CHAPTER 4
Stream processes in riparian areas
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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

![Diagram](image)

**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).

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.
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)].


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 through 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 cohesionless, 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 (D50 is the median grain size of the channel sediment) (Illustration by D. Cantrel modified from Rosgen, 1996 ).](image)
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


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