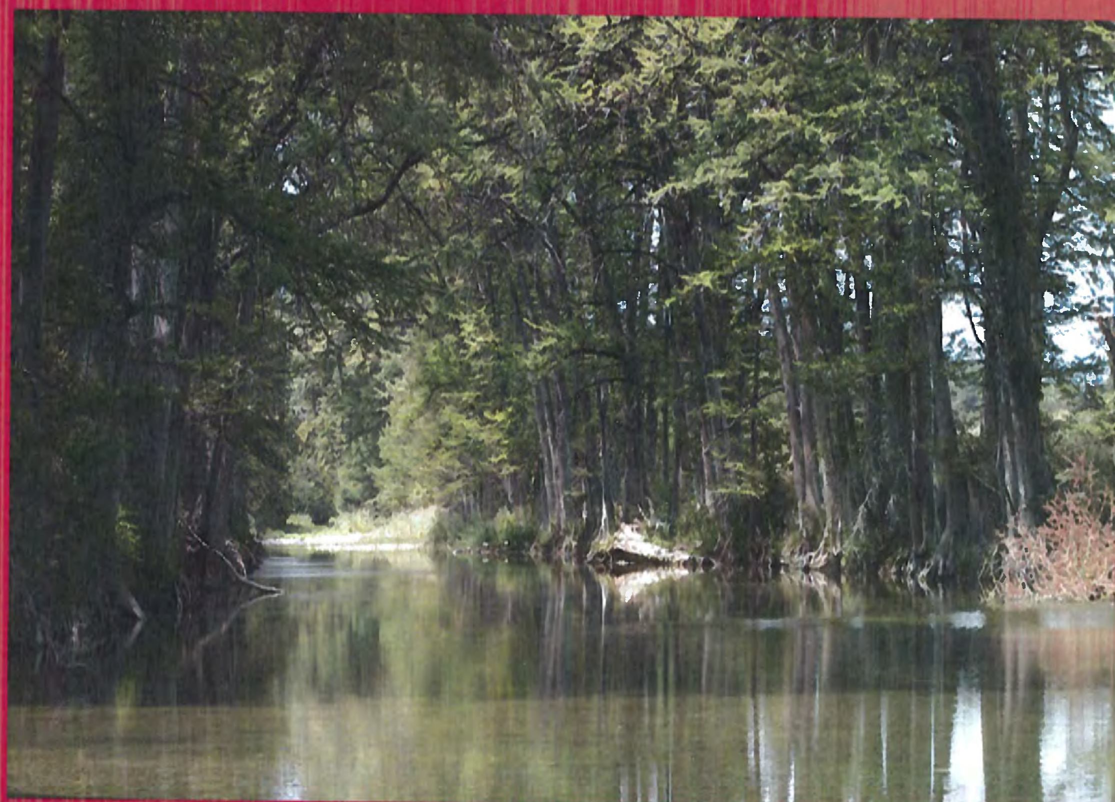
Texas Riparian Areas



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This book describes the physical setting of the river's edge environments in Texas. This corridor contains a diverse range of plant and animals, but we focused on the physical features of this environment. This book simplifies existing riparian jargon and provides definitions that will aid the Texas Instream Flow Program (TIFP) with setting high flow pulse and overbank flows that will maintain river edge health

EDITED BY

Dr. Thomas B. Hardy and Nicole Davis
Meadows Center for Water and Environment
Texas State University

June 1, 2013

TWDB Contract #1004831142

Final Report

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Preface

The physical environment of the river's edge has many hidden features that one does not normally notice. In this book, experts point out gradients and boundaries found in most riparian areas. With an understanding of these features, one hopes that a set of definitions will emerge that will assist land managers and the Texas Instream Flow Program (TIFP).

The book provides insights into riparian areas in the state of Texas as well as a hierarchical understanding of the physical setting of riparian corridors. It provides an overview of what government agencies are doing to protect or encourage people to protect this environment. The book also explains the physical landscape of the river's edge and addresses why Texas riparian areas have many unique characteristics. It also gives Texas river managers a set of terms to describe their riparian projects across multiple disciplines and across different river system boundaries.

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CHAPTER 1 - INTRODUCTION (MARK WENTZEL)

Riparian areas (also referred to as riparian zones or riparian floodplains) are complex transitional areas between aquatic environments of rivers and streams and terrestrial environments of upland areas. It's not surprising that descriptions and definitions of riparian areas differ, depending on the interests and perspectives of the observer. Watershed and land managers tend to focus on the differences between terrestrial and riparian areas. They recognize that management practices that are suitable for the rest of the landscape may not be suitable for riparian areas. From this perspective, the concept of a "buffer strip" (a portion of land of specified width) provides a quick and convenient way to define riparian areas and identify locations where upland land management practices are not suitable.

Water resource managers and river and stream ecologists focus on interactions between riparian areas and aquatic ecosystems. They view riparian areas as areas outside of the banks of the stream or river that are significantly influenced by flow conditions and, in turn, have a significant influence on environmental conditions within the stream or river. Land areas influenced by stream flows may be easy to distinguish as they often have plant communities that are different from those of surrounding terrestrial areas. Land areas that influence a river or stream (beyond simply providing contributing drainage area) may not be as easy to recognize. For example, areas of the valley bottom that provide spawning and rearing habitat for some fish species may only be covered with water during a portion of the year. During other times of the year, the importance of these areas to biotic conditions in the river may be much less obvious.

Over the years, people from different backgrounds and disciplines have developed many different ways to define and identify riparian areas. Different government programs focused on various types of riparian functions have continued this trend. Although this wide interest in riparian areas is warranted, an unfortunate outcome has been that communication about "riparian areas" between scientists, engineers, managers, regulators, policy makers, stakeholders and the public may often be garbled. In recent years, I've had the opportunity to observe and participate in many such conversations. Those conversations have involved concerned Texans from many professions and backgrounds and have frequently reminded me of the story of three old men sitting on a park bench. The first one says, "My, it's windy out here!" The second one says, "No, it's Thursday!" Finally, the third one says, "Me too. Let's get something to drink!" Unfortunately, when someone says "riparian area" in a crowd of Texans, it seems that we all hear something a little bit different.

The importance of clear communication about riparian areas in our state has never been greater. Our state has been blessed with abundant natural resources, but droughts make us aware of the impact of water scarcity on our environment, industries, and livelihoods. In the past, our natural resources, water management policies, and infrastructure were adequate to meet the needs of agriculture, industry, cities and the environment. In the future, the growing demands of industries and cities will make us more vulnerable to drought impacts (TWDB 2012). A recent publication by the National Academies of Science concluded that returning the hydrologic regime to a more natural state has the greatest potential for restoring degraded riparian areas (NRC 2002). In Texas, identifying and preserving key elements of the current flow regimes of rivers and streams would aid in preserving riparian areas and avoiding expensive restoration activities in the future. In coming years, careful management will be necessary to insure that Texans continue to enjoy the benefits of economic growth and healthy rivers, streams, and riparian areas.

While citizens of many regions around the world are being forced to make difficult and expensive decisions regarding the restoration of riparian areas, Texans are in the enviable position of still having many relatively healthy riparian areas. But we do need to take advantage of this opportunity and plan for the management of our water as it relates to riparian areas. This will require many conversations about what we mean by "riparian areas," why riparian areas are important to rivers and streams, how much of our riparian areas we want to preserve, and what flows are required to maintain those areas.

Recent actions by stakeholders, lawmakers, and government agencies have helped initiate many of these types of conversations across the state. These actions include passage by the Texas Legislature of Senate Bill (SB) 1 (1997), SB 2 (2001) and SB 3 (2007). SB 1 created a regionally based, stakeholder driven process for state water planning. The SB 1 water planning process develops plans "for the orderly development, management, and conservation of water resources and preparation for and response to drought conditions in order that sufficient water will be available at a reasonable cost to ensure public health, safety, and welfare; further economic development; and protect the agricultural and natural resources" (TWC §16.051 a). Plans are developed by Regional Water Planning Groups (RWPG) made up of representatives of stakeholders in each of 16 regions of Texas. This process has led to the development of Statewide Water Plans in 2002, 2007, and 2012, with revisions to be completed every 5 years in the future. Although RWPGs consider the water needs of the environment, the flow needs of riparian areas have not been mentioned specifically in any regional plan so far. One RWPG included a policy recommendation in the 2012 plan to "encourage riparian landowners to implement land stewardship practices" (TWDB 2012). Flows required to meet the needs of riparian areas could be considered in future plans as part of efforts by those groups to protect natural resources.

SB 2 created the Texas Instream Flow Program (TIFP) with a mandate of "determining flow conditions in the state's rivers and streams necessary to support a sound ecological environment" (§TWC 16.059 a). In recognition of the important contribution these areas make to river and stream ecosystems, state agencies involved in TIFP have agreed to consider flow requirements of riparian areas as part of "flow determinations for individual rivers and streams" (§TWC 16.059 d). In collaboration with local stakeholders, TIFP has developed study designs for priority river segments that included consideration of the flow requirements of riparian areas (TIFP & BRA 2010, TIFP & SARA 2012). In addition, TIFP has conducted research on methods to identify riparian areas in Texas (Miller et al. 2010) and quantify their flow requirements (Duke 2011, Moore and Alldredge 2011). An interim report for the lower San Antonio River includes consideration of the needs of riparian areas in flow recommendations (TIFP & SARA 2011).

Unfortunately, it may take many years for TIFP to complete instream flow studies for the entire state. In the meantime, as industries and cities grow, decisions need to be made regarding the use of the state's water resources. In recognition of this situation, SB 3 created a regionally based, stakeholder driven process to rapidly generate recommendations for environmental flows (both instream flows for rivers and streams and freshwater inflows to bays and estuaries). In the SB 3 environmental flows (E-Flows) process, regional Basin and Bay Expert Science Teams (BBEST) were selected by regional stakeholders (Basin and Bay Area Stakeholder Committees or BBASCs). The BBESTs were charged with using "the best science available" to make flow recommendations to meet the needs of the environment "without regard to the need for the water for other uses" (TWC §11.02362 m). BBEST recommendations are then considered "in conjunction with other factors, including the present and future needs for water for other uses related to water supply planning," by the BBASC (TWC §11.02362 n). Before adopting environmental flow standards for a basin and bay system, Texas Commission on Environmental Quality (TCEQ) considers recommendations of both the

BBEST and BBASC, human and other competing water needs, and other factors (TWC §11.1471 b). SB3 recognizes that "management of water to meet instream flow and freshwater inflow needs should be evaluated on a regular basis and adapted to reflect both improvements in science related to environmental flows and future changes in projected human needs for water" (TWC §11.0235 d-5). Therefore, the adopted standards may be reviewed and altered as additional information or results of studies become available.

The SB 3 E-Flows process has advanced the discussion of the flow needs of riparian areas in several ways. First, the underlying legislation recognizes that environmental flow recommendations "adequate to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats" are to be in the form of a flow regime, not a single minimum flow recommendation. Protection of a single, minimum flow is of limited benefit to riparian areas. As stated by Yuste and Santa-Maria (2008), "successful conservation of the biodiversity and functionality of riparian ecosystems depends on the ability to protect and restore the main aspects of the natural flow regime." SB 3 has moved the conversation in Texas beyond protection of a single flow (or two) and establishes a flow regime as the format for environmental flow standards. This format is at least compatible with the needs of riparian areas.

Second, as the SB 3 E-Flows process has progressed, scientists, stakeholders, and policymakers around the state have had many conversations about riparian areas and their flow needs. To date, seven BBESTs have provided reports documenting E-Flow recommendations (BBBEST 2012, CLBBEST 2011, GSABBEST 2011, NBBEST 2011, SNBBEST 2009, TSJBBEST 2009, and URGBBEST 2012). Each of these reports has mentioned riparian areas and their flow requirements as being considered by the expert science teams as they developed their recommendations. Two of the science teams quantitatively analyzed flows required to inundate riparian areas for at least some sites in their basins (CLBBEST 2011 and SNBBEST 2009). One group of experts on one science team did not recommend any specific high flow pulses or overbank flows to meet the needs of riparian areas, citing a lack of proven flow-ecology relationships specific to their region (TSJBBEST 2009). When examining two of their sites, the Upper Rio Grande science team did not find that a high flow pulse or overbank flow was necessary to maintain riparian areas at those sites (URGBBEST 2012). At all other sites (a total of 111 sites across 6 basin and bay systems of the state), the majority of expert scientists (65 of 72) recommended pulse flows in order to satisfy at least some of the needs of riparian areas. It appears that scientists and other experts around the state recognize 1) the importance of riparian areas to stream and river ecosystems, 2) that high flow pulses and overbank flows are required for the long term maintenance of riparian areas, and 3) that at least some flows should be protected in order to maintain riparian areas.

Five BBASCs have also submitted recommendations for E-Flows (BBBASC 2012, CLBBASC 2011, GSABBASC 2011, NBBASC 2012, and TSJBBASC 2010). Due to uncertainties created by a lack of site specific data, a sixth BBASC recommended that no E-Flow standards be adopted for their area (SNBBASC 2010a). Some committees declined to make recommendations for overbank flows. Concerns included potential liability created by flooding and limited time to make recommendations. Several committees also expressed confidence that suitable overbank flows will continue to occur without protection by standards. Nevertheless, four of six BBASCs (and a portion of a fifth) recommended at least some pulse flows be protected by E-Flow standards. Four BBASCs have also completed work plans (CLBBASC 2012, GSABBASC 2012, SNBBASC 2010b, and TSJBBASC 2012) describing information gaps and research topics that should be addressed in coming years in order to refine E-Flow recommendations. Topics related to the flow needs of riparian areas figure prominently in all four of these work plans. It appears that stakeholders across the state recognize 1) the importance of riparian areas to stream and river ecosystems, 2) that high flow pulses and overbank flows are required for the long term maintenance of riparian areas, and 3) that at least some pulse flows should be protected in order to maintain riparian areas.

A third way the SB 3 E-Flows process has sparked conversations about riparian areas is through the rule making process that TCEQ followed in developing standards to protect environmental flows. As part of that process, TCEQ received public comment on proposed flow standards. At the present time, comments have been received regarding standards for four areas (Sabine-Neches, Trinity-San Jacinto, Colorado-Lavaca, and Guadalupe-San Antonio). Comments were received from more than 75 organizations and 5,000 individuals. It is difficult to know the exact number of comments that included references to riparian areas, but TCEQ staff summaries of those comments include several references to riparian areas (TCEQ 2012a, TCEQ 2011). The comments that mentioned riparian areas indicate the proposed standards sparked at least a few conversations about flow needs for these areas.

To date, TCEQ's rulemaking process has resulted in the adoption of flow standards for four basin and bay areas. Riparian areas and their flow requirements are not mentioned explicitly in the standards, but a sound ecological environment for one region (Colorado-Lavaca) is defined as being "characterized by flow regimes that support existing biological communities in rivers, riparian, bay, and estuary habitats" (TAC §298.305). The standards prescribe flows at a total of 53 measurement points in four basin and bay systems. At least one pulse flow (within the banks of the river) is protected every season of the year at all measurement points. Two levels of pulse flow are protected at 18 points and three levels are protected at 19 points. No overbank flows are protected at any of the measurement points.

From the perspective of maintaining healthy riparian areas, the adopted flow standards appear to be a mixed bag. At least in format, the adopted standards appear to be an improvement from TCEQ's default desktop method previously used to describe the flow needs of the environment (including riparian areas). That method, known as the Lyons Method, relies on one base flow level (see TRG 2008 for a description of the Lyons Method). The inclusion of at least some pulse flow levels in the standards provides the opportunity to protect a portion of the larger flows associated with maintenance of riparian areas. The lack of protection for overbank flows, however, may limit the ability of the standards to maintain riparian areas over the long term. Without frequently occurring (every few years or so) moderate overbank flows, the connection between riparian areas and the river is broken. Both the influence of the river on riparian areas and riparian areas on the river is reduced. Decamps et al. (2008) describe the result as a "terrestrialization" process that undermines the ecological vitality of riparian areas.

So where are we in Texas, in terms of protecting water to insure preservation of at least some riparian areas along our rivers and streams? Some say it is unnecessary to provide this type of explicit protection because flows required to sufficiently maintain riparian areas will continue to occur without full protection in standards. Others argue that the standards should, in and of themselves, be sufficient to protect entire riverine ecosystems, including riparian areas.

For the sake of Texas' riparian areas, and the ecosystems and people that benefit from them, it's an important time to keep talking. What do Texans value about riparian areas? How much of these areas do they want to protect? What types of flows are required to protect these areas? Does ensuring these flows continue to occur in the future (they are occurring today) imply any liability related to the impacts of overbank flows on human development within riparian areas? This book can't answer all of those questions, but it can help keep the conversation going. After reading this book, it is my hope that Texans will be better prepared to have informed conversations about riparian areas, the flows required to maintain riparian areas, and whether there is a need to protect those flows.

Riparian areas in Texas are complex and unique landscapes. In Chapter 2 of this report, Nichole Davis and Thomas Hardy provide an overview of that complexity and the scientific disciplines that are important in describing riparian areas. Each of these disciplinary perspectives is valuable for TIFP as many of the qualities they describe are flow related. In Chapter 3, Jonathan Phillips describes the characteristics of riparian areas that make them effective buffers between terrestrial and aquatic areas. In Chapter 4, he describes riparian areas from the perspective of fluvial geomorphology. Physical processes are actively at work in riparian areas, creating and maintaining a variety of physical habitats. In Chapter 5 John Jacobs describes the distinguishing features of riparian areas from the perspective of soil science. He also describes how soils maps can be used to identify and gain insight about riparian areas. In Chapter 6, Jacquelyn Duke describes the complexity of riparian areas from the perspective of plant biology. Each of these disciplinary perspectives provide valuable insight related to how the flow regime of a river interacts with riparian areas and how the riparian area, in turn, interacts with the river.

Much like river ecosystems, riparian areas are influenced by a number of factors, including flow. It takes more than a suitable flow regime in order to maintain healthy riparian areas. Although TIFP does not deal directly with factors other than flow, the importance of other factors is recognized. Fortunately, there are other federal and state programs focused on these aspects of riparian areas. In Chapter 7, Steve Nelle describes how land management practices impact riparian areas. In Chapter 8, he describes several programs focused on land use and riparian areas. TIFP will monitor, but not duplicate, the results of these programs as it works to understand the flow requirements of riparian areas.

Chapter 9 of this book, "Coming to Terms," synthesizes the material from the previous chapters to develop a consistent definition of riparian areas in Texas and a basic methodology to delineate those areas. This chapter is crafted to meet the needs of TIFP, which is focused on flows required to maintain riparian areas. A general description of riparian areas emerges. Using that description to delineate riparian areas for site specific TIFP studies will require additional refinement. However, this basic definition should prove useful to study cooperators, stakeholders, and members of the public who participate in or are interested in the results produced by TIFP.

I hope the contents of this book prove useful to many Texans including study cooperators, stakeholders, and members of the public who participate in or are interested in the results produced by TIFP. This book doesn't address many important questions about Texas' riparian areas, such as: What do we value about riparian areas? What are the flow requirements of these areas? How much of these areas (and their beneficial services) do we want to maintain? Those questions will only be answered as TIFP and SB3 E-Flows processes run their course. In the meantime, Texans need to have many more conversations about these topics. My hope is that readers of this book will be better informed for those conversations than they would have been otherwise.

CHAPTER 2 – AN INTEGRATED OVERVIEW (NICOLE DAVIS AND THOMAS HARDY)

In general, riparian corridors are narrow, transitional strips of land located adjacent to, and regularly influenced by, streams, creeks, rivers, and lakes (water bodies) within the landscape (Naiman and Decamps 1997; Naiman et al. 2005). More specifically, riparian corridors are three-dimensional ecotones that interact with aquatic and upland ecosystems vertically, from groundwater to canopy, and laterally, from instream into the uplands as illustrated in Figure 2.1 (Verry et al. 2004). They differ from aquatic and upland (terrestrial) habitats by their physical structure and complexity. These transitional areas are unique corridors that provide various benefits to watersheds globally. For example, riparian ecotones can support a higher biodiversity than adjacent uplands depending on its location and orientation within the landscape. Additional benefits include the use of these ecotones as corridors for wildlife, increase of water quality within adjacent water body, and bank stabilization. Riparian ecotones are composed of unique land structures, soil, and vegetation. These riparian elements are influenced by river morphology drivers, such as sediment erosion and deposition processes (Heitmuller and Hudson 2009), as well as more constant, overarching factors, i.e. climate and geology.

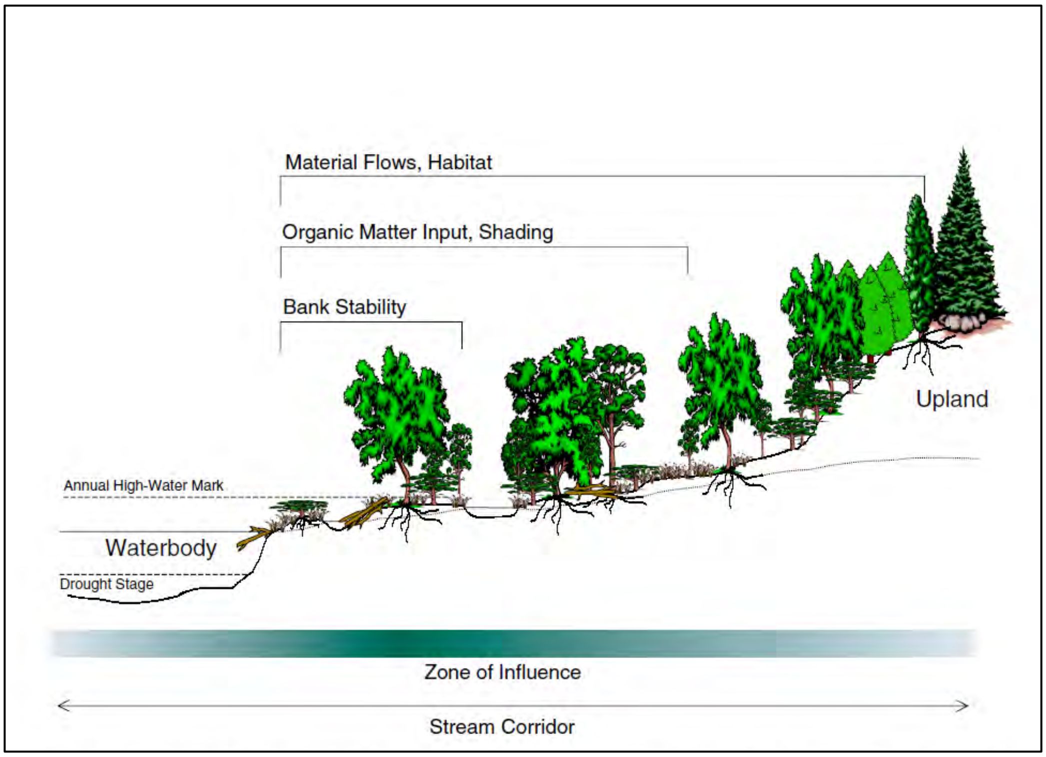

Figure 2.1. General riparian ecotone cross-section depicting its transitional location between aquatic and upland habitat, the intensity of influence occurring between aquatic, riparian, and upland habitats, and the exchange of materials (modified from USDA NRCS 2002).

INTERACTION BETWEEN HYDROLOGY, GEOMORPHOLOGY AND RIPARIAN SYSTEMS

The effects of climate are mostly easily seen during extreme conditions, in this case, drought and flood flow events. Droughts cause decreased flow volume and frequency available to riparian vegetation. As such, upland species are able to migrate into riparian ecotones, changing the composition of species, and decreasing riparian species biodiversity and available riparian habitat. Riparian vegetation has physiologically adapted to regularly flooded conditions; therefore, decreased flow volume and frequency reduces riparian regeneration and survival. Additionally, riparian vegetation can invade stream channels "in search of" water, which may cause channel narrowing during prolonged drought conditions. Some riparian species would not be able to flower, disperse seeds, germinate, or maintain seedling growth without the environmental influence of varying stream flow events, such as flooding or drought, which they have adapted to over time (Poff et al. 1997; Stromberg 2001). In contrast to flood events, long periods of reduced stream flow over time results in less diverse riparian vegetation and to more simplified floodplain communities (Stromberg 2001). Studies to determine the affect of reduced stream flow on vegetation within riparian zones have mostly been conducted along streams and rivers affected by anthropogenic activities such as construction and groundwater withdrawals (Auble et al. 1994; Busch and Smith 1995; Poff et al. 1997; Rood and Mahoney 1990; Stromberg 2001). These activities not only reduce water availability and nutrients that support riparian plants but also decrease floodplain area (Busch and Smith 1995; Nilsson and Svedmark 2002), increase non-native vegetation (Poff et al. 1997), and impede downstream flows of sediments. The loss of sediment for downstream habitats reduces native plant biodiversity and, therefore, associated riparian community productivity.

Though drought events seem to carry a negative connotation, these dry periods are also important for the development of healthy riparian corridors. South Texas is a semi-arid environment with characteristic droughts occurring in the summer months followed by the rainy season in the winter. If the drought is not prolonged thus occurring only through the summer, existing riparian vegetation develops strong roots through the pursuit of the descending water table. Once the rainy season arrives, these riparian species are more resistant to flood disturbance removal. Furthermore, natural droughts develop successional opportunities within riparian zones. That is, conditions favor the establishment of specific species whose life history strategies favor drought conditions and therefore, the composition of the riparian community changes.

Flood events, small and large, are also essential for healthy, functioning riparian ecotones. These events allow connectivity between instream and riparian areas, stimulate reproductive processes, provide habitat, move sediments, limit vegetation encroachment, and maintain channel form dynamics (SAC 2009). Additionally, high-and low-flow events are important to stream flow dynamics. These events can stimulate positive opportunities or be stressors for a variety of riverine species (Poff et al. 1997). High flow flood events transfer and deposit sediments at different depths to the water table, in different locations of light exposure, and with varying soil properties; hence, supporting different assemblages of plants within and along a river.

Streams and rivers flow from high-gradient, spring fed headwaters to mid-gradient streams and low-gradient streams of the coastal plain, thus, displaying changes in flow velocity and direction (Figure 2.2). During dry periods the river has low or base flows, which influence instream habitats more than surrounding habitats (BBEST 2011). However, during the wet season rivers experience high pulse or over bank flows, which influence a wider range of habitats from groundwater, instream, river banks, riparian ecotones, floodplains, and uplands. These high flow periods allow the stream to change course over time, allowing the formation of terraces, oxbow lakes, and braided channels depending on the local geology. These various hydrologic events continuously change local landforms. For example, the river thalweg, deepest water in the channel, moves laterally between stream banks causing alternating scour and deposition events. The eroded soil may be carried into the bays and estuaries depending on the flow regime, or may be deposited along the river banks or floodplains. Deposition of soils supports the development of new point bars along the course of the stream, which provide bare areas for riparian and wetlands vegetation establishment and, ultimately, habitat (Figure 2.2).

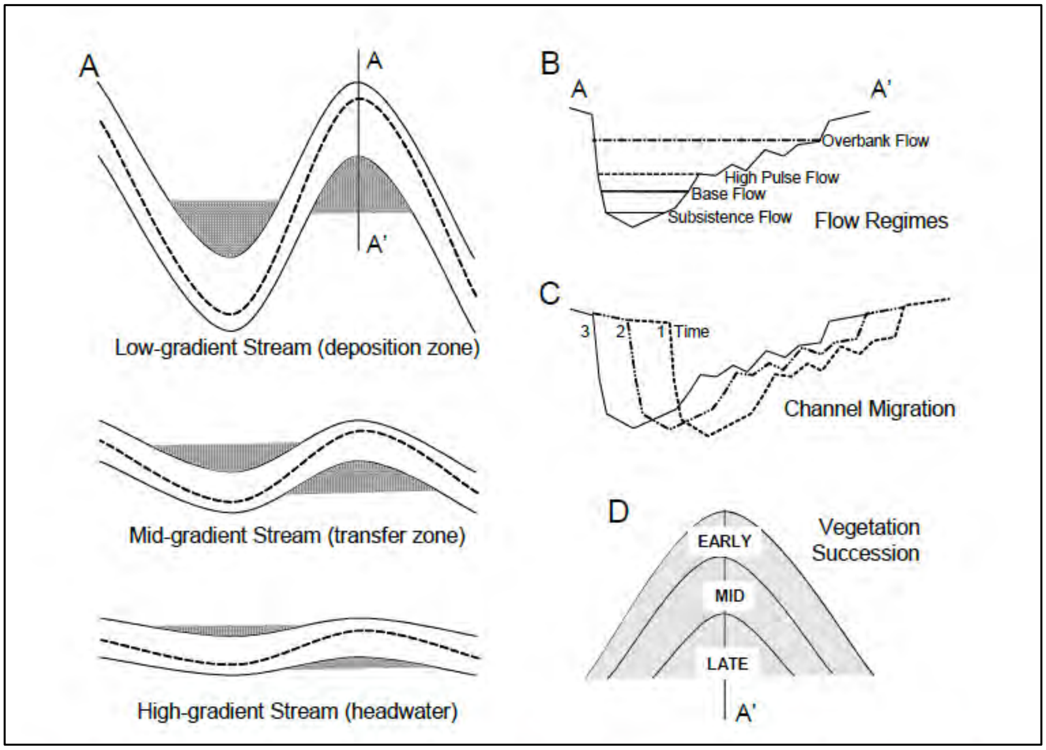

Figure 2.2. Schematic of river systems depicting A) river sinuosity and development of point bars on which riparian vegetation will establish, thalweg is shown as dotted line; B) flow regime levels; C) channel migration scenarios at meander bend; and. D) riparian vegetation establishment on the point bar over time relating to channel migration (modified from BBEST 2011).

One way riparian corridors are distinct from adjacent upland ecosystems is by soil characteristics. Riparian soils are able to hold unbound water longer than soils within upland ecosystems leading to increased moisture levels (USDA NRCS 1991). Moreover, riparian corridors are influenced from frequent disturbance events; therefore, riparian soils may be less developed or younger and more spatially diverse than soils in adjacent upland ecosystems. The distinct water and soil characteristics of riparian corridors support a higher diversity of vegetation and ecological functions than adjacent upland ecosystems (Zaimes et al. 2007). Riparian ecosystems can be distinguished from aquatic systems based on the presence of permanent water and dominate vegetation types. Riparian corridors primarily support woody vegetation and emergent herbaceous plant cover, whereas, aquatic systems support shallow water and submerged aquatic vegetation (NRC 2002).

Distinction between wetland and riparian ecosystems is less clear. Comparisons between wetland and riparian definitions (NRC 2002; Verry et al. 2004; Zaimes et al. 2007) produce overlap areas that meet both definitions; i.e. flooding levels, soil moisture, and vegetation (Mitsch and Goddelink 1986). Overall, riparian zones are defined as wetlands, but not all wetlands are riparian and not all riparian zones are wetlands (Figure 2.3). For example, riparian zones may include unsaturated areas, which do not meet the wetland criteria and wetlands may be present in areas not along streams or lakes and, therefore, are not riparian zones (Zaimes et al. 2007). So, a fuzzy area still exists in distinguishing riparian and wetland areas and eliminating this unclear distinction between these two ecosystems' definitions is essential for the protection of riparian zones. The wetland type Forested Wetland (FW), is an example of an ecosystem that causes confusion for land managers and agencies to agree on for differentiating certain riparian habitat from a wetland. The bottomland hardwoods of east Texas exemplifies this challenge and is discussed later in this chapter.

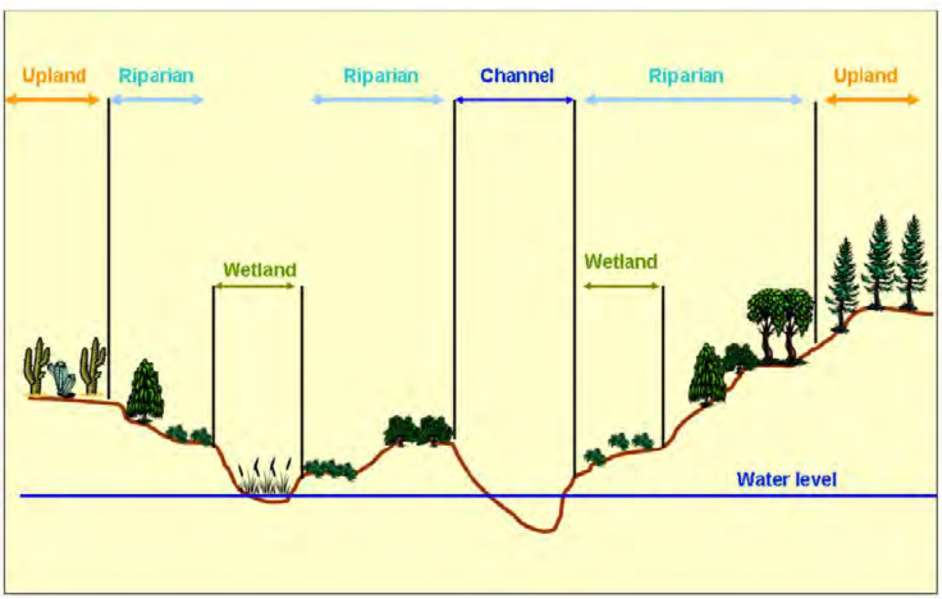

Figure 2.3. Ecosystem schematic depicting distinction and possible overlap between riparian and wetland areas (modified from Zaimes et al. 2007).

The vegetation component of riparian ecotones is strongly dependent on the above geomorphology, soil attributes, geographic location, and vegetation physiology. The different landforms present within riparian ecotones provide microhabitats or niches for vegetation development. For example, stream banks with little gradient are inundated more frequently than steep banks allowing water-obligate species to survive. These low gradient stream banks are also disturbed more frequently by the hydrology and thus plants that are more adapted to this disturbance are dominant (i.e. strong roots and resist abrasion). In general, riparian corridors along small headwater streams have narrower widths compared to those found along larger streams; hence, vegetation is less diverse because flood events and landforms are more uniform. Large streams with low gradient slopes have highly diverse riparian corridors due to more diverse hydrologic events influencing landforms and vegetation. Along these streams are usually extensive floodplains consisting of terraces, swales, and wetlands.

Patterns in riparian vegetation are associated with the fluvial landforms along rivers, or areas associated with hydrologic processes within the stream as illustrated in Figure 2.3 (Gregory et al. 1991; Hupp and Osterkamp 1985; Osterkamp and Hupp 1984; Poff et al. 1997). For example, a study along the Mission River (Davis 2011) documented only a small number of *Acer negundo* (box elder) and *Salix nigra* (black willow), and only found *Populus deltoids* (Eastern cottonwood) in swales far from the river. This pattern in pioneer species suggests the riparian corridor along the Mission River experiences less flood disturbance when compared to a study conducted along the San Antonio River (Bush and Van Auken 1984), which documented high importance values for all three woody species. Decreases in flood magnitude and frequency can reduce the biodiversity within the riparian corridor by allowing already established species to proliferate and by not providing the disturbance regime for new, early succession species to establish on recently deposited sediments.

The difference in density between the two studies for *A. negundo* (box elder), *P. deltoids* (Eastern cottonwood), and *S. nigra* (black willow) are indicative of differences in stages of riparian forest succession and channel geomorphology (Hupp and Osterkamp 1996; Osterkamp and Hupp 1984; Tabacchi et al. 1998). *Populus deltoids* (Eastern cottonwood), *S. nigra* (black willow) and *A. negundo* (box elder) are early succession, pioneer species that develop on non-competitive alluvial substrates (Friedman and Auble 1999; Naiman et al. 2010; Patten 1998; Rood et al. 1995; Rood et al. 2003). These geomorphic landforms are along streams where flood intensity is more severe (Baker and Wiley 2004) allowing disturbance events to remove older vegetation (Tabacchi et al. 1998), which then provides the new substrate for *P. deltoids* (Eastern cottonweood), *S. nigra* (black willow), *and A. negundo* (box elder) seedlings to establish (Baker and Wiley 2004; Tabacchi et al. 1998). Thus, the higher density of these three pioneer species along the San Antonio Rivers infer more alluvial landforms are present along the river providing more opportunities for a heterogeneous riparian corridor through disturbance and succession (Naiman et al. 2005).

A lot of variability exists in the type of landforms present within riparian corridors, which affects vegetation. Therefore, the vegetation present within riparian corridors depicts hydrology patterns influencing land structures as is seen from obligate, facultative wetland or facultative riparian species. These plant categories are wetland indicators that group similar vascular plants based on the probability that particular species will be located within a wetland based on its physiology (Reed 1997). Obligate (OBL) species are found within wetland habitat >99% of the time, Facultaive Wetland (FACW) 99<66%, Facultative (FAC) 66<33%, Facultative Upland (FACU) 33<1%, and Upland (UPL) <1%. Theoretically, landforms at higher elevations, such as terraces, are able to support FAC or FACW vegetation, whereas, lower elevation areas like swales provide conditions for OBL or FACW species (BBEST 2011).

RELATIONSHIP BETWEEN FLOW REGIME AND RIPARIAN SYSTEMS

Stream flow is a major factor in the distribution and abundance of riverine species as shown in Figure 2.4 (Poff et al. 1997). It derives primarily from precipitation reaching a stream through surface water, soil water, and ground water; thus, reflecting the importance of climate on riparian ecotones. Precipitation can change in intensity, timing, and duration, causing variable flow regimes in short and long time spans. This variation in flow at different time scales influences the five components of the flow regime (Figure 2.4), which affects the ecological integrity of the riverine system (Poff et al. 1997).

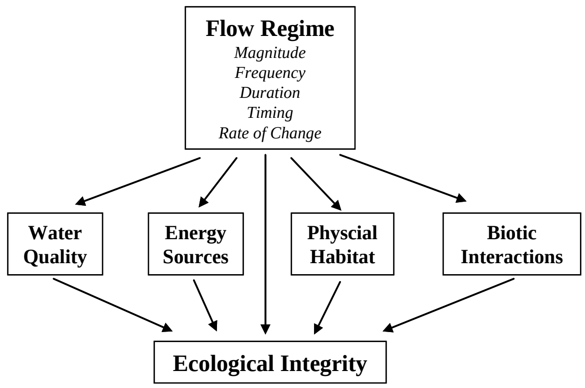

Figure 2.4. The five components of the flow regime (modified from Poff et al. 1997).

Variability in stream flow influences flow magnitude, frequency, duration (hydroperiod), rate of change and timing. This variability in flow within the channel and along the floodplain develops a varying physical environment. The rate of sediments transported by stream flow is associated with flow fluctuations, discharge, and availability of transportable material. These processes form a wide range of geomorphic features such as river bars, riffles, and floodplains (Poff et al. 1997). Different physical landforms cause diversity in the composition of riparian plant communities (Osterkamp and Hupp 2010; Pettit et al. 2001).

Riparian vegetation is generally able to adapt to establishment opportunities provided by geomorphic structures formed by the natural stream flow regime (Stromberg 2001). However, when stream flow is altered and inundation is infrequent or too consistent, riparian vegetation may not survive; hence, their establishment and senescence (i.e., aging and decline to death) are episodic (Auble et al. 1994). If varying low and overbank flow are not maintained then desiccation, reduced growth, competitive exclusion, ineffective seed dispersal, and unsuccessful seedling establishment may all occur within the riparian community (Pettit et al. 2001; Poff et al. 1997).

Recently, the state of Texas has recognized the effects of flow regimes on riverine systems throughout the state. In order to better manage freshwater inflows for an ecologically sound environment, studies have been conducted along various rivers to determine suitable flow regimes. These values vary across the state by river, even by station on the same river, and address multiple environmental factors, one being riparian systems. For a healthy, functioning riparian system, all the geomorphic, hydrologic, and biological elements would have to be supported by the proposed flow regime. For example, along the Guadalupe River at Victoria, the flow recommendations include subsistence flow, base flow, multiple high flow pulses, and multiple overbank flows (see Figure 2.5). Each flow recommendation is accompanied by an explanation of the influence each event has on riparian ecotones and the associated importance (BBEST 2011).

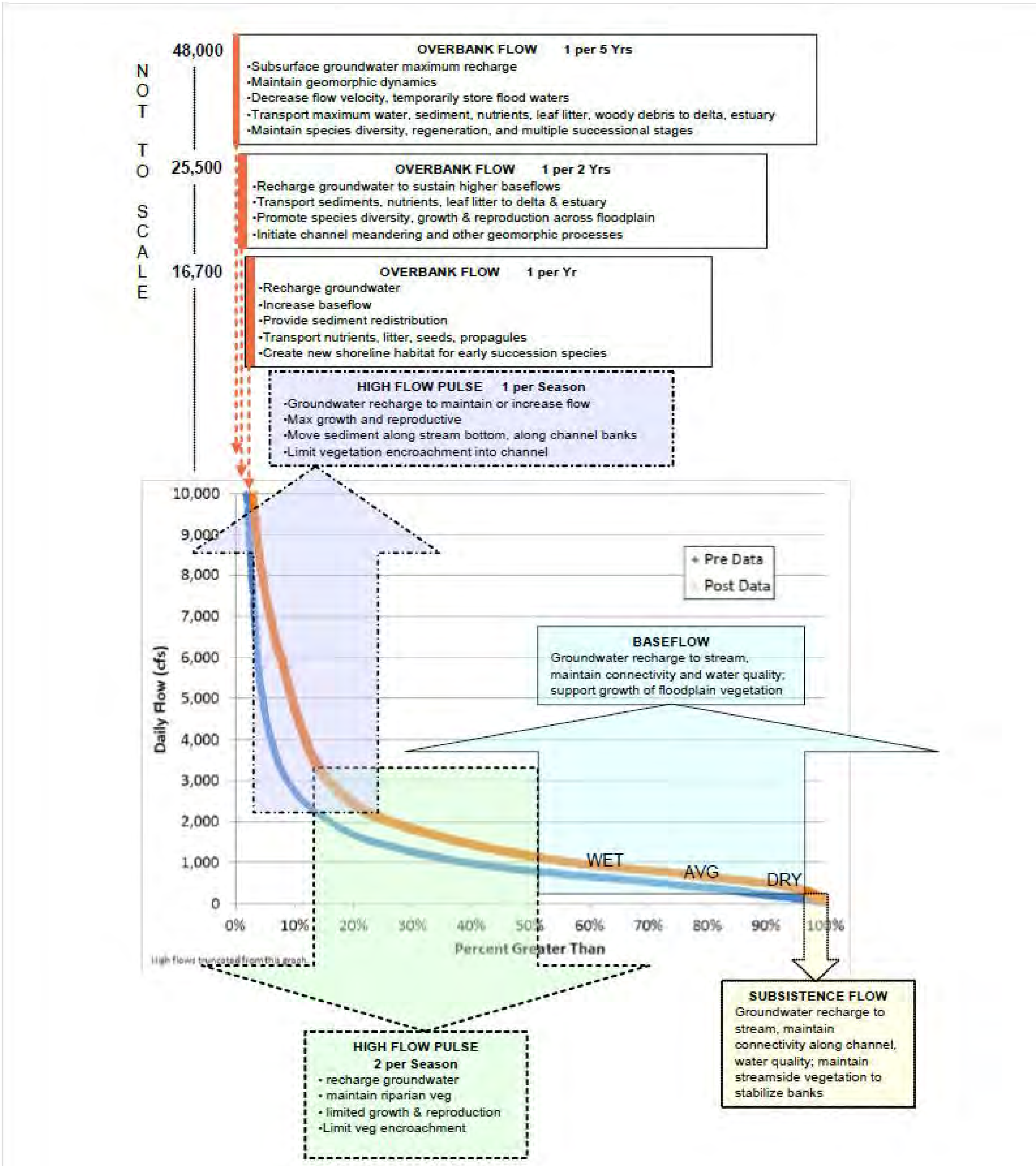

Figure 2.5. Conceptual example of environmental flow recommendations on the Guadalupe River at Victoria (modified from BBEST 2011).

RIPARIAN ECOTONES AND TEXAS ECOREGIONS

Because riparian areas naturally differ across the state of Texas, it's impossible to make 'one size fits all' flow recommendations to maintain riparian areas along Texas' rivers and streams. Riparian areas are different across the state because of many factors, including climate and geology. These factors also can be used to divide Texas in ecoregions, which in turn explain some of the natural variation in riparian areas across the state. A large gradient in precipitation and temperature exists across the state of Texas (Figure 2.6). Precipitation varies dramatically from east to west and temperature from north to south. These climate gradients together with other environmental factors divide Texas into 11 natural ecoregions (Figure 2.7). Each ecoregion encompass areas with similar biotic and abiotic conditions, i.e. the same climate, topography, vegetation, etc (Griffith et al. 2007). Therefore, riparian zones are most similar within an ecoregion and exhibit larger differences among ecoregions at furthest ends of the precipitation and temperature gradients; i.e. plant composition within east Texas riparian zones are largely different than those found in west Texas (Miller et al. 2009).

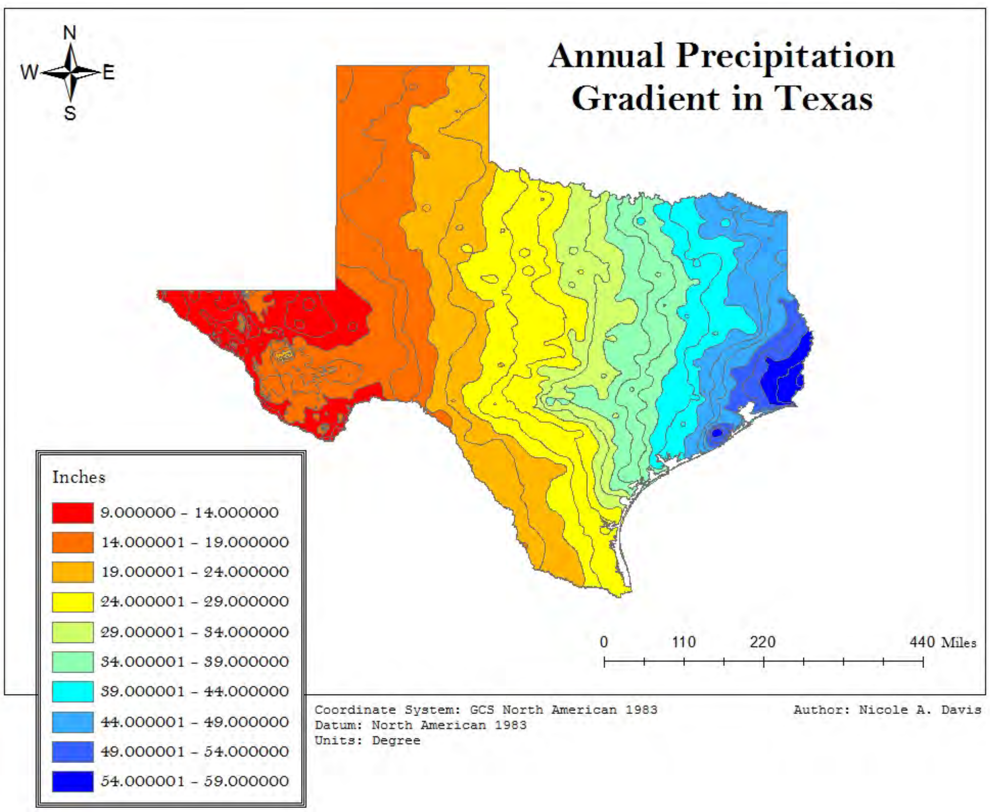

Figure 2.6. The annual precipitation gradient from east to west in the state of Texas (data provided by TNRIS.org).

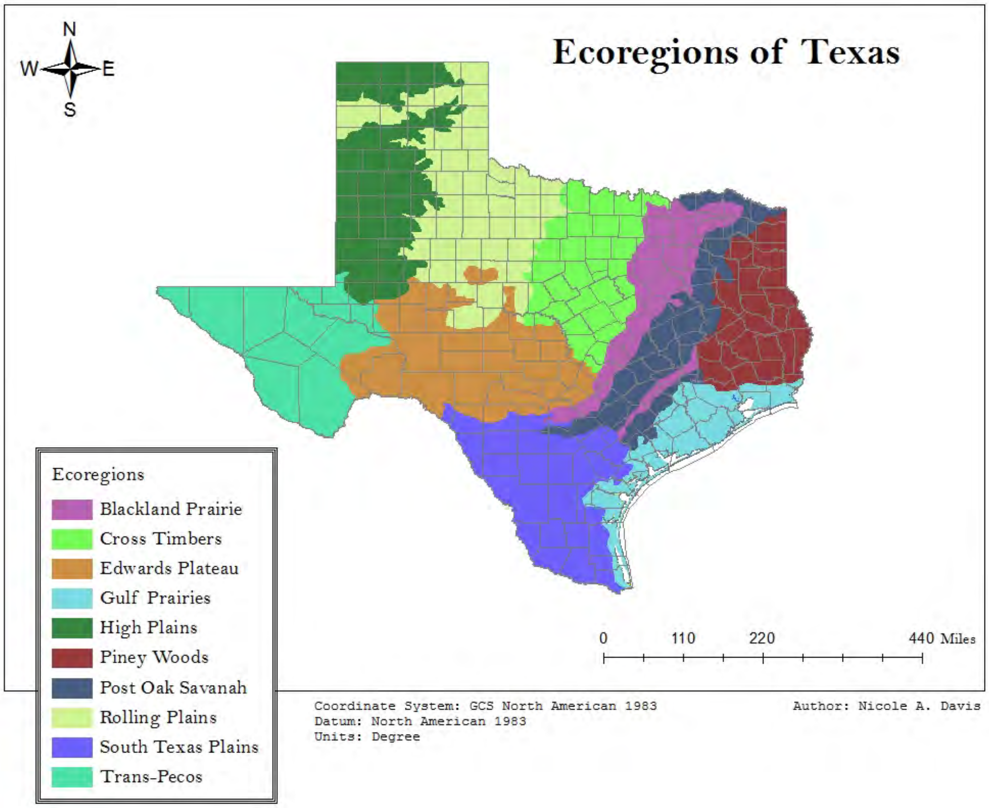

Figure 2.7. The eleven natural ecoregions of Texas as defined by Gould et al. 1960 (data provided by TPWD 2011).

Differences in riparian vegetation by ecoregions of Texas can be elucidated by extracting presence and absence data of woody riparian species documented in the literature and constructing a cluster dendrogram (Figure 2.8). Riparian species used to form the dendrogram were calculated as having importance values greater than or equal to 0.5% for all ten studies. Two studies, Nixon and Raines (1977) and Nixon et al. (1976) did not document importance values for all species; therefore, only those species with values noted as above or equal to 0.5% were included.

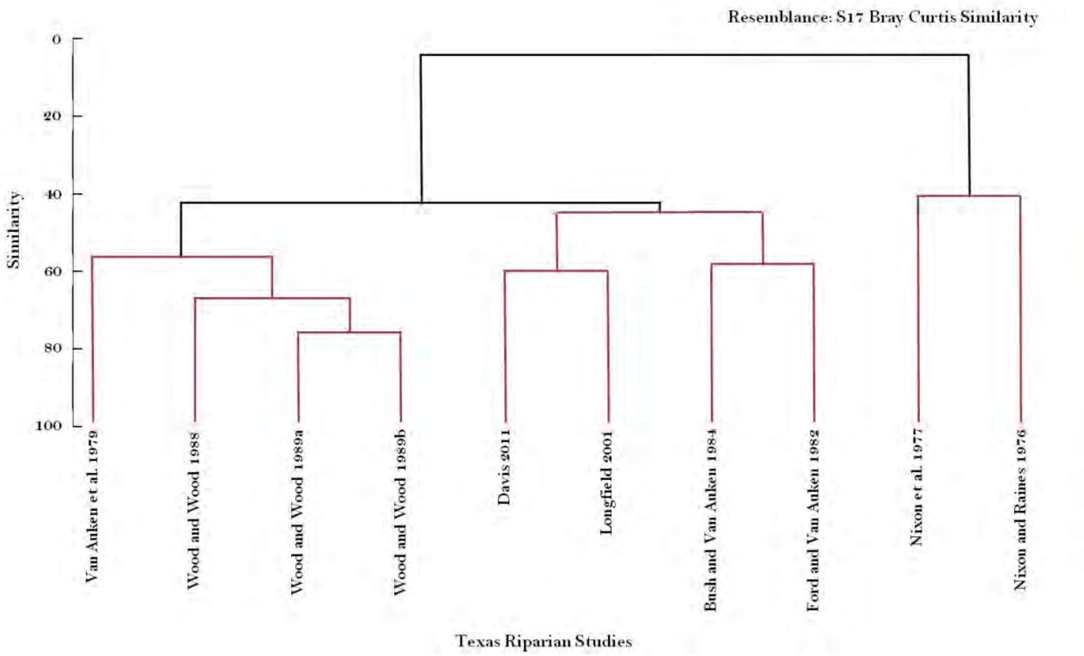

Figure 2.8. Bray-Curtis dendrogram from presence and absence of woody riparian species throughout Texas (modified from Davis 2011, unpublished data).

Each cluster is formed depending on the presence and absence of woody riparian vegetation, which is also related to which Texas ecoregion the study was performed (see Figure 2.8). The dendrogram showed significant clusters at 3.78 and 41.91% similarity (pi:13.06 significance(%):0.1; pi:3.53 significance(%):0.3). The 3.78% similarity emphasizes the effects of climate on riparian habitat. It separated the two east Texas, Piney Woods ecoregion studies from the other eight studies, which will be discussed in detail later in this chapter. The significant similarity cluster at 41.91% similarity separated the majority of the studies into two main groups; however, three ecoregions were interspersed.

The placement of the two studies conducted in the Gulf Prairies and Marshes ecoregion, Mission River (Davis 2011) and Aransas River (Longfield 2001), with the Bush and Van Auken (1984) and Ford and Van Auken (1982) may be due to differences in sampling more than similarities in vegetation. The latter two studies measured all woody species greater than 1cm in diameter or roughly 3cm in circumference whereas the first two studies measured stems greater than 3cm in diameter. Therefore, the studies conducted in the Edwards Plateau and South Texas Plains had a large number of species and samples, but only the species with important values of greater than or equal to 0.5% were used in the dendrogram. If all species present had been used within the dendrogram, the South Texas Plains and Edwards Plateau studies would have most likely separated from the Gulf Prairies and Marsh ecoregion studies.

In South Texas, riparian corridors support a diverse vegetation assemblage. Throughout these corridors plant species located more north, south, and/or west in Texas are collectively present (Smith et al. 2002). Along the San Antonio River in Wilson County, Texas (Bush and Van Auken 1984), *C. laevigata* (midland hawthorn) exhibited the highest density in the riparian corridor, followed by *A. negundo* and *U. crassifolia* (cedar elm). Importance values for *P. deltoids* (Eastern cottonwood), *S. nigra* (black willow), and *A. negundo* were high along the inner region, closest to the stream, with only *A. negundo* (box elder) extending into the middle and far regions of the riparian corridor.

On the Sabinal River (Wood and Wood 1989), *Taxodium distichum* (bald cypress) exhibited the highest importance, however, was not present beyond 15 m from the river edge. *Diospyros texana* (Texas persimmon) dominated throughout the riparian corridor with the highest calculated density, followed by

Quercus fusiformis (live oak), *Celtis reticulata* (net leaf hackberry), *Platanus occidentalis* (sycamore), *Carya illinoinensis* (pecan), *Taxodium distichum* (Bald-cypress), *Juniperus ashei* (Ashe juniper), *Sophora secundiflora* (Texas mountain laurel), and *Sapindus drummondii* (soap-berry).

A study along the Aransas River (Longfield 2001) concluded that *Celtis* spp. (hackberry species) was the most important species within the riparian corridor followed by *Melia azedarach* (chinaberry), *E. anacua* (anacua), *U. crassifolia* (cedar elm), *D. texana* (Texas persimmon) and *Z. fagara* (lime prickly-ash). *Celtis* spp. (hackberry species) had the highest relative dominance for all transects along the Aransas River with other species including *E. anacua* (Anacua), *U. crassifolia* (cedar elm), *S. nigra* (elderberry), *Melia azedarach* (chinaberry), and *C. illinoinensis* (pecan). *Melia azedarach* (chinaberry), an invasive species, had the greatest relative density for all transects along the Aransas River followed by *Celtis* spp. (hackberry species), *E. anacua* (Anacua), *D. texana* (Texas persimmon), *Z. fagara* (lime prickly-ash), *Zanthoxylum clava-herculis* (pepperbark), and *U. crassifolia* (cedar elm).

BOTTOMLAND HARDWOODS

The previously stated riparian definition that riparian corridors are narrow, transitional strips of land located adjacent to, and regularly influenced by, streams, creeks, rivers, and lakes (water bodies) within the landscape applies to most riparian corridors in Texas; however, some exceptions exist. For instance, riparian ecotones of east Texas are quite different, as seen from the cluster dendrogram (see Fig. 2.8). Riparian ecotones located in west, southwest Texas are captured by the general riparian definition and are similar to riparian systems in the western half of the United States. They are easily distinguished from surrounding upland habitat, and they are adapted to semiarid conditions and infrequent flood events (may not occur every year). The riparian ecotones of east, northeast Texas are characterized as bottomland hardwoods, similar to those in the eastern half of the United States. They experience more periodic flooding with prolonged duration of inundation at some point in the growing season.

Bottomland hardwoods are composed of species tolerant of long inundation time and more anaerobic conditions (Liu et al. 1997); therefore, they are an exception to the general riparian definition. These habitats are commonly referred to as forested wetlands more than riparian zones because permanent inundation causes stress similar to that found within wetlands. Bottomland hardwoods are found in east and northeast Texas along streams, rivers, and depressional wetland areas. These habitats are highly productive and diverse.

A study conducted along the Sabine River in northeastern Texas (Liu et al. 1997) characterized nine land cover types including bottomland hardwood. The woody species documented within the bottomland hardwood forest land cover were *Quercus nigra* (water oak), *Quercus phellos* (willow oak), *Nyssa sylvatica* (blackgum), *Ulmus americana* (American elm), *Quercus lyrata* (overcup oak), *Fraxinus pennsylvanica* (green ash), *Ilex decidua* (deciduous holly), *Ilex opaca* (American holly), *Crataegus spp*. (hawthorns), *Forestiera acuminata* (swamp privet), *Carpinus caroliniana* (American hornbeam), and occasionally *Sabal mexicana* (palmetto). Another study along the Sabine River in east Texas (Miller et al. 1997) documented other species including *Carya aquatica* (water hickory), *Taxodium distichum* (baldcypress), *Nyssa aquatica* (water tupelo), *Salix nigra* (black willow), *Liquidambar spp*. (sweetgum), *Quercus pagoda* (cherrybark oak), *Acer negundo* (boxelder), *Pinus taeda* (loblolly pine), *Magnolia grandiflora* (southern magnolia), *Cayra spp.* (hickories), *Fagus grandifolia* (American beech), *Pinus echinata* (shortleaf pine), *Cornus florida* (flowering dogwood), and *Ostrya virginiana* (eastern hophornbeam).

The bottomland hardwoods of east Texas are essential as they encompass approximately four-fifth of the 8 million acres of wetlands present within Texas (Texas Environmental Almanac 1995). Confusion arises in the protection of bottomland hardwoods similar to that found with all riparian ecotones; what factors define them and how do we delineate them consistently? As stated previously, bottomland hardwoods are sometimes referred to as forested wetlands rather than riparian ecotones. The difference between the definitions may seem small; however, the difference in the amount of important habitat defined by each is significant.

The definition of a wetland states "those areas inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions"; i.e. swamps, marshes, bogs and similar areas. Unlike the wetland definition, to claim bottomland hardwoods as riparian ecotones would encompass all wetlands within the area and go beyond into a portion of the upland, thus protecting more essential habitat. In contrast, if the USEPA or USACOE determine bottomland hardwoods to be forested wetlands, then they are considered jurisdictional wetlands under Section 404 of the Clean Water Act. This determination would reduce negative influence on bottomland hardwoods; however, it still may not encompass the full amount of essential habitat.

CHAPTER 3 - STREAM BUFFERS (JONATHAN PHILLIPS)

By their very nature, riparian zones are hydrologic buffers. They buffer the effects of upland runoff on streams, and mitigate the effects of high water and floods on terrestrial environments. Riparian zones (RZ) function as filters and valves in surface hydrologic systems, in the aquatic-terrestrial transition zone. Runoff from land within or adjacent to the RZ must pass through it, and high, overbank flows—which typically carry a disproportionate amount of the total water, sediment, and pollutant loads of streams—also must pass in part through the RZ. While these hydrologic buffer roles of the RZ are well known, and reflected in many water quality management schemes (for example, best management practices requiring maintenance of vegetated streamside zones in forestry operations), it is not always evident how wide or extensive riparian water quality buffer zones should be, or how they might be actively or passively used to protect water quality.

Establishment and maintenance of vegetated riparian buffer zones generally has one or more of four general goals. First is water quality protection, due to displacement of potential pollution sources from the water's edge, and filtering of pollutants as flows pass through the buffer. The latter may include a number of physical, chemical, and biological processes. A second major purpose of RZ buffers is to provide habitat for a variety of wildlife species including reptiles, amphibians, birds, and mammals. Other major purposes are to provide setbacks with respect to property boundaries, bank erosion or channel migration, and to provide streambank access and recreational space. These functions of the RZ buffer are all important, but this chapter focuses on hydrologic and water quality buffer zones.

WATER QUALITY BUFFER EFFECTIVENESS

The water quality buffer effectiveness is a function of four criteria listed below, any of which may be of either negligible or paramount importance for specific settings or water quality issues.

LOCAL RUNOFF PRODUCTION

Contrary to the common misconception of wetlands as "sponges" that soak up runoff and floodwaters (after all, a wet sponge doesn't soak up much water), wetlands and RZs are often important sources of overland flow. The low elevation, low slopes, and proximity to streams means that they are not infrequently saturated, or nearly so, and thus prone to produce saturation-excess runoff. Runoff produced within RZs may be of intrinsic concern, and may reduce the ability to buffer imposed flows. Riparian soils may also have, in addition to high water tables, low hydraulic conductivity and limited soil moisture storage capacity (see Chapter 5 - Riparian Soils), making them prone to runoff production even when not initially saturated. On the other hand, some riparian areas are comprised largely of coarse (sand and larger) material that produces little runoff. Riparian zones may also have significant depression storage, which reduces surface runoff.

DELAYING FLOW

The longer it takes effluents or runoff to pass through a riparian buffer, the more effective the buffer is, generally speaking. Longer transit times provide more opportunity for infiltration, sedimentation or settling of particulates, biological uptake, biochemical or geochemical transformations, and mortality of water-borne pathogens. The rate at which flow can pass through the buffer depends on flow length or distance, slope gradient, transmission losses via infiltration, surface roughness due to microtopography, coarse clasts, or organic debris, and vegetation and organic matter cover.

MINIMIZING STREAM POWER

The sediment or particulate transport capacity of flow is directly related to stream power, the rate of energy expenditure of flow per unit time. Stream power per unit weight of water is a function of flow velocity and energy grade slope. Thus, the factors other than length of flowpaths that determine ability to delay flow also affect stream power. Slope is particularly critical, as it is important independently as well as being related to flow velocity.

FILTERING POLLUTANTS

The ability of riparian buffers to remove or treat specific constituents is highly dependent on the specific characteristics and behavior of the pollutants involved, and the physical, chemical, and biological mechanisms of reduction and removal. However, some generalizations can be made. Some contaminants, such as oxygen-demanding wastes and bacterial pathogens, can be treated effectively by delaying flow, thus allowing time for decomposition and die-off. The ability to buffer sediment—often the single most common pollutant and the largest by total mass—and sediment-associated pollutants (adsorbed) and large particulates is largely controlled by transport capacity and stream power.

Other pollutants require specific biogeochemical processes such as denitrification[1] and require specific chemical as well as hydrologic conditions. Where processes such as denitrification require anaerobic conditions, the same conditions that promote buffer effectiveness for denitrification are detrimental with respect to potential runoff production, and delaying flow. This underscores the fact that there is no single index or indicator of buffer effectiveness applicable to all potential contaminants. Overviews of riparian and shoreline buffers and buffer strips for water pollution control are provided by Bren (1993); Barling and Moore (1994); Phillips (1996a; 1996b)

LOCAL AND UPSTREAM RUNOFF

The chapter on riparian geomorphology (Chapter 4) discusses the relative importance of along or down-valley and cross-valley fluxes in riparian zones. This can be important for evaluating buffer effectiveness, depending on the goal of buffer maintenance.

[1] Denitrification is a microbial process that reduces oxidized forms of nitrogen to ultimately produce molecular nitrogen (N_2).

In Texas rivers, the lower coastal plain alluvial reaches may be effective sediment bottlenecks, preventing the vast majority of fluvial sediment (and sediment-associated constituents) from reaching the coastal zone (Phillips et al., 2004; Phillips and Slattery, 2006; Slattery and Phillips, 2010; Slattery et al., 2010). The role of RZs in filtering floodwaters is widely recognized, but delineation of buffer zones is typically intended to protect water quality from effects of adjacent land uses.

RELATIVE IMPORTANCE INDEX

For a runoff event that produces both overland flow from the RZ and adjacent areas, and overbank flooding, an index of the relative importance of local hillslope (h) and upstream drainage basin (b) sources is (Phillips, 1996a):

$$Q_h/Q_b = (q_h A_h)/(q_b \; A_b \; - Q_{bf}) \tag{3.1}$$

q is runoff per unit area, *A* is the drainage area, and Q_{bf} is the bankfull discharge. Stream discharge and bankfull *Q* measurements and estimates are readily available for many areas (Asquith et al., 2006; 2007; Asquith and Heitmuller, 2008).

For any given time period:

$$Q_h/Q_b = [\Sigma(q_{h,l}\, t_i \; A_h)]/[\; \Sigma(\; q_{b,j}\, t_j\, A_b)] \tag{3.2}$$

where there are *i = 1, 2, 3, . . . , n* hillslope runoff events and *j = 1, 2, 3, . . . , m* overbank flow events, with durations t_i,t_j, respectively. An alternate approach is to identify a specific recurrence interval *q*. Then:

$$Q_h/Q_b = (q_{hql}\; t_{h,q}\; A_h)/(q_{b,j,q} t_{b,q} \; A_b \; - Q_{bf}\; t_{b,q}) \tag{3.3}$$

EVALUATING BUFFER EFFECTIVENESS

Evaluation of buffer effectiveness can be assessed relative to a baseline or reference condition, indicated by subscript *r*. The reference condition can be based on a riparian buffer known to be effective, on some easily accessible reference site, or on a relatively undisturbed control site. Then buffer effectiveness ratios are determined relative to the reference condition. Unfortunately, no single ratio can accurately assess overall buffer effectiveness. Rather, a suite of indices are needed, or an index suitable for a specific pollutant or pollution source of interest.

The ability to detain flow can be assessed using the detention time version of the Riparian Buffer Delineation Equation (RBDE). The equation is based on a Manning equation approximation of overland flow velocity, with runoff diminished via infiltration as a function of saturated hydraulic conductivity (*K*) and soil moisture storage capacity (*C*). Key assumptions are those associated with use of the Manning equation in general; that relative infiltration capacity at any moisture content is proportional to saturated hydraulic conductivity, and that saturation-excess runoff production potential is proportional to soil moisture storage capacity. Full development is described by Phillips (1989a; 1989b). Thus relative detention time (DT) for the buffer being evaluated (subscript *b*) is:

$$DT_b/DT_r = [(L_b/L_r)^2(K_b/K_r)^{0.4}(n_b/n_r)^{0.6}(C_b/C_r)] / (S_b/S_r)^{0.7} \quad 3.4$$

L is flow length (or width of the buffer), *n* is the Manning roughness coefficient, and *S* is energy grade slope. For overland flow conditions, *S* is usually assumed to be equal to the topographic slope gradient.

For subsurface flow, a ground water version was developed by Phillips (1996b), based on an assumption of Darcian flow:

$$GDT_b/GDT_r = (L_b/K_bS_b)/(L_r/K_rS_r) \quad 3.5$$

S in this case indicates hydraulic gradient or slope of the water table. This may be difficult to estimate in many riparian areas, as variable relationships between stream flow and local water tables make the assumption of water table roughly parallel to the ground surface problematic.

The hydraulic version of the RBDE is based on stream power per unit of water mass (equal to the product of velocity and slope), and again relies on a Manning equation description of flow velocity and accounts for loss of runoff within the buffer (Phillips, 1989a; 1989b):

$$H_b/H_r = [(L_b/L_r)^{0.4}(K_b/K_r)\ (n_b/n_r)^{0.6}(C_b/C_r)] / (S_b/S_r)^{-1.3} \quad 3.6$$

The propensity to produce runoff within the buffer can be estimated via the wetness index originally developed by Beven and Kirkby (1979) and widely used in rainfall-runoff models:

$$WI = ln[a/(T_e/T_i\ S)] \quad 3.7$$

Here *a* is upslope drainage area, T_e and T_i the local and mean soil transmissivities[2], and *S* the topographic slope gradient in the flow direction. Transmissivity integrates soil hydraulic conductivity above the water table or a confining layer. For multiple layers with conductivities K_i and thicknesses D_i:

$$T = \Sigma\ K_j\ D_j \quad 3.8$$

However, for riparian areas *a* and *s* are often very large due to upstream drainage areas, and only general values for transmissivity (as opposed to local and mean values as in eq. 3.6) are available. Thus, following Phillips (2003), a simpler transmissivity index can be used, based simply on T_b/T_r.

An alternative approach is based on the widely used curve number method of runoff estimation and modeling, described in detail by Conservation Engineering Division (1986) and reviewed in most standard hydrology texts. The potential maximum retention of precipitation *R* is a function of the curve number (*CN*), which is estimated based on soil type, surface characteristics, and land use, where $R = (1000/CN) – 10$. Phillips (2003) showed that for purposes of estimating relative runoff production:

$$q_b/q_r = R_b/R_r = [(1000/CN_b) – 10] / [(1000/CN_r) – 10] \quad 3.8$$

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[2] Transmissivities in this case refers to volume of flowing water and is directly proportional to horizontal hydraulic conductivity and thickness.

The relative importance of various factors in the buffer effectiveness ratios is shown in Figure 3.1.

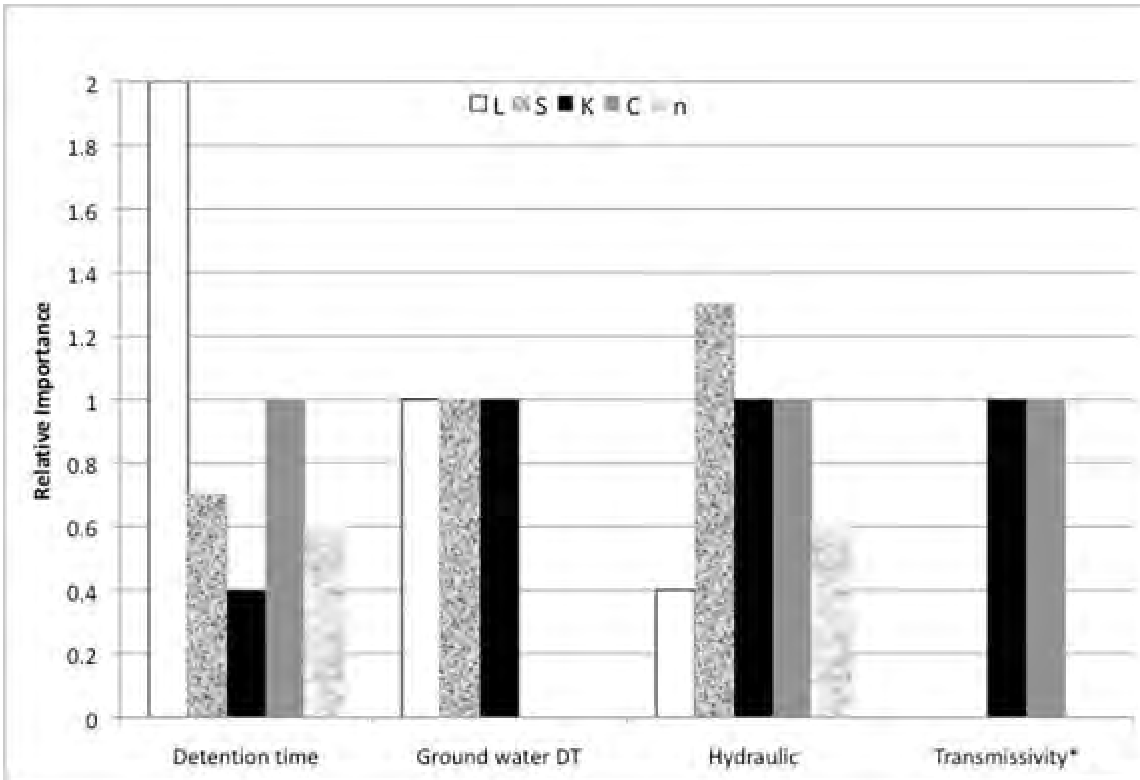

Figure 3.1. Relative importance of length or buffer width (L), slope (S), hydraulic conductivity (K), soil moisture storage capacity (C), and roughness (n) for the detention time, ground water detention time, hydraulic, and transmissivity indices of buffer effectiveness (*transmissivity is a function of conductivity and soil depth or thickness).

BUFFER EXAMPLE

As an example, some buffer effectiveness calculations are presented for the Guadalupe River corridor in Kerr County, Texas. Other examples of application of the methods described above for designing, or evaluating effectiveness of, riparian buffers include Phillips (1989c), Xiang (1993a;b), Prasnyat et al. (2000), Mitchell et al. (2003), Dosskey et al. (2008), and Hyman et al. (2010). The chosen reference condition is shown in Table 1, with properties typical of the Orif series, a common riparian soil in the area. A reference length of 50 m was selected arbitrarily, and a slope value typical of the Boerne series (see Dittemore and Coburn, 1986 for more information on these soils). A Manning's *n* value typical for overland flow through dense grass was chosen for the reference.

Two buffers were evaluated relative to this reference. The first had similar length and topographic properties, but soil properties associated with the Nuvalde series, also common in the Guadalupe River riparian zone, and $n = 0.13$, a value typical for natural rangeland. The second buffer was shorter, slightly less steep, with soil properties as shown in Table 3.1, and $n = 0.4$, representing woodland with understory vegetation. It was chosen to represent conditions associated with coarser alluvium.

Buffer 1 was only slightly less effective than the reference with respect to detention time, with relative buffer effectiveness (RBE) of 0.95. For the hydraulic version of the RBDE, buffer 1 was significantly less effective (RBE =0.49). Buffer 1 is more effective with respect to lower runoff production, however, with an RBE based on the transmissivity ration of 1.29.

Buffer 2 was about threefold less effective for detention time, and threefold more effective with respect to the hydraulic buffer (Table 3.1), reflecting in part the different relative importance of slope length and gradient in the two indices. The transmissivity ratio was also higher (RBE = 1.64).

Table 3.1. Properties of sample buffer zones on the upper Guadalupe River, Texas. See text for explanation.

Property	*Reference*	*Buffer 1*	*Buffer 2*
Length (m)	50	50	20
Slope	0.03	0.03	0.025
Saturated hydraulic conductivity (cm hr^{-1})	15.25	5.1	40.0
Soil moisture storage capacity (cm)	9.2	19.6	9.0
Transmissivity (cm hr^{-1})	3100	4000	5080
RBE: detention time RBDE	1.00	0.95	0.36
RBE: hydraulic RBDE	1.00	0.49	3.06
RBE: transmissivity ratio	1.00	1.29	1.64

DISCUSSION

The RBDEs show that buffer relative buffer effectiveness is a function of the amount or degree of variation in each parameter, and the exponents in equations 3.5 and 3.6. The detention time RBDE (eq. 3.4), for instance indicates that, for equal ranges of variation, runoff detention time within the buffer is most sensitive to slope length or buffer width, and least sensitive to *K*. However, if (for example) topographic or land use constraints limit buffer widths to, say, 10 to 20 m while *K* varies by an order of magnitude, hydraulic conductivity will contribute more to local variation in relative buffer effectiveness.

In general, buffer effectiveness is positively related to length, hydraulic conductivity, soil moisture storage capacity, transmissivity, and surface roughness, and negatively related to slope. Note, however, that these factors are not independent. Many coarse soils, for example, have high *K* values but low *C*, and soils with high clay content may exhibit the reverse. Other things being equal, low slopes are conducive to buffer effectiveness, but some low slope areas have high water tables (and thus lower values for *C* and *T*). This reflects the fact that soil thickness (in an absolute sense or relative to the water table or a confining layer) has important influences on soil moisture storage capacity and transmissivity.

In terms of riparian buffer management, length or buffer width and surface roughness (via vegetation) are the most amenable to management. Slope can also be modified via grading or terracing, but in low-relief alluvial systems there may be little reason or opportunity to undertake this. Soil hydrologic properties can be maintained and improved by standard soil conservation practices, but factors such as moisture storage capacity, hydraulic conductivity below the surface, and soil thickness are difficult to manipulate.

CONCLUSIONS

The effectiveness of riparian water quality buffer zones for specific contaminants or pollution problems must normally be assessed based on specific biogeochemical properties and processes. However, a more general assessment of buffer effectiveness can be made on the basis of hydrologic properties. Specifically, these relate to the ability to delay or detain flow through the buffer, the sediment transport capacity of flow through the buffer, and the propensity for runoff production within the buffer zone. By selecting a locally or regionally appropriate reference buffer, a quantitative relative buffer effectiveness index can be produced.

Various buffer properties have different degrees of influence on the three types of buffer effectiveness described above, and some properties enhancing buffer effectiveness may be negatively correlated. That is, properties enhancing effectiveness in one respect may be directly correlated with properties reducing effectiveness in other respects.

CHAPTER 4 - RIPARIAN GEOMORPHOLOGY (JONATHAN PHILLIPS)

Geomorphology is the study of Earth surface processes and landforms. Therefore, the geomorphology of the riparian zone deals with landforms that occur in that zone, and the processes that create, destroy, and modify those landforms.

A fundamental distinction exists between streams with and without floodplains. While "floodplain" is sometimes used to describe the area inundated by a given flow or stream stage, regardless of the landform or surface covered, here a geomorphic definition of floodplain is used. An active floodplain is a relatively flat, low relief area lying within a stream valley and adjacent to the stream channel. It is composed predominantly of geologically recent alluvium (sediment deposited by stream flows). The majority of the surface is below the maximum elevation of natural levees, and/or is flooded (on average) at least biennially, and/or shows evidence of regular influence by stream flow, via surface or ground water. The latter caveat is necessary because of the wide variability in frequency of overbank flows, even within a single river reach, and because even rough rule-of-thumb generalizations with respect to flooding frequency are often inapplicable to arid and semiarid streams.

For streams with floodplains (referred to here as alluvial) the riparian zone, at least from a geomorphic perspective, lies between the active channel and the outer margin of the active floodplain (Figure 4.1). Alluvial terraces (see below) within the river valley may also be included in the riparian zone if they meet standard criteria for designation as wetlands, or if there is clear hydrologic, geomorphic, pedologic, or biologic evidence that the area is regularly (≥ annually) directly influenced by stream stage or discharge, via either surface or ground water. For non-alluvial streams, where no active floodplains exist, the riparian zone is considered to be the area adjacent to the active channel that exhibits hydrologic, geomorphic, pedologic, or biologic evidence of regular influence by stream flow, via surface or ground water (Figure 4.2). The active channel is the entire area between the channel bank tops, unless evidence exists that lateral infill and channel narrowing is occurring. These definitions are summarized in Table 4.1.

Figure 4.1. Riparian zone in lower Menard Creek, an alluvial stream, at its confluence with the Trinity River near Romayor, Texas (base image from Google Earth™).

Figure 4.2. Narrow riparian zone on a non-alluvial reach of the upper Guadalupe River near Spring Branch, Texas.

Table 4.1. Definition of terms used in this chapter.

Term	*Geomorphic Definition*
Active channel	Area between channel bank tops, excluding areas exhibiting evidence of lateral infill and channel narrowing
Floodplain	Relatively flat, low relief area within a stream valley and adjacent to stream channel(s), composed predominantly of geologically recent alluvium. Majority of the surface is below maximum elevation of natural levees, and/or is flooded (on average) at least biennially, and/or shows evidence of regular influence by stream flow, via surface or ground water.
Riparian Zone (alluvial streams)	Area between active channel and outer margin of floodplain. Alluvial terraces may be included if they are designated wetlands, or show evidence of regular influence by stream flow, via surface or ground water.
Riparian Zone (non-alluvial streams)	Area adjacent to the active channel that exhibits hydrologic, geomorphic, pedologic, or biologic evidence of regular influence by stream flow, via surface or ground water

GEOMORPHIC PERSPECTIVE

Fluvial systems are inherently dynamic, and subject to frequent and chronic change. Delineations of active channels, floodplains, and riparian zones must be considered temporary and contingent. The same goes for mapping or identification of riparian landforms. A geomorphic view of streams also recognizes that they may sometimes reflect the effects of a relatively recent extreme event (e.g. flood or drought) rather than more typical contemporary and historic conditions. Some are so frequently influenced by such events that the notion of "typical" conditions may not be entirely relevant.

Like other scientists, geomorphologists often classify and categorize landscapes, landforms, and process regimes. However, even though mapping and management schemes may demand crisp, mutually exclusive, and exhaustive categories, in reality boundaries between landforms (as well as between soil types, ecosystems, etc.) are rarely sharp and regular. More often they are fuzzy, transitional, and irregular. Further, real geomorphic systems are, in essence, infinitely variable. It is, therefore, extremely difficult, and perhaps impossible, to devise any system of definitions or classifications that can readily accommodate the variety observed in real fluvial systems. In other words, exceptions or uncertainties can *always* be identified.

GEOMORPHOLOGY AND RIPARIAN ZONES

The most apparent differences between fluvial systems—or different portions of the same fluvial system—are geomorphological. Channel width and depth, bank type and steepness, floodplain width and morphology, slope, alluvial composition, valley wall confinement, etc. are important not only to fluvial geomorphologists, but also to river engineering and to any human access to or use of river resources. Fluvial and alluvial geomorphology also affects, and reflects, hydrology. Riparian and aquatic habitats are also directly related to specific landforms and geomorphic processes (e.g., Hupp and Osterkamp, 1996; Scott et al., 1996; Robertson and Augspurger, 1999; Johnston et al., 2001; Gumbricht et al., 2004; Moret et al. 2006).

Geomorphology is also critical to classification, delineation, and impact analysis of wetlands. For example, U.S. government agencies charged with wetlands regulatory and assessment programs have adopted an explicitly geomorphic/hydrologic approach to wetland identification and characterization known as the Hydrogeomorphic Method (Brinson, 1995; Johnson, 2005). The ubiquitous use of geomorphology- based classifications by ecologists, hydrologists, and water resource managers is evidence of the widespread recognition of the critical role of geomorphic properties. (Brinson, 1995; Newson and Newson, 2000; Parsons et al., 2002; Kondolf et al., 2003; Brierly and Fryirs, 2005; Johnson, 2005).

At least four general roles for geomorphology in riparian science and management can be envisioned:

1) Riparian landforms as critical components or building blocks in the description, assessment, and characterization of riparian zones;
2) Landforms as features that may change and evolve (or appear or disappear) as a result of riparian processes, and human management or modifications thereof;
3) Landforms and geomorphic processes as potential degrees of freedom in managing riparian environments (beyond the scope of this chapter);
4) Geomorphic indicators of hydrological, ecological, geological, climatological, and anthropogenic changes and disturbances.

GEOMORPHIC INDICATORS

Definitions of the riparian zone, active channel, floodplain, and related features depend, in the absence of long term, continuous monitoring or observation, on indicators of the nature, frequency, duration, and magnitude or intensity of flow, inundation, or saturation. Common geomorphic indicators are summarized in Table 4.2.

Direct hydrologic indicators of regular influence by stream flow, via surface or ground water, include direct observation; monitoring data from gaging stations, wells, level-loggers, pressure transducers, etc.; flood wrack (organic or other debris deposited by high flows), and evidence of water damage/effects on structures. Biological indicators may also be helpful, including presence or absence of obligate and/or facultative hydrophytes[3] and obligate aquatic or wetland fauna, fungi, or microorganisms; evidence of aquatic or wetland organisms (e.g. shells, skeletal remains, burrows, excreta); and algal or other biofilm coatings. Hydrological and biological indicators are typically used in conjunction with geomorphological and pedological indicators of influence by stream flow, via surface or ground water. Ground water is included due to the importance of hyporheic exchanges in some streams, and the general interrelationships between flow stages and water table levels in valley bottoms.

Indicators of surface flow include bedforms such as ripples and dunes. These are most common on dominantly sand-textured surfaces, but may occur on both coarser and finer surfaces. Scour holes around tree trunks, pilings, or other features, as well as rills and gullies in valley-bottom settings also indicate recent locally erosive flows. Smooth, rounded rock clasts[4] are an indicator of turbulent fluid transport, though two caveats are necessary. First, older fluvial deposits not associated with contemporary flow regimes may contain rounded clasts. Second, angular or non- rounded clasts do not necessarily indicate a lack of fluvial transport, as rounding by abrasion requires

[3] Hydrophytes are plants that have adapted to living in aquatic environments and are common wetland indicator species

[4] Clasts are rock fragments produced by weathering of larger rocks.

considerable cumulative time or distance of transport. Where rock fragments have been recently delivered to channels, or in upper stream reaches, rounding may not be evident. While this is most commonly applied to gravel and larger particles, microscopic analysis of quartz sand grains may also be useful. Smooth bedrock surfaces also indicate abrasion by fluvial sediment transport and/or solution. Again, however, the absence of smooth surfaces does not imply a lack of flow, as some bedrock channels are dominated by high-flow detachment of blocks loosened by weathering, a process that does not generally result in smoothed surfaces.

Alluvial deposition can usually be distinguished from other types of deposits (aeolian, mass wasting, glacial) by context. Indications of recent deposition include preservation of sedimentary layering and stratification, and burial of understory vegetation and of litter layers. The burial of the basal flares and root crowns of bottomland trees also indicates relatively recent deposition, and these features are often used to date recent alluvial deposits. Exposure of roots, on the other hand, is an indicator of recent erosion. During floods recirculating eddies, backwater zones, and ponded areas left behind as waters recede may leave slackwater deposits as indicators of inundation. These are especially useful in non-alluvial settings where other alluvial deposits may be rare. More generally, flows with significant suspended sediment concentrations often leave mud lines or coatings on trees, structures, and other surfaces.

Table 4.2. Geomorphic indicators of surface flow, inundation, and saturation.

Indicator	*Implied Process*	*Notes*
Scour holes, gullies, rills	Fluvial erosion	Rills, gullies may occur in upland as well as riparian environments
Fluvial bedforms	Bedload sediment transport	Most common on sandy substrates
Rounded rock fragments	Abrasion during fluvial transport	May be associated with older fluvial deposits
Smooth bedrock surfaces	Fluvial abrasion or solution	May occur outside riparian zone in karst areas
Exposed tree roots	Erosion	Not restricted to fluvial/riparian environments
Sedimentary stratification	Recent deposition	Stratification in some (especially older) deposits may be obscured by pedogenesis and/or bioturbation
Burial of understory vegetation or litter layers	Recent deposition	
Burial of tree basal flares and root crowns	Recent/historical deposition	Dates or timing may be constrained using dendrochronology
Mud lines & coatings	Deposition in backwater environments or during falling stages	Relevant to flows with significant suspended sediment
Slackwater deposits	Ponded or backwater deposition in floods	Useful in non-alluvial systems
Gley features; Eh indicating reduction	Reduction during saturation	Most useful in iron-bearing materials
Redoximorphic features	Weathering during wetting/drying episodes	Most useful in iron-bearing materials
Hydric soils	Frequent or prolonged saturation or high water tables	Hydric soils list maintained by USDA
Alluvial landforms	See *Riparian Landforms* below	

Long or frequent inundation or saturation results in weathering regimes in soils and sediments dominated by reduction of iron, aluminum, manganese, and other elements. This can be indicated by redox (Eh) measurements and monitoring. Reduction in iron-bearing materials results in characteristic gley (gray, blue, green) colors typically indicated by chromas of 2 or less in the Munsell soil color system. Concentrations of reduced and oxidized material in soils are referred to as redoximorphic features, and are indicative of repeated wetting/drying episodes. Gley colors, redoximorphic features, and other indicators of frequent saturation, are described in detail in the literature on hydric soils, which are used as wetland indicators. The presence of hydric soils themselves, either identified in the field or as delineated on soil maps or databases, is an indicator of wetness.

Other geomorphic indicators exist in specific environments. A comprehensive inventory is beyond the scope of this chapter, but two examples are sulfide formation in soils frequently saturated by salt or brackish water, and geomorphic features indicating solution in fluviokarst environments.

RIPARIAN ZONE PROCESSES

Geomorphic processes of the riparian zone fall into five general categories. These are processes associated with water flows; weathering, regolith, and soil formation; mass wasting; biogeomorphic processes; and locally important processes such as karst and aeolian processes and tectonic deformation.

Flow, Sediment Transport, and Deposition

The same hydraulic and physical principles govern flows within stream channels and those outside of channels, but the situations are much different. Standard flow resistance equations are of the form:

$$V = R^a \; S^b \;\; f^c \qquad 4.1$$

V is mean flow velocity, R is hydraulic radius (cross-sectional area/wetted perimeter), S is energy grade slope (typically approximated by water surface slope), and f *is* a friction or roughness factor. For the D'Arcy-Weisbach equation, for instance, $a = b = c = 0.5$, and for the Manning-Strickler equation a = 2/3, b =0.5, and c = 1.

Overbank flows in the riparian zone typically experience far lower R (which roughly equals mean depth in flows where width is much greater than depth), lower slopes, and much greater roughness (often due to vegetation) than in the adjacent channels.

Stream power is the rate of energy dissipation (work) against the flow boundary, and is a good indication of sediment transport capacity. Stream power at a channel cross-section is given by:

$$\Omega = \rho \; g \, Q \, S \qquad 4.2$$

ρ is the density of water, g is acceleration due to gravity and Q is discharge. Cross-sectional stream power—particularly as it relates to the ratio between sediment transport capacity and sediment supply—is important in determining the general aggradational, degradational, or steady-state of the river and riparian zone. However, for overbank flows, a lumped cross-sectional value provides little insight into riparian zone processes. For this, power per unit weight of water is more useful:

$$\psi = \Omega \,/\, (\rho \, g \, A) = VS \qquad 4.3$$

Unit stream power is often used in models to predict sediment transport by overland flow.

Problems related to whether a given flow is capable of eroding a surface or transporting a given particle are usually addressed using basal shear stress:

$$\tau = \rho\, g\, d\, S \qquad 4.4$$

where *d* is water depth (*R* is substituted for *d* to determine mean boundary, as opposed to local, shear stress). Values of τ can be compared to shear strength of surface materials, or to critical entrainment stress for particles, to determine whether erosion or entrainment is likely to occur.

In the riparian zone (RZ), depths and velocities are generally much lower than in the channel, and velocities are often negligible or zero due to ponding or backwater effects. In such situations, *S* is also negligible. This underscores three points about flow processes in the riparian zone: (1) in most cases net sediment deposition is more likely than net erosion; (2) significant depths, and rates of flow propagation down or cross-valley, are necessary to achieve erosion of riparian surfaces in most cases; and (3) deposition is generally dominant during recessional phases of flood flows. General areal stripping of riparian soils or surfaces is, therefore, rare. Riparian zone erosion is therefore attributable primarily to channel bank erosion and lateral channel migration, or to high flows confined to channels across the RZ, such as crevasse or flood channels. Features which serve to confine or concentrate overbank flows, such as roads or trails, may therefore be critical in stimulating riparian erosion.

DEPOSITION

Sediment deposition is a fundamental process of RZ creation and maintenance. Deposition of sediment transported by flows encroaching on the riparian zone is a direct, negative function of unit stream power, and a positive function of particle size or mass. This accounts for the tendency for deposition of larger, heavier particles to occur within the channel and near the channel margins, and for finer material to accumulate further from the active channel and in depressions with minimal flow. This also accounts for the formation of natural levees, as the reduction in transport capacity encountered just beyond the channel margin leads to immediate deposition.

Riparian deposition takes three general forms—deposition from suspension during overbank flows, bedload deposition by crevasses, and lateral channel migration. Suspended sand is rapidly deposited during overbank flows whereas silt is deposited more slowly due to the reduced transport capacity outside the channel (lower *d, S,* and higher resistance). The finest, colloidal material (as well as larger organic matter pieces) may be deposited only in backwater or ponded settings, or as mud drapes during rapidly falling stages.

Bed load, generally sand or larger particles, is deposited at channel margins or as local fan-like deposits at channel margins where strong flows impinge on the banks. More commonly, direct deposition of bed material on floodplains occurs when flow breaches the natural levee, creating a crevasse. In many cases, on the outside of the channel breach rapid flow spreading and deceleration leads to fan deposits called crevasse splays. In other cases the crevasse flow may incise a channel or reoccupy an old channel, with localized bed load deposits resulting. Crevasse channels are also the first stage in channel avulsions, though many do not result in avulsion.

Avulsions—channel shifts—occur in aggrading channels and valleys, and have the effect of refocusing the locus of alluvial deposition. Avulsions are common in delta settings everywhere, and are common in lower coastal plain reaches and bayhead deltas of most Texas rivers draining to the Gulf of Mexico (Aslan and Blum, 1999; Phillips, 2009).

Lateral channel migration in meandering rivers involves the growth of depositional point pars on the inside of bends, accompanied by cutbank erosion on outer bends. Eventually, the inner point bar sediments, originally deposited at channel margins, are no longer regularly inundated and become part of the floodplain.

Three basic conceptual models of floodplain formation exist. One involves an initial phase of lateral migration, during which lateral channel point bar deposits become part of the floodplain. In the second phase, accretion is dominated by deposition from suspension during overbank flows. This sequence results in finer sediments overlying coarser (typically sandy) material. The second model focuses on crevasses and avulsions. As channels aggrade, levee breaches become more likely, and splay deposition and avulsions occur into floodplain depressions and older channels. In some rivers—including many in Texas—this periodic channel switching is a major mechanism of floodplain formation (Aslan and Blum, 1999; Blum and Aslan, 2006). The third model involves vertical accretion of floodplains due to overbank sedimentation. The high banks confine ever-larger flows until eventually a large flood or sequence of smaller ones exerts sufficient shear stress to erode the banks, creating a wider channel with lower banks, and reinitiating the sequence.

The first two models and mechanisms are common in Texas, often both on the same river, such as in the cases of the Brazos and Trinity rivers. The third probably occurs locally, but has not been reported in the scientific literature in Texas, and is apparently of minor importance.

WEATHERING AND REGOLITH FORMATION

These processes are dealt with in the soil chapter (Chapter 5) and are not discussed in detail here. In alluvial streams, soils are formed in unconsolidated material, so weathering is critical in modifying sediments, but not in rock breakdown. Alluvial soils are often—correctly, in many cases, considered to be youthful, with limited pedogenic development, due to their geologic youth and frequent disturbance. Exceptions exist, however, when deposition is infrequent enough or occurs slowly enough for pedogenesis to keep pace. Alluvial terrace soils may be strongly developed.

In non-alluvial streams, riparian weathering and regolith formation differs little from that found in toeslope environments in the vicinity in general. Colluvial deposition in addition to occasional stream inputs in common, and so regoliths and soils formed in colluvial deposits, or colluvium over weathered bedrock, are common.

MASS WASTING

Slope failures and mass wasting are relevant to fluvial and riparian systems in two main ways. First, mass wasting may be a significant source of sediment to streams and valley bottoms, occasionally damming or partially blocking channels. This is particularly important in steep terrain. From the riparian perspective, sediment delivery by hillslope mass wasting is generally most important in smaller non-alluvial streams, and becomes less important in larger or wider floodplains and RZs become less sensitive, due to buffering effects. Second, mass wasting processes are significant in bank erosion, thus directly impacting RZs. Bank erosion, particularly on high, steep banks, is often due to a combination of direct hydraulic erosion by flow (corrasion), and slope failures. The two most common scenarios are triggering of mass wasting by erosional undercutting of stream banks, and the hydraulic removal of sediment delivered to the lower banks and channel edge by mass wasting. This removal may prevent the banks from reaching stable morphologies.

Slope failures on banks may also be important in the falling stages of floods or high flows, particularly if stages fall rapidly and bank materials are relatively permeable. During a quick decline in stage, the physical support of the water against the banks is rapidly removed, and the flux of ground water and saturated throughflow in soils returning to the falling base level of the river exerts significant pore water pressure. This can result in blowout-type failures on upper banks, particularly in sandy materials.

BIOGEOMORPHOLOGY

As a critical ecotone between terrestrial and aquatic environments, RZs commonly experience intense biological activity, much of which has geomorphological consequences. A full review is not possible here, but key geomorphic effects of biota include bioturbation, biogenesis, erosion, and sedimentation.

Bioturbation in riparian zones is often intense. A variety of burrowing, mounding, and digging organisms inhabit RZs. Some, such as crayfish (which dig extensive tunnel networks as well as surface mounds or towers), are confined to riparian, wetland, or aquatic habitats. Others, such as the red imported fire ant, which builds dense networks of tunnels and large surface mounds, occupy both upland and riparian environments. Still others, such as armadillos and feral pigs, migrate to RZs during dry periods for foraging.

Bioturbation also occurs due to trees. Mass displacement by root growth, and infilling of stump cavities may be significant (Phillips and Marion, 2006), but the major impact is via uprooting, where large volumes of soil may be displaced. In addition to the displacement, uprooting often leaves behind a characteristic mound-pit topography, which may provide significant local topographic heterogeneity in this environment. In addition, tree uprooting on natural levees sometimes creates local weak spots where crevasses may occur.

Biogenesis refers to landforms created mainly or entirely by organisms. The two most important RZ examples are beaver dams and ponds (though in alluvial rivers beavers will often utilize bank burrows and have no need to construct dams), and Histosols. Histosols are organic soils (peats and mucks) that often form in wet environments due to slow anaerobic decomposition of plant remains.

The most important biotic erosion effects in the RZ involve the trampling of pathways roughly perpendicular to the river for water access. This results in local soil erosion, and may contribute to bank instability. Gaps in the natural levee associated with such activity also provide potential crevasse sites. These impacts are often associated with livestock, but may occur due to wildlife species, too. Bank slides created by, e.g., alligators and otters may also be locally significant.

Backwater areas in the RZ, especially those where recirculating eddies occur, may contain thick deposits of organic matter. Floating organic debris becomes trapped in these flows, and is deposited after recession of the high water. Riparian vegetation also traps sediment during high flows and promotes deposition. Large woody debris may have the same effects.

RIPARIAN LANDFORMS

A number of geomorphic characterizations of Texas rivers have been carried out using the river styles framework (Phillips, 2006; 2007; 2008a; 2008c; 2011a; Phillips and Slattery, 2007). A detailed exposition of the river styles framework is given by Brierley and Fryirs (2005).

The river styles (RS) approach is hierarchical, with the catchment (watershed or drainage basin) as the broadest unit. Within watersheds are landscape units, which in the Texas examples translate to physiographic units. Within landscape units are the styles themselves, defined at the reach scale. *Geomorphic units* (GU) are specific landforms within reaches, e.g. point bars, natural levees, and riffle-pool sequences. Hydraulic and microhabitat units are the most detailed level in the RS scheme, comprising specific hydrological and ecological elements such as large woody debris, bedforms, aquatic vegetation, and individual flow obstructions or roughness elements.

Geomorphic units are erosional, depositional, or transportational landforms, referred to by Brierley and Fryirs (2005) as "the building blocks of river systems." Each GU represents a distinct form-process association. Geomorphic units are generally capable of significant change on the scale of approximately one year, but may range from ephemeral to persistent due to the episodic, threshold-dependent nature of geomorphic change.

ALLUVIAL VALLEY LANDFORMS

Coffman et al. (2011) synthesized geomorphic units found in alluvial valleys of Gulf Coastal Plain Rivers of Texas. They distinguished between valley units in lowland, coastal plain environments, and channel units. Valley geomorphic units include floodplains themselves, as well as alluvial terraces (former floodplain surfaces isolated by river downcutting). Because Texas rivers have undergone several cycles of incision and aggradation, as well as Holocene sea level rise, some terraces are now at or near the level of modern floodplains and are regularly inundated (Alford and Holmes, 1985; Blum and Aslan, 2006; Blum et al., 1995; Morton et al., 1996; Rodriguez et al., 2005). Other valley landforms discussed by Coffman et al. (2011) include crevasses and crevasse splays, cross-valley tributaries, paleochannels, anabranches, distributary channels, natural levees , and meander cutoff features (oxbows and meander scars). Coffman et al. (2011) also list floodplain depressions and tie channels (small channels connecting depressions with the active river channel).

Floodplain lakes on Texas rivers are treated in detail by Hudson (2010), who identified five mechanisms for lake formation, including cutoffs, avulsions, scour troughs due to flood incision, depressions associated with sedimentary deposition patterns, and neotectonics or subsidence. Paleochannels and cutoff features may take many forms, depending on the original channel change mechanism, their age or stage of development, the specific geomorphic and hydrologic context, and geomorphic changes since channel abandonment. In general, these include oxbow lakes, oxbow swamps, and meander scars, while longer channel segments may be flow-through or active anabranches, high-flow channels, tributary occupied, sloughs (billabongs), or infilled (Phillips, 2009; 2011c).

The hydrologic connectivity of floodplain lakes and depressions with the active river channel is important for a number of geomorphic, hydrologic, and ecological functions of riparian zones. Connectivity has been examined for Texas floodplain lakes and abandoned channel water bodies by Osting et al. (2004), Hudson (2010), and Phillips (2009, 2011c). Modes of connectivity include (Phillips, 2011c):

(1) Flow-through, where river flow regularly passes through and returns to the main channel.

(2) Flood channel, where there is no hydraulic connections at normal flows, but at high flows the floodplain channels convey discharge, at least part of which returns to the main channel.

(3) Fill-and-spill: At high flows the features fill to a threshold level, and then overflow into flood basins.

(4) Fill-and-drain, in which the features fill at high river discharges but do not (except in large floods) overflow. As river discharge declines water drains back to the river.

(5) Fill-and-hold, where the depressions fill during floods, but do not normally overflow or drain back to the river.

(6) Tributary-occupied: Tributaries draining to the abandoned channel continue to occupy it, flowing through it to the active channel. (7) Disconnected, where no flow is exchanged except during large floods.

The guidebook for application of the hydrogeomorphic method for assessment of wetlands in alluvial valleys of east Texas (Williams et al., 2010) identifies landforms in the region which are typical of those found in alluvial valleys of meandering rivers in general, including point bars, natural and artificial levees, abandoned channels, backswamp deposits, abandoned channels, and alluvial terraces. Backswamp areas are local low areas typically bounded by small alluvial ridges that represent former natural levees (termed point bar swales by Williams et al., 2010).

The geomorphic units identified in the lower Sabine River by Phillips (2008b) are shown in Table 4.3. These appear to be common to many, if not all, alluvial rivers in the Texas coastal plain region, based on observations in the Neches, Trinity, Navasota, Brazos, Guadalupe, San Antonio, and Nueces Rivers. Only a few features in Table 4.3 are not already mentioned above. These include channels that function as tributaries to the main channel at low flows, but distributaries or anabranches at high flows, sediment fans or wedges along valley walls due to deposition from tributary streams entering the valley or from slope processes, and the large Pleistocene meander scars and depressions that are distinct from those associated with the modern river. Also included are the islands that occur in anastomosing reaches of the Sabine and its tributaries.

BANK LANDFORMS

Mid-channel landforms are not riparian landforms (except to the extent that they exist in cross-valley-bottom tributaries and subchannels), but the channel banks can be considered part of the riparian zone. Coffman et al. (2011) recognize banks themselves as geomorphic units, and Phillips (2008b) subdivides these into several morphological types, including bedrock-controlled, concave (in profile), convex, straight, convex upper with concave lower bank, concave upper with concave lower banks, and channel banks buttressed by bald cypress roots, knees, and trunks. Coffman et al. (2011) also list bank failures, similar to Phillips (2008b), who recognizes both active slump features, and slump scars. Point bars and cross-bar or chute channels can also be considered important to the riparian environment. The sand rampart described by Phillips (2008b) on the Sabine (a thick sandy deposit draping the bank and extending from the base of the bank to the natural levee) has not yet been observed in other Texas locations, but similar features have been identified elsewhere.

Features with approximately flat surfaces along the channel bank, but below the level of the floodplain, are termed benches or insets if depositional, and ledges if erosional (Phillips, 2008b; Coffman et al., 2011).

NON-ALLUVIAL RIPARIAN LANDFORMS

No specific suite of landforms or geomorphic units is recognized for non-alluvial riparian areas. In general, riparian landforms in these systems comprise a subset of the alluvial valley forms discussed above, and hillslope forms. Non-alluvial streams may have small, discontinuous, or pocket floodplains and small-scale versions of the associated landforms. Bank landforms are also present, but unless channels are deeply incised the complex morphological forms are rare. Hillslope forms are those typically found in toeslope areas, including alluvial, colluvial, and debris fans; colluvial or cumulic soils and regoliths, and occasional slope failure features.

Table 4.3. Floodplain and alluvial valley geomorphic units (landforms) of the Lower Sabine River (see Phillips, 2008b, for specific examples).

Geomorphic Unit or Landform	*Alternate names/terms*
Abandoned channel (infilled)	Paleochannel
Abandoned channel (semi-active, high flow)	Flood channel
Anabranch	Subchannel
Delta distributary	
Alluvial distributary	
Slough	Billabong
Low-flow tributary/high-flow distributary or anabranch	
Tie channel	Batture channel
Alluvial/colluvial fans or wedges (valley wall)	
Backswamp, ridge-and-swale	
Backswamp, flat	
Pleistocene meander scars/depressions	
Cutoff meander	Chute cutoff
Oxbow lake or swamp	
Infilled oxbow	Meander scar
Crevasse splay	
Crevasse channel	
Natural levee	
Island	
Tributary	
Alluvial terrace	River or fluvial terrace

A GEOMORPHIC FRAMEWORK FOR UNDERSTANDING RIPARIAN ZONES

CROSS-VALLEY AND DOWN-VALLEY FLUXES

Two key geomorphological concepts lend themselves to the interpretation of the topography, hydrology, pedology, and ecology of riparian zones. The first is the relative importance of cross-valley vs. down-valley fluxes and gradients; the second is the palimpsest concept (see next section). With respect to cross- and down-valley gradients, two endpoints can be identified, from non-alluvial headwater streams, to the lowermost reaches of large alluvial rivers. In the former, hill and valley side slopes are long relative to upstream channel lengths, local hillslope drainage areas are relatively high relative to upstream drainage areas, and the riparian slope normal to the stream channel is likely to be steeper than riparian slope on an upstream-downstream axis. The absence of floodplains also provides limited buffering of channels from fluxes across the riparian zone. These areas are strongly influenced by cross- valley as well as down-valley fluxes.

In a large alluvial valley, by contrast, the riparian zone is essentially a floodplain, with low or flat cross-valley slopes, and upstream drainage areas very large compared to local hillslope/riparian drainage area. The large alluvial valleys are strongly dominated by downvalley fluxes.

Of course, many intermediate situations occur, and other factors also influence the relative importance of cross- and downvalley processes. More frequent and lengthy flooding increases channel and riparian connectivity and enhances cross valley fluxes, as does hydrologic connectivity of floodplain depressions. Figure 4.3 shows the major factors influencing the relative importance of cross- and downvalley processes.

The relative prominence of along-valley and across-valley processes has implications for vegetation zonation and ecological patterning (see, e.g., Bendix, 1994), distribution of sedimentary surface covers and soil types, and management options for riparian zones.

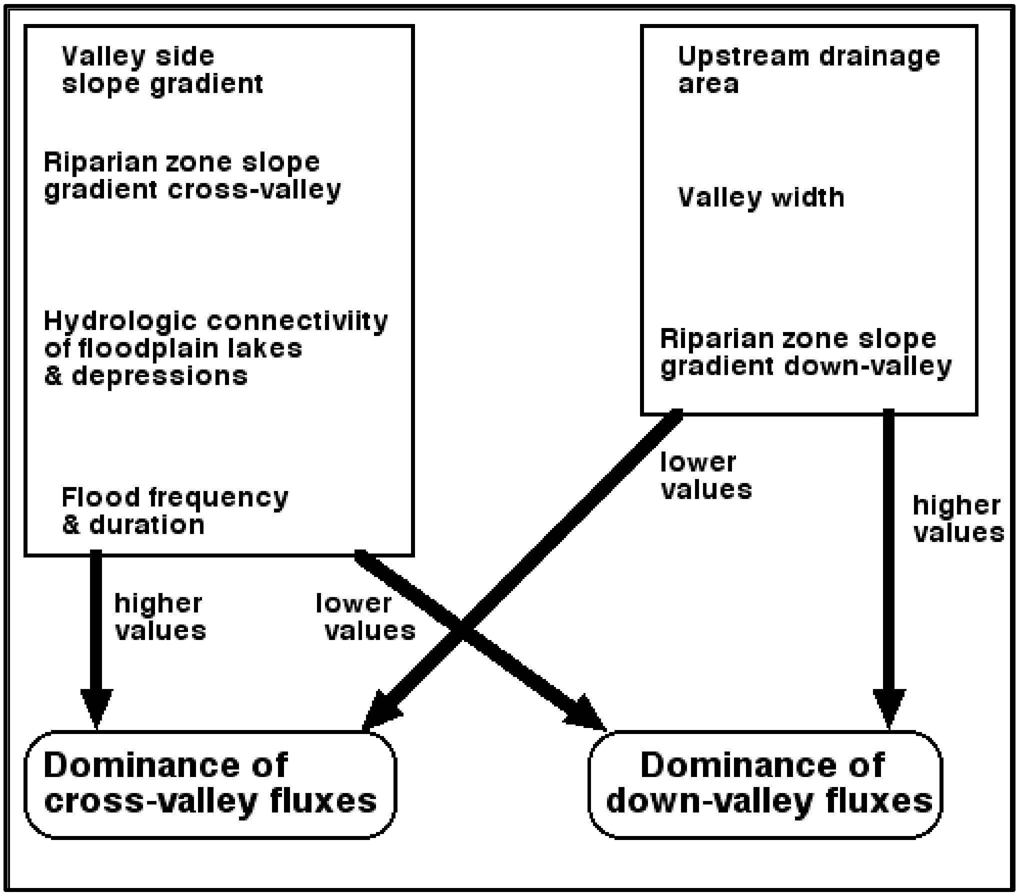

Figure 4.3. Major factors influencing the relative importance of cross- and down- valley fluxes.

AGE AND ACTIVITY OF RIPARIAN LANDFORMS

A palimpsest is a manuscript, typically parchment or papyrus, which has been written on more than once, with the earlier writing incompletely erased and still evident. The palimpsest metaphor is often applied to landscapes by geomorphologists, based on the fact that, even in landscapes such as fluvial and riparian where geologically contemporary processes and features are paramount, evidence of previous geomorphological regimes remains, and inherited features are a significant portion of the landscape. Several case studies show how various pre-Holocene—and older—features exert strong influences over alluvial morphology and processes in Texas rivers (e.g., Rodriguez et al., 2005; Phillips, 2007; Taha and Anderson, 2008; Phillips and Slattery, 2007; 2008).

Figure 4.4 shows the array of landforms of various ages and degrees of activity, with examples commonly found in Texas alluvial valleys. Active features are geologically modern, and subject to frequent modification at a range of flows. Semi-active features are similar, but are subject to modification only during high flows. Active transformed landforms are subject to ongoing or frequent modification, such as sediment accumulation, but are transformed in the sense that they were once (in the case of the examples of Figure 4.4) part of the active river channel, and transformed by processes such as cutoffs and avulsions. Transformed features may also be semi-active (modified only at high flows) or passive. The latter are minimally modified during all but the largest flood events, but exert significant influence over water and sediment fluxes and deposition.

Inherited features are similar to passive transformed landforms, but are one or more steps removed, in the sense that they reflect geomorphic and hydrologic regimes no longer active. The best Texas example is the large depressions and meander scars associated with higher discharges in the Pleistocene (often called Deweyville meander scars; Alford and Holmes, 1985; Blum et al., 1995; Sylvia and Galloway, 2006; Phillips and Slattery, 2008). The "ancient" category, in this context, refers to pre-Quaternary features of the alluvial valley. In the Gulf Coast region a common example is Cretaceous fault systems (and associated surface features) that exhibit neotectonic movements or reactivation by Quaternary sedimentation or human agency (e.g., Ouchi, 1985; Schumm et al., 2000; White and Morton, 1997; Phillips, 2011b).

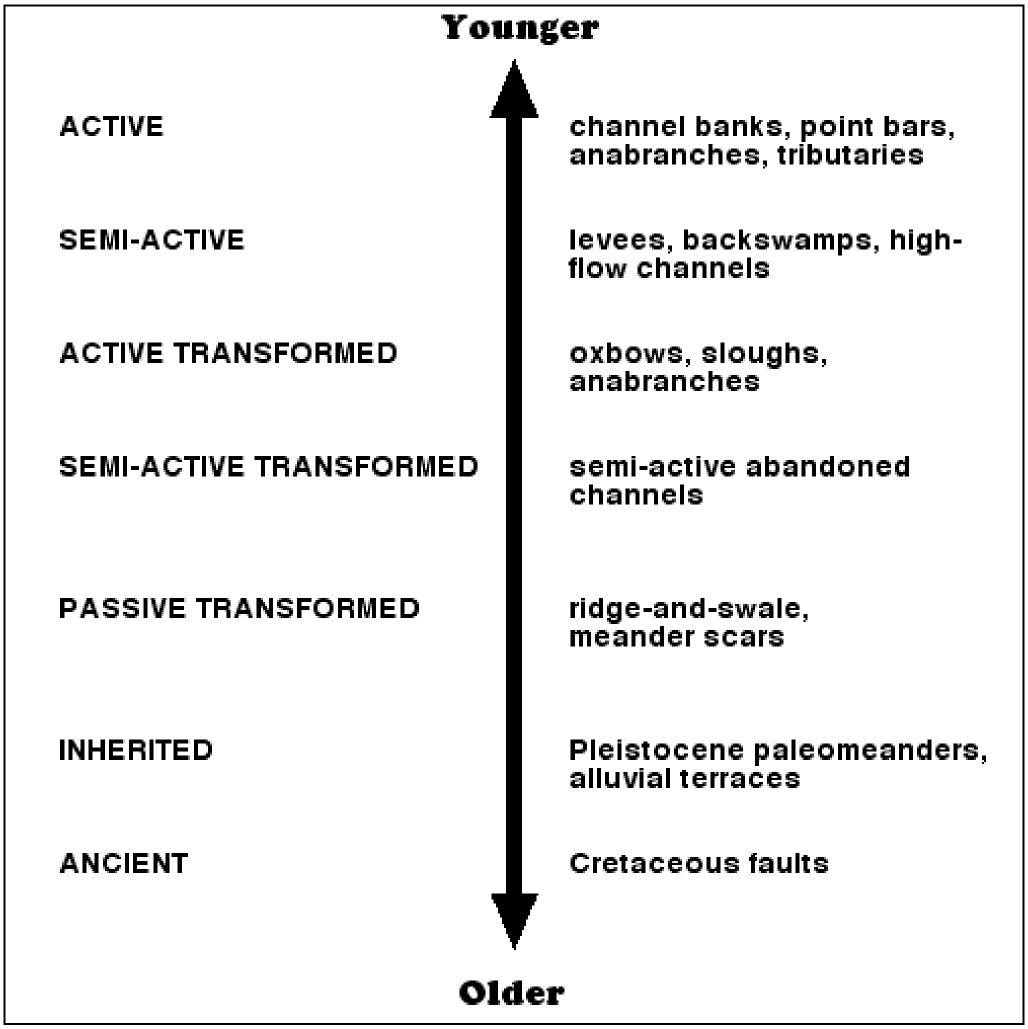

Figure 4.4. Description needed Relationship between geomorphic time scales and riverine channel features.

The view of riparian areas as active, dynamic features profoundly and frequently influenced by contemporary geomorphic processes is accurate. However, even in alluvial river valleys historical contingency, geological controls, and antecedent or inherited features are significant.

CONCLUDING REMARKS

Landforms and geomorphic processes in riparian zones both reflect and affect hydrological, ecological, and pedological features and processes. Because of this, geomorphic indicators of hydrological, ecological, geological, climatalogical, and anthropic processes, controls, changes and disturbances are a key tool in riparian zone science and management. Further, riparian landforms are critical, and in many schemes the predominant components or building blocks in the description, assessment, and characterization of fluvial and alluvial environments.

Fluvial and riparian areas are inherently dynamic and subject to frequent and chronic change. Riparian landforms, therefore, are features that may change and evolve (or appear or disappear) over timescales relevant to management. Specific delineations of riparian landforms must be considered impermanent and contingent. It must also be recognized that fluvial and riparian landscapes may reflect effects of a relatively recent events rather than any sort of "normal" or typical conditions. Even in geologically recent alluvial systems, antecedent or inherited features and controls are often significant—fluvial systems exhibit geomorphology memory. Riparian zones are influenced by both cross- and down-valley fluxes, with their relative importance varying from lower to higher-order streams, and influenced by local variations in factors such as valley and floodplain width.

Riparian landscapes, like other geomorphic systems, are infinitely variable. Thus, no system of definitions or classifications can be expected to fully accommodate the variety observed in real fluvial systems. Exceptions and uncertainties are inevitable, and a flexible approach that recognizes variability and change is required.

CHAPTER 5 - RIPARIAN SOILS (JOHN JACOB)

What kinds of soils occur in the floodplains of the Texas coastal plain? Can soils be used as a guide to identify riparian zones? Can we know anything about the riparian zone if we know what kinds of soils are found in floodplains? These are the questions I attempt to answer in this section.

Riparian soils are associated with rivers. They are soils that are influenced in one way or another by rivers. However, this definition is much too broad. Virtually all of the broad Texas Coastal Plain, defined here as all of the sediments Gulf-ward of the Balcones Escarpment, would be riparian by this definition, given that practically all of the sediments in this zone were laid down by the ancestral analogues of the present-day rivers that drain Texas, in a process of erosion and deposition that has gradually been filling in the Gulf during the past 65 million years or so. All of these sediments are thus riverine, or fluvial in origin, but most are not riparian.

The "*active*" floodplain is how riparian soils will be defined for this section. The floodplain is where *lateral* water flows occur: overbank flows associated with frequent or infrequent flooding events (Malanson 1993). This process, lateral water flow, determines in large degree the nature of the soils that exist in this zone. The active presence of the processes of overbank flow, erosion, and deposition result in weakly developed soils that are characterized in many ways more by their depositional signature than by soil development processes.

The same processes that formed and that are forming the active floodplains today (lateral and vertical erosion and deposition by a meandering stream across an alluvial valley) formed the ancestral floodplains that have long since been uplifted or abandoned and dissected, and that are no longer subject to the direct influence of the river (essentially all of the land coastward of the Balcones Escarpment, with the exception of the Sand Sheet). The key qualifier here is *active*: in the riparian zone erosion and deposition are occurring today or occurred in the recent past. The "recent" past may be a very long time ago in human terms, as much as 10 thousand or so years ago, but this is the *very* recent past in geologic time, and it is known as the Holocene geological epoch. This is just enough pedologic[5] or soil time to form recognizable features of soil development, but not enough time to develop the stronger soil features found on older surfaces.

How well developed soils are, or perhaps more precisely, how *un*developed soils are, can thus serve as somewhat of a predictive guide for the kinds of soils we might expect to find in riparian zones. However, to understand what weakly developed soils look like, we will have to delve at least briefly into the "grosser" details of soil development.

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[5] Pedology is the study of soil in its natural environment, focusing on processes at the landscape and at the pedon (or smallest soil volume for sampling) scales. It includes study of soil formation, morphology, classification, as well as biological processes in the soil (Schaetzel and Anderson, 2005).

After reviewing some of the basics of soil development, and what we might expect to see in a riparian soil, I layout the classic framework of the five factors of soil formation that help explain why particular soils occur where they do, and what this framework might tell us about riparian soils. I then explore Soil Taxonomy, the USDA soil classification system, in terms of riparian soils. I also look at the USDA Soil Survey and how it can be used to predict the occurrence of riparian zones. Finally, I use the Web Soil Survey and the Soil Web to examine soil distributions in riparian zones across the State of Texas.

SOIL DEVELOPMENT –THE VERY BASICS

Sediments can be radically transformed through the processes of soil formation. These processes are a complex combination of chemical and physical, biotic and abiotic processes that result in accumulations, losses, transformations, and translocations (Schaetzel and Anderson, 2005). A distinctive set of soil features will form depending on the context in which the soil is formed (see factors of formation, below). Accumulation of organic material at the surface (the "topsoil"), for example, is one of the very first transformations in the process of turning sediments into soil.

What is the difference, then, between sediment and soil? Some disciplines, such as geotechnical engineering, use the terms interchangeably. One functional definition simply states that soils are "materials capable of supporting plants out of doors" (Soil Survey Staff, 1993). For our purposes, soils are three-dimensional bodies found at the earth's surface that have been transformed by biotic and abiotic processes, and that have both biotic and abiotic characteristics.

Over time, sediments are transformed into soil "horizons" that are characterized by changes, versus the original sediments, in color, structure, and texture, among other features, and that are recognizable as soil attributes distinct from sedimentary or other geologic features. Soil scientists use an ABC nomenclature to classify these horizons:

- A: The topsoil. Maximum organic matter accumulation. Maximum biotic activity (worms, insects, etc). Darkest colors.
- B: The subsoil. Zone of maximum soil development under the A horizon and above the C horizon. Significant soil structure. May be characterized by accumulations of clay, iron, or salts.
- C: A layer relatively little affected by pedologic processes, but may display some weathering. Very often the parent material of the overlying soil. Not indurated.

Additional horizons include E (eluvial or leached horizon) and R (rock or indurated parent material). Soil scientists use numbers and lower case letters in combination with the ABC master horizon symbols to signify a wide variety of soil formation features. A Bt horizon, for example, refers to an accumulation of clay in a B horizon, a Bk horizon an accumulation of carbonates. A Bt horizon could be subdivided into a Bt1, Bt2, and Bt3 horizons based on color or some other differences. All of these symbols have some very specific definitions (Schoeneberger et al., 2002).

Floodplain or riparian soils will typically have an AC horizon sequence: an A horizon directly over a C horizon (usually the stratified alluvium that makes up the floodplain). There has not been enough time, on many floodplains, for significant B horizons to form. Time, in fact, is perhaps the most significant factor of soil formation in riparian zones. However, there are other factors that have a bearing on what kind of soils form in riparian zones, and thus bear some brief consideration below.

FEATURES OF SOIL DEVELOPMENT

There are many properties and features that differentiate soils from parent materials. Soils are extremely complex, perhaps the most complex of any environment on the earth. Not only are soils more complex than we imagine, they are likely more complex than we can even imagine them to be (Gardner, 1991). Even the very young soils of floodplains have very complex food webs and interactions between the biota and the physical-chemical template of the soil. The features of soil development that we can describe in the field are a meager representation of the underlying complexity. However, these are the features that we can easily identify, and they form in large part the basis of our classification system. There are many more of these features than we can examine here. The Keys to Soil Taxonomy (Soil Survey Staff, 2010) lays out the quantitative requirements for many "diagnostic horizons", which are based on developmental features, and it is a source that can be easily consulted for more information.

In pursuit of our quest to use soils to identify riparian zones, it is useful to differentiate, where possible, soil development features according to how fast they form, given that a short time frame, in pedological terms, is what characterizes these soils. Features that take a relatively long time to form would be unlikely in an active floodplain environment.

Examples of Long-Term Features:

- Argillic horizons: accumulations of illuviated (downwardly translocated) clay
- Calcic horizons: significant accumulations of soil-formed calcium carbonate
- Moderate or strong prismatic or blocky structure
- Iron concretions
- Cemented horizons

Examples of Short-Term Features

- Stratification: the absence of any soil feature.
- Bioturbation: displacement and mixing of soil materials by both vertebrates and invertebrates.
- Argilloturbation: displacement and mixing of soil materials through the process of shrink-swell and soil heaving.
- Drainage mottles: soil color patterns associated with poorly drained conditions, including wetlands.
- Organic matter accumulation: topsoil formation.
- Cumulization: organic matter aggradation in floodplains

Features in Riparian Soils

Most important is the *lack* of features. The youngest of soils in the floodplains will be characterized by few, if any, soil development features, perhaps just a weakly developed A horizon. The archetypal floodplain subsoil would consist of slightly or not-at-all modified bedding planes laid down by the river, and would be labeled as a C horizon (see Gaddy soil series side bar). Instead of soil structure or other features, *bedding planes (strata)* are described for this soil. Bedding planes are the individual layers of sediment laid by periodic flooding.

But what is archetypal isn't necessarily what is most common. Most floodplain soils in Texas are in fact described with a B horizon of some kind. However, the structure is usually described as "weak". The strength of soil structure refers to how easy it is to see in the profile. 'Weak' means that some structure can be seen, but it is not very well developed and does not stand out very well. It takes time for prominent soil structure, particularly prisms and blocks, to stand out.

Two very important processes in Texas' floodplain soils tend to confound this model of very simple soils easily distinguishable from upland soils. First is the process of argilloturbation, described above, which is the process of mixing (turbation) as a result of very active clays (argillo). High clay, shrink-swell soils are very common in Texas floodplains. Bedding planes are hard enough to see in a massive lens or stratum of clay, but whatever bedding planes might exist are destroyed very quickly by the mixing caused by the shrinking and swelling, if not heaving, of the

"Typical" Floodplain Soil

Gaddy loamy fine sand.

Taxonomy: Sandy, mixed, thermic Udic Ustifluvents

Ap--0 to 20 cm; brown loamy fine sand; weak fine granular structure.

C1--20 to 51 cm light brown loamy fine sand, *common thin strata of brown fine sandy loam.*

C2--51 to 200 cm; very pale brown fine sand; *common thin strata of brown loamy fine sand and fine sandy loam*.

very active clays found in the Texas coastal plain. The most common expression of shrinking and swelling in a soil is the slickenside, essentially a slip face where soil “slides” as it swells. The presence of slickensides in a subsoil will earn the designation of a B horizon, with a Bss suffix. Argilloturbation also occurs in upland soils of much greater age than floodplain soils. Upland soils affected by this process will be very similar in many respects to younger floodplain soils. For these kinds of soils, then, there is no easily distinguishing feature which would differentiate high shrink-swell floodplain soils from clayey high shrink-swell upland soils.

The other confounding process is cumulization, the process of thickening A horizons resulting from slow sedimentation, often of relatively organic matter-enriched sediments. Sedimentation occurs slowly enough that bedding planes are destroyed as the topsoil slowly accumulates, likely through simple bioturbation (Schaetzl and Anderson, 2005). Cumulic soils are common in Texas floodplains. These soils will have deep dark horizons will little or no strata. They will appear very similar to upland Mollisols found on the prairies, which also have an overthickend dark organic-rich topsoil.

Figure 5.1. A “typical” riparian soil with relatively unaltered bedding planes. Coarsewood Series. J Jacob photo.

THE FACTORS OF SOIL FORMATION

The five factors of soil formation were conceptualized by Hans Jenny almost 80 years ago (Jenny 1980), and they remain one of the main frameworks, if not the guiding framework, for understanding why given soils occur where they do. A brief understanding of these factors would be very helpful for understanding what kinds of riparian soils occur where they do in Texas.

$$S=f(CLORPT) \qquad 5.1$$

Soil is a function of **Cl**imate, the **O**rganic biota, **R**elief, **P**arent material, and **T**ime (Jenny, 1980).

Pedologists spend considerable time trying to isolate the influences of each of these factors, but in reality they are tightly intertwined and difficult to parse out. Nonetheless, CLORPT is a powerful framework for understanding soil distributions on the landscape and across the globe. Each of these factors is defined and briefly discussed below in the context of floodplain or riparian soils

Climate: On a global scale, climate is perhaps the most important predictor of soils. Desert soils are completely different from soils of the humid tropics, no matter the amount of time, kind of parent material etc. Even on a Texas scale, climate plays a very large role, with zones of precipitation surplus in the east ranging to zones of precipitation deficit versus evapotranspiration in the west. Wetland soils, for example, (discussed in greater detail below) predominate the floodplains of East Texas, but are only a minor part, if even present, of the floodplains of West Texas.

Organic biota. The biota includes the influence of both animals and vegetation. In the same climate, forests give rise to significantly different soils than those of the prairies. Forest soils will often be more acid and contain less organic matter than otherwise analogous grassland soils, for example.

Relief. Topography or landscape position often determines how much water is available for leaching and other pedogenic processes. Soil in a concave water-gathering landscape position will be more strongly developed than a similar soil on a water-shedding or convex landscape position. Most floodplain soils are going to be on planar slopes, but there will also be an abundance of convex and concave landscape positions on a meso-scale. Channel scars, sloughs, oxbows, etc are all concave, and soils formed in these positions will very often either be hydric or near-hydric soils, compared with the much drier soils of a convex meander scroll, for example.

Parent material. Because so little time is available for soil formation in riparian zones, riparian soils are more often than not dominated by the characteristics of the parent material or sediments in which they are forming. Riparian soils are perhaps most strongly characterized by the particle size of the sediments they are made up of; whether or not they are clayey or sandy, for example.

Time: climate, the biota, and relief need time for their effects on the parent material to be expressed. Thus, time itself is a factor of soil formation, and the perhaps the most important one in terms of floodplains or riparian zones, because riparian zones are usually among the youngest surfaces in the landscape. We thus tend to see very few features in floodplain or riparian soils associated with strongly developed soils.

In terms of riparian soils, parent material in general is going to be a determining soil formation factor, primarily because so little time will have been available for the other factors to exert their influence. Nevertheless, across a big state like Texas, there will be major differences, for example, between clayey soils on the Rio Grande versus those on the Sabine floodplains simply because of the climatic gradient. The soils on the Sabine might be underwater for several months at a time, whereas there will be only occasional overbank flooding on the Rio Grande. In addition, within a given floodplain, of course, there are pronounced topographic differences. A convex meander scar soil will be saturated for much shorter periods than adjacent convex soils. However, the generalization that riparian soils exhibit less variability from the effects of soil formation than adjacent upland soils is a valid one.

SOIL CLASSIFICATION/TAXONOMY

Soil classification can seem a bit more intimidating than botanical taxonomy, but just as in botany or zoology, a classification system is an essential way of referring to groups of objects. In a sense, classification is a short-hand way of packaging a lot of information into just a few words. Understanding the classification or taxonomy of riparian soils, then, beyond just being labeled "riparian", could open some valuable windows of understanding about the properties of riparian soils. Soil Taxonomy is much less intimidating than it appears to be.

Only the briefest introduction to soil classification is provided here, with a few shorthand tools to facilitate a basic understanding of a very complex system.

The most basic taxon is the soil *series*, in some sense equivalent to the biologic species. A soil series is a recognizable set of soil horizons and features in a specific biophysical context; for example, the Gaddy series described in the sidebar above. Soil series are tied to specific landscape and geologic features. A soil mapped on a bottomland or floodplain would not be mapped on adjacent upland surfaces no matter how similar the soil morphologies (See the discussion below on soil survey).

Classification above the series level gets very complex very quickly. Soil Taxonomy (Soil Survey Staff, 2010) is an incredibly complex system extending to hundreds of pages of criteria involving minutia comprehensible to only the most highly trained professionals. Yet for all its complexity, it is built on a very simple framework with some fairly simple elements. If this framework and the formative elements are understood even on only a very elementary level, significant meaning can be extracted from otherwise incomprehensible phrases such as *Lithic Psammaquents* or *Mollic Glossaqualfs*. A list of the taxonomic formative elements is provided in Appendix A.

The key is understanding both the framework (Figure 5.2) and the formative elements (Figure 5.3) that make up the system. The framework is a well-organized hierarchical system. The highest level is the Order, followed by the Suborder, and then the Great Group and the Subgroup[6]. There are only 12 orders at the high end, but there are several hundred taxa at the Subgroup lower end. There is of course much greater generalization at the order level, and much more specificity at the Subgroup level.

The formative elements fit onto this framework. The formative elements for the most part were derived from Latin and Greek roots. They refer to a wide variety of soil features, such as color, texture, salts, shrink-swell, etc. See the Formative Element list in Appendix A. "Mollic" is one such formative element. The term is derived from the Latin term *mollis*, which connotes softness and pliability. Within Soil Taxonomy the term refers to mineral soils with relatively high organic carbon content and that are both soft and dark, and there are of course very precise definitions of just how dark and exactly how much organic carbon content is required.

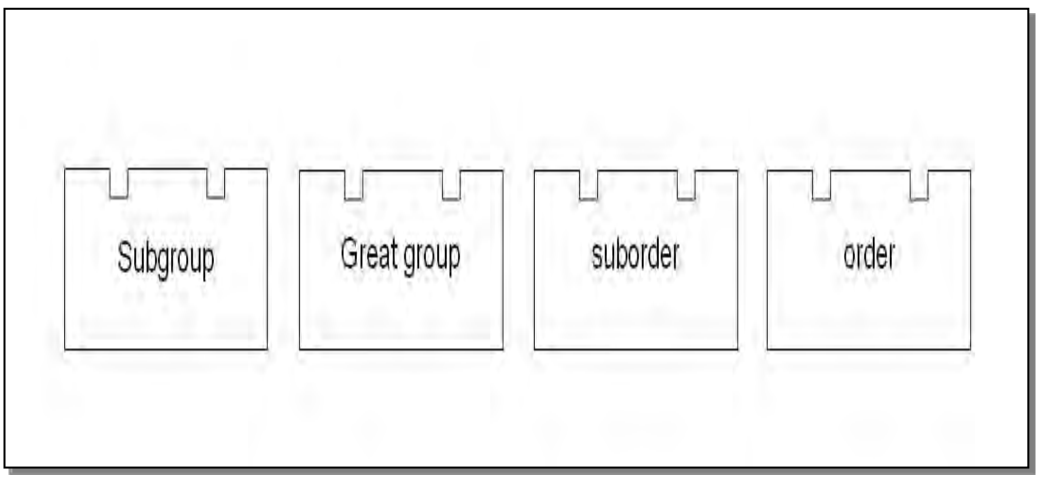

Figure 5.2. Soil Taxonomy framework. Four molds or guides upon which the formative elements can be placed.

[6] Below the subgroup, there is a family and a series level of classification. The soil series we deal in the section on soil survey. The family level deals mainly with particle-size, mineralogy, and temperature, and will not be addressed here.

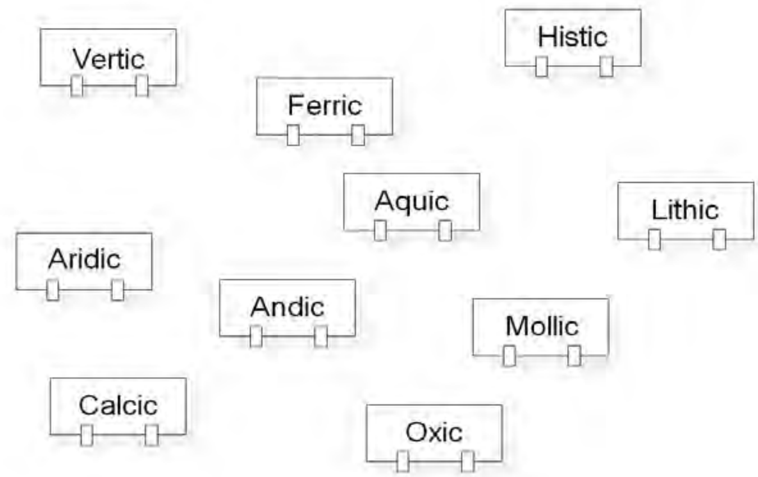

Figure 5.3. Some example formative elements (see Appendix A for interpretation), ready to be placed on the framework “guides” or molds in Figure 5.2.

The Formative Element list simply points to what a particular element refers to. Vertic, for example, refers to soils that ‘invert’ or turn. These are high shrink-swell soils. For a soil to be classified as a Vertisol, a series of quantitative metrics must be satisfied; for example high clay content and cracks that are of specific size and that are open for specific periods of time. The requirements are somewhat different but no less quantitative at the subgroup level. The point here is that it is not necessary to fully comprehend the highly quantitative side of Soil Taxonomy in order to be able to derive some significant meaning from these otherwise inscrutable names.

Not every formative element can fit onto each building block of the templates. There are only 12 orders, for example. The Mollic and Vertic elements mentioned above, and 10 others, can be placed on the Order guides or templates. Progressively more elements fit on each of the guides moving from right to left. Many, if not most, formative elements fit on the Subgroup mold, including those elements, such as Mollic and Vertic, that also fit on the Order mold.

One of the strengths of Soil Taxonomy is the provision for *intergrades*, taxa that don’t quite make the grade for a particular order, but yet have some important characteristics of the order. There are many Mollic subgroup level soils, for example, that don’t quite make the grade for the order Mollisols, but that still have relatively dark soft surface soils. Perhaps the surface soil was the right color and texture, but not thick enough.

We can think of the framework then as 4 guides or templates (see Figure 5.2) onto which we place formative elements (Figure 5.3). It is from the formative elements, and their position in the framework, that we can derive some meaning. The higher in the framework that a formative element is found (i.e., the farther it is to the right), the more significant the properties are that are associated with that element for the particular soil being classified.

A Soil Taxonomic "phrase" is formed by placing the Great Group, Suborder, and Order into one "word", with the Subgroup as a separate modifier, for example Fluventic Haplustoll in Figure 5.4. At the Order level, only the endings of the formative elements are used, in this case "oll" for Mollisols. At other places on the template, Moll or Mollic would be used. Using the Formative Element List (Appendix A), we can see that this soil would be a dark and soft mineral soil (Mollic or Mollisols), with a relatively high amount of organic carbon, that is found in a dry area (Ustic), with simple horizonation (Haplic), and with some "fluvial" characteristics (Fluventic). The "Fluv" modifer signals that this is a riparian soil. This level of understanding is far from what a pedologist would be able to infer from the taxonomic name, but it should be clear that some fairly significant meaning can be derived using the formative element list and understanding the positional relevance of guides or "building blocks" of the system.

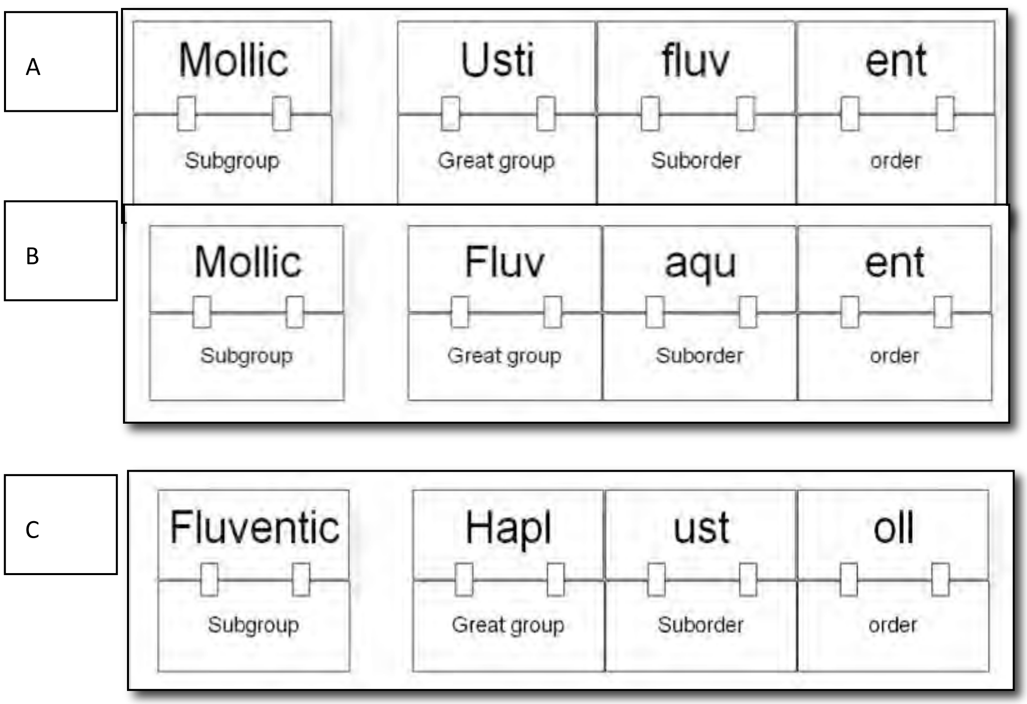

Figure 5.4. Three soil taxa using the formative element "fluv", progressively lower in the system. The first two (a and b) are in the Entisol order ("ent" formative element). The third (c) is in the Mollisol order ("oll" formative element). All three are riparian soils, but the fluventic character is most pronounced in the first taxon in this figure. The "mollic" formative element is also repeated in all three taxa. In the third taxon it occurs at the order level, and we would thus expect the mollic properties to be most strongly expressed in this soil.

SOIL TAXONOMY IN THE FLOODPLAINS OF TEXAS

Floodplain soils have figured into just about every soil classification system that has ever existed, from ancient to modern. Riparian soils have always been recognized as uniquely different from other soils, and this is no less true in Soil Taxonomy that it is in any other system of soil classification.

Time is perhaps the most important soil forming factor (see above) that distinguishes floodplain or riparian soils from upland soils. Specifically, riparian soils have had much less time to weather and develop compared to upland soils on older surfaces. Riparian soils are very *recent* soils, in geologic or even pedologic time. Soil Taxonomy recognizes weakly developed, relatively young soils at the highest level, in an Order all their own: the Entisols, etymologically derived from rec*ent*. The Entisols are at the very end of the dichotomous Keys to Soil Taxonomy (Soil Survey Staff, 2010), after all of the other kinds of surface and subsurface horizons and other features have been exhausted.

Entisols occur in more places than floodplains. They can occur for example on steep rocky slopes where erosion continuously rejuvenates a surface, or on a recent lava flow. A specific fluvial formative element, "fluv", was developed in Soil Taxonomy for recent soils in floodplains. A "Fluvent" is thus the prototypical floodplain or riparian soil. Quantitatively, the key characteristic of fluvic or fluventic soils is an irregular decrease of organic carbon with depth. An upland soil will typically have a uniformly decreasing distribution of organic carbon below the topsoil. A riparian or fluventic soil, on the other hand will have an irregular depth distribution due to the differing amounts of organic carbon that could be present in each fluvial deposit, or, very commonly, due to the presence of buried soils associated with temporarily stable surfaces.

Riparian soils are thus recognized at a fairly high level within Soil Taxonomy, the Suborder Fluvents. The Fluventic modifier can also be found at both the Great Group and Subgroup levels. Fluvents might be the prototypical or "textbook" riparian soil, but as is well known, textbook conditions are rarely the rule. On closer examination, there appear to be as many exceptions to the rule as there are examples of it. This is certainly the case with riparian soils. On a young floodplain surface subject to periodic inundation and sedimentation, a Fluvent is exactly what is expected. However, other processes are sometimes occurring in floodplains that result in different outcomes than what we might expect, as discussed below.

For example, clayey sediments are very common in the floodplains of the Texas Coastal Plain. However, they are not just any kind of clays. Montmorillonite is one of the most common clay minerals in the sediments of the Texas Coastal Plain. A key characteristic of montmorillonite is a very high shrink-swell potential. Soils with high amounts of montmorillonitic clays swell or increase in volume when wet, and they shrink when dry. Large cracks are very common in the summer. This kind of soil activity is so profound and affects so many other features of the soil that is it recognized at the highest level in Soil Taxonomy: the Vertisol order. Argilloturbation is so overwhelming of other soil processes that there is no real differentiation between Vertisols in uplands and Vertisols in floodplains. For example, there are no Fluvic or Fluventic taxa at any level within the Vertisols, although there are many Vertic subgroups, interestingly, of the Entisols, and particularly of the Fluvents, perhaps an indication that if a young floodplain soil meets the order-level criteria for a Vertisol, there is little chance that we would see features such as the irregular decrease in organic carbon with depth, because of the profound mixing resulting from strong shrink-swell phenomena. Cumulization, discussed above, is recognized in Soil Taxonomy exclusively at the subgroup level, and is restricted to floodplain soils. The presence of the “cumulic” formative element is a good indicator of a riparian soil with an overthickened A horizon, for example a Cumulic Hapludoll.

What is *not* likely to be found in a floodplain might be easier to spell out than what will be found there. Clay pan soils with argillic horizons are not likely to be found on a floodplain: no Alfisols and no Ultisols. Most “diagnostic” horizons will not be found in floodplains: no calcic or petrocalcic horizons, no fragipans or glossic horizons. A Mollic epipedon, however, is not uncommon in floodplain soils.

THE SOIL SURVEY AND RIPARIAN SOILS ON THE TEXAS COASTAL PLAIN

Floodplain soils are mapped as part of any soil survey. Soil survey floodplains are not exactly equivalent to Federal Emergency Management Agency (FEMA) maps. The soil survey represents more of a “pedogeomorphic” or soil-landscape approach to floodplain delineation. Hydrographic studies may sometimes inform soil survey delineations of floodplains (See Table 5.1), but more often than not, soil surveyors make use of their first-hand knowledge of landscapes and soil morphology to estimate the flooding frequency of a given floodplain. This method of delineating floodplains may actually be closer to a geo-ecological concept of riparian zones than a precise hydrology and hydraulics study that might inform a FEMA floodplain map, particularly in terms of the rare and very rare flooding frequencies.

The Soil Survey also uses Ecological Site classifications that are coterminous with the floodplain designations on the maps, but that synthesize the information somewhat differently. “Bottomland” ecological sites are the most common designation for riparian zones. Rather than being classified in terms of frequency, the ecological sites may be designated in terms of soil texture or even vegetation; for example loamy or clayey bottomland sites.

Hydric soils. Hydric soils are wetland soils and are defined as soils that are anaerobic in the upper part at some point in the growing season, usually for two weeks or longer, although this period is not defined explicitly. The USDA-NRCS soil survey maintains lists of soil series that are classified as hydric, and maps can be made of these soils. Hydric soils are discussed in more detail in the section on wetlands. It is important to note that hydric soils are *not* coterminous with riparian soils, a common misconception. While virtually all riparian soils were laid down fluvially, and virtually all experience inundation, not all riparian soils are inundated or saturated long enough to develop anaerobic conditions in the upper part. In East Texas, most of the soils in the riparian zone will be hydric, but in West Texas, most riparian soils will be too dry to be hydric, even though they are located in a floodplain.

Table 5.1. Soil Survey flooding definitions and durations (*National Soil Survey Handbook 618.26, http://soils.usda.gov/technical/handbook/contents/part618.html*

Flooding Frequency Class	Definition
None	No reasonable possibility of flooding; one chance out of 500 of flooding in any year or less than 1 time in 500 years.
Very rare	Flooding is very unlikely but is possible under extremely unusual weather conditions; less than 1 percent chance of flooding in any year or less than 1 time in 100 years but more than 1 time in 500 years.
Rare	Flooding is unlikely but is possible under unusual weather conditions; 1 to 5 percent chance of flooding in any year or nearly 1 to 5 times in 100 years
Occasional	Flooding is expected infrequently under usual weather conditions; 5 to 50 percent chance of flooding in any year or 5 to 50 times in 100 years.
Frequent	Flooding is likely to occur often under usual weather conditions; more than a 50 percent chance of flooding in any year (i.e., 50 times in 100 years), but less than a 50 percent chance of flooding in all months in any year.
Very frequent	Flooding is likely to occur very often under usual weather conditions; more than a 50 percent chance of flooding in all months of any year.

Flooding Duration Class	Duration
Extremely brief	0.1 to 4 hours
Very brief	4 hours to < 2 days
Brief	2 days to < 7 days
Long	7 days to < 30 days
Very long	> 30 days

SOIL SURVEY DATA

Soil survey data now accessible to the public was once confined to printed soil surveys for each county. All of this data is now readily available digitally through at least 3 outlets. The data can easily be explored in terms of what has been discussed in this Chapter, taxonomy, floodplains, etc.

GIS DATA: The full panoply of data, with the fullest availability for data manipulation, is provided in the SSURGO and STATSGO databases managed by the USDA Natural Resources Conservation Service (NRCS). This data can be downloaded directly from the Soil Data Mart (http://soildatamart.nrcs.usda.gov/).

This is the only data set that can be fully manipulated and customized, and it requires considerable knowledge of the soil data base itself as well as expertise in geographic information systems. Additionally, it also requires the use of sophisticated GIS software such as ARCGIS. Fortunately, two other outlets are available with more easily accessible data, albeit with less interpretive power.

THE WEB SOIL SURVEY: (http://websoilsurvey.nrcs.usda.gov/). Data is accessed through "areas of interest" (AOIs), no more than 10,000 acres in extent. The AOIs may cross county or parish boundaries. A soil map is provided for the AOI, and data for the map can then be accessed through a Soil Data Explorer. Maps showing floodplains, ecological sites, hydric soils, etc., can then be developed and saved or printed, with an accompanying report for the AOI.

THE SOIL SURVEY ON GOOGLE EARTH (SOILWEB): The soil survey for most if not all of Texas (and most of the country) is now available through a dynamic "kmz" file.[7] Loading this kmz file onto a computer with Google Earth installed provides an impressive amount of soil data, constantly updated. The data is not presented as elegantly as with the Web Soil Survey, and thematic maps cannot be easily developed, but the data is accessible much more quickly across wider areas. A simple click provides the map unit descriptive information, as well as specific information on the map unit components, and, most powerfully perhaps, access to lab data for specific "pedons" or soil bodies where available.

SOME CAVEATS ABOUT THE USE OF THE SOIL SURVEY

Soil surveys in the United States for the most part were developed for agricultural uses, at a scale and intensity consistent with agricultural operations. Soil surveys are not site specific. Farmers speak of the "back 40" acres, and that is about the scale of the soil survey in most places. Most soil surveys specify a minimum size delineation; in central and east Texas this will be about 10-15 acres. In west Texas the minimum delineation may be much larger, perhaps more than 50 acres in some cases. The minimum size delineation means that a surveyor would not delineate smaller patches of differing soil on the landscape. The result is that small areas of distinctive soils, say 5 to 10 acres, would not be separated out in most soil surveys. For a site-specific study, this size could make quite a difference. A minimum size delineation is a critical part of managing a soil survey, as this determines the cost of a survey. Smaller-size minimum delineations exponentially increase the cost of the survey, and for agricultural uses would not add much value.

The second caveat has to do with what is actually mapped in a soil survey. Individual soil *series* are generally not mapped. Soil "*map units"* are what is mapped. Confusion arises because the series names are also used in the map unit names. Some map units may be dominantly one series or another, but some units list more than one series, and all map units have "inclusions" of other soils, but that do not occur regularly from one polygon to

[7] http://casoilresource.lawr.ucdavis.edu/drupal/node/429

another within a given map unit. The soil map unit in other words is not "pure". The user of a soil survey should first consult the map unit description before focusing on the series descriptions.

In spite of the above limitations and caveats, the use of soil survey maps appears to be the simplest if not most accurate method of defining riparian areas on the ground, based on soils, outside of an actual field survey.

WETLANDS IN THE RIPARIAN ZONE OF THE TEXAS COASTAL PLAIN

Riparian zones are associated with wetness. Wetlands are associated with wetness. Therefore, riparian zones are zones of wetlands. This syllogism appears to be in common currency even amongst many scientists. Like many simple syllogisms of this nature, however, it is not at all true. Riparian zones do flood, at least occasionally, but not all of them flood long enough and/or frequently enough to support wetland hydrology. There are many riparian zones with nary a wetland, and many upland, non-riparian zones with an abundance of wetlands.

In this section, we explain what wetlands are, and how they are defined, jurisdictionally and otherwise. We also examine the distribution of wetlands in the riparian zones of the Texas Coastal Plain.

WETLANDS DEFINED

Wetlands are transition zones. They are transition zones between areas wholly aquatic and areas wholly terrestrial. They are *wet lands*: they are neither aquatic nor terrestrial. Wetlands have characteristics of both zones, but there are also emergent properties that are found in neither aquatic nor terrestrial zones.

The fill or destruction of certain wetlands is regulated under Section 404 of the Federal Clean Water Act. Transition zones such as wetlands are, by definition, fuzzy zones with indefinite boundaries. Indefinite or fuzzy boundaries do not lend themselves well to jurisdictional programs that are predicated on being able to precisely delineate zones of concern. Government officials need to know whether a given parcel of land is wetland or not; not that it is somewhat wet or slightly wet. It has to be in or out with no shades of gray.

Section 404 of the CWA is predicated precisely on the ability to accurately draw a boundary around a wetland. A boundary that is based largely on hydrology: saturated or inundated $\geq$ 14 days on one side of the line, $\leq$ 14 days on the other. Aside from the problem of rarely having enough data to be able to precisely find such a line on the landscape, there is the issue of ecological integrity of a wetlands ecosystem. Is the full utility of a wetland ecosystem at all maintained when we only preserve the middle member of the transition zone, the wetlands themselves, without taking into account the end members into which the wetlands transition, i.e., the adjacent uplands and water bodies?

Wetlands existed long before the appearance of Section 404 of the Clean Water Act. However, the definition and study of wetlands is now very much colored by this section of law, even in scientific settings. However, because the jurisdictional program offers a very convenient framework for discussing wetland characteristics, we will use it here as well.

The official definition[8] of wetlands focuses on hydrology, vegetation, and soil. To be a "jurisdictional[9]" wetland, an area must satisfy specific criteria for each of these three parameters, and have a "significant nexus" to a traditional navigable water (TNW). Hydrology is the driver; wetlands have to be wet, after all. To be specific, wetland hydrology is met if an area is inundated or saturated for at least 5% of the growing season, and that in at least one single continuous period. In a frost-free zone like the Texas coast, this might be about 2 weeks in most years, and for all practical purposes, the same period pretty much holds for the rest of Texas as well. This is a long-enough period in most soils for anaerobic conditions to develop, and thus create an environment where only vegetation adapted to such conditions can survive.

Hydrophytic vegetation can be identified based on a variety of adaptational features, such as hollow stems. But for jurisdictional purposes, each plant species is given a wetland ranking according to the probability of finding that plant in a wetland, and this ranking can be found by consulting a list[10]. The hydrophytic vegetation criterion is met when at least 50% of the vegetation meets a minimum ranking.

A soil which meets wetland criteria is called a hydric soil. This is a soil that undergoes anaerobic conditions. Note that the definition for soils and hydrology is for all practical purposes identical.

If an area meets all three criteria, and is found to have a significant nexus to a TNW, then the area would be a jurisdictional wetland. Currently, the US Army Corps of Engineers considers all wetlands within a 100-yr floodplain to pass the significant nexus test. A field scientist rarely has all the equipment on hand to make the detailed measurements needed to precisely determine wetland status, let alone the data time-series that would be necessary to judge accurately how long an area is saturated in most years. Most frequently, the field investigator must rely on *indicators* of saturation and/or inundation, rather than direct observation. Using these indicators, seasoned wetland delineators can make fairly consistent delineations of wetlands. Indicators of hydric soils center on color patterns, primarily drainage mottles, and indicators of hydrology might include such things as wrack lines, tree lines, water-stained leaves etc. See Figures 5.5 through 5.7 below.

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[8] http://www.epa.gov/owow/wetlands/facts/fact11.html

[9] i.e., a wetland subject to regulation by the US Army Corps of Engineers.

[10] https://rsgisias.crrel.usace.army.mil/apex/f?p=703:1:

WETLANDS IN FLOODPLAINS ON THE TEXAS COASTAL PLAIN

There are two major axes with respect to wetland distribution in the riparian zones/ floodplains of the Texas coastal plain (See Figure 5.8). There is a pronounced precipitation gradient from west to east, and as might be expected wetlands in floodplains increase markedly as this axis is traversed from west to east. Medium to large floodplains in east Texas will be close to 100% wetlands, while similar floodplains in west Texas may have no wetlands, or what wetlands that might be present are likely confined to the deepest part of the bottoms, such as deep meander scars or oxbow lakes.

The other gradient is perpendicular to the coast, generally in a NW-SE direction. Wetlands increase on floodplains as one moves coastward, as floodplains widen and water table rise. This gradient is not so evident on large East Texas rivers like the Neches, which is covered in wetlands all along its length. However, on other rivers, wetland coverage invariably increases toward the coast, and the drier the climate, the closer to the coast will be the zone where wetlands increase.

The controlling hydrology for wetlands in floodplains is either from overbank flooding or from groundwater. It is difficult to sort out the relative importance of these two sources, especially in East Texas, where periods of overbank flooding are both more frequent and much longer lasting than areas farther west. Water tables are also much more likely to be higher in floodplains in east Texas. Saturation from below, from water tables, is clearly more of a factor in deep meander scars in east Texas. Very few, if any, actual measurements have been made of riparian wetland hydrology anywhere in the state. As we move toward the west, overbank flooding very likely becomes the dominant component of wetland hydrology, complemented of course by some runoff accumulations and some occasional overbank flooding.

Figure 5.5. Some fence trash in a Texas bottomland. This surface has obviously been inundated. But what does this feature indicate about frequency and duration of the inundation?

Figure 5.6. Standing water is an indication that this area gets wet, but much more significant are the flared trunks of these tupelo trees (which are themselves an indication of wetness) and the very pronounced water lines on these trees. In contrast with the Fig 5.5, these indicators strongly suggest long-term periods of inundation and saturation, likely at least months at a time.

Figure 5.7. Redoximorphic concentrations of iron (red zones) along root channels are a strong indicator that this soil undergoes prolonged periods of saturation and reduction. Photo J Jacob

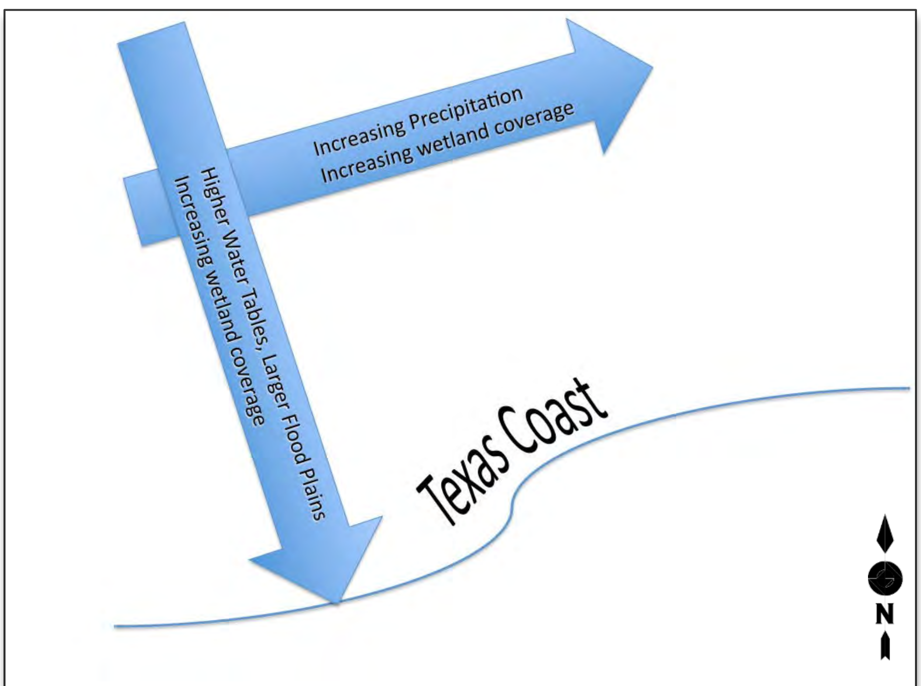


Figure 5.8. Longitudinal axes across and along the Texas coastal plain indicating relative distribution of wetland coverage on floodplains.

APPENDIX A - REPRESENTATIVE SOIL AND WETLAND TRANSECTS FROM FLOODPLAINS ON THE TEXAS COASTAL PLAIN

The Web Soil Survey and the SoilWeb on Google Earth are used here to examine soil changes in the Texas Coastal Plain across floodplains and between floodplains and uplands. Floodplain-soil relationships across the full breadth of wet-dry gradient across Texas are examined. National Wetland Inventory data are examined across the same gradient.

Three transects were chosen to represent range of characteristics of soils and wetlands on the Texas coastal plain (See Figure 5.9). The intent was to place the transects more or less in the mid coastal plain region, e.g., about midway between the Balcones escarpment and the coast. Data, however, particularly for the wetlands, was not equally available across all regions. Thus the West Nueces River transect is considerably farther upstream on the mid coastal plain region just described than the other two transects. While the context for these three transects was perhaps not as well controlled as would be desired, they nonetheless display the broad trends described in the text above.

Figure 5.9. Location of the three soil-wetland transects on the Texas Coastal Plain. Texas geologic map, USGS. The Balcones Escarpment parallels the western contact between the blue and tan colors.

NECHES RIVER TRANSECT: The location and characteristics of the Neches River Transect is shown in Figures 5.10, 5.11, and 5.12.

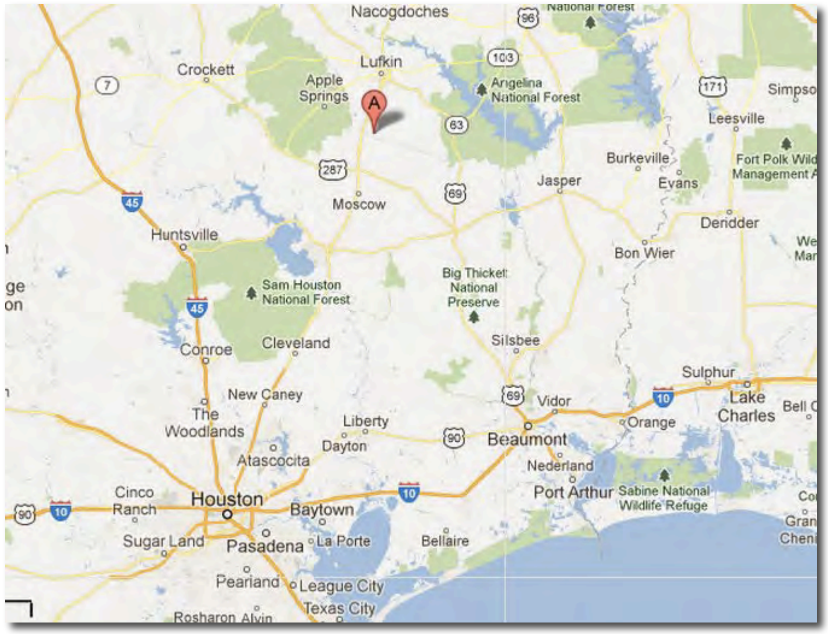


Figure 5.10. Location of the Neches River Transect.

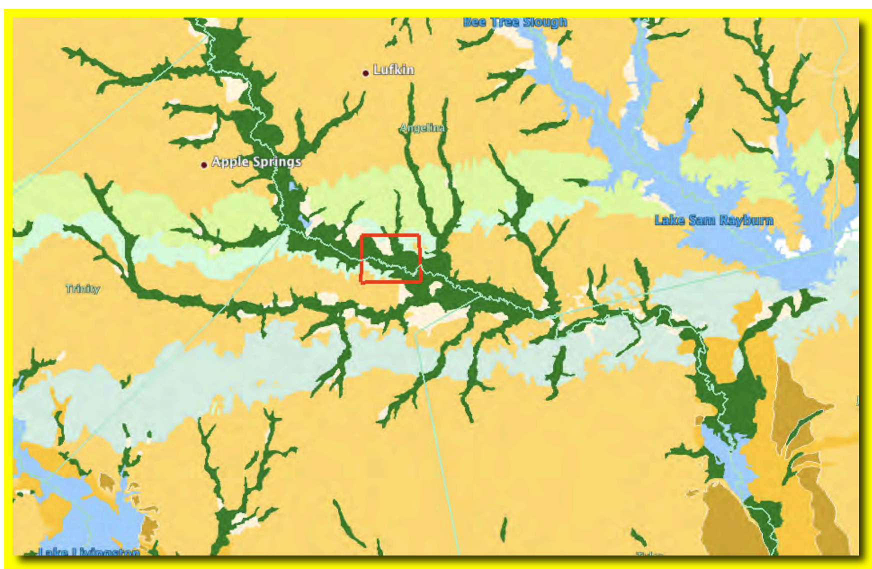


Figure 5.11. Intermediate location map on Texas Bureau of Economic Geology Google Earth geology map. Dark green areas are Holocene alluvium.

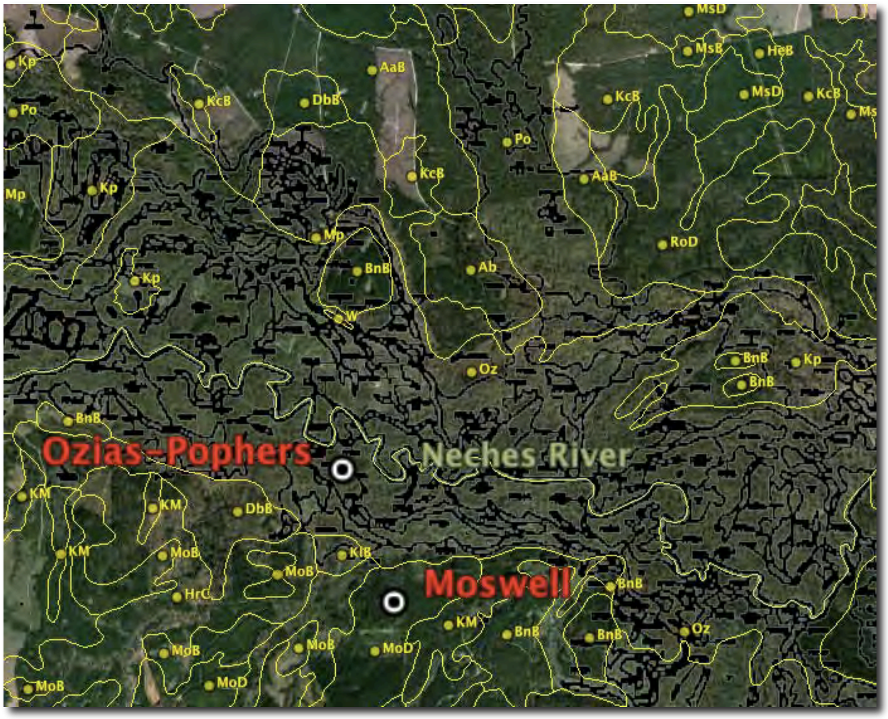


Figure 5.12. Google Earth map of the Neches River Transect. Polk County is to the south and Angelina County is to the north of the river. Yellow lines and labels are from the SoilWeb (http://casoilresource.lawr.ucdavis.edu/). Dots and red labels are soil map units discussed in the text. Black lines and labels are the National Wetland Inventory lines.

The Neches River Transect in Polk County, Texas represents a broad floodplain in east Texas, in an area of relatively high rainfall. The area is in a 45-50 inch rainfall belt. This is the easternmost transect covered in this report.

Inundation: The Neches River in this area floods at least frequently or very frequently according to the Web Soil Survey (see definitions in the text, above). Consultation of the archived PDF version of the printed survey of Angelina County reveals that the deepest part of the floodplain in this transect frequently floods for long periods of time (Ozias and Popher map units), with the shallower parts of the floodplain (Koury map units) flooding frequently for very brief to long periods.

Soil Morphology/Properties: All of the floodplain mapping units in this transect are labeled as "partially hydric". The *named* series in all of the floodplain units of this transect are hydric. The "partially hydric" label indicates that non-hydric inclusions might be found in these map units. Long periods of flooding guarantee that anaerobic conditions will occur in saturated soils in most years in this floodplain, and that most of the soils on this floodplain are hydric.

Figure 5.12 shows the two main floodplain/riparian soils in this transect and one adjacent upland soil for comparison. No lab data are available for these soils from the National Soil Survey Laboratory.

The two floodplain soils (Ozias and Pophers) both have aquic moisture regimes, evidenced by the "aqu" formative element in the suborder level. The aquic element indicates substantive saturation with water, and is consistent with the hydric status.

The Pophers soil profile exhibits classic floodplain morhphology with an irregular distribution by depth of organic carbon. This soil has a "buried" topsoil in its profile, indicative of earlier periods of reduced sedimentation and stable periods of soil formation. The "Agb" horizon in this soil is a buried soil that was formerly at the surface. A similar period of soil stability also likely occurred where the Ozias soils are mapped today, but the Ozias soil is very clayey throughout, such that *argilloturbation* likely has obliterated any remnants of a buried surface soil. The "Bss" horizons in the Ozias soil indicate the presence of slickensides, slip planes associated with active soil movement (shrink-swell activity). The Ozias series is a Vertisol, that is wet (aqu), that is somewhat leached of nutrients (Dystr), and somewhat on the dry side of wet (aeric).

The Pophers soil is an Entisol, meaning minimal soil development is present. The Pophers is wet (aqu), with floodplain characteristics (Fluv—bedding planes or irregular distribution of organic carbon), but somewhat more aerated or drier (Aeric) than the typical Fluvaquent.

By comparison, the adjacent upland Moswell soil series is a strongly developed clay pan soil (Alfisol), in a humid moisture regime (ud), within the central concepts of the Udalfs (hapl), but with significant shrink-swell activity (Vertic). The "Bt" horizons in the profile of the Moswell soil in Figure 5.13 indicate the location of the "argillic" or clay pan horizon. The ss designation in the B horizons are where the maximal expression of shrink-swell features occur. Note also the much brighter colors in the cartoon version of the Moswell subsoil versus the much darker colors of the floodplain soils. The grayer colors of the floodplains soils (represented by the "g" suffix in the B horizons of these soils, for "gleyed" colors) are consistent with the poorly-drained condition of these soils versus the well-drained status of the upland soils.

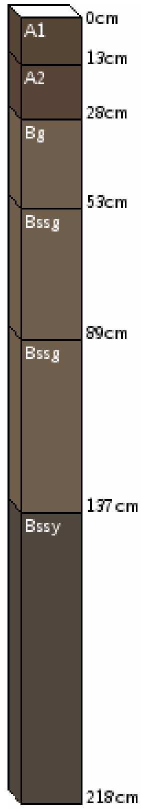
<table>
<tr><td>Landscape Position</td><td colspan="2">Floodplain/Riparian Zone</td><td>Uplands</td></tr>
<tr><td>Soil Profile</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Series</td><td>Ozias</td><td>Pophers</td><td>Moswell</td></tr>
<tr><td>Hydric</td><td>Yes</td><td>Yes</td><td>No</td></tr>
<tr><td>Taxonomy</td><td>Aeric Dystraquerts</td><td>Aeric Fluvaquents</td><td>Vertic Hapludalf</td></tr>
<tr><td>Flooding Frequency/ duration</td><td>Frequent/long</td><td>Frequent/long</td><td>None</td></tr>
</table>

Figure 5.13. The Neches-Diboll Transect. Basic soil morphology. Retrieved from the SoilWeb.

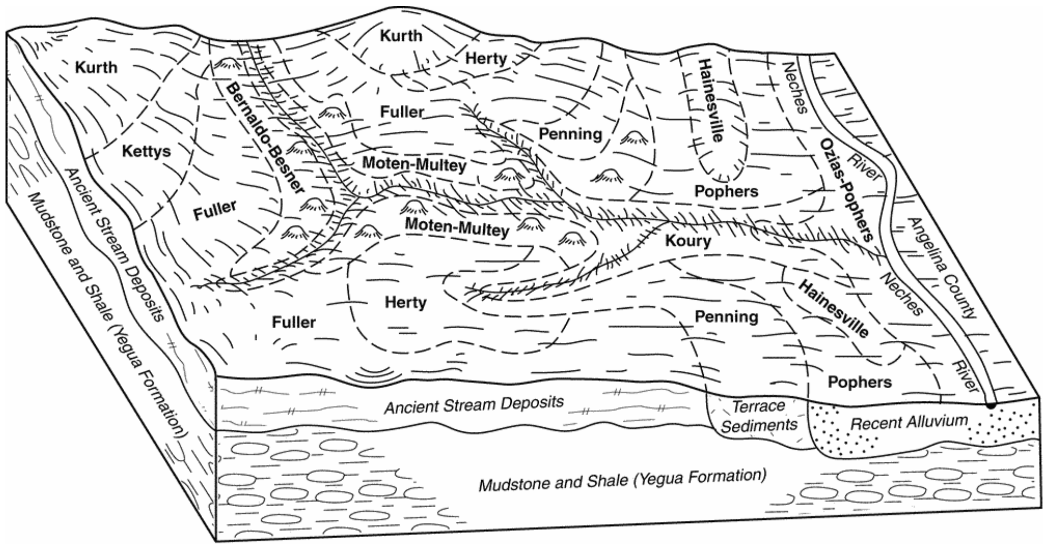


Figure 5.14. Soil survey block diagram for an area similar to the Neches River Transect. The riparian zone is the area of recent alluvium. Retrieved from the Soilweb.

Wetlands

The National Wetland Inventory lines for this area have not been fully digitized. The wetland lines shown in Figure 5.12 are simply a digitized, georectified picture of the lines, with no separate polygons or attribute data. The polygons are labeled, however. Of note here is that the entire floodplain is wetlands of one kind or another. Almost all of the wetlands are PFO1 (Palustrine Forested) by the Cowardin System, with broad-leaf deciduous vegetation (1). Water regimes are temporarily (A), seasonally (C), or semi-permanently (F) flooded.

The Neches floodplain is dominated by forested wetlands nearly all the way to its mouth in Sabine Lake, with estuarine wetlands becoming dominant only for about the last 10 miles before the lake.

COLORADO RIVER TRANSECT: The location and characteristics of the Colorado River Transect is shown in Figures 5.15, 5.16, and 5.17.

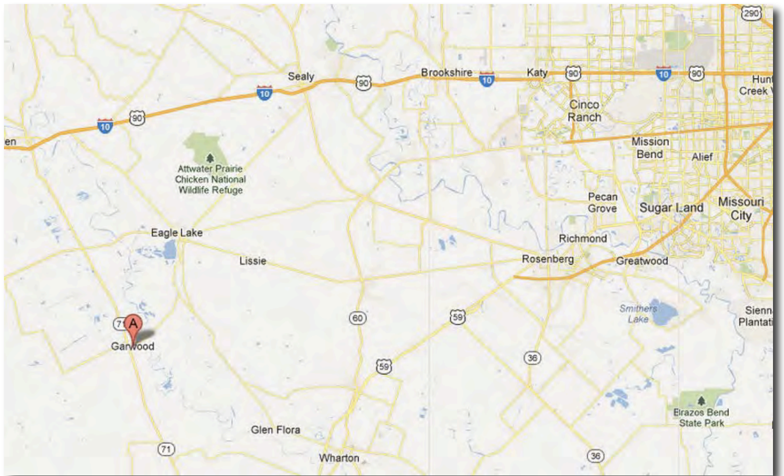


Figure 5.15. Location of the Colorado River Transect.

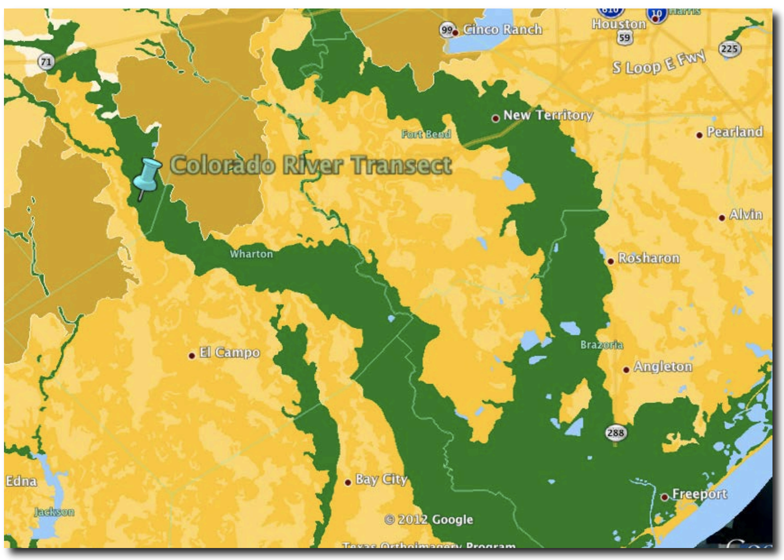


Figure 5.16. Location of the Colorado River Transect on the BEG Google Earth geology map. Dark green is Holocene Alluvium.

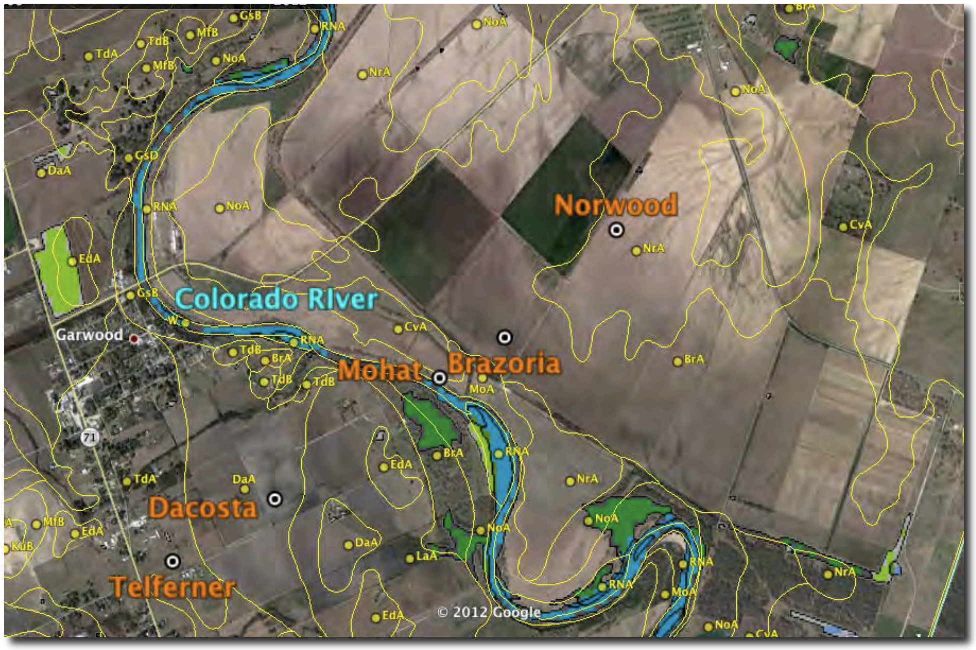


Figure 5.17. The Colorado River Transect with SoilWeb soil survey lines (yellow) and NWI wetlands (solid green and blue polygons).

The Colorado Transect represents a broad floodplain in central Texas. This transect occurs in about a 38-40 inch rainfall belt.

Inundation: The Colorado River and its tributaries are extensively flood controlled, such that flooding is now rare, in the soil survey sense, in this floodplain (although catastrophic floods do occur on a decadal or so scale). Both dams/flood control and climate contribute to the great differences in wetlands found in this floodplain and that of the Neches to the east.

Soil Morphology: None of the floodplain soils in this transect are hydric. The mapping units named after these series (see Figure 5.18 below) do have minor hydric components, but the named soils themselves are not hydric. There is a Brazoria depressional phase that is hydric, but the Brazoria series mapped in this transect is not hydric.

The Norwood and the Mohat soils exhibit the classic floodplain distribution of irregular organic carbon with depth. Both of these soils have the *fluvic* formative element in their taxonomic names. Note in particular the buried soil in the Norwood profile, the Ab horizon. The organic carbon profile for the Norwood soil shows a very distinct bump at the level of the Ab horizon (see Figure 5.21). This is the classic distribution for floodplain soils subject to sedimentation with periods of quiescence and soil formation. There is also a substantial increase in clay at this level, suggestive of a position farther back in a slack water area of the floodplain during this period. Perhaps the river migrated even farther away during or after this period allowing for the period of soil formation and accumulation of organic carbon.

The much clayeyer Brazoria soil, a Vertisol, in spite of the active heaving and churning that likely occurs in this soils, exhibits somewhat of an irregular carbon trend with depth in one of the sampled pedons (94P0173) (Figure 5.22). Three pedons on the web soil survey have data for % clay, and there is quite an irregular distribution of clay with depth, both within and across the three pedons. Note, however, that the scale for clay begins at 55% clay, a high amount for any soil. Several layers or horizons within these soils are in excess of 70% clay, extremely clayey.

Data for the Telferner series, an upland soil in this transect, is shown for comparative purposes (Figure 5.23). The Telferner is a good example of a clay-pan soil, with a sharp increase in clay between the E and Bt horizons. This transition is enough of an increase to qualify as an "abrubt texture change", a significant feature controlling hydrology and soil-root interactions.

<u>Wetland Distribution</u>: Compared to the geomorphically similar Neches transect, at least in terms of river size and relative location on the coastal plain, this floodplain has very few wetlands. On this transect, wetlands are confined to the river channel itself and only the lowest part of the floodplain, rarely extending more than ¼ to a ½ mile into the floodplain away from the river. "Lower perennial" riverine wetlands, dominantly with an unconsolidated shore or bottom, are mapped along the river channel itself. Outside of the channel there are small patches of forested (PFO) or herbaceous (Pem) wetlands, most of which are classed as temporarily flooded (A). No permanently flooded palustrine wetlands were noted on this transect, as compared with a large amount of permanently flooded wetlands on the Neches transect.

As one moves south along the Colorado River, wetland coverage continues to be sparse, similar to what we see in this transect, with a few forested wetland patches here and there with wetland coverage not becoming very extensive until about 10-12 miles before the coast. Estuarine wetlands dominate the delta built by the logjam.

Relatively more extensive wetland complexes are found in some of the smaller bayous paralleling the Colorado and Brazos Rivers on their way to the coast.

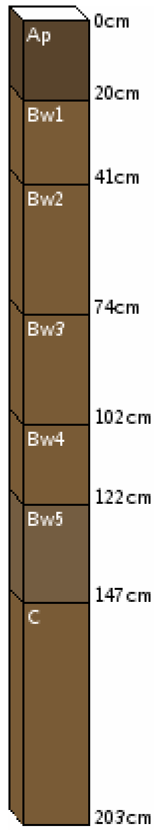
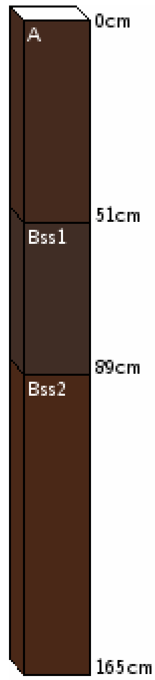
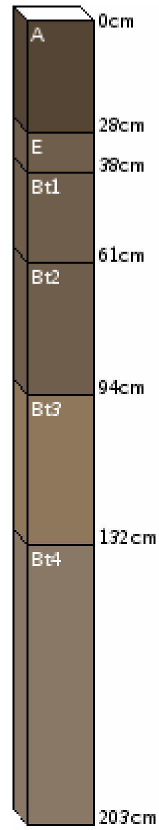
Landscape position	Floodplain			Upland	
Profile					
Series	Norwood	Mohat	Brazoria	Dacosta	Telferner
Hydric	No	No	No	No	No
Taxonomy	*Fluventic Eutrudepts*	*Typic Udifluvents*	*Chromic Hapludert*	*Vertic Argiudolls*	*Oxyaquic Vertic Hapludalfs*
Flooding frequency/ duration	*Occasionally*	*Rarely*	*Rarely*	*None*	*None*

Figure 5.18. Soil transect for the Colorado Garwood transect.Retrieved from the SoilWeb.

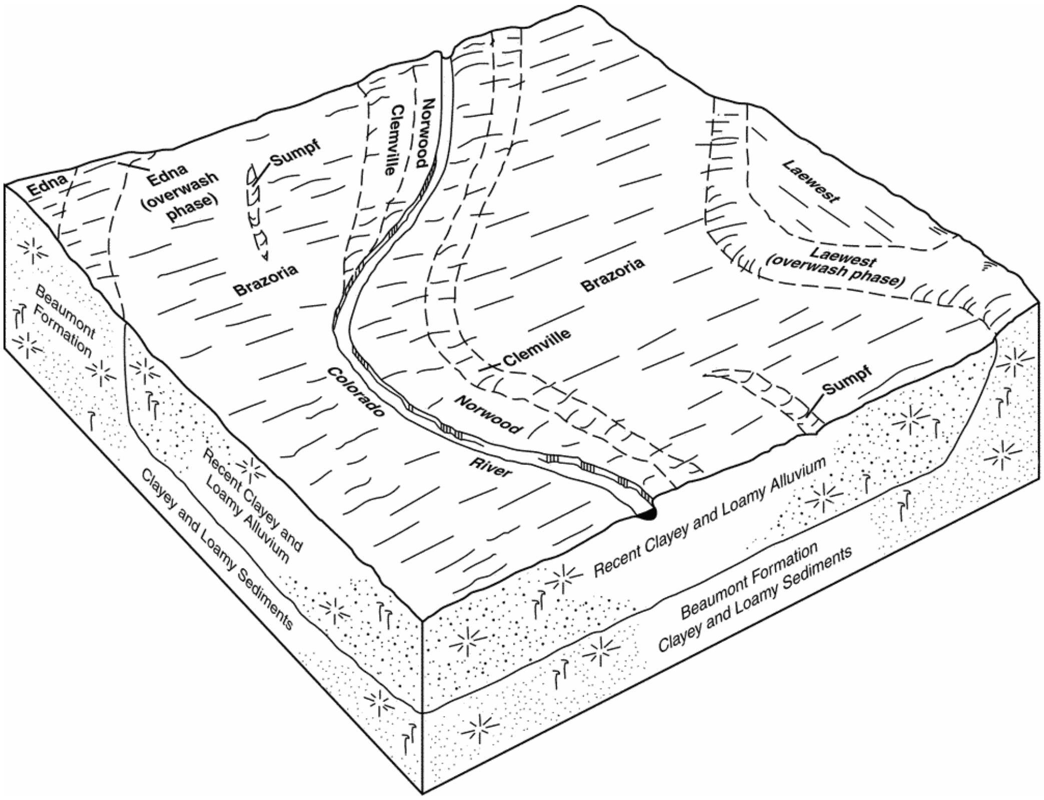


Figure 5.19. Block Diagram for a soil landscape similar to the Colorado-Garwood transect. The area overlying sediments labeled as recent alluvium is the riparian zone. Retrieved from the SoilWeb.

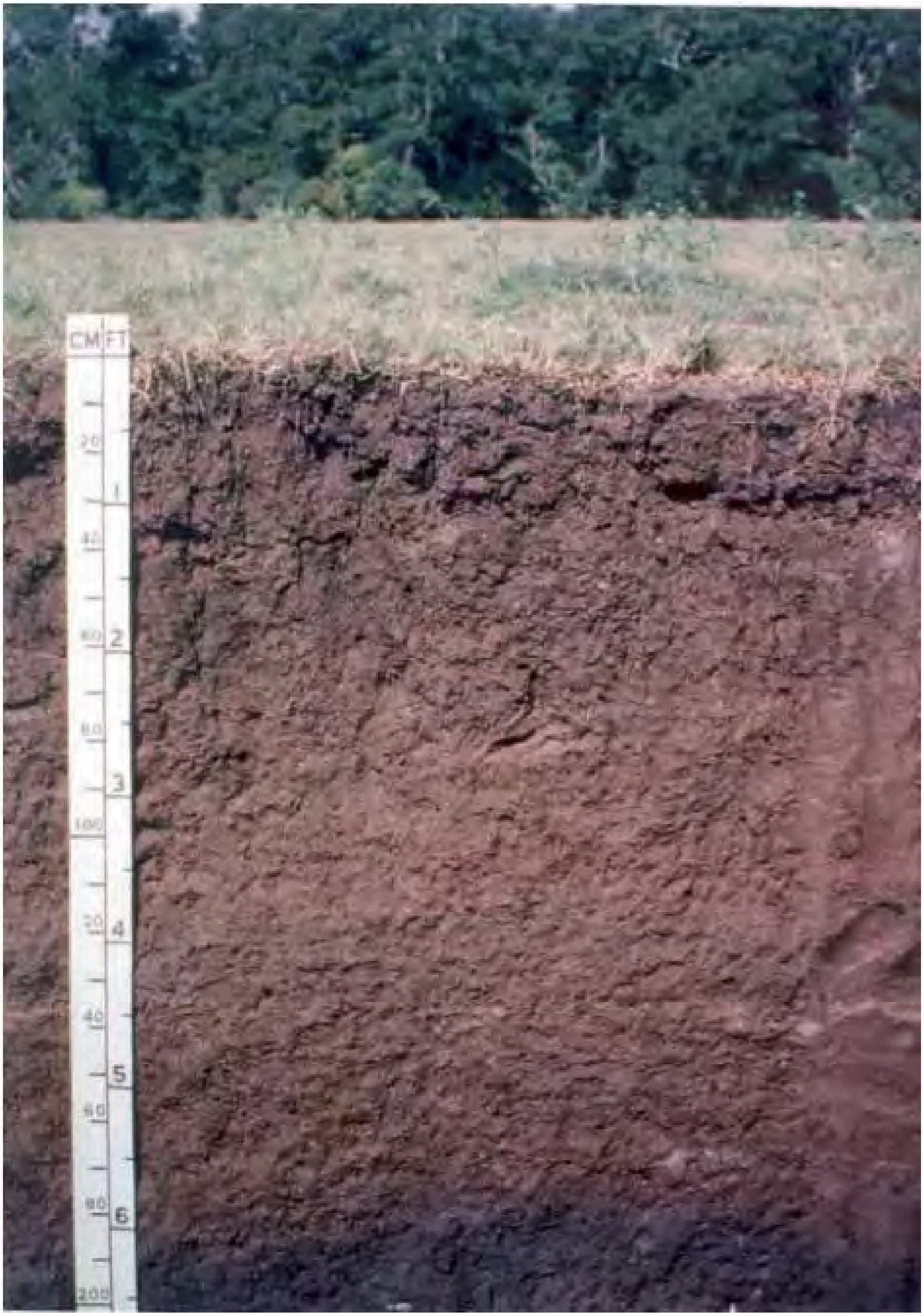


Figure 5.20. Profile of Brazoria Clay, taken from the pdf manuscript of the Colorado County soil survey. The profile is clayey throughout. Note the presence of a buried A horizon at about 6.5 feet.

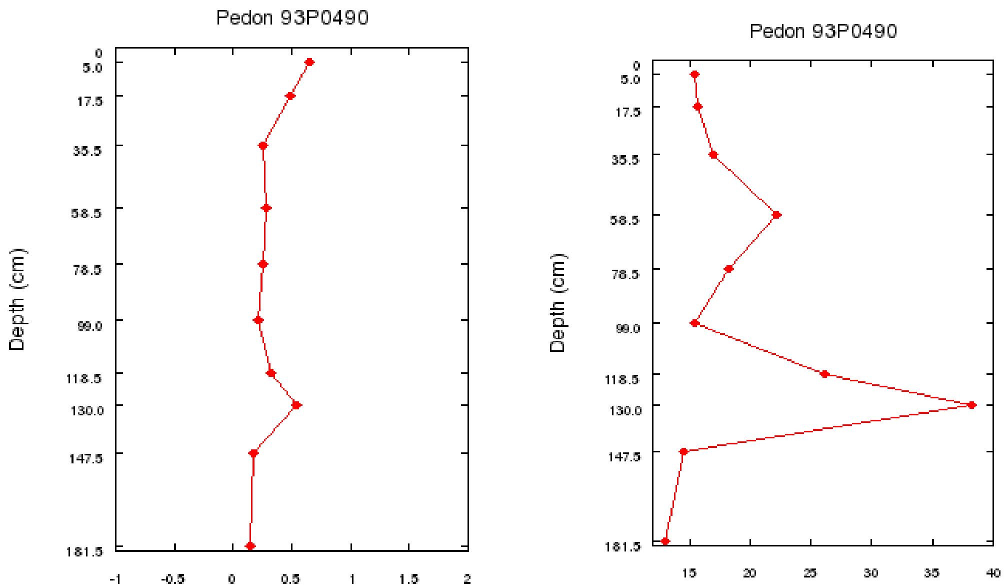


Figure 5.21. Data for the Norwood soil series, from the National Soil Survey Laboratory, retrieved through the SoilWeb. Organic carbon to the left and carbonate-free clay to the right (both wt. %). Note the increase in % organic C at about 130 cm, also corresponding to a large increase in clay at the same depth. This layer represents relatively stable period of soil formation.

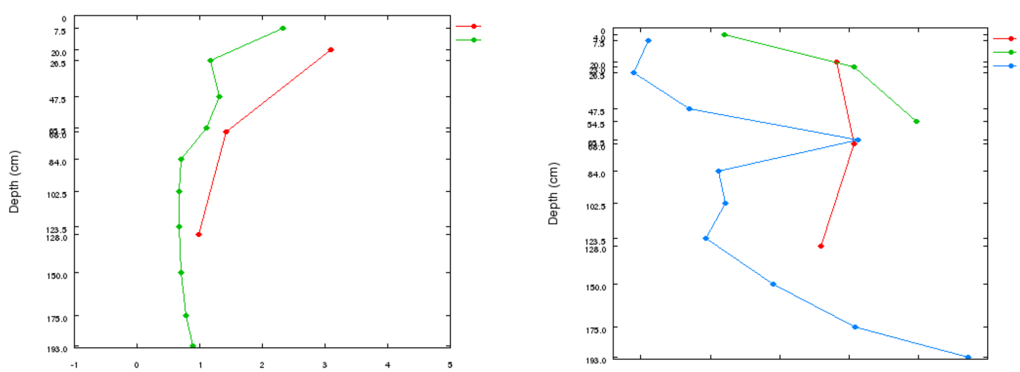


Figure 5.22. Data for the Brazoria soil series from the National Soil Survey Laboratory, retrieved through the SoilWeb. Organic C to the right (2 pedons), % clay to the left (3 pedons).

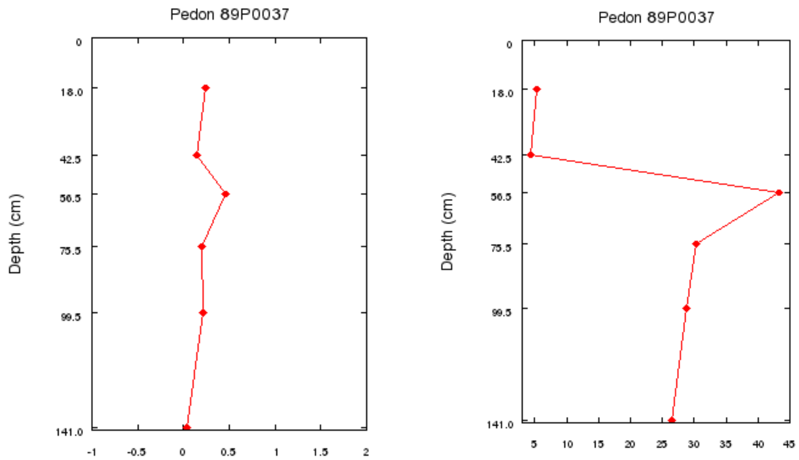


Figure 5.23. Data for the Telferner soil series (% organic C to the left, and % clay to the right).

WEST NUECES TRANSECT: The location and characteristics of the West Nueces River Transect is shown in Figure 5.24, 5.25, and 5.26.

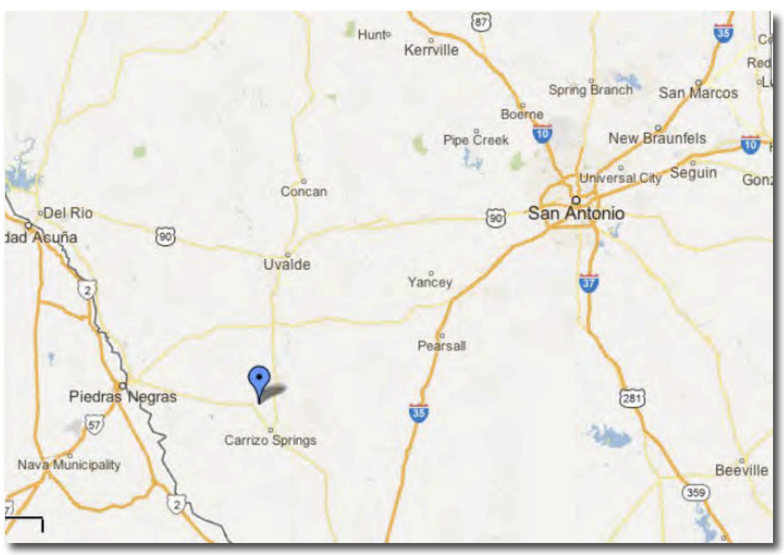


Figure 5.24. General location of West Nueces River Transect

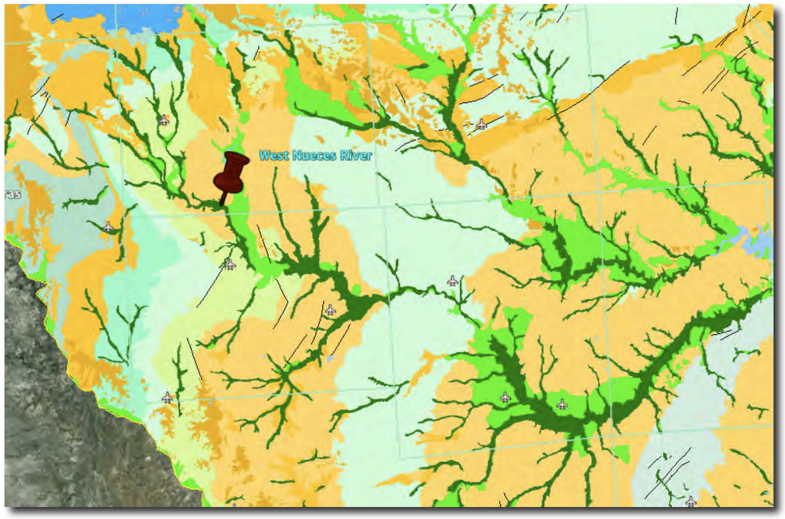


Figure 5.25. Geologic Context of the West Nueces River transect.

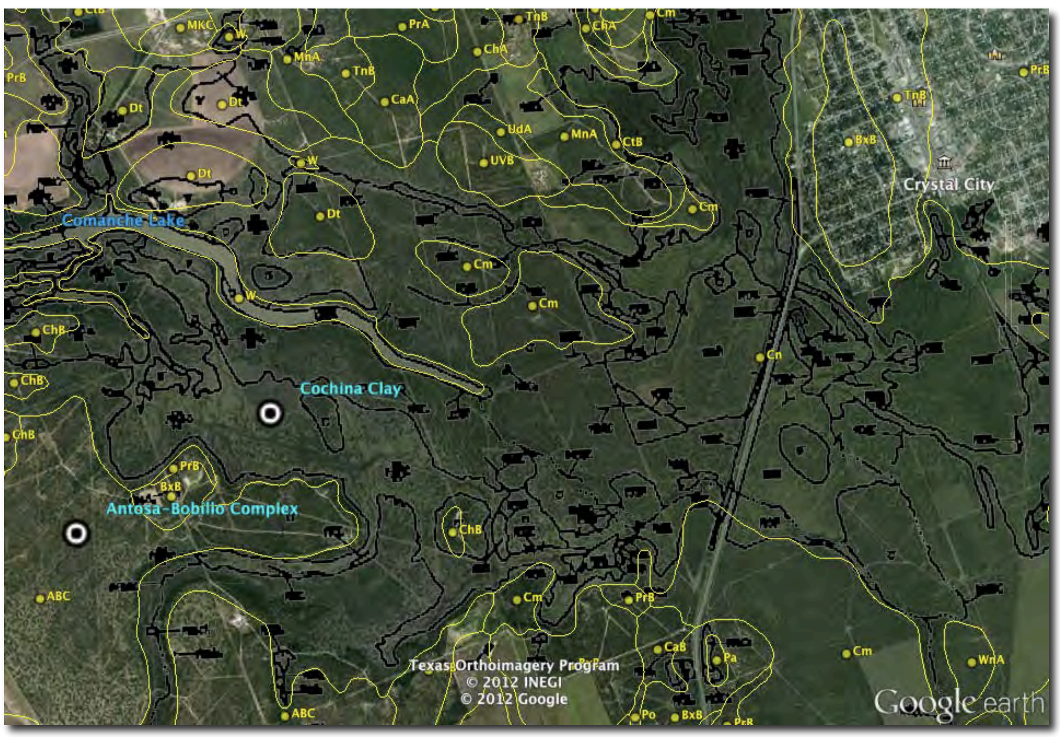


Figure 5.26. Google Earth map of the West Nueces River transect near Crystal City, Texas. Width of frame is approximately 4 miles. Yellow lines and labels are from the SoilWeb (http://casoilresource.lawr.ucdavis.edu/). Dots and blue labels are soil map units discussed in the text. Black lines and labels are the National Wetland Inventory lines.

The West Nueces River transect is considerably upstream of where the other two transects occurred. There was no wetland data available for west or southwest Texas rivers of this size in the mid coastal plain location. This transect occurs in about an 18-22 rainfall belt, but where evapotranspiration significantly exceeds precipitation.

Inundation: The bulk of this floodplain is frequently flooded, meaning a more than 50% chance of flooding in any year, which seems somewhat surprising given the relatively low rainfall in the area.

Soil Morphology: The Cochina Clay is the predominant soil in this floodplain. It is not listed as a hydric soil and it does not even have an aquic moisture regime. Its taxonomic classification reveals that it is a high shrink-swell soil (V*ert*isol), in a dry or ustic moisture regime, somewhat bright colors (chromic), and some characteristics of a weakly developed soil (entic). This soil has gypsum (BSSnz horizon) at about 34 inches, indicative of a shallow water table.

The two non-floodplain soils are Alfisols, or soils with an argillic or clay pan horizon. The arenic and grossarenic modifiers indicate thick sand lenses about the clay pan.

Wetlands: Significant wetlands are shown on the NWI map for this transect area. There appears to be somewhat of a disjuncture between the soil and wetland. The soil data, especially the lack of a recognized aquic moisture regime, indicate that little if any wetlands would be present here. If wetlands are indeed present, it is likely that they have a very short saturation period (e.g, about 2 weeks at the most)

This is a headwater area, and it is possible that the area is not particularly well drained such that more wetlands than usual might be expected here. Downstream from this area, wetlands are few and far between, for the most part very sparsely distributed. No significant wetland complexes appear until about 12-15 miles above the mouth of the river on Nueces Bay.

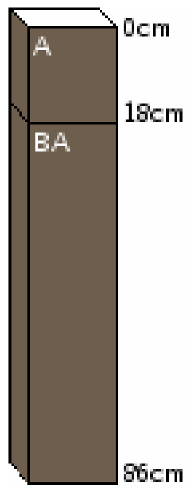
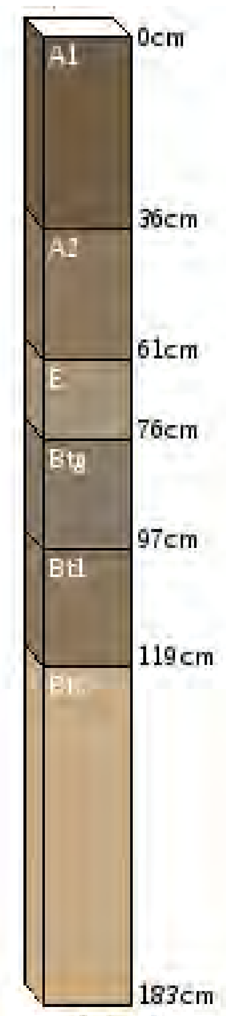
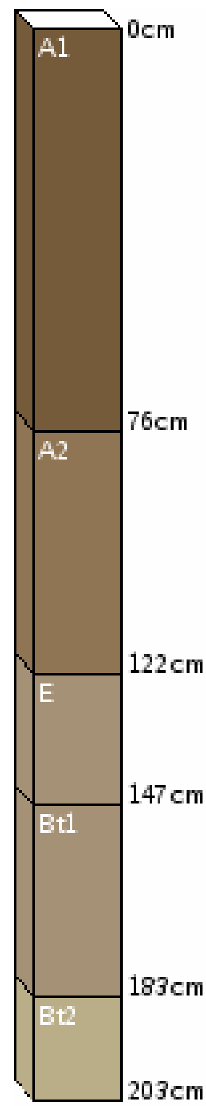
Landscape position	Floodplain	Upland	
Profile			
Series	Cochina Clay	Antosa	Bobillo
Flooding Frequency	*Frequently*	*None*	*none*
Taxonomy	*Entic Chromusterts*	*Aquic Arenic Paleustalf*	*Grossarenic Paleustalf*

Figure 5.27. Soil transect for the West Nueces transect. Retrieved from the SoilWeb.

APPENDIX B - SOIL TAXONOMY FORMATIVE ELEMENTS.

This list is of the formative elements used at various levels in Soil Taxonomy. Within Soil Taxonomy, each taxa of the system has specific and quantitative criteria. This list provides only the barest qualitative indication of what each taxa refers to.

Taken from http://soils.usda.gov/education/facts/formation.html.

Table 5.2. Soil Orders. Soil taxonomy at the highest hierarchical level identifies 12 soil orders. The names for the orders and taxonomic soil properties relate to Greek, Latin, or other root words that reveal something about the soil. Sixty-four suborders are recognized at the next level of classification. There are about 300 great groups and more than 2,400 subgroups. Soils within a subgroup that have similar physical and chemical properties that affect their responses to management and manipulation are families. The soil series is the lowest category in the soil classification system.

Soil Order	**Formative Terms**	**Pronunciation**
Alfisols	Alf, meaningless syllable	Pedalfer
Andisols	Modified from ando	Ando
Aridisols	Latin, aridies, dry	Arid
Entisols	Ent, meaningless	Recent
Gelisols	Latin gelare, to freeze	Jell
Histosols	Greek, histos, tissue	Histology
Inceptisols	Latin, incepum, beginning	Inception
Mollisols	Latin, mollis, soft	Mollify
Oxisols	French oxide	Oxide
Spodosols	Greek spodos, wood ash	Odd
Ultisols	Latin ultimus, last	Ultimate
Vertisols	Latin verto, turn	Invert

Table 5.3. Formative Elements in Names of Soil Suborders.

Element	**Derivation**	**Sounds Like**	**Connotation**
Alb	L, *albus,* white	Albino	Presence of albic horizon
Anthr	Modified from Gr. anthropes, human	Anthropology	Modified by humans
Aqu	L. *aqua,* water	Aquifer	Aquic conditions
Ar	L. *Arare*, to plow	Arable	Mixed horizons
Arg	Modified from argillic horizon; L. *argilla*, white clay	Argillite	Presence of argillic horizon
Calc	L. calcis, lime	Calcium	Presence of a calcic horizons
Camb	L. cambiare, to exchange	Am	Presence of a cambic horizon
Cry	G. kryos, icy cold	Cry	Cold
Dur	L. durus, hard	Durable	Presence of a duripan
Fibr	L. *fibra,* fiber	Fibrous	Least decomposed stage
Fluv	L. *fluvius,* river	Fluvial	Flood plain
Fol	L. *folia*, leaf	Foliage	Mass of leaves
Gyps	L. gypsum, gypsum	Gypsum	Presence of a gypsic horizon
Hem	Gr h*emi,* half	Hemisphere	Intermediate stage of decomposition
Hist	Gr. histos, tissue	Histology	Presence of organic materials
Hum	L. *humus,* earth	Humus	Presence of organic matter
Orth	Gr. *orthos,* true	Orthodox	The common ones
Per	L. Per, throughout in time	Perennial	Perudic moisture regime
Psamm	Gr. *psammos,* sand	Sam	Sandy texture
Rend	Modified from Rendzina	End	High carbonate content
Sal	L. base of sal, salt	Saline	Presence of a salic horizon
Sapr	Gr. *sapros,* rotten	Sap	Most decomposed stage
Torr	L. *torridus,* hot and dry	Or	Torric moisture regime
Turb	L. Turbidis, disturbed	Turbulent	Presence of cryoturbation
Ud	L. *udus,* Humid	You	Udic moisture regime
Vitr	L. vitrum, glass	It	Presence of glass
Ust	L. *ustus,* burnt	Combustion	Ustic moisture regime
Xer	Gr. *xeros, dry*	Zero	Xeric moisture regime

Table 5.4. Formative Elements in Names of Soil Great Groups.

Formative Element	Derivation	Sounds Like	Connotation
Acr	Modified from Gr. *Akros* , at the end	Act	Extreme weathering
Al	Modified from aluminum	Algebra	High aluminum, low iron
Alb	L. *Albus,* white	Albino	An albic horizon
Anhy	Gr. *anydros,* waterless	Anhydrous	Very dry
Anthr	Modified from Gr. *anthropos,* human	Anthropology	An anthropic epipedon
Aqu	L. *aqua,* water	Aquifer	Aquic conditions
Argi	Modified from argillic horizon; L. argilla, *white clay*	Argillite	Presence of an argillic horizon
Calci, calc	L. *calcis*, lime	Calcium	A calcic horizon
Cry	Gr. *kryos,* icy cold	Cry	Cold
Dur	L. *durus,* hard	Durable	A duripan
Dystr, dys	Modified from Gr. *dys,* ill; dystrophic infertile	Distant	Low base saturation
Endo	Gr. *endon, endo,* within	Endothermic	Implying a ground water table
Epi	Gr. *epi,* on, above	Epidermis	Implying a perched water table
Eutr	Modified from Gr. *eu,* good; euthrophic, fertile	You	High base saturation
Ferr	L. *ferrum,* iron	Fair	Presence of iron
Fibr	L. *fibra,* fiber	Fibrous	Least decomposed stage
Fluv	L. *fluvius,* river	Fluvial	Flood plain
Fol	L. *folia,* leaf	Foliage	Mass of leaves
Fragi	Modified from L. *fragilis,* brittle	Fragile	Presence of fragipan
Fragloss	Compound of fra (g) and gloss		See the formative elements "frag" and "gloss"
Fulv	L. *fulvus,* dull brownish yellow	Full	Dark brown color, presence of organic carbon
Glac	L. *glacialis,* icy	Glacier	Ice lenses or wedges
Gyps	L. *gypsum,* gypsum	Gypsum	Presence of gypsic horizon
Gloss	Gr. *glossa,* tongue	Glossary	Presence of a glossic horizon
Hal	Gr. *hals,* salt	Halibut	Salty
Hapl	Gr. *haplous,* simple	Haploid	Minimum horizon development
Hem	G. *hemi,* half	Hemisphere	Intermediate stage of decomposition
Hist	Gr. *histos,* tissue	History	Presence of organic materials
Hum	L. *humus,* earth	Humus	Presence of organic matter
Hydr	Gr. *hydo* , water	Hydrophobia	Presence of water
Kand, kan	Modified from kandite	Can	1:1 layer silicate clays
Luv	Gr. *louo,* to wash	Ablution	Illuvial
Melan	Gr. *melasanos,* black	Me + Land	Black, presence of organic carbon
Moll	L. *mollis* , soft	Mollusk	Presence of a mollic epipedon
Natr	Modified from *natrium* , sodium	Date	Presence of natric horizon
Pale	Gr. *paleos,* old	Paleontology	Excessive development
Petr	Gr. comb. form *of petra,* rock	Petrified	A cemented horizon
Plac	Gr. base of *plax,* flat stone	Placard	Presence of thin pan
Plagg	Modified from Ger. *plaggen,* sod	Awe	Presence of plaggen epipedon
Plinth	Gr. *plinthos* , brick	In	Presence of plinthite
Psamm	Gr. *psammos,* sand	Sam	Sandy texture
Quartz	Ger. *quarz* , quartz	Quarter	High quartz content
Rhod	Gr. base of *rhodon,* rose	Rhododendron	Dark red color
Sal	L. base of *sal* , salt	Saline	Presence of salic horizon
Sapr	Gr. *saprose,* rotten	Sap	Most decomposed stage
Somb	F. *sombre,* dark	Somber	Presence of sombric horizon
Sphagn	Gr. *sphagnos,* bog	Sphagnum	Presence of Sphagnum
Sulf	L. *sulfur,* sulfur	Sulfur	Presence of sulfides or their oxidation products
Torr	L. *torridus,* hot and dry	Torrid	Torric moisture regime
Ud	L. *udus,* humid	You	Udic moisture regime
Umbr	L. *umbra,* shade	Umbrella	Presence of umbric epipedon
Ust	L. *ustus*, burnt	Combustion	Ustic moisture regime
Verm	L. base of *vermes,* worm	Vermilion	Wormy, or mixed by animals
Vitr	L. vitrum, glass	It	Presence of glass
Xer	Gr. *xeros,* dry	Zero	Xeric moisture regime

CHAPTER 6 - RIPARIAN VEGETATION (JACQUELYN DUKE)

The vegetative, and particularly the woody component of a riparian zone is one of the easiest, least invasive methods for providing a general, visual delineation of that zone. Whether viewed from an aerial perspective or streamside, forest dynamics along the stream provide a quick accounting of the general abiotic factors that are likely in play to support the given biotic panorama.

The abiotic nature of any stream system *determines* the biotic community and to a lesser extent the plants that live along the stream will in turn influence the physical nature of the system. Therefore, an understanding of the community dynamics of a stream can provide major clues to two very important questions:

1) What is the spatial extent of the riparian zone? And
2) Is the riparian zone functionally "healthy" and sustainable?

While a range of data collection from multiple disciplines, covering numerous features, and at various spatial scales is a valuable and robust approach for defining the riparian boundary and state, this is not always a feasible choice for the riparian assessor. Instead a quick, comprehensive inventory of a (select) key indicator(s) can infer much about the system *without* exhaustive sampling. This chapter will consider abiotic influences on riparian vegetation, and how such influences can be inferred from within-plant community characteristics, as well as indicators that the forest is positively influencing stream dynamics in a feedback mechanism. Riparian delineation using general community features versus key indicator species will be discussed, with recommendations for maintenance and management. Discussion will focus on tree species as sentinels of riparian/stream dynamics. Here a key indicator is considered a given plant/plant feature(s) that both provides an assessment of riparian boundary and responds in a known way to disturbance. Use of key indicator species offers simplicity in determining riparian delineation and maintenance. All riparian forest communities share several common features and the presence/absence of these key features allows an efficient method of riparian boundary/function evaluation.

DEFINING THE DEFINING NATURE OF BOUNDARIES

The term "boundary" seems unwarranted when discussing riparian zones, given their characteristic identifiers include terms like "transitional" and "ecotone" and imply a gradient nature rather than strongly bounded edge. However, applying distinctive boundary characteristics to riparian zones allows better examination of whether the current zone's spatial coverage is existing at its maximum potential. Using a distinct boundary also facilitates monitoring of past and future changes that otherwise may be lost if these dynamic systems are considered too variable to be nailed down with defining edges. A boundary trait may include 1) origin and historical (natural) maintenance, 2) spatial structure, 3) function, 4) temporal dynamics (Naiman *et.al.* 2005). Each trait seems a plausible variable. How best to represent? One simple method is to use the biota for contextual information of each parameter. A simple visual examination of select key indicator tree species has the potential to provide a quick classification of *each* factor, leading to insights into biotic factors at play.

"KEY INDICATOR" PROS AND CONS

How one approaches delineation and management of the "riparian zone" depends heavily on how that riparian zone is perceived. Riparian zones are interchangeably referred to as ecotones (gradations between two distinct areas) and buffers/boundaries between two distinct areas. What usually distinguishes the two is the spatial scale of interest: at small scales the riparian area has spatial features and even variation within the spatial extent *vs.*

large scales, where the zone may in fact be better represented as a line (boundary) that cuts through two ecosystems (water and land surface). Additionally, there are varied opinions on whether riparian areas are better represented using an autecology approach of identifying key indicator species vs. a synecology approach that uses the more traditional community associations (e.g. Facultative Wetland, etc. groupings). Both have validity and can be very useful in multiple settings. So, given the need for an efficient, cost-and time-effective method, how to decide which is most applicable? Following is a discussion on the merits of each, and then a word on why one is preferred above the other. A summary of several pros and cons for this method is shown in Table 6.1.

An argument *against* using key indicators would be that riparian zones are not only distinct from the surrounding landscape, but are usually also distinct from each other. Additionally, along a river continuum riparian systems are expected to change in their characteristics (Quinn *et.al.* 2001). This variation can complicate comparison within and among sites unless a well-defined, and comprehensively-understood indicator is chosen.

In the Hydrogeomorphic Classication Method (HGM) Brinson (1993) proposed a broad assessment method to reduce complexity, based on ecosystem functionality and *abiotic* parameters. While Brinson (1993) argues for using geomorphic, physical, and chemical descriptors of ecosystems, he acknowledges that vegetation structure may provide important clues of the forces *at work* in the system. His issue with biological classification is that, similar to Quinn *et.al.* (2001) he argues community compositions vary, and emphasizes that choosing major forcing functions can be useful at the broad scale. We would argue that while the functional approach has benefits, function may not always be easily discernable, and may have been altered from historic functions. For example, soils that historically have been under hydric conditions will display their historic condition, even though the water table may have recently been permanently altered. A better method would be to find a correlative indicator between vegetation and hydrogeomorphic conditions that can give rapid, real-time data on both riparian condition and functionality. To overcome the issue of community variation, a key indicator of one to three broadly dispersed species can instead be chosen. Selection of this key indicator(s) must include characteristics that demonstrate very distinctly, stream influence/reliance.

Further argument *for* the key indicator approach is that although a multitude of variables and intensive data collection is assumed to provide a robust analysis of the riparian zone, there may in fact be no consistency or universality of assumed ecological function, owing to the very nonlinear nature of processes and responses in riparian zones. Disturbance is a given. Disturbance frequency, size/duration of the last disturbance, and time since last disturbance will result in vastly different *short-term* outcomes. The distinctness of a riparian zone *is* its variability. Because riparian features are only seen at relatively small scales in landscape mapping, and because they represent an ecotone between two vastly different large scale landscape features (water and uplands) their features are expected to be highly variable on a small spatial scale (see Figure 6.1). Therefore, even though considerable resources into, and extensive data generation out of a site may be considered a robust evaluation, the large variation in compounding factors may obscure or even be misleading in their short-term, small-scale indications. In contrast, using the easily assessable information that can be quickly gleaned from indicator trees presents a snapshot assessment that can be used to both efficiently cover many more sites given limited resources, and can be used to determine whether further assessment of any given site is warranted.

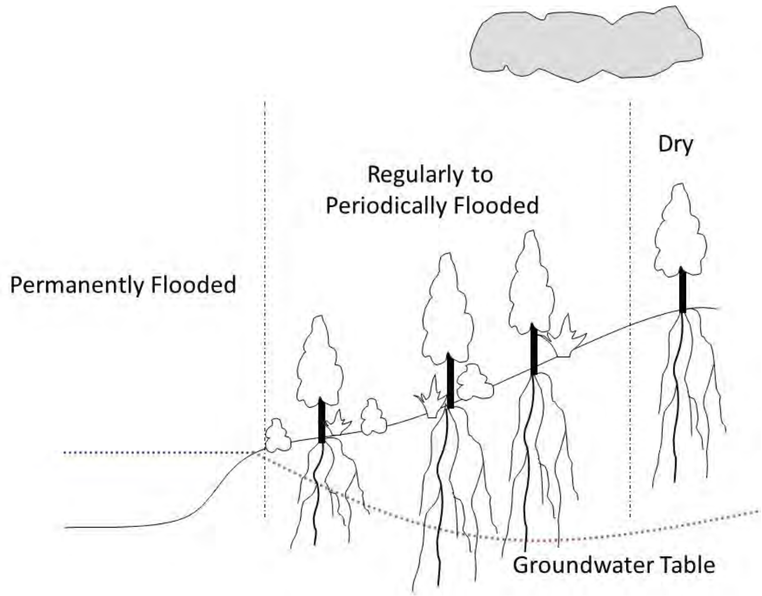


Figure 6.1: The riparian zone as an ecotone between stream water (permanently flooded) and uplands (dry). In the “regularly to periodically flooded” zone, key to riparian community development is an accessible water table.

Verry *et.al.* (2004) proposed a redefining of riparian areas to encompasses the geomorphology of the stream. They argue that the riparian ecotone can easily be determined as the floodprone area plus 30m on each side of the valley; and that this calculated area will encompass the important adjacent riparian *functions* for most rivers (see Figure 6.2). Floodprone is calculated as double the elevation of the active floodplain height above stream bottom. They emphasize this method as a simple, straight-forward, versatile and easily learned method for field researchers, and include references for the technique of determining bankfull, one of which is to utilize riparian species such as dogwood and willow as markers for delineation. This fully underscores the well-established relationship between specific riparian-indicator species and water dynamics within the stream, and emphasizes the usefulness of woody key indicators for simplifying the process.

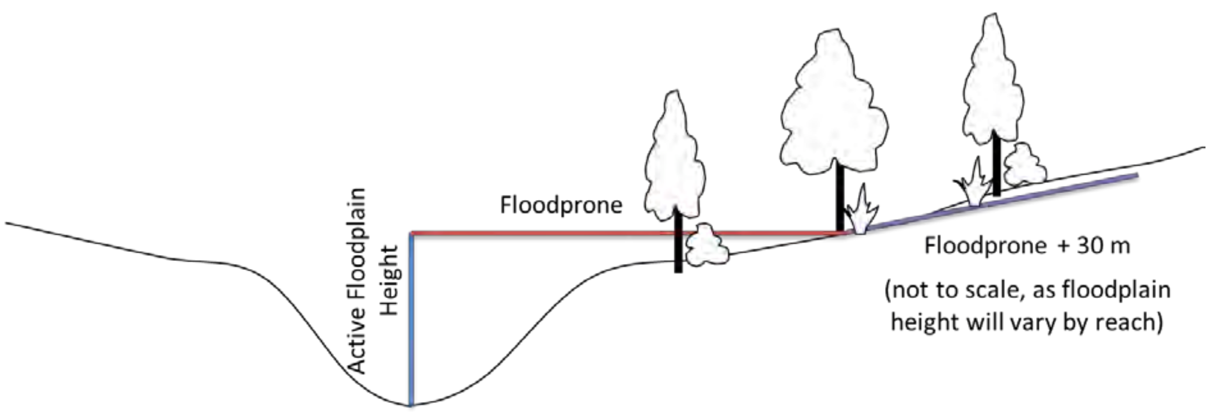


Figure 6.2: Representation of a riparian ecotone as defined by Verry *et.al.* (2004) using the floodprone + 30m designation.

The use of key indicator species can also be much more revealing than more generalized methods. The variability between multiple species' locations, seed dispersal, and productivity for species typically grouped together (community/synecology approach) poses a limitation to the traditional method of determining riparian functionality and health. The key indicator species approach can better infer long-term past maintenance as a way to predict future maintenance.

Osterkamp and Hupp (1984) demonstrated that certain riparian species can and do show tight correlations with geomorphic surfaces of a stream, and that those geomorphic surfaces in turn often show tight correlations to flow frequencies. This reinforces the notion of select indicator species that can be quickly utilized in the field to infer stream properties simply by their presence/absence and spatial distribution.

An additional advantage to the key indicator species method for riparian delineation is its solution to the problem of training. Whereas field crews examining a set of abiotic and/or community characteristics, riparian classes, etc. can be both costly and time-consuming endeavors, knowing just one or two key indicator species and their fundamental indications facilitates less funding and time. The advantage of the key indicator approach is not only its ease of use, but also the potential for a general assessment of the health and adaptability to disturbance to be gleaned (given an adequate, fully understood parameter is chosen).

Given the advantages and disadvantages of using key indicator species in delineating riparian boundaries, functions, etc. the usefulness of such greatly outweighs other methods. This is especially true when large-scale, multi-stream studies need to be rapidly assessed and managed long-term.

Table 6.1: Pros and Cons for the key indicator method of delineating riparian boundary and function

Key Indicator Method for Delineating Boundary and Function

Pros	Cons
Simplicity in determining	Community compositions vary along the river continuum
Less exhaustive sampling	Indicator not present in all sites
Time/cost effective	More complex/variable than abiotic variables
Reduced training of techniques	Functionality may change along the river continuum
Based on known response(s) to disturbance, provides clues to previous disturbances	
Biota infer abiotic information	
Reveals long-term processes that may not otherwise be apparent	
Real-time data may reveal historic alterations to functioning	
Can be used to make future predictions	

TREES AS SENTINELS

The simple story is that riparian trees grow along wetness gradients. This very feature can provide powerful insights to the soil water conditions of streamside systems. The varied arrangement of trees along and adjacent to the stream can speak volumes to the underlying dynamic processes at play. This will be further explored in this chapter under both the section on the influences of abiotic factors on riparian trees as well as the section on selected trees that make useful key indicators of riparian boundaries/functioning.

Additionally, trees provide a long-term view of historical riparian functioning very useful to riparian managers looking to determine not only past disturbances but potential responses by plants to alterations in those disturbances. Dendrohydrology, a subfield of dendrochronology, can assist with reconstruction of water table changes, land subsidence, landslides, flood height and energy as well as stream flow cycles. (Schweingruber 1996). Trees record these events as scars, ring size, and reaction wood, including suppression, release, compression and tension wood. The tupelo trees in Figure 5.6 illustrate their usefulness in identifying long-term water inundation.

Flooding can be documented via flood rings, abrasive scarring and debris impact damage, age demographic gaps (indicating relative size loss of trees during an event), leaning due to undercutting, and establishment of trees on newly deposited bars or benches. Scar height is indicative of flood/debris height (Begin et.al. 2010). Anatomical changes in the earlywood vessels of trees have also been used to determine both root submergence during prolonged flood inundation and the loss of leaves from floodwater force (Yanosky and Jarrett 2001). This information not only assists with reconstruction of past stream flow, but can provide long-term data for future water allocation and management of naturally variable water resources (see Speer 2010 for several examples).

Droughts and their severity are easily detected, and their frequency effect can be extracted from tree ring records. Additionally, the timing and extent of ecological and manmade changes (water releases, water diversion, groundwater pumping) to streamflow, sedimentation, etc. can be studied from riparian tree growth (Schweingruber 1996).

ABIOTIC FACTORS: HOW THEY INFLUENCE (AND ARE INFLUENCED BY) RIPARIAN FORESTS

GEOMORPHOLOGY

Geomorphology is both literally and figuratively *foundational* to riparian forest development. Its spatial influence ranges from large-scale catchment (headwater to sea level) to the microscale; its temporal influence can be measured over billions of years or in a single event. Geomorphology drives soil deposition (and therefore many soil properties), water energy both along the stream channel and horizontally perpendicular, and the ability of plants to colonize, survive and tolerate the myriad processes that arise from distinct geomorphologic features. Below are several geomorphologic features that constrain and determine plant growth to varying degrees. Also mentioned are any feedback processes by plants themselves that would serve to drive future geomorphic characteristics.

Bedrock

Typically bedrock is not a consideration for riparian forest existence. The only time it would pose a constraint would likely be in extreme headwaters where erosion has carried away overlying soils, and areas along the stream where shallow bedrock has been exposed. Root penetration and lack of water pockets would present constraints to plant proliferation in such cases. The very limited feedback plants would provide to bedrock features would be in preventing further exposure of bedrock by stabilizing overlying soils during high flow events.

Erosional/Depositional Processes

Headwaters are more erosional in nature than other reaches, and will tend to remove sediment from the stream channel; naturally deepening the channel, and making it more difficult for woody growth along the channel banks themselves (see Figure 6.3). Because obligate riparian species are constrained to saturated water sources for at least one critical life stage, riparian lateral boundaries will be tightly constrained to a sharply declining water table with distance to stream. Along the river continuum, lowland regions will perpetuate transfer zones, wherein erosion and deposition are often in dynamic equilibrium. Plant persistence here requires high adaptability to both conditions and to laterally moving, meandering reaches. In deltaic areas, deposition dominates and moving/meandering is more frequent. Sediment buildup may result in alluvial fans such that land adjacent to rivers is elevated (sometimes considerably) above the surrounding landscape. In such scenarios, riparian vegetation may be excluded adjacent to the river and instead be sparsely located far distances from the streambank. Observations of mature trees in such a pattern are indicative of 1) a past river channel and/or 2) low areas or "pockets" where distance to water table is more accessible than the depositionally perched streambank. In these reaches, plants may have the feedback potential to enhance hyporheic flow adjacent to the active stream channel.

Figure 6.3: An erosional headwater stream in Central Texas (photo by J.Duke). A slump on the far bank has created a low-lying bench for vegetation to occupy.

Channel slope

Because of their erosional nature, headwater stream channels are typically more narrow and steep. The lateral (perpendicular to the river) extent of the riparian zone is going to be more constrained here than anywhere else along the continuum because of a sharp decline in water table with increasing distance to stream. Figure 6.4a shows a steep slope with a narrow riparian forest, compared to Figure 6.4b in which trees are further horizontally dispersed because of the shallow access to adjacent groundwater along the stream reach.

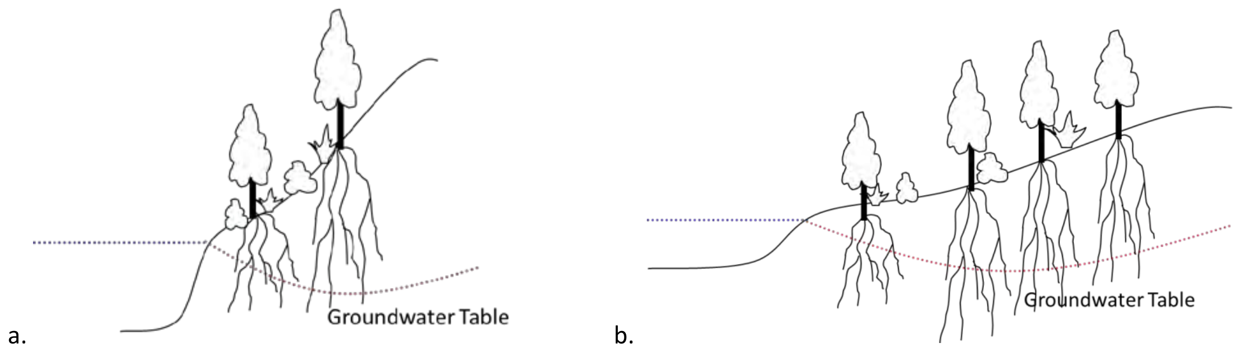


Figure 6.4: A comparison of riparian zone width for a steep (a.) and more gently sloping (b.) channel. In scenario (b.) trees growing further distances to the stream still have ready access to the groundwater table hyporheically connected to the stream water, whereas sceanario (a.) results in very rapid loss of connectivity (and lack of tree presence) with increased elevation.

Debris Movement

Mass wasting of slopes (driven by competing shear stress and shear strength) and debris flow place stress upon the biota. Particularly in headwaters and transfer zones, trees consistently face losing their substrata and becoming part of the downstream movement of debris. Stream energy increases with velocity, depth, and sediment load. The best strategy against this force is a comprehensive root network. This includes both depth as well as breadth. And the beauty of such a strategy is that not only does a well-built matrix ensure a higher “gripping” integrity, but it also presents a positive feedback mechanism to the stream system whereby channel erosion itself is mitigated and deposition of sediments and debris increase into the zone (see Figure 6.5).

Figure 6.5: Debris within the riparian zone following a recent ~2yr flood event for a headwater stream in Central Texas (photo by J. Duke)

If roots fail (or stems snap) and a tree does become part of debris flow, it then becomes a potential contributor to the flow regime itself, creating impediments to the downstream energy. Figure 6.6 shows a debris pile from a recent flood event that is partially obstructing river flow. During low flows, sediments will tend to build behind debris piles, which may subsequently be freed during a flood event. If deposited sediments do not release, they may actually create enough of a disruption in local flow that considerable deposition actually creates a bench; feeding forward the spatial potential for future plant colonization upon the new surface (Abbe and Montgomery 2003).

Figure 6.6: A recently deposited debris pile partially obstructing streamflow along a headwater stream. The stream is in a semi-urban setting, and debris includes both human–contributed and natural debris. (photo by J. Duke)

Meanders

Point bars along meandering streams represent vital sections where exposed, often gently sloping surfaces provide real estate for seedling dispersal. Though soil features are undeniably important, research along streams has shown most species' distribution correlated better to a surface than to a sediment type (Osterkamp and Hupp 1984), particularly with respect to depositional bars. This possible effect of flow frequency alterations at point bars on vegetation can be useful in verifying flood surface inundation with key indicator species identification. Additionally, point bars represent vital sections along the stream where maintenance of riparian species may be focused to ensure long-term survivability of some of the key indicator species. This is especially true when those species' abundances are threatened along incised, or otherwise impaired stretches of the river. Figure 6.7 shows the beginning of a point bar (in the foreground) just downstream of a cut bank (in the background). Notice the large willow and seedling deposition occurring in the point bar region.

Figure 6.7: A point bar (foreground) and cut bank (background) for a large River in Central Texas (photo by J.Duke)

WATER

Water is a crucial component of riparian zones, which are both *made* and *destroyed* in water. Water creates the strata for life to grow upon; it gives life to the trees via delivery of nutrients; it perpetuates life along the streambank through the carriage of seeds to be laid down upon newly built or scoured sites. Water nourishes thirsty seedlings, saplings and even their mature counterparts; and it often provides the mechanism of destruction of those very plants. In short, water is one of the major drivers of riparian vegetation growth, delineation, and limitation. This is what makes plants a useful tool for assessing general water properties in a riparian zone.

Water Table Depth

Riparian plants are so-named because they really like having their roots in or just above abundant (typically saturated or near-saturated) soil water. These plants will grow in distinctive patterns relative to, and often directly related to, changes in the water table. This simple relationship presents a powerful tool for using select species as indicators of below-ground soil water properties. No digging, and no invasive time-consuming data collection are necessary. Of course this is altogether dependent upon the assumption being correctly justified and aptly indicative of the spatial patterning being observed.   Therefore any species put forth as an indicator of this relationship should be well-examined for its potential in correctly "identifying" the physical characteristics it is being called upon to verify; in this case soil water properties conducive to its growth. Figure 6.8 shows a well-developed riparian community of cottonwoods, sycamore and willow trees in photo (a.). Photo (b.) is taken at the top of the channel slope and illustrates the well-defined riparian tree boundary - which helps to identify underlying soil water conditions necessary to support those species.

a.  b. 

Figure 6.8: A typical riparian zone with a well-defined boundary. (photo by J. Duke)

In some regions such arid climates, terrestrial (non-riparian-classified) plants will be in the riparian area, but will grow much larger, and show more robustness in growth form compared to their more-upland-located counterparts. Growth form refers to the health, compactness, crowding, size, structure and/or number of individual plants. The difference is ease of water access. The active flood plain will be present, but possibly only in the area of a bench. Though these plants help to further solidify knowledge of the water table's presence/absence their use as true key indicators is lessened by their ability to thrive outside of these constrained zones. Therefore, the best indicators are the highly-constrained-by-water-table-depth species.

Capillary Fringe

The story of the water table and its direct relationship to riparian forest spatial patterning feeds forward to the capillary fringe. Often the relationship between water table depth and a plant's presence/absence directly above is more a story of the distance to the capillary fringe than it is to the actual water table. Either (capillary fringe or water table depth), if understood to be mechanistic drivers to riparian patterning, are equally identifiable by such sentinel species. Figure 6.9 shows the influence that capillary fringe may have on woody vegetation distribution. Actual water table may be located below the tree's root depth, but capillary fringe may facilitate a more shallow water availability.

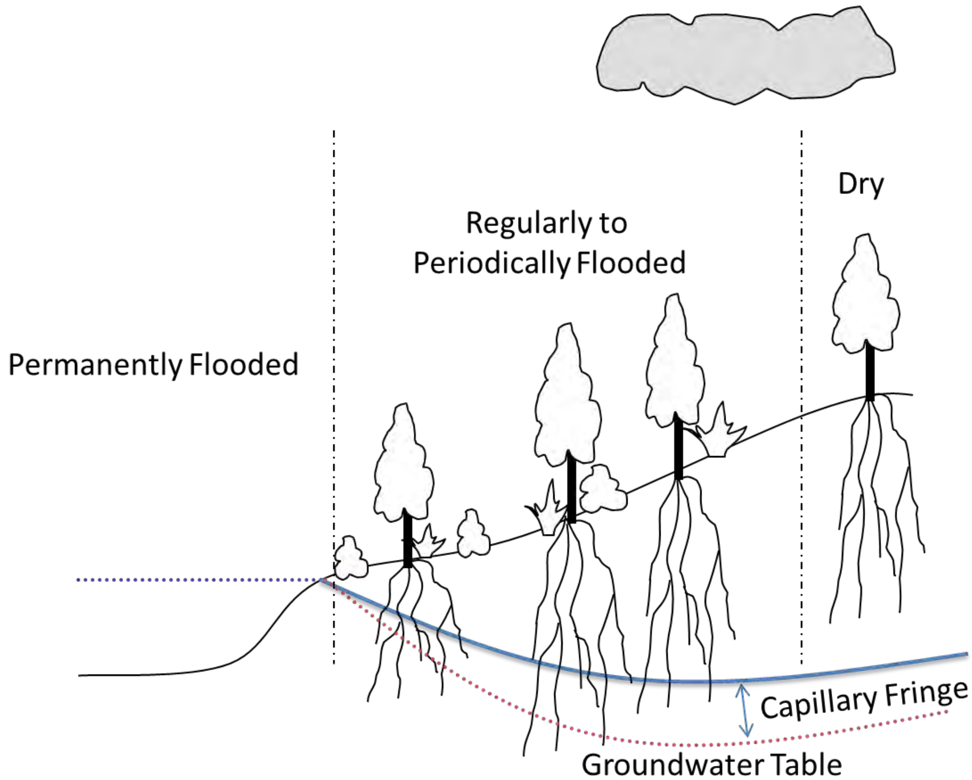


Figure 6.9: The importance of a capillary fringe to transpiring trees' root depth. Water table depth is represented by the red line; the capillary fringe by the thick blue line.

Seasonality

Of course any discussion of water has to take into account the seasonality of rain patterns that drive flood events and influence water table depth. In order for a species to persist long term in the system, its seed dispersal, seedling and sapling survivability, and drought/submergence traits must be highly adapted not only to those overarching patterns but also to the extreme variability that comes with the year-to-year timing and duration of such, and even the event-to-event variability. In Texas this variation can be one of the most important drivers in distinguishing "true" riparian species from the more facultative water-seekers.

Flood Supplementing vs. Persistent Water Table

When life stages (particularly early stages: seedling, sapling) are considered, the story of the connectivity between woody plant distribution and water availability is often more about soil moisture maintenance than depth to water table. Until a tree has reached a maturity level wherein root depth has penetrated the water table or has amassed enough root mass in the capillary fringe to support productivity, supplementation of the unsaturated soil zone via above-ground runoff during rain events and flood pulsing into the channel banks are vital to survival. The best indicator of such conditions being met on a regular basis are those species whose survivability not only tolerates, but also demands these conditions. Additionally, comprehensive understanding of the life strategies by riparian trees to reach and utilize the water table and its capillary fringe allow for historical water table conditions to be assessed via observations of age distribution among the trees.

SOIL

Soil types, size, drainage

Studies suggest that hydraulic sorting results in different size distributions for geomorphic surfaces (with depositional bars being more coarse grained relative to higher surfaces), and silt-clay percentages tend to increase with height of alluvial features. (Osterkamp and Hupp 1984.) For a more in depth discussion of soil features in riparian zones, refer to the soils chapter.

Soil Water Conditions

One of the key soil characteristics most closely associated with true riparian species is soil water, and whether the soil is hydric. Hydric soils, formed under prolonged periods of saturation are typically anaerobic and therefore highly selective in that only certain plants can tolerate/thrive in them. Therefore a very strong linkage between hydric-adapted plants and soil water makes for a useful indicator of such conditions below-ground in the presence of such vegetation. See Figure 5.7 for an example of an identifiable hydric soil.

Soil depth

Soil depth can vary considerably within a riparian area, and no one soil depth is closely associated with "riparian" vegetation. Sedimentation may increase depth via building, and intense floods may decrease via erosion. Therefore, a key characteristic of well-adapted riparian species is the ability to form an adequate root base (whether tap root or increased lateral root mass) to both penetrate to soil waters and prevent being swept away in high flows.

TIME SCALE

Monitoring over time, if possible, is the absolute best of all worlds. At any point the river may be recovering from disturbance, and the best way to both recognize and to gauge an outcome is to make repeat visits. Without that luxury, a greater reliance must be placed on indicators of whether the system appears to be currently recovering or degrading. Recurrent monitoring also serves as a learning tool. Seeing a site multiple times, and through multiple disturbances is the best path to comprehensive understanding of the system.

BIOTIC FACTORS INFLUENCING RIPARIAN FOREST DYNAMICS

Biotic influences on riparian forest development create "noise" in the abiotic signal. Awareness of these variables allows for better interpretation of physical-feature influences when their input can be assessed and removed from the equation. Examples include competition and herbivory. Competition can be above or below ground. Above ground competition among trees entails primarily the fight for sunlight, which is more easily accessed in an open canopy. One effect of a lack of competition would be increased growth in sparsely-populated areas. As canopies close and stratify, competition among community members intensifies. Below-ground competition would be both the spatial distance between plants and their root zone requirements. Typically, a lack of competition would more likely obscure physical factors simply because increased competition requires the presence of members of the species, whereas a *lack* of normal competition may allow for a skewed age distribution prevalence that could incorrectly be attributed to physical features. As an example: natural death of a single or few large mature trees may open up real estate upon which several seedlings of black willow happen to disperse. Fifteen years later the heavy proportion of these now-mature trees is simply indicative of the biotic variable of lessened competition, rather than an underlying ideal physical factor.

Excessive herbivory will potentially remove indicator species (and may even increase prevalence of invasive or non-riparian species), thus obscuring abiotic factors and their influences. Background knowledge of the historic herbivory, particularly by agricultural stock is very valuable when riparian biotic features are being evaluated.

PIONEER SPECIES

Prevalent pioneer species are a sign of recent flood activity (Wrede 2005). While their early establishment indicates "healing" of a flood-cleared spot or newly created bar/bench, their long-term establishment would indicate less ideal conditions for long-term riparian species. Pioneer plants are both adapted to quick establishment of newly scoured bare spots, and are a necessary community successional stage for a flood prone stream system. Key here is *successional stage*. Their replacement is as much a component of a healthy stream ecosystem as is their establishment. Age structure of pioneer species can be used to determine length of persistence for woody species. Size/density can be used for perennial and annual shrubs/forbs.

CONSIDERATION OF THE HUMAN INFLUENCE

LAND-USE CHANGE

One of the major effects that humans have had on riparian zones has been in both the direct destruction (for various purposes) of riparian habitat as well as the conversion of the landscapes that feed into riparian zones away from natural habitat. Crucial to the longterm maintenance of a riparian area is the presence of a healthy uplands in addition to a functioning stream system. Conditions in the surrounding landscape will influence conditions in the riparian zone and must be considered from a maintenance perspective. A heavily degraded uplands may change discharge, overland flow, erosion, etc. Consideration of the uplands and potential degradation is however, only in pertinence to its potential degradation of the riparian zone (a degraded upland is not the focus, but rather whether that degradation feeds forward into the functionality of the riparian area.) Sustainability of a riparian zone is therefore just as much a function of the influence of uplands as stream dynamics, and both should be incorporated into analysis and maintenance plans.

DOWNCUTTING/INCISION

One of the consequences of urbanization/land use change is often downcutting in the stream because of increased surface erosion from the landscape and/or channel straightening. When such conditions occur the effect is a disconnect between riparian root systems and hydric water availability (with dropping water table adjacent to incising streams). Even though a soil analysis may indicate historic hydric conditions exist, this can be deceiving, particularly if downcutting has been rapid and recent. What has historically been mapped as a hydric soil may in fact now be experiencing a drier, aerobic condition. The best way to identify whether this is in fact the case is to examine the riparian vegetation condition. Groffman *et. al.* (2003) demonstrated the effect of one such "riparian hydrologic drought" which caused a shift in riparian community toward upland species, with a subsequent loss of riparian functioning in the zone. Figure 6.9a. is an example of a non-incised stream, exhibiting a strong connectivity between tree roots and water. The average distance across the stream at the top of the channel is

10m and the average height of the channel is 4m. Figure 6.9b. shows this same stream below a section that was channelized by a landowner along the reach. The average distance across this downcut section is 23m and average height is 10m. The trees have lost connectivity to the stream water because of a nickpoint created from the channelization.

a.  b. 

Figure 6.9: A reach (a.) upstream and (b.) downstream of a channelized section (not shown) that has caused severe downcutting of the channel (photo by J. Duke)

Figure 6.10 demonstrates the effect of channel incision along a small headwater stream. Photo (a.) illustrates the non-incised upstream section, photo (b.) is the downstream reach undergoing downcutting, and photo (c.) shows a manmade structure intended to prevent further upstream migration of the nick point. The cause for downcutting in this stream is largely because of agricultural processes that have increased landscape erosion.

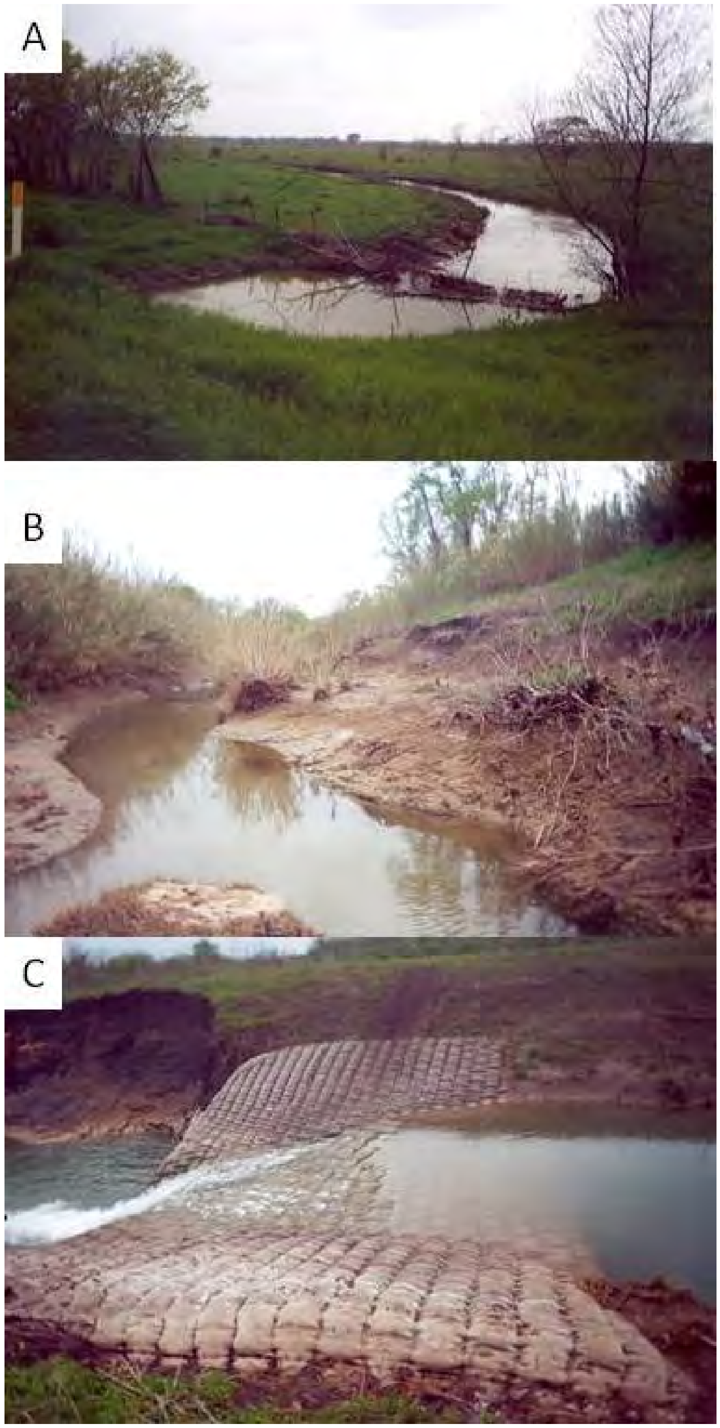


Figure 6.10. A headwater stream (a.) undergoing downcutting (b.) because of agricultural erosion, and an installed structure (c.) attempting to prevent further upstream creep of the nick point (photo by J. Duke)

DAMMING

Damming creates mayhem in a riparian ecotone. Often floodwater delivery of nutrient-rich sediments is attenuated well below riparian spatial location both because the actual water pulse is less and because sediments are removed from the water when passing through the reservoir. Water released from dams is sediment-poor and "hungry" to capture more sediment instead of depositing it in a natural fashion (Pennington and Cech 2010). Not only are many natural flood flows eliminated or lessened, but abrupt dam releases may cause a high-energy water surge that acts to further flush deposits from soil banks. Flood releases from dams often arrive at the wrong time ecologically (Pearce 2006) disrupting both seasonal seed dispersal and/or seedling and sapling survival of riparian adapted forests.

POLLUTANTS

Pollutants have the potential to obscure physical attributes of the river. Because they may provide an additional limitation to the presence of one or more indicator species (or any plant growth for that matter) their influence would mask the true physical potential for a site. Any known recent or historical pollution events should be recognized and taken into consideration.

INDICATORS OF BALANCE BETWEEN BIOTIC AND ABIOTIC

The key phrase in the balance of a riparian ecosystem is dynamic equilibrium. Five hundred year floods *will* do damage. Prolonged, severe droughts will do damage. But for the most part riparian communities are constantly adapting to a much smaller fluctuations to their habitat (drought *will* follow floods and floods *will* break droughts). Inevitably any given snapshot of a riparian zone (particularly small scale) may indicate extreme health or show signs of much stress. Therefore a set of indicators can be used (in successive timeframes) to determine ecological functioning - with an understanding that the smaller the spatial scale, the less the entire continuum is represented. Riparian functions have been extensively studied and include:

- Improved water quality
- Increased biodiversity (both streamside and within the stream)
- Temperature moderation of stream (with a closed canopy)
- Slowed water flow along banks
- Stabilization of banks
- Varied stream conditions (natural bends, runs, pools, etc.)

General riparian characteristics have been identified to include:

- A mixture of woody and herbaceous species that help to dissipate flow energy of both runoff from uplands and streamflow
- Sufficient woody plant root mass to stabilize banks, prevent erosion, and trap incoming sediments
- Floodplain development
- Sufficient woody root mass: hyporheic connections that facilitate the underground flow
- Sufficient woody plant stems (varying sizes)
- Sufficient canopy
- Biological and spatial diversity
- Decaying matter on forest floor: This is seasonally driven; however, rich organic matter should build in the riparian zone, unless a recent flood has scoured the soil surface.
- An inverse relationship between channel steepness and riparian width

As mentioned earlier a steeper channel will have a narrower riparian zone. Distance from baseflow water level to upper trees should not exceed rooting depth of trees to ensure that woody species root water availability is adequate to sustain the forest. Knowledge of whether recent water conditions have increased above historic levels or recently been drawn down is highly beneficial for interpreting current conditions, and highlights why a series of visits provides the best evaluation. Persistence of either condition can threaten the current riparian community, and should be considered for whether predicted changes are acceptable for future maintenance.

Because riparian ecotones are a subclass of wetland type, the functions of wetlands as described in Table 2 and Figure 8 of Smith *et.al. (*1995) apply fully to the functionality of stream riparian ecotones. Fennessy *et.al.* (2004) and Papas (2006) debate whether assessment of riparian ecotones should entail "condition" or "functionality" and provide several examples and indicators of such. Fennessy *et.al.* (2004) argue for the highest level of the 'functionality hierarchy' outlined in Smith *et.al.* (1995): maintenance of ecological integrity, encompasses all ecosystem structure and processes. This is in effect a "super" function which infers the condition of an intact ecosystem at all levels.

In order to determine whether a riparian forest and its associated stream are functioning in a sustainable manner it is necessary to determine both the vigor of the existing community as well as its ability to provide for the continued maintenance and recovery of desirable stream traits in the future. To address future maintenance of a stream, a full understanding of the historic nature of the system, and how any current alterations have either benefited or impacted the riparian zone is needed. While the spatial scale of riparian forest is often in a state of dynamic stability as the river experiences both long-term and episodic high/low flows, the temporal scale for determining riparian relationship to river flow is best examined in decades to centuries. Therefore in addition to studies that provide repeatability over multiple decades such as that in Bush *et. al.* (2006), the use of trees (Anderson and Mitsch 2008) can provide a long-term examination of tree productivity and/or response to river flow. Figure 6.11 shows a less-functional riparian zone in which an incised channel has reduced water table depth well below the root extent of trees, and hence no trees are present along the channel. Figures 6.12 and 6.13 on the other hand, are representative of healthy, functioning well-connected riparian zones communities.

Figure 6.11: A functionally-compromised riparian zone in which an incised channel has reduced water table depth well below the root depth of trees, and hence no trees are present along the channel (photo by J. Duke)

Figures 6.12: A healthy, functioning riparian zone community that has undergone a recent depositional event, removing some saplings but depositing nutrients and water to young seedlings. (photo by J. Duke)

Figures 6.13: A healthy, functioning riparian zone community along a large river in Texas. (photo by J. Duke)

TRADITIONALLY DEFINED RIPARIAN SPECIES

There are 222 native trees in Texas (Simpson 1999) representing up to 45% of all native tree species in the US. Of those few fit the criteria of "riparian" in the strictest sense. Commonly riparian trees are grouped into general wetland classes (obligate, facultative wetland, facultative uplands, etc.) One of the disadvantages of this method is that lumping together trees so broadly does not take into account their unique differences in life stage water needs (e.g. *P. deltoides* must reach a suitable, moist bed within one to two weeks, needs frequent flooding as a sapling, but develops a deep tap root upon maturity). While there are uses for such groupings (simplification of reporting, generalization of trends), such groupings also have the potential to obscure any one of those grouped species' predictive ability as a key indicator species. For example the differing water needs of *P. deltoides* at different life stages makes it a great indicator of historical stream conditions: recruitment along a stream is indicative of frequent, small-duration flood events, while the presence (and distance to stream) of mature trees are indicators of shallow water tables that are either hyporheically connected, or once may have been connected to a previous stream channel that has since shifted.

For this reason an evaluation of the more common, widely-distributed-across-Texas "riparian" trees is given. Various biotic features that link riparian trees to underlying physical processes are shown in Table 6.2, and select trees are ranked according to their ability to "indicate" riparian parameters in the following sections. Because one of the major criteria for longterm persistence of riparian trees along the stream is connectivity to the water table/hyporheic zone, special attention is given to those species who depend heavily on such conditions. Root depth and water table level must be compatible, and even representative of geomorphic conditions driving community dispersal. Numerous studies of root depth in trees has shown that seldom do tree roots extend beyond 2m vertically, and up to 99% of a tree's total root mass occurs in the upper 1m of soil (Crow 2005, Danjon *et.al.* 2008). Based on this general relationship of rooting depth White *et.al*. (2002) developed an equation (Eq. 6.1) which predicts riparian width based on channel slope steepness:

Eq. 6.1: $d = z/(\text{tangent})\,alpha$ Where d = riparian width (m)

z = rooting depth (m)

alpha = land slope angle (degrees)

The assumption is that beyond this ~2 m depth tree root prevalence is not significant enough to maintain transpiration unless saturated soils exist to support riparian species. This model underscores the very distinct relationship between biota and the abiotic condition, and illustrates how useful a key indicator can be in making quick assessment of non-easily-measured abiotic variables (in this case groundwater depth).

WOODY SPECIES COMMONLY FOUND ALONG TEXAS RIVERS

- Acer negundo (Maple Box Elder)
- Carya illinoinensis (Pecan)
- Celtis laevigata (Hackberry)
- Fraxinus pennsylvanica (Green Ash)
- Morus rubra (Red Mulberry)
- Platanus occidentalis (Sycamore)
- Populus deltoids (Cottonwood)
- Ptelea trifoliate (Wafer Ash)
- Salix nigra (Black Willow)
- Taxodium distichum (Baldcypress)
- Ulmus crassifolia (Cedar Elm)

Table 6.2: Common riparian-associated species and their general characteristics (modified from Duke 2011).

Species	Common Name	Span (yrs)	Reproductive Maturity	Seed Dispersal	Germination Needs	Seedling Drought / Water Tolerance	Drought / Water Tolerance	Confined to Stream	Rooting Depth (m)
Acer negundo	Box Elder	75-100	8-11 yrs, annual	Wind	Overwinter	Flood tolerance < 85 days, or up to 50% of growing season	Both, once estab; flooding for entire growing season	Yes	shallow, spreading; fibrous
Carya illinoinensis	Pecan	100-300	20 yrs, opt=75-225	Water, animal	Moisture, Overwinter to April	Low drought tolerance, flood tolerant 1-4 wks	Low drought; req.well drained soils; no prolonged flooding	No	Deep tap, fibrous w/ maturity
Celtis laevigata	Hackberry	150	15 yrs, opt=30-70	Water, animal	dormancy at41F	Flood intolerance	Fair drainage, flooding 1-4 wks (10% growing season)	No	3-6, occasional taproot
Fraxinus pennsylvanica	Green Ash	30-50	Unk	Wind, water	50% immed, 50% OW;	up to 30 days shallow flooding tolerance	Tol of flood <40% growing season; Intol of shading	Yes	2-3m
Morus rubra	Red Mulberry	Unk	10	Animal	Overwinter	Moderate flood tolerance	Moderate flood tolerance	No	Unk
Platanus occidentalis	American sycamore	250+	25 yrs, opt=>50	Water, wind	Moisture, direct light; <2" soil	flood tolerance ~30 days	Tolerates saturation 2-4 mos; Riverbottoms	Yes	Wide, strongly branched
Populus deltoides	Eastern Cottonwood	100-200	5-10 yrs, opt=35 yrs	Wind, water	must reach bed 1-2 wks; Immed germ	Req frequent flooding; flood tolerance to 50% of growing season	Req periodic flooding; mod drought; roots die if sat >1 mo.	Yes	3-5 (avg=2.5)
Salix nigra	Black Willow	40-100, 65 avg	10-30 yrs, annual	Water, wind	must reach bed 12-24 hrs; Immed germ	Dies if >5 dry days	Drought intolerance; survives >30 days of saturation	Yes	Shallow, extensive
Ulmus crassifolia	Cedar Elm	100	Unk	Wind	Overwinter	Highly adaptable	Highly drought tolerant once estab; mod water tolerance	No	Shallow, spreading

TREES SELECTED AS KEY INDICATORS

Among the trees listed above, select species quickly move to the forefront as potential key indicators. When the definition of key indicator is constrained not only to indicators of ecological processes, but also includes a local distribution that is *strictly* associated with particular environmental conditions (shallow water table depth, adequate capillary fringe, regular, seasonally-appropriate channel bank supplement by flood waters) the list becomes more exclusionary; and the presence of the indicator becomes an appropriate inference that such conditions exist. Add in a broad spatial distribution across the state, and three main indicators are noted: green ash, cottonwood, and black willow. These species are proposed to be delineators of soil/water characteristics important in designating the true riparian zone. A discussion of each is given below.

FRAXINUS PENNSYLVANICA (GREEN ASH)

Fraxinus pennsylvanica is not as widespread across Texas as the other two proposed indicators, but its relatively extensive coverage across East, Central and South Texas does make it useful for much of the state. *F. pennsylvanica* seeds drop in late fall and winter, but do not germinate until the next spring. Wind dispersal can usually carry samara a few hundred feet. Water dispersal requires adequate flow (bankful and inundation into the floodplain) during winter/fall months. It is highly tolerant of disturbance and its presence often indicates frequent flooding into that area.

The rooting depth of *F. pennsylvanica*, referenced in table 6.2, ranges from 2 to 3 m, with extensive laterally-spreading roots (USDA 2013). *F. pennsylvanica* is often confined not only to streamside areas, but often to the channel slope itself, indicating its adaptation to this unique area. Its ability to form an extensive root system allows it to grow on extremely steep channel slopes (stabilize these slopes) where most trees cannot exist. It is browsed by many woodland species and is an important food source for wildlife.

POPULUS DELTOIDES (COTTONWOOD)

Populus deltoides (var. *deltoids* Eastern Cottonwood) is found all across East and Central Texas. It covers Wichita County (west) to Sabine River (east), Red River (north) and Gulf Coast and Rio Grande River (south). It grows in almost any soil type, though best in sands and sandy loams at river edges. Constant flooding (bog areas) may inhibit growth, but especially during seedling/sapling stages water is *essential* for survival. Until mature trees have grown tap roots that can penetrate the water table, frequent flooding is necessary to ensure soil moisture in the unsaturated zone. *P. deltoides* typically drops its seeds in late spring/early fall and rely on overbank spring flows - not so much for dispersal as to ensure that seedlings, which germinate immediately reach moist, nutrient-rich soil within 1-2 weeks of dispersal. Because seedlings and saplings can tolerate flooding for up to 50% of their growing season, and demand flooding for survival, their presence infers such recent conditions have persisted. Presence of larger mature trees in the same location indicate this has been the historic regime. Missing mature trees and/or a location of such at some distance to seedling/saplings may indicate a relocated stream channel or other alteration from past conditions. Missing seedlings and saplings would indicate a more recent alteration that is preventing recruitment into the historic riparian spatial extent.

The rooting depth of *P. deltoides*, referenced in Table 6.2, as an average 2.5m and maximum recorded depth of 5m is based on research done in part by Braatne *et.al.* (1996) and Heilman *et.al.* (1996). The very rapid growth of *P. deltoides*, along with an extendedtaproot make them excellent stabilizers of bank soils. They are browsed by a variety of wildlife.

SALIX NIGRA (BLACK WILLOW)

Salix nigra (Black Willow) is ubiquitous in Texas. It grows in standing water, flowing streams, dry streams, and any low points where water pools or has pooled in its past. Its only non-documented areas of the state are a few High Plains in western counties, but its absence is assumed unlikely (Simpson 1999).

S. nigra drops seeds usually from April to July. Though also wind dispersed, adequate flow during these months must be maintained to allow for water dispersal. Seeds germinate immediately and must reach moist, fertile soils within a day or two of dispersal, showing the importance of adequate, correctly-timed flood flow to survival success. *S. nigra* saplings have been shown to fair best when wetted frequently (daily to weekly) but also allowed a period of several dry days in between to allow for soil draining. (Li *et. al.* 2004).

S. nigra of diverse age classes growing along channel slopes and very near water's edge indicate adequate flows including events that overbank at least partially the channel slope to allow for water dispersal. Persistence would require such events typically occur every year or two. *S. nigra* has been shown to be consistently limited to regions where the water table is more shallow than 3-4m (Duke 2011) making it an excellent marker for this feature. One of the main features of *S. nigra* is its intolerance to drought and extreme tolerance to flooding. This, and its limitation to a shallow water table make it a preferred sentinel for inferring stream and soil water conditions.

Little research exists on measured *S. nigra* rooting extent, but its very limited constraint to the lowest, wettest regions of stream channel banks, along with its severe intolerance to drought underline its importance for inferring site water conditions. *S. nigra* not only functions to stabilize banks with its shallow, but highly branched roots that extensively penetrate laterally in soils, it also is a preferred browse for deer and other woodland species.

A SPECIAL NOTE CONCERNING *CELTIS LAEVIGATA* (HACKBERRY)

This non-riparian species can actually be used to assist in assessing riparian health in that it can become invasive when true riparian functionality is compromised. A site with expanding *C. laevigata* to the point of competitively excluding indicator species and/or establishment inside the bank channel may indicate an inadequate flow to both prevent establishment and remove invaders. The presence of invasive species *of any kind* are also suspect as indicators of a stressed, altered stream system.

GENERAL MANAGEMENT USING SUGGESTED KEY INDICATORS

Management of streams depends on an understanding of within-riparian zone processes as well as how stream processes affect functionality of those zones. Prichard (1998) argued for the importance of understanding the riparian forest: *a properly functioning riparian forest is necessary to maintain the integrity of the stream system itself* (paraphrased). If we are to keep Texas stream systems functional then we would do well to maintain the health of their riparian components, and an easy assessment begins with examination of the dominant trees along those streams.

Given the above discussion and identified indicator species, it should be noted that while the presence/abundance of all three is ideal, any one alone will suffice (for reaches that don't contain all in their natural communities). Because each of these trees represent species indicative of a healthy riparian zone tied directly to water availability, the combined information of their individual responses provides a richer picture for predicting future flows, but does not negate the use of any one individually. *S. nigra*, with its widespread geographic range, and severe limitation to shallow water tables near stream reaches is probably the most versatile indicator, though all three are reliable sources for delineating stream/soil conditions. In instances where no woody species (or indicator species) are present (*e.g.* an intermittent headwater stream unable to sustain woody species or another with only herbaceous species), managers must resort to directly measuring geomorphic, soil and water properties to determine 1) spatially expected extent of the riparian zone and 2) whether the lack of woody species is normal for that reach or indicative of an unhealthy disturbance.

Figures 6.14 through 6.17 show various willow, cottonwood, and green ash-dominated riparian zones. These indicator species are often jointly found along many Texas rivers, but may be found individually along various streams.

Figure 6.14: Black willows, green ash and box elder (another common riparian tree) line both banks of this Texas river. (photo by J. Duke)

Figure 6.15: A large green ash drapes the channel slope of this Texas river, while several mid-sized black willows grow streamside in the background (photo by J. Duke)

Figure 6.16: Quickly growing cottonwoods tower over black willow and other trees in this headwater stream. (photo by J. Duke)

Figure 6.17: A dense stand of black willows dominate the banks of a large Texas river. (photo by J. Duke)

Flow regime management should mimic natural seasonal flows both in spring and fall to cover seedling dispersal and sapling survival at least on a semi-annual basis. Shallow groundwater provides for establishment/revegetation of *Salix* and *Populus* (Stromberg 1998) following episodic events, and is vital to providing trees the resistance to withstand major flood disturbances. Without such resiliency, large floods can cause adverse ecological effects to the riparian forest (Middleton 2002). Additionally, the loss of shallow groundwater increases the potential for deeper-rooted invaders to persist in such areas, and an increase in upland plant abundance is often an indicator of declining water table (Myers 1989). Refer to the Special Note Concerning *C. Laevigata* section above for a discussion of such an indication.

Riparian species' vigor above ground is a reflection of their below ground conditionAt issue is not only the plants' ability to sustain themselves, but also their capacity to prevent channel soil degradation. This underscores the need for streamflow maintenance to ensure species vigor is maintained - increasing resiliency of those trees in weathering inevitable large floods or droughts, and their ability to revegetate post-disturbance. Seed germination for these riparian species can be critically dependent on flood pulsing into the zone to disperse seeds, followed by drawdown to allow for germination and establishment of seedlings (Junk and Piedade 1997). Key to long-term sustainability is minimum-maintenance flows coupled with larger floods to provide a healthy disturbance regime.

A major advantage to using the key indicator species method for rapid riparian boundary defining and management is that it can be broadly applied at the EPA's National Wetland Program "three-tier framework" levels of wetland assessment. Even at the Level 1 scale (broad, landscape) key indicator species can often be discerned in aerial images; at Level 2 (rapid field method) the key-indicator approach is ideal; at Level 3 biological and physical/chemical measures are easily inferred and validated once key indicators have been specified and mapped. The hierarchical assessment was originally proposed to provide sound quantitative information with a relatively small investment of time and effort (Fennesy *et.al.* 2004), and our key indicator method further refines this approach. Identify the sentinel species whose presence *require the most stringent conditions for functionality*, and then manage those species – and you'll be managing for the betterment of the entire system.

FINAL NOTES

Keep in mind that riparian evaluation doesn't begin and end with any one variable or indicator (nor should it). Once an assessment has been made of the riparian boundary/functionality using the woody species key indicators, further evaluation can commence if shown to be necessary. The next step is to consider not only how well the indicators appear to have represented the system of interest, but to place such data in light of known abiotic variables. Additionally, the geologic and climatic processes (regulators of all other abiotic features) must also be taken into account to ensure that the site appears to be functioning both within its historical context and its given potential.

CHAPTER 7 - THE SPECIAL CHARACTER OF RIPARIAN MANAGEMENT (STEVE NELLE)

INTRODUCTION

Riparian areas are most simply defined as the transition or interface between comparatively drier upland areas and wetter areas. Riparian areas can exist along the margins of creeks, rivers, ponds, lakes, wetlands and bays. This chapter will focus on the management of riparian areas that exist along creeks and rivers.

Streams and their riparian areas can be classified according to the duration of flow. Perennial creeks and rivers flow continuously on the surface except during the most severe drought. Seasonal creeks, also called intermittent creeks, flow for only a portion of the year, and yet maintain a connection to the associated alluvial water table. Ephemeral creeks only flow in direct response to rainfall and runoff and have no connection to a water table. Perennial and seasonal streams usually have well developed riparian areas. Ephemeral creeks and draws usually have poorly developed riparian areas due to a lack of a contributing water table and are not addressed in this chapter.

There is tremendous variability in riparian areas across Texas, and for this reason, the appropriate management will also vary from place to place and should be site specific. The information presented here is general in nature and not intended to prescribe specific management for a specific riparian area. Onsite technical assistance by experienced riparian professionals is available to help determine specific management that may be needed.

SMALL YET SPECIAL

The relative value of riparian areas in the landscape far exceeds their relatively small size. In most settings, the actual riparian area only makes up only one to five percent of the total land area, but the ecological, hydrological, economic and human values of these areas is comparatively much greater. Riparian areas have been referred to as “ribbons of gold” to help communicate their great worth. Those who own or manage land adjacent to creeks or rivers should understand their responsibility for conservation and sustainable management of these special resources.

When considering the management of riparian areas there is one guiding principle that needs to be remembered: Riparian areas are special places (Figure 7.1); they need preferential treatment (Figure 7.2). The same kinds of management that work well on upland areas, do not necessarily work well in riparian areas. The management needed in the riparian area is different and distinct and should be specially prescribed and carried out. Understanding this truth will help riparian managers take better care of these special places.

Figure 7.1. Although riparian areas comprise only a small part of the landscape, their contributions and values far exceed their small size. Riparian areas are special places.

Figure 7.2. Riparian areas need preferential management. This healthy riparian area in the Panhandle is receiving preferential management in the form of specialized grazing management.

SENSITIVE YET RESILIENT

Riparian areas are both more sensitive, yet also more resilient than other parts of the landscape. Riparian areas are sensitive and potentially vulnerable to the high energy of turbulent floodwaters that apply tremendous stress to banks and channels. The stress is compounded by the transport of gravel, cobble, logs, trees and other objects during flood events. Riparian areas are also sensitive due to the disproportional amount of human activity that often takes place in and near creeks and rivers. These activities can potentially increase physical, biological or chemical stress to the stream and associated riparian area.

Yet, riparian areas are also extremely resilient to stress and disturbance, especially if the proper kinds and amounts of riparian vegetation are present (Figure 7.3). The resiliency is a function of extra water, fresh inputs of nutrient-rich sediment and inputs of seed and plant materials from upstream. The inherent resiliency of riparian areas and their tendency to naturally restore themselves after disturbance is the basis of most riparian management.

Figure 7.3. Riparian areas are especially sensitive to disturbance, but they are also resilient. Natural resiliency is the basis for most successful riparian management.

THINK WATER CATCHMENT (NOT WATERSHED)

Even though the focus of this publication is on the larger river systems, major tributaries, and the importance of maintaining flow regimes, it is important to note the essential connection of larger creeks and rivers to the entire landscape (Kershner 1997). The waters that make up the flow of larger streams originate on the uplands via precipitation and runoff, which then pass through a series of small drainages and ephemeral creeks until they progressively merge into larger and larger creeks, and finally into the major river systems of Texas. Likewise, the water that percolates into aquifers and subsequently discharges into creeks and rivers via springs also originates on the uplands.

The importance of watershed management has gained a great deal of attention in recent years (Adler 1995). Yet, the term "watershed" can convey an unintentionally wrong message. Literally understood, an area of land that repels, or "sheds" water is not the goal of a healthy landscape. Instead, some people have adopted the term "water catchment" to more aptly communicate how healthy landscapes should function. Consider the contrast between these two terms. A water catching landscape retains and stores water for a slow and prolonged release. A water shedding landscape moves water quickly down slope, off site and downstream for a rapid and short lived release. The management of riparian areas should also generally strive to create or enhance water-catching conditions rather than water shedding conditions. Desirable riparian vegetation is the key component that determines the water catching, water slowing, and water holding capacity of riparian areas. In both upland and riparian areas, the goal of management, in most cases, is to slow down the movement of water thus keeping water on the land longer (compare Figure 7.4 and 7.5).

Figure 7.4. Properly managed, well-vegetated upland areas can be referred to as "water catchments". A water catching, landscape with good soil health will absorb and store rainfall, allowing for slow and prolonged release. Management of upland areas to reduce runoff volume and slow runoff rates will help maintain riparian areas.

Figure 7.5. Poorly managed upland areas repel water and increase runoff rates. Water shedding landscapes inhibit the natural water cycle and exacerbate riparian problems.

The Greek philosopher Plato clearly recognized the connection of land, water and people, and understood the concept of the land as a water catchment in about 400 B.C.:

> *"In the primitive state of the country, the mountains and hills were covered with soil and there was an abundance of timber. The plains were full of rich earth, bearing an abundance of food for cattle. Moreover, the land reaped the benefit of the annual rainfall, having an abundant supply of water in all places; receiving the rainfall into herself and storing it up in the soil. The land let off the water into the hollows, which it absorbed from the heights, providing everywhere abundant fountains and rivers. Such was the state of the country, which was cultivated by true husbandmen, who made husbandry their business, and had a soil the best in the world and abundance of water."*

The roles of upland catchment areas, infiltration, surface runoff and subsurface flow are all critical components of the water cycle, which influence the character of creeks, rivers and riparian areas. Successful riparian management strategies also include an emphasis on the entire catchment area as well as the importance of the myriad smaller tributaries that support the flow of larger creeks and rivers illustrated in Figure 7.6 (USDA 1998).

Figure 7.6. Good management of small headwater tributaries is an important aspect of good overall land and water management.

Former President Lyndon B. Johnson, raised on a Texas ranch and active in early water management issues, also understood this interconnectivity: “Saving the soil and the water must start where the first raindrop falls”.

Upland areas in good hydrologic condition can do a great deal to maintain the integrity of associated riparian areas. Good management on upland water catchments helps to process and protect the waters of Texas in the following ways:

- Vegetation or plant litter intercepts raindrop impact thus reducing the erosive energy of rainfall
- Rainwater seeps gently into the soil surface
- Soil maintains good structure, good porosity, high organic matter content, and microbial life
- These soil qualities promote rapid infiltration and high water storage capacity
- Runoff begins more gradually at a slower and more prolonged rate
- Water quality of runoff is improved

Luna Leopold, former Chief Hydrologist with the U. S. Geological Survey stated:

> "Water is the most critical resource issue of our lifetime and our children's lifetime.
> The health of our waters is the principal measure of how we live on the land."

What happens on each acre of land has an impact on the waters of Texas. Astute landowners will incorporate this kind of holistic perspective as they manage the uplands as well as creek and river areas. Everything is connected.

However, it must also be noted that good conditions and good management of the uplands do not necessarily mean that the associated riparian areas will also be in good condition. It is possible for upland areas to be in healthy functional condition while adjacent riparian areas are in poor functional condition (Platts and Nelson 1985). This disparity can be caused by disturbances far upstream or downstream which disrupt riparian function many miles away.

RIPARIAN MANAGEMENT – PAST, PRESENT AND FUTURE

The current condition of riparian areas is largely the product of past management and activity. Humans have been attracted to settle and live near riparian areas for centuries and millennia. As European settlement progressed in the mid 1800's Texans naturally settled in large numbers in close proximity to creeks and rivers. Cutting of timber, grazing, farming, milling, development of transportation corridors, and other essential activities often took place near the creek, and riparian areas were negatively impacted (Figures 7.7 and 7.8). In many rural locations in recent years, this intense human activity near creeks and rivers has diminished and many riparian areas are recovering. In other rural locations, land is being subdivided into smaller tracts, which often result in more activity and greater impacts in riparian areas.

Figure 7.7. Decades of poorly managed grazing, beginning in the late 1800's have caused extensive damage to creeks and riparian areas. Overcoming the effects of past mismanagement is one of the challenges of modern riparian management.

Figure 7.8. Teaching people what healthy riparian areas look like is an important part of riparian education. Many people still prefer a manicured appearance and do not yet fully understand the value of a natural functional riparian area.

In many cases, there has been little or no specific management targeted at riparian areas other than what has happened accidentally and unintentionally. The principle of "benign neglect" has served dual yet opposing roles in riparian management. In some cases, neglect has maintained intact functional riparian areas. Sometimes doing nothing is the best form of riparian management. However, other forms of neglect have caused or accelerated riparian problems.

In some cases, riparian management has been intentional but not always with a good outcome. This intentional management is usually done with good motives, but too often is based on myths, misinformation, and traditions. In too many cases, management of riparian areas is applied without a good understanding of riparian dynamics. Riparian problems have often been caused simply by the side effects and spillover of management of the adjacent uplands. Remember – riparian areas are special places; they need preferential treatment.

Creeks and rivers, and their associated bottomlands have long been appreciated for the water, fish, wildlife, forage, timber, rich soils and other associated values they provide, but the basic functional attributes of riparian areas have not been widely considered. Likewise, until fairly recently in Texas, there has been little emphasis on proper riparian management. University programs in natural resource management and agriculture seldom address the critical role of riparian management. Most natural resource agencies and professionals do not yet have a good practical understanding of riparian dynamics. Consequently, few landowners are aware of the principles that govern riparian areas. However, landowners do pay attention to what happens in their creek and river bottom areas. Equipped with a basic and practical level of understanding, many landowners will make responsible choices regarding activities and management in riparian areas.

The future of riparian management in Texas will depend largely on long-term education and outreach (Figure 7.9). Landowners are clearly a primary target audience for such outreach. However, government agencies, conservation organizations, agricultural organizations, real estate agents, land improvement contractors, students, and the public all need to become educated about basic creek-river-riparian dynamics and management and the contributions these areas make to our quality of life (Orr 1990).

Figure 7.9. Outreach and education will be a key element in training and motivating people about the importance of good creek, river and riparian management.

The future success of riparian management also hinges on people wanting to do the right thing. Voluntary conservation and management of private land riparian areas is much preferred and generally more successful than the regulatory approach. Appropriate incentives and financial and technical assistance are available to help increase the adoption of good riparian management.

COOPERATIVE RIPARIAN MANAGEMENT

Because the waters of Texas are a shared resource and because water knows no landownership boundaries, the proper management of water is a shared responsibility (NRC 2002). This is especially true for creeks, rivers and riparian areas that run through dozens if not hundreds of different properties on their course downstream. Management of the upland water catchments as well as riparian areas affects everything downstream. Therefore, successful landscape conservation must emphasize cooperative riparian management. In a state like Texas, where landowner independence and private property rights are strong core values, cooperative management can be a challenge. The time tested, proven model is voluntary cooperation of neighboring landowners to achieve common, mutually beneficial natural resources goals.

The most successful model of cooperative natural resource management in Texas is found among the many independent wildlife management associations. These formal or informal associations are sometimes referred to as "wildlife coops" and their purpose is to promote the proper management of shared wildlife resources that live on multiple properties. The key to the success of these associations is twofold. First, the individual landowners declare some level of voluntary commitment to the goals of the association; and secondly, the group meets on a regular basis for educational purposes and to monitor the success of their management (Figure 7.10).

Figure 7.10. Successful large scale riparian and watershed management will depend on many adjacent landowners working cooperatively toward mutual goals. Landowner associations such as the South Llano Watershed Alliance are a good way to encourage widespread adoption of good land and water conservation.

Many of these existing wildlife management associations are formed on watershed boundaries or along creeks. The landowners already know each other and have worked together for years. It makes perfect sense to incorporate the riparian management message into these existing associations. In areas where these associations do not currently exist, the formation of new natural resource associations with emphasis on cooperative riparian management will be a worthwhile endeavor. Some of these organizations already exist, including South Llano Watershed Alliance, Trinity Waters, and Wimberley Valley Watershed Association.

Riparian authority, Wayne Elmore, speaks from over 40 years of direct riparian experience as he summarizes the importance of a cooperative grassroots approach in dealing with riparian issues:

> "Riparian restoration will not happen by regulation, changes in the law, more money, or any of the normal bureaucratic approaches. It will only occur through the integration of ecological, economic, and social factors, and the active involvement of affected people. "

This truth does not negate the value of appropriate regulations, financial resources or governmental assistance; it merely points out that people who are actively and cooperatively engaged in riparian issues are the most valuable asset. When people share a common understanding and appreciation for riparian resources – this is a first critical step toward good riparian management.

STEWARDSHIP ETHICS – A PREREQUISITE FOR SUCCESSFUL RIPARIAN MANAGEMENT

Those who are fortunate enough to own or manage land adjacent to creeks and rivers have an ethical obligation to be conscientious custodians and caretakers of the riparian area. Those who do not own land, but who benefit from healthy functional creeks, rivers and riparian areas, at the very least, owe a great debt of gratitude to those who practice such stewardship.

The ownership of riparian land (as well as all other land) should come with the deep inner sense of responsibility to take good care of the land and carry out proper management (Orr 1990b). Land ethics is the moral philosophy dealing with man's relationship to land. The proper attitude of the land steward is that even though they own title to a tract of land and pay taxes on the land, and make costly improvement to the land, they consider themselves merely tenants or trustees of the land. The tenant has the responsibility to take care of land entrusted to him and to ensure that it is maintained and managed during his tenure for future sustainability (Figure 7.11).

Figure 7.11. Landowners with a strong land stewardship ethic are motivated and compelled to take good care of the land under their management. Where land ethics are weak, land management is often poorly understood and poorly practiced.

Many landowners will readily apply management that provides short-term personal benefits, and most will implement management practices that will benefit their children and grandchildren. But genuine land stewardship goes beyond these primary motivations and considers the benefits to society. There is a great deal of altruistic benevolence involved in true land stewardship. For the genuine land steward, self-imposed responsibilities become of equal if not greater importance as landowner rights. One of the more desirable benefits of a long-term land stewardship ethic is that it is often an economically profitable way to manage the land. Genuine land stewardship is truly a winning combination for the land, the landowner and society as a whole.

Land stewardship ethics provide the motivation that compels, inspires and energizes the owner or manager to be deeply-principled caretakers of the land (Figure 7.12). Without an active land stewardship ethic, it is doubtful that creek and river landowners will see the need to provide the special management required in riparian areas. On the other hand, landowners and managers who possess a genuine land ethic are likely to embrace stewardship of the creek and riparian area and to become riparian advocates to their neighbors and examples to their community. These communities, at some point in the future, may want to consider some system of remuneration for the landowners who provide critical natural resource benefits to the public.

Figure 7.12. Genuine land stewards are those who understand the inner workings of the land and who take responsibility for maintaining or restoring the health of the land.

THE BASIS FOR RIPARIAN MANAGEMENT

INTENSITY OF RIPARIAN MANAGEMENT

Riparian management comes in many different forms with no two situations alike. Differences between riparian areas, differences in landowner goals, and differences in the resources available for management all combine to create infinite variability in riparian management. While the same general principles apply across most situations, the specific ways in which management is carried out will differ a great deal from place to place.

Riparian management can be divided into three broad categories, each requiring a different intensity of management (Balch). Some projects call for a combination of approaches:

- Maintain existing riparian condition
- Improve or enhance riparian condition
- Restore degraded and nonfunctional riparian condition

The various intensities of management required for riparian areas also suggest a logical priority of management. Maintaining an intact riparian area is much easier and more economical than attempting to restore a nonfunctional, deteriorated area. Furthermore, the likelihood of success is much greater and the risk of failure is much lower (NRC 1992). If resources are limited, funds invested in maintaining or enhancing riparian condition will go much further than intensive and expensive restoration projects. As with many other aspects of natural resource management, it is always better to prevent riparian problems rather than trying to repair problems. However, this should not discourage intensive restoration projects if resources are available.

RIPARIAN FUNCTION – THE CORNERSTONE OF RIPARIAN MANAGEMENT

Riparian function has been described in many different ways. Most descriptions and definitions of the term mix various biological and human values with the underlying physical processes. For the purpose of this chapter, it is important to be able to differentiate between the values provided by riparian areas and the basic physical-mechanical processes that support those values. It is vital to understand that the physical processes are what generate and sustain the values that we desire.

If riparian managers understand the importance of maintaining the physical functional processes, they will discover that, in most cases, the values they desire will follow. Riparian management that is focused primarily on these human-biological-economic values without understanding the physical processes is likely to experience frustration and limited success and have false expectations of what is possible.

For the purpose of this chapter, the following definition of riparian function is used. A functional riparian area is one that has adequate vegetation, landform, or large woody material to accomplish the following physical processes: dissipate the energy of high flow events; protect banks from excessive erosion; stabilize channels; trap sediment; build floodplains; store water; provide recharge of shallow aquifers; and sustain base flow (Prichard 1998) (Figure 7.13).

Figure 7.13. A riparian area in properly functioning condition is more stable and resilient, better able to hold up to moderately high flow events. Management that insures the right kinds and amounts of vegetation is the key to maintaining good functional condition.

Each of these components of riparian function involves physical processes, which are governed by the universal natural laws of physics and energy. When these basic functional attributes are working together, they in turn, produce or enhance many of the important creek, river, and riparian values listed in Table 7.1.

Table 7.1. Some values provided by functional riparian areas

Improved water quality
Fish and aquatic habitat
Terrestrial wildlife habitat
Livestock forage
Aesthetic values
Real estate and economic value
Recreational potential
Sustained flows
Reduction of downstream flood damage

It should be emphasized that the physical functional processes take place in the context of adequate riparian vegetation, landscape formation (boulders, sinuosity, and channel roughness), and large woody material. The most successful riparian managers will have a good understanding of how these factors affect riparian function (compare Figures 7.14 through 7.16).

Figure 7.14. When riparian managers understand the physical processes that drive the riparian area, they are better able to implement management that works. A working knowledge of riparian dynamics is crucial for proper management.

Figure 7.15. A non-functional riparian area lacks adequate vegetation to dissipate energy, protect banks, trap sediment, and slow down the water.

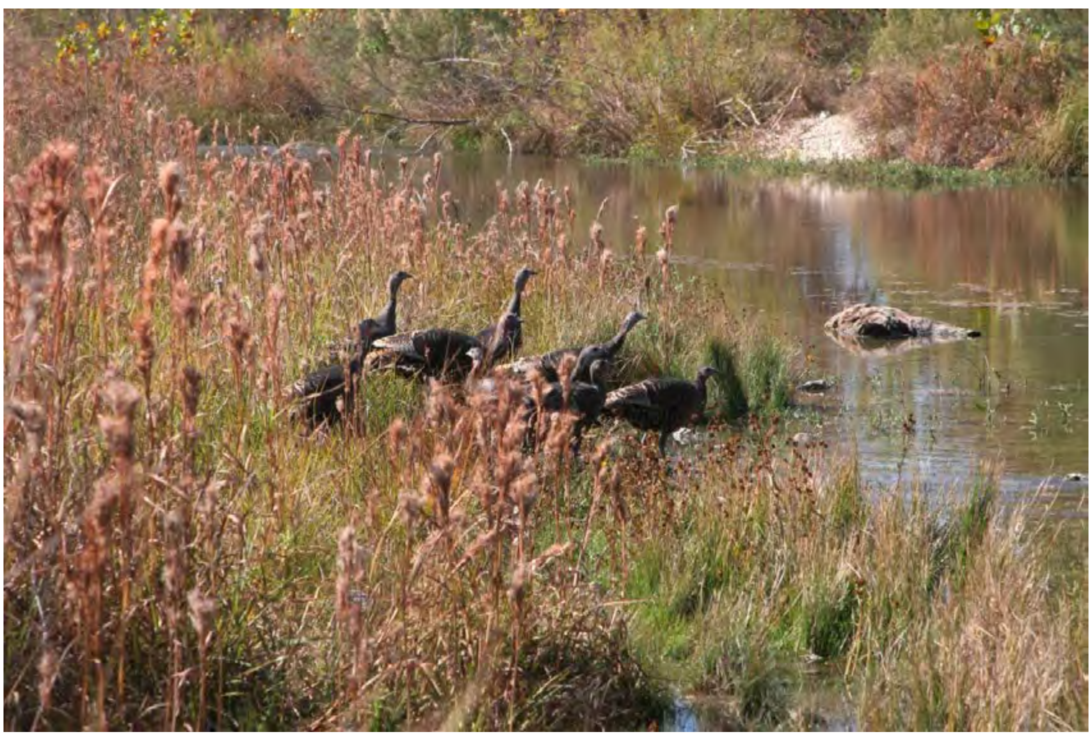


Figure 7.16. A properly managed and properly functioning riparian area is the foundation and basis for many of the associated values we desire, including wildlife, fish, water quality, forage, and recreational potential.

MAINTAINING EQUILIBRIUM

In a natural setting and in the absence of significant artificial disturbances, most riparian areas will maintain themselves in a relatively stable condition known as "dynamic equilibrium" (Figures 7.17 and 7.18). According to this concept, creeks, rivers and riparian areas react to normal disturbances in a manner that compensates and helps correct for the disturbance. In this way, creeks and rivers utilize these disturbances for their own benefit, and are always at work to "fix themselves".

Figure 7.17. Riparian areas under good management are able to sustain a relative balance between the forces of erosion and sediment deposition.

Figure 7.18. This riparian area in South Texas is in the process of rebalancing after years of disturbance. Sediment is being trapped by vegetation and assimilated into the floodplain, as the channel redevelops a more natural and narrow dimension. Good management is allowing these natural processes to take place.

This concept of equilibrium should not be misunderstood. It does not mean a perfectly stable balance, nor does it mean the absence of disturbance. Riparian areas are naturally prone to significant and even extreme disturbances. These natural disturbances include both erosion and the deposition of eroded material both spatially and temporally. The intensity, duration and frequency of flooding and/or drought are the most common disturbances that temporarily upset the equilibrium. Other natural disturbances that may temporarily upset equilibrium include the washing out of beaver dams, insect or disease problems that disrupt key riparian vegetation, wildfire, and natural grazing and browsing by wildlife. These natural disturbances often cause lateral migration of banks, formation of new gravel and sand bars, and the subsequent changes in sinuosity and channel gradient (Leopold et al. 1964). These changes are countered by the eventual stabilization of the new surfaces by riparian vegetation.

When various abnormal activities cause severe and prolonged disturbances, the creek or river attempts to accommodate the disruption with an equally severe reaction, thus upsetting the normal equilibrium. Most of the chronic riparian problems seen in Texas are the result of these excessive or abnormal disturbances that repeatedly disrupt the equilibrium and keep the creek or river out of balance (Figure 7.19). Extreme and recurring bank erosion, channel downcutting, excessive deposition of sediment and aggradation of channel are common indicators that creek and river systems may be out of balance and attempting to re-establish a new equilibrium.

Figure 7.19. Disturbance with heavy equipment along the banks for floodplain will often result in large additions of sediment to the channel, which disrupts the balance. Photo courtesy of Sky Lewey, Nueces River Authority.

A basic understanding of these dynamics will greatly enhance a manager's ability to recognize what is happening in the riparian area. Often, a perceived problem is merely the creek making necessary adjustments to rebalance equilibrium. Managers who do not understand the natural seesaw process of imbalance and rebalance are often tempted to fix something that does not need to be fixed. The unnecessary fixing of some problems actually impedes the normal and natural process of equilibrium and can be very expensive.

The basic principles of dynamic equilibrium are best illustrated by the diagram in Figure 7.20. Emory Lane was a hydrologist with the Bureau of Reclamation who first described the four basic variables of equilibrium – discharge of water; sediment load; slope of channel; and size of sediment. The qualitative equation he published in 1955 is commonly known as Lane's Relationship (Lane 1955). A co-worker of Lane, Whitney Borland drew the diagram depicting the four interrelated variables as a beam balance. The Lane-Borland Stable Channel Balance is now widely used to help teach these principles (Rosgen 1996). A few common examples of how this balance works are described below.

Example 1. If vegetation is reduced on the contributing watershed, increased runoff rates will deliver more water to the creek channel. This might be caused by heavy grazing, wildfire, land clearing or urbanization. This increase in water will tip the right side of the balance beam downward, which will cause erosion (degradation of channel bottom or lateral erosion) in the channel. To correct for this imbalance, the creek channel may increase it meandering or sinuosity, which in turn will decrease the slope of the channel. This decrease in channel slope will correct for the increase in discharge and bring the channel back into balance.

Example 2. If some disturbance in the watershed or floodplain is occurring (such as gravel mining or construction activity), an increased amount of sediment will be delivered to the channel. This will tip the left side of the balance beam downward, which will lead to aggradation or deposition of sediment in the channel. This imbalance can be corrected by an increase in channel slope, which occurs when channel meandering and sinuosity decreases. As the amount of meandering decreases, and the slope of the channel increases, there is greater energy to move the sediment, thus reestablishing equilibrium.

Example 3. If dams are constructed on perennial creeks or rivers, sediment is trapped behind the dam. This is true for small low head dams or large reservoirs. The water that goes over the dam or is released from the dam has a decreased sediment load. This decrease in sediment will tip the left side of the balance beam upward, which will cause erosion or degradation of the channel. The channel correction that often begins to take place downstream is an increase in meandering, which eventually decreases the slope of the channel. As this occurs, the balance can be gradually reestablished.

Riparian managers do not need to become expert hydrologists or fluvial geomorphologists. However, if mangers understand how the balance works in theory, they can learn to predict responses to disturbances and will be able to see how creeks and rivers make adjustments to restore the balance.

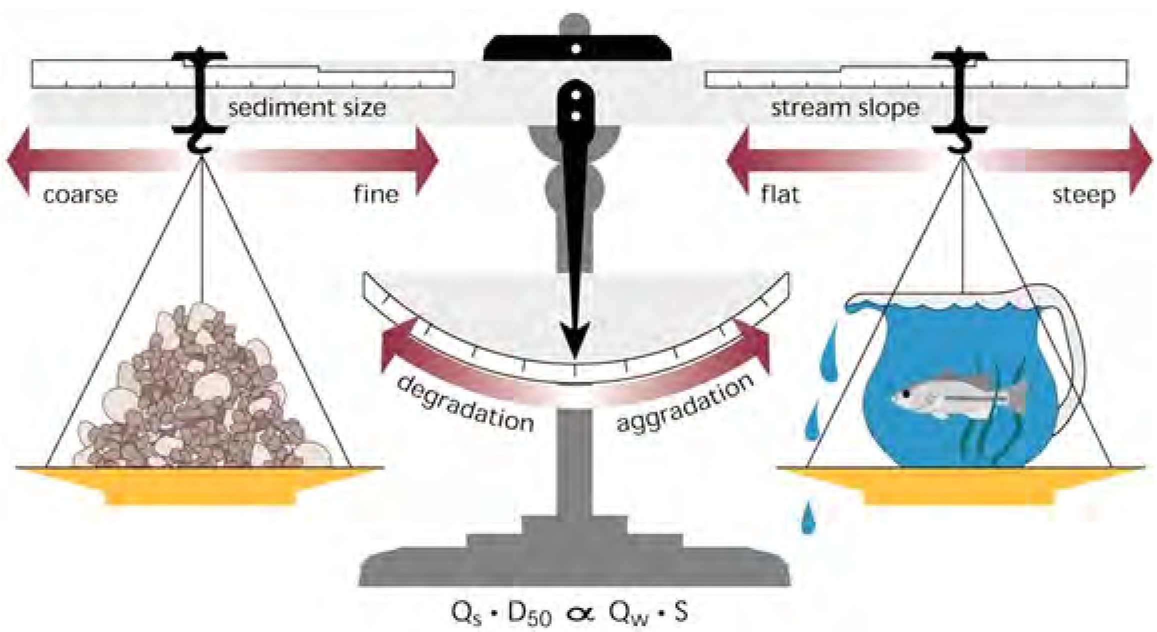


Figure 7.20. Diagrammatic model of the Lane-Borland Stable Channel Balance

REMOVING HINDRANCES – THE KEY TO RIPARIAN MANAGEMENT

Riparian workers have discovered a fundamental truth that helps to deal with most out-of-balance riparian conditions. If one or more activities or issues can be identified that are hindering the normal equilibrium dynamics, and if those disrupting activities can be corrected, then in most cases, the riparian area will begin to mend itself (Kauffman et al. 1997). Stated more simply – stop doing those things that hamper the natural rebuilding process and the riparian area will tend to restore itself. It is not so much a matter of knowing precisely how to fix a degraded riparian area, but rather allowing natural processes to work unimpeded.

In most cases where there are chronic or acute riparian problems, one or more activities or issues are obstructing the proper function and balance of the riparian area (see Figures 7.21 through 7.26). In many cases, these activities hamper the growth of necessary riparian vegetation. Listed below are some of the common hindrances that can disrupt the equilibrium, and keep a creek-river-riparian area out of balance:

- Farming, mowing, or spraying weeds or brush too close to the bank
- Logging and related timber harvest activities adjacent to the creek
- Manicured or altered residential or park landscapes next to the creek
- Prolonged grazing concentrations in creek areas
- Excessive populations of deer, exotic hoofstock, or feral hogs in creek areas
- Burning in riparian area
- Removal of large dead wood and downed trees
- Artificial manipulation of banks, channels or sediment
- Physical alteration of floodplain
- Excessive vehicle traffic in creek area
- Excessive recreational activity or foot traffic in creek area
- Excessive alluvial pumping or other withdrawals
- Low water dams
- Large reservoirs
- Poorly designed road crossings / bridges

Figure 7.21. Any practice that hinders the natural processes will prevent or retard restoration of the riparian area. When such practices are altered or eliminated, riparian areas will tend to gradually fix themselves. In this example, recreational driving in the riparian area has removed a large area of vegetation in the floodplain. Restricting vehicle driving will allow the area to heal. Photo courtesy of Sky Lewey, Nueces River Authority.

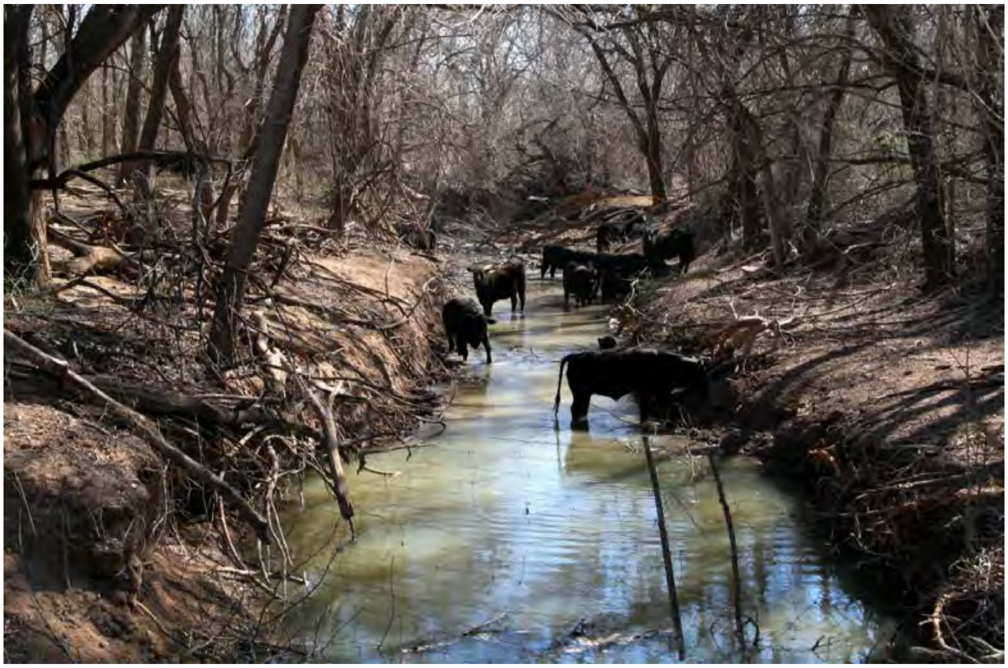


Figure 7.22. An extreme example of chronic livestock concentration hindering riparian recovery. A change in grazing management will be required to allow natural processes to restore vegetation. Photo courtesy of Ricky Linex, NRCS.

Figure 7.23. Excessive mowing near the creek will hinder the development of necessary vegetation and prevent or retard natural recovery. Changing mowing practice will allow the growth of needed vegetation and help restore proper function. Photo courtesy of Ricky Linex, NRCS.

Figure 7.24. Excessive and extreme recreational impacts frequently hinder proper riparian function in parks and heavy use areas. By altering and managing access, riparian managers can help promote a degree of restoration while still allowing recreational enjoyment.

Figure 7.25. Creekside landowners sometimes manicure the landscape, creating a park-like appearance. Riparian outreach and education can help teach landowners the value of maintaining dense riparian vegetation. Photo courtesy of Sky Lewey, Nueces River Authority.

Figure 7.26. Thousands of low head concrete dams have been built on Texas creeks. These dams disrupt the natural movement of sediment that is needed downstream to build point bars and sinuosity. Erosion is often accelerated below the dams, creating additional problems. Some landowners are now considering the removal of these dams. Photo courtesy of Ricky Linex, NRCS.

The relative ease or difficulty of addressing each of these hindrances varies considerably. For example, it is relatively simple for a landowner to stop mowing vegetation close to the creek bank. It is a matter of recognizing the impacts and potential damage and making an intentional decision to stop the practice, or modify the practice to reduce the impacts. Likewise, it is straightforward for a livestock rancher to alter grazing management to reduce or eliminate chronic livestock concentrations in creek areas. However, first, he or she must become convinced that livestock concentrations in riparian areas are detrimental. Although straightforward, it still may require considerable effort and expense to implement needed changes in riparian grazing management.

Other practices are a much greater challenge to overcome. For example, excessive populations of free-ranging exotic wild ungulates such as axis deer are a severe problem on hundreds if not thousands of miles of riparian area in the Edwards Plateau. While many landowners and natural resource professionals acknowledge the problem, long-term solutions are exceedingly difficult to apply.

There are still other hindering practices so difficult to overcome that they are not yet being seriously discussed. Examples include the thousands of low head concrete dams that have been constructed in creeks, mostly on private land; as well as thousands of poorly designed crossings, culvert installations and bridges. Many of these are under the jurisdiction of county or municipal road and bridge departments or Texas Department of Transportation.

Other hindering practices may require legislation and regulation to overcome. An example of this is the tremendous riparian damage caused by unrestricted motor vehicle driving in public riverbeds. In 2003, Senate Bill 155 was passed by the Texas Legislature, which restricted and regulated such driving. In the years since this legislation, many miles of riparian land are restoring themselves naturally in the absence of vehicle traffic. Restrictions and control of pumping of shallow alluvial aquifers may be another instance where legislative and regulatory solutions are warranted. Exploitation of alluvial aquifers for agricultural irrigation or other purposes is severely depleting the base flow of some rivers and creeks in Texas.

THE BEAUTY OF NATURAL REGENERATION

In most cases, if the factors that are hindering riparian recovery are dealt with, the riparian area will begin to restore itself naturally (Figure 7.27). The natural regeneration of appropriate riparian vegetation is often the mechanism that allows this recovery to take place (NRC 2002). Within nearly all medium sized or larger creek systems, there is an adequate source of desirable native riparian vegetation upstream. These intact or partially intact upstream plant communities provide a source of seed and plant material for downstream establishment.

Figure 7.27. This small creek has started to recover on its own after a long period of continuous grazing. The riparian vegetation will continue to improve with time.

During runoff events that exceed bankfull discharge, where floodwaters spread out across the floodplain, these seed and plant parts are carried downstream and deposited on wet ground. Seeds that are dispersed in floodwater include cypress, button bush, sycamore, maple, elm, pecan, oaks, sedges, rushes, cutgrass, knotgrass, eastern gammagrass, water primrose and many others. Other plant parts that detach and float downstream and root in a new location are called plant propagules. This can be a large clump of sedge or grass that gets washed out in a flood, with the clump being broken up into many individual plants and floating to new locations. Or, it can be the detachment of stems or stolons (runners) of riparian plant such as water willow, watercress or knotgrass which will root from stem segments. Once established in a new location, these plants will make additional seed and root stock to increase new plant establishment.

Other plants have different modes of dispersal. The seeds of certain riparian plants are dispersed by the wind. Examples of wind-dispersed plants are bushy bluestem, baccharis, willow, cottonwood, cattail, goldenrod and brickelbush. Other riparian plants are commonly spread by wild animals or livestock into new locations. Regardless of the specific method of plant dispersal, it is important to understand that the natural regeneration of riparian plants is an effective method of re-vegetation and is usually the primary means of establishing appropriate vegetation.

The beauty of natural regeneration of riparian vegetation is that it takes place naturally and effectively, without the high cost and intensity of artificial re-establishment (Figure 7.28). Normally, this natural process will establish an appropriate and desirable diversity of native riparian species including both early stage “colonizer” species, as well as stronger “stabilizer” species. After a single high flow event, where fresh new seed is deposited, it is not uncommon to observe seedling densities of 50 to 100 plants per square foot. Furthermore, natural regeneration takes place progressively and repeatedly over time, with new seed and new species added. Natural regeneration usually takes place within a reasonable period, but is closely tied to the timing and frequency of overbank flow events, rainfall and other climatic factors.

Figure 7.28. Seedlings of bushy bluestem establish naturally in bare areas and fresh sediment deposits. The seed of this riparian grass is dispersed by the wind.

Unfortunately, in some locations, regeneration of native plant species is hampered by the rapid establishment of exotic and sometimes invasive plant species. This is discussed in a separate section later in this chapter.

As with any natural process, there are times, when desired vegetation does not establish according to our expected timeline. Patience is a critical virtue for the riparian manager. There is little that can be done to speed up the process without high inputs and costs and no guarantee of success.

ARTIFICIAL RE-VEGETATION

In some special cases, it may be important to establish new vegetation as quickly as possible and not wait for natural regeneration to occur (NRC 2002). Other times, the on-site and upstream source of native plant materials may be so impaired that natural regeneration will occur too slowly or ineffectively. These circumstances may warrant the planting of riparian grasses, sedges, shrubs and trees (Figure 7.29).

Figure 7.29. Various artificial re-vegetation techniques are used to jump-start the development of riparian vegetation. Re-seeding and transplanting have been successfully used in riparian restoration projects.

The re-planting of riparian vegetation on degraded or heavily disturbed sites should generally attempt to mimic the natural plant communities to the extent possible (if soil conditions permit). Project managers should search for nearby stream reaches that support intact, functioning native plant communities. These may serve as helpful benchmarks to guide in the selection of plant materials. In the future, Ecological Site Descriptions (ESD) for riparian areas will help managers determine appropriate plant species to use. ESD's have been developed for many upland soils in Texas and are compiled and published by the Natural Resources Conservation Service. However, ESD's for riparian areas have not yet been developed in Texas.

At the present time, there are commercially available seed sources for only a few important riparian species. This shortage creates a challenge for establishing appropriate plant diversity. Commercially available seed for riparian species includes switchgrass, eastern gamma grass, bushy bluestem, western wheatgrass, Canada wildrye and Virginia wildrye. In addition to establishment by seed, some growers now offer rootstock of riparian plants for sale. If growers are contacted one to two years ahead of time, some are willing to custom grow riparian plants on a contract basis.

Perhaps the most effective means of artificially re-establishing riparian plant communities is to locate nearby intact riparian areas and seek permission to dig and transplant fresh rootstock (Figure 7.30). Although the process is labor intensive, results have been very promising. Riparian species that have been successfully transplanted includes Emory sedge, sawgrass, switchgrass, eastern gamma grass, knotgrass, spikerush, goldenrod and scouring rush. Many other species have not yet been tried, but hold much promise. Plants are ideally dug in winter or early spring and immediately transplanted in a similar location, paying special attention to moisture requirements and the depth to the water table.

Figure 7.30. Sawgrass, native to much of the Edwards Plateau, is a good candidate for transplanting. Large clumps can be dug and divided into smaller units. Sawgrass is somewhat resistant to heavy grazing by livestock and deer. Once established, it provides exceptional bank stability and energy dissipation.

For the establishment of riparian woody plants, nurseries offer bare root or containerized plants of bald cypress, sycamore, rough leaf dogwood, bur oak, chinquapin oak, pecan, cedar elm, and many other native riparian trees.

The fastest way to get large numbers of woody plants established is to use stem cuttings and pole plantings of species that are known to root from dormant stems. All species of willow and cottonwood will readily root from dormant branches, twigs or poles planted in late winter. The butt of the stem must be planted deep enough to stay in contact with moist soil during the first year or two. Other woody plants that are known to root from dormant stems include buttonbush, sycamore, American elder and some species of baccharis.

For new plantings, protection from livestock and wildlife grazing or browsing is important and will often be the primary factor in success or failure. Damage by beaver or nutria can also be significant. Proper use of irrigation and weed control may also materially improve the success of re-vegetation projects, but will increase costs.

It is beyond the scope of this chapter to discuss artificial re-vegetation techniques in any detail. The use of mulches, hayseed, hydromulch, erosion control blankets, bioengineering, and other specialized techniques are often employed in large restoration projects (USDA 1996, Hoag and Fripp 2002). The use of experienced consultants, engineers and contractors will help maximize success and reduce the risk of failure in these projects.

GENERAL RIPARIAN MANAGEMENT GUIDELINES

Riparian management practices and techniques are determined in large part by the surrounding land use. Land that is in agricultural production usually has different riparian issues than urban land or recreational land. Likewise, land that is used for timber production has different issues than land that is used for row crops or livestock grazing. Basic riparian management issues and guidelines are summarized below for major land uses in Texas.

CROPLAND

Approximately 27 million acres of Texas land is used for crop production. A large portion of the cropland in Texas is located in the High Plains where creeks and riparian areas are few and far between. However, cropland is scattered across all parts of Texas and much of it is located in proximity to creeks and rivers. The potential impacts of farming on adjacent riparian areas are numerous. Plowing and planting too close to creek and river banks is a serious problem that can cause significant riparian damage. The removal of deep-rooted perennial vegetation and the conversion to cropland will greatly accelerate the risk of severe erosion and bank failure. A common sense solution for this problem is the establishment of non-cropped permanent buffers composed of appropriate native deep-rooted vegetation between the edge of cropland fields and the banks (Figure 7.31).

Figure 7.31. A filter strip of dense perennial grass is needed at the edge of this cropland field to slow down runoff, trap sediment and reduce erosion. Switchgrass and Indiangrass are good choices for native grass filter strips in many locations. Photo courtesy of Ricky Linex, NRCS.

The proper width of non-cropped buffers will vary from place to place. Larger creeks will need wider buffers than smaller creeks. The safest buffer would include the entire 100-year floodplain, which would insure that very little cropland would be subject to flooding and erosion even in very large events. Another consideration is to leave a significant buffer along the edge of the high bank. These high banks are often unstable, especially on outside bends. Leaving a buffer of natural vegetation equal to three to five times the height of the vertical bank will help accommodate the development of vegetation as the bank erodes.

Another consideration is to plant a dense herbaceous buffer between the edge of the cropland field and the beginning of the slope that leads to the riparian areas. The purpose of this grass strip is not only to stabilize the soil, but also to help trap sediment coming off the cropland field and to reduce concentrated flow into the riparian area (Dillaha et al. 1989). The most commonly used grasses for this include switchgrass, Indiangrass and eastern gammagrass, although species will vary by region. Farmers should resist their inherent urge to manicure, mow or spray weeds in this buffer area after establishment.

In addition to traditional commodity crops, cropland areas are also commonly used for grazing. Where crops or crop residue is grazed by livestock, there are other riparian considerations that must be addressed. Refer to the section on grazing management in this chapter.

Farming methods on upland fields can also have an impact on adjacent riparian areas. Farming practices that slow down the movement of water and reduce sediment and nutrient-laden runoff into the creek will help maintain the integrity of riparian areas (Dillaha et al. 1989). These practices include terraces, contour farming, cover crops, crop rotations using high residue crops, conservation tillage, residue management, contour buffer strips and filter strips (Figure 7.32). In addition, the proper application of pesticides and fertilizer will help reduce or eliminate the movement of potential contaminants into the creek.

Figure 7.32. A riparian buffer established between cropland fields and the riparian area will reduce the movement of sediment, nutrients and pesticides into the creek. In this example, farming is taking place too close to the creek. Incentives are available to farmers to plan and establish buffers and filter strips. Photo courtesy of Ricky Linex, NRCS.

Assistance in developing a system of conservation farming techniques suited to the individual needs and goals of the landowner can be obtained through local field offices of the Natural Resources Conservation Service.

PASTURELAND

Approximately 11 million acres of Texas land is classified as pastureland. Pastureland is defined as perennial grasses under intensive management grown for grazing and/or hay production. Pastureland almost always involves a monoculture of exotic grasses, but occasionally native grasses are utilized. Pastureland is not to be confused with rangeland (see next section), even though both are used for grazing. Common pastureland grasses in Texas include coastal bermudagrass and other hybrids, bahiagrass, various exotic bluestems, buffelgrass, kleingrass, and wilman lovegrass. Management of pastureland usually involves the regular application of fertilizer and the control of weeds and woody plants.

Pastureland is often established in the best and deepest soil on a farm or ranch and therefore is commonly located near creek, riparian and bottomland settings. The potential risk of having pastureland immediately adjacent to riparian areas is the danger of erosion and bank failure. Most pastureland grasses do not have the same stabilizing ability as native riparian plant communities. Riparian management in and near pastureland should include the use of buffers of native vegetation adjacent to the creek (Figure 7.33). Routine weed and brush control should not be carried out in or immediately adjacent to the riparian area.

Figure 7.33. Fencing of creek areas is often a practical way of managing livestock grazing in the riparian area. However, fences should normally be placed well away from the edge of the creek to create a wide buffer and give the creek room to meander. Photo courtesy of Ricky Linex, NRCS.

Another potential risk associated with pastureland is the presences of livestock concentrations in the creek area. In many cases, livestock will drink water from the adjacent creeks and seek shade in the riparian area. If livestock concentrations persist without adequate rest and recovery periods, the damage to riparian plant communities will be substantial and long term. In this case, management should include the development of alternate water supplies away from the riparian area. Water can be pumped with solar energy from the creek to troughs. Where livestock continue to loaf in the riparian area, fencing may have to be established to exclude or manage grazing animals. Pastureland used for hay production rather than grazed forage will eliminate potential grazing problems in nearby riparian areas. For additional information, refer to the section on grazing management in this chapter.

RANGELAND

Approximately 97 million acres of Texas land is classified as rangeland. Rangeland is by far the most predominant type of land in Texas, comprising nearly 60% of the land area of Texas. Rangeland is defined as land that supports predominantly native vegetation and is normally managed extensively rather than intensively. Rangeland includes many types of land including grasslands, shrublands, deserts, savannas, woodlands, and some wetlands. Rangeland is commonly used for the production of grazing animals, but not all rangeland is grazed. Rangelands are also commonly used for the production of deer and exotic wild hoofstock.

The majority of creeks and rivers in Texas originate and run through rangelands (Figure 7.34). The importance of rangeland management on Texas riparian areas cannot be overemphasized.

Figure 7.34. The majority of riparian areas in Texas run through rangeland, used for livestock production. When proper management is applied, ranchers can not only benefit from riparian forage but also maintain good riparian condition. Without good management, livestock will tend to concentrate in riparian areas, causing damage to riparian vegetation.

Historically, since the late 1800's, rangeland has been the basis of the vast Texas livestock industry. In the early days, creeks and rivers provided the only watering locations for livestock and many riparian areas were very heavily grazed for decades. Even after the development of countless earthen ponds and the drilling of water wells to provide livestock water, creeks and rivers have continued to provide important sources of water on many ranches. In addition to water, riparian areas also provide large amounts of forage and shade for summertime temperature regulation.

Because of the presence of water, shade and forage, riparian areas are often subjected to unintentional concentrated and disproportional livestock grazing and loafing (Bryant 1982). Without intentional management, this tendency for livestock to congregate in riparian areas can have severe and detrimental effects on riparian vegetation (Clary 1987. In addition to impacts on the vegetation, livestock concentrations can cause accelerated bank failure and trails can create secondary erosion problems.

Livestock grazing affects many different kinds of riparian vegetation, including grasses, sedges, forbs and woody plants. Many desirable riparian plants are also very good livestock forage plants. Careful management and preferential treatment of riparian areas is essential to maintain or restore functional riparian conditions on rangeland that is used for livestock grazing. Refer to the section on grazing management in this chapter for more information.

FORESTLAND

Approximately 7.5 million acres of Texas is commercial forestland that lies exclusively in East Texas. Forestland is dominated by a dense canopy of trees, including pine and/or various hardwood species. The distinction between wooded rangeland and forestland is not always easy to make. Some areas traditionally regarded as rangeland have a dense canopy of trees. This is especially true in the Cross Timbers and the Post Oak Savanna and is also true in many heavily wooded riparian corridors in the central part of the state. For the purpose of this chapter, forestland is restricted to the East Texas Timberlands and Pineywoods ecological regions. Management of riparian area in forestland primarily involves timber harvest practices. The size of the equipment used in timber harvest and the intensity of disturbance involved in transporting logs can lead to extreme disruption of the soil surface and associated vegetation. Furthermore the subsequent preparation of seedbeds to plant the next crop of trees adds even more disturbance. For these reasons, it has become standard practice for timber harvesting activities to include Streamside Management Zones or SMZ's. These SMZ's are similar in purpose to riparian buffers. The intent is to maintain undisturbed or lightly disturbed areas of native trees and shrubs adjacent to creeks and rivers (Palik 2000). Streamside Management Zones are often planned at least 50 feet away from the top of the bank but width should vary according to the size of the creek and the length of side slopes (Fallon 1998). When private landowners sell timber, it is recommended to have a written contract with stipulations to protect riparian areas, and to utilize the services of forestry professionals. General guidelines for management within the SMZ often include:

- Minimize stream crossings
- Build no roads in the SMZ other than necessary crossings
- Use temporary bridgements to skid logs were possible
- Avoid traffic in wet weather to minimize rutting
- Keep skidders away from banks; do not skid logs across the creek channel
- Use cable and chokers to skid logs
- Limit harvest to individual high value trees

In addition to timber harvest considerations, cattle grazing also affects riparian areas in forestland. In this part of Texas, cattle often graze upland pastureland fields during the growing season, and allowed to graze the woods in winter. Refer to the section on grazing management in this chapter for more information.

URBAN LAND

Land within urban settings or developing areas creates one of the greatest challenges to riparian management for several reasons. The land area that drains into urban creeks is often highly altered with a large proportion of impervious surface with the associated high runoff, water shedding landscape. These impervious surfaces create rapid and high volume runoff even with small rainfall events. The greater volume of runoff entering tributaries and creeks can wreak havoc on channels, causing abnormal and severe erosion, bank failure, down cutting and other problems (Figure 7.35).

Figure 7.35. Most creeks in urban areas have been altered in one way or another. Removal or alteration of natural riparian vegetation is commonly carried out. The increased runoff in urban areas combined with riparian alteration creates a greater risk of erosion during high flow events. Retaining or restoring a buffer of natural vegetation will help maintain a degree of riparian function. Photo courtesy of Ricky Linex, NRCS.

In addition to the "flashy" nature of urban creeks, urban development often encroaches into the floodplain, restricting the ability of the creek to naturally meander. Encroachment of development into the floodplain results in the alteration of floodplain topography and vegetation (NRC 2002). The net result of these alterations is a reduced capacity for the floodplain to function as it should (Figure 7.36).

Figure 7.36. Extreme disruptions of channels, bank, sediments and vegetation make the creek and riparian area vulnerable to severe damage during high flow events. Photo courtesy of Ricky Linex, NRCS.

During the construction phase of development, abnormal amounts of sediment as well as runoff may enter creeks. The use of temporary sediment fences may reduce the delivery of sediment to the creek, but fail to control sediment adequately during large runoff events.

After construction is complete and pavement is installed, sediment load is often decreased while runoff is greatly increased. This combination leads to severe erosion of banks and/or the bottom of the channel, since the "hungry water" free of sediment has greater energy with which to cause erosion.

In an effort to deal with erosion, and increased discharge, cities often resort to alterations of the stream channel and floodplain. Where erosion is severe, hard or soft engineering solutions are often implemented. Vegetation and large wood is often removed to allow floodwaters to move through the channel faster in an effort to reducing the magnitude of flooding. However, by removing the roughness from the stream or riparian area, the energy of floodwater is increased, causing an increase in bank and channel erosion. Furthermore, when floodwater is moved more rapidly through urban areas, it exacerbates flooding problems farther downstream.

Municipalities or subdivisions that desire to minimize damage to creeks and help maintain semi-functional riparian conditions can plan developments to retard runoff and retain wide, well vegetated riparian areas. The reduction of impervious surfaces, rainwater harvesting, detention storage for storm water, water gardens, greenbelts and other practices are used in some developments to help maintain some natural riparian function. City engineering departments should be taught about the basic processes of riparian function and especially the role of vegetation and large wood in creeks and riparian areas.

RECREATIONAL LAND

Land that is intensively used for recreational purposes is also vulnerable to riparian degradation (Weaver and Dale 1978). Creek and river areas subject to heavy recreational use can be some of the most abused and degraded riparian areas in the state. Continual long-term human foot traffic often reduces dense riparian vegetation and creates compacted bare ground (Manning 1979). Public and private parks and recreation areas used for hiking, biking, swimming, camping, fishing, birding, and horseback riding can be degraded by sustained use, but those impacts can be minimized by management (Cole 2000).

The following management practices can be used in recreation areas to reduce negative impacts (Figures 7.37 and 7.38):

- Eliminate or restrict vehicle traffic in riparian areas
- Trails should not be aggressively de-vegetated.
- Trails should not be immediately adjacent or parallel to creeks.
- Meander trails back and forth across floodplain
- Main trails should be on higher ground with periodic access trails down to the stream
- Periodic access trails should be located on inside bends with less stream energy
- Separate heavy use areas with buffers of thick natural vegetation
- Choose less vulnerable areas for heavy use such as inside bends
- Rotate heavy use areas to allow for periods of recovery
- Limit mowing and increase the interval between mowing to encourage vegetation
- Rotate mowed areas to help manage human activity
- Rotate heavy use access points to allow adequate time for vegetation to recover
- Do not remove large logs and dead fallen trees in creek or along banks or in floodplain
- Provide educational material to describe the reasons why these practices are carried out

Figure 7.37. Restricting access to small mowed areas will help maintain good vegetation in heavily used recreational areas. Pictured here is Devils River State Natural Area, managed by Texas Parks and Wildlife Department.

Figure 7.38. Unrestricted access by too many recreational users will keep a riparian area in poor condition. Managing access spatially or seasonally will allow rested areas to develop improved vegetation. In this example, heavy recreational use (fishing) is combined with unrestricted grazing.

RIPARIAN MANAGEMENT ISSUES

FRAGMENTATION IN RIPARIAN AREAS

Larger, ecologically intact properties, under sustainable management for multiple generations has been a keystone for sustaining intact watersheds and functional riparian areas. The recent trend toward dividing large tracts of rural land into smaller and smaller tracts is a significant conservation issue in Texas and is especially critical for riparian areas. The progressive selling and subdividing of large tracts into small units often places increased human, livestock and infrastructure pressure on natural resources. As land and riparian areas become more divided, it creates much greater challenges for sustainable management and for maintaining ecological function.

Reducing the rate of land and riparian fragmentation through conservation easements is an effective way of addressing this problem. Conservation easements, developed with the assistance of private land trust organizations provide incentives and guarantees to keep larger land units intact. Conservation easements are customized to meet the needs and desires of individual landowners, but they all have provisions to restrict future subdivision and development of the property. Conservation easements are not a transfer of ownership, nor a grant of public access. When a landowner chooses to establish a conservation easement with a land trust, he maintains ownership and the ability to continue using the property as he has in the past including farming, ranching, hunting and recreational activity. A conservation easement simply restricts future development regardless of who owns the land in the years ahead. Conservation easements include land management plans outline land and riparian management practices mutually agreed by the landowner and the land trust.

GRAZING MANAGEMENT IN RIPARIAN AREAS

Livestock grazing has been the most widespread and predominant use of land in Texas since the 1880's, and has affected almost all creeks and rivers in the state (Figure 7.39). During the early years of the Texas livestock industry, stockmen had little understanding of or interest in sustainable grazing management. In recent years, many ranchers have taken a much deeper interest in proper grazing management, including riparian management. More riparian areas can be positively (or negatively) affected by grazing management than by any other single land-use practice.

Figure 7.39. Cattle will naturally congregate in riparian areas in search of forage, water and thermal regulation. Grazing managers have found ways to overcome this disproportional grazing. Short term seasonal grazing followed by a long recovery period is one way to insure that riparian vegetation stays in good condition.

The impact of grazing on riparian vegetation can be understood by this simple fact – one full-grown cow will consume approximately 10,000 pounds of vegetation each year on a dry weight basis. Even a few cows can have a significant effect on vegetation if they stay in comparatively small riparian areas for a long time. The key to sustainable grazing in riparian areas is the timing, duration and frequency of grazing and the length of recovery between grazing periods (Mosley et al. 1997).

Grazing can affect the following functional attributes of riparian areas: energy dissipation, root mass and root stability, bank and channel stability, sediment trapping, colonization of new sediments, plant diversity, plant recruitment and plant vigor (Figure 7.40). Proper riparian grazing management will favor these elements and improper management will inhibit them (Elmore 1992).

Figure 7.40. Excessive grazing in the riparian areas has removed the cover of riparian vegetation needed to dissipate energy, protect banks and trap sediment. A change in grazing management can, with time restore good vegetation.

Because of the natural attraction of cattle to creeks, these areas require extra care and attention to insure they are grazed properly and receive periods of rest after being grazed. One of the most common and successful forms of riparian grazing management is to establish separate riparian pastures. This often requires substantial fencing to separate the creek areas from the rest of the pasture. Ranchers who choose this option are usually careful to create creek pastures that are large enough to be manageable, not simply a long skinny pasture. Often the rancher will set the fence 100 or 200 yards from the edge of the creek. When this is done, the riparian area becomes much easier to manage. The rancher determines when, how many, and for how long the creek pasture should be grazed and uses the pasture as part of a flexible grazing rotation (Clary and Webster 1990).

It is better to graze riparian pastures with a larger number of cattle for a shorter period of time, rather than a small number of cattle for a long period of time. This approach is sometimes called flash grazing. But this does not mean the riparian areas are grazed short. By managing the number of days of grazing, the manager can insure the desired level of grazing is achieved. Good residual cover should remain even at the end of the graze period. By controlling the length of the rest period, the rancher can be assured that adequate time is given for re-growth. One or two short grazing periods per year with a long rest in between will generally allow for good development of riparian vegetation and a strong, deep root system. Financial incentives are available to landowners who wish to construct riparian pastures to help defray the cost of fencing.

One of the most potentially damaging times to graze a creek area is when the banks are saturated. Saturated banks are weaker and more prone to sloughing and trampling damage by livestock. The least damaging time to graze creek areas is during the dormant season as long as good stubble remains intact. Grazing during early or mid-spring must be carefully managed since key riparian grasses, sedges and woody plants are making a flush of new tender growth and are more vulnerable.

For those managers unable to establish separate riparian pastures, there are other ways to help overcome disproportional grazing in the creek area (Skovlin 1984). Providing alternate water locations away from the creek often helps lure cattle out of the creek. Studies have shown that cattle generally prefer to drink from troughs on level ground compared to walking down steep banks. Cattle will often choose to drink out of troughs even when they have access to creek water. This may or may not be enough of an enticement to eliminate concentrated grazing of the creek area, but it will usually help.

Another way to reduce the time that cattle spend near the creek is to move all mineral, salt, hay, tubs and supplemental feeding one-half mile away from the creek, or to the far side of the pasture. When feeding areas and water locations are moved away from the creek, cattle will spend less time grazing and loafing in the riparian area and the vegetation and banks will stay in better condition (Leonard 1997).

For creeks that have been severely damaged by decades of unmanaged grazing, a good solution may be to temporarily suspend grazing for several years to jump-start the recovery of desirable vegetation (Elmore and Kauffman 1994). This method of riparian management is being used on many Texas ranches with excellent results (Figure 7.41). Landowners and managers seem gratified with the speed and degree of recovery and improvement. The goal is not permanent removal of livestock; as the vegetation recovers and the condition of the riparian area improves, livestock grazing is often resumed using the principles described above.

Figure 7.41. Some livestock ranchers have chosen to temporarily suspend grazing in riparian areas to allow the vegetation time to fully develop.

In some cases, ranchers have preferred to permanently remove livestock from riparian areas. This is especially true where the creek or river forms the boundary of the property and there is no practical way to keep livestock from wandering away or to keep neighboring cattle out.

MANAGEMENT OF NATIVE AND EXOTIC WILDLIFE

Parts of Texas support large numbers of native deer and/or large numbers of exotic hoofstock. Where deer and exotic numbers are not properly managed, they can cause significant damage to riparian vegetation (Figure 7.42). When their numbers are kept in balance, riparian condition can be maintained.

Figure 7.42. In this example, a combination of poorly managed grazing and excessive populations of axis deer have degraded the riparian area. Management of grazing and control of exotic deer must be done simultaneously in order for the area to recover.

White-tailed deer, which are abundant in many parts of Texas, consume primarily browse and forbs. Their primary effect on riparian areas is the browsing of riparian shrubs and trees, especially seedlings and small plants. Excessive populations of deer can essentially eliminate the reproduction and recruitment of key riparian shrubs. Deer also graze several species of important riparian forbs, including water willow, goldenrod, watercress, water hyssop, and water primrose. Fortunately, white-tailed deer do not readily consume grasses or sedges and therefore have little effect on this important class of riparian vegetation. Deer densities in riparian areas are often five to ten times higher than adjacent upland areas (Figure 7.43). During drought, the disparity is much greater as deer populations shift toward the riparian areas in search of forage and water. Monitoring of browsing on woody plants is an important aspect of riparian management. Managers can learn to recognize the visual signs of hedging and the development of browse lines, using this information to help guide deer herd management.

Figure 7.43. Extreme browsing of important riparian shrubs by exotic and native deer harms plant vigor and eliminates successful reproduction of shrubs. Keeping deer numbers in balance is a key issue for riparian health in some locations.

Axis deer are the most common and most troublesome species of exotic deer because they naturally congregate in riparian areas. It is common to see groups of 20 to 50 or more axis deer traveling up and down riparian areas in central Texas. Axis deer consume all classes of riparian vegetation including grasses, sedges, forbs and woody plants. For this reason, they can cause extreme overgrazing and overbrowsing of riparian areas. The damage caused by excessive numbers of axis deer is severe on many miles of Edwards Plateau creeks and rivers. Options for the management of exotic deer include aggressive hunting and trapping, or the construction of high fences to exclude them from riparian areas. Axis deer and other exotics are not regulated game species and may be legally hunted any time of the year.

Other common species of exotic deer include fallow deer, sika deer, red deer and elk. Several less common species of deer can also be found. Many species of exotic antelope and sheep are also found in Texas but they have not generally caused widespread damage to riparian areas.

Feral hogs are widespread in Texas and their numbers and range are increasing. The primary riparian damage caused by feral hogs is physical damage by their destructive rooting habits. Hog wallows can cause extensive damage to banks, seeps, springs, and wet areas. Sediments disturbed by hog rooting and wallowing are easily eroded away, often causing further erosion. The best time for riparian managers to begin hog control efforts is when the first hog is observed. Relentless and perpetual trapping, shooting, and other control methods will be needed to reduce hog numbers in some areas and reduce riparian damage.

RETAINING LARGE WOOD

In recent decades, one of the most relevant riparian discoveries is the importance of large wood for the proper function of many creek and river systems (Magilligan et al. 2008; NRC 2002). Large wood refers to logs and dead trees that fall or wash into the channel, banks or floodplain (Figures 7.44 and 7.45). Some washed out trees may float long distances before they are caught on point bars or other channel obstructions. Other trees become trapped near where they fall, especially if there are living trees or shrubs to help hold them in place. The attached root wad often helps anchor large wood in place initially until it can become incorporated into the sediment. When these large trees become lodged and locked into place, they begin to provide many important and diverse functional benefits to the riparian area.

Figure 7.44. Trees falling into creeks and rivers is a natural and beneficial process. The wood helps dissipate energy and trap sediment. Eventually much of the wood becomes buried in the sediment where it becomes a structural component of the channel.

Figure 7.45. Large fallen trees and logs that become lodged on the floodplain provide functional benefits of energy dissipation, which promotes the trapping of sediment. In most cases, wood should be left in place in channels, banks and floodplain. Photo courtesy of Ricky Linex, NRCS.

Large wood provides effective energy dissipation during high flow events and begins to trap sediment, much like a retaining wall. Eventually, many logs become partially or completely buried in sediment, where they become structural components of the channel (Sedell and Luchessa 1982). The presence of large wood buried in the channel is likened to rebar that strengthens and reinforces concrete. Research across the United States and in other countries has shown that buried wood remains intact for hundreds and even thousands of years.

Large sunken wood has been routinely removed from many creeks and rivers across North America for the past 200 years for economic and navigation purposes. Many riparian systems have been damaged by the removal of wood and the natural restoration of suitable amounts of wood will be a very long and slow process.

Many Texas landowners and some riparian managers still remove logs and fallen dead trees in the misguided belief that creeks needs to be cleaned out. This is usually done with good intentions but without understanding the inevitable side effects. By removing or burning the wood, they are also speeding up the flow of floodwater, which increases erosion, damages banks and undermines channel stability. By leaving large wood in place, landowners and managers help dissipate energy, slow down the water, reduce erosion, trap sediment and build bank stability.

There are some cases where large wood should be managed when it presents a safety hazard to bridges or other infrastructure. However, in the vast majority of cases, large wood should be left in place, recognizing the necessary benefits it provides. Riparian landowners can learn to appreciate the natural value of wood even though some consider it unsightly.

MANAGEMENT OF EXOTIC RIPARIAN PLANTS

Exotic plant species often find their way into riparian areas (Figure 7.46). This is especially true in urban riparian areas and downstream from urban development. Many of the exotic species now commonly found in riparian areas originate from residential landscapes.

Figure 7.46. Giant cane *Arundo donax* is one of the common exotic invasive plant species causing problems in riparian areas. It spreads aggressively by enlargement of clumps and can completely dominate banks and floodplains. Control efforts should ideally begin when plants are scattered and small.

Not all exotic species found in the riparian zone are problematic. Problems can develop when plants aggressively reproduce and if they tend to dominate and monopolize at the expense of native species. Some of the common exotic plant species which are causing problems along Texas rivers and creeks are listed in Table 7-2.

Table 7-2. Some common exotic plants found in riparian areas that have invasive characteristics

Wax leaf ligustrum	Giant cane
Chinese privet	Japanese honeysuckle
Chinese tallow tree	Elephant ear
Salt cedar	Lilac chaste tree
Russian olive	Water hyacinth
Chinaberry	

Control or management of aggressive exotic plants may be warranted, where the species is known to rapidly reproduce and displace native riparian vegetation (NRC 2002). The challenge is to find control methods that are selective and specific to the target species without harming nearby native plants. This kind of work is tedious, laborious, expensive and slow. Often, the most feasible approach is the individual treatment of plants with bark-applied or foliar applied herbicides that are labeled for that purpose. You will often have to treat an area several times to achieve adequate levels of control. Localized control efforts by individual landowners can be very frustrating when upstream control efforts are lacking. When upstream seed sources are not addressed, recurring problems can be anticipated. This reinforces the importance of cooperative riparian management by many adjoining landowners.

Where isolated and scattered patches of exotic plants are found and when future problems are anticipated, it is strongly advised to begin control efforts early rather than wait for populations to expand and increase in density. Regular scouting of riparian areas for early detection of problematic plants is an important aspect of riparian management. Riparian managers should be able to identify the exotic plant species that are found in their region and seek assistance on effective control methods.

Extensive control of dense stands of exotics can backfire with unintended consequences if not carefully planned and executed. In some cases, exotic plants may be the only vegetation holding banks together. If removed all at once, the banks and floodplain become extremely vulnerable to damage. One of the first cardinal rules in riparian management is "first, do no harm". A bank protected by unwanted exotic species is better than an unstable, eroding bank. For example, some riparian areas in west Texas are totally dominated by salt cedar, which is doing a good job of stabilizing banks and channel. If the salt cedar is killed all at once, the bank becomes vulnerable to serve erosion during high flow events. Similar examples have been observed with wax leaf ligustrum and giant cane (Arundo donax).

Where dense monocultures of exotic plants exist, managers are urged to take a progressive, incremental approach rather than an aggressive or extensive approach. Control can begin in small pockets, not large areas. Control pockets will be surrounded by intact exotic vegetation. Monitoring the natural regeneration of native plants into these pockets is an important part of exotic plant control projects. If desirable native plants begin to establish in the pockets, continue control efforts with additional pockets. As native plants begin to grow and provide needed stability, the size of control pockets can be enlarged. This approach helps retain root stability and energy dissipation and reduces the vulnerability of the control project to severe erosion. The gradual increase in the size and number of control areas can occur until the exotics are removed and replaced by natives. Several years of followup control and maintenance will be needed in most cases to kill new seedlings, root sprouts or plants previously missed. If natural regeneration of desirable native riparian plants does not take place, managers will need to plan for the artificial re-planting of desired vegetation.

Some non-native plants can add functional value to the riparian area and should not automatically be viewed as detrimental; see Table 7-3. Some exotic plant species fill a similar niche as native plant species without dominating the riparian area or displacing native species. Although native riparian plants are almost always preferred, it is neither realistically possible nor economically feasible to attempt to control any or all infestations of exotic plants.

Table 7-3. Some common exotic plants found in riparian areas which contribute functional benefits and which are not generally considered invasive.

Watercress	Vasey grass
Wild mint	Dallis grass
Bermudagrass	Tall fescue
St. Augustine grass	Rabbits foot grass

RIPARIAN MANAGEMENT DOWNSTREAM FROM RESERVOIRS

Riparian areas that are located downstream from major reservoirs often present special challenges for management. Due to the nature of reservoir management and releases from the floodgates, problems often occur which are out of the control of downstream landowners (NRC 2002). The common situation across the western half of Texas is little or no release below dams for months or even years at a time. All normal inflow is detained in the reservoir and natural bank full or out of bank flow rarely occurs. As a result, the alluvial water tables may no longer be recharged. As the water table is lost or greatly reduced, riparian wetland vegetation cannot survive and vegetation may slowly change to non-riparian species (Figure 7.47). The effect of the dam may be a major long-term shift from riparian to upland conditions, even in close proximity to the channel. If and when abnormally large rainfall is received and reservoirs fill, large releases are made, but without intact riparian vegetation, the large sudden releases typically result in severe downstream erosion.

Figure 7.47. Riparian areas downstream from reservoirs are sometimes heavily impacted due to the way that water is released. As reservoir managers seek to mimic how natural flood flows rise and decline, these impacts can be minimized. Photo courtesy of Ricky Linex, NRCS.

For the wetter part of Texas, where constant releases usually take place below dams, the problems are much different. In these situations, an artificial base flow exists most of the time. Larger flows may take place periodically to keep reservoir levels at the desired stage. When large rain events occur above the reservoir and when lake levels rise, reservoir managers dump huge volumes of water out of the floodgates or spillways. It is common for these large releases to persist for days or weeks. In some ways, these flows mimic large natural flood events, but usually last much longer than natural flood flows. When lake levels have been reduced to the desired stage, reservoir managers close the gates and water levels drop immediately. Saturated banks, which have been underwater for extended periods are suddenly exposed, which causes severe bank sloughing.

Another important problem exists for releases below reservoirs. Reservoirs trap upstream sediment and water released from reservoirs lacks sediment. This lack of sediment creates what is known as "hungry water" which is more erosive than water with a normal sediment load.

Downstream landowners can do everything right with their riparian management and still have severe problems. The retention of dense natural riparian vegetation and large wood will help minimize the damage that is often caused by sudden and prolonged releases followed by rapid drawdown. A desirable solution would be to work with reservoir managers to manage these releases to more closely approximate the frequency, intensity and recession of natural flows.

ENGINEERED SOLUTIONS

In some deteriorated creek and river areas, the damage has been so severe, that intensive engineering solutions are sought to help restore desired conditions. These fixes are extremely expensive. In most cases, the only ones that can afford such costly solutions are government entities. Very few private landowners are able to justify the expense. These intensive restoration projects require specially trained engineers who have expertise and experience in hydrology, fluvial geomorphology, stream processes, vegetation, permitting and working with large equipment operators. There are relatively few engineers in Texas who currently have this kind of experience. Civil engineers who do not have the necessary specialized training are more likely to recommend hard engineering practices, such as concrete, riprap, gabions, grade control structures and other traditional solutions (Keown 1983).

Experienced riparian and stream restoration engineers learn to work with the natural dynamics of the creek rather than force rigid structures into a dynamic system (Elmore and Beschta 1989). They try to re-establish normal channel dimensions, sinuosity, slope, velocity, and sediment transport, paying special attention to the critical role of the floodplain and stabilizing vegetation. The use of cross-vanes, J-hook vanes or other similar structures composed of large boulders and/or logs helps direct high flow energies to the center of the channel rather than the banks. These kinds of structures although artificial, augment the natural process of stream equilibrium and help banks to establish appropriate vegetation. With time and the development of vegetation, many of these structures blend in and are hardly noticeable.

RIPARIAN ASSESSMENT AND MONITORING

The effectiveness of riparian management can be evaluated by conducting formal or informal assessments and periodic monitoring (Myers 1989). Assessments provide a snapshot of riparian conditions at a point in time. Monitoring is the periodic tracking to determine what changes if any are taking place over time and if those changes are in line with desired goals and objectives. By keeping track of riparian conditions and trends, the manager will be more aware of what kinds of management may be needed (Collins 1992, Platts 1987).

CURSORY RIPARIAN ASSESSMENT

Formal riparian assessments are desirable but are not always feasible or necessary. Cursory assessment of riparian areas can be useful and will vary in detail according to the level of experience of the manger (Figure 7.48). A cursory assessment of a specific creek or river segment can include observations and notes on any combination of the functional attributes listed below. As with any kind of riparian assessment, photographs keyed to a date and location and with explanatory notes are of great value.

- Apparent stability of banks and channel
- Extent of active erosion
- Floodplain adequacy and functionality
- Presence of riparian-wetland plants expected for the site
- Reproduction and vigor of riparian plants
- Adequacy of riparian vegetation to dissipate energy
- Presence of large wood and other energy dissipating features
- Presence of excessive sediment deposits

Figure 7.48. Cursory assessment of riparian areas is an alternative to formal assessment methods. In a cursory assessment, managers may make written notes of plant coverage, plant diversity, plant vigor, and reproduction of key species, or other riparian attributes.

FORMAL RIPARIAN ASSESSMENT

Formal riparian assessment methods are useful if managers have the right training or have access to those with proper experience or expertise. These formal methods have not been widely used in Texas due to the relatively recent interest in riparian issues.

A popular riparian assessment method widely used in New Mexico, Arizona and many other western states is known as Proper Functioning Condition, or the PFC method (Prichard 1998). This method uses a qualitative Yes or No checklist with 17 visual indicators of hydrology, vegetation, and erosion-deposition. This method requires an interdisciplinary team with experience in the region. Several Texas riparian professionals have received considerable training and experience with this technique and have found it to be useful for assessing Texas riparian areas. The PFC method focuses on functional attributes and the physical processes of energy dissipation, channel stability, sediment trapping, floodplain development, and water storage. With this method, the reach being evaluated is placed in one of three categories based on the preponderance of visual evidence. These categories are: Proper Functioning Condition; Functional At-Risk; or Non-functional.

A variation of the PFC method was developed for use in central and southwest Texas riparian areas. It is called the Riparian Function Worksheet and is found in Your Remarkable Riparian, a field guide to riparian plants within the Nueces River Basin of Texas, published by the Nueces River Authority.

Another assessment method that has been used to a limited extent in Texas is the Stream Visual Assessment Protocol, or SVAP2, developed by the Natural Resources Conservation Service (NRCS 1998). This method combines the evaluation of aquatic habitat features with some functional attributes of riparian areas. The SVAP method utilizes a numerical score for each evaluation element and combines the scores for a final numerical rating of condition. This nationwide method is designed to be modified for use in different regions and states. This method does not require the same level of training as PFC, nor does it require an interdisciplinary team.

Another riparian assessment technique that can be used on rangeland is found in A Texas Field Guide to Evaluating Rangeland Stream and Riparian Health, developed by Texas A&M AgriLife Extension Service. This technique combines functional attributes with aquatic habitat attributes in a matrix format and is adapted from the SVAP and other methods. Some County Extension Agents have been trained in this method.

There are numerous other formal riparian assessment and evaluation techniques that have been developed in other states and regions (Stacy 2006). Most share some similarity to PFC and /or SVAP. With any evaluation technique, the most important information gained is not the numerical score or the final rating, but rather, the notes written by the observers. No evaluation method is complete or useful unless the observers have taken the time to carefully write notes to describe what is seen and to provide the basis for rating of each evaluation element. Photographs would add even greater value to any evaluation effort.

PHOTO POINT MONITORING

Monitoring of riparian areas is best carried out systematically and regularly to help keep the manager or landowner apprised of changes and trends (compare Figures 7.49 through 7.52. Monitoring can be quantitative, descriptive or visual. One of the most effective means of keeping track of riparian change is by annual fixed-point photos. A series of photos of the same location taken from the same place over a period of several years is one of the best ways to document what is happening in riparian areas. If only one monitoring tool is used, photo points are often the most useful, as well as inexpensive, and easy. It is important to have a point of reference in each photo such as a large boulder, a peak in the background, or other feature that can be used to frame the photo the same each time. Riparian areas in heavily wooded locations do not usually lend themselves as well to photo points.

Figure 7.49. 2007. Photo point monitoring was began on this private ranch on the Nueces River in 2007. Floodplain is clearly lacking adequate vegetation.

Figure 7.50. 2009. Two years later (during drought conditions) sycamore and baccharis have established naturally, starting the recovery process.

Figure 7.51. 2011. In the worst one-year drought on record, the Nueces River is dry, but the water table sustains the growth of riparian vegetation.

Figure 7.52. 2012. In the sixth year of photo point monitoring, the rapid rate of recovery is apparent with dense vegetation providing energy dissipation, sediment trapping, narrowing of channel and improved sediment transport.

INFORMAL RIPARIAN MONITORING

Informal monitoring may involve the keeping of dated notes in a riparian journal with periodic regular visits to describe observations and changes (Figure 7.53).

Figure 7.53. Informal riparian monitoring involves repeat observations or measurements over time to determine change and trends. Making notes of plant density, especially new seedlings, with written accounts or photographs is one example of informal monitoring.

The use of random photos or photo points enhances the value of informal monitoring. Examples of this kind of monitoring are found in Table 7-4.

Table 7-4. Examples of informal monitoring observations and notes

June-05	Large number of new bushy bluestem plants noted on low bank side. Young willow plants heavily browsed Spikerush and water hyssop beginning to grow on new sediment
September-05	Cattle grazed in lower creek area for past 45 days; heavy use on Emory sedge Light grazing noted on switchgrass and bushy bluestem
July-06	Noticed 3 chinaberry trees at upper end and many seedlings
May-07	Big rains; out of bank flows for two days New sediment deposited below second bend; 1 – 3 inches deep 1 - 2 feet of bank lost on first outside bend Large elm tree washed out and lodged in creek 2nd crossing washed out
August-07	Several small walnut seedlings and many young baccharis noted on large gravel bar Knotgrass expanding rapidly by runners in fresh sediment
March-08	Feral hogs observed; large new wallow near spring
September-09	Walnut and baccharis noted in Aug 2007 now 3 – 5 ft tall and healthy
April-10	Large pecan struck by lightning; split in half; top fell in creek
June-11	8 mo. into drought; no flow above ground Large willow losing leaves Deer concentrating in creek bottom; eating water willow very short
October-11	Several large willow dead; drought persists
May-12	Good spring rains; creek began to flow again

FORMAL RIPARIAN MONITORING

Most private landowners do not have the resources or the need to implement formal riparian monitoring. Formal monitoring methods are sometimes required on public land or as a part of long-term research projects. Formal monitoring involves measurements and the collection of data, and may include monitoring of riparian vegetation, flow, channel characteristics, or floodplain features (Winward 2000, Rosgen 1996) It is beyond the scope and purpose of this chapter to describe formal riparian monitoring methods, but the information is readily available to those who are interested.

HIGH FLOWS ARE ESSENTIAL

It seems almost intuitive that creeks and rivers should be allowed to flow and this truth is an important component of riparian management. Maintaining base flow is obviously important for the integrity of perennial creeks and rivers. When natural base flow is robbed by excessive withdrawals, creeks and rivers become little more than drainage ditches. In addition to normal base flow, creeks and rivers must also experience periodic high flow events of varying size and duration (Figures 7.54 and 7.55). These flows range from smaller pulse flows to channel filling flows to larger out-of-bank flows that spill on to the floodplain. Flooding is not something bad that happens to a river – it is an essential process of the river. The functional and ecological integrity of creeks and rivers can only be sustained when these flows are maintained (NRC 2002, Poff et al. 1997).

Figure 7.54. Large frequent pulse flows and bank filling flows are essential to maintain the integrity and proper function of creeks and rivers. As withdrawals and altered flows become more frequent, the intentional provision of high flows will become an important part of riparian management.

Figure 7.55. Larger out-of-bank flows that spill into the floodplain are critical for trapping sediment, storing water and providing ground water recharge. Without larger flows, even on over-allocated rivers, their functions and values will be impaired and diminished.

Some may argue that these necessary flows are not something that can be managed by people; that they are entirely dependent upon rainfall and weather patterns. But as the population of Texas has grown and as our demands for surface water have increased, most rivers and many creeks are now heavily impacted by dams and other withdrawals that interrupt these flows. In too many cases, flows are greatly diminished if not essentially eliminated for significant reaches of creeks and rivers. One primary key of riparian management in Texas is that creeks and rivers be specifically managed to allow them to flow, and that these flows mimic natural flow regimes to the extent possible. Without these managed flows, many other aspects of riparian management are irrelevant.

CONCLUSION AND SUMMARY

Riparian areas are special places. They are special for many reasons. They are special because they provide the 190,000 miles of connections through which the waters of Texas flow. They are special because they connect people, they connect nature and they connect people with nature. They are special because they help cleanse the waters, sustain the flows and recharge the aquifers. Creeks, rivers, and the surrounding bottomlands are special to our soul and spirit just as they are special to our mind and body. We depend on creeks, rivers and riparian areas. For sustenance; for renewal; for reflection. Each bend, each pool, each riffle, each sunken log, each sandbar, each backwater slough, each cut-bank, each boulder, each tree, each clump of grass, are parts of the whole, just like the parts of the body. They work together. The more we understand these interworkings, the better job we can do to apply the specific management needed to sustain them (Figure 7.56).

Figure 7.56. Functional, balanced creeks, rivers and riparian areas are perpetually self-renewing natural resources providing tangible benefits to people and sustaining nature. Riparian areas are special places; they need preferential treatment and managment.

A functional, balanced riparian area is perpetually self-sustaining. As a renewable resource, riparian areas provide tangible assets to people and contribute to the bounty of nature. If we use and manage the resource wisely, it will continually perpetuate itself and we will perpetually benefit. It only requires that humans do not interfere too much. The key to managing riparian areas is first to understand how they work. Then we must understand how we can make beneficial use of them without upsetting the balance.

Because they are special places, riparian areas need preferential treatment and special management. With a genuine land stewardship ethic, a creative mind, and a basic understanding of how the creek works, the riparian manager will discover the right combinations of techniques and practices to maintain or restore riparian areas for now and for future generations. The material in this chapter is meant to be a catalyst for this.

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LIQUID HISTORY - DAN CAUDLE 2012 © (USED WITH PERMISSION).

Texas rivers are our liquid history -
Chronicles of the past,
Barometers of the present,
Prophets of the future.

Thousands of insignificant tributaries
Contribute their relatively minor aqueous deposits
Into rills, which become rivulets, then creeks
That finally feed into larger watercourses to become rivers –
Major arteries conveying the essential element of life across the land
As they wind their way toward the Gulf.

From the dawn of time rivers have been the focal point for settlement –
The location of cities and towns, the preferred sites for factories and commerce.
They have long been the basis for land ownership, boundary disputes, wars, and lawsuits
Between people, states, and nations, each seeking control of the water
To use for their own purposes and to gain advantage over others.

Our waters have been governed by the laws of six different nations.
They have seen once dominant civilizations and governments disappear entirely
They have witnessed the overnight establishment of bustling communities
Only to see them vanish almost as suddenly as they appeared.
They were the lifeblood of remote frontier outposts
Which have now become densely populated metropolitan cities.

For eons they weaved their way through the countryside
Unencumbered as they charted their own course.
They conformed only to the topography of the land
And yielded only to the laws of nature.

They ran wild and free – sometimes as raging torrents
That might cut a new channel
Leaving an oxbow vestige of the old watercourse.
Other times they just meandered
Lazily and aimlessly across the landscape.

Today the rivers have been subdued and tamed.
No longer are they unconfined and natural.
Now they are controlled and manipulated
To fit the needs and wishes of modern civilization.
Some rarely flow and consist mostly of occasional pools of water.
They run only when torrential downpours occur.
Then they become a thick, soupy, reddish brown mix of water, debris, and soil,
As they churn and stir and overflow their banks,
Destroying lives and structures that encroached into the floodplain.

Many of the rivers have been altered - straightened, narrowed, deepened -
By engineers, bulldozers, draglines, government planners - all with good intentions.
They have been restricted by artificial barriers,
Civilized by dams, weirs, locks, berms, and levees,
To control their flow and their route.

Rivers and streams are harnessed and contained in earthen reservoirs
To supply the voracious demands of urban landscapes - lush lawns and golf courses,
Water parks and swimming pools, industries, and thirsty city dwellers.
They say there is a desperate need to construct more dams and reservoirs for the future!
More dams to further diminish the rivers and creeks?

Our legacy will not only be recorded in journals,
It is there in the water for all to see.
The handwriting is not on the wall
Or in the pages of a book.
It is in the river.

Texas rivers are our liquid history -
Chronicles of the past,
Barometers of the present,
Prophets of the future.

CHAPTER 8 - LANDOWNER ASSISTANCE PROGRAMS FOR RIPARIAN MANAGEMENT BY STEVE NELLE

A wide variety of programs are available to help landowners carry out good riparian management. Assistance is obtainable through several state and federal agencies as well as a number of private organizations. Riparian assistance programs include a combination of technical and financial assistance as well as education and outreach assistance. Knowledgeable and dedicated landowners across the state are using these programs with positive riparian benefits.

NATURAL RESOURCES CONSERVATION SERVICE (NRCS)

The NRCS is an agency within the U. S. Department of Agriculture (USDA) with offices in each county of Texas staffed with conservation professionals. The NRCS (formerly the Soil Conservation Service or SCS) has a long history of providing practical, voluntary conservation assistance to landowners including technical assistance and financial incentives. In recent years, since about 2000, the agency has begun to offer riparian assistance through several different programs. The programs offered by NRCS are delivered as part of the Farm Bill.

It is important for landowners to understand that the Farm Bill changes every five years; therefore the provisions for landowner assistance programs also changes. Sometimes the changes are minor, sometimes major. Sometimes old programs are abolished and new and different programs implemented. Sometimes programs are combined and given a new name. Any discussion of NRCS assistance must emphasize the ever-changing nature of federal programs. Conservationists at the local NRCS office will explain the current programs and will walk interested landowners through the process and all the necessary steps.

TECHNICAL ASSISTANCE AND CONSERVATION PLANNING

NRCS technical assistance is available at no cost to all landowners, regardless of enrollment in any program. Often, the development of a basic conservation plan and technical assistance is the precursor to enrollment in any of the financial assistance programs offered by NRCS. This technical assistance involves an ongoing relationship with a trained conservationist who is familiar with local natural resources and local conservation issues. Technical assistance usually includes an assessment of natural resources, including soil, water and vegetation resources and periodic visits to the property to discuss landowner goals, natural resource problems and issues and possible solutions to the problem. If the landowner desires, a conservation plan will be developed to help guide landowners in their conservation activities. These plans are designed to addresses both the conservation needs of the land and the objectives of the landowner. Up-to-date maps and aerial photographs of the property showing fences, pasture acreage, soil information ,water locations, land improvements are part of the conservation planning package. All landowners are urged to become familiar with their local NRCS office where they can stay abreast of the most current conservation issues and assistance programs.

ENVIRONMENTAL QUALITY INCENTIVES PROGRAM (EQIP)

EQIP is the largest and most comprehensive conservation incentive program offered by NRCS and is available to agricultural producers. EQIP offers incentives on a wide range of conservation practices. The most common type of incentives are direct payments to landowners (sometimes called cost-sharing) for needed conservation practices. The payments are made after the practice is installed and usually cover 50% or more of the cost of the practice. Landowners know up front how much they will receive as an incentive since the EQIP agreement is in the form of a binding two-way contract. Landowners may apply for a single practice to address a specific need or apply for a suite of practices to address more comprehensive needs. EQIP offers assistance on a wide range of practices to achieve conservation on agricultural lands, but for the purpose of this chapter, only those management practices applicable to riparian areas are discussed.

Financial incentives for riparian management are provided for the following practices:

- Fencing of riparian areas to manage livestock grazing
- Alternate livestock water development, including wells, pipelines, water storage tanks and troughs to reduce livestock watering in creeks
- Prescribed grazing incentives to encourage specific grazing practices to improve riparian vegetation
- Temporary livestock exclusion from riparian areas to jump start recovery
- Selective thinning of undesirable brush species to enhance riparian vegetation
- Planting of desirable stabilizing grasses adjacent to the riparian area

In addition to providing assistance for direct benefit to riparian areas, NRCS programs provide assistance to help landowners conserve and manage their entire property. When a good program of conservation is being applied on the upland "water catchment", the benefits extend to the riparian area. A comprehensive, long-term program of conservation on each field and each acre of a farm or ranch is the goal of NRCS assistance. But, in order to reach this goal, landowners often desire to work on one field at a time or one project at a time.

The advantage of EQIP is the large amount of money that has typically been available for the program. However, there are also many landowners making application for the program, and not all applications are funded. Each application is ranked by a set of uniform criteria to determine expected conservation benefits, and contracts are approved and funded accordingly.

The disadvantage of EQIP and other NRCS programs is the lack of flexibility and the amount of paperwork involved. This can be frustrating for landowners who are not accustomed to federal government programs. Landowners are urged to develop and maintain a good working relationship with their local NRCS office, which will help minimize confusion

WILDLIFE HABITAT INCENTIVES PROGRAM (WHIP)

WHIP is similar to EQIP in many ways and is offered to non-agricultural landowners as well as agricultural producers. The overall goals of WHIP in Texas are to restore native habitats; therefore, riparian management fits well within the priorities of WHIP. The list of practices and the incentives offered under WHIP are usually identical to EQIP. The advantage of WHIP is that there are often more funds available than there are applications for the program. However, the level of funding varies from year to year.

OTHER NRCS PROGRAMS

In addition to EQIP and WHIP, there are several other conservation programs and initiatives available to landowners that can be used for riparian management. Landowners who may be interested in learning more about these programs should contact the local NRCS office. Keep in mind that each new Farm Bill will bring changes to conservation programs, priorities and level of funding:

- Conservation Security Program (CSP)
- Grassland Reserve Program (GRP)
- Wetland Reserve Program (WRP)
- Farm and Ranch Lands Protection Program (FRLPP)
- Agricultural Water Enhancement Program (AWEP)
- Gulf of Mexico Initiative (GoMI)

- Cooperative Conservation Partnership Initiative (CCPI)
- National Water Quality Initiative (NWQI)

FARM SERVICES AGENCY FSA)

The Farm Services Agency (formerly the Agricultural Stabilization and Conservation Service, or ASCS) is a sister agency to NRCS. In most cases, the offices of these two USDA agencies are in the same building. The programs of the FSA are dictated by the Farm Bill, and are subject to change over time. The primary work of the FSA in Texas is to administer the various crop and commodity subsidy programs, but FSA also administers a very important and very popular riparian conservation program.

CONTINUOUS CONSERVATION RESERVE PROGRAM (CCRP)

CCRP is the largest and most effective riparian assistance program in Texas. The intent of CCRP is to provide long-term incentives to protect, conserve and manage environmentally sensitive areas. The primary benefit of CCRP for riparian landowners is the practice called Riparian Buffers. Under this program, riparian areas associated with perennial and seasonal creeks that are not functioning properly are eligible for the program.

CCRP is administered through the FSA office but all of the field work and planning is done by the NRCS office. Landowners will work with NRCS staff to determine eligibility, establish buffer acreage, and all other technical aspects of the riparian buffer. The width of riparian buffers under this program will range from 35 to 180 feet on each side of the creek.

CCRP Riparian Buffers are enrolled for 10 to 15 years with no grazing allowed during the contract period. The program pays the participant an annual rental payment for the area included in the riparian buffer. The rental payment varies geographically from about $16.00 per acre per year in far west Texas, to over $50.00 per acre per year in east Texas.

An up-front Signing Incentive Payment of $100 per acre is paid immediately upon approval of the contract by the FSA office. In addition, incentives and payments are provided for practices which are needed to establish the riparian buffer, such as fencing and off-site livestock water development. In some cases, the selective removal of undesirable woody plants such as salt cedar, chinaberry or juniper is also needed. An initial payment of 50% cost share is made as soon as individual practices are completed. After all needed practices are installed, an additional 40% Practice Incentive Payment is made for a total 90% reimbursement of costs.

There are several advantages of CCRP Riparian Buffers when compared to NRCS programs. One advantage is that the program is non-competitive; all eligible applications are automatically accepted into the program. Landowners do not have to wait and wonder if they will be funded or not. The combination of incentives and payments makes CCRP Riparian Buffers the most financially advantageous program for the landowner who is willing to suspend grazing during the contract period.

Another CCRP practice that benefits riparian areas is called a Filter Strip. Filter Strips involve the planting of stiff stem perennial grass around the perimeter of cropland fields to reduce the movement of sediment into adjacent creeks and rivers.

U. S. FISH AND WILDLIFE SERVICE (USFWS)

The USFWS is an agency within the U. S. Department of the Interior. Their mission is to work with others to conserve, protect and enhance fish, wildlife and plants and their habitats for the benefit of the American people. Primary responsibilities of the USFWS include enforcement of federal wildlife laws, protect endangered species, manage migratory birds (especially waterfowl), and manage the National Wildlife Refuge system.

PARTNERS FOR FISH AND WILDLIFE PROGRAM (PFW)

The Partners for Fish and Wildlife Program, often referred to as the Partners Program provides technical and financial assistance to private landowners to restore or enhance fish and wildlife habitats for the benefit of Federal Trust Species (migratory birds, threatened, endangered, and other declining species).

The cornerstone of the Partners Program is partnerships, not only with private landowners, but with state and local agencies, conservation organizations, schools and other entities with an interest in wildlife. The program emphasizes conservation practices directed at restoring habitats, including, riparian areas, wetlands, bottomland hardwoods, upland forests, native grasslands, savannahs and shrublands.

USFWS works with the following groups to help implement the Partners Program in Texas: Texas Parks and Wildlife Department, Texas A&M Forest Service, Ducks Unlimited, National Wild Turkey Federation, Nueces River Authority, The Nature Conservancy, Environmental Defense, and others.

One example of successful riparian management accomplished through the Partners Program is the control of giant cane on private land in the Nueces River basin. Working through the Nueces River Authority and their Riparian Network, the Partners Program provided funding for the selective individual plant control of this invasive riparian plant.

WILDLIFE AND SPORT FISH RESTORATION PROGRAM (WSFR)

This program provides substantial federal funding to state wildlife agencies including TPWD through the tax that is levied on firearms, ammunition and fishing tackle. The funds are used to conserve, protect, and enhance fish and wildlife habitat that supports hunting and fishing. Many of the activities of TPWD that benefit private land riparian areas receive their funding through WSFR. The TPWD Landowner Incentive Program described below is funded in large part by this federal program.

TEXAS PARKS AND WILDLIFE DEPARTMENT (TPWD)

TPWD is a large multi-faceted agency charged with the responsibility to manage and conserve the natural and cultural resources of Texas and to provide hunting, fishing and outdoor recreation opportunities. The agency has a long history of providing direct and indirect landowner assistance for the conservation of fish and wildlife and the habitats that support these. Assistance available through TPWD includes both technical and financial assistance.

PRIVATE LANDS AND HABITAT PROGRAM

TPWD provides technical assistance to landowners who desire to include wildlife management considerations into their land use practices. This service is strictly advisory and is provided without charge to cooperating land managers. The goal of the program is to provide advice and information to land managers for the conservation and development of wildlife habitat and the proper management of wildlife that utilize this habitat.

Since riparian areas provide critical wildlife habitat, the inclusion of riparian management recommendations is often an important part of this assistance. TPWD biologists and professionals have a wide range of knowledge and expertise on nearly any aspect of wildlife management and habitat conservation. Landowners are urged to seek the assistance and advice of these experts to help guide their land management efforts, including riparian management.

LANDOWNER INCENTIVE PROGRAM (LIP)

The Landowner Incentive Program is designed to provide technical and financial assistance to landowners wishing to enact good fish and wildlife habitat management. LIP focuses on projects that benefit terrestrial, aquatic or riparian ecosystems with emphasis on habitat for rare species. This includes projects on uplands or riparian areas that improve watershed conditions, reduce soil erosion, restore and enhance native vegetation, and restore proper functioning of rivers, creeks and riparian areas.

LIP is funded through partnerships with the USFWS Partners Program, the National Fish and Wildlife Foundation and others. LIP is a cost-share program with TPWD reimbursing 50% to 75% of the total cost. The landowner portion of the project may be cash or in-kind contributions. Each application is ranked according to anticipated benefits, and funds are allocated based on this and other related factors. One of the benefits and advantages of LIP is the flexible nature of the program, with less rigid requirements than federal programs.

There are several different options available for landowners interested in LIP. A statewide LIP is available across all parts of Texas. There are also separately funded programs available for landowners in the North and South Llano River Watershed and the James River Watershed for practices which restore or enhance hydrologic condition on uplands and which improve riparian conditions in these watersheds. The ultimate goal of these special watershed programs is to improve water quality and other essential habitat features for the Guadalupe bass, the State Fish of Texas.

WATERSHED POLICY AND MANAGEMENT PROGRAM (WPMP)

The Watershed Policy and Management Program was created to help restore and maintain aquatic and riparian habitats as well as well as the watersheds that support these habitats. The program works through local partnerships to promote awareness and stewardship of riparian and aquatic resources and helps promote community involvement in conservation projects. The WPWM provides technical guidance and planning assistance to landowners and/ or partnership groups. Program staff includes professionals with expertise in aquatic biology, hydrology, fluvial geomorphology, riparian ecology, and watershed management. Although no direct financial assistance is provided, the WPMP often utilizes state, federal or private funding to help accomplish it purposes, which benefits individual landowners and all Texans.

The program will work with existing watershed groups or will help develop and initiate new watershed conservation initiatives to achieve the following objectives:

- Healthy upland conditions
- Functional riparian areas
- Improved water quality
- Appropriate hydrologic conditions for aquatic species
- Appropriate in-steam habitat
- Appropriate sediment flows
- Proper ecological balance in habitats affected by invasive or problem species

WILDLIFE MANAGEMENT AREAS (WMA)

TPWD owns, and manages Wildlife Management Areas scattered across the state. WMA's often serve as excellent demonstration areas to teach and show landowners, students and citizens about sustainable natural resource management. Formal and informal research, demonstrations, field days, seminars and workshops are held on WMA's to promote and encourage good land, water and wildlife practices. Riparian management is one of the many kinds of conservation that is fostered on state WMA's.

TEXAS A&M FOREST SERVICE

The Texas A&M Forest Service was previously known as the Texas Forest Service. The agency is most active in the forests and timberlands of east Texas, but are also involved in promoting windbreaks in west Texas and the protection of woodlands, riparian forests and other wooded land in other parts of the state. The agency does not currently provide any direct financial assistance for riparian management but they do offer technical assistance and tree planting programs.

FOREST STEWARDSHIP PROGRAM

The purpose of the Forest Stewardship Program is to encourage the long-term stewardship of private forestland by educating landowners on ways to actively manage their forest resources including wooded riparian areas. The Forest Stewardship Program is jointly funded by the Texas A&M Forest Service and the USDA Forest Service. Technical on-site assistance is provided to landowners by trained professional foresters upon request. Foresters will advise landowners of any problems or issue observed in wooded areas and will offer suggestions on how to properly manage these areas. If desired, landowners may request that foresters assist them in developing a written Forest Stewardship Plan, which outlines and documents the management needed to maintain, restore and improve forest and woodland resources. This program is most well suited for landowners in east Texas, but is also available to landowners in other locations that have heavily wooded land, including riparian areas.

CENTRAL TEXAS RESTORATION AND RECOVERY PROGRAM

This program provides low cost, high quality seedlings for several important riparian trees important in central Texas. The seedlings are grown at the Forest Service facility in West Texas, but the genetic origin of the trees is from native central Texas trees. Tree species that are usually available through this program include bald cypress, native pecan, bur oak, chinquapin oak, red mulberry and desert willow. The demand for the seedlings is high, so landowners are urged to place orders early.

TEXAS A&M AGRILIFE EXTENSION SERVICE

The Extension Service, as it is commonly known, is a large agency that provides educational outreach on all aspects of agriculture, natural resources and land management. With offices in each county, the County Extension Agent runs the local program of outreach and education. In recent years, Extension Service field days, workshops and seminars have frequently included information on the proper management of riparian areas on farms and ranches.

TEXAS WATERSHED STEWARD PROGRAM (TWS PROGRAM)

At the state level, the Extension Service has leadership for the Texas Watershed Steward Program. The TWS Program is a one-day educational program for citizens, landowners and stakeholders designed to improve the quality of Texas' water resources. Management of riparian areas has become a part of this curriculum and stakeholders are taught about the essential connection between functional riparian areas and water quality. The program is co-sponsored by the Texas State Soil and Water Conservation Board and is made possible through grants from the U. S. Environmental Protection Agency.

The TWS Program often targets creek and rivers that have some kind of water quality problems caused by nonpoint sources of pollution. These areas are often in the process of developing locally driven Watershed Protection Plans (WPPs) that serve as a mechanism for addressing water quality problems. The goal of a WPP is to protect healthy water bodies from potential pollutant threats and to restore polluted water bodies.

TEXAS STATE SOIL AND WATER CONSERVATION BOARD (TSSWCB)

The Texas State Soil and Water Conservation Board is the state agency that administers Texas' soil and water conservation law and coordinates conservation and nonpoint source pollution programs throughout the State. The agency works in conjunction with the 216 local Soil and Water Conservation Districts (SWCD's), to encourage the wise and productive use of natural resources. Within each county, NRCS offices work closely with the local SWCD.

TECHNICAL ASSISTANCE

The agency offers technical assistance grants to local SWCD's, which are used to hire conservation technicians. These technicians administer TSSWCB programs and augment the assistance provided by NRCS agents.

WATER SUPPLY ENHANCEMENT PROGRAM

This program was previously called the Texas Brush Control Program. The program offers cost share to landowners for brush control in targeted watersheds. The intent of the program is to generate additional base flow or aquifer recharge.

WATER QUALITY PROGRAM

The TSSWCB works in cooperation with other agencies and with landowners to develop Water Quality Management Plans (WQMP's) which address nonpoint sources of water quality problems. Riparian management practices are often incorporated into these plans. The agency also works with the AgriLife Extension Service to develop and carry out comprehensive Watershed Protection Plans to help local citizens and landowners understand the cause and effect of water quality problems.

RIVER AUTHORITIES

The Texas state legislature has created twelve separate river authority agencies since 1929. Each river authority has its own enabling legislation; therefore, each has different powers, purposes and authorities. River authorities levy no taxes and receive no tax revenues. Each is self-supporting and governed by a board of directors. The riparian activities and assistance of these agencies vary. Many of them are involved in outreach and education to promote good watershed management, while others have specific riparian programs. A list of Texas river authority agencies is provided in Table 8.1. Specific information about each one is available on their websites. Two river authorities deserve special mention for their active and successful riparian assistance programs.

NUECES RIVER AUTHORITY (NRA)

The Nueces River Authority is widely recognized for their outstanding success in riparian education and teaching riparian principles to landowners. Through the NRA Riparian Network, over 30 riparian workshops were held on private ranches across the Nueces Basin, teaching landowners how riparian areas function. The Nueces River Authority was the first entity in Texas to teach riparian principles to landowners. Their pioneering efforts are widely applauded and the teaching model is now being replicated across other parts of Texas. Because of the dedication and foresight of Sky Jones-Lewey, Director of Education and Resource Protection for NRA, riparian concepts are now appreciated and understood by many landowners and natural resource professional across the state.

One of the key messages of these workshops is the critical importance of riparian vegetation. Emphasis is placed on being able to recognize and identify riparian plants, and understand the important attributes of the plants. To reinforce this message, NRA published the first riparian plant field guide, entitled *Your Remarkable Riparian.* The field guide has been distributed free of charge to thousands of people and has generated a great deal of interest and enthusiasm for riparian conservation and management across Texas.

LOWER COLORADO RIVER AUTHORITY (LCRA)

LCRA is unique among Texas river authorities with its Creekside Conservation Program. Landowners in the 11 county area served by LCRA are eligible for cost share funding to carry out conservation practices that directly or indirectly improve riparian conditions and water quality in creeks and rivers. This is a good example of creative partnerships being used to improve riparian management on private land. Landowners work with the local NRCS office to develop conservation plans and LCRA provides the funding to cover 50% of cost of the practices

Table 8.1. Texas river authority agencies.

Angelina-Neches River Authority	Red River Authority
Brazos River Authority	Sabine River Authority
Guadalupe-Blanco River Authority	San Antonio River Authority
Lavaca-Navidad River Authority	Trinity River Authority
Lower Colorado River Authority	Upper Colorado River Authority
Nueces River Authority	Upper Guadalupe River Authority

LAND TRUSTS

Land trusts are private nonprofit organizations devoted to protecting natural resources on private lands through voluntary conservation easements or other conservation agreements. Land trusts work with private landowners who desire to maintain and conserve the integrity of larger properties in perpetuity. These land trusts then have the responsibility for working with landowners to insure the management and stewardship of those lands. A listing of some Texas land trust organizations is found in Table 8.2.

Conservation easements are not a transfer of ownership, nor a grant of public access. When a landowner chooses to establish a conservation easement with a land trust, he maintains ownership and the ability to continue using the property as he has in the past including farming, ranching, hunting and recreational activity. A conservation easement simply restricts future development or other damaging activities regardless of who owns the land in the years ahead.

Land trusts provide one of the most effective long-term ways to encourage good land, watershed and riparian management and to protect them from future development. The land trust will work with landowners to develop a conservation plan that will help achieve the landowner’s objectives for land management, including riparian management. Periodic followup assistance by land trust staff and conservation professionals will help landowners carry out sustainable land and water management.

OTHER PRIVATE ORGANIZATIONS

Numerous private organizations directly or indirectly promote good riparian management in Texas, and their contributions are important. In most cases, these organizations provide riparian education and outreach, but no financial assistance. In some cases, these organizations cooperate and collaborate with state and federal agencies to increase the benefit and effectiveness of government programs. Partnerships between landowners, private organizations and government agencies are becoming increasingly important to achieve large landscape goals such as riparian management. It is beyond the scope of this chapter to describe each organization and their contributions. A partial list of these organizations is found in Table 8.3. The most current information on these organizations and their riparian activities can be found on the internet.

Table 8.2. Some Texas land trust organizations.

Bayou Land Conservancy	Katy Prairie Conservancy
Big Thicket Natural Heritage Trust	Native Prairie Association of Texas
Cibolo Conservancy	Pines and Prairies Land Trust
Coastal Bend Land Trust	Texas Agricultural Land Trust
Colorado River Land Trust	The Nature Conservancy
Connemera Conservancy	The Texas Land Conservancy
Frontera Land Alliance	Upper Trinity Conservation Trust
Galveston Bay Foundation	Valley Land Trust
Guadalupe-Blanco River Trust	Willbarger Creek Conservation Alliance
Hill Country Conservancy	Wimberley Valley Watershed Association
Hill Country Land Trust	

Table 8.3. Some private organizations involved in riparian management assistance

Armand Bayou Watershed Partnership	Lampasas River Watershed Partnership
Arroyo Colorado Watershed Partnership	Meadows Center for Water and the Environment
Attoyac Bayou Watershed Partnership	National Wild Turkey Federation
Buck Creek Watershed Partnership	Nueces River Watershed Partnership
Caddo Lake Institute	Plum Creek Watershed Partnership
Cedar Bayou Watershed Partnership	San Marcos River Foundation
Dickenson Bayou Watershed Partnership	South Llano Watershed Alliance
Dixon Water Foundation	Texas Riparian Association
Ducks Unlimited	Texas Wildlife Association
Edwards Aquifer Authority	The Nature Conservancy
Geronimo and Alligator Creeks Watershed Partnership	Trinity Waters
Hill Country Alliance	Upper Cibolo Creek Watershed Partnership
Lake Granbury Watershed Partnership	Wimberley Valley Watershed Association

CHAPTER 9 - COMING TO TERMS (MARK WENTZEL)

The preceding chapters have described the unique and varied characteristics of riparian areas. Now it's time to put together a description of riparian areas in Texas. That description, really a simplified conceptual model of how they work, will be an important guide as TIFP studies the flow requirements of riparian areas. It will guide us in terms of who (which disciplines) to consult, what aspects to investigate, where to study (how to delineate riparian areas), when to carry out specific studies (how to prioritize the use of limited resources), and which aspects of riparian areas to investigate. That definition will guide subsequent classifications of riparian areas, allowing us to compare conditions across time for the same riparian area, between riparian areas along the length of the same river, or along completely different rivers. Over time, it will allow clearer communication as we discuss issues related to riparian areas with managers, technical experts, stakeholders and members of the public.

In the context of TIFP, what is our understanding of a riparian area? What exactly constitutes the riparian area of a stream or river? A basic definition (and understanding) might be something like this: land areas outside the banks of a stream or river that are significantly influenced by flow conditions and, in turn, have a significant influence on environmental conditions within the stream or river. But how do we define "significant influence?" All areas of a watershed or basin influence conditions within a stream or river by providing, at the least, contributing drainage area that provides flow to the stream or river through rainfall-runoff and infiltration-return flow processes. In turn, during large flooding events (such as the 1 in 100 or 1 in 500 year return period flood) large areas of the watershed (at least the valley portion) may be inundated by a stream or river. What criteria should be used to limit the definition of riparian areas within this overly broad context?

The goods and services provided by riparian areas and the functions required to provide those goods and services can be used to craft an appropriate description of riparian areas. In the context of TIFP, we will focus on the functions of riparian areas that are most directly influenced by flow regime. We seek a general description, but realize that in a state as diverse in climate, geology, and ecology as Texas, riparian functions will vary somewhat for specific river segments. Our description of riparian areas will need to be adapted for specific locations across the state (Miller et al. 2010).

Table 9.1, adapted from NRC (2002), provides a list of some of the more notable goods and services valued by society and the functions of riparian areas that must be maintained in order to provide them. The first function listed is "short term storage of surface water." For a functioning riparian area, during high flow events in the stream or river, water spills out onto the floodplain. That water encounters both physical and biological features of riparian areas that slow the return of flood waters to the main channel. Physical features such as oxbow lakes, floodplain depressions, and other variations in topography (such as ridges and swales) provide resistance to flow and short term storage. Biological features (riparian vegetation such as trees, shrubs, and grasses) also increase flow resistance and act to slow flood waters. A functioning riparian area reduces downstream flooding by providing short term storage of peak floodwater and releasing this flow back to the river over a longer time period. In contrast, a channelized or entrenched stream with little or no riparian area transmits flood peaks downstream unattenuated. The Federal Emergency Management Agency's (FEMA) National Flood Insurance Program recognizes the ability of healthy, functioning riparian areas to reduce flood damages (Smardon and Felleman, 1996).

Table 9.1. Riparian area functions and associated goods and services (adapted from NRC 2002).

Function	Indicator that Function Exists	Effect of Function	Goods and Services Valued by Society
Hydrology and Sediment Dynamics			
Short term storage of surface water	Floodplain connected to stream channel	Downstream flood peak attenuation	Reduced flood damages
Maintenance of water table	Presence of flood-tolerant and drought-intolerant plants	Maintain structure of vegetation community	Diverse habitats that contribute to regional biodiversity
Accumulation and transport of sediments	Diverse habitats such as riffle(or transverse bar)-pool sequences, point bars, etc.	Active processes of fluvial geomorphology	Creation of predictable yet dynamic channel and floodplain habitats
Biogeochemistry and Nutrient Cycling			
Organic carbon production	A balanced biotic community	Energy source for aquatic and terrestrial food webs	Healthy populations of organisms
Promotion of biodiversity	High species richness (plants and animals)	Provide reservoirs of genetic diversity	Biocomplexity
Cycling and accumulation of chemical constituents	Good chemical and biotic indicators	Intercept nutrients and toxicants before they enter stream	Improved stream water quality
Sequestration of carbon in soils	Organic-rich soils	Retain nutrients and remove carbon dioxide from the atmosphere	Improved air quality
Habitat and Food Web Maintenance			
Maintain streamside vegetation	Presence of shade-producing canopy	Provide shade to stream during warm season	Suitable habitats for organisms
Support characteristic terrestrial animal species	Appropriate species have access to riparian area	Allow movement/ migration at daily to annual time scales	Animals for bird watching, wildlife enjoyment, and hunting
Support characteristic aquatic animal species	Maintenance of fish migrations and populations	Allow migratory fish to complete life cycles	Fish for food and recreation

One way to evaluate this function is to measure or estimate the extent of inundation associated with river flows of a particular magnitude. For example, the extent of inundation associated with a flood peak with an expected return period of once in 100 years is an indicator used by FEMA. Inundation maps associated with such events are used to assist managers in land use planning, setting insurance rates, and directing development of human infrastructure. Large, infrequent flows (such as the 1 in 100 year flood) may play a disturbance role in riparian areas, much like fire on a terrestrial landscape. However, vegetation that can exist without being inundated by a river for up to 100 years is generally considered to be terrestrial, not riparian, in nature. Also, floodplain habitat that may be utilized only once every hundred years is not generally considered critical for preservation of riverine species. Smaller, more frequent overbank flows (such as the 1 in 1 to 1 in 10 year flood events) are generally considered to be most responsible for maintaining and preserving riparian areas (Doring and Tockner, 2008). Inundation maps associated with these smaller magnitude events can be developed as part of an effort to delineate riparian areas (see, for example, FNI 2005 and TIFP&SARA 2011).

A second function of riparian areas, from Table 9.1, is "maintenance of water table." A shallow water table in riparian areas serves to provide water for riparian adapted vegetation, which is unique from terrestrial vegetation. The key feature of the water table in riparian areas is that it is within the rooting zone of riparian plant species (or more precisely, the capillary fringe above the water table is within the rooting zone of these plants, (see Chapter 6 for further explanation). The location of the water table can be measured directly by installing piezometers or monitoring wells. Such studies are quite useful but may be limited in spatial extent due to limited resources. As a surrogate, the presence of plants that have benefited from increased availability of water (relative to the surrounding land area) may be used as an indicator of suitable water table conditions in the immediate to recent past. One definition of riparian areas that focuses on this function (and surrogate indicator) is the area with vegetation "of species with a composition and physical structure distinct from those of adjacent land areas" (DWAF 2005). The distinction may be either in types of plants (riparian areas may have riparian adapted plants which are flood tolerant and drought intolerant) or plants that display more vigorous or robust growth (due to the greater availability of water in riparian areas). Areas that display these types of vegetation differences can be identified with a combination of field work and/or examination of spatial imagery (e.g. Ward et al, 1997, DWAF 2005). Land use practices (e.g. clearing of natural vegetation) can make it more difficult to employ this method of riparian area delineation.

A third function of riparian areas from Table 9.1 is the "accumulation and transport of sediments." In systems where the river is entrenched, the force of water moves sediment from the landscape to the channel, where it is quickly evacuated downstream. In systems with functioning riparian areas, sediment moves both from the land area to the channel and from the channel to riparian areas. The result is a mosaic of diverse physical habitats (see Chapter 4 for a description of this diversity and the processes that create it), both within the channel and the riparian area. These physical habitats may be delineated by a combination of field work and inspection of spatial imagery (e.g. Coffman et al. 2011, Phillips 2011). Creation of some of these habitats can take many years, others a single year or less. After annual or slightly larger overbank events (1 in one year to possibly 1 in 10 year return period), the area outside the channel banks where sediment has been deposited can be observed in the field. This area of "active floodplain development" is roughly equivalent to the area where the "accumulation and transport of sediments" function is active. Near many rivers, there may be "inactive" floodplains (or terraces) which are remnants of floodplains from previous geologic periods. Although they may be inundated on rare occasions by large magnitude flood events (such as the 1 in 100 or 1 in 500 year return period floods), terraces are not part of the modern riparian area.

Other examples of riparian area delineations focused on this function include "active meander belt width" and "setback distance." For some programs, these indicators may be used to keep human development away from areas that will be impacted by actively meandering rivers (e.g. Parish Geomorphic 2004 and CRWP 2006). But TIFP focuses on the ecological benefits associated with meandering. For example, in systems where oxbow lakes are important, the process of river meandering and meander cutoff is necessary to create new oxbow lakes. Without creation of new oxbow lakes, these habitats would disappear as existing oxbow lakes gradually age and disappear (Giardiono and Lee 2012). In forested systems, river meandering removes old, established trees and creates areas for establishment and growth of seedlings, insuring a wide variety of tree age classes. For TIFP, the "active meander belt width" provides an estimate of the area where the function of "accumulation and transport of sediments" is taking place.

A fourth function of riparian areas is "promotion of biodiversity." Riparian areas are some of the most biologically diverse areas on earth (Tockner and Stanford 2002). The diverse physical habitats created and maintained within riparian areas make that biological diversity possible. A riparian area is really a mosaic of habitats, each small area with its own degree of connectivity to the river, frequency and duration of inundation, distance to groundwater, etc. The net result of this physical diversity is biodiversity of the plants, animals, and organisms that inhabit riparian areas. Biodiversity in riparian areas can be measured by metrics such as species richness and relative abundance. In particular, trees and woody shrubs are often the focus of measures of riparian biodiversity (see Chapter 6). A change in plant diversity can be used to delineate the extent of riparian areas based on this function. This change may be more noticeable in arid regions than in humid regions.

A fifth function of riparian areas from Table 9.1 is "cycling and accumulation of chemical constituents". Riparian areas can intercept chemical constituents in water that is flowing from the landscape to the channel (see Chapter 6 for a description of the mechanics of how this happens). Fisher and Fischenich (2000) list a number of studies documenting the effectiveness of riparian areas to reduce nitrates, phosphorous, potassium, fecal bacteria, suspend sediment, and other constituents in surface water. Based on intensive observations of a few systems and some calculations (see Chapters 4 and 6), it may be possible to designate a specific width of land ("stream buffer") adjacent to Texas' rivers that carry out the function of "cycling and accumulation of chemical constituents." However, as this function is not directly related to flow conditions, it provides only general guidance to TIFP related to delineating riparian areas. Stream buffers are more effectively employed in programs that relate to land use management in riparian areas.

A sixth function of riparian areas is "sequestration of carbon in soils." Riparian soils are different from terrestrial soils. As a result of interactions between riparian vegetation and fluvial processes that form and rework them, riparian soils exhibit considerable variability in structure, particle size, and other properties (NRC 2002). Because they are relatively recently deposited (from a geologic standpoint), riparian soils are generally less developed than soils on the surrounding landscape (see Chapter 5). TIFP can make use of existing data sets (NRCS soil surveys and maps) to identify soils that are influenced by rivers and streams (see Chapter 5). This delineation method for riparian areas can be employed even in areas that have experienced significant land use change.

A seventh function of riparian areas is to "maintain streamside vegetation." This may or may not be a highly visible characteristic. In forested, humid areas, it may be difficult for an untrained eye to discern the extent of the rivers influence on the landscape. Nevertheless, even with such a background, differences in species and vigor can be identified. In drier terrestrial landscapes, riparian areas of perennial streams may be easier to recognize. For intermittent or flashy streams, the influence of a stream or river on streamside vegetation may be more or less obvious during certain times of the year. An indicator that can be used to discern the extent of this riparian function are differences in plant community composition, abundance, and size/density relative to the same measures in adjacent, terrestrial landscapes.

An existing data set (Texas Ecological Systems Classification or TESC) provides a classification of land cover types (based primarily on vegetation) for most of the state at a scale of about 35 feet by 35 feet. The goal of TESC is to provide land cover data suitable "for planning and management at a sub-county or large ownership, scale of resolution" (TPWD & TNRIS 2009). In addition to greater resolution, TESC provides roughly 10 times the number of land cover classes than were previously available. Many of the land cover classes are related to riparian areas. For example, in Phase I of the project (which covers Central and North Central Texas), TESC identified 114 land cover types, 43 of which were associated with riparian and wetland systems. Characteristic vegetation species for each land cover type are included in TESC documentation, as well as general descriptions of geology, landform, and soils. TESC is being completed in 6 phases. Phases 1 through 3 are now complete, covering about 55% of the State of Texas. TESC is a valuable tool, but TIFP will still need to conduct field assessments of riparian areas for specific locations and studies. For example, for studies related to flow requirements of specific riparian areas, transects will need to be surveyed in the field. For some locations, the difference in flow rate needed to inundate adjoining areas (even those as small as 35 foot by 35 foot) may be significant.

An eighth function of riparian areas is to "support characteristic terrestrial animal species". Because of their varied habitats, riparian areas support a variety of animal species. These animals may spend some or only a portion of their life cycle in riparian areas. For some species, riparian areas may provide a conduit for migration between otherwise isolated habitats. Fisher and Fischenich (2000) list a number of studies documenting the effectiveness of riparian areas to provide habitat for reptiles, amphibians, birds, and mammals. They list widths of riparian areas required to provide habitat for these creatures from a minimum of 100 feet to more than 1,500 feet. In order to delineate areas where this function is being carried out, researchers could survey the presence or absence of particular species across the landscape. However, many of these species are difficult to observe or may use riparian areas only for parts of the year. As a surrogate, it may be more practical to identify areas with suitable habitat for key riparian dependent creatures (similar to habitat evaluation procedures described by USFWS 1980).

Supporting terrestrial animal species has not been a primary focus of TIFP. To some degree, providing flows required to maintain physical habitats and streamside vegetation in riparian areas provides benefits to terrestrial animal species. However, direct linkages between flow regimes and terrestrial animal species have not been the topic of extensive study in Texas. Studies in other states have documented relationships between flow regimes and habitat for endangered terrestrial species, for example least tern, piping plovers, and whooping cranes on the Platte River in Nebraska (Murphy et al. 2004). Terrestrial animal species may be of concern for some studies conducted by TIFP. For example, Cagle's map turtle may be a concern on the lower Guadalupe River (Killebrew et al. 2002). In such cases, it may be necessary to evaluate the habitat requirements of those species and modify, as necessary, the definition of riparian areas for that study. To the extent possible, TIFP will make use of existing research related to flow and habitat requirements of terrestrial animal species in riparian areas. In some cases, it may be necessary to conduct original research to establish those relationships.

A final function of riparian areas from Table 9.1 is to "support characteristic aquatic animal species". Riparian areas may indirectly impact aquatic animal species by improving in-channel habitats or water quality. In addition, some fish and other aquatic species are known to utilize riparian floodplains for at least some portion of their life cycle (Crance 1988). Waiting for suitable overbank flow conditions in riparian areas to arrive and then sampling for the presence of riverine species or even measuring suitable habitat conditions would be expensive and challenging. Sampling within the river during normal, base flow conditions for the presence or absence of those same species also has limitations. Riparian areas important for spawning and/or juvenile stages may be a considerable distance away from locations where adult individuals can be sampled in the river. For a particular reach of a stream or river, factors other than suitable riparian areas may contribute to the absence or presence of species. Some studies have found a correlation between healthy riparian conditions and the presence or absence of fish in a stream or river (Stauffer et al. 2000). In other cases, the relationship may be more subtle, such as impacting population dynamics rather than presence/absence (Fischer et al. 2009). As for terrestrial animal species, providing flows required to maintain physical habitats and streamside vegetation in riparian areas will provide some benefit to aquatic animal species that use those habitats. To the extent possible, TIFP will make use of existing work related to floodplain habitats of aquatic species (e.g. Winemiller et al. 2004). However, it may also be necessary to conduct specific studies related to flows required to carry out this function. Overall, this function does not lend itself for an easy means of delineating riparian areas.

So how do we wrap it all together? One of the goals of this document was to develop a consistent description of riparian areas in Texas. We began with the following basic description: "Land areas outside the banks of a stream or river that are significantly influenced by flow conditions and, in turn, have a significant influence on environmental conditions within the stream or river". So, what have we learned about the meaning of "significant influence" in the context of TIFP? Each chapter of this book reinforces the idea that riparian areas are complex, but also provides significant background understanding of these areas. Putting together that background understanding and focusing on riparian functions refines our basic description of riparian areas and leads to these conclusions:

- The general extent of riparian areas can be refined by looking at hydrologic connectivity between the main channel of rivers and overbank areas. Areas inundated by flows between the one in one year return period flood (overbank flow) and the one in ten year return period flood provide a general idea of the extent of riparian areas. There can be quite a bit of difference between the areas inundated by this range of flows, but even this first step of refinement is helpful. Accepting this refined definition of riparian areas does allow us to distinguish between flows required to maintain riparian areas and flows that cause significant damage to human development on floodplains (see Text Box).
- Riparian areas are created by unique physical processes. Delineating the land areas where those processes are active provides further refinement of riparian areas. Since some of these processes are carried out on geologic time scales, it's sometimes easier to observe the clues left on the landscape than the processes themselves. Those clues can help us identify the active floodplain and active meander belt width of the river, both of which can be used to refine the extent of a riparian area associated with a river.
- The unique characteristics of riparian vegetation and soils make it possible to delineate riparian areas from the background landscape. Available data sets for the state of Texas (soil surveys and maps and the soon to be completed TESC) make it possible (on a broad scale) to rapidly identify areas that have been influenced by rivers and streams. Spatial resolution and the objectives that guided classification need to be considered when using these data sets. For site specific TIFP studies it will be necessary, in most cases, to refine riparian area delineations based on field work.
- Riparian functions are not the same in every riparian area. At specific locations, various functions will have varying degrees of significance (even before considering the influence of humans) due to differences in geology, climate, and ecology. A detailed definition of Texas' riparian areas and means of differentiating them from surrounding landscapes will be site specific as well. This document describes the factors that will go into developing that site specific definition.

A general description of riparian areas, in the context of TIFP, emerges:

> Riparian areas are land areas along, but outside the banks, of a stream or river that are significantly influenced by flow conditions and, in turn, have a significant influence on environmental conditions within the stream or river. Significant influence includes:
>
> - hydraulic connectivity with the river or stream on a relatively frequent basis,
> - active fluvial geomorphic processes such as meandering and floodplain creation, and
> - measureable influence on the composition and condition of soils and vegetation.
>
> For specific locations, it may also be necessary to consider the needs of animals (aquatic and terrestrial) that rely on riparian areas when delineating these areas.

At first glance, it might seem that the goal of maintaining functioning riparian areas would be incompatible with the goal of reducing flood impacts on humans and their infrastructure. Nevertheless, in reality, because riparian areas are maintained by lower magnitude floods and they also contribute to the reduction in magnitude of larger floods downstream, these two goals are not incompatible. In fact, the Federal Interagency Floodplain Management Task Force concludes that functioning riparian areas are "the most sensible, least costly approach to flood hazard protection" (Smardon and Felleman, 1996). A functioning riparian area maintains channel and bank stability during large flood events, maintains long-term flood conveyance capacity of the main river channel by reducing in-channel deposition of sediments and encroachment of vegetation, and reduces downstream flood peaks.

Removal of moderate overbank (flood) flows or pulses of the type required to maintain riparian areas can actually increase flood damages. Recent studies in Texas have identified examples where a decrease in frequency of overbank and pulse flows (compared to historical conditions) resulted in greater flood damage when larger floods eventually occurred. Dean (2009) studied the Rio Grande in the area of Big Bend National Park. Gaging data for that system shows that the frequency of modest flood flows (35,000 cfs) has decreased significantly (from about once every four years before 1942 to about once every 20 years after). This has resulted in a narrowed channel choked with encroaching vegetation (including non-native species such as salt cedar and giant reed). Ecological impacts include the loss of important habitats such as backwaters, side channels, and low velocity portions of the channel. These changes to the channel shape have resulted in flooding impacts at lower discharges and higher flood stages when flooding does occur.

Winters and Baldys (2011) found similar results on the Wichita River near Wichita Falls, Texas. They identified a reduction in annual peak flows since 1938, but limited gage data for that system prevented a precise quantification of the change. Since 1938, channel changes have included narrowing and increased encroachment of vegetation. Winters and Baldys did not investigate the ecological impacts of these changes, but did quantify a significant change in flood characteristics. A recent flood of relatively modest size (10,000 cfs on June 30, 2007) resulted in the highest flood stage since 1938 (24.4 feet). In comparison, a much larger flood (17,800 cfs on October 3, 1941) had a lower flood stage (24.0 feet). Both the Rio Grande and Wichita River in Texas appear to be examples of what Collier et al. (1996) predicted: "Without periodic high flows, some channels downstream from dams will aggrade with sediment or narrow with overgrown vegetation. Two or three flood-free decades may have been traded for more devastating floods in the future."

The following example visually demonstrates how flows proposed to maintain riparian areas compare with flows that impact human infrastructure. This location, the San Antonio River near Goliad, was chosen because of the availability of suitable data. However, the use of data for this example does not imply any endorsement or critique. Historic stream flow data is available from USGS gage 08188500, the 1 in 100 year floodplain has been delineated by FEMA (NFIP 2010), overbank and pulse flow recommendations have been made by both the local BBEST (GSABBEST 2011) and BBASC (GSABBASC 2011), and E-Flow standards that include pulse events have been adopted for this site (TCEQ 2012). The approximate magnitude of these flows and associated stage and water surface elevations are shown in Table 9.2.

NWS (2012a) lists some of the impacts of flooding associated with various river stages (water surface elevations) at this location. These impacts are provided in Table 9.3. Note that, according to NWS, it isn't until floodwaters reach a local stage of 53.7 feet (corresponding to a flow in excess of 120,000 cfs) that evacuation of residences would be required. This is a stage slightly above that associated with the 1 in 100 year flood (53 feet) calculated by FEMA. It appears that state and federal programs to keep residences and other vulnerable human infrastructure outside the 100 year floodplain have been effective in this area.

Note also that flood impacts are listed at 40 feet, the stage associated with the largest overbank flow recommended by the BBEST (23,600 cfs). Although this stage is 13 feet lower than that associated with the 1 in 100 year flood, there are still some impacts associated with this flow. These include damage to Goliad State Park (located next to the river, west of Highway 183), floodwaters on some roads and low bridges, and stranding of some livestock in pastures near the river. On average, a flow of this magnitude (23,600 cfs) occurs at this location about once every five years. Allowing flows of this magnitude to occur in the future would have some flood impacts, but would also benefit existing riparian areas.

In balancing the needs of the environment with other needs, the BBASC recommended a maximum overbank flow which has a stage of 33 feet, seven feet lower than the maximum BBEST overbank flow recommendation and 20 feet lower than the 100 year floodplain. At this stage, NWS lists impacts that include flooding within Goliad State Park and stranding of livestock.

The E-Flow standard that was adopted for this site has a stage of 24 feet. This is only two feet above bankfull conditions, as described by NWS. Flooding would occur in the lowest areas of Goliad State Park and, even at this low flow rate, there is still potential for livestock in low pastures to be cutoff and drowned.

Thanks to a NWS website that displays the extent of inundation associated with various stages for the San Antonio River at Goliad (NWS 2012b), we can get a visual display of the trade-offs between flood impacts and riparian area that may benefit from these various flows. Figures 9.1 and 9.2 show results for several flows, specifically (A) the 1 in 100 year flood, (B) the largest overbank flow recommended by the BBEST, (C) the largest flow recommended by the BBASC, and (D) the largest flow adopted in the E-Flows standard. Figure 9.1 shows results for the general area around Goliad, while Figure 9.2 shows results in the area of Goliad State Park. From these two figures, it's pretty clear that the BBEST recommended flow (B) inundates a significantly smaller area than the 100 year floodplain (A). This is expected since riparian areas rarely extend to the limits of the 100 year floodplain. The upper areas of the 100 year floodplain are very rarely inundated and vegetation in those areas is adapted to much more "terrestrial" conditions. In Goliad State Park, the flow recommended by the BBEST (B) covers a high-flow, side channel of the San Antonio River. This side channel is not inundated by either the BBASC recommended flow (C) or the flow protected by the standards (D).

Table 9.2. Approximate water surface elevation of overbank and pulse flows of various magnitudes for USGS gage 08188500, San Antonio River at Goliad.

Flow Estimate/ Recommendation	Approximate Frequency	Flow (cfs)	Approximate Local Stage (ft)	Water Surface Elevation NAVD88 (ft)[1]
FEMA	1:100 Year	75,000*	53	143.9
BBEST	1:5 Year	23,600	40*	130.9
	1:2 Year	10,600	28*	118.9
	1:1 Year	7,680	22*	112.9
	1:Spring	3,540	15*	105.9
BBASC	1:Season	14,000	33*	123.9
	1:Season	11,500	29*	119.9
	2:Season	8,000	24*	114.9
E-Flows Standard	2:Season	8,000	24*	114.9

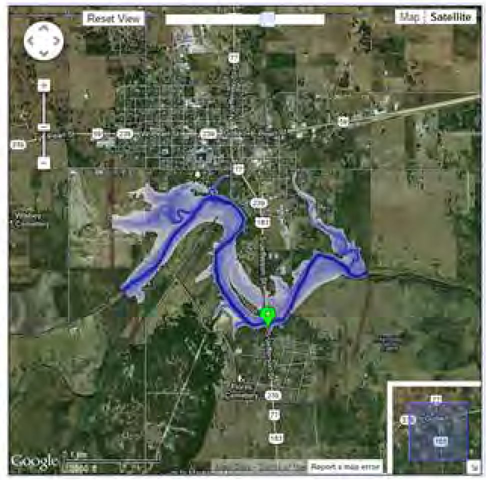
[1]North American Vertical Datum 1988 values from NWS 2012a.

*Estimated from provisional rating curve for USGS gage 08188500 (USGS 2012).

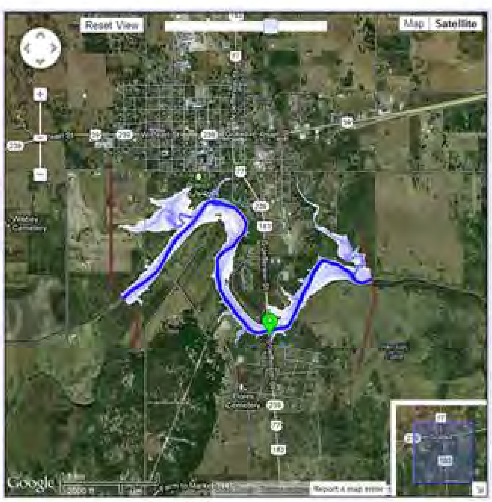
Table 9.3. Flood impacts associated with flows reaching specific stages at USGS gage 08188500, San Antonio River at Goliad (NWSa 2012).

Local Stage (ft)	**Flood Impacts**
53.7	This is flood of record...from the remnants of hurricane Beulah on Sep 23, 1967. Water is near the bottom of the new bridge on highway 183...which will require evacuations of residents to prevent them from being stranded.
44	Major flooding occurs. Nearly all of Goliad State Park is under water...except the headquarters and mission area...causing major damage. Many livestock are cut off and are potentially drowned above Goliad...to the Guadalupe River confluence. Water also approaches the lowest residences which may be stranded in the south edge of Goliad.
40	Major flooding occurs. Nearly all of Goliad State Park floods...except the headquarters area and mission...causing major damage to the park. Many secondary and primary roads and low bridges flood. The flow is within a few feet of the lowest residences in the south edge of Goliad and highway 183. Hundreds of livestock are cut off...and can potentially drown in the flood plain below Falls City to the Guadalupe River confluence.
35	Major lowland flooding occurs. Roads...many camp sites...RV and temporary shelter sites in Goliad State Park flood. Hundreds of livestock downstream in the flood plain are cut off and potentially drown.
33	Moderate flooding occurs. Roads...many camp sites...RV and temporary shelter sites in Goliad State Park flood. Hundreds of livestock downstream in the flood plain are cut off and potentially drown.
32	Roads and several camp sites through Goliad State Park flood. Moderate lowland flooding above Goliad to the Guadalupe River confluence...cuts livestock off and potentially drowns them.
30	Moderate lowland flooding occurs...covering much of camping area at Goliad State Park.
25	Minor lowland flooding occurs...with water in the lowest areas of Goliad State Park. Livestock below Goliad to the Guadalupe River confluence are cut off and potentially drown.
22	Bankfull conditions occur. The lowest camp sites in Goliad State Park flood. Livestock below Goliad to the Guadalupe River confluence are cut off and potentially drown.
15	Nuisance flooding occurs. Livestock are cut off in the flood plain downstream below Goliad to the Guadalupe River confluence.

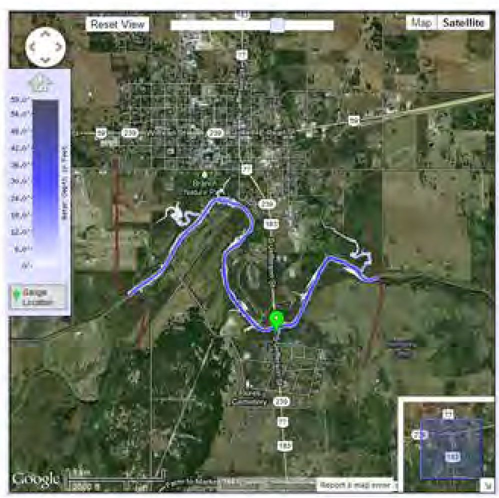
(A) The 1 in 100 year return period flood, roughly 75,000 cfs with an elevation of 143.9' (NAVD88).



(B) Largest flow recommended by the Guadalupe-San Antonio BBEST; 23,600 cfs with an elevation of roughly 130.9' (NAVD88).



(C) Largest flow recommended by the Guadalupe-San Antonio BBASC; 14,000 cfs with an elevation of roughly 123.9' (NAVD88).



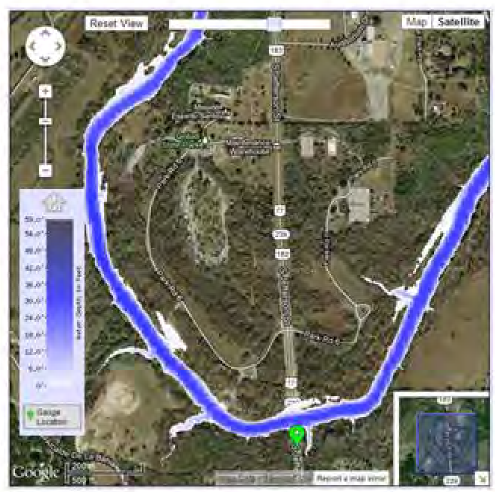
(D) Largest flow in E-Flow standards; 8,000 cfs with an elevation of roughly 114.9' (NAVD88).

Figure 9.1. Inundation around the city of Goliad associated with various flow rates (from NWS 2012b).

A) The 1 in 100 year return period flood, roughly 75,000 cfs with an elevation of 143.9' (NAVD88).

B) Largest flow recommended by the Guadalupe-San Antonio BBEST; 23,600 cfs with an elevation of roughly 130.9' (NAVD88).

C) Largest flow recommended by the Guadalupe-San Antonio BBASC; 14,000 cfs with an elevation of roughly 123.9' (NAVD88).



D) Largest flow in E-Flow standards; 8,000 cfs with an elevation of roughly 114.9' (NAVD88).

Figure 9.2. Inundation in and around Goliad State Park associated with various flow rates (from NWS 2012b).

CHAPTER 10 - REFERENCES

Abbe, T.B; Montgomery, DR. 2003. Patterns and process of wood debris accumulation in the Queets River basin, Washington. *Geomorphology.* 51:81–107.

Alford, J.J., and Holmes, J.C., 1985, Meander scars as evidence of major climate change in southwest Louisiana: Annals of the Association of American Geographers, v. 75, p. 395–403.

Anderson, CJ; Mitsch, WJ. 2008. Tree basal growth response to flooding in a bottomland hardwood forest in Central Ohio. *Journal of the American Water Resource Association*. 44:1512-1520.

Aslan, A. and Blum, M.D. 1999. Contrasting styles of Holocene avulsion, Texas Gulf Coastal Plain, USA. In Fluvial Sedimentology VI, N.D. Smith, J. Rogers (Editors). Special Publication, International Association of Sedimentology. Oxford, Blackwell, pp. 193-209.

Asquith, W.H., Heitmuller, F.T., 2008. Summary of Annual Mean and Annual Harmonic Mean Statistics of Daily Mean Streamflow for 620 U.S. Geological Survey Streamflow-Gaging Stations in Texas Through Water Year 2007. U.S. Geological Survey Data Series 372.

Asquith, W.H., Roussel, M.C., Vrabel, J., 2006. Statewide Analysis of the Drainage- Area Ratio Method for 34 Streamflow Percentile Ranges in Texas. U.S. Geological Survey Scientific Investigations Report 2006-5286.

Asquith, W.H., Vrabel, J., Roussel, M.C., 2007. Summary of Annual Mean, Maximum, Minimum, and L-scale Statistics of Daily Mean Streamflow for 712 U.S. Geological Survey Streamflow-Gaging Stations in Texas Through 2003. U.S. Geological Survey Data Series 248.

Barling, R.D., Moore, I.D., 1994. Role of buffer strips in management of waterway pollution: a review. Environmental Management 18, 543-558.

Basnyat, P., Teeter, LD., Lockaby, B.G., Flynn, K.M., 2000. The use of remote sensing and GIS in watershed level analyses of non-point source pollution problems. Forest Ecology and Management 128, 65-73.

BBBASC (Brazos Basin and Bay Area Stakeholder Committee). 2012. Environmental flows recommendations report. TCEQ. Austin, TX. http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/eflows/brazos_bbasc_report_8_22_2012_bbasc.pdf

BBBEST (Brazos Basin and Bay Expert Science Team). 2012. Environmental flow regime recommendations report. TCEQ. Austin, TX. http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/eflows/brazos_bbest_complete_document.pdf

Bégin, Y; Sirois, L; Meunier, C. 2010. The effects of hydroelectric flooding on a reservoir's peripheral forests and newly created forested islands. Pages 241-256 in Stoffel, M; Bollschweiler, M; Butler, DR; Luckman, BH. (Éditeurs). *Tree Rings and Natural Hazards: A State-of-Art.* Springer, Dordrecht, Pays-Bas.

Bendix, J., 1994. Scale, direction, and pattern in riparian vegetation-environment relationships. Annals of the Association of American Geographers 84, 652-665.

Beven, K.J., Kirkby, M.J., 1979. A physically based variable contributing area model. Hydrological Sciences Bulletin 24, 43-69.

Blum, M.D. and Aslan, A. 2006. Signatures of climate vs. sea-level change within incised valley-fill successions: Quaternary examples from the Texas Coastal Plain. Sedimentary Geology 190: 177-211.

Blum, M.D., Morton, R.A., and Durbin, J.M. 1995. "Deweyville" terraces and deposits of the Texas Gulf coastal plain. Gulf Coast Association of Geological Societies Transactions 45: 53-60.Braatne, J.H., Rood, S.B, Heilman, P.E.. 1996. Life history, ecology, and conservation of riparian cootonwoods in North America. In: Seller, R.F. ed. Biology of *Populus* and its implications for management and conservation. Ottawa, ON: National Research Council of Canada, NRC Research Press: 57-85.

Bren, L.J., 1993. Riparian zone, stream, and floodplain issues: a review. Journal of Hydrology 150, 277-299.

Brierley, G.J. and Fryirs, K. 2005. Geomorphology and River Management. Applications of the River Styles Framework. Blackwell, Oxford.

Brinson MM, Rheinhardt RD, Hauser FR, Lee LC, Nutter WL, Smith D, Whigham, D. 1995. A Guidebook for Application of Hydrogeomorphic Assessments to Riverine Wetlands. U.S. Army Corps of Engineers , Wetlands Research Program Tech. Rep. WRP-DE-11.

Brinson, MM. 1993. A Hydrogeomorphic Approach to Wetland Functional Assessment. Technical Report WRP-DE-4. Waterways Experiment Station, U.S. Army Corps of

Bush, JK; Richter, FA; Van Auken, OW. 2006. Two decades of vegetation change on terraces of a south Texas river. *Journal of the Torrey Botanical Society*. 133:280-288.

CLBBASC (Colorado and Lavaca Basin and Bay Area Stakeholder Committee). 2012. Draft work plan. TCEQ. Austin, TX. http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/eflows/20120626clbbasc_draft%20work%20plan.pdf

CLBBASC (Colorado and Lavaca Basin and Bay Area Stakeholder Committee). 2011. Environmental flow regime recommendations report. TCEQ. Austin, TX. http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/eflows/collavbbascreport_82011.pdf

CLBBEST(Colorado and Lavaca Basin and Bay Expert Science Team). 2011. Environmental flow regime recommendations report. TCEQ. Austin, TX. http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/eflows/20110301clbbest_enviroflowreport.pdf

Coffman, D.K., Malstaff, G., Heitmuller, F.T., 2011. Characterization of Geomorphic Units in the Alluvial Valleys and Channels of Gulf Coastal Plain Rivers in Texas, with Examples from the Brazos, Sabine, and Trinity Rivers, 2010. U.S. Geological Survey Scientific Investigations Report 2011-5067. URL: http://pubs.usgs.gov/sir/2011/5067/

Conservation Engineering Division, Natural Resources Conservation Service, 1986. Urban Hydrology for Small Watershed. US Department of Agriculture, Technical Release TR-55. URL: http://www.cpesc.org/reference/tr55.pdf

Crow, P. 2005. The influence of soils and species on tree root depth. *Forestry Commission*. DOI: http://www.efita.org/opensite.html?rec=570&window=new

Danjon, F., Barker, D. , Drexhage, M., Stokes, A. 2008. Using three-dimensional plant root architecture in models of shallow-slope stability. *Annals of Botany* 101:1281-1293.

Decamps, H., R.J. Naiman, and M. M. McClain. 2008. Riparian systems as zones of pervasive anthropogenic stress, in Arizpe, D., A. Mendes, and J.E. Rabaca, eds. Sustainable riparian zones, a management guide. Generalitat Valenciana, Valencia, Spain. http://www.cma.gva.es/webdoc/documento.ashx?id=143055

Dittemore, W.H., Coburn, W.C., 1986. Soil Survey of Kerr County, Texas. U.S. Department of Agriculture, Natural Resource Conservation Service. URL: http://soildatamart.nrcs.usda.gov/Manuscripts/TX265/0/Kerr.pdf

Dosskey, M.G., Helmers, M.J., Eisenhauer, D.E., 2008. A design aid for determining width of filter strips. Journal of Soil and Water Conservation 63, 232-241.

Duke, J.R. 2011. Riparian productivity in relation to stream dynamics along two rivers: San Antonio and Brazos, in Central/South Texas. TWDB. Austin, TX. http://www.twdb.texas.gov/RWPG/rpgm_rpts/100011020_Riparian.pdf

Engineers, Vicksburg, MS.

Fennessy, MS; Jacobs, AD; Kentula, ME. 2004. Review of Rapid Methods for Assessing Wetland Condition. EPA/620/R-04/009, U.S. Environmental Protection Agency, Washington, D.C.

Gardner, W.R., 1991. Soil Science as a Basic Science. Soil Science. 151:2-6.

Groffman, PM; Bain, DJ; Band, LE; Belt, KT; Brush, GS; Grove, JM; Pouyat, RV; Yesilonis, EC; Zipperer, WC. 2003. Down by the riverside: urban riparian ecology. *Frontiers in Ecology and Eviron*. 1:315-321.

GSABBASC (Guadalupe and San Antonio Basin and Bay Area Stakeholder Committee). 2012. Work plan for adaptive management. TCEQ. Austin, TX. http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/eflows/20120525gsabbasc_wpam.pdf

GSABBASC (Guadalupe and San Antonio Basin and Bay Area Stakeholder Committee). 2011. Recommendations report. TCEQ. Austin, TX. http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/eflows/20110901gsabbasc_report.pdf

GSABBEST (Guadalupe and San Antonio Basin and Bay Expert Science Team). 2011. Environmental flows recommendations report. TCEQ. Austin, TX. http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/eflows/20110301guadbbest_transmission.pdf

Gumbricht, T.T., McCarthy, J., and McCarthy, T.S. 2004. Channels, wetlands and islands in the Okavango Delta, Botswana, and their relation to hydrological and sedimentological processes. Earth Surface Processes and Landforms 29: 15-29.

Heilman, P. E., Fogle, D., Ekuan, G. 1994. Above- and below-ground biomass and fine roots of 4-year-old hybrids of *Populus trichocarpa* and *Populus deltoides*. *Canadian Journal of Forest Research*. 24: 1186-1192.

Hudson PF. 2010. Floodplain Lake Formation and Dynamics in the Lower Reaches of the Large Texas Coastal Plain Rivers: Brazos, Guadalupe, and San Antonio Rivers. Austin: Texas Water Development Board, report no. 0600010583: http://www.twdb.state.tx.us/RWPG/rpgm_rpts/IndividualReportPages/0600010583.asp

Hupp, C.R., and Osterkamp, W.R, 1996. Riparian vegetation and fluvial geomorphic processes. Geomorphology 14: 277-295

Hyman, G., Mayfield, M.W., Velasquez, S., 2010. Delineating Effective Riparian Buffer Widths for Water Quality Protection. United Nations Environment Program, URL: http://www.grida.no/prog/global/cgiar/awpack/water.htm (last accessed 10/26/11).

Jenny, H. 1980. Factors of Soil Formation: A System of Quantitative Pedology. Dover Publications (2011 reprint). 320 pp.

Johnson, J.B., 2005. Hydrogeomorphic Wetland Profiling: An Approach to Landscape and Cumulative Impacts Analysis. Washington, U.S. Environmental Protection Agency EPA/620/R-05/001.

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

Junk, WJ; Piedade, MTF. 1997. Plant life in the floodplain with special reference to herbaceous plants. *cited in* Middleton, 2002.

Kondolf, G.M., Piegay, H., 2003. Geomorphic classification of rivers and streams. In Tools in Fluvial Geomorphology (Kondolf, G.M., Piegay, H., eds.). Wiley, Chichester, p.171-204.

Li, S; Prezeshki, SR; Goodwin, S; Shields, FD Jr. 2004. Physiological responses of Black Willow (*Salix nigra*) cuttings to a range of soil moisture regimes. *Photosynthetica* 42:4. 585-590.

Malanson, G.P. 1993. Riparian landscapes. Cambridge University Press. 296 pp.

Middleton, B. 2002. Flood Pulsing in Wetlands. John Wiley and Sons, New York, USA. 308 pp.

Miller, A.J., R.S. McNamee, H.M. Williams, M.W. McBroom, and M.B. Brown. 2010. The Sabine River riparian area: a definition and GIS based methodology for delineation. TWDB. Austin, TX. http://www.twdb.texas.gov/RWPG/rpgm_rpts/0704830783_Riparian%20Ecotone.pdf

Mitchell, B., Williams, D., Butler, D., Griffith, J., 2003. Streamside management zone delineation for control of non-point source pollution. 2003 ESRI User Conference Proceedings, Environmental Systems Research Institute, Inc., URL: http://proceedings.esri.com/library/userconf/proc03/p1034.pdf

Mitsch, W.J. and Gosselink, J.G. 1986. Wetlands. John Wiley & Sons, Inc., New York, NY.

Moore, G., and B. Alldredge. 2011. Sabine River riparian vegetation assessment related to flow modifications. TWDB. Austin, TX. < http://www.twdb.texas.gov/RWPG/rpgm_rpts/ 1004831021_Sabine.pdf>

Moret, S.L., Langford, W.T., and Margineantu, D.D. 2006. Learning to predict channel stability using biogeomorphic features. Ecological Modelling 191: 47-57.

Morton, R.A., Blum, M.D., and White, W.A., 1996, Valley fills of incised coastal plain rivers, southeastern Texas: Transactions of the Gulf Coast Association of Geological Societies, v. 46, 321–331.

Myers, LH. 1989. Riparian area management: inventory and monitoring of riparian areas. TR 1737-3. Bureau of Land Management, BLM/YA/PT-89/022+1737, Service Center, CO. 89 pp.

Naiman, RJ; Decamps, H; McClain, ME. 2005. Riparia, 1st Edition Ecology, Conservation, and Management of Streamside Communities. Elsevier Academic Press. Burlington, MA, USA. 430 pp.

National Resource Council (NRC). 2002. Riparian areas: functions and strategies for management. National Academy of Science. Washington, D.C. 436 pp.

NBBASC (Nueces Basin and Bay Area Stakeholder Committee). 2012. Environmental flows recommendations report. TCEQ. Austin, TX. http://www.tceq.state.tx.us/assets/public/ permitting/watersupply/water_rights/eflows/nuecesbbasc_recommendationsreport.pdf

NBBEST (Nueces Basin and Bay Expert Science Team). 2011. Environmental flows recommendations report. TCEQ. Austin, TX. http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/eflows/20111028nuecesbbest_recommendations.pdf

Newson, M.D., and Newson, C.L, 2000. Geomorphology, ecology, and river channel habitat: mesoscale approaches to basin-scale challenges. Progress in Physical Geography 24: 195-217.

NRC (National Research Council). 2002. Riparian areas: functions and strategies for management. The National Academies Press. Washington, DC. http://books.nap.edu/catalog.php?record_id=10327

Osterkamp, WR; Hupp, CR. 1984. Geomorphic and vegetative characteristics along three northern Virginia streams. *Geological Society of America Bulletin* 95: 1093 -1101.

Osting T, Furnans J, Mathews R. 2004. Surface Connectivity Between Six Oxbow Lakes and the Brazos River, Texas. Austin: Surface Water Resources Division, Texas Water Development Board, www.twdb.state.tx.us.

Ouchi, S. 1985. Response of alluvial rivers to slow active tectonic movement. Geological Society of America Bulletin 96, 504-515.

Papas, P. 2006. The Index of Wetland Condition – Review of wetland assessment methods. The State of Victoria Department of Sustainability and Environment. Melbourne, Australia. 22 pp.

Parsons, M., Thoms, M. and Norris, R. 2002. Australian River Assessment System: Review of Physical River Assessment Methods — A Biological Perspective. Cooperative Research Centre for Freshwater Ecology Monitoring River Health Initiative Technical Report 21. Environment Australia, Canberra.

Pearce, F. 2006. When the Rivers Run Dry - The Defining Crisis of the Twenty-first Century. Beacon Press, Boston, MA, USA. 324 pp.

Pennington, KL; Cech, TV. 2010. Introduction to Water Resources and Environmental Issues. Cambridge University Press, New York, USA. 457 pp.

Phillips, J.D. 1989a. An evaluation of the factors determining the effectiveness of water quality buffer zones. Journal of Hydrology 107: 133-145

Phillips, J.D. 1989b. Nonpoint source pollution control effectiveness of riparian forests along a coastal plain river. Journal of Hydrology 110: 221-237.

Phillips, J.D. 1989c. Evaluation of North Carolina's estuarine shoreline area of environmental concern from a water quality perspective. Coastal Management 17:103-117.

Phillips, J.D. 1996a. Wetland buffers and runoff hydrology. In Wetlands: Buffers, Boundaries, & Gradients (G. Mulamoottil, B.G. Warner, E.A. McBean, eds.). Boca Raton,FL: Lewis Publishers, pp. 207-220.

Phillips, J.D. 1996b. Natural and legal shoreline buffers. In Estuarine Shores (K. Nordstrom, C. Roman, eds.). New York: John Wiley , pp. 449-465.

Phillips, J.D. 2003. Impacts of surface mine valley fills on headwater floods in eastern Kentucky. Environmental Geology 45: 367-380.

Phillips, J.D. 2006. Geomorphic Context, Constraints, and Change in the lower Brazos and Navasota Rivers, Texas. Austin: Texas Instream Flow Program: http://www.twdb.state.tx.us/RWPG/rpfgm_rpts.asp, report no. 0605483564

Phillips, J.D. 2007. Field Data Collection in Support of Geomorphic Classification of in the lower Brazos and Navasota Rivers. Phase 2 of the Project: Geomorphic Context, Constraints, and Change in the lower Brazos and Navasota Rivers, Texas. Austin: Texas Instream Flow Program: http://www.twdb.state.tx.us/RWPG/rpfgm_rpts.asp, report no. 0604830639.

Phillips, J.D. 2008a. Geomorphic Processes, Controls, and Transition Zones in the Middle and Lower Trinity River. Austin: Texas Instream Flow Program: http://www.twdb.state.tx.us/RWPG/rpfgm_rpts.asp, report no. 070483071.

Phillips, J.D. 2008b. Geomorphic Units of the Lower Sabine River. Austin: Texas Instream Flow Program: http://www.twdb.state.tx.us/RWPG/rpfgm_rpts.asp, report no. 0704830782.

Phillips, J.D. 2008c. Geomorphic controls and transition zones in the lower Sabine River. Hydrological Processes 22: 2424-2437.

Phillips, J.D. 2009. Avulsion regimes in southeast Texas rivers. Earth Surface Processes and Landforms 34: 75-87.

Phillips, J.D. 2010. Relative importance of intrinsic, extrinsic, and anthropic factors in the geomorphic zonation of the Trinity River, Texas. Journal of the American Water Resources Association 46: 807-823.

Phillips, J.D. 2011a. Geomorphic Processes, Controls, and Transition Zones in the Guadalupe River. Texas Instream Flow Program: http://www.twdb.state.tx.us/RWPG/rpfgm_rpts.asp, report no. 0904831034.

Phillips, J.D. 2011b. Channel Change Caused by Water and Sediment Distribution in the San Antonio River Deltaic Plain. Guadalupe-Blanco River Authority & Texas Water Development Board: http://www.twdb.state.tx.us/RWPG/rpfgm_rpts.asp, report no. 1004831024.

Phillips, J.D. 2011c. Hydrological connectivity of abandoned channel water bodies on a coastal plain River. River Research and Applications DOI: 10.1002/rra.1586.

Phillips, J.D., Marion, D.A. 2006. The biomechanical effects of trees on soils and regoliths: beyond treethrow. Annals of the Association of American Geographers 96: 233-247.

Phillips, J.D., Slattery, M.C. 2006. Sediment storage, sea level, and sediment delivery to the ocean by coastal plain rivers. Progress in Physical Geography 30: 513-530.

Phillips, J.D., Slattery, M.C. 2008. Antecedent alluvial morphology and sea level controls on form-process transition zones in the lower Trinity River, Texas. River Research and Applications 24: 293-309.

Phillips, J.D., Slattery, M.C., 2007. Downstream trends in discharge, slope, and stream power in a coastal plain river. Journal of Hydrology 334: 290-303.

Phillips, J.D., Slattery, M.C., Musselman, Z.A. 2004. Dam-to-delta sediment inputs and storage in the lower Trinity River, Texas. Geomorphology 62: 17-34.

Prichard, D. (Editor). 1998. Riparian Area Management. Technical Reference 1737-15. U.S. Department of the Interior. Bureau of Land Management, National Applied Resource Sciences Center, P.O. Box 25047, Denver, CO 80225-0047. 126 pp.

Quinn, JM; Brown, PM; Boyce, W; Mackay, S; Taylor, A; Fenton, T. 2001. Riparian zone classification for management of stream water quality and ecosystem health. *Journal of the American Water Resources Association*. 37:1509-1515.

Reed, P.B. 1997. Revision of the National List of Plant Species that Occur in Wetlands. Department of the Interior, U.S. Fish and Wildlife Service. Federal Register Notice 62.

Robertson, K.M., and Augspurger, C.K., 1999. Geomorphic processes and spatial patterns of primary forest succession on the Bogue Chitto River, USA. Journal of Ecology 87: 1052-1063.

Rodriguez, A.B., Anderson, J.B., Simms, A.R. 2005. Terrace inundation as an autocyclic mechanism for parasequence formation: Galveston estuary, Texas, U.S.A. Journal of Sedimentary Research 75: 608-620.

Schaetzel, R., and S. Anderson. 2005. Soils. Genesis and geomorphology. Cambridge

Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., and Broderson, W.D. (editors), 2002. Field book for describing and sampling soils, Version 2.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE. University Press. 817 pp. (available at ftp://ftp-fc.sc.egov.usda.gov/NSSC/Field_Book/FieldBookVer2.pdf).

Schumm, S.A., Dumont, J.F., and Holbrook, J.M., 2000, Active Tectonics and Alluvial Rivers: New York, Cambridge University Press.

Schweingruber, FH. 1996: Tree rings and environment. Paul Haupt Bern. Available at Swiss Federal Institute for Forest, Snow and Landscape Research, CH-8903 Birmensdorf.

Scott, M.L., Friedman, J.M., and Auble, G.T. 1996. Fluvial process and the establishment of bottomland trees. Geomorphology 14: 327-339.

Simpson, BJ. 1999. A Field Guide to Texas Trees. Rowan & Littlefield Publishing Group. Lantham, MD, USA. 372 pp.

Slattery, M.C., Phillips, J.D. 2010. Controls on sediment delivery in coastal plain rivers. Journal of Environmental Management 92: 284-289.

Slattery, M.C., Todd, L.M., Phillips, J.D., Breyer, J.A. 2010. Holocene sediment accretion in the Trinity River delta, Texas, in relation to modern fluvial input. Journal of Soils and Sediments 10: 640-651.

Smith, RD; Ammann, A; Bartoldus, C; Brinson, MM. 1995. An approach for assessing wetland functions using hydrogeomorphic classification, reference wetlands, and functional indices. Technical Report WRP-DE-9. Waterways Experiment Station, U.S.Army Corps of Engineers, Vicksburg, MS.

SNBBASC (Sabine and Neches Basin and Bay Area Stakeholder Committee). 2010a. Recommendations report. TCEQ. Austin, TX. http://www.tceq.state.tx.us/assets/ public/permitting/watersupply/water_rights/ eflows/2010snbbasc_final recommendations.pdf

SNBBASC (Sabine and Neches Basin and Bay Area Stakeholder Committee). 2010b. Work plan. TCEQ. Austin, TX. http://www.tceq.state.tx.us/assets/public/permitting/watersupply/ water_rights/eflows/sabine_neches_work_plan_final_20101206.pdf

SNBBEST (Sabine and Neches Basin and Bay Expert Science Team). 2009. Environmental flows recommendations report. TCEQ. Austin, TX. http://www.tceq.state.tx.us/assets/public/permitting/watersupply/water_rights/eflows/ sn_bbest_recommendationsreport.pdf

Soil Survey Division Staff. 1993. Soil survey manual. Soil Conservation Service. U.S. Department of Agriculture Handbook 18.

Soil Survey Staff (2010). Keys to Soil Taxonomy. 11th Edition. USDA. Natural Resources Conservation Service. (available at: ftp://ftp-fc.sc.egov.usda.gov/ NSSC/ Soil_Taxonomy/keys/ 2010_Keys_to_Soil_Taxonomy.pdf)

Speer, JH. 2010. Fundamentals of Tree-ring Research. The University of Arizona Press, USA. 333 pp.

Stoffel, M; Bollschweiler, M; Butler, DR; Luckman, BH. (Editors). 2010. *Tree Rings and Natural Hazards: A State-of-Art, 1st Edition.* Springer, Dordrecht, Pays-Bas. 505 pp.

Stromberg, JC. 1998. Functional equivalency of saltcedar (*Tamarix chinensis*) and Fremont cottonwood (*Populus fremontii*) along a free-flowing river. *Wetlands* 18: 675-686.

Sylvia, D.A., and Galloway, W.E., 2006, Morphology and stratigraphy of the late Quaternary lower Brazos valley: implications for paleo-climate, discharge, and sediment delivery: Sedimentary Geology, v. 190, p. 159–175.

TAC (Texas Administrative Code). Available online at: http://www.sos.state.tx.us/tac/

Taha, Z.P., and Anderson, J.B., 2008. The influence of valley aggradation and listric normal fauling on styles of river avulsion: a case study of the Brazos River, Texas, USA: Geomorphology, v. 95, p. 429- 488.

TCEQ (Texas Commission on Environmental Quality). 2011. Description of adopted rule, Chapter 298 – Environmental flow standards for surface water, Rule Project No. 2007-049-298-OW. TCEQ, Austin, TX. http://www.tceq.texas.gov/assets/public/legal/rules/ hist_rules/Complete.07s/07049298/07049298_ado_clean.pdf

TCEQ (Texas Commission on Environmental Quality). 2012. Description of adopted rule, Chapter 298 – Environmental flow standards for surface water, Rule Project No. 2011-059-298-OW. TCEQ, Austin, TX. http://www.tceq.texas.gov/assets/public/legal/rules/ hist_rules/Complete.11s/11059298/11059298_ado_clean.pdf

TIFP & BRA (Texas Instream Flow Program and Brazos River Authority). 2010. Instream flow study of the middle and lower Brazos River: Draft study design. TIFP. Austin, TX.

TIFP & SARA (Texas Instream Flow Program and San Antonio River Authority). 2012. Instream flow study of the lower San Antonio River and lower Cibolo Creek: Study design. TIFP. Austin, TX. http://www.sara-tx.org/public_resources/library/documents/ water_quality_monitoring/LSAR_Study_Design_March12.pdf

TIFP & SARA (Texas Instream Flow Program and San Antonio River Authority). 2011. Instream flow study of the lower San Antonio River and lower Cibolo Creek: Interim progress report and instream flow recommendations. TIFP. Austin, TX. http://www.sara-tx.org/ public_resources/library/documents/LSAR_FINAL_INTERIM_REPORT_20110831.pdf

TIFP (Texas Instream Flow Program). 2008. Texas instream flow studies: technical overview. TWDB Report 369. Austin, TX. http://www.twdb.state.tx.us/publications/reports/ numbered_reports/doc/R369_InstreamFlows.pdf

TNRIS. 2013. Texas National Resource Information System part of the Texas Water Development Board. www.tnris.org. Accessed 07 May 2013.

TRG (Technical Review Group). 2008. Review of desk-top methods for establishing environmental flows in Texas rivers and streams. Final report to TCEQ. TCEQ, Austin, TX. http://www. tceq.texas.gov/assets/public/permitting/watersupply/water_rights/txefsacdesktop.pdf

TSJBBASC (Trinity and San Jacinto Basin and Bay Area Stakeholder Committee). 2012. Work plan report. TCEQ. Austin, TX. http://www.tceq.state.tx.us/assets/public/permitting/ watersupply/water_rights/eflows/ trinity_san_jacinto_bbasc_workplan_final.pdf

TSJBBASC (Trinity and San Jacinto Basin and Bay Area Stakeholder Committee). 2010. Recommendations report. TCEQ. Austin, TX. http://www.tceq.state.tx.us/assets/ public/permitting/watersupply/water_rights/eflows/ tsjbbasc2finalreport_conditional.pdf

TSJBBASC (Trinity and San Jacinto Basin and Bay Expert Science Team). 2009. Environmental flows recommendations report. TCEQ. Austin, TX. http://www.tceq.state.tx.us/assets/ public/permitting/watersupply/water_rights/eflows/trinity_sanjacinto_bbestrecommendationsreport.pdf

TWDB (Texas Water Development Board). 2012. Water for Texas: 2012: State water plan. TWDB. Austin, TX. http://www.twdb.texas.gov/waterplanning/swp/2012/USDA Forest Service. 2013. Fire Effects Information System online database. http://www.fs.fed.us/database/feis/plants/trees. Last modified April 2, 2013.

URGBBEST (Upper Rio Grande Basin and Bay Expert Science Team). 2012. Environmental flows recommendations report. TCEQ. Austin, TX. http://www.tceq.state.tx.us/assets/public/ permitting/watersupply/water_rights/eflows/urgbbest_finalreport.pdf

U.S. Department of Agriculture Natural Resource Conservation Service (USDA NRCS). 1991. General Manual, 190-GM, part 411. Washington, D.C. USDA NRCS.

Verry, ES; Dolloff, CA; Manning, ME. 2004. Riparian ecotone: a functional definition and delineation for resource assessment. *Water, Air and Soil Pollution: Focus.* 4:67-94.White, J. D., Running, S. W., Ryan, K. C., Key, C. C.. 2002. Fuzzy Logic Merger of Spectral and Ecological Information for Improved Montane Forest Mapping. *Geocarto International* 17: 59-66.

Williams, H.M., Miller, A.J., McNamee, R.S., Klimas, C.V., 2010. A Regional Guidebook for Applying the Hydrogeomorphic Approach to the Functional Assessment of Forested Wetlands in Alluvial Valleys of East Texas. U.S. Army Corps of Engineers Environmental Laboratory ERDC/EL TR-10-17. URL: http://el.erdc.usace.army.mil/elpubs/pdf/trel10-17.pdf

Wrede, J. 2005. Trees, Shrubs, and Vines aof the Texas Hill Country. Texas A&M University Press, College Station, TX, USA. 246 pp.

Xiang, W.-N., 1993a. Application of a GIS-based stream buffer generation model to environmental policy evaluation. Environmental Management 17, 817-827.

Xiang, W.-N., 1993b. A GIS method for riparian water quality buffer generation. International Journal of Geographical Information Systems 7, 57-70.

Yanosky, TM: Jarrett, RD. 2001. Dendrochronologic evidence for the frequency and magnitude of paleofloods. In: Ancient Floods, Modern Hazards: Principles and Application of Paleoflood Hydrology. *Water Science and Application*. 5:77-89.

Yuste, J.A.F., and C.M. Santa-Maria. 2008. Basic river-restoration principles, in Arizpe, D., A. Mendes, and J.E. Rabaca, eds. Sustainable riparian zones, a management guide. Generalitat Valenciana, Valencia, Spain. http://www.cma.gva.es/webdoc/documento.ashx?id=143055

Zaimes, G., Nichols, M., and Green, D. 2007. Characterization of riparian areas: pages 15-29, *In* George Zaimes (ed), Understanding Arizona'a Riparian Areas. The University of Arizona: Arizona Cooperative Extension AZ 1432. 110 pp.