carleton, 1986).

Although annual precipitation volume is dominated by summer thunderstorm rainfall in southeastern Arizona, the general precipitation pattern is characterized by a bimodal precipitation distribution that provides both winter and summer rain. Winter precipitation results from storms characterized by long duration, low intensity, and large aerial coverage (Sellers, 1960). These precipitation events generally result from air mass lift caused by slow moving storm fronts emerging from the Pacific Ocean into and across California and Arizona. The bimodal precipitation pattern is less pronounced at higher elevations and in northern regions of Arizona where snow plays an important part in the hydrologic cycle.

In addition to seasonal patterns of precipitation in Arizona, climate patterns across longer time scales affect precipitation. Within the last decade, connections between climate and larger scale atmospheric phenomenon have been the subject of scientific interest and research. Characterizing the climate of the southwestern United States has revealed connections between increasing sea surface temperatures in the eastern Pacific Ocean and above-average winter precipitation totals (El Niño) and the related atmospheric component that includes barometric pressure variations that drive air flow patterns (Southern Oscillation). On an interannual time scale El Niño has been identified as a cause of quasi-periodic climate variability. El Niño episodes, which are associated with wetter winters in the southwest, have been identified as a major source of variability in precipitation (Woolhiser et al., 1993; Andrade and Sellers, 1988; Carleton, et al., 1990; Redmond and Koch, 1991). A series of wetter winters since the 1970's in the southwest has been linked to the more frequent occurrence of El Niño episodes, especially in the decade from 1980 to 1990 (Trenberth and Hoar, 1996).

Runoff and Infiltration

If the rate of precipitation that falls exceeds the capacity of the ground to absorb it, the excess rainfall becomes runoff. Runoff traveling across the surface of the landscape is termed sheetflow, or overland flow. Overland flow may be absorbed into soils further downslope through the process of infiltration, or it may reach the channel network as surface flow. Water that seeps, or infiltrates, through sediment in channels may contribute to groundwater recharge.

In southern Arizona, precipitation during the summer "monsoon" season causes most of the overland flow. Overland flow collects in the channel network, and the resulting flows are typically very flashy, have large peak discharge rates and are short lived (Lane, 1983; Boughton, et al., 1987; Goodrich et al., 1997). Snowmelt in higher elevations contributes to runoff.

In contrast to thunderstorm generated runoff, the consequences of precipitation during non-summer months are less dramatic, but are still important to semiarid ecosystems. Infiltration and soil moisture distribution dominate the hydrologic cycle from October through May. Precipitation during non-summer months is more likely to be gentle, long duration, soaking rain that produces very little runoff. Conditions during these cooler months are more favorable for soil moisture storage because during the summer months, high temperatures result in large evaporation losses. Vegetation in semiarid ecosystems has evolved to make efficient use of this temporally distributed precipitation. Land use and management strategies have been developed to accommodate dry periods and the subsequent “monsoons”.

Evaporation and Transpiration

Evaporation is the return of water to the atmosphere from surfaces such as streams, lakes, puddles, ponds, and soil pores. Plants contribute water vapor to the atmosphere through the process of transpiration. The combined contributions of these processes is termed "evapotranspiration". The rates of both evaporation and transpiration depend on temperature and humidity, which are influenced by longitude and latitude, elevation, and proximity to the ocean. In addition, local climate factors such as temperature and wind speed affect both evaporation and transpiration. Transpiration also varies by species with the amount and kind of vegetation, as well as with the growing season.

Transmission losses

In semiarid regions, ephemeral channels that flow only in response to rainfall or snowmelt make up many channel networks. Within these normally dry channels, transmission losses are an important component of the water budget. Transmission losses, also called abstractions, refer to the water that infiltrates into the channel bed and banks during stream flow.

As a flow travels through a normally dry channel, water that infiltrates into the channel reduces the runoff volume and the peak rate of flow downstream. Water lost to this infiltration can contribute to groundwater recharge, and at a minimum will affect soil moisture distribution in surface sediment layers. Groundwater recharge can be seen as increases in water levels in wells in and adjacent to channels following flood events. Runoff losses to this type of infiltration can be large.

An example of transmission losses from measurements taken on the Walnut Gulch Experimental Watershed follows (Figure 2). The watershed is instrumented to measure runoff along the main channel through a network of runoff measuring flumes. A runoff producing storm on August 27, 1982, was isolated in the upper 95 km^2 of the watershed (and not all of that produced runoff). No additional runoff entered the channel as it traveled through Flumes 6, 2, and 1. The runoff measured at Flume 6 amounted to 246,200 m^3 with a peak discharge of 107 m^3s^{-1}. Runoff traversing 4.2 km of dry streambed between Flume 6 and Flume 2 resulted in significant infiltration losses. For example, in the 4.2 km reach the peak discharge was reduced to 72 m^3s^{-1} and 48,870 m^3 of water were absorbed in the channel alluvium. During the course of the 6.7 km from Flume 2 to Flume 1, the peak discharge was further reduced, and 41,930 m^3 of runoff was infiltrated in the channel alluvium.

Ephemeral channel transmission losses play an important role in ground water/surface water dynamics in arid and semi-arid basins in the southwest. However, identifying the processes driving these dynamics is difficult. Quantifying recharge with greater certainty

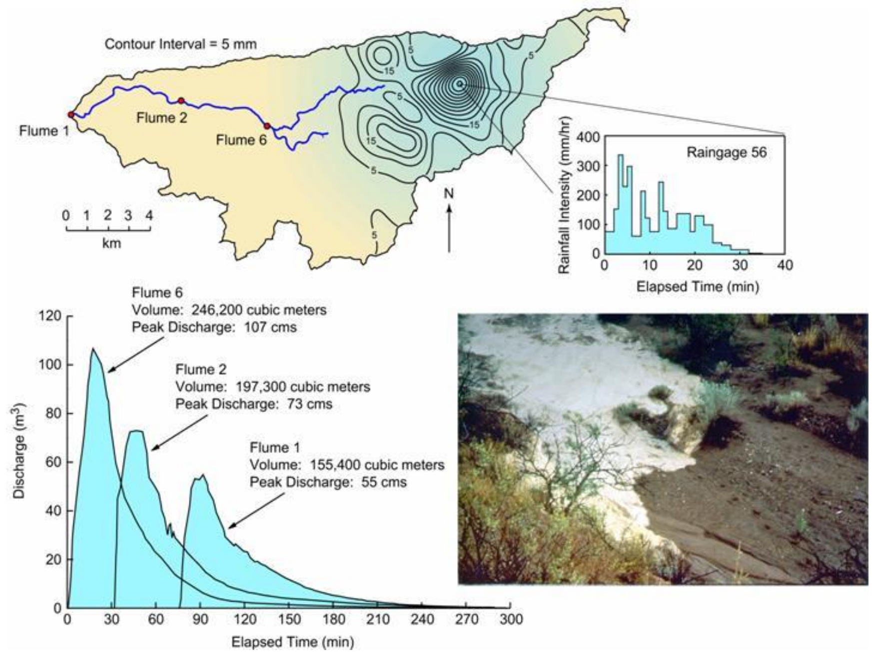


Figure 2. Summary of reduction in peak discharge associated with transmission losses as a flood flow travels through the Walnut Gulch channel (illustration by Carl Unkrich).

is a critical need for managing basins whose primary source of water supply is derived from groundwater. Currently, an intensive research effort to estimate groundwater recharge using a variety of direct measurement and chemical, isotopic, tree sap flux, micrometeorological, and microgravity techniques is underway in the San Pedro River Basin (Goodrich et al., 2004). Wet monsoon seasons in 1999 and 2000 caused substantial changes in near-channel groundwater levels. Results indicate relatively good agreement between the average estimates from each of the methods, in that they differ by less than a factor of three. This range is not surprising given the limitations of the various methods, and the differences in time scales over which they are applicable. Crudely scaled to the basin level, this recharge would constitute between 20 and 50% of basin recharge as estimated from a calibrated groundwater model.

The water balance - an accounting method

How do we summarize the amount of water that is cycling from the atmosphere, across the land surface, into the ground, through plants, into the ocean, back to the atmosphere through evaporation? One commonly used method is a water balance. This convenient method of book keeping is a good framework for understanding hydrologic processes. An example water balance is provided to illustrate the accounting of water within the Walnut Gulch Experimental Watershed which is an ephemeral tributary watershed within the large San Pedro River Watershed.

The Walnut Gulch Experimental Watershed water balance (Figure 3), although variable from year to year as well as across the area, is obviously controlled by precipitation. The annual water balance is illustrated for average conditions. Given the average 305 mm precipitation input, approximately 254 mm is detained on the surface. Surface water may infiltrate, or it may evaporate. Because potential evaporation is approximately 2600 mm per year, which is approximately 7.5 times the annual precipitation, essentially all of the infiltrated moisture is either evaporated or transpired by vegetation back to the atmosphere. Based on data collected from small watersheds less than 1.5 hectares in area in Walnut Gulch, approximately 51 mm of the incoming precipitation is in excess of that which is intercepted and/or infiltrates. This is referred to as "onsite runoff." As the runoff moves over the land surface and into dry alluvial channels, transmission losses begin. Approximately 45 mm of transmission losses occur and less than 10 mm of surface runoff are measured at the watershed outlet. The 45 mm of transmission losses result in some ground water recharge and some evaporation and transpiration from vegetation along the stream channels. Quantities for ground water recharge and evaporation and transpiration of channel losses are not shown because their quantification is difficult and very site specific. This is an area of active research. The geology along and beneath the stream channel creates some reaches that are underlain by impervious material, whereas in other locations, the channel extends to regional groundwater and permits appreciable recharge. In areas where the channel is underlain by impermeable material, riparian aquifers connected to the channel can become saturated and will support phreatophytes.

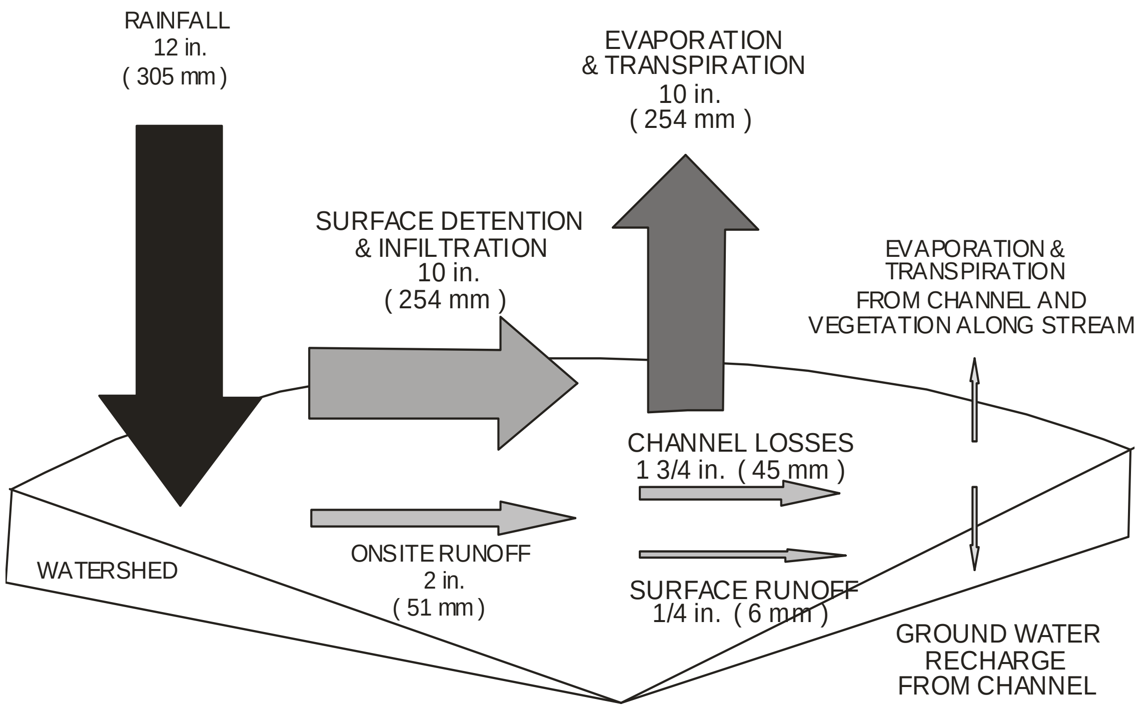


Figure 3. Annual water balance for the USDA-ARS Walnut Gulch Experimental Watershed in southeastern Arizona (illustration from Renard et al., 1993).

Floods and Droughts

Floods and droughts are common in Arizona. Although the destructive effects of floods in eroding and reshaping channels receives much attention, floods provide critical out-of-bank deposits in riparian areas that replenish nutrient supplies. Floods occur on both local and regional scales. Local floods occur with greater frequency largely in response to summer thunderstorms. Historically, regional flooding in Arizona generally has occurred between September and March, largely as the result of the cumulative effects of precipitation and runoff across many small watersheds. Precipitation lasting for several days and covering large areas causes runoff over large areas that accumulates as flow travels through the channel network.

Although floods are more dramatic in their suddenness and destruction, the persistence of droughts can cause more severe consequences. Droughts may initially be associated with a lack of precipitation, but long-term consequences such as soil moisture deficit, reduced surface water flow, and a drop in groundwater level have severe impacts on ecosystems and water supply. A summary of the major and other memorable floods and droughts in Arizona from 1862- 1988 (Paulson et al. 1989) is presented in Table 1.

Summary

Knowledge of hydrologic processes is critical for understanding the sources, distribution, and circulation of Arizona's water resources. The need for information describing Arizona's hydrologic processes will continue to escalate as demand increases across a broad range of users competing for limited water resources. Throughout the semiarid southwest, water resource management is challenging because precipitation, runoff, and infiltration exhibit great variability in time and space. However, measurements to quantify these hydrologic processes can be used to develop water budgets. This type of information will play a critical role in managing Arizona's riparian areas.

Table 1. Chronology of major and other memorable floods and droughts in Arizona, 1862- 1988 (Paulson et al. 1989).

Flood or Drought	Date	Area Affected	Recurrence Interval (in years)	Remarks
Flood	Jan. 19-23, 1862	Gila and Colorado Rivers	Unknown	Severe at Yuma. Wet year in Verde and Bright Angel basins, but not in upper Salt.
Flood	Feb. 18- 26, 1891	Central Highlands	25 to 100	Phoenix and Yuma flooded. In Clifton, deaths, 18; damage, $1 million.
Flood	Nov. 27- 30, 1905	San Francisco to Verde Rivers	5 to 10	Several moderate to severe floods, particularly at Phoenix and along the lower Gila River.
Flood	Jan. 19- 22, 1916	Central Highlands	10 to 0	Intense rain on melting snow produced large flows in central Arizona. Deaths, 4; damage, $300,000.
Flood	Aug. 21, 1921	Phoenix (Cave Creek)	Unknown	Six inches of rain in two days flooded 1,600 hectares and the State capitol building. Damage $240,000
Flood	Sept. 27- 29, 1926	San Pedro River and Mexico	>100	Tropical storm. Peak flow 2 - 3 times larger than any other in 70 years. Damage, $450,000
Drought	1932- 36	Statewide	10 to 20	Effects differed among basins.
Flood	Mar. 14- 15, 1941	Central Arizona	5 to 40	One of several storms that caused general runoff and filled reservoirs
Drought	1942- 64	Statewide	>100	Second most severe in 350 years, on the basis of tree-growth records.
Flood	Sept. 26- 28, 1962	Brawley and Santa Rosa Washes	>100	Deaths, 1; damage, $3 million, mostly to agriculture near Casa Grande.
Flood	Dec. 22, 1965 to Jan. 2, 1966	Verde, Salt, and Gila Rivers and Rillito Creek.	10 to 50	First large flow through Phoenix since reservoirs were built on Verde River (1939). Damage, $10 million.
Flood	Dec. 5- 7, 1966	Grand Canyon to southwestern Utah.	>100	Mudflows and channel erosion damaged Indian ruins that had been undisturbed for 800 years.
Flood	Sept. 5- 7, 1970	Tonto Creek to Hassayampa River.	40 to 100	Labor Day weekend floods in recreation areas. Reservoirs stored most runoff. Deaths, 23; damage, $8 million
Flood	Oct. 17- 21, 1972	Upper Gila River	10 to 40	Tropical storm. Deaths, 8; damage, $10 million.
Drought	1973- 77	Statewide	15 to 35	Most severe in eastern Arizona.
Flood	July 17, 1974	Safford (Holyoke Wash)	>100	Thunderstorm produced flow of 1,740 cubic feet per second from 0.85 square mile.
Flood	Oct. 1977 to Feb. 1980	Central and southeastern Arizona	5 to 100	Seven regional floods. Phoenix declared a disaster area three times. Deaths, 18; damage, $310 million.
Flood	July 26, 1981	Tucson (Tanque Verde Falls)	less than 2	Flash flood at recreation area on Sunday; deaths, 8. Two larger peak discharges in the same week were not noticed.
Flood	June 20 to Aug. 17, 1983	Colorado River	20 to 40	Upper basin rain and snowmelt. First reservoir spill since Hoover Dam was built (1935). Damage, $80 million.
Flood	Oct. 1- 3, 1983	Santa Cruz to San Francisco Rivers	10 to >100	Record floods on 18 streams; two peak discharges doubled 65-year-old records. Deaths, 8; damage, $226 million.

References

Andrade, E.R. and W.D. Sellers. 1988. El Nino and its Effects on Precipitation in Arizona and Western New Mexico. Journal of Climatology 8:403-410.

Boughton, W.C., K.G. Renard, and J.J. Stone. 1987. Flood Frequency Estimates in Southeastern Arizona. Journal of Irrigation and Drainage, Division ASCE 113(IR4):469-478.

Carleton, A.M. 1986. Synoptic-dynamic character of "bursts" and "breaks" in the Southwest U.S. summer precipitation singularity. Journal of Climatology 6:605-623.

Carleton, A.M., D.A. Carpenter, and P.J. Weber. 1990. Mechanisms of interannual variability of the Southwest United States summer rainfall maximum. Journal of Climate 3:999-1015.

Goodrich, D.C., L.J. Lane, R.M. Shillito, and S.N. Miller. 1997. Linearity of Basin Response as a Function of Scale in a Semiarid Watershed. Water Resources Research 33(12):2951-2965.

Goodrich, D.C., D.G. Williams, C.L. Unkrich, J.F. Hogan, R.L. Scott, K.R. Hultine, D. Pool, A.L. Coes, and S. Miller. 2004. Comparison of methods to estimate ephemeral channel recharge, Walnut Gulch, San Pedro River Basin, Arizona. In: Groundwater Recharge in a Desert Environment: The Southwestern United States, J.F. Hogan, F.M. Phillips and B.R. Scanlon (editors), Water Science and Applications Series, Vol. 9, American Geophysical Union, Washington, DC, pp. 77-99.

Lane, L.J. 1983. SCS National Engineering Handbook, Section4, Hydrology, Chapter 19: Transmission Losses. USDA, SCS, Washington, D.C., 32 pp.

Osborn, H.B. 1982. Quantifiable Differences in Air-Mass and Frontal-Convective Rainfall in the Southwest. In: Statistical Analysis of Rainfall and Runoff, International Symposium on Rainfall/Runoff Modeling, Mississippi State University, MS, pp. 21-32.

Paulson, R.W., E.B. Chase, R.S. Roberts, and D.W. Moody (compilers). 1991. National Water Summary 1988-89-- Hydrologic Events and Floods and Droughts**:** U.S. Geological Survey Water-Supply Paper 2375, pp. 591.

Redmond, K.T. and R.W. Koch. 1991. Surface Climate and Streamflow Variability in the Western United States and their Relationships to Large-scale Circulation Indices. Water Resources Research 27(9):2381-2399.

Renard, K.G., L.J. Lane, J.R. Simanton, W. E. Emmerich, J.J. Stone, M.A. Weltz, D.C. Goodrich, and D.S. Yakowitz. 1993. Agricultural Impacts in an Arid Environment: Walnut Gulch Studies. Hydrological Science and Technology 9:145-190.

Sellers, W.D. 1960. The Climate of Arizona. In: Arizona Climate, C.R. Greene and W.D. Sellers (editors). University of Arizona Press, Tucson, Arizona, pp. 5-64.

Trenberth, K.E. and T.J. Hoar, 1996. The 1990-1995 El Nino-Southern Oscillation event: Longest on record. Geophysical Research Letter 23(1):57-60.

Upper San Pedro Partnership, 2005. Water Management of the Regional Aquifer in the Sierra Vista Subwatershed, Arizona - 2004 Report to Congress. US Department of the Interior, pp. 36.

Woolhiser, D.A., T.O. Keefer, and K.T. Redmond, 1993. Southern oscillation effects on daily precipitation in the southwestern United States. Water Resources Research 29(4):1287-1295.

CHAPTER 4
Stream processes in riparian areas

By Mary Nichols

Introduction

Throughout Arizona, a visit to a riparian area is a welcome respite from the sharply contrasting drier, sparsely vegetated, desert uplands. Riparian areas are characterized by a relative abundance of water and even the channels that are dry most of the time hold sufficient soil moisture to support a wide variety of plants, animals, and birds. It is easy to imagine water flowing through a channel reach, over rocks, past a sand bar covered with mud, and around a bend. Why does the channel bend and where did the rocks come from? What happens when a flood comes, where did all the mud come from, is this the way the channel is supposed to look? A general understanding of channel morphology and the dynamics of channel adjustment is a first step in answering these questions.

Channel morphology is the study of the form and physical characteristics of a channel. The term morphology is often used in general to refer to the form and physical characteristics of a landscape such as a riparian area. Although the current channel morphology is often the first thing one notices, it is the result of dynamic processes occurring within the riparian area. Channels are always changing and adjusting as flowing water moves sediment within and through a watershed. The processes by which water flowing through a drainage network acts to erode, transport, and deposit sediment are called 'stream processes.' These processes are the mechanism through which riparian landscape features such as channels, floodplains, and cienegas are formed. An understanding of how stream processes interact with channel characteristics is necessary to interpret the current channel morphology and plan conservation and restoration efforts.

The value of riparian areas has been increasingly recognized in recent years and as a result, their condition is receiving more attention. Attention to condition is often preceded by a visual assessment. Visual assessments of channel morphology need to be coupled with quantitative measures and an understanding of stream processes. In addition, attempts to restore riparian areas to prior condition must consider both direct and indirect watershed alterations that may dictate the extent to which channels can be altered. Current upstream and downstream conditions, including sediment supply and flow conditions, must be evaluated to determine the extent to which the historic balance has been altered.

This chapter includes an introduction to the morphology of channels and floodplains followed by a description of stream processes in riparian areas.

Watersheds and Channel Networks

Watersheds comprise all the area that drains to a lower elevation such as a channel, stream, river, lake or other water body. For example, the San Pedro River watershed includes all of the land area that drains water into the San Pedro River. A watershed can also be thought of as all the land area that drains to a particular point in a stream. For example, the Upper San Pedro watershed is all the land that contributes to flow at the point in the river that divides the Upper San Pedro from the downstream portion of the river. The channels in a watershed form a branching network called the drainage network. Channels that make up the drainage network may be (see also Meinzer, 1923):

1) ephemeral - flowing only occasionally after rain storms or snowmelt and the channel is well above the water table,
2) intermittent - flowing for only part of the year, but in contact with the water table for a certain period during the year, or
3) perennial - flowing year round and the channel is in direct contact with the water table.

Figure 1 offers a visual depiction of the relation of drainage paths to the water table. Among watersheds in similar hydrologic regimes, channel size and amount of water conveyed are directly related to watershed area.

The foundations of channel network analysis and subsequent work in the field of quantitative geomorphology were established by R. E. Horton (1945). Horton introduced a consistent method of ordering streams, which provided a basis for identifying mathematical relationships between channel networks and watershed areas. The method

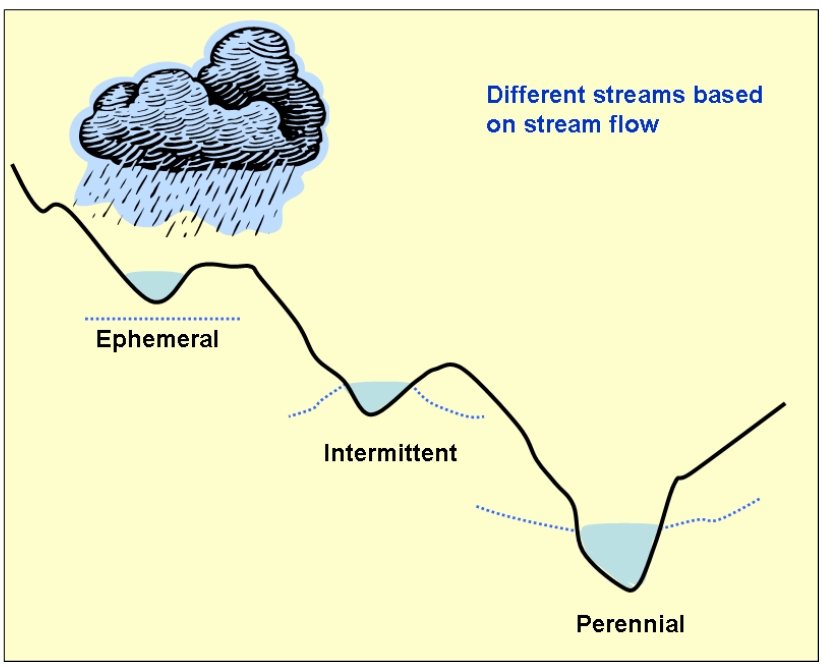
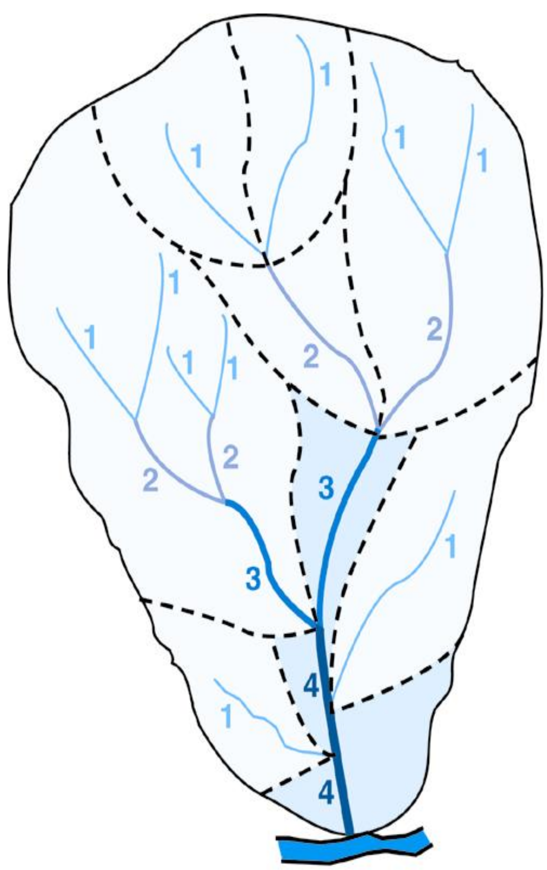


Figure 1. Ephemeral, intermittent, and perennial channels in relation to the ground water table. Dash line indicates the water table (illustration by G. Zaimes).

of ordering streams was modified by Strahler (1952) and can be described as follows: the uppermost tributaries farthest from the watershed outlet are first (low) order streams, which join to produce second order streams, which join to form third (higher) order streams, and so on (Figure 2). This hierarchical approach to classifying channels provides a framework for analyzing channel size, shape, and position of a watershed. A watershed can be divided into three zones: the headwaters, the transfer zone, and a deposition zone (Schumm, 1977) (Figure 3). Within the headwaters zone, usually we expect low order streams that are steeper and narrower than high order streams found in the deposition zone. Analysis of channel networks can provide important information for understanding the hydrologic impacts of landscape alteration. For example, channel networks can be significantly altered through suburban development (Graff 1977).



(after Leopold, Wolman and Miller, 1964)

Figure 2. Schematic illustrating the Strahler stream order classification system (illustration from Schultz et al., 2000).

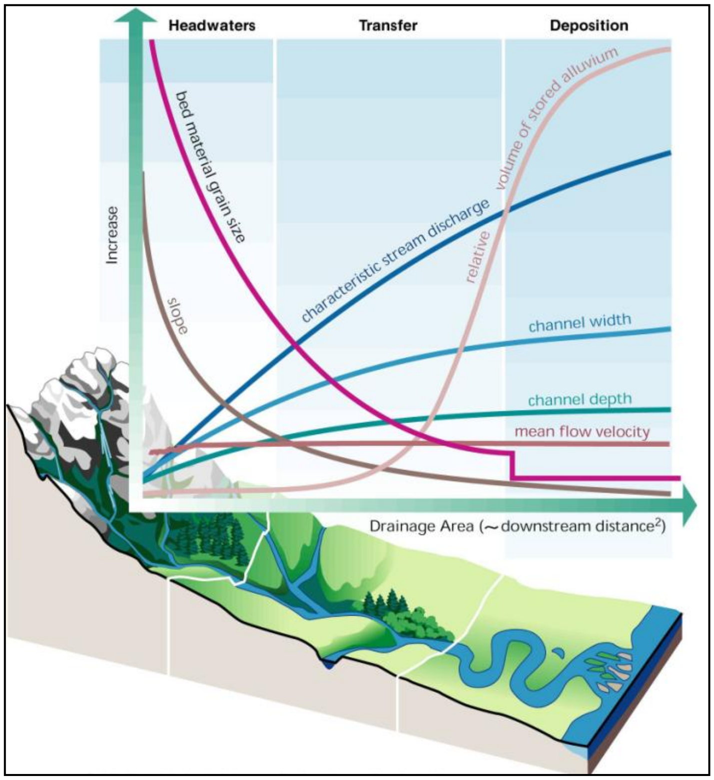


Figure 3. The hydrologic and geomorphic changes among the three functional zones of the streams [from "Stream Corridor Restoration: Principles, Processes, and Practices, 10/98, by the Federal Interagency Stream Restoration Working Group (FISRWG)].

Channel form

Channels and their floodplains are dominant morphological features of riparian areas. Several measures of stream channel dimensions can be used to quantify the size and shape, also called the morphology, of these features.

A plan view of a channel, such as from an aerial photograph or a topographic map, can reveal the lengthwise stream pattern. The lengthwise stream pattern can be described as (Gordon et al., 2004):

1. *Straight*: channels have a single thread that is straight and is rare
2. *Meandering*: channels also have a single threads but the channels has many curves
3. *Braided*: channels have multiple threads with many sand bars that migrate frequently
4. *Anastomosed*: streams that also multiple threads but do not migrate laterally.

These patterns can be quantified by measuring the sinuosity, meander length, and radius of curvature (Figure 4). Sinuosity is calculated as the distance water flows along the thalweg (deepest channel path), the stream length, divided by the straight-line distance between starting and ending points, the valley length. As meandering increases, sinuosity increases. A straight channel will have a sinuosity equal to one. In general, straighter channels are found in steeper areas, and as watershed gradient decreases, meanders develop and sinuosity increases. Channel meander bends develop to minimize the amount of work done in transporting water and sediment (Langbein and Leopold, 1966). Meander bends are characteristics of many high order perennial streams. Braided channels are multiple smaller channels that, under most flow conditions are confined within a wider, generally straighter channel that formed during very large flood flows. Braided channels form when sediment loads are high relative to flow, and often migrate laterally within the wider channel area.

Meanders are one of the characteristics that people think of when they envision water flowing across a low-lying valley floor. Channels in low-lying valleys typically have very low slopes. Meandering channels form as friction between flowing water and the channel bed and banks causes shear and turbulence that lead to instabilities. Adjustments among flow and sediment load occur as the higher velocity flows that occur along the outside of a meander bend erode the bank, and lower velocity flows around the inside of the meander bed deposit sediment and build point bars. Although meanders are commonly envisioned when one thinks of a "healthy" riparian area, not all channels meander. This is the case in mountainous with high-velocity flash flood flows in channels with steep slopes that are often highly turbulent. Flow under these conditions carry sufficient momentum to prevent cross channels flows, and limit the creation of alternating point bars. As one travels up out of a valley floor onto an alluvial fan, channel slopes become sufficiently steep to limit meandering. The fan shape of alluvial

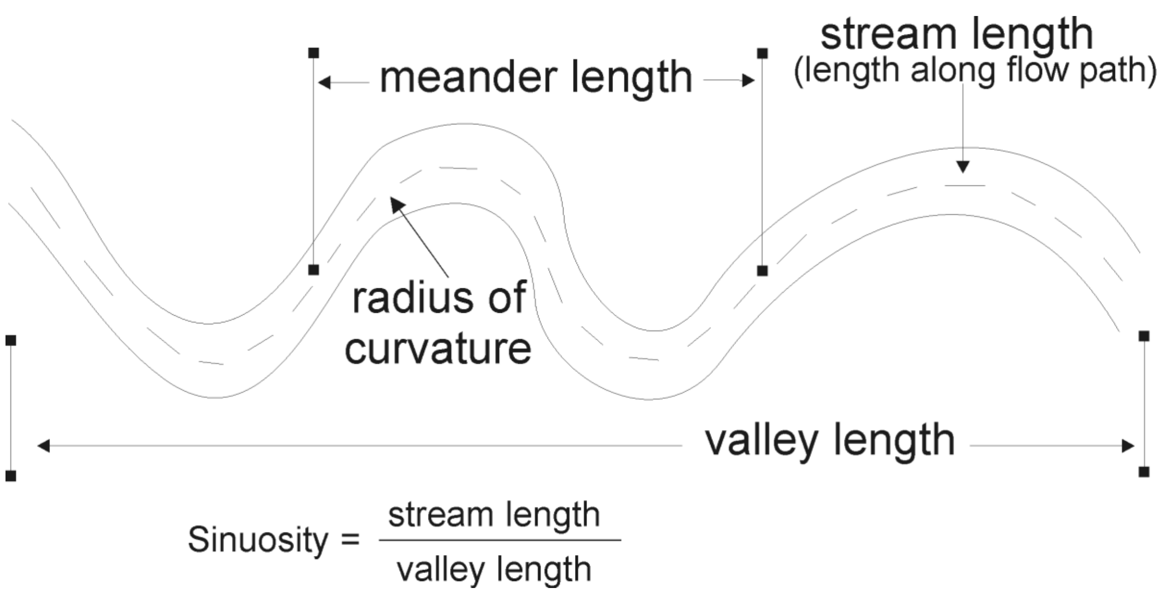


Figure 4. Schematic showing meander length, radius of curvature, and measurements needed for computing sinuosity.

fans is created as unstable channels shift across the fan surface distributing sediment. The rate of fan development is related to variations in flow magnitude and frequency. Unstable channels offer a considerable challenge for management, which should be carefully considered with respect to runoff and sediment transport processes.

In addition to plan-view features, channels can be characterized by the geometry of cross sections and the channel profile. At any given point along a channel, a cross section can be measured to characterize the two-dimensional shape of the channel perpendicular to the direction of flow (Figure 5). The basic characteristics of channel width and depth can be determined from a cross section. From the basic cross section geometry, additional characteristics such as width/depth ratio can be computed. Narrow and deep channels have lower width to depth ratios than wider, shallower channels. Cross sections in natural channels are rarely uniform and are often compound to accommodate a range of flow sizes. Channels may contain a low flow channel through which the main thread of flow passes in the absence of a flood flow. During flood flows, the entire channel width may be inundated and cross sectional shape can change abruptly because of scour and deposition. Cross sections can be re-evaluated to detect net gains (aggradation) and losses (degradation) of channel bed material between individual flows or over long time periods.

The longitudinal slope of a channel can be measured to determine the profile shape. Channels are generally steeper in their upper reaches and flatten towards the lower reaches (Figure 3). Channel gradient can be computed as the length of the channel divided by the difference in elevation of the upper and lower end points (e.g. ft/mile). Over long periods, a channel may aggrade or degrade in response to upstream or downstream influences. For example, a channel may degrade as the slope adjusts in response to a drop in elevation of the channel downstream. Alternatively, a channel may aggrade if the upstream sediment supply is increased.

Floodplains

While the primary function of channels is to convey water and sediment, floodplains act as overflow buffers and serve a critical function in mitigating the downstream impacts of floods. Floodplains comprise the area adjacent to channels over which out-of-bank flows are diffused. Former floodplains may be visible on the landscape as the channel cuts deeper and new floodplains are formed. The former floodplains are referred to as terraces.

Floodplains develop over time as the result of flood inundations. The water moving over a floodplain travels at a lower velocity than the channel flow, and as flow velocity decreases, sediment is deposited. Over time, deposits of nutrient-rich sediment are built up in layers. These deposits provide nutrients for riparian vegetation.

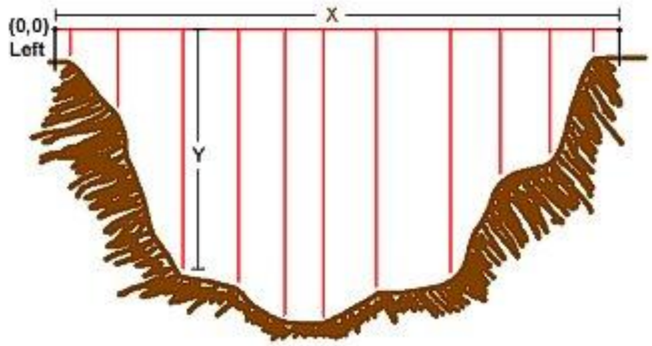


Figure 5. Schematic showing a general channel cross section, x indicates channel width and y indicates channel depth.

Processes that shape channels

Understanding the connections between channel morphology and the stream processes that drive channel adjustment is critical for managing riparian areas. Understanding how stream process act to distribute water and sediment within watersheds and through riparian environments is important for several practical reasons. These include:

1) understanding which factors can be changed through management,
2) understanding the potential and actual impacts of upstream and downstream conditions and their connectivity,
3) understanding how historic land use and watershed evolution patterns are likely to determine the extent to which current conditions can be modified, and
4) creating realistic goals of what the channel should look like in response to management under current conditions.

Flow and sediment transport

Water and sediment discharge vary in time and space. At a given point along a channel, water discharge can be computed as the average flow velocity multiplied by the cross-sectional area of flow (Figure 6). A plot of discharge versus time is called a hydrograph (Figure 7). The shape of the hydrograph provides information on the character of the flow event. In the semiarid southwest, short-duration and high-intensity thunderstorms result in flash floods that yield rapidly rising runoff hydrographs. In contrast, a flat hydrograph is indicative of constant discharge. A hydrograph generated by snowmelt will typically rise as snow melts during the spring and then will return to a low flow condition. When measured over time, characteristics of individual flows, such as the peak (maximum) runoff rate and the total volume of water, can be used to compute flood frequencies. Flood frequencies are a measure of probability. For example, every year there is a 1 in 100 chance that a 100-year flood will occur.

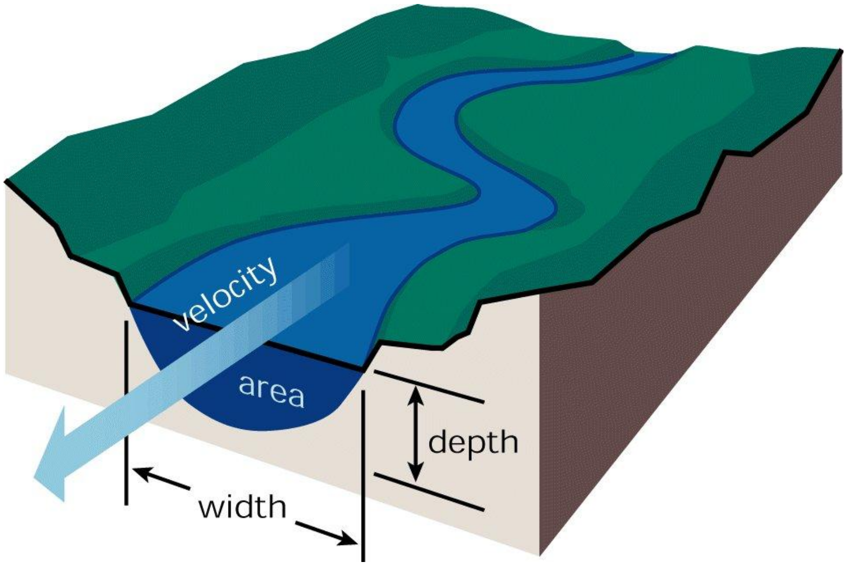


Figure 6. Stream flow discharge is estimated by multiplying the water's mean velocity by the stream cross sectional area at a specific point [from "Stream Corridor Restoration: Principles, Processes, and Practices", 10/98, by the Federal Interagency Stream Restoration Working Group (FISRWG)].

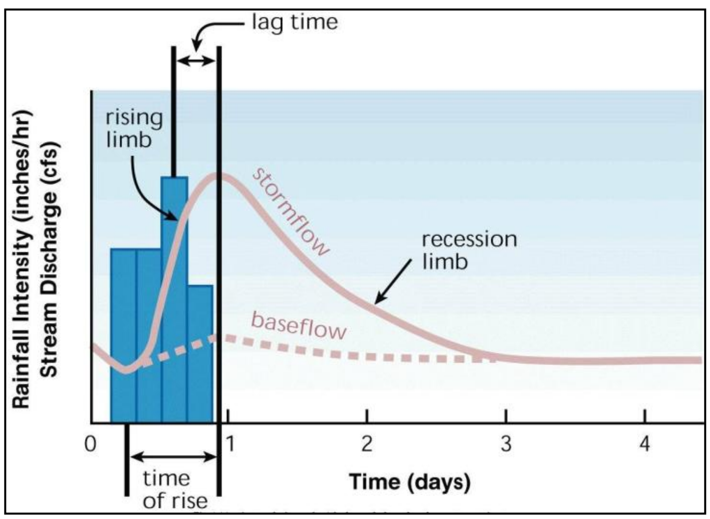


Figure 7. Typical hydrograph [from "Stream Corridor Restoration: Principles, Processes, and Practices", 10/98, by the Federal Interagency Stream Restoration Working Group (FISRWG)].

The magnitude and frequency of flows have important implications for sediment transport. Although large flood flows erode and evacuate large quantities of sediment and are responsible for channel formation, they are relatively infrequent. The relative amount of work done by smaller flows in transporting sediment may add up to a considerable amount. In contrast, during prolonged periods of no flow, no sediment is transported.

The total load carried by water flowing through the channel network is made up of several components. The dissolved load includes those constituents that are chemically dissolved in the runoff. They are primarily the result of chemical weathering of geologic material and include salts and other chemicals. Large particles, such as sands, gravel, and cobbles can travel either in suspension or as bedload. The distinction between suspended load and bedload is a distinction between mode of transport and the particular size of particle traveling in each mode changes as flow velocity changes. Large particles usually travel in short bursts along the channel bed through the process termed saltation. However, they can be picked up by flow and travel in suspension if the drag and lift forces exerted on the particle by the flow exceed the submerged weight of the particle.

Sediment particles are generated from four primary sources: hillslopes, tributary flows, and channel beds and banks. Raindrops can directly dislodge particles as they strike bare soil. Once dislodged, these particles are ready to be transported across hillslopes through overland flow, or sheetwash. Overland flow can carry particles directly into the channel network, or they may be re-deposited and stored on the hillslope. Once particles in overland flow reach a channel, they become part of the channel sediment load. The sediment load is also made up of sediment delivered though joining tributaries, as well as sediment picked up from the channel bed and eroded from channel banks.

Sediment directly interacts with flowing water. Several sediment characteristics, such as size and shape affect channel flow. Resistance to flow is provided by both the roughness of the sediment grains on the channel surface and form roughness imparted by the overall channel shape. When these resistive forces are overcome, the channel bed and banks will erode. Most alluvial channel beds are comprised of cohensionless, or loose, sediment that is readily picked up, with increasingly large particles picked up as discharge increases. In general, as the depth of flow increases, the effects of grain roughness become less important.

Channel banks can contribute sediment to flowing water. The sediment making up channel banks often contains a higher proportion of clay than the sediment on the channel bed. As a result channel banks may be more resistant to erosion than the channel bed. Bank steepness is related to the proportion of clay, and throughout the southwest, vertical channel banks are a sign that these banks have relatively cohesive substrates. However, these banks are subject to erosion during flows.

The maximum quantity of solid material that a stream can carry is termed "transport capacity." Transport capacity is directly related to discharge (velocity) and is highest during storm-generated runoff when flow velocities increase. The amount of transported sediment can be limited by the available supply or by the capacity of the flow to transport available material. Sediment transport in ephemeral channels is often limited by transport rather than by sediment supply because flows are infrequent and of short duration.

Sediment is naturally sorted during deposition. In general, channel bed sediment is coarse in upper stream reaches and becomes finer in the downstream direction. The steep upper channel reaches can become armored, or covered with a layer of larger, less transportable rocks, as the supply of finer material is depleted from the channel bed and transported downstream (Figure 3). As channel slope lessens on the lower reaches of the channel, increasingly smaller sediment particles are deposited (Figure 3). In addition to longitudinal sorting, sediment can be sorted across the width of a channel as well as vertically within deposits. Variations in flow velocity around a channel bend will generally result in erosion on the outside of the bend and deposition on the inside of the bed. The size of deposited sediment will vary with discharge and coarse deposits may be overlain with finer deposits during subsequent flows. Deposits that remain in place can provide a record of past runoff events. Changes in bed material size are usually an indication of a change in flow regime or sometimes to changes in sediment supply.

Vegetation

The relatively dense stands of vegetation found along channels in Arizona form in response to available moisture. Vegetation typically colonizes channel floodplains and banks, and in the absence of scouring flood flows, can become established on the channel bed. Vegetation, both on channel banks and within channels, can play an important role in controlling morphologic adjustment of channels by altering resistance to erosion and affecting flow hydraulics. In extreme cases, riparian vegetation can act as a primary control on channel shape (Tal et al., 2003). Because of its importance in affecting channel morphology, vegetation can be used as a beneficial tool for managing riparian areas.

Vegetation can act as an important stabilizing force. On the floodplain and along channel banks, roots provide a network of reinforcement to bind the soil matrix and increase soil strength (Simon and Collison, 2002). There is a wide range in rooting depth among riparian species. The roots of woody vegetation such as mesquite may extend to many feet while the rooting depth of some grasses may not exceed several inches. The range in rooting characteristics leads to a range in the stabilizing forces of riparian plants.

Although intense flood flows can scour, uproot, and remove young and newly established vegetation, established vegetation can act to stabilize channel bed sediment that would otherwise be readily mobilized. As the vegetation matures, it becomes increasingly resistant to removal during flood flows.

In addition to its role in stabilizing soil and sediment, vegetation interacts directly with flowing water. Because vegetation imparts a resistance as water flows past stems and through leaves and branches, it slows the flows and affects the pattern of erosion and deposition along the channel. The relatively stiff stems of woody vegetation may create high turbulence as flow travel around the stem and produce local pockets of erosion. Grasses and finer-stemmed vegetation may simply bend as flow passes over them, thus contributing to channel roughness. Vegetation can also act as a filter promoting deposition as sediment-laden water passes.

Channel adjustment to changes in water and sediment load

Viewed over very long time periods and under relatively stable climate regimes, undisturbed channels and their floodplains exist in a state of relative equilibrium. Through conveyance of water and sediment over long periods of time, channels adjust to accommodate variations in load through erosion and deposition processes that generally offset each other. Through adjustment to width, depth, profile and planform patterns, a long-term balance between water and sediment may form such that the channel neither aggrades nor degrades and the channel comes to a state of dynamic stability.

The dynamic stability can be expressed as the balance among sediment load, sediment size, stream slope, and water discharge (Figure 8). Specifically, the product of sediment load and sediment size is proportional (but not equal) to the product of discharge and channel slope (Lane, 1955). Changes to any one of the factors can affect each or all of the remaining three factors. For example, if the sediment load is increased, the channel will aggrade as the transport capacity is exceeded and sediment is deposited.

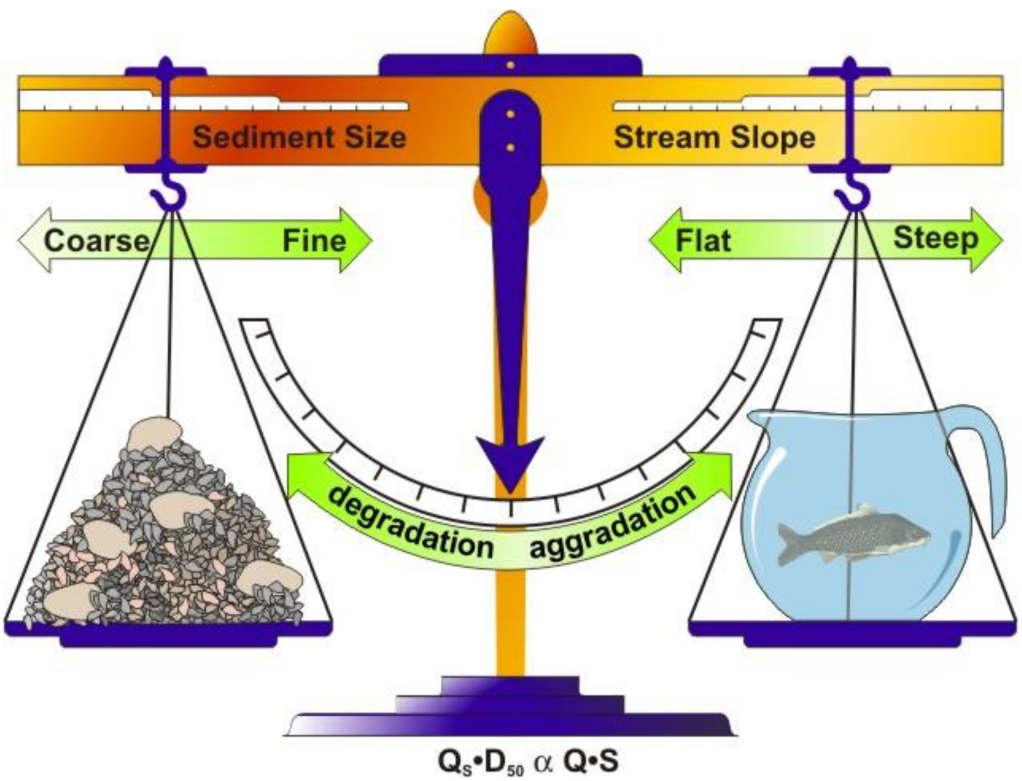


Figure 8. Relationship among stream discharge (Q), channel slope (S), sediment discharge (Q), and channel sediment size (D_{50} is the median grain size of the channel sediment) (Illustration by D. Cantrel modified from Rosgen, 1996).

Alternatively, if the discharge increases, the channel will degrade through scour as sediment is picked up to satisfy the transport capacity. During the period of adjustment the channel can be considered unstable.

Within a watershed, alterations that change any of the factors affecting the balance among sediment load, sediment size, stream slope, and water discharge will cause physical changes in the channel. Watershed alterations may be direct or indirect (Knighton 1984). Direct changes to channel and riparian systems include bank stabilization, canalization, and river regulation. Indirect changes include road construction, sand and gravel mining, and vegetation removal as land use changes. Increasingly, urbanization is contributing to alterations in hydrology and sediment supply. Construction itself can increase sediment supply (Wolman and Schick, 1967) and paved surfaces can increase peak runoff rates and stormwater runoff (Dunne and Leopold, 1978; Hollis, 1975). Although there are many examples of human-induced alterations to the balance among sediment load, sediment size, stream slope, and water discharge, the balance can also be tipped through natural causes. For example, land slides and mass failures can alter sediment loads and fire can remove vegetation. In contrast, geologic features such as bedrock outcrops and faults act as controls on channel adjustment. Historically, landscapes in the southwestern United States have experienced cycles of valley fill and entrenchment (Schumm and Hadley, 1957).

Since the settlement of the southwestern United States by homesteaders, population pressures have been on the rise and have had a significant impact on the landscape. Road construction in response to population and development pressures has significantly altered both the landscape and hydrologic function of many rangeland watersheds. Many riparian areas across the southwest have been significantly altered. Though some managed grazing has occurred in the southwestern United States since the establishment of Spanish ranches in the early 1800s, intensive grazing in Arizona began in the 1880's (Hamilton, 1884; Wagoner, 1952). Though channel and riparian measurements from the late 1800's are limited, anecdotal reports and limited measurements have been coupled with recent measurement to assess temporal changes along several Arizona channels. Several rivers, such as the San Pedro (Hereford, 1993), the Santa Cruz (Parker, 1995), and the Gila (Burkham, 1972; Klawon, 2003) flowed through shallow channels over unentrenched valleys. Many valleys in southeastern Arizona experienced entrenchment during the late 1800's through the early 1900's. Although several causes for the regional entrenchment, including climate, fire, intensive grazing have been suggested (Hastings and Turner 1980; Humphrey 1987) channels adjusted in response to a combination of factors that altered the balance between water and sediment supply.

Conclusion

Riparian areas in Arizona exhibit a broad range of forms derived through a balancing act among sediment load, sediment size, stream slope, and water discharge. Managing riparian areas, especially if management includes treatments to alter the current channel form, must take into account the processes that act to shape the channel and floodplain.

In addition, critical consideration must be given to both upstream and downstream conditions that may be controlling influences on water and sediment delivery in a managed channel reach. A vision of future channel form alone is not enough to guide management decisions. Riparian area management must take stream processes into account to understand the relations among historic channel evolution, current condition, and future expectations.

References

Burkham, D.E. 1972. Channel Changes of the Gila River in Safford Valley, Arizona 1846-1970. USGS Professional Paper 655-G, Washington, D.C. pp. 24.

Dunne, T. and L.B. Leopold. 1978. Water in Environmental Planning. W.H. Freeman and Co. New York, NY.

Federal Interagency Stream Restoration Working Group (FISRWG) (10/1998). Stream Corridor Restoration: Principles, Processes, and Practices. By the Federal Interagency Stream Restoration Working Group (FISRWG) (15 Federal agencies of the United States government). GPO Item No. 0120-A; SuDocs No. A 57.6/2:EN 3/PT.653. ISBN-0-934213-59-3.

Graf W.L. 1977. Network characteristics of suburbanizing streams. Water Resources Research 13:459-463

Gordon, N.D., T.A. McMahon, B.L. Finlayson, C.J. Gippel, R.J. Nathan. 2004. Stream Hydrology: An introduction for ecologists. 2nd edition. John Wiley & Sons. Chichester, England.

Hamilton, P. 1884. The resources of Arizona. Its mineral, farming, grazing and timber lands; its history, climate, productions, civil and military government, pre-historic ruins, early missionaries, Indian tribes, pioneer days, etc., etc. A. L. Bancroft & Company, San Francisco, CA. pp. 414.

Hastings, R.H. and R.M. Turner. 1980. The Changing Mile. University of Arizona Press, Tucson, Arizona. pp. 334.

Hereford, R. 1993. Entrenchment and widening of the Upper San Pedro River, Arizona. Special Paper 282. GSA, Boulder, CO. pp. 46.

Hollis, G.E. 1975. The effect of urbanization on floods of different recurrence. Interval. Water Resources Research Vol. 11 no. 3.

Horton, R.E. 1945. Erosional development of streams and their drainage basins. Geological Society of America Bulletin 56: 275-370.

Humphrey, R.R. 1987. 90 Years and 535 Miles, Vegetation Changes Along the Mexican Border. 448 pp., University of New Mexico Press, Albuquerque, New Mexico.

Klawon, J.E. 2003. Upper Gila River Fluvial Geomorphology Study. US Department of the Interior Bureau of Reclamation, Washington, DC.

Knighton, D. 1984. Fluvial Forms and Processes. Edward Arnold, London. pp. 218.

Lane, E.W. 1955. The importance of fluvial morphology in hydraulic engineering. Proceedings of the American Society of Civil Engineers 81. (paper no. 745).

Langbein, W.B. and L.B. Leopold. 1966. River Meanders - Theory of Minimum Variance. USGS Professional Paper 422-H US Government Printing Office, Washington, DC.
Leopold, L.B., M.G. Wolman, and J.P. Miller. 1964. Fluvial Processes in Geomorphology. W.H. Freeman, San Francisco, CA. pp. 522.
Meinzer, O.E. 1923. Outline of ground-water hydrology with definitions. U.S. Geological Survey Water-Supply Paper 494.
Parker, J.T.C. 1995. Channel Change on the Santa Cruz River Pima County, Arizona, 1936-86. USGS Water-Supply Paper 2429. Washington, D.C. pp. 58.
Rosgen, D. 1996. Applied River Morphology. Wildland Hydrology. Pagosa Springs, CO.
Schumm, S.A. 1977. The fluvial system. John Wiley & Sons, Inc., New York, N.Y., pp. 338.
Schumm, S.A. and R.F. Hadley. 1957. Arroyo and the semiarid cycle of erosion. American Journal of Science 225:161-174.
Simon, A. and A.J.C. Collison. 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth Surface Processes and Landforms 27:527-546.
Strahler A.N. 1952. Dynamic basis of geomorphology. Geological Society of America Bulletin 63:923-928.
Tal, M., K. Gran, A.B. Murray, C. Paola, and D.M. Hicks. 2003. Riparian vegetation as a primary control on channel characteristics in multi-thread rivers. Riparian Vegetation and Fluvial Geomorphology: Hydraulic, Hydrologic, and Geotechnical Interaction. Water Science Application, Vol. 8. American Geophysical Union.
Wagoner, J.J. 1952. History of the cattle industry in southern Arizona. University of Arizona, Tucson, AZ. Sociology Science Bulletin 20. pp. 132.
Wolman, M. G. and A.P. Schick. 1967. Effects of construction on fluvial sediment, urban and suburban areas of Maryland. Water Resources Research 3:117-125.

CHAPTER 5
Biological Processes in Riparian Areas – Habitat
By Douglas Green

Introduction

Biological processes operate at a variety of spatial and temporal scales. Examples of these processes include, but are not limited to germination, establishment, growth, photosynthesis, respiration, predation, and decomposition. Some processes such as decomposition are biogeochemical in nature and include both biological and non-biological components. Riparian areas and the adjacent uplands have similar biological processes, however the riparian area differs due the presence of water in excess of that in the adjacent uplands and the degree of disturbance caused by running water. The presence of water allows for certain biological processes such as decomposition photosynthesis to occur at greater rates and for more extended periods of time than in the uplands. The summation of biotic and abiotic processes such a flooding creates the highly diverse habitat associated with riparian areas. The term 'habitat' refers to the place where an organism lives and is comprised of both biotic and abiotic factors (Odum, 1971). Riparian areas are highly valued for habitat. For example, in the southwest it has been estimated that 70% of threatened and endangered vertebrate species are riparian obligates (species that require riparian habitat to complete some portion of their life cycle) (Johnson 1989). Riparian areas also have higher species richness and density than the surrounding uplands (Jobin et al., 2004; Lyon and Gross, 2005).

The linear nature of the riparian area gives it another important function: that of a corridor. River systems and their riparian corridors traverse great distances and diverse landscapes; as such they provide dispersal routes for many species. Riparian corridors also serve other functions, including acting as filters, sinks, and sources of biological and non-biological materials (Malanson, 1993; Forman, 1995).

Riparian Habitat

A riparian habitat is the summation of physical and biological processes occurring on several different spatial and temporal scales. Operation of these processes over time creates high spatial and temporal diversity resulting in the high biodiversity that is usually attributed to riparian areas. Riparian habitats are typically referred to as corridors in a larger landscape matrix (Figure 1). A matrix is the dominant cover on the land surface (Forman, 1995). Patches are a relatively homogenous area that differs from matrix in which it is embedded (Forman, 1995). The corridor is a special type of a patch that is linear. The small-scale patterns of patches, corridors, and matrices are termed a mosaic (Forman, 1995).

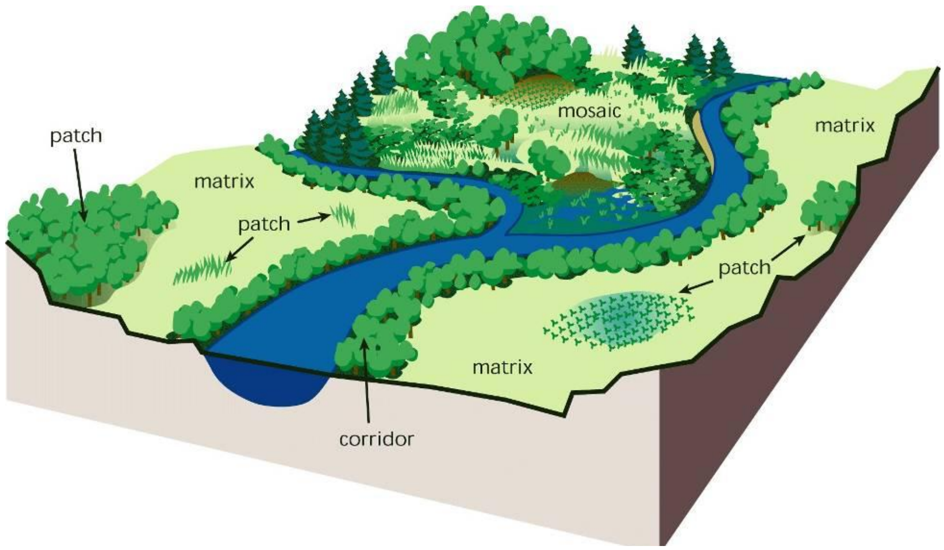


Figure 1. Landscape relationships of uplands and riparian habitats [From Stream Corridor Restoration: Principles, Processes, and Practices, 10/98, by the Federal Interagency Stream Restoration Working Group (FISRWG)].

Spatial diversity

Riparian areas are spatially diverse. This high degree of spatial diversity occurs along three dimensions: longitudinally, transversely, and vertically.

Longitudinal diversity involves viewing the riparian area from the headwaters to the mouth or along a specific reach of interest (Figure 2 and 3a). Stream ecologists have long used the river continuum concept as a framework for many studies (Figure 2) (Vanote et al., 1980). The river continuum concept stresses the connectivity of upstream and downstream ecosystems and the influence of riparian vegetation on the in-stream invertebrate community. For example, in 1st to 3rd order streams, the high availability of leaf litter influences favors organisms adapted to consumption of leaf litter (shredders). As the stream becomes larger and more channel is exposed to sunlight, grazing organisms that specialize in consuming algae and diatoms found on various substrates are favored and the number of shredding organisms declines. In large rivers such as the lower Colorado, organisms that specialize in the trapping of very fine particulate matter (collectors) dominate. The reduced numbers of grazers reflects reduced numbers of attached algae due to turbidity of the water column. The abundance of shredders is reduced to reduced litter input relative to size of the channel. The zones of production, transport and deposition refer to movement of sediments through the river system and are discussed in other chapters.

The concept of a "riparian continuum" is not commonly applied in the southwestern United States. Geology, elevation and hydrology changes greatly as one moves up or down the riparian area. These variations drive changes in the nature of the riparian habitat. For example, the riparian habitat at Grapevine Creek in the Prescott National

Forest changes from alder-(*Alnus oblongifolia*) dominated habitats at 5500 feet to cottonwood-(*Populus fremontii)* dominated habitats at 4500 feet over the longitudinal distance of 3 miles.

Another aspect of longitudinal diversity is geological variation encountered across landscapes. Streams and their riparian habitats cross differing geological parent material leading to differing geomorphologies (ie. broad valley vs confined valley) of the riparian area (Figure 4a). In broad valley systems, the active channel is wider and channel gradient is less resulting in lower unit stream power. As a result, floodplains in these reaches are frequently wide, complex geomorphic surfaces with secondary channels and soils or substrates of widely varying texture.

Some low areas of the floodplain, such as channel cutoffs, sustained by source water from the stream system, may develop hydric soils if saturated hydraulic conductivity is low and biological demand for oxygen is high. The biogeochemistry of anaerobic soils differs markedly from aerobic soils. Hydric soils, despite occupying a limited area in riparian corridors, are important sites of anaerobic activity. Anaerobic activity is favored by high organic matter content, shallow water table, and warm soil surface temperatures (Mitsch and Gosselink, 2000). Under anaerobic conditions high activity microbial activity leads to denitrification. Significant amounts of nitrate can be reduced to nitrogen gas (Johnston et al., 2001; Mitsch and Gosselink, 2000). In addition, redoximorphic

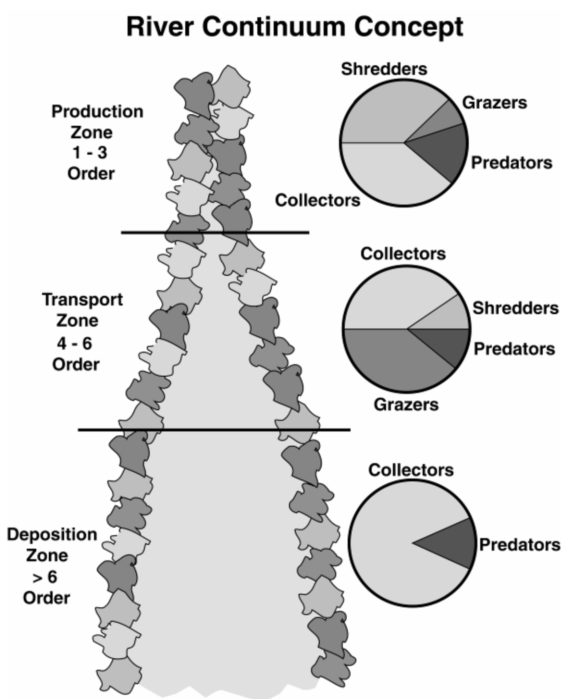


Figure 2. Diagram of the river continuum concept. (illustration from Schultz et al., 2000).

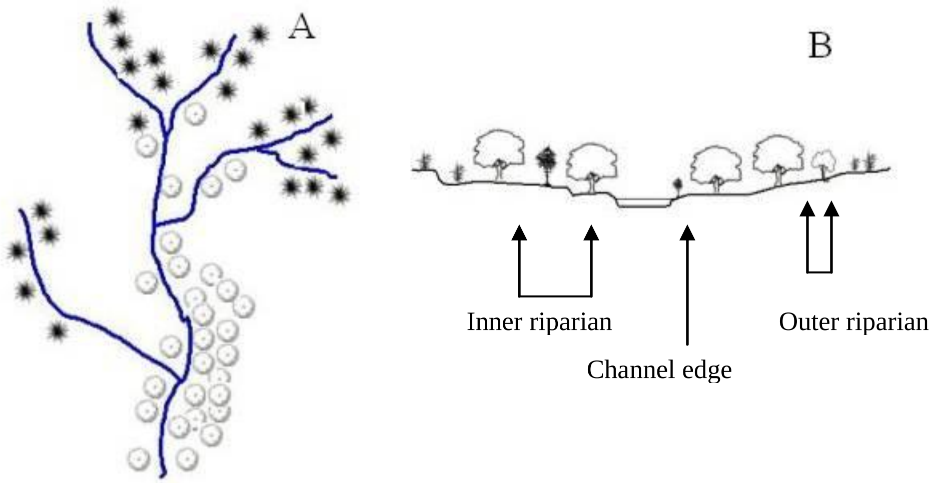


Figure 3. a) Longitudinal and b) transverse views of a riparian habitat. (illustrations by D. Green)

features such as mottles, gleying of the soil by reduced iron, also occur (USDA, 2003). Vegetation on these soils consists primarily of shallow-rooted herbaceous hydrophytes such as cattail (*Typha* spp.), bulrush (*Scirpus* spp.), spikerush (*Eleocharis* spp) knotgrass (*Paspalum* spp.) and Carrizo (*Phragmites* spp) that tolerate wet, anoxic environments. Tree species such as willow (*Salix* spp.) and cottonwood (*Populus* spp.) are typically found on floodplain sites that do not experience prolonged anaerobic conditions. Unlike narrow confined reaches, these floodplains form the basis of a diverse riparian habitat with many patches and ecotones.

a b

Figure 4. Views of riparian habitat along the Salt River, Gila County, AZ, April 2005. a) Gleason Flat, a reach of relatively unconfined geomorphology, and right, downstream of Gleason Flat, a confined high energy environment. The outer region of the riparian area at Gleason Flat is dominated by mesquite (foreground) while the inner edge is dominated by saltcedar and willows. b) In the high energy environment, note the absence of fine sediments and therefore the absence and or reduced presence of mesquite, cottonwood and willow (photos by D. Green).

In confined reaches, the active channel is narrower and slopes are greater resulting in higher unit stream power. In these reaches most fine sediments are transported through the reach, remaining soils or sediments are coarse-textured and limited in extent (Platts et al., 1987). The extent of anaerobic soils is extremely limited in these habitats due to the high hydraulic conductivity of the sediments. Because of the low water holding capacity of the sediments of these reaches, scouring action of high flows, and confinement by adjacent valley walls, these reaches have limited riparian habitat diversity and are of limited width (Figure 4b).

Geology and geomorphology also influence the connectivity of riparian habitats to upland habitat and other riparian patches. Connectivity of the riparian system is important, as well connected system promote species dispersal (movement to new areas), migration (seasonal movement between areas) and gene flow within populations. Connection of the riparian area to the adjacent uplands increases the ease that uplands species can use the riparian area as habitat for resting, feeding or other activities. Riparian habitat patches developed in incised canyons, such as Grand Canyon or Salt River Canyon, are isolated from the adjacent upland by canyon walls, while habitat patches on point bars are often isolated from each other (Malanson, 1993).

Spatial diversity associated with riparian areas can also be observed in a cross-section running from the stream to the uplands (Figures 3b and 5). As one traverses the riparian system from stream to upland, three major habitats are crossed: the channel edge, the inner riparian area and the outer riparian habitats. If the floodplain contains multiple channels, it may be possible to pass through each of these habitats more than once. In narrow confined reaches the channel edge, inner and outer riparian habits may be greatly compressed.

The channel edge is that part of the riparian habitat that abuts the stream channel (Figure 3b). This habitat forms the critical interface between terrestrial and aquatic ecosystems. Many species, particularly aquatic invertebrates, depend on habitat at the stream bank as a site to emerge and pupate into the adult forms (Benke and Wallace, 1990). By providing plant materials (litter) to the aquatic system, the channel edge habitat plays a critical role in carbon dynamics of the instream community, especially in small first and second order streams (Figure 2), (Vannote et al., 1980; Giller and Malmqvist, 1998; Wpfli, 2005). Water temperatures in many smaller stream reaches are significantly influenced by shade from overhanging vegetation (Brown, 1969; Hauer et al., 2000; Naiman et al., 2000). In narrow confined reaches the channel edge may be characterized as a high-energy environment where vegetation is exposed to high unit stream power and subject to scour. Lower gradient broad valley reaches the channel edge may contain significant numbers of hydrophytic plant species and hydric soils. This is a result of saturation of fine textured substrate that may accumulate in these areas.

Figure 5. View of the Verde River downstream of Horseshoe Dam, September 2006 (photo courtesy of D. Green). Note the transverse spatial complexity of this river reach.

The inner riparian area is found between channel edge habitat and outer riparian habitat (Figure 3b). It is typically dominated by wide range of mostly riparian obligate species on diverse fluvial surfaces. On surfaces with finer sediment textures and a favorable hydrologic regime, species such as willow and cottonwood predominate. Riparian tree species located close to the channel edge may enter the stream system and become part of the coarse woody debris load (woody material greater than 3 in. in diameter (Platts et al 1987)). Coarse woody debris represents an important habitat in smaller rivers and can have significant effects on channel geometry (Beschta, 1979; Hamon et al., 1989; Maser and Sedell, 1994; Dahlström et al., 2005). The inner riparian area can play a critical role in fish habitat. Shading of the stream channel modifies stream temperatures and coarse woody debris that enters the stream can modify channel morphology creating habitat elements such as hiding cover and thermal refugia. Modification of riparian vegetation in addition to introduction of non-native fishes and flow modification are major contributors to the decline of native fish populations in the southwest (Rinne, 1995; Rinne and Miller, 2006). Coarse woody debris in the inner riparian area represents an important habitat for a wide range of reptiles (Warren and Schwalbe 1985; Szaro and Belfit, 1986). Portions of the inner riparian area can be relatively dry or droughty due to low water holding capacity associated with large particle sizes for example on cobble bars shown (Figure 5). These habitats are dominated by riparian species capable of growing in a relatively dry environment such a seep willow (*Baccharis* spp), desert willow (*Chilopsis linearis*), and burrobush (*Hymenoclea monogyra*).

The outer riparian habitat is that portion of the riparian habitat that borders the adjacent uplands and has a significant number of upland species (Figure 3b). These habitats occur on the outer margins of the floodplain and on river terraces. Mesquite (*Prosopis* spp.) bosques are a good example of this habitat type. Other species commonly associated with the upland edges or margins of the outer riparian area include wolfberry (*Lycium andersonii* spp.) and catclaw (*Acacia greggii*).

The high value of riparian areas as habitats is also due to the structure and density of the habitats. Riparian vegetation is often denser, particularly in the southwest, than adjacent uplands (Figure 6). This higher density provides increased cover for many wildlife species. In these arid areas, many rodent species may be attracted more to denser vegetation than the presence of water (Ohmart and Anderson, 1978). Bird species such as the southwestern willow flycatcher (*Empidonax traillii extimus*) are sensitive to vegetation density of riparian patches. These dense vegetation patches are interspersed with relatively open low density patches such as burrobush communities on cobble bars that further increase structural variety and the amount of edge available in the riparian area. Vertical structure of riparian areas is often markedly different from the surrounding uplands, especially in arid regions of the southwest. For example, rivers such as the Hassayampa, San Pedro, Verde, and Lower Gila contain large numbers of woody species that are significantly taller than the adjoining uplands. The increased height relative to the upland matrix influences movement of wind dispersed seeds, pollen and dust. Tall woody vegetation has significant influences on instream habitat by shading the water column and moderating temperature (NRC, 2002). Shade also influences stream organisms by reducing the amount of photosynthesis in the stream reach. Tall woody vegetation is an important source of leaf material for instream decomposers in these settings (Vannote, 1980; Giller and Malmqvist, 1998). Many bird species utilize these taller tree canopies as perching, nesting cover, and feeding sites.

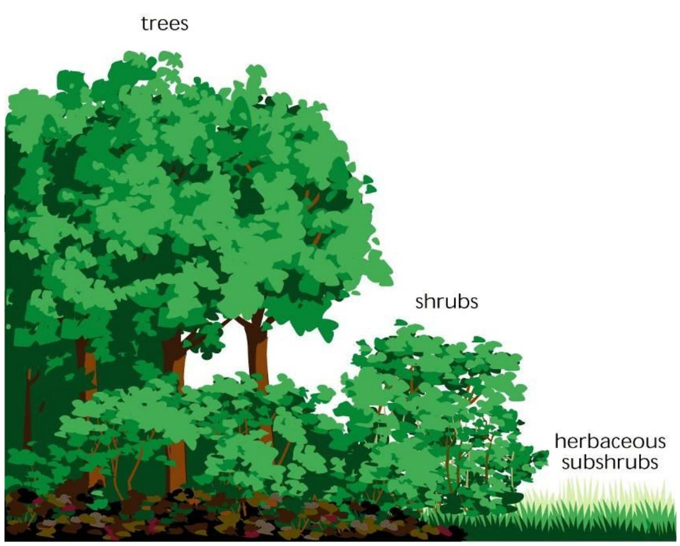


Figure 6. Vertical structure at the upland riparian edge. [From Stream Corridor Restoration: Principles, Processes, and Practices, 10/98, by the Federal Interagency Stream Restoration Working Group (FISRWG)].

Temporal diversity

Riparian habitats often experience significant change over time resulting in a large number of habitat patches of differing ages in a small spatial area. Variation of habitat over time is high due to the random nature of two abiotic drivers: floods and drought.

Floods are an important regenerative mechanism to riparian habitat (Miller et al., 1995; King et al, 1998; Fierke and Kauffman, 2005). Floods can remove herbaceous and woody species, accumulated woody debris, scour substrates, deposit sediments and create new sites for germination and establishment of plant species. Many riparian woody species such as cottonwood and willow require the open mineral seedbed created by scouring for successful germination. The effect of an individual flooding event is determined by the season of flooding, frequency, magnitude, duration, and spatial extent of flooding. A study by Friedman and Aubel (2000) illustrates the influence of flooding disturbance, channel dynamics, sediment deposition and the importance of future flow events on establishment of woody species (Figure 7).

In riparian patches that experience little year-to-year variation in flood flows, sites created by flood scour are limited and little seedling establishment would be expected (Figure 7a). Stream reaches that experience channel narrowing or a large flood event may have significant establishment of woody species (Figure7b and c). Establishment of woody species in either of these scenarios depends on future flow events; seedlings may die under subsequent drought if too high on the floodplain or they may be scoured out by future flood events. On point bars of meanders seedlings can become established on newly deposited sediment on the bar and persist if future flow events are moderate in size and the channel thalweg meanders away from the site (Figure 7c).

Drought conditions can influence riparian habitat by reducing peak flows, thus permitting the establishment of vegetation in the channel especially in low gradient reaches. In larger rivers of the southwest typical species that may encroach into the channel include bulrushes (*Sciprus* spp.), cattail (*Typha* spp.), knotgrass, (*Paspalum* spp.), and Carrizo (*Phragmites* spp). Fine sediments trapped by these species result in a net increase in the extent of anaerobic habitat and function along stream margins. When larger peak flows return many of these habitats created during drought are scoured and the sediments transported downstream (Figure 8). Drought conditions may also reduce riparian habitat width due to mortality of species especially in the outer riparian zone. The encroachment of vegetation into stream channels and mortality in the outer riparian area has also been noted as a result of water diversion for various human uses (Harris 1986; Martin and Johnson, 1987; Sedgwick and Knopf, 1989; Webb and Leake, 2005).

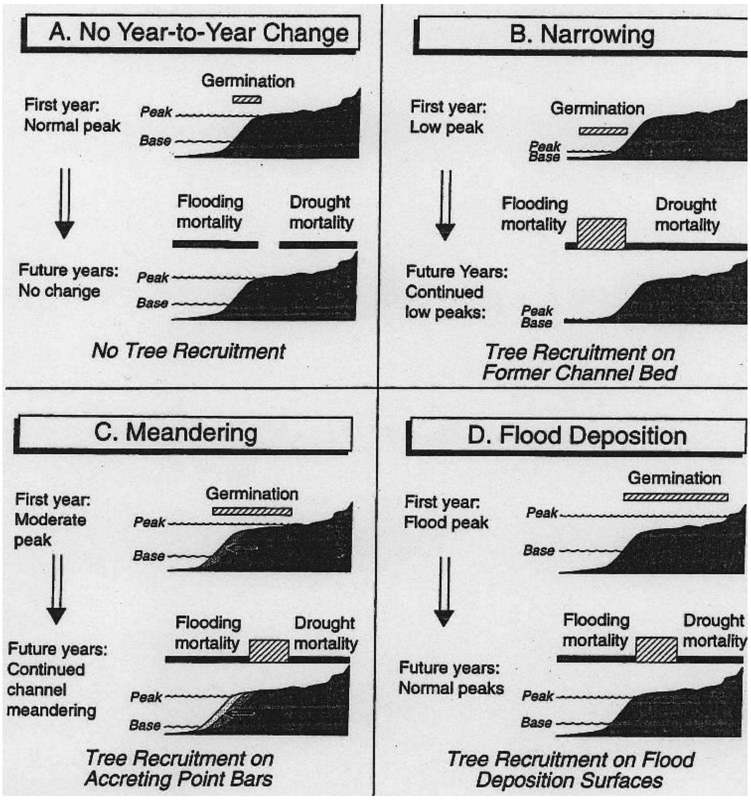


Figure 7. Hydrogeomorphic control of cottonwood recruitment. A representation of four combinations of geomorphic position and hydrology on seedling establishment (illustration from Friedman and Auble, 2000).

Figure 8. Verde River at Sheepbridge. Left, April 2002. Note encroachment into channel by riparian vegetation coincident with low discharges of the previous years. Right, same location September 2005. Note the lack of herbaceous and woody vegetation after a major flood occurred (photos by D. Green).

Riparian Corridors

The riparian areas and their associated river or stream are usually distinct linear or sublinear habitats that cuts across a larger landscape matrix. Because of this characteristic feature, the corridor function of riparian areas has long been recognized (Vannote et al., 1980; Lowrance et al., 1984; Brinson, 1990; Malanson, 1993; NRC, 2002). The riparian corridor influences the movement of non-biological materials such as nutrients and sediments (Gregory and Walling, 1973; Loweranc,e 1984; Peterjohn and Correll, 1984). Riparian corridors also influence dispersal (movement of individual to an area not previously occupied) and migration (movement of animals between seasonal home ranges) of plant propugules and animals across landscapes (Forman, 1995). The riparian corridor has several structural and functional attributes that influence movement, dispersal and migration of non-biological and biological materials.

Structural attributes of riparian corridors

The structural attributes affecting function of riparian corridors include continuity, shape, and width.

Riparian corridors are not uniform or continuous along their length. Discontinuities occur in the riparian corridor for a number of reasons. These include stream meanders and geological confinements (for example a cliff face and human-built structures including roads, dams cities and agricultural fields). Naturally occurring breaks in the corridor provide edges for species to enter or exit the corridor. For example point bars create breaks in the channel edge habitat and provide a site important for willow seeds to enter the channel edge habitat, germinate and establish (Dietz, 1952).

Shape and orientation on the landscape are important determinants of riparian corridor function. Riparian corridors generally have a branching structure on the landscape. This allows a funnel effect that can disperse or concentrate moving species (Forman, 1995). In the funnel effect, species moving upstream along the corridor are dispersed into new habitats (Forman and Gordon, 1986; Malanson, 1993). The funnel effect can act to concentrate species moving downstream leading to increased competition, but the ecological significance of this is unclear. Orientation of the corridor relative to prevailing winds is an important feature for species that utilize wind to disperse seeds such as willows and cottonwoods. If the riparian corridor is perpendicular to prevailing winds, the bulk of these seeds will fall outside the corridor in unsuitable seed beds. Prevailing winds parallel to the corridor will increase the effectiveness of wind as a dispersal mechanism.

Corridor width varies as a result of factors such as geology, climate, hydrology, and human activities. The necessary width to maintain corridor function depends on the ecological process of interest and the size of the river system (Forman 1995). For example, the corridor width needed to maintain effective movement of bird species may be quite different from that needed to trap or detain eroded particles from the uplands.

Functional attributes of corridors

Riparian corridors function as species habitat, conduits for movement, filters for non-biological and biological materials, sources of materials, and as sinks for materials.

Riparian corridors function as habitat and the species in the riparian corridor can be placed into three broad groups. Edge species are those that occur on the edges of the riparian system. Catclaw occurs on the upland of the many lower elevation riparian systems and less commonly in the interior. Hydrophytic plant species are restricted to the channel edge by a lack of available water in the interior riparian habitat. Interior species, because of their need for a larger, more homogenous habitat or inability to tolerate full sun, are restricted to the interior of the riparian area. The southwestern willow flycatcher or understory plant species such as coffeeberry (*Rhamnus californica*) are good examples of interior species. Multihabitat species that occur across the riparian zone and can include many larger mammals or plant species such as Bermuda grass (*Cynodon dactylon*).

Riparian corridors can function as conduits for the movement of materials and species (Malanson, 1993; Forman, 1995) (Figure 9a). Much of the species dispersal that takes place along a riparian corridor occurs at the upland edge or the channel edge. Interior habitats have several disadvantages for dispersal. These include highly heterogeneous habitats that must be crossed, the discontinuous nature of the corridor, and change in corridor structure induced by floods (Malanson, 1993). The significance of these constraints is related to the species of interest.

Most corridors, including riparian corridors, can act as a filter or barrier to select against certain species or materials from crossing (Figure 9b). The intensity of the filter effect

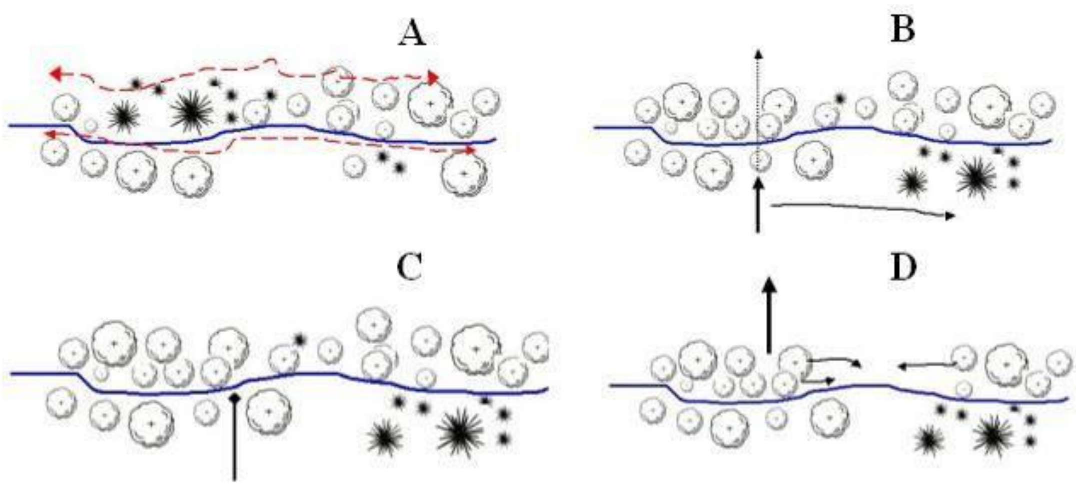


Figure 9. Four corridor functions, a) conduit for movement, b) as a filter, c) as a sink, and d) as a source of materials to the uplands or the corridor.

depends on the width of the riparian system and its associated river. Low order streams present little difficulty to species crossing. Larger river systems can have a significant filter effect as in the case of fox populations separated by the Mississippi River (Storm et al., 1976). Riparian corridors can also act as a sink where materials entering do not leave (Figure 9c). This may include wind deposited material such as dust and seeds (Brandle et al., 1988) or sediment from adjacent uplands. Riparian corridors can be strong sinks for nitrate. Nitrate entering riparian corridors that contain bodies of anaerobic soils undergoes the process of denitrification and is converted to nitrogen gas (Lowrance et al, 1995; Schade et al., 2001).

The riparian corridor functions as an important source of materials to adjacent uplands, the riparian habitat, and the aquatic habitat (Figure 9d). The sediment produced during flood-caused scour can provide new sites for vegetation establishment. After sediment deposition, the site is usually repopulated by corridor species for example, cottonwood, by seeds from adjacent adult trees.

Conclusion

Biological and non-biological processes operating in riparian areas create important habitat for many terrestrial and aquatic organisms. These habitats are highly diverse in terms of structure and function on the landscape. These habitats are highly dynamic and can be short lived as they respond to the effects of floods and droughts. Because of their linear nature, riparian habitats are often termed corridors. The structure of these corridors, especially in the southwest is naturally discontinuous however humans have contributed significantly to fragmentation of riparian corridors. Riparian corridors have been commonly viewed as conduits for dispersal of wildlife and other materials, but also function as habitat, filters, source areas, and sinks. Riparian habitats and corridors should not be considered in isolation from the surrounding uplands. These habitats can be influenced by management decisions and their impact on processes such as infiltration, runoff and sediment regime on the surrounding uplands.

References

Benke, A.C. and J.B. Wallace. 1990. Wood dynamics in coastal plain blackwater streams. Canadian Journal of Fisheries and Aquatic Sciences 4792-99

Bestcha, R.L. 1979. Debris removal and its effect on sedimentation in an Oregon Coast Range stream. Northwest Science 53:71-77.

Brandle, J.R., D.L. Hintz, and J.W. Sturrock. 1988. Windbreak technology. Elsevier, Amsterdam, Netherlands.

Brinson, M.M. 1990. Riverine forests In: A.E. Luge, M. Brinson, and S. Brown (eds) Forested Wetlands. Ecosystems of the World 15. Elsevier, Amsterdam, Netherlands.

Brown, G.W. 1969. Predicting temperatures of small stream. Water Resources Research 5:68-75

Dahlström, N., K. Jönsson, and C. Nilsson. 2005. Long-term dynamics of large woody debris in a managed boreal forest stream, Forest Ecology and Management 210:363-373.

Dietz, R.A. 1952. The evolution of a gravel bar. Annals of the Missouri Botanical Garden 39:249-254.

Fierke, M.K. and J.B. Kauffman. 2005. Structural dynamics of riparian forests along a black cottonwood successional gradient. Forest Ecology and Management. 215:149-162.

Forman, R.T.T. 1995. Land Mosaics: The ecology of landscapes and regions. Cambridge University Press, Cambridge, England.

Forman, R.T.T. and M. Gordron. 1986. Landscape Ecology. Wiley, New York.

Friedman, J.M. and G.T. Auble. 2000. Floods, flood control and bottomland vegetation. In E. Wohl, (ed) Inland flood hazards: Human riparian, and aquatic communities. Cambridge University Press, Cambridge, England.

Gregory, K.J. and D.E. Walling. 1973. Drainage basin form and process. John and Wiley and Sons, New York, NY.

Giller, P.S. and B. Malmqvist. 1998. The biology of streams and rivers. Oxford University Press, New York, NY.

Harris, R.R. 1986. Occurrence patterns of riparian plants and their significance to water resources development. Biological Conservation 38:273-286.

Harmon, M.E., J.F. Franklin, F.J. Swanson, P. Sollins, S.V. Gregory, J.D. Lattin, N.H. Anderson, S.P. Cline, N.G. Aumen, J.R. Sedell, G.W. Lienkaemper, K. Cromack, Jr., K.W. Cummins,. 1989. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15:133-302.

Hauer, F.R., J.A. Stanford, J.J. Giersch, and W.H. Lowe. 2000. Distribution and abundance patterns of macroinvertrbrates in a mountain strea: An analysis along multiple environmental gradients. Verh. Internat. Verin Limnology 27:1-4.

Jobin, B., L. Bélanger, C. Boutin, and C. Maisonneuve, C. 2004. Conservation value of agricultural riparian strips in the Boyer River watershed, Québec (Canada). Agriculture, Ecosystems & Environment 103:413-423.

Johnson, A.S. 1989. The thin green line: riparian corridors and endangered species in Arizona and New Mexico. In: Mackintosh G. (ed.) In defense of wildlife: preserving communities and corridors. Defenders of Wildlife, Washington, DC. pp. 35-46.

Johnston, C.A., S.D. Bridgham, J.P. Schubauer-Berigan. 2001. Nutrient dynamics in relation to geomorphology of riverine wetlands. Soil Science Society of America Journal. 65:557-577.

King, S.L., J.A. Allen, and J.W. McCoy. 1998. Long-term effects of a lock and dam and greentree reservoir management on a bottomland hardwood forest. Forest Ecology and Management 112:213-226.

Lowrance, R.R., R.L. Todd, and L.E. Asmussen. 1984. Nutrient cycling in and agricultural watershed: I. Phreatic movement. Journal of Environmental Quality 13:22-26.

Lyon, J. and M. Gross. 2005. Patterns of plant diversity and plant-environmental relationships across three riparian corridors. Forest Ecology and Management. 204:267-278.

Malanson, G.P. 1993. Riparian landscapes. Cambridge University Press, New York, NY.

Martin C.W. and W.C. Johnson. 1987. Historical channel narrowing and riparian vegetation expansion in the Medicine Lodge River basin, Kansas, 1871-1983. Annals of the Association of American Geographers 77:436-449

Maser, C. and J.R. Sedell. 1994. From the forest to the sea: The ecology of wood in streams. St. Lucie Press, Delray Beach, Fl.

Miller, J.R., TT. Schulz, N.T. Hobbs, K.R. Wilson, D.L. Schrupp, W.L. Baker. 1995. Changes in the landscape structure of a southeastern Wyoming riparian zone following shifts in stream dynamics. Biological Conservation 72:371-379.

Mitsch, W.J. and J.G. Gosselink. 2000. Wetlands. John Wiley & Sons, Inc., New York, NY.

Naiman, R.J., R.E. Bilby, and P.A. Bisson. 2000. Riparian ecology and management in the Pacific coastal rain forest. BioScience 50:996-1011.

National Research Council (NRC). 2002. Riparian areas: functions and strategies for management. National Academy of Science. Washington, DC.

Odum, E.P. 1971. Fundamentals of Ecology. W.B. Saunders Co. Philadelphia PA.

Ohmart, R.D. and B.W. Anderson. 1978. Wildlife use values of wetlands in the arid southwestern United States. In P.E. Greeson, J.R. Clark, and J.E. Clark (eds.) Wetland functions and values: The state of our understanding. Proceedings of the National Symposium on Wetlands. American Water Resources Association, Minneapolis MN.

Peterjohn, W.T., and D.L. Correll. 1984. Nutrient dynamics in an agricultural watershed: Observations on the role of a riparian forest. Ecology 65:1466-1475.

Platts, W. S., C. Armour, G. D. Booth, M. Bryant, J. L. Bufford, P. Cuplin, S. Jensen, G. W. Lienkaemper, G. W. Minshall, S. B. Monsen, R. L. Nelson, J. R. Sedell, J. S. Tuhy. 1987. Methods for evaluating riparian habitats with applications to management. USDA Forest Service Gen. Tech. Rept. INT-221.

Rinne, J.N. 1995. Desired future condition: Fish habitat in southwestern riparian-stream habitats. In: D.W. Shaw and D.M. Finch (technical coordinators) Desired future conditions for Southwestern riparian ecosystems: Bringing interests and concerns together. USDA Forest Service Gen. Tech. Rept. RM-GTR-227 pp. 336-345.

Rinne, J,N. and D. Miller. 2006. Hydrology, geomorphology, and management: Implications for sustainability of native Southwestern fishes. Reviews in Fisheries Science 14:91-110.

Schade, J.D., S.G. Fisher, N.B. Grimm, and J.A. Seddon, 2001. The influence of a riparian shrub on nitrogen cycling in a Sonoran desert stream. Ecology 82:3363-3376

Schultz, R.C., J.P. Colletti, T.M. Isenhart, C.O. Marquez, W.W. Simpkins, C.J. Ball, and O.L. Schultz. 2000. Riparian forest buffer practices. In North American agroforestry: an intrgrated science and practice. American Society of Agronomy, Madison WI

Sedwick, J.A. and F.L. Knopf. 1989. Demography, regeneration, and future projections for a bottomland cottonwood community. In: R.R. Sharitz and J.W. Gibbons (eds.) Freshwater Wetlands and Wildlife. US Department of Energy Symposium Series No. 61, CONF-8603101, Oak Ridge pp 249-266

Storm, G.L., R.D. Andrews, R.L. Phillips, R.A. Bishop, D.B. Sniff, and J.R. Tester. 1976. Morphology, reproduction, dispersal and mortality of midwestern red fox populations. Wildlife Management 49:5-82.

Szaro, R.C. and S.C. Belfit. 1986. Herpetofaunal use of a desert riparian island an dits adjacent scrub habitat. Journal of Wildlife Management 50:752-761.

United States Department of Agriculture Natural Resource Conservation Service (USDA-NRCS). 2003. Field Indicators of Hydric Soils in the United States, Version 5.01. G. W. Hurt, P. M. Whited, and R. F. Pringle (eds.). USDA, NRCS in cooperation with the National Technical Committee for Hydric Soils, Fort Worth, TX.

Vannote, R.L. G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E.Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences. 37:130-137.

Warren, P.L. and C.R. Schwalbe. 1985. Herpetofauna in riparian habitats along the Colorado River in Grand Canyon. In: Riparian ecosystems and their management; reconciling conflicting uses. USDA Forest Service General Technical Bulletin RM-120 pp. 347-354.

Webb, R.H. and S.A. Leake. 2005. Ground-water surface-water interactions and long-term change in riverine riparian vegetation in the southwestern United States. Journal of Hydrology, In Press, Corrected Proof, Available online 25 August 2005, (http://www.sciencedirect.com/science/article/B6V6C-4GYH9T4-1/2/ebdebffbd15869bc059c4f2800c51d23)

Wipfli, M.S. 2005. Trophic linkages between headwater forests and downstream fish habitats: implications for forest and fish management. Landscape and Urban Planning 72:205-213.

CHAPTER 6
Arizona Climate and Riparian Areas

By Mike Crimmins

Introduction

Despite its notoriety as a dusty and dry place, Arizona possesses an exceptional diversity in landscapes, ecosystems, and even riparian areas. Its dramatic topographic features and geographic position bring a range of temperatures and precipitation equivalent to the range experienced between Mexico and Canada. Topographic features create steep gradients in temperature and precipitation that support ecological community types from mixed conifer at high elevations to desert scrub at lowest elevations. Riparian system composition and function varies within these community types and are further linked to climate through seasonal and interannual variability in precipitation type (rain vs. snow) and amount and temperature regimes.

This exceptional variability in Arizona temperatures and precipitation amounts affects riparian areas in complex ways. Patterns in temperature and precipitation related to topography directly impact riparian areas by controlling the amount of water available for streamflow and length of growing season for riparian vegetation. Upper elevation locations are often wetter than lower elevation locations but cooler with shorter growing seasons. Lower elevation locations are the opposite with less direct precipitation, but with warmer and longer growing seasons. Many lower elevation riparian areas in Arizona rely on upper elevation precipitation to produce perennial streamflow. Slow springtime snowmelt and groundwater movement can provide a stream with a baseflow that extends well into the summer season. Riparian vegetation can flourish when this water is available through the dry and hot spring and early summer season. Interannual variability in winter precipitation amounts can disrupt spring streamflows and impact riparian vegetation. Dry winters with low snow pack levels can cause streams that normally flow perennially to run dry even in the early spring.

Background on Arizona Climate

Coarse climate classifications label Arizona as a hot, mid-latitude to subtropical desert. This classification is correct in labeling Arizona as generally arid, but misses the fine-scale variability in precipitation and temperature regimes induced by topography across the state. Elevations range from 20 meters above sea level in the southwest corner of the state to over 3000 meters in the San Francisco Peaks north of Flagstaff. Temperatures decrease with elevation, so upper elevation sites will experience substantially cooler annual average temperatures than low desert locations (Figure 1a). Precipitation amounts are also strongly tied to topography (Figure 1b) with higher elevation locations generally receiving more annual precipitation. The term 'orographic lifting' describes the process by which moist air is forced upward over mountains, inducing the formation of precipitation. Winter storm systems coupled with orographic lifting can deliver relatively large

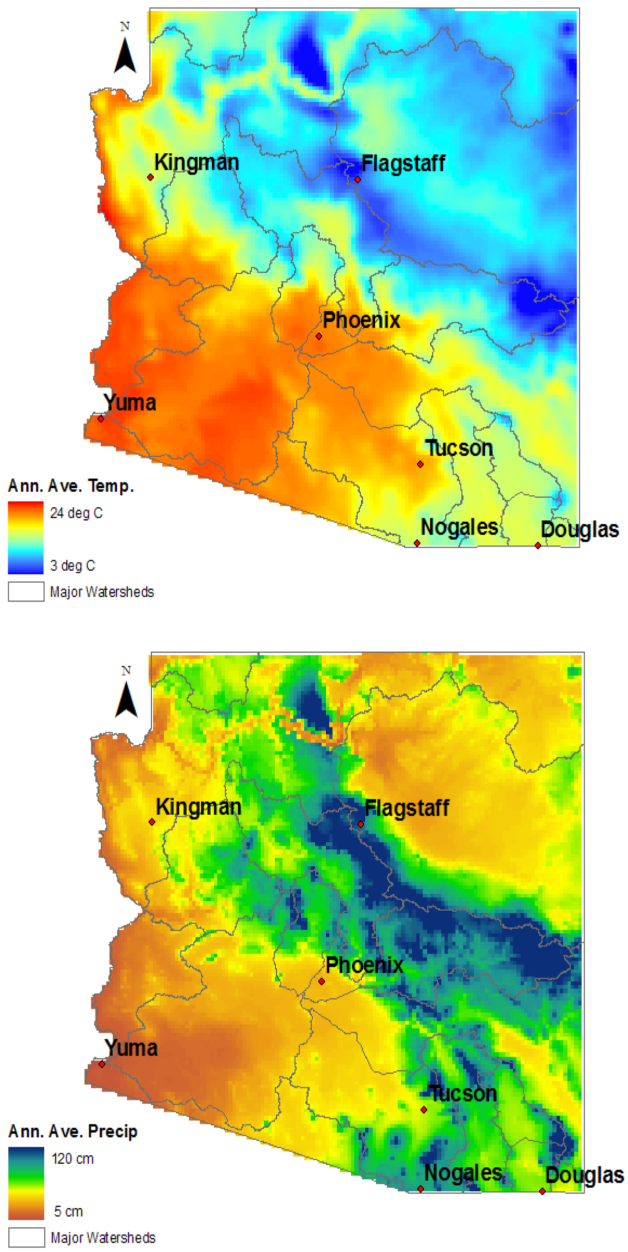


Figure 1. a) Annual average temperature (top) and b) annual average precipitation for period of 1971-2000 (bottom) (data source: PRISM Oregon Climate Service).

amounts of both rain and snow to Arizona's mountains during the winter season (Sheppard et al., 2002). Lower elevation areas downwind of large mountain ranges in Arizona can also experience decreases in precipitation related to this orographic effect. Large-areas of northeastern Arizona are in the 'rain shadow' of the Mogollon Rim mountain range that runs from northwest to southeast across central Arizona. Storm systems that move in from the west or southwest are stripped of moisture by orographic lifting and subsequent precipitation that occurs along the Rim. This limits the moisture available for precipitation to the north and east of the Rim.

Patterns in temperature and precipitation affect riparian areas by controlling the amount of water available to enter streams. The intensity, duration and frequency of precipitation events all govern how quickly and how much water is available to stream systems. Temperature adds an additional dimension to the hydrologic cycle by controlling the rate of evapotranspiration within the system. Higher temperatures lead to higher rates of evapotranspiration and a flux of water out of the system and into the atmosphere.

Looking at large-scale patterns in precipitation and temperature can lend insight into where perennial water may be found. The combination of higher precipitation and cooler temperatures at higher elevations can create the situation where water entering the system through precipitation exceeds water leaving the system through evapotranspiration. This surplus in water is shed as runoff or as the movement of water in soil to streams. The slow movement of water in soil to streams can help sustain the baseflows in perennial streams. Low desert areas where annual precipitation amounts are low and temperatures are high often have deficits in available water for streams. High temperatures and plentiful sunshine drive high potential evapotranspiration rates. Actual evapotranspiration rates are in fact quite low due to the low annual precipitation amounts and subsequent low soil water amounts in the low desert areas of Arizona.

Large-scale atmospheric controls on AZ Climate

Topography is not the only reason Arizona has an exceptionally diverse range of climatic regimes. Its location near the west coast of North America and its position near 30^o north latitude are critical determinants of a semi-arid climate. Global circulation patterns cause a semi-permanent circulation feature called a subtropical high to form around 30^o north and south of the equator around the globe (Figure 2). There are many of these subtropical high pressure systems and almost all of them are associated with limiting annual rainfall and creating arid conditions. Deserts in places like northern Africa and Australia are associated with the position of subtropical high pressure systems. Arizona is influenced by two subtropical high pressure systems, the Pacific High and the Bermuda High.

Arizona receives most of its annual precipitation in two distinct seasons, winter and summer (Figure 3). Winter precipitation comes from large-scale low pressure systems that traverse the Southwest, drawing in moisture from the Pacific Ocean and producing widespread rain and snow. Energy to fuel these large-scale low pressure systems comes from the mid-latitude and subtropical jet streams that can be active in proximity to the southwestern United States during the winter (Woodhouse, 1997).

Summer precipitation in Arizona is the result of very different atmospheric dynamics. The mid-latitude jet stream retreats far north during the summer and the subtropical jet stream is replaced by a large high pressure system anchored over the eastern Pacific

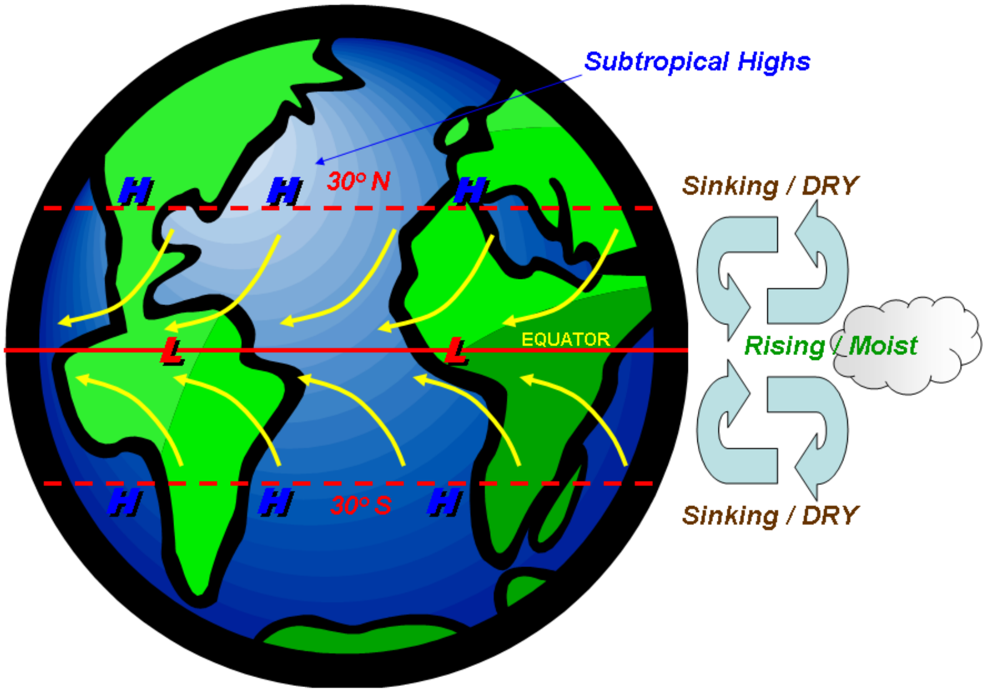


Figure 2. Conceptual model of global circulation patterns in the subtropics.

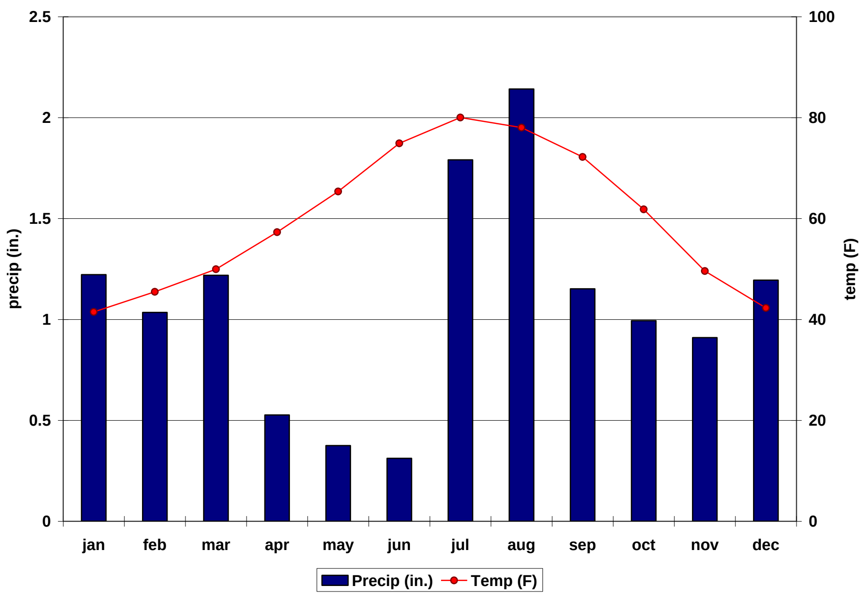


Figure 3. Average Arizona precipitation and temperature by month.

Ocean. The mechanism that produces summer precipitation is not associated with large-scale jet streams or strong low pressure systems, but from convective thunderstorms that arise through the combination of solar heating and moisture. Sunshine and solar heating are plentiful across Arizona during the spring and summer, but moisture levels adequate for thunderstorm development are not always present. A subtle change in circulation patterns during the summer opens up a flow of moisture from the south that dramatically increases convective thunderstorm activity across the state. That shift in circulation marks the beginning of the Arizona monsoon season.

Arizona is situated between strong low pressure systems occurring to the north in the wintertime and strong monsoonal thunderstorms occurring to the south during the summer months (Figure 4). The energy and atmospheric dynamics responsible for producing precipitation during each of these seasons are far to the north and south during each of these seasons. The moisture needed to produce precipitation in conjunction with these dynamical systems is also far to the north during the winter and to the south during the summer (Figure 4).

The fact that Arizona is on the periphery of the dynamics and moisture sources necessary to produce precipitation in any given season can help explain why it is an arid place. This creates large amounts of variability in precipitation amounts geographically and temporally. Subtle shifts in the position and strength of the mid-latitude and subtropical jet streams during the winter or the Bermuda subtropical high pressure system during the summer can bring the dynamics and moisture necessary for precipitation right over Arizona or move it far away. Variability in large-scale circulation and sea surface temperature patterns can cause these subtle shifts to occur, especially during the winter, and they can persist for months to years impacting precipitation amounts over Arizona.

El Niño – Southern Oscillation

Arizona climate and hydrology are strongly influenced by sea surface temperature patterns in the equatorial Pacific region. These patterns can disrupt the location and track of jet streams that bring winter weather systems to the southwestern United States. Winter precipitation and subsequent streamflow from snowmelt can be dramatically above or below average depending on conditions in the Pacific. The variability in equatorial Pacific sea surface temperatures is controlled by a phenomenon called the El Niño-Southern Oscillation.

Pacific sea surface temperatures tend to oscillate between warm and cold along the equator in the eastern Pacific every two to seven years. This oscillation is called the El Niño-Southern Oscillation (ENSO). Atmospheric pressure and circulation patterns are strongly tied to these changes in sea surface temperatures. Weak surface low pressure systems and broad areas of thunderstorms form in response to areas of warm ocean water, while cool water reinforces surface high pressure systems and clear and dry weather. Within ENSO, El Niño refers to periodic changes in sea surface temperatures while the

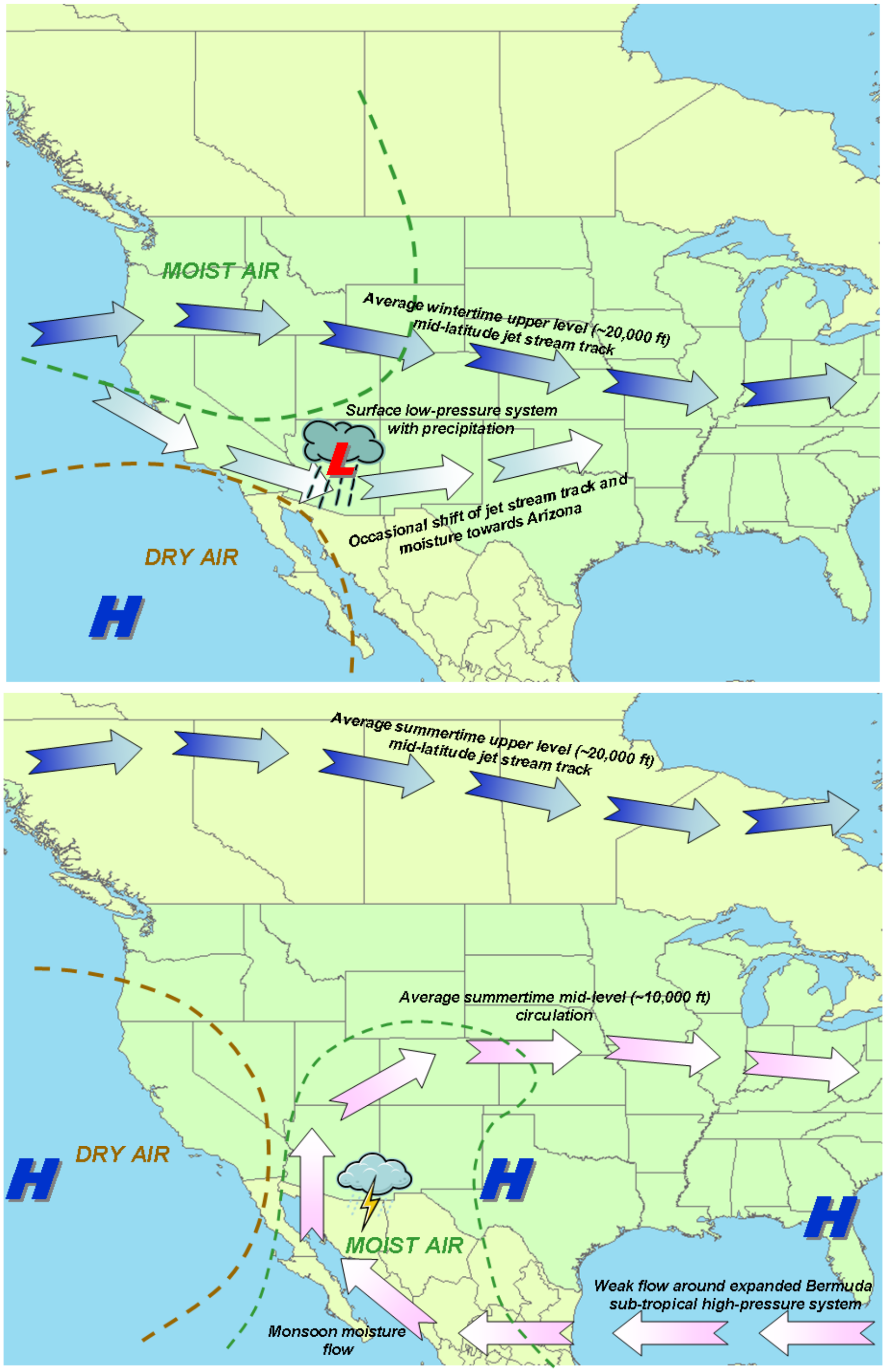


Figure 4. Average flow patterns and moisture airmass boundaries for a) winter (top) and b) summer (bottom).

Southern Oscillation is the atmospheric response to these patterns. Periods when sea surface temperatures are above-average at the equator along the coast of South America are called El Niño events. When the pattern is reversed and temperatures are cold it is called a La Niña event.

El Niño and La Niña events create disruptions in the winter mid-latitude and subtropical jet streams that favor and hinder precipitation across Arizona. The circulation pattern associated with El Niño is a strengthened subtropical jet that delivers moisture and wet weather directly to Arizona. La Niña events tend to create a blocking high-pressure ridge (strengthening of Pacific subtropical high) over the western U.S. that directs winter storms towards the Northwest coast leaving Arizona dry.

The Southern Oscillation Index (SOI) is used to track whether the Pacific is experiencing an El Niño or La Niña event or just neutral conditions. The SOI is an atmospheric index that is calculated by measuring the pressure differences between two weather stations located in the Pacific, Tahiti (an island in the east-central Pacific) and Darwin (a city in northern Australia). If the pressure in Tahiti is much lower than Darwin, the index will be a relatively large negative number. This indicates an El Niño event. The warm waters around Tahiti will cause the atmospheric pressure to be lower than the Darwin location. When Darwin has warmer waters and lower pressures than Tahiti it is a La Niña event.

Figure 5 shows mean annual flow for a gauging station in eastern Arizona and the state of ENSO in the Pacific using SOI. Note the connection between the frequency of strong La Niña events during the 1940's and 1950's and the low flows at the gauging station. The persistent La Niña events are believed to have caused many years of below-average winter precipitation over Arizona and the broader western U.S. region leading to the 1950's drought (Cole and Cook, 1998). In contrast, the period from the mid 1970's through the late 1990's was a wet period associated with an increased frequency of El Niño activity.

The connection in Arizona between below-average winter precipitation and La Niña events is much stronger than the one between above-average winter precipitation and El Niño events. Figure 6 is a scatterplot depicting the relationship between ENSO state and statewide winter precipitation for Arizona. Note how most La Niña events (positive SOI values/blue dots) are related to below-average winter precipitation while there is a large spread in precipitation amounts associated with El Niño events (negative SOI values/red dots). This difference is important when using climate forecasts based on ENSO state for upcoming winter precipitation amounts. La Niña events will typically bring below-average winter precipitation while El Niño events can bring either very wet or dry conditions depending on subtle variations in jet stream position and moisture availability. Also, note the high variability in precipitation during ENSO neutral conditions (green dots). Variability in winter precipitation is normally very high for Arizona due to its relatively unfavorable geographic position with respect to the mid-latitude winter storm track.

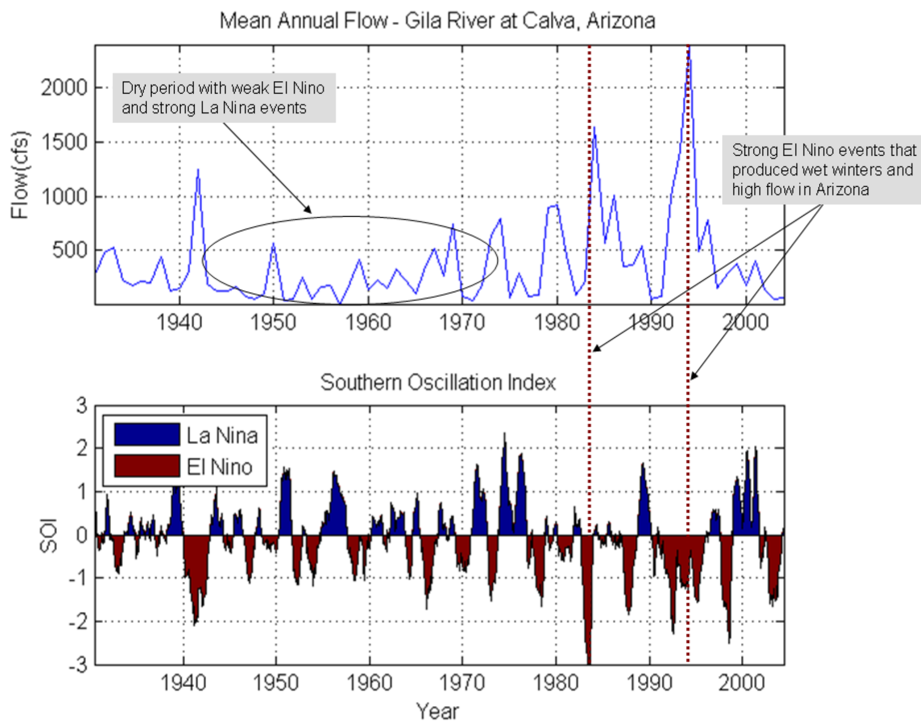


Figure 5. Mean annual Gila River flow at Calva and ENSO state.

Pacific Decadal Oscillation

The historical and reconstructed paleo-records for precipitation in Arizona show variability in precipitation at much longer timescales than the 2-7 year period characteristic of ENSO. Persistent multi-decade wet and dry periods are present throughout Arizona's climate records. The famous 1950's drought was a persistent dry period, while the latest period from the 1970's to late 90's was a persistent wet period. A potential culprit for this long-term variability in precipitation is a phenomenon called the Pacific Decadal Oscillation (PDO). The PDO manifests itself as decadal changes in sea surface temperature and circulation patterns in the north Pacific. During the positive (negative) phase of PDO, sea surface temperatures along the northern North American Coast are above (below) average with a stronger (weaker) persistent low pressure system in the Gulf of Alaska.

The phase of PDO is important to Arizona because of its apparent relationship with ENSO activity and broader atmospheric teleconnection patterns (Brown and Comrie 2004). An atmospheric teleconnection occurs when a meteorological event (e.g. thunderstorms associated with warm water during an El Niño event) induces a related atmospheric response (e.g. change in jet stream position and storm track) at a distant location. The teleconnection pattern of wet conditions during El Niño events tends to be stronger when the PDO is in its positive phase. The opposite is true during negative PDO, when the La Niña's dry winter teleconnection is more evident. There is controversy

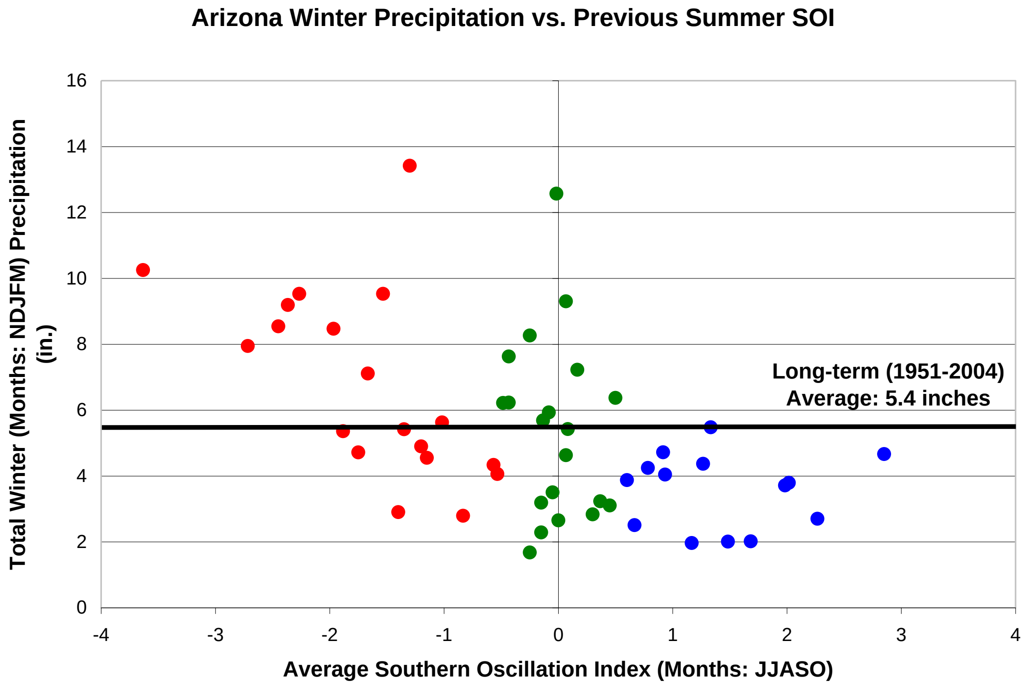


Figure 6. Scatterplot of Arizona statewide total winter precipitation versus previous summer ENSO state represented by the Southern Oscillation Index (SOI). Data points represent the period from 1951-2004. Red dots represent El Niño events, green dots neutral conditions, and blue dots La Niña events.

over the origin and mechanisms of PDO. There is growing consensus that PDO is nothing more than a long timescale reflection of ENSO variability in northern Pacific (Schneider and Cornuelle, 2005). Nonetheless, it does appear to represent a real phenomenon that affects winter precipitation across the southwestern United States. Many La Niña events and a negative PDO were present during the 1950's drought and may have been the cause of the persistent below average winter precipitation during that period.

Characteristics of precipitation in Arizona

Some of the major large-scale mechanisms that control winter and summer precipitation from year to year have been discussed, but not the nature of precipitation during each season. The intensity, duration, frequency and type of precipitation are all critical to how much water is available and when it is available for riparian processes. Wintertime precipitation is typically associated with large-scale circulation features like low pressure systems. These systems usually produce broad areas of precipitation at low intensities for extended periods of time (hours to days). Precipitation can often fall and accumulate as snow at higher elevation locations. These low-intensity, long-duration events can allow precipitation to infiltrate more deeply in areas with soil and reduce runoff rates. Snowfall is held in storage until melting occurs from the warm ground below or a combination of above freezing air temperatures and direct solar radiation. Melting from these mechanisms is typically slow and allows water to enter streams over extended period of time. It is not uncommon in Arizona for snow levels (elevation at which snow falls) to vary from storm to storm. One storm may bring heavy snowfall to an area and the next heavy rainfall. Accumulated snow can be rapidly melted during storms with heavy rainfall, producing large amounts of runoff and flooding.

Summertime precipitation, in contrast, is characterized by localized, high-intensity short-duration events. The North American Monsoon System pulls moisture into Arizona, creating an environment that is favorable for 'airmass' thunderstorms. Airmass thunderstorms are not initiated or focused by large-scale circulation features, but by small-scale topographic features. These convective thunderstorms can produce high rainfall rates (> 25 mm/hr), but are often short-lived (< 5 hours) and small in extent (< 10km wide). Watershed areas that receive rainfall from a convective storm can experience flash flooding that recedes quickly after the storm has dissipated.

Conclusions

Arizona's dramatic extremes in climate can be explained by its varying topography and unique geographic location. Spatial patterns in temperature and precipitation are strongly constrained by topography with highest elevations possessing the coolest and wettest climatic regimes in the state. Arizona's hottest and driest locations are in lowest parts of the state in the western deserts along the Colorado River. Most of the water available for streamflow in perennial streams originates in these upper elevation areas that receive the most precipitation. Winter precipitation in the form of snow is an especially important source of water through the spring and summer for streamflows and riparian vegetation.

Precipitation amounts can vary widely from year to year because of Arizona's location with respect to large-scale circulation features. A sub-tropical high pressure system with warm and sunny conditions can dominate the weather over the southwestern United States in almost every month of the year. Winter precipitation comes from low pressure systems that ride along a jet stream that is displaced south over Arizona. This type of storm system is relatively infrequent during most years. Summer precipitation is dependent on the strength and position of the expanded Bermuda high. If the high weakens or moves slightly during the summer season, the flow of moisture to Arizona can be cut off.

Variability in Pacific sea surface temperatures patterns can influence these large-scale circulation patterns important to Arizona precipitation mechanisms. This is especially true during the winter months when ENSO can influence circulation patterns that favor (El Niño) or hinder (La Niña) winter precipitation. These relationships can even persist for many years to decades, as shown by the effect of PDO on winter ENSO teleconnection patterns.

Arizona riparian areas are especially sensitive to the interannual climatic variability discussed above. Winter and summer precipitation amounts vary widely from year to year under 'average' conditions not influenced by ENSO activity. 'Normal' thunderstorm activity can bring extremely heavy rain and flooding to small watershed areas over the course of a summer, altering stream channels and impacting riparian vegetation. El Niño events can produce exceptionally wet winters beneficial to riparian areas, while La Niña winters are typically dry for Arizona and can negatively impact streamflows and riparian function. Years of persistent below-average winter precipitation are not uncommon in Arizona and are typically related to persistent La Niña events and long-term variability in the PDO. Drought conditions can negatively impact riparian areas by stressing vegetation and limiting or eliminating baseflows critical to maintaining riparian habitat.

References

Brown, D.P. and A.C. Comrie. 2004: A winter precipitation 'dipole' in the Western United States associated with multidecadal ENSO variability. Geophysical Research Letters 31 (doi:10.1029/2003GL018726).

Cole, J.E. and E.R. Cook. 1998. The changing relationship between ENSO variability and moisture balance in the continental United States. Geophysical Research Letters 25:4592-4532.

Schneider, N. and B.D. Cornuelle. 2005. The forcing of the Pacific Decadal Oscillation. Journal of Climate 18:4355-4373.

Sheppard, P.R., A.C. Comrie, G.D. Packin, K. Angersbach, and M.K. Hughes. 2002: The climate of the U.S. Southwest. Climate Research 21:219-238.

Woodhouse, C.A. 1997. Winter climate and atmospheric circulation patterns in the Sonoran Desert region, USA. International Journal of Climatology 17:859-873.

CHAPTER 7
Human Alterations to Riparian Areas
By George Zaimes

Introduction

Throughout history, riparian areas have been a main point of interest to humans and have always been used by humans. Many early and great civilizations developed along rivers, like the Egyptian along the Nile River. Even today many of the world's major cities are along rivers.

Native Americans also utilized riparian areas as transportation corridors and as a source of food like seeds, berries, wildlife, or fishes (NRC, 2002). The proximity of riparian areas to water made these areas easy sources of water and also shelters from the hot and dry conditions that Native Americans endured in most of the western United States.

In the southwestern United States before European settlers, small population densities led to minimal and localized impacts in riparian areas. However, the population of this region significantly increased during the 16th century when Spaniard settlers arrived (DeBano and Schmidt, 2004). This trend continued under Mexican rule and after the arrival of American settlers (Debano and Schmidt, 2004). Increases in population led to a significant increase in the use of riparian areas with negative impacts on their quantity and quality. In the United States, it is estimated that 66% of riparian areas have been converted to other land-uses, primarily that of agriculture (Swift, 1984). In some regions of the country it is reported that this loss is up to 95% (Brinson et al., 1981). Both these percentages suggest that the human impact has most severely affected riparian areas. In Arizona and New Mexico, the most common percentage mentioned is that as much as 90% of riparian forests have been lost because of various changes to land usage (Ohmart and Anderson, 1986). The fact is that nobody really knows the exact percentage of riparian areas lost in Arizona and New Mexico (Webb, 2006)

Water quality is another indicator of poor condition in a riparian area. Only 2% of all streams and rivers in the United States have high water quality (Benke, 2000). The Environmental Protection Agency (EPA) indicated that at least 485,000 km of streams and more than 2 million hectares of lakes in the United States do not meet water quality standards (EPA, 2000). Both estimates are considered to be conservative because of the lack of extensive monitoring on streams, rivers and lakes (NRC, 2001). The degraded condition of riparian areas is not surprising when you consider that 54% of the worldwide river runoff is used by humans (Postel et al., 1996).

There are many different types of human activities (Figure 1) that have caused major alterations to riparian areas. These primarily involve changes in hydrology, geomorphology and vegetation. The following review of the various human alterations on riparian areas was aided significantly by material drawn from 'Riparian Areas: Functions and Strategies for Management' (NRC, 2002) and 'Riparian Areas of the Southwestern United States Hydrology Ecology and Management' (Baker et al., 2004).

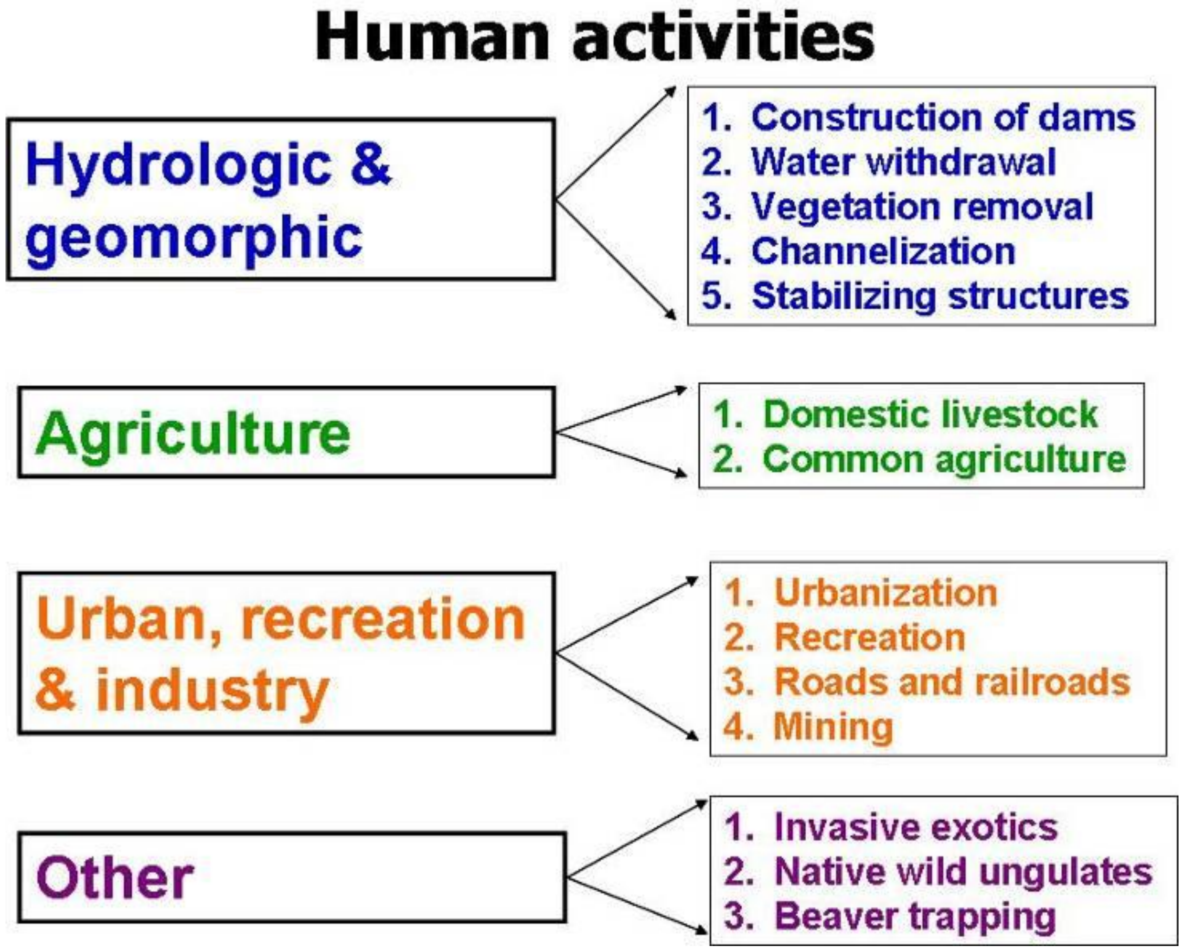


Figure 1. Different types of human activities that can cause alterations to riparian areas in Arizona (illustration by G. Zaimes).

Hydrologic and geomorphic alterations

Humans have long tried to regulate water resources to accommodate their water needs. In Arizona, the Hohokam started building canals as early as 300 A.D. and continued until the 1450 A.D. They built ~3,200 km of canals (Masse, 1981).

In the West, the increasing population of European settlers in the late 1800's led to heavy use and eventually regulation of water resources. Almost all rivers greater than ~1,000 km in length in the United States (except Yellowstone River in Montana) have been regulated in some way (Benke, 1990). In addition, 58% of rivers greater than ~200 km have also been regulated (Benke, 1990). These regulations include dams, levees, basin diversions and water removal for irrigation.

Typically, the regulation of watercourses leads to changes in the hydrology and sediment transport of streams (hydromodification) (Figure 2). Both upstream and downstream reaches as well as adjacent riparian areas feel the impacts. Examples of these impacts to adjacent reaches include flooding of the adjacent riparian areas with several feet of water that is transformed into a lake, changes in the timing and quantity of downstream flow, the magnitude of peak flows, and/or the stream sediment load.

Construction of dams

In the United States, there are currently 75,000 dams on streams and rivers (Meyer, 1996; Graf, 1999). In Arizona, there are 431 registered dams (Tellman et al., 1997) (Figure 3). These dams range in water storage capacity from 2 to 3,500,000 hectare-m (Tellman et al., 1997). Dams provide one or a combination of the following valuable uses: hydroelectricity, flood control and protection, water storage for irrigation, domestic and industrial uses, and recreation. In Arizona, Hoover (Figure 3) and Glen Canyon Dams are the two biggest dams.

The majority of construction of the dams took place during a short period of time (primarily the 1950's). The short time frame was the biggest problem for the riparian

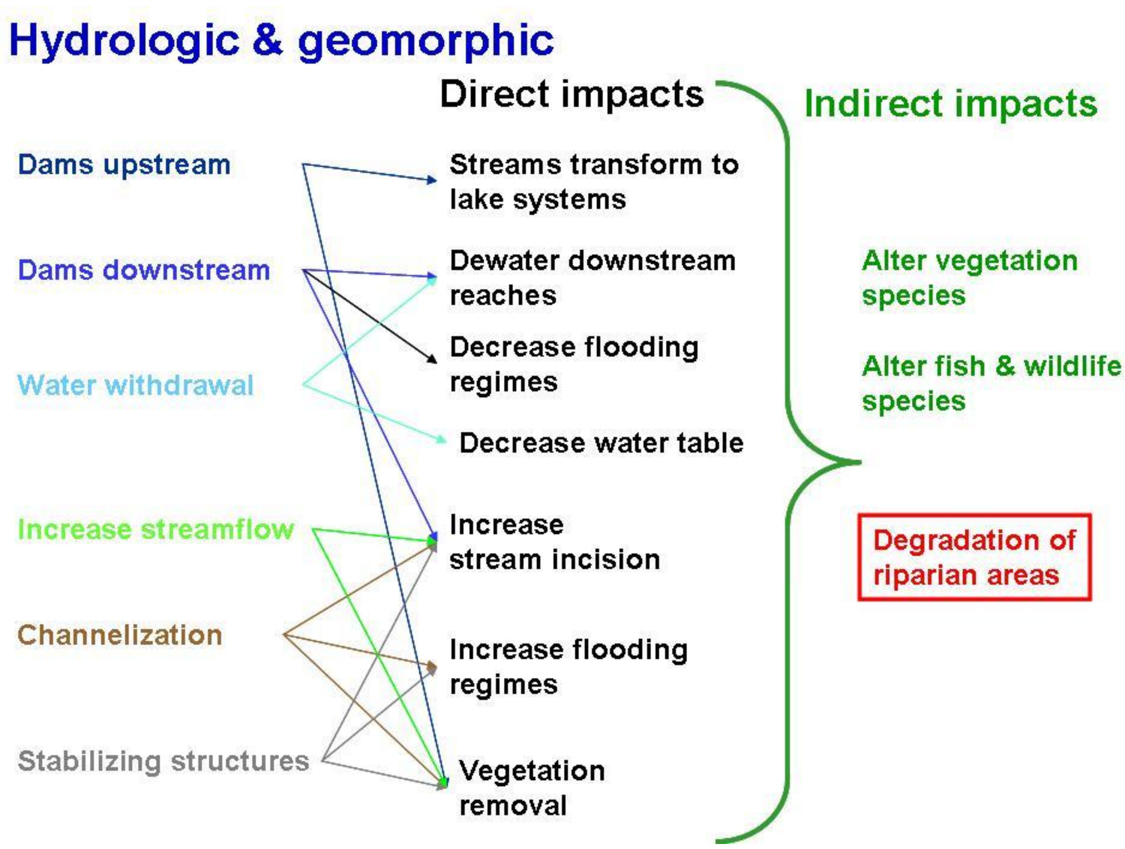


Figure 2. Direct and indirect impacts of different types of hydrologic and geomorphic alterations (illustration by G. Zaimes).

Figure 3. Arizona has many dams including the Hoover (left) and Imperial dam (right) (photos courtesy of USDA-NRCS photogallery).

vegetation because there was not enough time for the vegetation to adjust to the new flow river conditions (Dynesius and Nilsson, 1994). Impacts of dams are felt both upstream and downstream from the structure, though upstream impacts are typically easier to identify.

Upstream from the dam, the ecosystem shifts from a river to a lake ecosystem. In rivers, there is typically a narrow flowing watercourse while lakes are much wider with slow-moving water (DeBano and Schmidt, 2004). These two ecosystems have significant differences in aquatic species, hydrology and sediment dynamics (NRC, 2002). The water level of the lake is much higher than the old streams and the riparian vegetation of the stream is inundated and asphyxiated by the higher water level (Tellman et al., 1997; Wood and LaFayette, 1993). Fauna changes from wildlife terrestrial species and stream fishes to lake fishes. Stream banks are much more expansive and in many cases unstable because the floodplain vegetation has been eliminated (NRC, 2002). In addition, the new hydrologic condition along with the elimination of native riparian vegetation often promotes the invasion of saltcedar (*Tamarix* ssp. L.) and/or other invasive exotic plants (Tellman et al., 1997; Wood and LaFayette, 1993). Finally, the larger water surface of the constructed reservoir leads to higher evaporation rates compared to rivers (smaller surface area). It is estimated that from the Colorado River reservoirs, more than 250,000 hectare-m of water evaporates each year (DeBano and Schmidt, 2004). Overall, Brinson et al. (1981) says that 5% of the total length of the larger streams in the United States has been inundated by large reservoirs along with their associated riparian areas.

The impacts on downstream reaches of dams have recently been attracting more attention (Rood and Mahoney, 1991). The main problem downstream from dams is the substantial decrease in stream water flow, and particularly the decrease in peak flows, temperature and material transported. These changes lead to decreased plant, wildlife and fish biodiversity (Stanford et al., 1996). In dams where the water is used for consumptive uses (like irrigation, municipal or industrial uses), downstream reaches are dewatered or have much lower stream flows (Stromberg and Patton, 1990). Consumptive water use means that the water that is used is not returned back to its source or is returned to its source in a much lower quality. The decrease in stream flow induces stress on riparian vegetation. Although in some cases the quantity of water leaving the dam (used for flood control or hydropower) might remain similar, the pattern of river flow has changed (DeBano and Schmidt, 2004). Typically, dams reduce the magnitude of peak flows that are essential for the survival of certain plant or fish species. Water velocity behind dams is typically slow and as a result most sediment is deposited. The water released from dams is typically sediment starved and can cause bed degradation in the downstream reaches (NRC, 2002). In addition, native fish populations can be impacted because of changes in water temperature released from the dam (either colder or warmer). Increased evaporation of the reservoir can lead to salinity problems (DeBano and Schmidt, 2004).

Finally, another indicator of the impact of dam on riparian areas is the large number of threatened and endangered species that continue to increase in or along the large flow regulated rivers (Stromberg et al., 2004). In general, the smaller the size of the dam, the smaller the problems it will cause to riparian areas.

Withdrawing surface and ground water

Withdrawals of surface or ground water are very common in the western United States (NRC, 2002). This trend will continue to grow along with the population. This water is used for municipal, industrial or irrigation purposes, all typically consumptive water uses. The main surface water distribution system in Arizona is the Central Arizona Project (CAP) (DeBano and Schmidt, 2004). In this system 185,000 hectare-m of water are annually removed from the Colorado River, transferred and temporary stored in Lake Pleasant northwest of Phoenix. This water is transferred over 541 km of canals, tunnels, siphons and pipelines and raised up to 880 m with 14 pumping stations. The water is used primarily in the Phoenix and Tucson metropolitan areas. Another important surface water distribution system for the Phoenix area is the Salt River Project (SRP) that also provides electricity for this area.

Ground water pumping occurs throughout the state of Arizona. For this state, 60% of all water comes from ground water pumping. The extent of ground water pumping and the subsequent ground water decline in many areas of Arizona is extensive. In certain reaches of the Santa Cruz River as it passes through Tucson, the depth to ground water is more than 90 m (Stromberg et al., 2004). Many areas have had subsidence because of ground water pumping.

The decrease of shallow alluvial ground water along the streams has significant impacts on riparian vegetation. If the depth to ground water increases by more than 1 m, cottonwood trees experience leaf desiccation that can lead to branch dieback and even mortality (Scott et al., 1993). In addition, the lowering of ground water levels aids the invasion of exotic and drought tolerant species. An example in Arizona is the San Pedro River where the native Fremont cottonwood (*Populus fremontii* S. Wats). populations have declined, while the abundance of the invasive exotic saltcedar has increased, primarily because of the lowering of the ground water table (Stromberg, 1998).

Interestingly, withdrawals of surface waters can impact ground water and vice versa. Ground and surface water are interconnected. Reducing stream surface water by diversions or withdrawals increases the depth to ground water because of the decreased levels of ground water recharge from streams. Similarly, ground water withdrawals can lead to deeper water table levels that may cause streams to lose water to the ground water instead of gaining water from it. Surface and ground water withdrawals are two of the main reasons that many perennial streams and rivers in the western United States have been transformed into intermittent and ephemeral streams and rivers that cannot maintain healthy riparian vegetation (Luckey et al., 1988).

Riparian vegetation removal for stream flow

In the 1960's and 70's many experiments that manipulated vegetation were conducted to determine if stream flow could be increased downstream (Baker, 1999; Hibbert, 1979). Many of these experiments involved replacing riparian trees and shrubs with herbaceous vegetation. The primary idea was that riparian trees use a lot of water and compete with other water uses. By reducing riparian vegetation, the amount of water that transpires to the atmosphere is significantly decreased (NRC, 2002).

A classic example of the removal of water-loving vegetation is the Gila River in Arizona. Removal of vegetation started 50 years ago (Turner and Skibitzki, 1952). Initially, it was believed that water losses from riparian vegetation due to evapotranspiration were five times higher than river evaporation (Gatewood et al., 1950). Later studies found that this occurred only under specific conditions (Rowe, 1963). More recent studies have shown that open water can in some cases have higher annual water losses from evaporation than riparian trees and their associated evapotranspiration (Goodrich, 2005). In the southwest, vegetative manipulation to increase stream water flows is no longer a focus because of environmental concerns (Ffolliott et al., 2004). It is also essential to take into consideration that removal of riparian vegetation eliminates many of the benefits that the vegetation provides, like stabilizing the soils of the stream banks or providing shade, food and habitat for wildlife, fishes and other organisms in the stream.

Stream channelization

The process of channelizing streams includes the use of machinery in making the stream straighter, wider and deeper as compared to what the form of the natural stream was (Figure 3). Channelization is primarily done to protect from flooding for buildings and other structures along the stream/river. Because channelized streams are straighter, stream slope increases. The increase of the stream slope, width and depth leads to a higher capacity to carry water and sediment. These stream channels move more water and sediment downstream while also reducing flooding of the adjacent floodplains. Schoof (1980) estimated that in the United States, 322,000 km of streams were channelized before 1970. By using vegetative, bedrock and/or engineering structures to control the changes in the stream channel some of the impacts mentioned above and downcutting can be reduced (Skinner et al., 2000).

Channelization can cause direct and indirect impacts to riparian vegetation (NRC, 2002). The heavy machinery necessary to straighten, deepen and widen the channel destroys most riparian vegetation. In addition, deepening the channel increase the depth to the water table (Gordon et al., 1992) and reduces the frequency of out-of-bank flows that results in much drier stream banks (NRC, 2002). The drier conditions induce stress on the remaining riparian vegetation that was not destroyed by machinery. Streams also become more prone to flash floods because of the shorter water storage time in the channel and downstream reaches experience higher flood peaks that will increase stream bank and bed erosion. Flashier streams have high discharges for short periods of time after precipitation events. In general the water moves in a very short period of time through the stream channel leaving little to no water in the stream channel the rest of the time.

Finally, it is also important to not that once a stream is channelized maintenance is required. Streams even after they are channelized will try to go back to their natural channel pattern.

Structures to stabilize stream banks

Some artificial, structural approaches to protect or increase stream bank stability include riprap, concrete (Figure 3), dikes, fences, asphalt, gabions, matting and bulkheads. Their main purpose is to protect stream banks, buildings, and other structures along the streams from flooding. Although these structures can be very effective, typically their negative impacts on riparian areas have been ignored (Sedell and Beschta, 1991; Fischenich, 1997). By using structural approaches, any microhabitat for riparian vegetation is eliminated (NRC, 2002). In addition, flow velocities of the stream increase because these structures have lower hydraulic roughness compared to vegetated banks. The elimination of riparian vegetation can impact the in-stream ecosystem because the vegetation provides benefits such as shade and organic matter, a significant food source for in-stream organisms. These artificial structures can also cause problems to the animals that

Figure 3. Stream channelization and bank stabilization structures along two rivers in Arizona (photos courtesy of G. Zaimes (left) and D. Green (right)).

use riparian corridors as transportation routes (Buech, 1992). Ohmart and Anderson (1978) found that undisturbed rivers had double the number of bird species as compared to rivers with artificial structures along their stream banks.

Agriculture

In the past, riparian trees were not considered a valuable resource to maintain on stream banks and the floodplain (Illhardt et al., 2000). As a result, riparian trees were removed to accommodate other uses considered more valuable. In the southwest, in addition to removing trees to increase stream flow, riparian trees were removed and in some cases converted to other plant species, for agricultural crops and grazing livestock (Figure 4).

Domestic livestock

Domestic livestock grazing is one of the most traditional land-use practices in the southwest. Its origin dates as far back as the 16th century (DeBano and Schimdt, 2004). In 1891, the livestock industry was flourishing in Arizona with an estimated 1.5 million cattle and 700,000 sheep (Wilderman and Brock, 2000; Sayre, 1999). Twenty years before, the number of cattle in Arizona was estimated at only around 40,000 (Sayre,

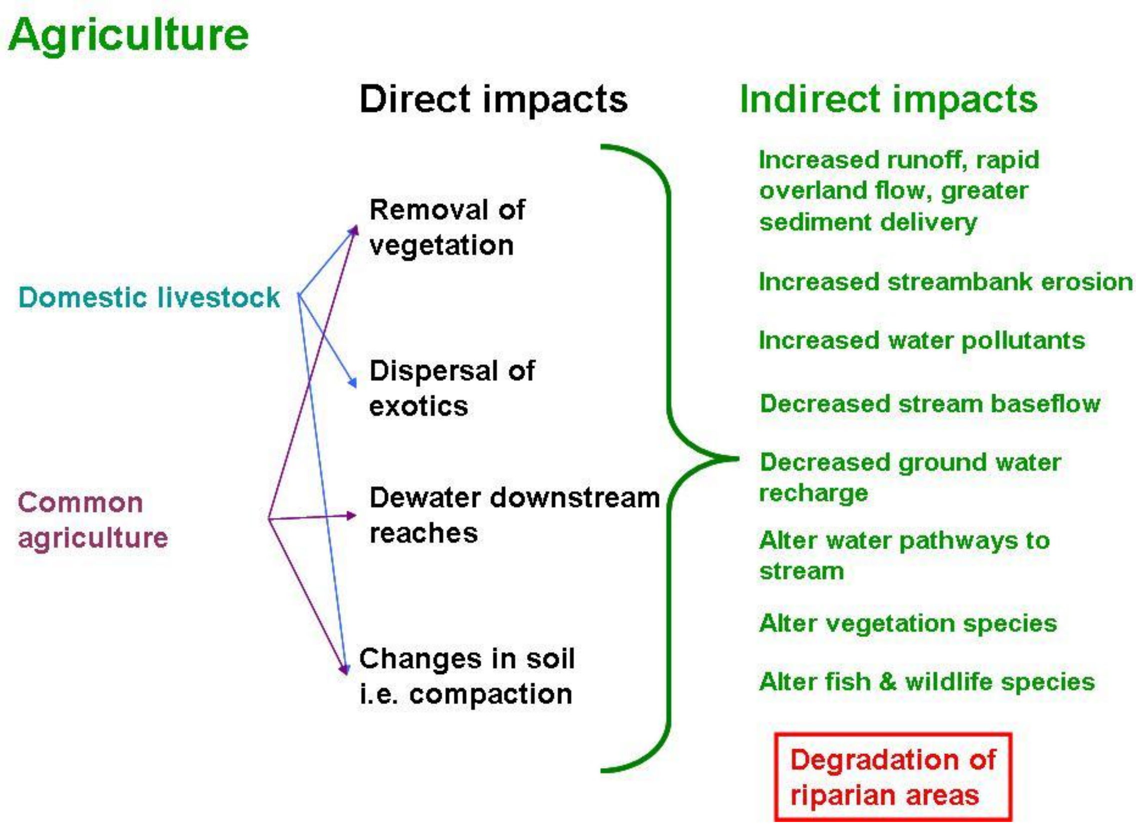


Figure 4. Direct and indirect impacts of different types of agricultural alterations (illustration by G. Zaimes).

1999). The great number of livestock in 1891 that exceeded the grazing capacity of Arizona and the inexperience the new settlers had with grazing in arid ecosystems led to overgrazing impacts to riparian areas and rangelands in general. These impacts were even more accentuated because of drought conditions that occurred at the same time. By 1893, 50 to 75% of the cattle had perished (Sayre, 1999). In the late 19th century, 30% of the San Carlos Reservoir was filed with eroded sediment (Tellman et al., 1997). One of the main reasons for excessive surface and channel erosion was overgrazing although homesteading and dry land farming also contributed to the siltation of the reservoir.

Today, ranching still accounts for a significant portion of the agricultural economy of Arizona (approximately 25%) (Ruyle et al., 2000). Livestock grazing, in particular, is implicated as a significant factor in the degradation of riparian areas in the western United States (Ohmart, 1996; Belsky et al., 1999). Domestic livestock are more attracted to riparian areas (Roath and Krueger, 1982; Szaro, 1989) for the same reasons that wildlife prefers riparian areas including high forage abundance (Pinchak et al., 1991) and water availability (Ames, 1977). In recent years in the southwest, many legal actions have been taken to reduce livestock grazing on public lands primarily in riparian areas (Cartron et al., 2000).

Livestock grazing directly impacts riparian areas through removal of vegetation by grazing and browsing or trampling vegetation and soil (NRC, 2002) (Figure 5). Excessive forage removal by livestock can lead to changes of plant and animal structure, composition and productivity of the riparian area (Ryder, 1980; NRC, 2002). In contrast, removal of some forage in riparian areas can lead to increased forage production (Heitschmidt, 1990). Removal of excessive vegetation can also have indirect impacts such as the alteration of nutrient distribution in the soils (NRC, 2002) as well as giving a competitive edge to exotic plant species that are unpalatable to livestock (Cartron et al., 2000; NRC, 2002). Heavy hoof action causes trampling that results in soil compaction by decreasing the soil macropore space and reducing infiltration that can increase runoff and sediment yield (Bohn and Buckhouse, 1985). In addition, soil compaction inhibits root growth and subsequently plant growth (Bohn and Buckhouse, 1985). Stream bank vegetative cover and trampling can heavily influence stream morphology and stream bank erosion potential, particularly in small streams (Clary and Leininger, 2000). Riparian pastures with high grazing intensities experience accelerated stream bank erosion (McInnis and McIver, 2001). Although livestock can be detrimental to riparian areas, more recent studies indicate that with proper management, livestock grazing can be compatible with healthy riparian areas (Cartron et al., 2000; Larsen et al., 1997).

Many grazing problems are due to improper livestock distribution (Holechek et al., 2000; Severson and Medina, 1983) that is an even greater problem for riparian areas because of the existing water, shade and forage abundance (Stuth, 1991). To maintain healthy, functional riparian areas, the amount of time that livestock spend in riparian areas needs to be controlled. Proper livestock distribution can be achieved by providing off-stream water sources placed in strategic locations (Miner et al., 1992). One of the major reasons cattle spend less time in upland areas is the greater distance to drinking water (Smith and Prichard, 1992). Another way to have livestock spend less time in riparian areas is by

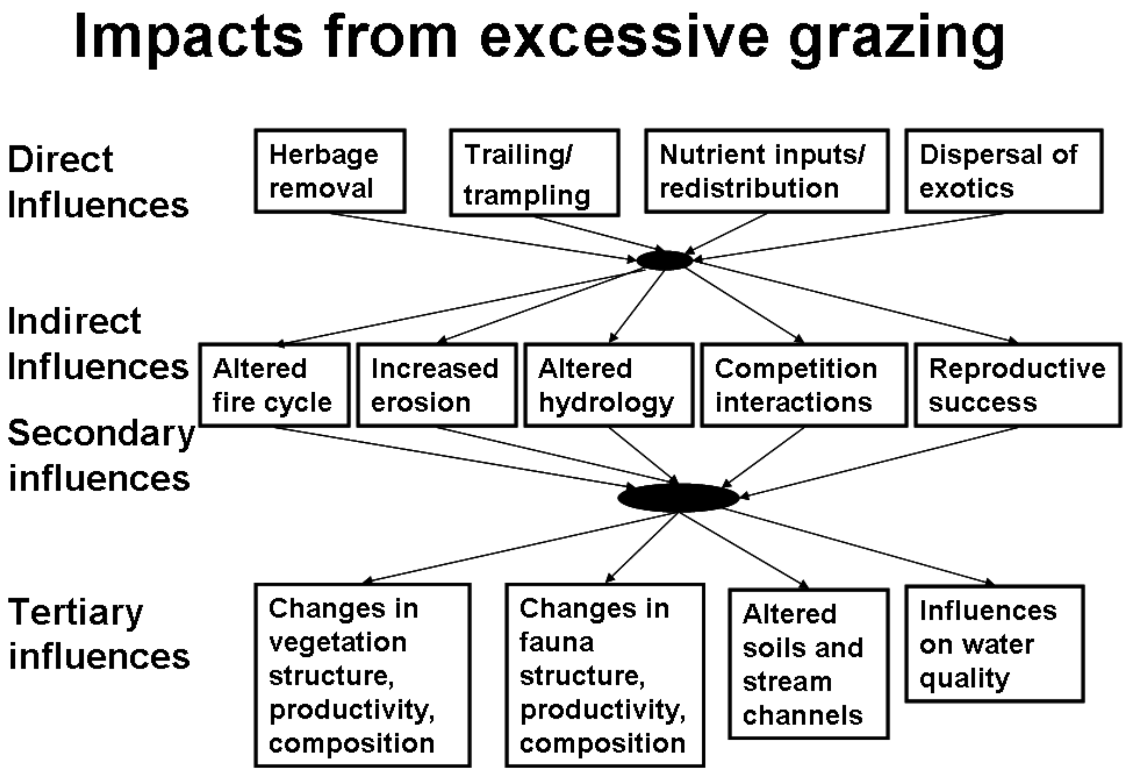


Figure 5. Direct and indirect impacts from excessive grazing (illustration by G. Zaimes; based on Kaufman and Kyle, 2001).

also placing supplements in strategic locations in the uplands and herding livestock out of riparian areas. The number of animals and period of time they graze the rangeland can lead to different impacts on riparian areas (Skovlin, 1984; Clary and Webster, 1989). The proper number of livestock will depend on the potential and resiliency of the riparian area. Most problems will occur with overgrazing. Overall conservative (moderate to low) stocking rates have been scientifically proven to be the best grazing approach in maintaining and improving rangeland conditions (Holechek et al., 1994; Martin and Cable, 1974). In some cases rotating pastures can also minimize grazing impacts. Finally, many have suggested that riparian pastures should be grazed only during specific seasons when the livestock would have the minimal impact on these areas and their vegetation.

Common agriculture

Dillaha et al. (1989) suggests that nationwide, agriculture has been responsible for the greatest decline in the quantity and quality of riparian areas. Riparian areas, especially in lowlands, have very fertile soils that are ideal for agriculture (NRC, 2002). In addition, these areas typically have plenty of water for irrigation that is in close proximity. As a result, many riparian areas have been converted to agricultural uses.

The major direct change when a riparian area is converted into an agricultural area is the change in vegetation. In natural settings, riparian vegetation protects soils from rain splash, overland flow and stream bank erosion (Schultz et al., 2000). In addition, it provides habitat and food for wildlife. Riparian vegetation has deeper and more extensive root systems compared to most agricultural crops. The heavy machinery used for tilling in agricultural fields compacts soils and alters the soil structure. As a result, areas with natural riparian vegetation have higher soil porosity and infiltration while areas with agricultural crops have higher overland flow and sediment production (Menzel, 1983). This can lead to more and higher peak flows resulting in subsequent flooding downstream. Increased flows in the stream channel in turn, increase stream incision and stream bank erosion. Although more peak flows occur, base flow decreases because the water is moving very fast out of the watershed. These changes alter the local hydrologic cycle and have transformed many perennial streams to intermittent or ephemeral streams.

Indirectly, agriculture impacts riparian areas because of irrigation requirements that lead to significant water withdrawals from streams (the impacts on riparian areas of water withdrawal have been discussed in a previous section).

Although common agricultural practices can be very detrimental using best management practices can decrease the impacts on riparian areas. Some of these best management practices include: riparian forest buffers, grass filters, terraces, no till farming, strip cropping, grassed waterways, and more efficient irrigation methods (drip irrigation) that use less water.

Urban, recreation and industrial impacts

The growth of human population in urban areas has put even more pressure on riparian areas because of their multiple uses in addition to the more traditional agriculture uses. Riparian areas are very commonly used for residential areas and recreation (Figure 6). In addition, the increase in population has increased the need for transportation routes and industrial uses (Figure 6). Industry can use and degrade significant amounts of water withdrawn from ground or surface water sources.

Urbanization impacts

The population of Arizona has doubled in the last 15-20 years and is expected to double again by the year 2040 (Department of Commerce, 2005). Most of this increase has and will continue to lead to the expansion and creation of urban areas.

In urban settings, riparian vegetation is typically completely removed or significantly decreased, altering the functionality of riparian areas. Urbanization also increases the amount of impervious area of a watershed. This includes the surface area now covered with homes, buildings, roads, sidewalks and parking lots that eliminate infiltration (Figure 7). Most precipitation becomes overland flow that leads to more and higher discharge volumes and flooding events (Figure 7). Gutters, culverts, stormwater sewers and line channels enhance overland flow, as these structures are excellent for water conveyance to streams and increase the speed that water reaches the stream (NRC, 2002).

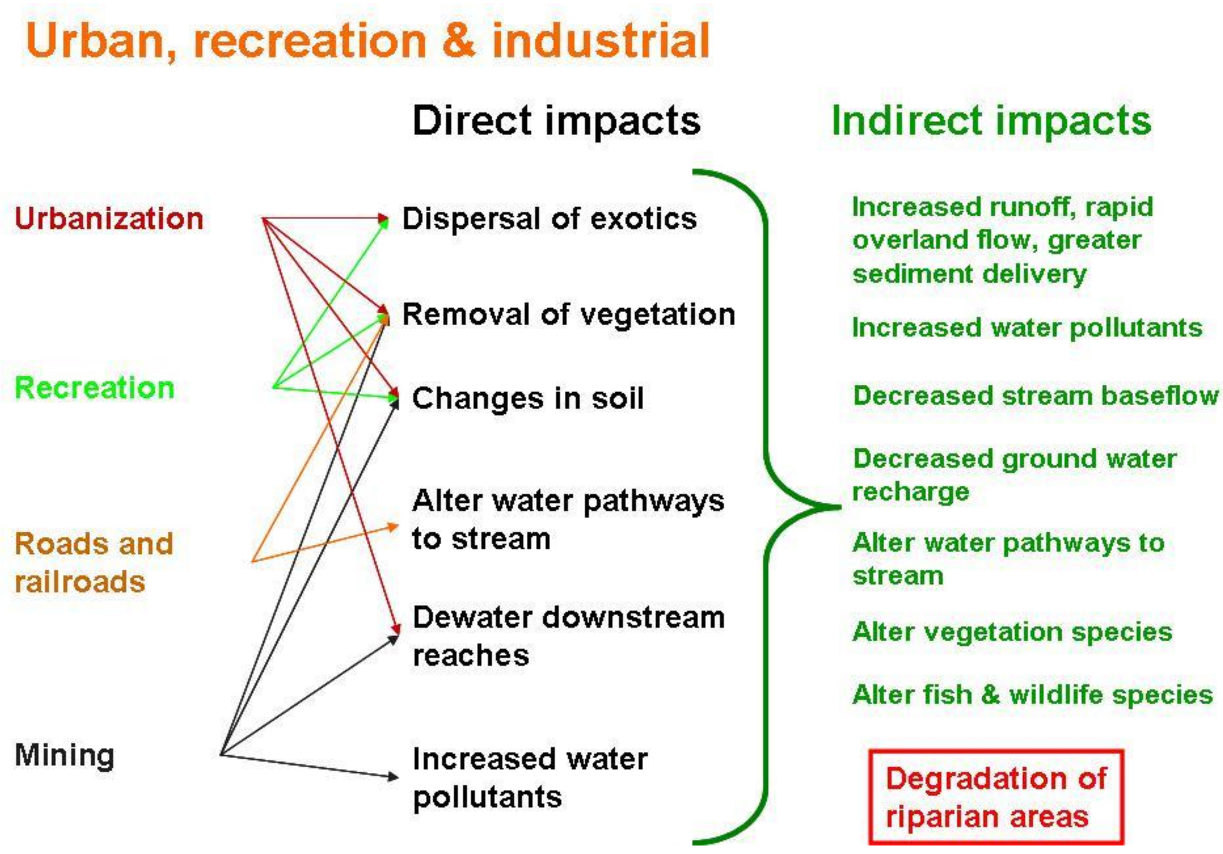


Figure 6. Direct and indirect impacts of urban, recreation and industrial alterations (illustration by G. Zaimes).

In Los Angeles, California in 1930, less then 10% of rainfall became stormwater (Drennan, et al., 2000). In 1990, the percentage of rainfall that becomes stormwater was almost 90% (Drennan, et al., 2000). Decreased infiltration leads to decreased ground water recharge, reducing the overall ground water contribution to the stream and eventually resulting in decreased base flow. Higher discharge volumes and flooding events lead the stream to a state of disequilibrium and channel instability. This results to accelerated stream incision and bank erosion and habitat degradation. Accelerated stream incision and bank erosion are also enhanced because sediment loads that reach the stream from overland flow in urbanized areas can in some cases decrease one to two orders of magnitude as compared to pre-development conditions (Schueler, 1987).

In addition, streams can have increased loading of nutrient, bacteria, oil, grease, salts, heavy metals, and other toxics resulting from overland flow of impervious urban surfaces that leads to decreased water quality. Some researchers state that when the percent of total impervious surfaces becomes 20-25% of the total watershed area the stream habitat is classified as poor (Booth and Jackson, 1997). These changes, along with stream water temperature increases (no riparian shading), lead to significant declines in native fish and aquatic diversity (NRC, 2002). Of course, many of these negative effects can impact

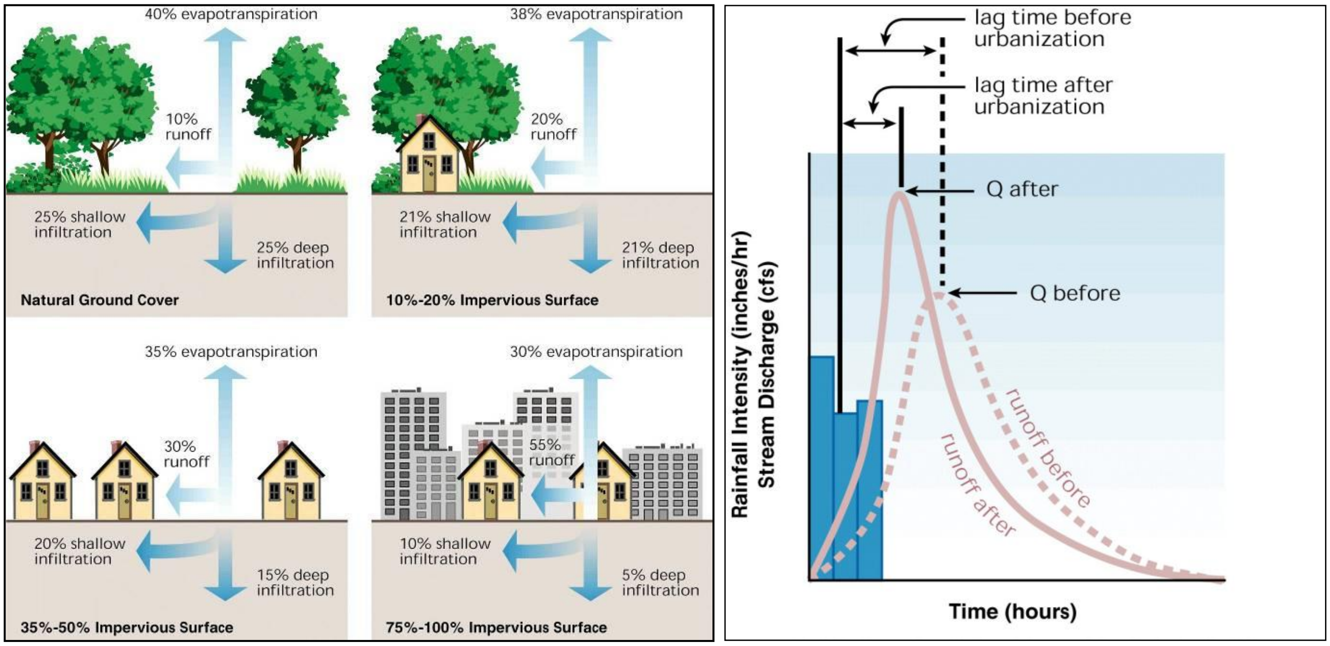


Figure 7. As impervious surface area increases in urban areas so does runoff (left graph). The increase in runoff leads to increased stream discharge (right graph). Base flow is not shown in this hydrograph (graph right) [from "Stream Corridor Restoration: Principles, Processes, and Practices, 10/98, by the Federal Interagency Stream Restoration Working Group (FISRWG)].

stream reaches and riparian areas several miles downstream or upstream from urban settings.

However, the actual impacts of urbanization will depend on the types of the development. Urban areas that are more lightly developed with parks, trails, ball fields, grassed or cobble waterways, and also maintain large functional riparian areas will have significantly less negative impacts. It is also important to have stormwater best management practices in urban settings that can include: infiltration systems, detention basins, minimization of impervious surfaces, and dispersion of the concentrated flow to green areas. Detention basins are used frequently as part of many new subdivisions in the southwest. Most detention facilities in the southwest are dry basins meaning that they only contain water following after a runoff event. These basins have been effective in reducing, but not eliminating increased peak flows associated with urbanization. These types of urban developments will not only mitigate negative impacts on riparian areas but also enhance the appeal and marketability of the urban developments. Of course, the protection of riparian areas is more difficult in many already developed urban areas that have had traditional planning.

Recreational activities

A significant increase in the urban population as compared to the rural population is an important trend in the state of Arizona. Urban and rural communities have different opinions on public and state land values (Kennedy et al., 1995). Larger urban population leads to a significant increase in recreation-oriented values for public and state riparian areas. As a result riparian areas need to support a greater number of recreational activities. Recreational activities in riparian areas include hiking, cycling, golfing, horse-back riding, bird watching, picnicking, camping, fishing, hunting, swimming, rafting, boating and off-road vehicular traveling.

Riparian vegetation is eliminated completely through the construction of certain recreational amenities such as boat ramps, fishing access points, golf courses, campsites trails and roads (NRC, 2002) (Figure 8). In addition, these structures can impact the hydrology and functionality of riparian areas. Golf courses use large amounts of water, fertilizers and pesticides to maintain turf. Irrigation consumes significant amounts of stream water while fertilizers and pesticides can negatively impact water quality (NRC, 2002). Heavy human, animal and vehicle traffic can also destroy vegetation through trampling and can increase soil compaction (Figure 8). Waterbodies adjacent to recreational uses have increased loads of sediments, nutrients, bacteria, pesticides and petrochemicals either by direct recreational activities of indirectly because of an increase in overland flow due to recreational activities (Andereck, 1995).

Motorized boats and watercrafts cause in-stream problems such as water and noise pollution, increase stream bank erosion and sediment suspension that negatively impacts aquatic life (Garrison and Wakeman, 2000). Pollution, alteration and destruction of habitat, hunting and fishing, introduction of diseases or animals for recreational purposes can all cause reduction of native wildlife populations in riparian areas and the adjacent waterbodies (Cunningham, 1996; Knight and Gutzwiller, 1995). In Colorado, Stuber (1985) found a significant increase in trout populations and improved stream health of reaches that were fenced to recreationists and grazing. All terrain vehicles (ATV's) that have gained in popularity can be very detrimental to riparian areas by increasing soil compaction and erosion, destroying vegetation, disturbing wildlife and decreasing vegetation regeneration (Figure 8) (Webb and Wilshire, 1983; Bleich, 1988). Again, it is important to repeat that the degradation of riparian areas speeds the establishment of invasive exotic species (this is discussed in more detail in a following section). The conversion to invasive exotic species is further enhanced as people, motor vehicles, ATV's, horses, etc. act as vectors of dispersal for the invasive exotic species to disturbed riparian areas (Green, 1998).

Because recreation impacts are growing, certain tools need to be utilized to mitigate their negative impacts on riparian areas. Some of these tools could be:

1) education on proper use by recreationists,
2) monetary fines for recreationists that abuse riparian areas,
3) estimation and enforcement of proper capacity levels of humans for a specific recreational area.

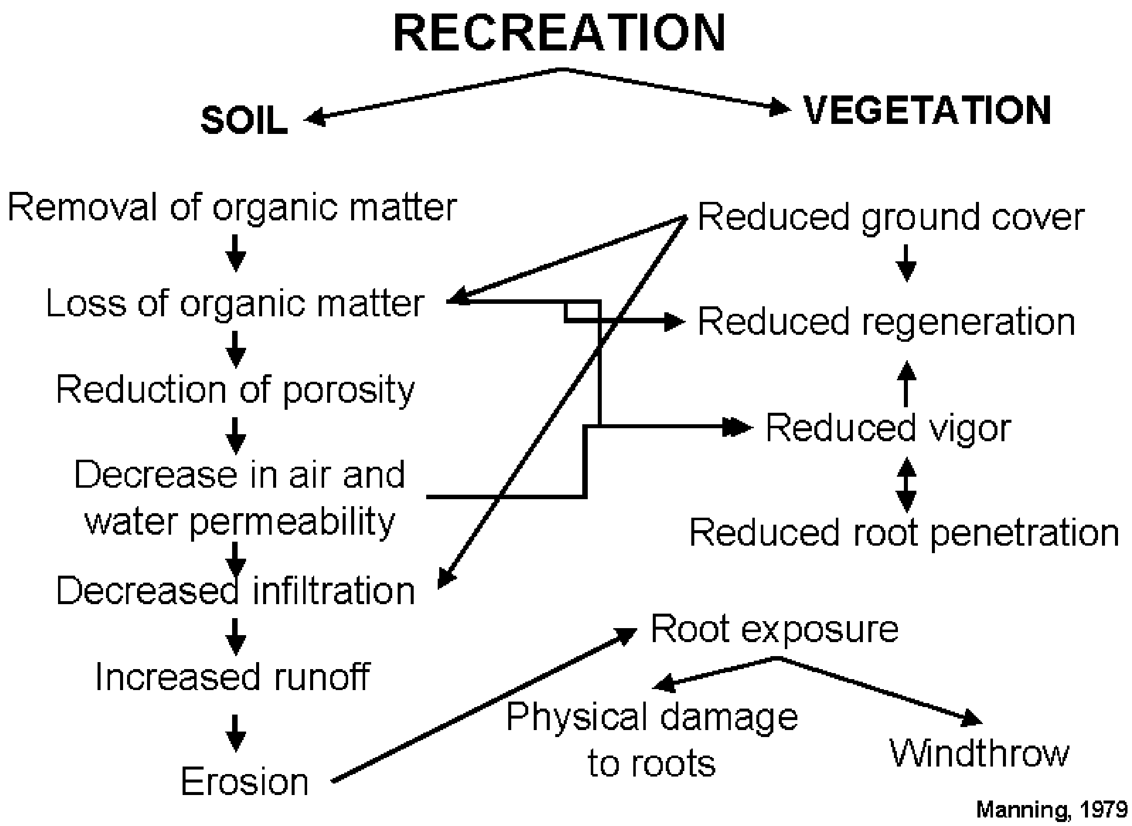


Figure 8. Impacts of recreation on soil and vegetation (illustration by G. Zaimes; based on Manning, 1979).

Figure 9. Impacts of all terrain vehicles (ATV's) on riparian areas (photos courtesy of D. Green).

Roads and railroads

Roadways, as our primary mode of transportation, can be found almost everywhere. Though significantly fewer in number, railroads can have impacts similar to those of roads. Many roads and railroads were constructed along streams because it was easier and more cost effective. Unfortunately, during their construction there was no consideration on the impacts to riparian areas. The placement of highways in riparian areas can have ecological impacts up to 100 m on each side of the road (NRC, 2002). These impacts include the removal of riparian vegetation and replacement with road pavement or gravel, alteration of topography and reduction in infiltration rates that will impact surface and subsurface flows. In addition, roads and railroads cross many rivers and streams that resulted in the construction of bridges and culverts (NRC, 2002). These structures eliminate future lateral adjustments of the stream. Stream naturally will shift it's channel through time. As a result the stream will always try to change and humans will always have to maintain these structures.

Roads can significantly impact riparian areas even when they are outside of the riparian area (Furniss et al., 1991; Adams and Ringer, 1994). When extensive road systems (example urban settings) are built, increased peak flows in streams are observed which in turn impact riparian areas. Water coming off roads is typically concentrated and can accelerate into channel and gully erosion. In addition, water flowing across these roads will carry substance (like pesticides, petrochemicals) to streams that would not naturally be found in streams. Finally, ditches along roads can also lead to the spread of invasive exotic species to riparian areas since these ditches can act as transportation corridors for dispersal of their seeds (Parendes and Jones, 2000).

Mining activities

In the early 1900's, mining was the largest industry in the state and Bisbee, Mammoth, San Miguel, and Tombstone were some of the most important mining cities (DeBano and Schimdt, 2004). The annual value of minerals such as gold, silver, lead, zinc, copper, and coal was at that time more than that of all the agricultural production. Although only a small percentage of the United States land has been mined (Starnes, 1983), these areas have caused major impacts on adjacent and downstream riparian areas (Nelson et al., 1991).

One major impact of mining was the removal of trees for fuel and for construction in mines (DeBano and Schimdt, 2004). In the valley bottoms, dredge mining removes not only all the vegetation but also several feet of soils (NRC, 2002). Mining operations also use substantial amounts of water either by surface water diversion and/or excessive ground water pumping (Debano and Schimdt, 2004). Gravel mining from stream terraces can lead to channel incision, degradation of riparian vegetation and influence ground water levels (NRC, 2002). In general, mining operations leave large areas of bare ground that increase overland flow and sediment production (NRC, 2002). These actions eventually change physical characteristics of the stream channel. In southeastern Arizona, in the Bonita Creek watershed, the stream was deeply incised up to 3.5 m, with

50% of topsoil lost. Today, Bermuda grass (*Cynodon dactylon* (L.) Pers.), is an invasive exotic species that covers most of the stream banks (Tellman et al., 1997). The main reasons for these impacts were mining, construction of water supply lines for Safford, timber harvesting and overgrazing. The impacts of these practices were further accentuated because of weather conditions.

In addition, mining operations have other direct impacts, like polluting the adjacent surface water and air. Acid mine drainage and waste piles of toxic metals like arsenic, lead, etc. are major water pollutants when exposed to surface or ground water (Nelson et al., 1991). An example of a single-event mining impact in Arizona is the spill of acidic water that contained 1,100 tons of uranium tailings in the Puerco River (Tellman et al., 1997).

Mining impacts can be significantly reduced with proper rehabilitation efforts although in some cases it is very difficult and/or expensive. When large areas of bare ground are exposed, well-designed detention ponds can significantly reduce overland flow and sediment to adjacent rivers and streams. Reclamation of these mined areas can also be much more successfully by removing stockpiling and reusing the topsoils of the areas.

Other human alterations

This last category includes alterations types that do not fit in any of the above three categories or into any general characterization. They are still important to discuss because of their significant impacts to riparian areas (Figure 10).

Invasive Exotic species

Species that are not native to an area or region are called exotics, although some can be native to other regions of North America. Not all exotic species are problematic, but some species aggressively out-compete local (native) species. If left unchecked, these invaders can actually eliminate native species from huge areas. Many species have been introduced intentionally while others came accidentally. These invasive exotic species are both plants and animals. Of the 22,000 plant species in the United States approximately 23% are considered exotic (Heywood, 1989). Riparian areas have some of the most aggressive invasive exotic plant species (Figure 10) (NRC, 2002). Along the Rio Grande River in New Mexico, Muldavin et al. (2000) estimated that 25% of the herbaceous plants are exotic and in tree species that percentage is up to 40%.

Invasive exotic species outcompete their native counterparts in many cases because of the lack of and/or minimal controls on their populations, including control by predation, parasites, or pathogens (NRC, 2002). Human disturbances (eg. reduction of flooding events, decreased water table) can also give a competitive edge to invasive exotic species. The replacement of native species with invasive exotic species can also be through predation, competition and/or by altering the natural ecosystem to be more favorable

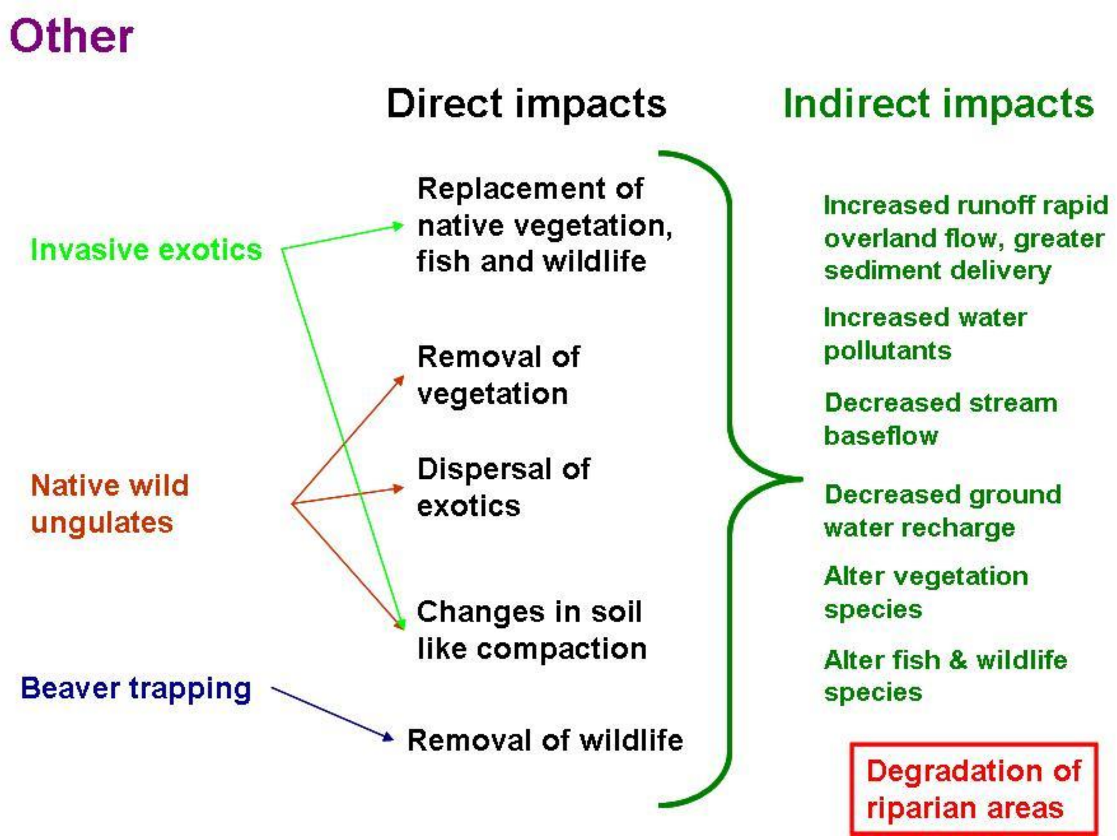


Figure 10. Direct and indirect impacts of invasive exotic species, excessive wildlife grazing and beaver trapping (illustration by G. Zaimes).

towards exotics than natives. A direct outcome of this phenomenon is that ecosystems with exotic species tend to be more homogeneous/monocultures (single species dominated) that have lower biodiversity. In addition, exotic plant species may also introduce toxic fruits that can be deadly for wildlife. One report puts invasive exotic species at the top of the list of contributors to the decline of the designated threatened or endangered species. Invasive exotics are responsible for up to 42% of the decline of these species (Wilcove et. al, 1998). Some of the most threatening invasive exotic plants in Arizona include: saltcedar (Figure 11), Russian olive tree (*Elaeagnus angustifolia* L.), tree of heaven (*Ailanthus altissima* (Mill.) Swingle), silktree (*Albizia julibrissin* Durazz.), purple loosestrife (*Lythrum salicaria* L.), Bermudagrass (*Cynodon dactylon* (L.) Pers.) (Figure 11), Johnsongrass (*Sorghum halepense* L.) Pers.), buffelgrass (*Pennisetum ciliare* L.) Link), Russian knapweed (*Acroptilon repens* (L.) DC.), Lehmann lovegrass (*Eragrostis lehmanniana* Nees), Eurasian watermilfoil (*Myriophyllum spicatum* L.), water hyacinth (*Eichhornia crassipes* Mart.) and cheatgrass (*Bromus tectorum* L.). The main invasive exotic animal invaders of Arizona include: American bullfrogs (*Rana catesbeiana*), virile crayfish (*Orconectes virilis*), small-mouthed bass (*Micropterus dolomieu*), bluegill (*Lepomis macrochirus*), sunfish (*Lepomis marginatus*), and channel catfish (*Ictalurus punctatus*). Saltcedar is a species of special interest in the arid and semiarid southwest that was introduced as an ornamental tree as well as a tool for erosion control. Between 1920 to 1987, the area that saltcedar occupied increased from 4,000 to

Figure 11. Major invasive species of riparian areas of Arizona are saltcedar (left) and Bermuda grass (right) (photos courtesy of G. Zaimes).

600,000 hectares (DiTomaso, 1998). It has spread vigorously in this region because it is more tolerant to high soil salinity and alkalinity and periods of drought (it develops deeper roots). Furthermore, the trees produce seeds for longer periods than native riparian species such as cottonwood, willow, or ash (Horton et al., 2001). The conditions favoring saltcedar have been established in many riparian areas due to ground water pumping that has dropped the water table significantly. The alteration of flow regimes with dams (reduced flooding events) along with livestock that have a preference for native trees has also been detrimental for the native willow and cottonwood populations. These activities have given a competitive edge to the saltcedar. Examples of areas now dominated by saltcedar in Arizona include Tonto Creek and the Lower Colorado River.

Some of the main activities to reduce invasive (noxious) weeds in Arizona include:

1) learning to identify invasive/noxious weeds that occur in your area
2) using weed free forage for livestock
3) cleaning all vehicles/equipment and inspecting clothing and pets before leaving an infested area
4) eliminating individual weeds before they become patches (Early detection/Rapid response)
5) pulling out small plant populations before they have flowered,
6) minimizing disturbances that negatively impact native species, and
7) maintaining native plant communities.

Native wild ungulates

Riparian areas have always been grazed. Many large ungulates like elk (*Cervus elaphus*), mule deer (*Odocoileus hemionus*), white-tail deer (*Odocoileus virginianus*) and pronghorn antelope (*Antilocapra americana*) have used riparian areas for grazing since before the arrival of European settlers. The native ungulates can cause similar problems to those of domestic livestock like removal of vegetation and trampling of plants and soil. Native wild ungulates can also disperse seeds of exotic plants and modify the stream channel (NRC, 2002) (Figure 5 and 10). Because they like to browse young seedlings or branches, these animals can hinder regeneration, suppress vigor and even cause mortality (Opperman and Merenlender, 2000). This typically occurs when animal populations explode due to the elimination of natural predators because of human intervention. Cottonwoods, willows and aspens have been eliminated or significantly reduced with limited regeneration because of browsing by elk and moose (*Alces alces*) in many national parks (Matson, 2000). The populations of elk and moose have been growing because of the extinction of bears (*Ursus ssp.*) and wolves (*Canis ssp.*), their natural predators (Berger et al., 2001) as well as the lack of regulation on hunting. To avoid problems with wild ungulates it is necessary to know the carrying capacity of the sites they occupy and try to control their population by various ways (eg. hunting).

In general, native wild ungulates cause less damage than their domestic livestock counterparts, although this is not always true. The main differences between wild ungulates and livestock are that when the forage in riparian areas decreases native wild ungulates can move to another riparian area (Meehan and Platts, 1978), or their numbers decline because of lack of food. We must not that in many cases there is a destructive lag period for the riparian area because of wild ungulate grazing that these areas might have to recover from. Wild ungulates are also better adapted to arid conditions and need less water as compared to domestic livestock (Nelson and Leege, 1982). On the negative side, wild ungulates are more difficult to manage and control in order to minimize use of riparian areas compared to domestic livestock. Although big native ungulates and domestic livestock compete for the same food there are indications that with proper management riparian areas can sustain both (Larsen et al., 1997).

Beaver trapping

In the mid 1800's trapping led to the almost complete elimination of beavers (*Castor canadensis*) in the Southwest (DeBano and Schimdt, 2004). Today, very few beavers exist on certain perennial rivers. Many scientists suggest that the significant reduction in beaver population has been very detrimental to riparian areas. Beavers are an important agent in riparian succession because they help in the expansion of the floodplains and structure diversity and productivity of the riparian community (Smith and Prichard, 1992). The removal of beaver dams has also led to loss of control structures, increased stream bank instability, and decreased water table. The latter change resulted in the elimination of stream side wetlands and the loss of large woody material downstream (Cartron et al., 2000). In contrast, others suggest that the removal of beaver has been beneficial. Riparian trees now grow without being eaten by the beavers or being damaged by floodflows after the beaver dams break (Wood and LaFayette, 1993). The importance or not that beavers have for riparian ecosystems is an ongoing debate.

Conclusions

Human activities that have led to the negative alteration of riparian areas began with the intentions of benefiting society. Still, these alterations have had significant impacts in the degradation of riparian areas. In Arizona, these alterations are even more important since there are fewer riparian areas.

In future projects, environmental assessments on the impacts to riparian areas should be obligatory (NRC, 2002). Projects should include ecological designs that protect or improve the health of riparian areas or minimize alterations to riparian areas in a cost-effective way. A monitoring component should also be established for these projects to allow for the detection of negative impacts within the riparian areas. It is also important to determine the acceptable conditions of riparian areas.

As the human population of the southwest grows, the number of users of riparian areas will continue to increase. It is essential to maintain functional riparian areas in order to provide services for all users.

References

Adams, P.W. and J.O. Ringer. 1994. The effects of timber harvesting and forest roads on water quantity and quality in the Pacific Northwest: Summary and annotated bibliography. Forest Engineering Department, Oregon State University. Corvallis, OR.

Ames, C.R. 1977. Wildlife conflicts in riparian management: Grazing. In: Importance and management of riparian habitat. USDA Forest Service General Report RM-43, Rocky Mountain Forest and Range Experiment Station, Ft. Collins, CO. pp. 39-51.

Andereck, K.L. 1995. Environmental consequences of tourism: a review of recent research. In: McCool, S. and A. Watson (eds.), Linking tourism, the environment, and sustainability. General Technical Report INT-GTR-323. USDA Forest Service. Ogden, UT. pp. 77–81.

Baker, M.B. (compiler). 1999. History of watershed research in the central Arizona highlands. General Technical Report RMRS-GTR-29. USDA Forest Service. Ft. Collins, CO.

Baker, M.B., P.F. Ffolliott, L.F. DeBano, and D.G. Neary (eds.). 2004. Riparian areas of the Southwestern United States Hydrology Ecology and Management. CRC Press. Boca Raton, FL.

Benke, A.C. 1990. A perspective on America's vanishing streams. Journal of the North American Benthological Society 9:77–88.

Belsky, A.J., A. Matzke, and S. Uselman. 1999. Survey of livestock influences on stream and riparian ecosystems in the Western United States. Journal of Soil and Water Conservation 54:419-431.

Berger, J., P.B. Stacey, L. Bellis, and M.P. Johnson. 2001. A mammalian predator-prey imbalance: grizzly bear and wolf extinction affect avian neotropical migrants. Ecological Applications 11:947–960.

Bleich, J.L. 1988. Chrome on the range: off-road vehicles on public lands. Ecology Law Review 15:159-187.

Bohn, C.C. and J.C. Buckhouse. 1985. Some responses of riparian soils to grazing management in northeastern Oregon. Journal of Range Management 38:378-381.

Booth, D.B. and C.R. Jackson. 1997. Urbanization of aquatic systems: degradation thresholds, stormwater detention, and the limits of mitigation. Journal of American Water Resources Association 33:1077-1090.

Brinson, M.M., B.L Swift, R.C. Plantico, and J.S. Barclay. 1981. Riparian ecosystems: their ecology and status. FWS/OBS-81/17. Office of Biological Services, United States Fish and Wildlife Service. Washington, DC.

Buech, R.R. 1992. Streambank stabilization can impact wood turtle nesting areas. Abstract in Proceedings of the 54th Midwest Fish and Wildlife Conference, December 6-9. Toronto, Canada.

Cartron, J-L.E., S.H. Stoleson, P.L.L. Stoleson and D.W. Shaw. 2000. Riparian areas. In: Jemison R. and C. Raish (eds.), Livestock management in the American Southwest: Ecology, society and economics. Elsevier Science. Amsterdam, Netherlands. pp. 281-328.

Clary, W.P. and B.F. Webster. 1989. Managing grazing of riparian areas in the intermountain region. General Technical Report INT-263. USDA Forest Service, Intermountain Research Center. Ogden, UT.

Clary, W.P. and W.C. Leininger. 2000. Stubble height as a tool for management of riparian areas. Journal of Range Management 53:562-573.

Cunningham, A.A. 1996. Disease risks of wildlife translocations. Conservation Biology 10:349-353.

DeBano, L.F. and L.J. Schmidt. 2004. Settings and history. In: Baker, M.B et al. (eds.), Riparian areas of the Southwestern United States Hydrology Ecology and Management. CRC Press. Boca Raton, FL. pp. 29-50.

Department of Commerce. 2005. Population and Demographics. Available at: http://www.commerce.state.az.us/prop/eir/popanddemo.asp (accessed 01-37-2005)

Dillaha, T.A., R.B. Reneau, S. Mostaghini, and D. Lee. 1989. Vegetative filter strips for agricultural non-point source pollution control. Transactions of the American Society of Agricultural Engineers 3:513–519.

DiTomaso, J.M. 1998. Impact, biology and ecology of saltcedar (*Tamarix* ssp.) in the southwestern United States. Weed Technology 12: 326-336.

Drennan, M, G. Moore, A. Lipkis, and S. Davis. 2000. How the impacts of urbanization are being addressed in the Los Angeles River watershed. In: Flug, M. and D. Frevert (eds.), Watershed 2000: Science and Engineering Technology for the New Millennium. American Society of Engineers. Reston, VA. CD-ROM.

Dynesius, M. and C. Nilsson. 1994. Fragmentation and flow regulation of river systems in the northern third of the world. Science 266:753–762.

Environmental Protection Agency (EPA). 2000. Atlas of America's polluted waters. EPA 840-B-00-002. U.S. Environmental Protection Agency, Office of Water. Washington, DC.

Ffolliott, P.F., L.F. DeBano, M.B. Baker, D.G. Neary, and K.N. Brooks. 2004. Hydrology and impacts of disturbances on hydrologic function. In: Baker, M.B. et al. (eds.), Riparian areas of the Southwestern United States Hydrology Ecology and Management. CRC Press, Boca Raton, FL. pp. 51-76.

Fischenich, J.C. 1997. Hydraulic impacts of riparian vegetation; summary of the literature. Technical Report EL-97-9. U.S. Army Corps of Engineers. Washington, DC.

Furniss, M.J., T.D. Roelofs, and C.S. Yee. 1991. Road construction and maintenance. In: Meehan, W. R. (ed.), Influences of forest and rangeland management on salmonid fishes and their habitats. Special Publication 19. American Fisheries Society. Bethesda, MD. pp. 297-323.

Garrison, P.J. and R.S. Wakeman. 2000. Use of paleolimnology to document the effect of lake shoreland development on water quality. Journal of Paleolimnology 24(4):369-393.

Gatewood, J.S., J.W. Robinson, B.R. Colby, J.D. Hem, and L.C. Halpenny. 1950. Use of water by bottomland vegetation in the Lower Safford Valley, Arizona. United States Geological Survey Water-Supply Paper 1103. United States Government Printing Office. Washington, DC.

Goodrich, D. 2005. Personal communication.

Gordon, N.D., T.A. McMahon, and B.L. Finlayson. 1992. Stream hydrology: an introduction for ecologists. John Wiley and Sons. Chichester, UK.

Graf, W.L. 1999. Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. Water Resources Research 35:1305-1311.

Green, D.M. 1998. Recreational impacts on erosion and runoff in a central Arizona riparian area. Journal of Soil and Water Conservation 53:38-42.

Heywood, V.H. 1989. Patterns, extents, and modes of invasions by terrestrial plants. In: Drake, J.A. et al. (eds.), Biological invasions: A global perspective, SCOPE 37. John Wiley and Sons. Chichester, UK.

Heitschmidt, R.K. 1990. The role of livestock and other herbivores in improving rangeland vegetation. Rangelands 12:112-115.

Hibbert, A.R. 1979. Managing vegetation to increase flow in the Colorado River Basin. General Technical Report RM-66. United States Department of Agriculture, Forest Service. Fort Collins, CO.

Holechek, J.L., A. Tembo, A. Daniel, M. Fusco, and M. Cardenas. 1994. Long term grazing influences on Chihuahuan Desert Rangeland. Southern Naturalist 39:342-349.

Holechek, J.L., R.D. Pieper, and C.H. Herbel. 2000. Range management: Principles and practices, 4th edition. Prentice Hall. Upper Saddle River, NJ.

Horton, J.L., T. Kolb, and S.C. Hart. 2001. Responses of riparian trees to interannual variation in ground water depth in a semiarid river basin. Plant Cell Environment 24:293-304.

Illhardt, B.L., E.S. Verry, and B.J. Palik. 2000. Defining riparian areas. In: Verry, E.S. et al. (eds.), Riparian management in forests of the continental eastern United States. Lewis Publishers. New York, NY. pp. 23-42.

Kauffman, J.B., and D.A. Pyke. 2001. Range ecology, global livestock influences. In: Levin, S. et al. (eds.), Encyclopedia of Biodiversity, Volume 5. Academic Press. San Diego, CA. pp. 33-52.

Kennedy, J.J., B.L. Fox, and T.D. Osen. 1995. Changing social values and images of public rangeland management. Rangelands 17:127-132.

Knight, R.L. and K.J. Gutzwiller (eds.). 1995. Wildlife and recreationists: coexistence through management and research. Island Press. Washington, DC.

Larsen, R.E., W.C. Krueger, M.R. George, M.R. Barrington, J.C. Buckhouse, and D.E. Johnson. 1997. Viewpoint: livestock influences on riparian zones and fish habitat: literature classification. Journal of Range Management 51:661-664.

Luckey, R.R., E.D. Gutentag, F.J. Heimes, and J.B. Weeks. 1988. Effects of future ground-water pumpage on the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. U.S. Geological Survey Professional Paper 1400-E. U.S. Geological Survey. Washington DC.

Martin, S.C. and D.R. Cable. 1974. Managing semidesert grass-shrub ranges: vegetation responses to precipitation, grazing, soil texture, and mesquite control. Technical Bulletin 1480. USDA. Washington, DC.Masse, W.B. 1981. Prehistoric irrigation systems in the Salt River Valley, Arizona. Science 214:408-415.

Matson, N.P. 2000. Biodiversity and its management on the National Elk Refuge, Wyoming. In: Clark T.W. et al. (eds.) Developing Sustainable Management Policy for the National Elk Refuge, Wyoming. Bulletin Series No. 104. Yale School of Forestry and Environmental Studies. New Haven, CT. pp. 101–38.

McInnis, M.L. and J. McIver. 2001. Influence of off-stream supplements on stream banks of riparian pastures. Journal of Range Management 54:648-652.

Meehan W. R., W. S. Platts. 1978. Livestock grazing and the aquatic environment. Journal of Soil and Water Conservation. 33:274–278.

Menzel, B.W. 1983. Agricultural management practices and the integrity of instream biological habitat. In: Schaller, F.W. and G.W. Bailey (eds.), Agricultural management and water quality. Iowa Sate University Press. Ames, IA. pp. 305-329

Meyer, J.L. 1996. Beyond gloom and doom: ecology for the future. Bulletin of the Ecological Society of America 77:785-788.

Miner, J.R., J.C. Buckhouse, and J.A. Moore. 1992. Will a water trough reduce the amount of time hay-fed livestock spend in the stream (and therefore improve water quality)? Rangelands 14:35-38

Muldavin, E., P. Durkin, M. Bradley, M. Stuever, and P. Melhop. 2000. Handbook of wetland vegetation communities of New Mexico. New Mexico Heritage Program. Albuquerque, NM.

National Research Council (NRC). 2001. Assessing the TMDL approach to water quality management. National Academy Press. Washington, DC.National Research Council (NRC). 2002. Riparian areas: functions and strategies for management. National Academy Press. Washington, DC.

Nelson J.R. and T.A. Leege. 1982. Nutritional requirements and food habits. In: Thomas J.W., Toweill D.E. (Eds.) Elk of North America: Ecology and Management. Stackpole Books. Harrisburg, PA. pp 323–367.

Nelson, R.L., M.L. McHenry, and W.S. Platts. 1991. Mining. In: Meehan, W.R. (ed.), Influences of forest and rangeland management on salmonid fishes and their habitats. Special Publication 19. American Fisheries Society. Bethesda, MD. pp. 425–457.

Ohmart, R.D. 1996. Historical and present impacts of livestock grazing on fish and wildlife resources in western riparian habitats. In: Krausman, P.R. (ed.), Rangeland wildlife. The Society for Range Management. Denver, CO. pp. 245-279.

Ohmart, R.D. and B.W. Anderson. 1978. Wildlife use values of wetlands in the arid southwestern United States. In: Greeson, P.E. et al. (eds.), Wetland functions and values: the state of our understanding. Proceedings of the National Symposium on Wetlands. American Water Resources Association. Minneapolis, MN. pp. 278-295.

Ohmart, R.D. and B.W. Anderson. 1986. Riparian Habitats. In Cooperrider, A.Y. et al. (eds.), Inventory and Monitoring of Wildlife Habitat. USDI, Bureau of Land Management. Denver, CO. pp. 169-199.

Opperman, J.J. and A.M. Merenlender. 2000. Deer herbivory as an ecological constraint to restoration of degraded riparian corridors. Restoration Ecology 8: 41-47.

Parendes, L.A. and J.A. Jones. 2000. Role of light availability and dispersal mechanisms in invasion of exotic plants along roads and streams in the H.J. Andrews Experimental Forest, Oregon. Conservation Biology 14:64-75.

Petersen, M. S. 1986. Levees and associated flood control works. In: Petersen, M.S. (ed.), River engineering. Prentice-Hall. Englewood Cliffs, NJ. pp. 422–438.

Pinchak, W.E., M.A. Smith, R.H. Hart, and J.W. Waggoner Jr. 1991. Beef cattle grazing distribution patterns on foothill range. Journal of Range Management 44:267-275.

Postel, S.L., G.C. Daily, and P.R. Ehrlich. 1996. Human appropriation of renewable freshwater. Science 271:785-788.

Roath, L.R. and W.C. Krueger. 1982. Cattle grazing influences in a mountain riparian zone. Journal of Range Management 35:100-104.

Rood, S.B. and J.M. Mahoney. 1991. Impacts of the Oldman River dam on riparian cottonwood forests downstream. Department of Biological Sciences, University of Lethbridge. Alberta, Canada.

Rowe, P.B. 1963. Streamflow increases after removing woodland–riparian vegetation from a southern California watershed. Journal of Forestry 61:365-370.

Ruyle, G.B., R. Tronstad, D.W. Hadley, P. Heilman, and D.A. King. 2000. Commercial livestock operations in Arizona. In: Jemison, R. and C. Raish (eds.), Livestock Management in the American Southwest: Ecology, Society and Economics. Elsevier Science, Amsterdam, Netherlands. pp. 379-417.

Ryder, R.A. 1980. Effects of grazing on bird habitats. In: DeGraff, R.M. and N.G. Tilghman, (eds.), Management of Western forests and grasslands for nongame birds. United States Department of Agriculture, Forest Service Intermountain Forest and Range Experiment Station. General Technical Report INT-86. Ogden, UT. pp. 51-66.

Sayre, N. 1999. The cattle boom in Southern Arizona: Toward a critical political ecology. Journal Southwest 41:239-271.

Schoof, R. 1980. Environmental impact of channel modification. Water Resources Bulletin 16:697-701.

Schueler, T.R. 1987. Controlling urban runoff: a practical manual for planning and designing urban BMPs. Metropolitan Washington Council of Governments. Washington, DC.

Schultz, R. C., J.P. Colletti, T.M. Isenhart, C.O. Marquez, W.E. Simpkins, and C.J. Ball. 2000. Riparian forest buffer practices. In: Garrett, H.E. et al. (eds.), North American agroforestry: An integrated science and practice. American Society of Agronomy. Madison, WI. pp. 189-281.

Scott, M.L., M.A. Wondzell, and G.T. Auble. 1993. Hydrograph characteristics relevant to the establishment and growth of western riparian vegetation. In: Morel-Seytoax, H. J. (ed.), Proceedings of the 13th Annual American Geophysical Union Hydrology Days Publications. Atherton, CA. pp. 237-246.

Sedell, J.R., and R.L. Beschta. 1991. Bringing back the "bio" in bioengineering. American Fisheries Society Symposium 10:160-175.

Severson, K.E. and A.L. Medina. 1983. Deer and elk habitat management in the Southwest. Journal of Range Management Monograph No. 2.

Skinner, Q.D., K.K. Crane, J.G. Hiller, and J.D. Rodgers. 2000. Wyoming – Watershed and riparian areas. University of Wyoming. Laramie, WY. pp. 112.

Skovlin, J.M. 1984. Impacts of grazing on wetlands and riparian habitat: A review of our knowledge. In: Committee on Developing Strategies for Rangeland Management, National Research Council, National Academy of Sciences, Developing Strategies for Rangeland Management. Westview Press, Boulder, CO. pp. 1001-1004

Smith, B. and D. Prichard. 1992. Riparian Area Management: Management Techniques in Riparian Areas. United States Bureau of Land Management. Technical Reference 1737-6. Denver, CO. pp. 43.

Stanford, J.A., J.V. Ward, W.J. Liss, C.A. Frissel, R.N. Williams, J.A. Lichatovich, and C.C. Coutant. 1996. A general protocol for restoration of regulated rivers. Regulated Rivers 12:391-413.

Starnes, L.B. 1983. Effects of surface mining on aquatic resources in North America. Fisheries 8:2-4.

Stromberg, J. 1998. Dynamics of Freemont cottonwood (*Populus fremontii*) and saltcedar (*Tamarix chinesis*) populations along the San Pedro River, Arizona. Journal of Arid Environments 40:133-155.

Stromberg, J.C. and D.T. Patten. 1990. Riparian vegetation instream flow requirements: a case study from a diverted stream in the eastern Sierra Nevada, California. Environmental Management 14:185-194.

Stormberg, J., M. Briggs, C. Gourley, M. Scott, P. Shafroth and L. Stevens. 2004. Human alterations of riparian ecosystems. In: Baker, M.B. et al. (eds.), Riparian areas of the Southwestern United States Hydrology Ecology and Management. CRC Press. Boca Raton, FL. pp. 99-126.

Stuber, R.J. 1985. Trout habitat, abundance, and fishing opportunities in fenced vs. unfenced riparian habitat along Sheep Creek, Colorado. In: Johnson, R. et al. (tech. coords.), Riparian ecosystems and their management: reconciling conflicting uses. General Technical Bulletin RM-120. United States Department of Agriculture Forest Service. Fort Collins, CO. pp. 310-314.

Stuth, J.W. 1991. Foraging behavior. In: Heitschmidt, R.K. and J.W. Smith (eds.), Grazing management: An ecological perspective. Timber Press. Portland, OR. pp. 65-83.

Swift, B.L. 1984. Status of riparian ecosystems in the United States. Water Resources Bulletin 20:223-228.

Szaro, R.C. 1989. Riparian forest and scrubland community types of Arizona and New Mexico. Desert Plants 9:70-138.

Tellman, B., R. Yard, and M.G. Wallace. 1997. Arizona's changing rivers: How people have affected the rivers. Water Resources Research Center Issue Paper #19, College of agriculture, University of Arizona. Tucson, AZ.

Turner, S.F. and H.E. Skibitzke. 1952. Use of water by phreatophytes in a 2000-foot channel between Granite Reef and Gillespie Dams, Maricopa County, Arizona. Transactions of the American Geophysical Union 33:66-72.

Webb, R.H. 2006. Personal communication.

Webb, R.H. and H.G. Wilshire (eds.). 1983. Environmental effects of off-road vehicles: impacts and management in arid regions. Springer-Verlag. New York, NY.

Wilcove, D.S., D. Rothstein, J. Bubow, A. Phillips, and E. Losos. 1998. Quantifying threats to imperiled species in the United States. BioScience 48:607-615.

Wilderman, G. and J.H. Brock. 2000. Grazing in the Southwest: History of land-use and grazing since 1540. In: Jemison, R. and C. Raish (eds.), Livestock Management in the American Southwest: Ecology, Society and Economics. Elsevier Science, Amsterdam, Netherlands. pp. 1-25.

Wood, M.K. and R.K . LaFayette. 1993. New Mexico’s riparian areas. New Mexico Wildlife 38: 20-26.

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