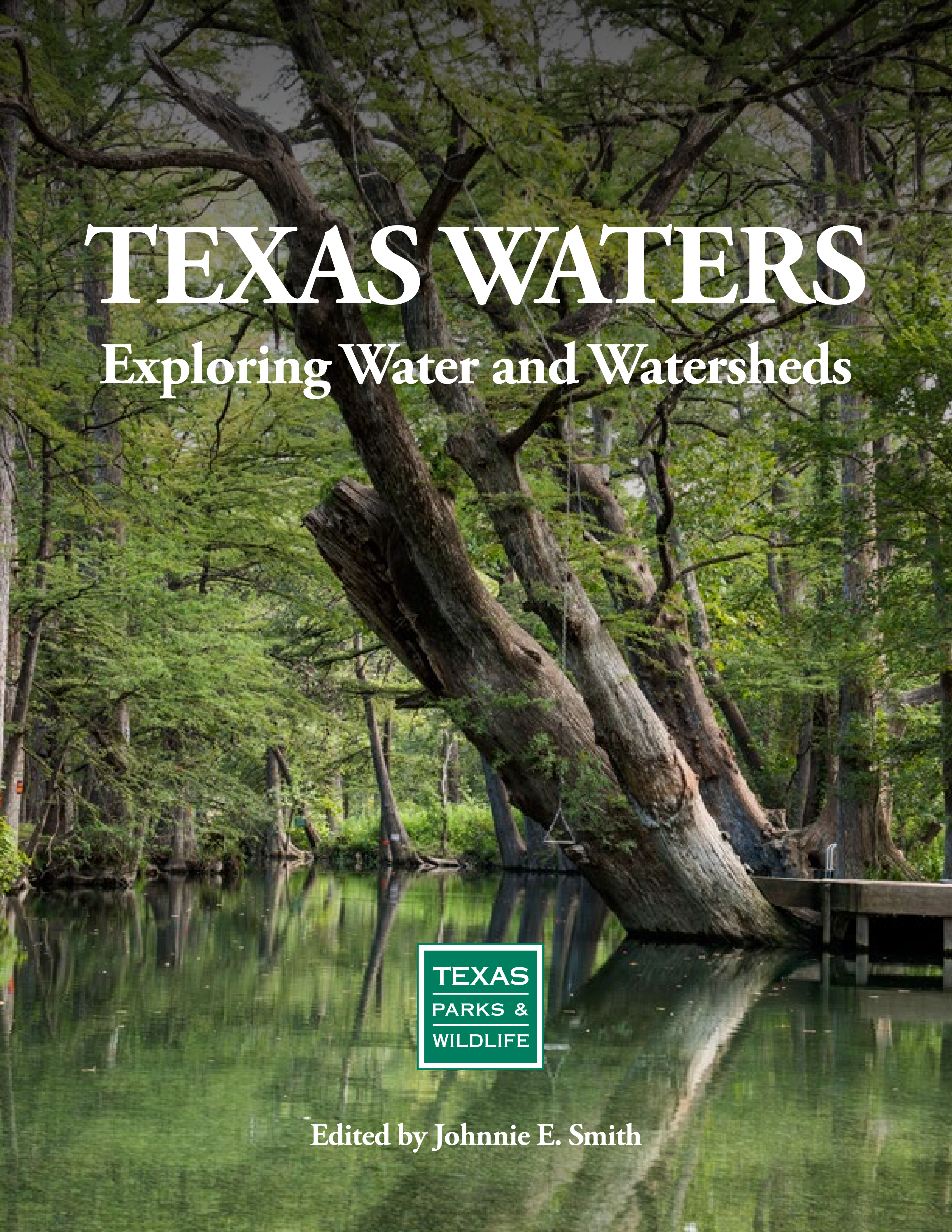


TEXAS WATERS

Exploring Water and Watersheds

TEXAS PARKS & WILDLIFE

Edited by Johnnie E. Smith

TEXAS WATERS
Exploring Water and Watersheds

EDITED BY JOHNNIE SMITH

TEXAS PARKS & WILDLIFE

About the Texas Waters Curriculum Project

This project's aim is to inform and educate the citizens of Texas about the most precious natural resource Texas possesses, its water. Many challenges face our state concerning water, in particular in our aquatic habitats, the water for wildlife. Texas Parks and Wildlife wants you to know that we value the natural and cultural resources of Texas and want there to always be drinkable, swimmable, and fishable waters in our great state.

The curriculum was adapted and edited by Johnnie Smith, Texas Parks and Wildlife Conservation Education Manager. Nancy Herron, Outreach and Education Director for Texas Parks and Wildlife Department, provided leadership, direction, as well as content review. The Texas Waters curriculum project was funded by the Sport Fish Restoration Program of the U.S. Fish and Wildlife Service (USFWS).

The information, drawings, photos and/or other content in this curriculum can be used for noncommercial and/or educational purposes as long as they are not reproduced for sale or presented as original works. Credit lines must be maintained if already displayed in this curriculum. Organizations seeking to use drawings, artwork, or photos that were used by this curriculum with specific permission must obtain their own permission from the source. Reproduced information that is utilized verbatim should be credited as follows: "Information courtesy of Texas Parks and Wildlife: Texas Waters."

In accordance with Texas State Depository Law, this publication is available at the Texas State Publications Clearinghouse and/or Texas Depository Libraries.

10 9 8 7 6 5 4 3 2

Acknowledgements

The Texas Waters Curriculum project was funded by the Sport Fish Restoration Program of the U.S. Fish and Wildlife Service and was made possible through the support and contributions of several agencies and many individuals. Special thanks go to the U.S. Environmental Protection Agency who granted permission to use and adapt their Watershed Academy Web materials for this project.. This content was the primary source for Texas Waters. In addition, the Texas A&M Agrilife Extension Service's *Texas Watershed Steward's Handbook*, the Texas Water Development Board's State Water Plan, the Missouri Department of Conservation, and the U.S. Global Change Research Program's 2014 National Climate Assessment all granted permission to use and/or adapt materials for this project.

Thanks go out to the American Institute of Biological Sciences, Baylor University, Canadian Science Publishing, the City of Austin, the Guadalupe-Blanco River Authority, the Lower Colorado River Authority, the National Water Management Center, the Texas Agrilife Extension Service, the Texas Parks and Wildlife Department, the Texas Water Development Board, The Groundwater Foundation, The Meadows Center for Water and the Environment, the U. S. Geological Survey, the U.S. Global Change Research Program, and Zara Environmental, LLC.

Additional contributors and reviewers include:

Sally Alderman
R. D. Bartlett
Dr. Timothy Beardsley
Nathan Bendik
Lisa Benton
John Botros
Kathryn Burger
Dee Ann Chamberlain
Stephen Curtis
Chase Fountain
Robin Gary
Julia Gregory
Tom Harvey
Nancy Herron
Gordon Linam
Cindy Loeffler
Dr. Sandra Johnson
Cindy Kreifels
Dr. Jean Krejca
Genevieve Lung
Stephan Magnelia
Marsha May
Kira McEntire
Monica McGarrity
Temple McKinnon
Wyman Meinzer
Melissa Mullins
Earl Nottingham
Tulsi Oberbeck
Dr. Howard Perlman
Rima Petrossian
Thera Pritchard
Dr. Larry Redmon
Katie Reeves
Clint Robertson
Dr. Rudolph Rosen
Joshua Schauer
Cappy Smith
Jan Surface
Valerie Taber
Cinde Thomas-Jimenez
Dr. Kevin Wagner
Dr. Mark Wentzel

Introduction

Texas' hydrology seems to be an ongoing cycle of feast or famine. The National Drought Mitigation Center calls this pattern of flood and drought the "Hydroillogical Cycle." Public awareness and a willingness to conserve water is most evident when strict water conservation efforts are in place and the drought is regularly in the news. But, when lake levels and aquifers run high, water use and conservation no longer makes headlines.

Sadly, water awareness in Texas is not as "top-of-mind" as we wish it were. Although studies show that knowing the source of one's drinking water is one of the greatest predictors of water conservation practices, in a 2014 statewide survey conducted by the Texas Water Foundation, only 28 percent of Texans indicated they "definitely know" the source of their drinking water.

In addition, most Texans don't pay for the true value of their water. At most, they pay for water infrastructure and the cost of delivery. In fact, many Texans pay more for their cell phone plan than they do for the life sustaining water that is readily available at their faucet. At times, it seems our priorities are a bit out of whack.

Our economy, our natural ecosystems, and our very way of life in Texas are reliant on fishable, swimmable, drinkable water. We need water that is available in sufficient quantities to sustain life, not only in our urban centers, but also in the rural Texas countryside. Perhaps more importantly, Texas needs clean water, in the right amounts, with seasonal variability to sustain the diverse aquatic ecosystems throughout our great state.

I hope you'll find the contents of this curriculum challenging and enlightening, encouraging and empowering. I hope that you'll take away a new understanding of Texas Waters, from the nuts and bolts of the individual watershed and ecosystem structures, to the big picture of how they all tie together to create the beautiful mosaic that is Texas. Mostly, I want to inspire your appreciation and love of the outdoors, and create in you a willingness to protect and conserve it.

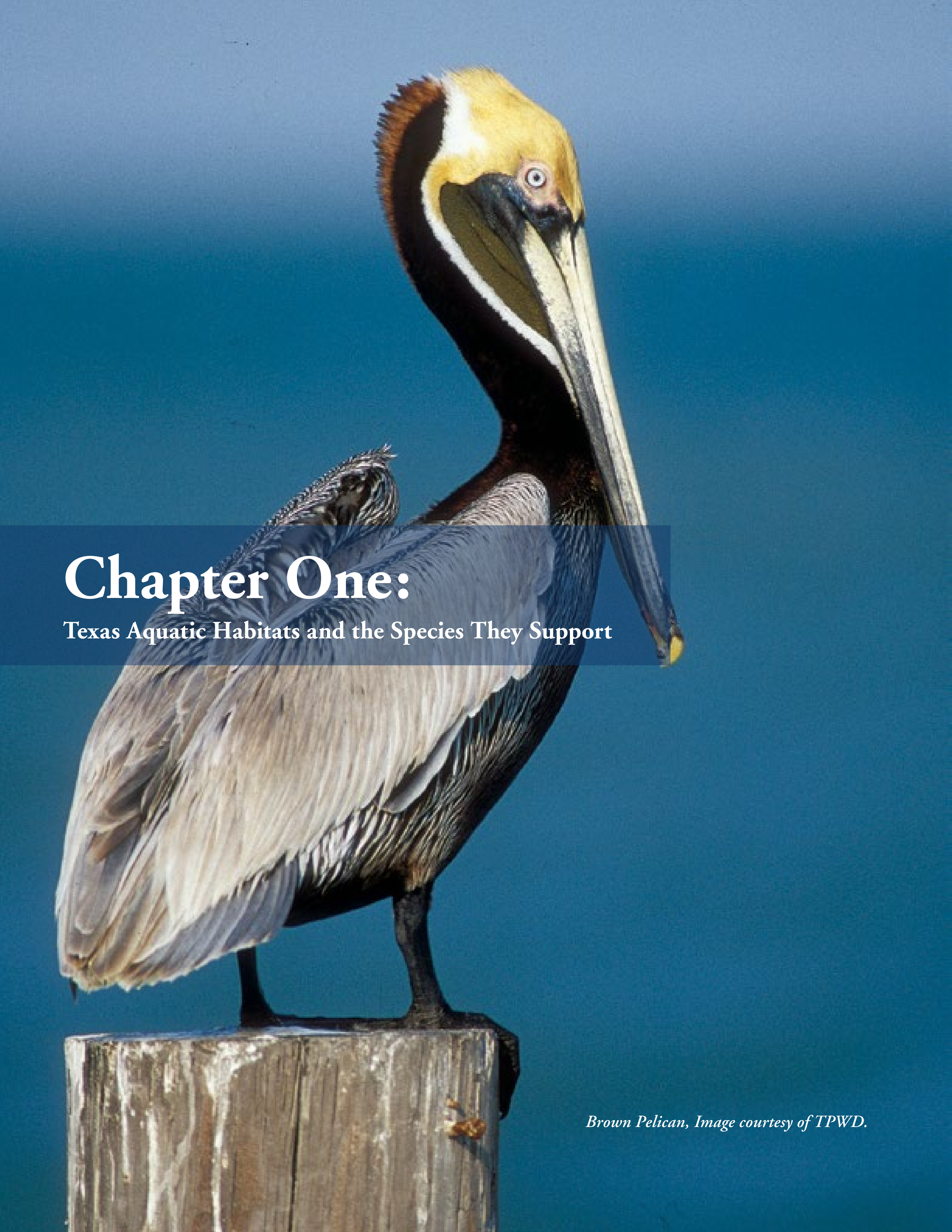
Johnnie E. Smith

Conservation Education Manager,
Texas Parks and Wildlife (TPWD)

Table of Contents

Chapter One:

Texas Aquatic Habitats and the Species They Support



Brown Pelican, Image courtesy of TPWD.

Chapter One:
Texas Aquatic Habitats and the Species They Support

Questions to Consider

- What types of **aquatic ecosystems** are present in Texas?
- What is the relationship between **aquifers**, **springs**, and **surface water**?
- Why are species, found in the habitat of springs, so sensitive to environmental changes?
- How do you know a **wetland** is a wetland?

Introduction

The longest journey begins with a single step. You've begun such a journey here to learn about Texas Waters and Watersheds. As this curriculum progresses, we'll explore the many nuances of watersheds and ecosystems, their ecological significance, and the tremendous value that Texas aquatic habitats represent in our natural world and to human society.

As you move through the curriculum, you'll see some terms in **bold**; these are especially important to your understanding of Texas Waters and Watersheds and can be found in the glossary. Let's begin your journey with a discussion of aquatic habitats. Texas has a rich array of aquatic habitats. They include lakes, reservoirs, and fresh and saltwater wetlands. There are bays, marshes, and estuaries, rivers, streams, creeks, and springs. These habitats support a huge diversity of plants and animals, sustain the Texas economy, and provide recreational opportunities for Texans of all ages. This chapter sets the stage for the rest of your learning about Texas Waters and Watersheds. We'll explore each of these habitats and for each, we'll present a few of the unique species they support and their significance in the habitat. We begin with a look at rivers and streams.

Figure 1.1 - The Rio Grande at Big Bend Ranch State Park. Image courtesy of TPWD.

Rivers and Streams

Texas has more than 3,700 named streams and 15 major rivers. They wind through 191,000 miles of Texas landscape. These aquatic ecosystems provide invaluable ecosystem services such as nourishing watersheds with water and nutrients, assimilating waste, and providing fish and wildlife habitat. In addition, each year these habitats provide recreational opportunities to millions of Texans and visitors from all over the world.

We depend on our rivers to provide wildlife habitat, safe drinking water, irrigation for agriculture, and recreation for millions of Texans. The burden that we place on our state's drainage basins can lead to water quality degradation and reduced environmental flows. In fact some Texas river and stream segments do suffer from water quality and water quantity (flow) issues. In coming chapters, you'll learn how various state and non-governmental agencies work to ensure swimmable, drinkable, fishable water across our state. Streams receive water as runoff from precipitation, or from groundwater spring flow or seeps. These streams then converge to form larger rivers and thus play a major role in the form and structure of a watershed. Now we'll look at some of the species our rivers and streams support.

Species as Indicators of Stream Health

Many species rely on life sustaining levels of water quality and quantity in our Texas rivers. In one way or another, they are uniquely adapted to the habitat in which they live. These adaptations create a wealth of **biodiversity** in aquatic plant and animal species across the state. Because of this, Texas and/or the Federal government list a number of these species as threatened or endangered. This chapter highlights several of these protected organisms in addition to some of the more common and/or unique species. Find the full list of threatened and/or endangered species at http://tpwd.texas.gov/huntwild/wild/wildlife_diversity/nongame/listed-species/

White Bass

White Bass are an important reservoir sport fish species that make a spring spawning migration into rivers above major reservoirs. Their spawning behavior relies heavily on the early spring rains and the resulting high impulse flows. You will learn more about natural flow regimes and their ecological significance in **chapter five**. Schools of males migrate upstream to spawning areas as much as a month before females. There is no nest preparation. Spawning occurs either near the surface, or in midwater. Running water with a gravel or rock substrate is preferred. Females rise to the surface and as they release eggs several males crowd around and release sperm. Large females can sometimes release nearly a million eggs during the spawning season. Eggs sink to the bottom and adhere to the substrate. Eggs hatch in 2-3 days and fry grow rapidly, feeding on small invertebrates. White Bass may grow eight or nine inches during the first year. Adult White Bass school and feed near the surface where they find fish, crustaceans, and emerging insects in abundance. Gizzard and threadfin shad are preferred food items. White Bass more than four years of age are rare. White Bass are the fifth most preferred species among licensed Texas anglers. Much of the fishing for White Bass is done during their spawning migration when they are concentrated in rivers above reservoirs.

Figure 1.2 - White Bass. Image courtesy of TPWD.

Smalleye and Sharpnose Shiners

The Smalleye and Sharpnose Shiner are found nowhere in the world other than the upper Brazos River in Texas. Historically, they were common throughout the entire Brazos River system, but hydraulic alteration (e.g., dams, water diversions) and drought have dealt them near-fatal blows. A string of dams in the mid-section of the Brazos River took away the ability of the species' semi buoyant eggs to drift downstream for 50 or more miles while they hatch and grow into small fry. During the intense drought of 2011 the Upper Brazos—the Salt Fork, the Double Mountain Fork and the North Fork of the Double Mountain Fork—stopped flowing. Habitat for endangered smalleye shiner and sharpnose shiner dwindled to small intermittent pools. Scientists from the Texas Parks and Wildlife Department (TPWD) and Texas Tech University collected both species and transported them to the Possum Kingdom Fish Hatchery. They were held for future restocking, should the upper river become completely dry. The following May TPWD released smalleye and sharpnose shiners into the lower Brazos River near Hearne, Texas, as part of an experiment to see if they could become re-established in the lower river. This species is a historic resident there, but has not been documented for several decades. Streamflows in the upper Brazos have since recovered from the drought of 2011, and there has been successful spawning and some increase in the abundance of both species of shiners. However, the U.S. Fish and Wildlife Service recently listed the two species as endangered and designated habitat in the upper Brazos River as critical. Details on the listing are available on the USFWS website; https://www.fws.gov/southwest/es/arlingtontexas/shiner.htm.

Figure 1.3 - Texas Fawnsfoot Mussel, views of the inner and outer shell. Images courtesy of Clint Robertson.

Texas Fawnsfoot Mussel

Freshwater mussels are some of the most imperiled organisms in the United States. Texas hosts more than 50 species of native freshwater mussels. Because scientists have only recently become aware of the severe decline in mussel populations, some species may have become extinct before their decline could be documented. Currently, Texas lists 15 mussel species as threatened. Six of those 15 species are now candidates for listing under the U.S. Endangered Species Act. The Texas Fawnsfoot is included in this list of candidate species. This species is **endemic** to the Colorado and Brazos River watersheds of Texas.

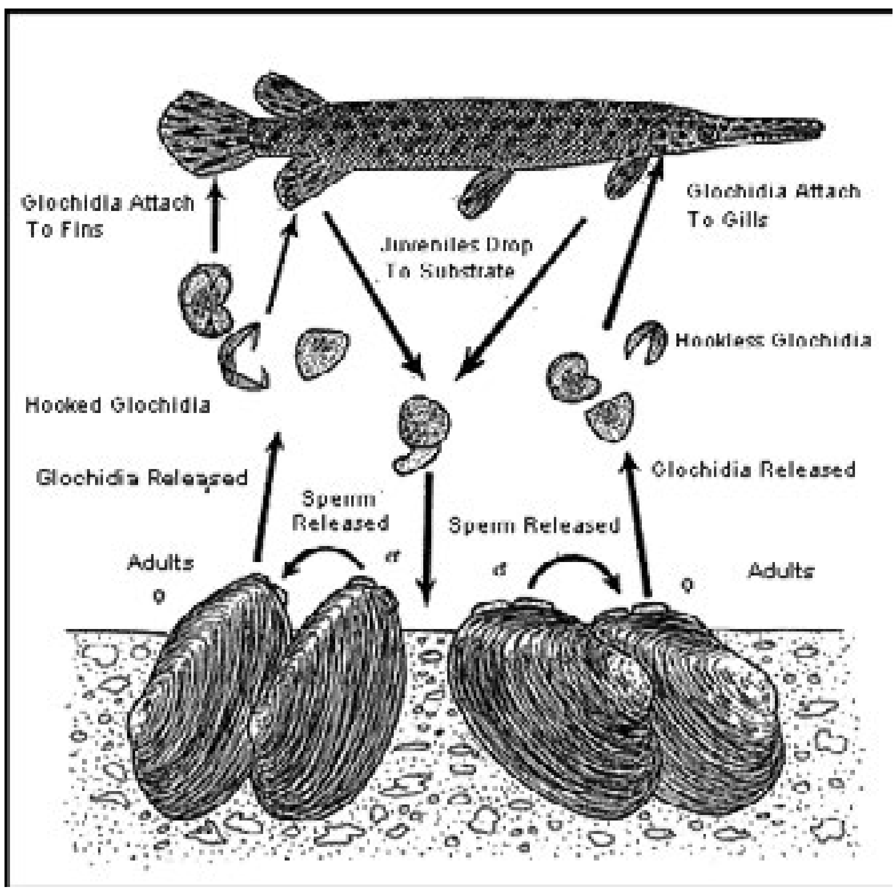


Figure 1.4 - Mussel life cycle. Image courtesy of TPWD.

Freshwater mussels like the Texas Fawnsfoot feed by filtering algae and small particles from the water. The life cycle of freshwater mussels is unique. The larvae, called glochidia, are dependent upon fish in order to grow and survive. Female mussels full of glochidia attract host fish using elaborate lures. When the fish gets close, the female releases the glochidia, which then attach to the fish, typically on the gills or fins, where they remain for a few weeks or months.

Larval mussels rarely harm infected fish under natural conditions. When they become juveniles, they drop back to the substrate for the cycle to begin again. If too many of the essential, target fish species (those used for mussel reproduction) are removed from the habitat, mussels will not be able to reproduce. It is currently unknown which host fish the Texas Fawnsfoot use; however, it is believed that freshwater drum are at least one of the host fish for this mussel species.

Mussels are often the first species to vanish when environmental conditions change or decline, and are therefore good indicators of changes in the aquatic environment. As filter feeders, mussels concentrate substances dissolved in the water in their bodies. Scientists examine mussel tissues to check for many toxic chemical pollutants of our rivers, lakes, and streams. Healthy mussel populations mean purer water for humans and countless aquatic plants and animals. Reasons for decline in freshwater mussel populations include:

- Changes in flow rates of rivers and streams due to droughts, floods, or building of dams;
- Increased deposition of soft silt due to excessive run-off;
- Scouring of stream beds during storm events;
- Increased amounts of aquatic vegetation;
- Lack of suitable native fish hosts for larval stage;
- Aquatic contaminants; and,
- Introduction of exotic species.

Freshwater mussels (unionids) are an important component of healthy aquatic ecosystems, both as a food source for many other aquatic and terrestrial creatures, and as key indicators of water quality and habitat health. In early life stages, mussels are food for a variety of aquatic insects, small fishes, and water birds; as they mature, they become food sources for larger fishes, waterfowl, and terrestrial animals. Ultimately, their protection helps preserve and enhance the hunting, fishing, and outdoor recreation opportunities that are part of Texas natural heritage.

Interior Least Tern

The Interior Least Tern is a migratory shoreline bird that breeds along inland river systems in the United States and winters on the Central American coast and the northern coast of South America. Historically, the birds bred on sandbars from Texas to Montana and from eastern Colorado and New Mexico to southern Indiana. Today, the Interior Least Tern continues to breed in most of the major river systems, but its distribution is generally restricted to the less altered and more natural or little-disturbed river segments.

Channelization, water withdrawals, and the construction of dams and reservoirs have contributed to the elimination of much of the tern's natural nesting habitat. Discharges from dams built along these river systems pose additional problems for the birds nesting in the remaining habitat. The nesting habits of the Interior Least Tern evolved to coincide with natural declines in river flows. Today, flow regimes in many rivers differ greatly from historic regimes due to many factors, perhaps the most significant of which is damming of rivers to create reservoirs. High flow periods may now extend into the normal nesting period, there-

Figure 1.5 - Interior Least Tern. Image courtesy of TPWD.

by reducing the availability of quality nest sites and forcing terns to nest in less-than-optimum locations. Extreme fluctuations can inundate potential nesting areas, flood existing nests, and dry out feeding areas.

Historical flood regimes (volume and timing of floods) scoured areas of vegetation, creating and maintaining habitat. However, depletion of river flows into reservoirs has resulted in encroachment of invasive vegetation and reduced channel width along many rivers, thereby reducing sandbar habitat formation. Reservoirs also trap much of the sediment load, further limiting formation of suitable sandbar habitat. You will learn more about flows, **impoundments**, and human caused change in watersheds in **chapter eight**.

In Texas and elsewhere, rivers are often the focus of recreational activities. For many inland residents, sandbars are the recreational counterpart of coastal beaches. Activities such as fishing, camping, and all-terrain vehicle use on and near sandbar habitat are potential threats to nesting terns. Even sand and gravel pits, reservoirs, and other artificial nesting sites receive a high level of human use. Studies have shown that human presence reduces reproductive success, and human disturbance remains a threat throughout the bird's range.

Water pollution from pesticides and irrigation runoff is another potential threat. Pollutants entering rivers upstream and within breeding areas can adversely affect water quality and fish populations in tern feeding areas. By eating contaminated fish, Least Terns accumulate contaminants that may affect reproduction and chick survival. Least Terns throughout their range test positive for mercury, selenium, pesticides, and industrial chemicals called polychlorinated biphenyls (PCBs) at levels warranting concern, yet with no known reproductive difficulties reported thus far.

Finally, too little water in some river channels may be a common problem that reduces the birds' food supply and increases access to nesting areas by humans and predators. Potential predators include coyotes, gray foxes, raccoons, domestic dogs and cats, raptors, American Crows, Great Egrets, and Great Blue Herons. Both the state and federal authorities list the Interior Least tern as endangered.[1]

Bald Eagle

As a top predator, the Bald Eagle is one of nature's most impressive birds of prey. Since they prey on many fish, fowl, and mammals in aquatic habitats, they provide a unique view of aquatic habitat health.

Males generally measure 3 feet from head to tail, weigh 7 to 10 pounds, and have a wingspan of 6 to 7 feet. Females are larger, some reaching 14 pounds with a wingspan of up to 8 feet. In Texas, Bald Eagles nest from October to July. Peak egg-laying occurs in December, with hatching primarily in January. The female lays a clutch of 1 to 3 eggs, but the usual clutch is 2 eggs. A second clutch may be laid if the first is lost. Incubation begins when the first egg is laid and usually lasts 34 to 36 days. The young generally fledge (fly from the nest) in 11 to 12 weeks, but the adults continue to feed them for another 4 to 6 weeks while they learn to hunt. When they are on their own, young Bald Eagles migrate northward out of Texas, returning by September or October.

Habitat loss and pesticide intake are the factors most consistently associated with declines in Bald Eagle populations. The ultimate threat to Bald Eagles is habitat loss caused by human expansion into historical nesting and foraging habitat.

Historically, the most dramatic declines in Bald Eagle populations nationwide resulted from environmental contaminants. Beginning in 1947, reproductive success in many areas of the country declined sharply, and remained at very low levels through the early 1970s. After several years of study, scientists linked the low reproduction of Bald Eagles and many other birds to widespread use of the insecticides DDT (dichlorodiphenyltrichloroethane) and dieldren. These insecticides saw extensive use in agriculture and forestry beginning in 1947. As DDT entered watersheds, it became part of the aquatic food chain, and was stored

Figure 1.6 - Bald Eagle in nest, calling. Image courtesy of TPWD.

as DDE (dichlorodiphenyldichloroethylene) in the fatty tissue of fish and waterfowl. As eagles and other birds of prey fed on these animals, they accumulated DDE in their systems.

Although it occasionally caused death, DDE mainly affected reproduction. Some birds affected by the chemical failed to lay eggs, and many produced thin eggshells that broke during incubation. Eggs that did not break were often addled or contained dead embryos, and the young that hatched often died. Unlike DDT, dieldren killed eagles directly rather than causing thin eggshells; however, DDT was likely the most significant factor in overall Bald Eagle declines. In 1972, the Environmental Protection Agency (EPA) banned the use of DDT in the United States. Since the ban, DDE residues in Bald Eagle eggshells have dropped significantly, and a slow recovery of eagle productivity has occurred. Most populations appear to be producing chicks at the expected rate.

After decades of conservation efforts, the Bald Eagle was removed from the Federal Endangered Species list in 2007. The eagles experienced a dramatic improvement from barely 400 nesting pairs in the lower 48 states in 1963 to nearly 10,000 nesting pairs at the time of de-listing. Due to ongoing challenges in the areas of habitat destruction, Texas lists the Bald Eagle as threatened.[2]

Since 1981, the Texas Parks and Wildlife Department has conducted extensive aerial surveys to monitor Bald Eagle nesting activity. The 2005 survey identified 160 active nests, which fledged at least 204 young. This compares with only five known nest sites in 1971. These numbers show encouraging trends for Texas. A conservation success story, the Bald Eagle's recovery serves as an example of how things can be turned around. With continued vigilance, protection, and informed management, today's Texans can insure that future generations will have the opportunity to enjoy the sight of our majestic national symbol - the only eagle unique to North America.

Beaver

Beavers are a semi-aquatic species, dependent on water and sensitive to human caused changes in aquatic habitats. They are a **keystone species**, with their presence and activities greatly affecting other wildlife. You will learn more about this concept in **chapter two**. They build dams and create wetlands, making new habitat on which other species depend. Beavers live throughout Texas, in streams, ponds, and lakes, but mainly in the eastern half of the state and along the Rio Grande. They construct houses of sticks, logs, and mud or burrow in banks. They also build dams, which serve to slow down water flow and create niche habitats for a variety of aquatic-dependent organisms. Although beavers have many natural predators, their largest threats are associated with human activity. Water pollution and habitat loss are the most common factors that negatively affect beaver populations.

Figure 1.7 - Beaver at Abilene SP. Image courtesy of TPWD.

Aquifers and Springs[3]

Rivers and streams are perhaps the most visible of our surface water features in the state, but since groundwater is such a huge portion of Texas' water supplies, let's now look into our next Texas Aquatic habitat, aquifers and springs.

An **aquifer** is an underground layer of **permeable** rock or sand. Aquifers collect, hold, and conduct water. The materials act like underground sponges allowing water to flow very slowly through it. Water in an aquifer is groundwater. Many aquifers are like reservoirs because they store water useful to humans and **aquatic ecosystems**.

Aquifers vary in size, from narrow to wide, and may be hundreds of feet thick. They may span one to two counties, or may stretch across thousands of square miles and several states. When precipitation falls on the land and seeps into the ground it recharges, or refills aquifers. They give rise to Texas streams and rivers where springs form headwaters. People also drill wells into the aquifer to pump groundwater to the surface to use for drinking, irrigation, or industrial purposes.

In some places, groundwater emerges from an aquifer as springs. When an aquifer's **water table** reaches the surface, groundwater releases as **surface water** into **rivers** and **lakes**.

Aquifers

Most of Texas' land surface lies above aquifers, some large and some small. There are nine major aquifers (Fig. 1.8) and 21 minor aquifers (Fig. 1.10) in Texas. A major aquifer contains large amounts of water spread across a large area. Minor aquifers contain smaller amounts of water spread over large areas, or larger amounts of water spread over small areas.

Aquifers are an important source of water for humans, supplying about 60% of the water we use. Most of the water pumped from aquifers goes to agriculture to irrigate food crops. Over 80% of the irrigation water used in Texas comes from one aquifer: the Ogallala. The largest aquifer in the United States, the Ogallala stretches from South Dakota southward into Texas. It underlies much of Texas' High Plains region. This aquifer's thickness averages 95 feet, although it can be over 800 feet thick in some places.

The groundwater in some aquifers can be ancient. The Ogallala aquifer formed about 2 to 6 million years ago. Groundwater can also be very new. Water that

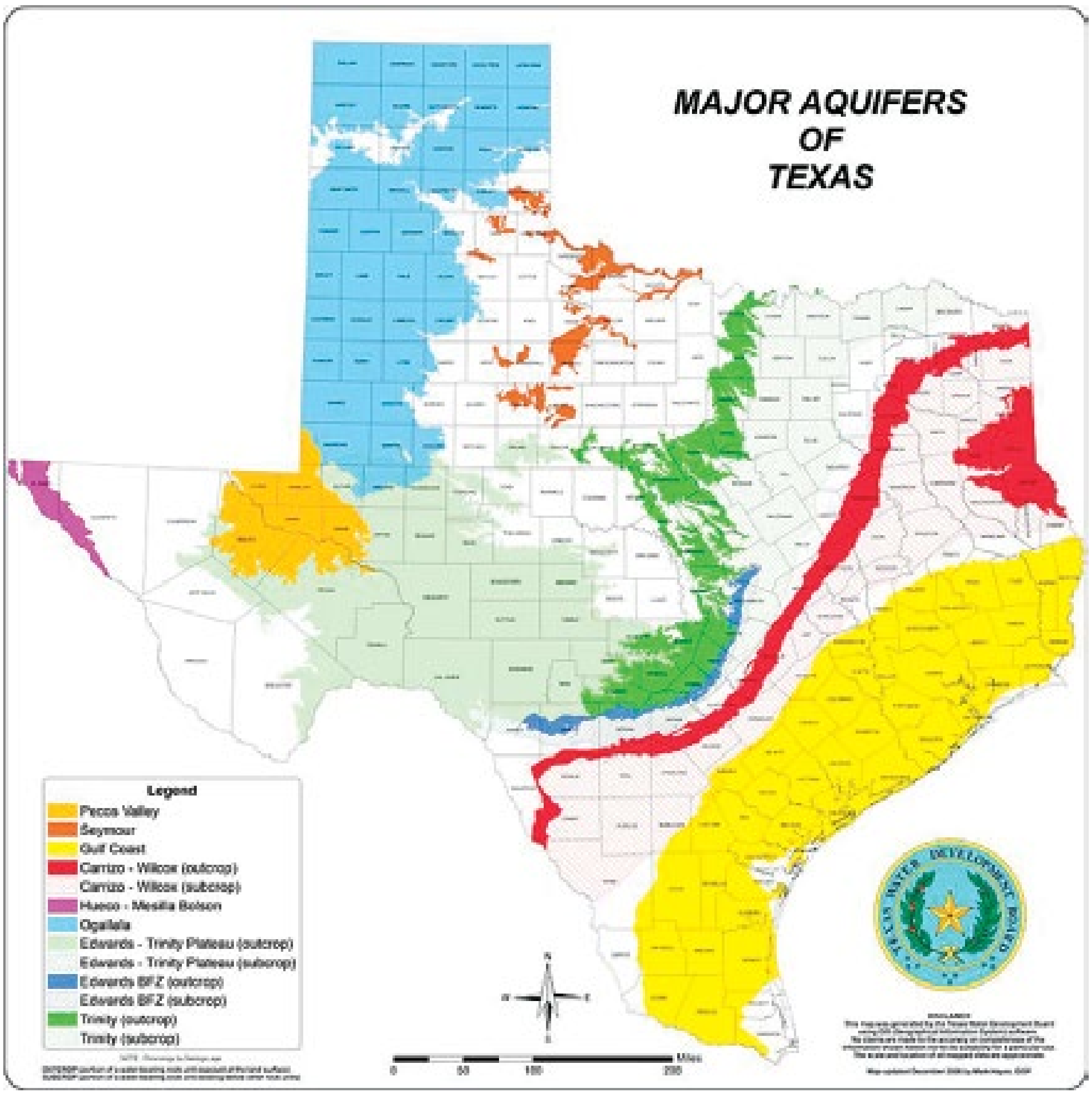


Figure 1.8 - Major Aquifers of Texas. Image courtesy of TWDB.

falls as rain and enters the Edwards Aquifer near San Marcos emerges from springs a few days or even hours later. Groundwater can flow like a river through large openings in the underground limestone that forms this aquifer. For example, parts of the Edwards aquifer are like a giant underwater cave system.

Texas has three kinds of aquifers

Unconfined aquifers are connected directly to the surface and have water levels dependent on relatively constant recharge. Groundwater flows to the surface whenever the aquifer's upper **saturated** layer, called the water table, rises to the level of the land's surface. Perhaps the best-known unconfined aquifer is the Ogallala. In many places, this aquifer is near the surface. Its recharge depends on water that collects at the surface in wetlands. As much as 95% of the recharge water in Texas' portion of the Ogallala comes from **playa lakes**. A playa lake is a naturally occurring wetland (averaging about 17 acres). They form when rain fills small depressions in the prairie. There are about 20,000 playa lakes in the High Plains of Texas.

Confined aquifers are saturated layers of pervious rock bounded above and below by largely **impervious** rock. Water can't pass through this rock. This placement of the aquifer between impervious rock layers can "squeeze" the groundwater, placing it under pressure. A confined aquifer containing water under pressure is an **artesian aquifer**. Artesian flow feeds many of Texas' famous springs, including San Solomon Springs in West Texas and Texas' largest springs, the Comal Springs in New Braunfels. Artesian pressure can be so great that groundwater pushes up all the way to the surface without the need for well pumps.

Karst aquifers exist in limestone and marble rock. Over long periods, water can dissolve these two types of rock. This can form large holes, channels, and even large underground caverns, lakes, and streams. One of the most famous aquifers in the world, the Edwards Aquifer is a confined karst aquifer flowing through limestone in Texas. There are many well-known locations where water from this aquifer flows to the surface creating large springs. In some places, cave entrances open directly on the surface and lead deep into the aquifer. Underwater divers have explored

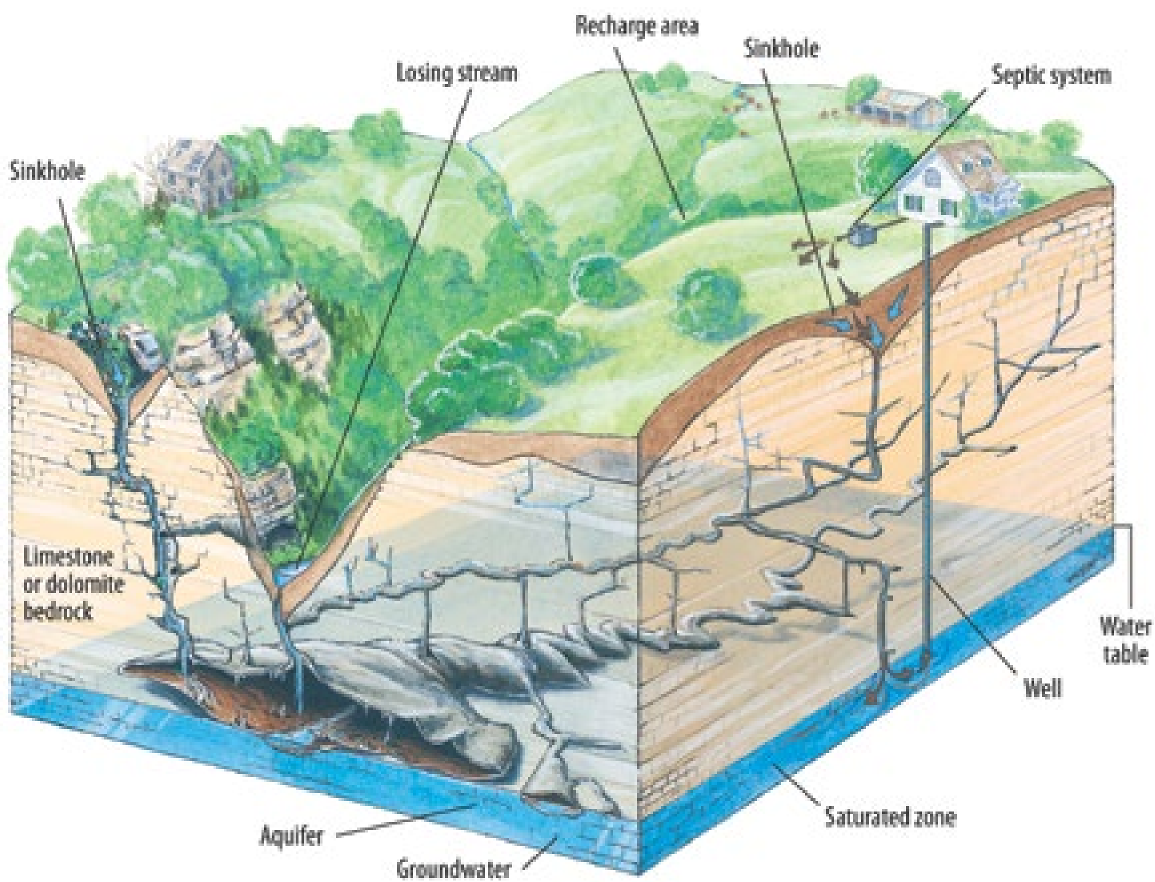


Figure 1.9 - Aquifer cross-section.. Image used with permission from the Missouri Department of Conservation.

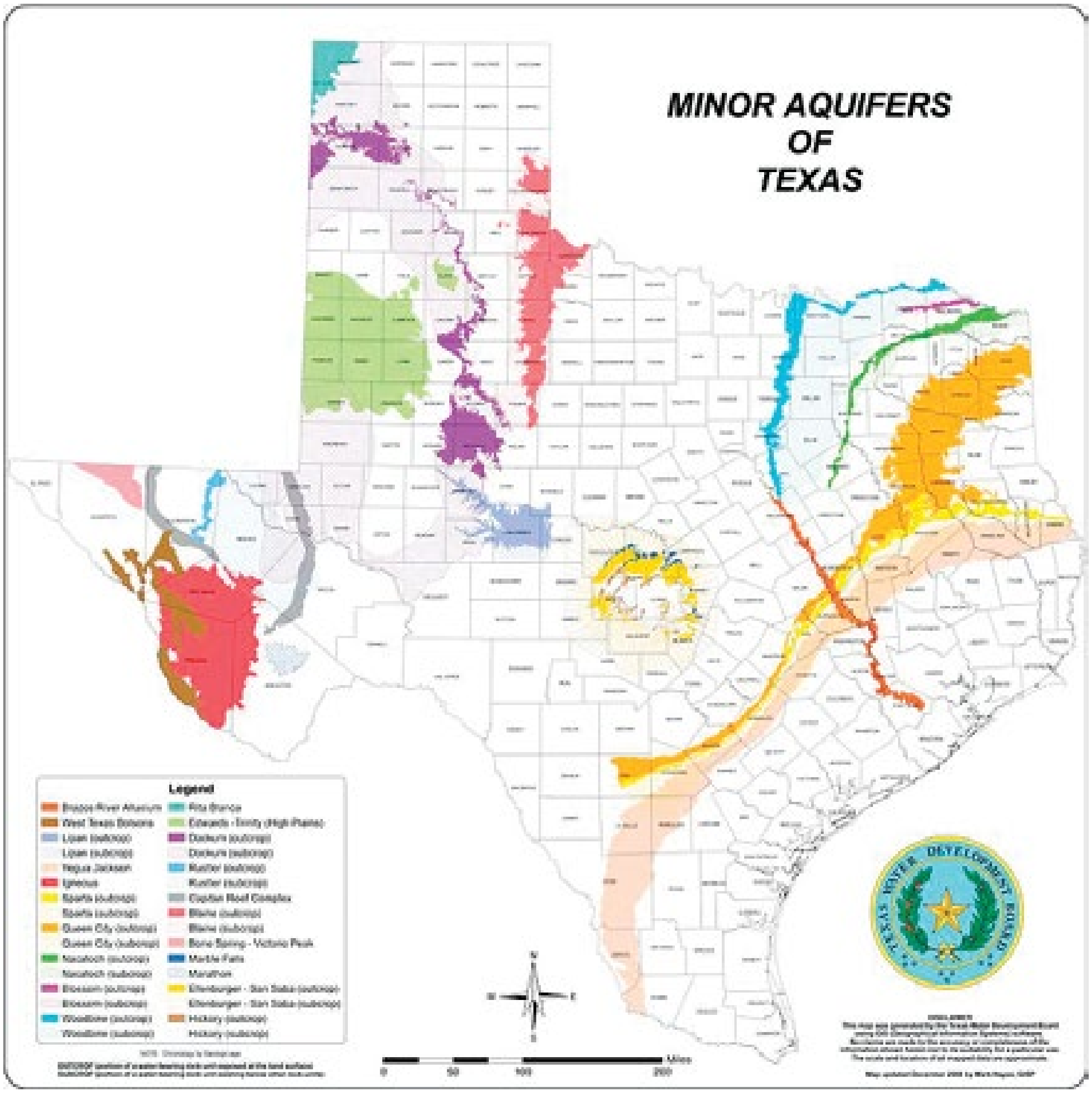


Figure 1.10 - Minor Aquifers of Texas. Image courtesy of TWDB.

some of the Edwards Aquifer's underwater caves and flowing rivers.

Springs

Springs are the places aquifer water flows to the surface forming pools and often streams. Texas is home to more than 3,000 springs. Springs can be cool water or so hot the water steams and almost boils when it reaches the surface.

Springs often form along **faults**, where geologic processes like earthquakes or uplifts have cracked and split open the earth, exposing the aquifer's water-bearing rock. One such fault in Texas is the Balcones fault, which runs from approximately the southwest part of the state near Del Rio, to the north central region near Waco along Interstate 35. For a distance of about 300 miles, this fault has exposed the Edwards Aquifer creating many prominent springs (Fig. 1.11).

Springs have played a large role in the economic development of Texas. Native Americans and early settlers built settlements and later, cities, near springs that provided them with water.

Salado Springs

Salado formed around Salado Springs, the twelfth largest spring in Texas. Salado Springs is located near the Stagecoach Inn, on the east side of Interstate 35.

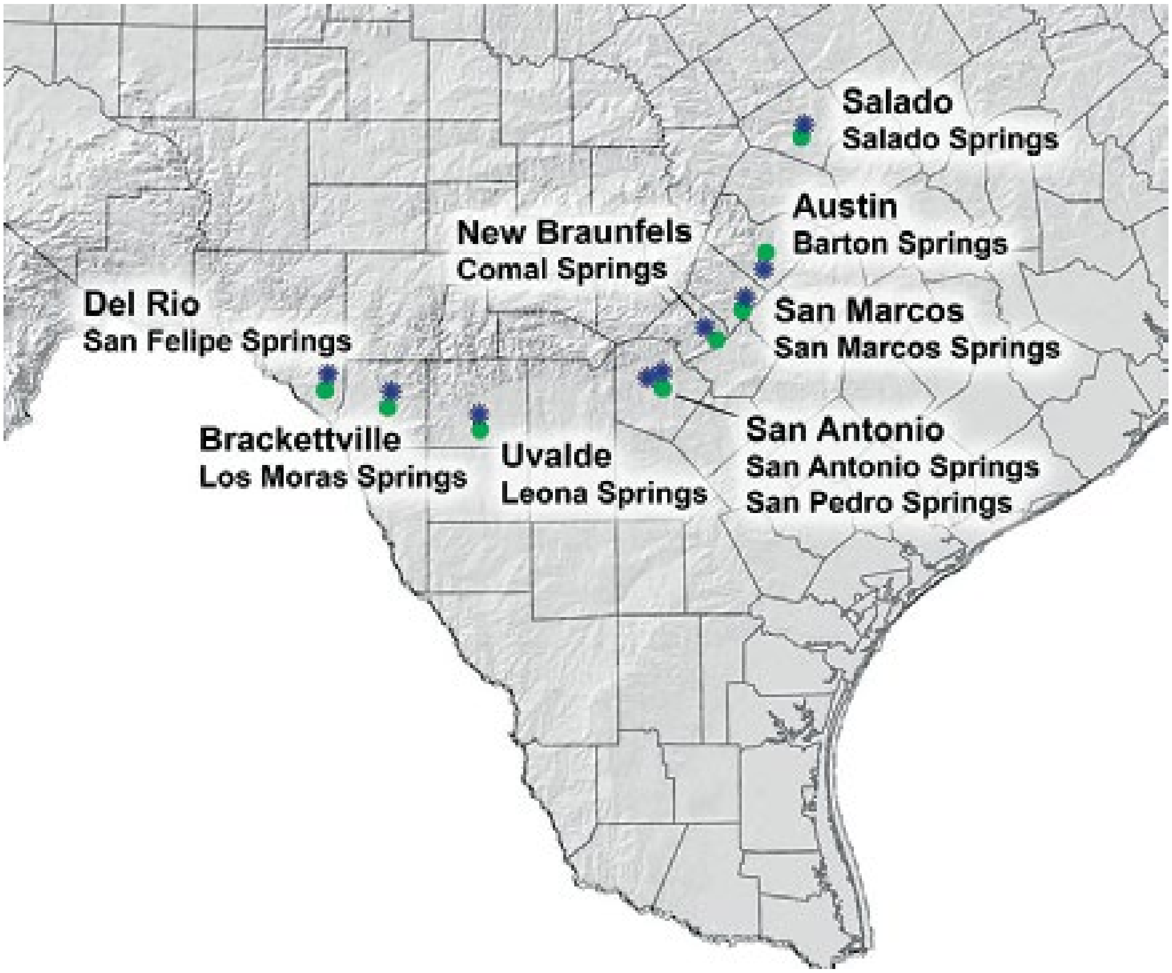


Figure 1.11 - Texas Springs along the Balcones Fault line. Image courtesy of Texas Aquatic Science.

Barton Springs

Austin, the Texas state capitol, developed where it is because of the consistent and abundant flow of water from Barton Springs, the 5th largest spring in the state. Today people know the springs as Barton Springs Pool, which is located in Zilker Park and is open for swimming year-round.

San Marcos Springs

San Marcos sprang up around the San Marcos Springs, the second largest in Texas. These springs were home to Native Americans long before Europeans arrived. We believe them to be the longest continually inhabited site in North America. For many years, it was the location of Aquarena Springs, an amusement park featuring glass-bottom boat rides so visitors could view the underwater life. Today, the springs are part of the campus of Texas State University where visitors can still take glass-bottom boat rides and learn about the aquatic ecosystems in the spring.

Comal Springs

Built at the largest of Texas' springs, Comal Springs, we find the city of New Braunfels. These springs, combined with the San Marcos Springs ("Sister Springs") are the largest in the United States west of the Mississippi River. Comal Springs are located at Landa Park and form the headwaters of the Comal River. Just downstream of the park is Schlitterbahn, a popular waterpark, where hundreds of thousands of Texans enjoy the Comal River's waters each summer.

San Antonio and San Pedro Springs

San Antonio was built around San Antonio and San Pedro Springs. San Antonio Springs flow out of the

Edwards Aquifer on the property of the University of the Incarnate Word north of downtown San Antonio in a place called the Headwaters Sanctuary. The waters then flow in the San Antonio River through Brackenridge Park into downtown San Antonio. San Pedro Springs emerge in San Pedro Park, the second oldest public park in the United States. Spanish missionaries located here in the early 1700s.

Leona Springs

Established near the Leona River, fed by Leona Springs, is Uvalde. This large group of springs experiences occasional periods of reduced flows.

Las Moras Springs

Fort Clark, now called Brackettville, grew around Las Moras Springs. These springs supplied the military fort with water from 1852 until just after World War II. The springs now feed into a public swimming pool.

San Felipe Springs

Built on Texas' fourth largest springs, the San Felipe Springs, is Del Rio. These are a group of ten or more springs that extend for over a mile along San Felipe Creek on the grounds of the San Felipe Country Club and several ranches to the north of Highway 90.

Aquifer and Spring Ecosystems

The caves and underground lakes and rivers within karst aquifers can support entire ecosystems that include **invertebrates**, fish, amphibians, and microorganisms such as bacteria and protozoans. These species are unlike any we are used to seeing above ground. The aquifer has no sunlight and therefore no green plants or **algae** with **chlorophyll** taking the sun's energy and converting it to food. Without these primary producers, these aquatic systems do not have a lot of nutrients or food available. Available food is constantly recycled among the organisms, with only occasional additions from the outside. These underground ecosystems have a very low **carrying capacity**. They can only support a few individuals of any one species, and these individuals do not grow very large.

The lack of sunlight has another consequence. The single most amazing **adaptation** of invertebrates, fish, and amphibians to the dark underground aquatic ecosystems is an absence of eyes. Without light, there is no need for eyes. **Predators** have adapted ways to find and catch **prey** in the dark, and prey have adapted ways to escape. Underground dwelling species have highly developed sensory adaptations such as antennae, **chemoreceptors**, and touch receptors.

These species also often have a very low metabolism, allowing them to live on very little food. Aided by the constant temperatures of aquifer waters, this adaptation increases survival. Groundwater species live in a very stable and predictable environment. As with aquatic ecosystems above ground, there can be overlaps with other ecosystems. This means species in the aquifer may not be completely isolated from life on the surface. The land surface above karst aquifers is an integral part of the **habitat** of animals inhabiting the underground areas. Holes in the limestone and marble of these aquifers often extend to the surface. Jacob's Well, near Wimberley, is a good example. (Figure 1.12) Here, a large opening in the **streambed** of Cypress Creek is actually a water-filled cave, extending deep into the aquifer.

Because plants can't grow in darkness, the cave and associated underwater ecosystem is dependent on plant and animal materials washed into the cave from the outside. Food in a cave can also come from organisms such as bats, mice, and crickets that take shelter in caves. They can become food (prey) for cave dwellers or leave "food" behind when they leave. For example, bat and mouse feces dropped on a cave floor provides nutrients **fungi** need to grow. Several species of insects that wander in and out of the cave eat fungi. These insects reproduce rapidly, move about the cave, and become prey for predatory invertebrates that live their entire lives in the cave. Swept away after falling into the water, these invertebrates become food for species such as the Texas blind salamander. The salamander is food for the toothless blindcat, a catfish that lives over 1,000 feet below the Earth's surface.

The aquifer ecosystem extends beyond the aquifer itself where groundwater emerges into the spring. Here the groundwater mixes with surface water in springs, streams, rivers, and lakes. However, it is in the springs formed by the aquifer's emerging waters where the unique underground ecosystem truly extends to the surface. We occasionally get a rare glimpse of life in the underground ecosystem when an invertebrate, fish or, salamander from the aquifer squirts out at a spring.

Figure 1.12 - Jacob's Well. Image courtesy of TPWD.

While many aquifers do not contain aquatic life, most major springs in Texas do. Some even contain species found nowhere else. The Edwards aquifer ecosystem and its springs contain over 60 species of plants and animals that live nowhere else in the world.[4] Species of salamanders, fish, amphipods, beetles, spiders, and others have evolved in isolated habitats within the aquifer and springs. Many of these live in the dry caves above the water table and others live in the many springs fed by the aquifer. Barton Springs, located in Austin, is the only place where the Barton Springs and Austin blind salamanders live. Fountain Darters live only in San Marcos and Comal Rivers' headwaters. Texas Wild-rice lives only in the San Marcos Springs and river immediately downstream of the springs.

As with species adapted for a life underground, even small changes to their habitat have detrimental effects. For spring dependent species, lowered spring flow due to **drought** or groundwater withdrawals may reduce habitat and create significant stress. **Invasive species** may quickly overwhelm and outcompete native spring species. Flow reductions and invasive species negatively affect many of Texas' stream ecosystems.

Humans have made changes to many springs, often damming the water flowing from the spring to convert them into swimming pools. Two examples include Barton Springs Pool in Austin and San Solomon Springs, located at Balmorhea State Park in West Texas, home to the largest spring-fed swimming pool in the world. At such places, the native spring ecosystems no longer exist as they once did; however, many still support their endemic and/or endangered species.

Significant Species

Springs host species who rely on very stable water conditions. These include temperature, water quality, and flow.

Texas Wild-rice

Texas Wild-rice has long green leaves up to 45 inches in length and 1/4 to 1 inch wide. Rice "seeds" are black or brown. Related to the wild rice grown for human food, it is an aquatic perennial grass found in a limited stretch of the San Marcos River in central Texas. On a sunny day, one can see this plant's bright green leaves waving in the current near the river bottom in areas where the water is clean and clear. Nutria, a non-native rodent that lives in wetland areas, is also a threat because it eats the wild rice. Today Texas Wild-rice, along with other threatened and endangered species associated with the Edwards Aquifer, are protected by the Edwards Aquifer Habitat Conservation Plan.

Austin Blind Salamander

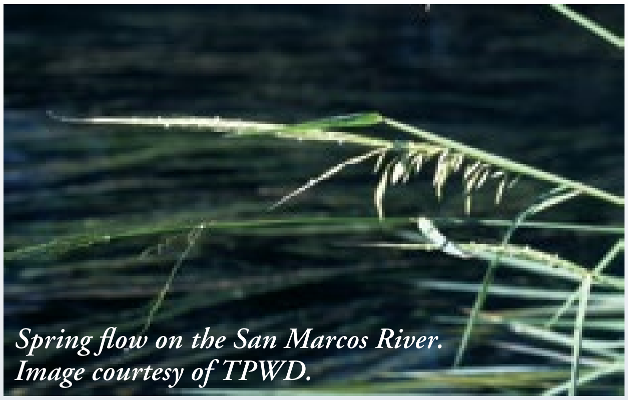
The only known habitat for the Austin Blind Salamander is Barton Springs. Austin Blind Salamanders occupy the habitat below the surface of the springs, where their unique adaptations likely give them a selective advantage in a world of total darkness and limited food. Both the state and federal authorities list the Austin Blind Salamander as endangered.[5]

Figure 1.13 - Austin Blind Salamander. Image courtesy of Dee Ann Chamberlain.

Barton Springs Salamander

Because the Barton Springs Salamander relies on the clear, pure water of the Edwards Aquifer, protection of the quality and quantity of water flowing from Barton Springs is essential for its survival. Threats to water quality abound:

- urban runoff
- increased development in the Barton Creek watershed
- the risks of a toxic chemical spill or sewer



Spring flow on the San Marcos River. Image courtesy of TPWD.

San Marcos River State Scientific Area

On a sunny spring or summer day a favorite activity of the residents of San Marcos is to cool off in the constant 72-degree waters of the San Marcos River. The clear, spring-fed river winds through several city and university parks as it makes its way through town. These waters offer plenty of recreation, such as boating, tubing, swimming, and fishing. The river is a large attraction for students attending the Texas State University and has a significant value for the City of San Marcos. It is also the only place in the world Texas Wild-rice is found.

Texas Wild-rice (*Zizania texana*) is related to the wild-rice grown for human consumption and is found in a limited stretch of the San Marcos River, between the Spring Lake Dam and the city's wastewater treatment facility. The plant requires cool, flowing water at least one foot deep and habitat free of sedimentation. Many factors have led to the near elimination of the population in the past. Invasive plants and siltation of the river substrate have damaged the wild-rice habitat, drought has threatened the required spring flows, and recreational users often uproot the plant while wading and tubing.

In order to protect this state and federally listed endangered species and its habitat, Texas Parks and Wildlife Department declared the upper portion of the San Marcos River a State Scientific Area (SSA). The San Marcos State Scientific Area is a continuation of efforts to protect endangered species with the Edwards Aquifer Recovery Implementation Plan (EARIP). This designation allows officials to issue fines to any person caught uprooting the wild rice. They may also limit access to vulnerable areas during times of low flow. The designation has been received positively by community organizations who view it as a way to educate the public about the vulnerability of wild-rice. Texas Wild-rice is one of the features of the San Marcos River that make it one of the most unique rivers in the world and a state treasure. The power to designate its habitat as a State Scientific Area is a valuable tool for balancing the needs of recreational users and the protection of the species. For more information visit http://tpwd.texas.gov/newsletters/eye-on-nature/2011spring/page2.phtml.

line breakage in the urban zone surrounding Barton Springs
- reduced groundwater supplies due to increased urban water use

Prior to 1989, aquatic plants were abundant in Barton Springs Pool. Surveys in the early 1970s showed that the Barton Springs Salamander was quite abundant and easily found by searching through submerged leaves in Eliza Springs. From 1970 to 1992, the population of this species dropped sharply. We now know that certain pool maintenance practices, such as the use of high-pressure hoses, hot water, and chemicals were harmful to the salamanders and the aquatic plants in the pool and nearby spring outlets that provide their habitat. Today, modified pool maintenance minimizes damage to the salamander and its habitat. The City of Austin's Environmental and Conservation Services Department also planted aquatic vegetation in the deep end of the pool to restore habitat and they plan more plant restoration for this area. Since the new pool maintenance practices began, the habitat in the pool and nearby springs has rapidly improved. Although the salamander has expanded into its former range in the Barton Springs Pool, scientists believe it probably has not reached the extent of its pre-1970 distribution.

Residents and visitors to Austin will be happy to know that swimming in Barton Springs Pool does not pose a threat to the salamander or its habitat. With proper management, the pool will continue to provide refreshing enjoyment for people and habitat for the

Figure 1.14 - Barton Springs Salamander. Image courtesy of Nathan Bendik, http://creativecommons.org/licenses/by-nc-sa/4.0/legalcode.

Figure 1.15 - Cascade Caverns Salamander. Image courtesy of Nathan Bendik, http://creativecommons.org/licenses/by-nc-sa/4.0/legalcode.

Barton Springs Salamander. Both the state and federal authorities list the Barton Springs salamander as endangered.[6]

Cascade Caverns Salamander

The Cascade Caverns salamander is endemic to Cascade Caverns in Kendall County, Texas. It is translucent, with a faint, net-shaped pattern that is brown in color, often with white speckling. Like other cave salamanders of the state, this species is difficult to observe and gauging the exact extent of the species' geographic range and population numbers is difficult. They are **neotenic**, meaning they retain characteristics into adulthood that are usually associated with juvenile salamanders, such as external gills. They have stout bodies, with short legs, and reduced eyes set under a layer of skin.[7] Texas lists the Cascade Caverns salamander as threatened.[8]

Georgetown Salamander

The Georgetown salamander is completely aquatic and does not metamorphose. They are known only from the immediate vicinity of spring outflows, under rocks and leaves and in gravel substrate, and from two water-containing caves. Little is known of its breeding biology, though scientists believe some other spring-dwelling species of central Texas *Eurycea* (the cave salamander genus) deposit eggs in gravel substrates. Populations within the city of Georgetown proper probably are on the brink of extinction. Development of retirement and leisure communities, and quarrying

Figure 1.16 - Georgetown Salamander. Used with permission- R. D. Bartlett.

(Middle Fork San Gabriel River), is taking place near some salamander populations, but currently these do not appear to be a major threat to salamander habitat.[9] Their federal listing is threatened.[10]

Jollyville Salamander

While not as restricted as the Barton Springs or Austin Blind salamanders that only are found in one closely spaced group of springs, the Jollyville Plateau Salamander is confined to the springs, spring-fed streams, and wet caves in and around northwest Austin,

The Federal government lists the Jollyville Plateau salamander as threatened under the Endangered Species Act as of September 2013. In urbanized watersheds, scientists have observed population declines but numbers remain stable in undisturbed portions of their range.

Figure 1.17 - Jollyville Salamander. Image courtesy of Mark Saunders.

Texas Blind Salamander

The Texas Blind salamander is an active predator. It moves its head from side to side, as it searches for food on the bottom. It hunts animal food by sensing water pressure waves created by prey in the still underground waters where it lives. Tiny snails, shrimp, and other aquatic invertebrates make up its diet. Reproduction occurs year round. It is unknown how many Texas Blind salamanders exist. The Texas Blind Salamander lives in water-filled caves of the Edwards Aquifer near San Marcos, Texas.

The Texas Blind salamander depends on a constant supply of clean, cool water from the Edwards Aquifer. Pollution and overuse of water caused by the growth of cities threaten its survival. Both the state and federal authorities list the Texas Blind salamander as endangered.[11]

Figure 1.18 - Texas Blind Salamander. Image courtesy of TPWD.

Fountain Darter

The Fountain Darter is a member of the family Percidae, the perches. It is mottled brown in color for camouflage, with dark markings along its sides and dark spots at the base of the tail, opercule, dorsal fin, and around the eye (Gilbert 1887; Schenck and Whiteside 1976). They are usually less than an inch in length but can reach up to two inches.[12]

Their habitat is limited to the Comal and San Marcos Springs. Fountain Darters require clear, clean, flowing waters of a constant temperature, adequate food supply, undisturbed sand and gravel substrates, rock outcrops, and areas of submerged vegetation for cover (Schenck and Whiteside 1977; McKinney and Sharp 1995; USFWS 1996). Young Fountain Darters are found in heavily vegetated areas with slow moving water while adults can be found in all suitable habitats (Schenck and Whiteside 1976). The present population of Fountain Darters in the San Marcos River is well established; however, the Fountain Darter population in the Comal River has been erratic. Numerous Fountain Darters were collected in the Comal River in 1891, but between 1973 and 1975, biologists were unable to collect any. This indicated that Fountain Darters no longer existed in the Comal aquatic ecosystem. The most probable causes of the **extirpation** were the five months the Comal Springs ceased flowing in 1956 during the prolonged drought, the extensive use of rotenone (an insecticide) by TPWD during this period, or a combination of both.[13] In 1975, biologists from Texas State University took Fountain Darters from the San Marcos River and successfully reintroduced the species to the Comal aquatic ecosystem (USFWS 1996).[14]

Both the state and federal authorities list the Fountain Darter as endangered.[15]

Figure 1.19 - Fountain Darter. Image courtesy of TPWD.

Wetlands

Wetlands are areas that are routinely inundated or saturated by surface or ground water. Plants growing in wetlands are typically adapted for life in saturated soil conditions. Wetlands are often referred to as swamps, marshes, or bogs; however, some wetlands are not easily recognized, because they are dry during part of the year or "they just don't look very wet" from the roadside. Some of these wetland types include, but are not limited to, bottomland forests, **pocosins**, pine savannahs, wet meadows, potholes, and wet tundra.

What determines a wetland?

Wetlands have lots of natural variation, but they typically have the following characteristics:

1. Hydrology: Wetlands have water that is present for part or all of the year, at or above the surface, or within the root zone.
2. Soils: Wetlands have soil characteristics that differ from surrounding uplands.
3. Vegetation: Wetlands will contain plants that are adapted to the presence of water, and generally lack plants that are intolerant of wet conditions.

Types of Wetlands

Texas is a large and ecologically diverse state containing many different types of wetlands.

Figure 1.20 - Bald Cypress. Image courtesy of TPWD.

Deepwater Swamps

Found primarily in East Texas, swamps are forested wetland ecosystems that contain standing water for all or most of the year, and, in Texas, are typically characterized by the presence of bald cypress trees.

Texas Wild-Rice, Image courtesy of TPWD.

Edwards Aquifer Habitat Conservation Plan

The Edwards Aquifer is one of the largest and most unique aquifers in the world. This artesian treasure surfaces through springs along the Balcones fault in Central Texas. The two largest expressions of the aquifer, the San Marcos Springs and the Comal Springs, have a great economical, ecological, cultural, aesthetic, and recreational value to the inhabitants of the region. These springs are headwaters for their namesake rivers, which contribute their waters to the Guadalupe River. Native Americans have occupied the areas around the springs for thousands of years. The area around the San Marcos Springs is believed to be the oldest continuously inhabited place in the North America. Locals refer to it proudly as America's Oldest Neighborhood. The headwaters are also home to a number of endangered species, including rare beetles, salamanders, Texas Wild-rice, and the fountain darter. During the drought of record, in the 1950s, the Edwards Aquifer levels dropped low enough that only a few small pools were left at Comal Springs and the resident fountain darter disappeared. The springs were eventually repopulated with fountain darters from San Marcos Springs, but the episode raised concern over the future conservation of their habitat. As pumping increased in the region over recent decades, the concern became great that the springs could dry up again and take a longer period to recuperate.

In 1991, conflict over the water supply of the aquifer led to a law suit under the Endangered Species Act and the development of the Edwards Aquifer Authority. In 2006 the Edwards Aquifer Recovery Implementation Program recommended that several stakeholders apply for an Incidental Take Permit under the Endangered Species Act. The permits are issued to parties that are engaged in activities that may threaten a listed species or their habitat (a "take"). As part of that process Texas Parks and Wildlife Department, Texas State University, the City of San Marcos, the City of San Antonio, the City of New Braunfels, and Edwards Aquifer Authority developed the Edwards Aquifer Habitat Conservation Plan (EAHCP). The goal of the EAHCP is to assure that flows from the springs will remain sufficient to sustain habitat for the covered species. The plan focuses conservation efforts into three categories: habitat protection measures, flow protection measures, and supporting measures. These measures which include a Critical Period Management Plan attempt to conserve the spring flow in periods of drought. In 2013 the efforts of the participating stakeholders were honored. The EAHCP participants were awarded the 2013 Partners in Conservation Award from the Secretary of the Interior for "innovating and collaborating in ways that address today's complex conservation and stewardship challenges." The EAHCP is born of a decades-long effort between various stakeholders to end regional conflict and provide protection for the springs smallest residents. Read the plan here: https://www.fws.gov/southwest/es/Documents/R2ES/EARIP_HCP_Final_Nov_2012.pdf.

Freshwater Marsh

Freshwater marshes are non-forested, non-tidal wetlands. Grasses, sedges, and other freshwater emergent plants dominate them. They can occur in low depressions in the Gulf Coast region. They also occur in shallow water along lakes, rivers, or streams, or can exist as abandoned oxbows. Freshwater marshes are highly productive ecosystems. They sustain a wide variety of plant communities, and provide diverse habitat for wildlife. In addition, the flat topography of marshes helps in mitigating flood damage and filtering excess nutrients from surface runoff.

Figure 1.22 - Riparian Wetlands--Here a flooded bottomland hardwood forest. Image courtesy of TPWD.

Playa Lakes

Playas are ephemeral wetlands characterized by Randall or Ness clay soils and occur in portions of Colorado, Kansas, New Mexico, Oklahoma, and northwestern Texas. The vast majority of recharge to the Texas' portion of the Ogallala Aquifer comes from playa lakes.

Figure 1.21 - Playa Lakes viewed from Caprock Canyons State Park. Image courtesy of TPWD.

Riparian Wetlands

Most riparian wetlands in Texas are bottomland hardwood forests. These ecosystems experience periodic overbank flooding from adjacent rivers or major streams.

Saline and Brackish Marshes

Saline (salty) and brackish (somewhat salty) marshes occur along the Gulf Coast of Texas. These complex and highly productive ecosystems contain a variety of plant and animal species. They are specially adapted to fluctuations in salinity, water levels, and seasonal temperatures. Marshes along the Gulf Coast receive an abundance of silt from the major rivers that traverse Texas. The plants that reside in saline and brackish marshes help protect the aquatic life in Gulf Coast bays by filtering sediment and pollutants from overland flow.

The health and abundance of Gulf Coast marshes has a direct impact on economically significant species such as shrimp and crab. They also provide food and habitat for numerous species of migrating birds.

Figure 1.23 - Salt Marshes may be saline or brackish. Image courtesy of TPWD.

Significant Species

Houston toad

The Houston toad lives primarily on land, but requires still or slow-flowing bodies of water for breeding and egg and tadpole development. Its range is in the loose, deep sands of woodland savannahs in the southeastern part of the state, with the largest population found in Bastrop County.

Habitat loss and alteration are the most serious threats facing the Houston toad. Alteration of ephemeral and permanent natural wetlands for urban and agricultural uses eliminates breeding sites. Draining a wetland or converting an ephemeral wetland to a permanent pond can eventually eliminate or cause declines in the Houston toad populations. Conversion to permanent water makes them more vulnerable to predation by snakes, fish, and other predators. It also increases competition and hybridization with closely related species.

Figure 1.24 - Houston toad. Image courtesy of TPWD.

Periodic drought is also a threat, particularly long-term drought such as that experienced during the 1950s and in the 2010s. Drought may result in the loss or reduction of breeding sites as well as enhanced mortality of toadlets and adults.

High traffic roads are a barrier to Houston toad movement. Traffic causes many toad deaths. Other linear features such as pipelines and transmission lines can create barriers between foraging, hibernating, and breeding sites, especially after removal of native vegetation.

Believed to be adapted to fire regimes, the Houston toad mortality may increase due to prescribed burning. Frequent and/or severe burns may be detrimental to the toad, particularly for small, fragmented populations. However, increased fuel loads due to prolonged periods of fire prevention may result in very hot wildfires. We need additional research to determine the effects of prescribed burning programs on the Houston toad population.

Other threats to the Houston toad include fire ants and the use of chemicals in and near their habitats. In addition, human activity causing habitat fragmentation further divides toad populations. Houston toads cannot easily re-colonize widely scattered parcels of habitat. This is true especially if extensive areas of unsuitable habitat occur between populations, or human impacts eliminate a population. Both the state and federal authorities list the Houston toad as endangered.[16]

American Oystercatcher

Figure 1.25 - American Oystercatcher. Image courtesy of TPWD.

The American Oystercatcher is an easily recognized shorebird that makes its home on the beach or near salt marshes and mudflats. The bird's long orange bill is knife-shaped. It uses its beak to pry open oysters and other bivalves for food, hence the name "oystercatcher." The genus name *Haematopus* is Greek for "blood foot," and refers to the oystercatcher's pink legs. *Palliatus*, the species name, means cloaked in Latin, referring to the black cloak of feathers on its head. During the eighteenth and nineteenth centuries, people hunted American Oystercatchers for food and for their plumage. When protected under law in 1918, the species was near extinction along the Atlantic Coast. Its numbers are now increasing throughout its range. However, as cities and towns grow along beaches in North America, oystercatchers have fewer available nesting areas.

Brown Pelican

The Brown Pelican has an 18-inch long bill and large throat pouch. Its head is white in front and dark brown behind, extending down the neck and back. During the breeding season, the white plumage turns a vibrant yellowish-gold color. Silver-gray feathers cover the rest of the pelican's body. The Brown Pelican weighs about 9 pounds and has a 6-foot wingspan. When feeding, pelicans soar in the air looking for fish near the surface of the water. When a fish is spotted, the pelican goes into a dive, plunging 30 to 60 feet bill-first into the water. The impact of hitting the water would kill an ordinary bird, but the pelican is equipped with air sacs just beneath the skin to cushion the blow.

The loose skin on the underside of the bill extends to form a scoop net with an amazing capacity of 2.5 gallons. The pelican drains the water from its pouch and tosses its head back to swallow the fish. Their diet consists of menhaden and mullet fish. They lay 2 to 4 white eggs during breeding season, and live up to 30 years or more. Young pelicans are fed for about 9 weeks. During this time, each nestling will eat about 150 pounds of fish.

Figure 1.26 - Brown Pelican. Image courtesy of TPWD.

Brown Pelicans nest on small, isolated coastal islands where they are safe from predators such as raccoons and coyotes. They are found along the Atlantic and Gulf of Mexico Coasts.

Brown Pelicans almost disappeared from Texas because the pesticide DDT caused them to lay thin-shelled eggs, which broke during incubation.

In 1970, the Brown Pelican was placed on the Federal Endangered Species List. The plight of this and other species led to a ban on the use of DDT in the United States in 1972 and a reduction in the use of endrin, another pesticide, during the 1970s. Reproduction soon improved, and pelican numbers began to rise. Recovery was so successful that the Brown Pelican was removed from the Endangered Species List in the southeastern United States in 1985 and in the remainder of its range in 2009. Once a symbol of the detrimental effects of pollution in marine ecosystems, the Brown Pelican now symbolizes the success of wildlife-conservation efforts.[17]

Wood Stork

Wood Storks are gregarious, nesting in colonies and feeding in flocks. They use freshwater and estuarine wetlands for feeding, roosting, and nesting sites. The largest threat to the Wood Stork is habitat loss or degradation. Texas lists the Wood Stork as threatened.[18]

Figure 1.27 - Wood stork. Image courtesy of USFWS.

Bays and Estuaries

Bays and estuaries occur where freshwater from rivers mix with saltwater from the ocean. They typically contain saltwater or brackish wetlands. Texas bays and estuaries are some of the most biologically productive places in the marine environment. Most of the marine fishes and invertebrates people are familiar with spend large parts of their sub-adult lives in the sea grass areas or near the shorelines. The wetland areas are also sources of food and protection for shore birds, small mammals, and terrestrial invertebrates like crabs. Natural and artificial reefs provide food and protection functions similar to wetlands on shore.

Seagrass

Submerged seagrass meadows are dominant and unique subtropical habitat in many Texas bays and estuaries. These marine plants play critical roles in the coastal environment. This includes nursery habitat for estuarine fisheries, a major source of organic biomass for coastal food webs. They are also effective agents for stabilizing coastal erosion and sedimentation, and in nutrient cycling and water quality processes.

Significant Species

Whooping Crane

At nearly 5 feet tall, Whooping Cranes are the tallest birds in North America. They have a wingspan of 7.5 feet.

The Whooping Crane breeds in the wetlands of Wood Buffalo National Park in northern Canada and spends the winter on the Texas coast at Aransas National Wildlife Refuge near Rockport. Whooping Cranes begin their fall migration south to Texas in mid-September and begin the spring migration north to Canada in late March or early April. Whooping Cranes migrate more than 2,400 miles a year. As many as 1,400 Whooping Cranes migrated across North America in the mid-1800s. By the late 1930s, the Aransas population was down to just 18 birds. Because of well-coordinated efforts to protect habitat and the birds themselves, the population is slowly increasing. In 1993, the population stood at 112. In February of 2015, it was estimated that there were 310 whoopers - an important increase. Today, three populations exist: one in the Kissimmee Prairie of Florida, the only migratory population at Aransas National Wildlife Refuge, and a very small captive-bred population in Wisconsin, making for a total population of 603.[19]

Whooping Cranes mate for life, but will accept a new mate if one dies. These long-lived birds can survive up to 24 years in the wild. The mated pair shares brooding duties; either the male or the female is always on the nest. Generally, one chick survives. It can leave the nest while quite young, but is still protected and fed by its parents. Chicks are rust-colored when they hatch; at about four months, chicks' feathers begin turning white. By the end of their first migration, they are brown and white, and as they enter their first spring, their plumage is white with black wing tips.

Figure 1.28 - Whooping Crane. Image courtesy of TPWD.

The hatchlings will stay with their parents throughout their first winter, and separate when the spring migration begins. The sub-adults form groups and travel together. Cranes live in family groups made up of the parents and 1 or 2 offspring. In the spring, Whooping Cranes perform courtship displays (loud calling, wing flapping, leaps in the air) as they get ready to migrate to their breeding grounds. Their diet consists of blue crabs, clams, frogs, minnows, rodents, small birds, and berries.

Whooping Cranes are one of the rarest bird species in North America. Whooping Cranes have protected status in Canada, the United States, and Mexico. The greatest threats to Whooping Cranes are human-caused: power lines, illegal hunting, and habitat loss. Because the Gulf International Waterway goes through their habitat area, the cranes are susceptible to chemical spills and other petroleum-related contamination. Public awareness and support are critical to Whooping' survival as a species. Both the State and Federal authorities list the Whooping Crane as endangered.[20]

Reddish Egret

The Reddish Egret, a beautiful wading bird, is a permanent resident of the Texas coast. Although recognized as one species, Reddish Egrets may be either white (white phase) or gray with a reddish or rusty colored head and neck (dark phase). It is currently listed in Texas as a threatened species. Reddish Egrets can live up to 12 years.

In Texas, nests are built mostly on the ground near a bush or prickly pear cactus or on an oyster shell beach. Both parents build the nest, and sticks are continuously added to the nest during incubation. Reddish Egrets sometimes nest alongside other birds such as herons, egrets, cormorants and spoonbills. Their predators include raccoons, coyotes and great-tailed grackles, which destroy their eggs and eat the young birds.

Nests usually contain three to four smooth, pale blue-green eggs with no markings. Two dark phase birds can have white phase chicks, but two white phase birds can never have dark phase chicks. When a dark phase bird and a white phase bird mate, their chicks are almost always dark phase. The white phase of the Reddish Egret was once thought to be a completely different species. In Texas, only 10 to 20 percent of the Reddish Egret population is white phase. In the 1950s, just four percent of the whole United States' population was white phase.

The Reddish Egret is crepuscular (it is most active at dawn and dusk). When feeding, Reddish Egrets will spread their wings to create shade and reduce glare so that they can see their prey more easily in the water. Small fish, frogs, tadpoles, and crustaceans make up most of their diet. When chasing fish, they also run in circles. Reddish Egrets use their long, spear-like bills to stab their prey. After feeding, Reddish Egrets regurgitate all the inedible parts of their prey, such as bones, much like owls do. Parents feed their young by regurgitating into the chicks' mouths.

Figure 1.29 - Reddish Egret. Image courtesy of TPWD.

Reddish Egrets are most often found in salt and brackish water wetlands. The Reddish Egret can be found along the Gulf Coast of Texas and some parts of Louisiana and southern Florida. It is rare along the Gulf Coast of Mexico, West Indies and Baja California.

Until the late 1800s, people hunted Reddish Egrets for their feathers, which they used to decorate women's hats and clothing. Hunters nearly exterminated them from the United States. In Florida, the species completely disappeared. The Migratory Bird Treaty Act passed in 1918, finally protecting Reddish Egrets and other birds from plumage hunters. Although their populations are still recovering, it is a slow process. There are only 1,500 to 2,000 nesting pairs of Reddish Egrets in the United States - and most of these are in Texas. Intrusion of habitat by recreationists, pesticide runoff, and land development all harm the egret's habitat. Texas lists the Reddish Egret as threatened.[21]

Gulf Coast

In Texas, 11,250 named rivers, streams, creeks, and bayous drain to the Gulf of Mexico providing 367 miles of gulf shoreline and 3,300 miles of bay beaches. The Texas Gulf Coast is rich with natural and cultural resources providing a stunning array of biological diversity.

Figure 1.30 - A typical Texas beach. Image courtesy of TPWD.

Texas Gulf Ecological Management Sites (GEMS)

The Gulf Ecological Management Site (GEMS) Program is an initiative of the Gulf of Mexico Foundation, the EPA Gulf of Mexico Program and the five Gulf of Mexico states (Texas, Louisiana, Alabama, Mississippi and Florida). The program goal is to provide a regional framework for focusing attention on geographic areas that have special ecological significance. This significance focuses on fish, wildlife, and other natural resources, or a geographic area that features unique habitats. The GEMS program furthers conservation through inter-agency coordination, public/private partnerships, and targeting of research, monitoring, and action projects.

Since the inception of the GEMS Program in 1996, each Gulf state has granted GEMS status to marine areas with special ecological significance. Those designated areas garner high priority for protection, restoration, and conservation by both state and federal governments. There are twenty-four sites in Texas.

- Anahuac National Wildlife Refuge
- Aransas National Wildlife Refuge
- Armand Bayou Coastal Preserve & Nature Center
- Candy Cain Abshier Wildlife Management Area
- Christmas Bay Coastal Preserve
- Clive Runnels Family Mad Island Marsh Preserve
- Flower Garden Banks National Marine Sanctuary
- Freeport Liberty Ship Reef Complex
- Guadalupe Delta Wildlife Management Area
- Laguna Atascosa National Wildlife Refuge
- Laguna Madre
- Lower Rio Grande Valley National Wildlife Refuge
- Matagorda Island Wildlife Management Area
- McFaddin National Wildlife Refuge
- Murphree Wildlife Management Area
- Mustang Island State Park
- North Deer Island Sanctuary
- Padre Island National Seashore
- Scenic Galveston Inc. Nature Preserve
- Sea Rim State Park

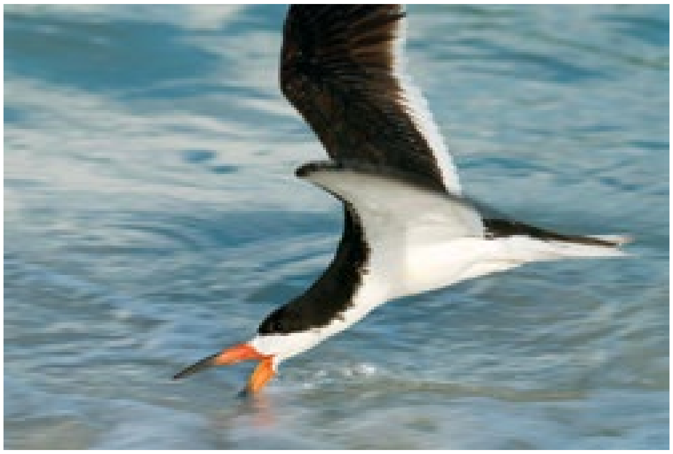


Figure 1.31 - Black Skimmer in flight. Image courtesy of USFWS.

- Shamrock Island Management Complex
- South Bay Coastal Preserve
- Texas Point National Wildlife Refuge
- Welder Flats Wildlife Management Area

To find more information on GEMS and to find out what you can do to further enhance conservation efforts visit http://tpwd.texas.gov/landwater/water/conservation/txgems/.

Significant Species

Black Skimmer

The Black Skimmer has a truly unique feeding strategy! In Figure 1.31, you can see it in action. The Black Skimmer holds its lower bill slightly below the surface of the water, feeling for tiny fish. Then it snaps them up. Sadly, the Black Skimmer faces many threats as human population increases and undeveloped areas become developed. Thus, habitat loss due to coastal development is its primary threat.

Piping Plover

The Piping Plover is a small shore bird, about 7 1/4 inches long with a 15 inch wingspan.

Piping Plovers reach sexual maturity at one year, and mate from late March through April. Males compete against each other for females' attention. They perform elaborate flights, and then scrape nests in the sand, tossing shells and small stones and twigs into them with their beaks. To create a nest, they scrape a shallow depression in the sand about 1 by 2.5 inches. After their nests are built, they stand beside them with their wings partially spread and tails fanned. The males repeat this behavior until a female indicates interest. Once he has her attention, he begins a high-stepping "dance," continuing the courtship ritual. Females will lay about four gray to pale sand-colored eggs with a few dark spots. Although both sexes share responsibility for incubating the eggs, females commonly leave the young when the hatchlings are 14 to 20 days old. Males often remain with them until they can fly.

There are just over 5,000 known pairs of breeding Piping Plovers. Texas is the wintering home for 35 percent of the known population of Piping Plovers. They begin arriving in late July or early August, and will remain for up to nine months. The Piping Plover's diet includes marine worms, beetles, spiders, crustaceans, mollusks, and other small marine animals. Their average life span is less than 5 years, but they can live up to 14 years. These shorebirds live on sandy beaches and lakeshores.

Habitat alteration and destruction are the primary causes for the decline of the Piping Plover. Loss of sandy beaches and lakeshores due to recreational, residential, and commercial development has reduced available habitat on the Great Lakes, Atlantic Coast, and the Gulf of Mexico. Reservoir construction, channel excavation, and modification of river flows have eliminated sandbar-nesting habitat along hundreds of miles of the Missouri and Platte Rivers. Winter habitats along the Gulf Coast are threatened by industrial and urban expansion and maintenance activities for commercial waterways. Pollution from spills of petrochemical products and other hazardous materials is also a concern.

On the breeding grounds, Piping Plovers have lower reproductive success due to human disturbance. Vehicular and foot traffic destroys eggs and chicks. The presence of people on beaches and sandbar islands inhibits incubation and other breeding behavior. Changes in land use such as agricultural development, urbanization, and use of beaches has brought an increase in the number of unleashed pets and other predators such as gulls, skunks, and foxes.

Increased recreational use of Gulf beaches may also threaten the quality of wintering sites. Beach traffic, including automobiles and all-terrain vehicles (ATVs), as well as the activities of unleashed dogs, can disturb birds and degrade habitat. Beach raking, a practice associated with high recreational use, removes

Figure 1.32 - Piping Plover. Image courtesy of USFWS.

driftwood, seaweed, and other debris used by roosting plovers, and may disrupt nutrient cycles and remove prey organisms from foraging areas where plovers forage on the beach.

In 2011, estimates of the total population of Piping Plovers were only 5,723 breeding adults. The Texas Gulf Coast had the highest wintering population, with about 2,145 individuals detected. This represents about 54% of birds detected on the wintering grounds during the 2011 International Piping Plover Census. Most of the plovers that winter on the Texas coast congregate in the lower Laguna Madre, where tidal flats are extensive and productive. It is up to Texans to insure that the wintering habitat so vital to the survival of this species is protected. Both the state and federal authorities list the Piping Plover as threatened.[22]

Summary

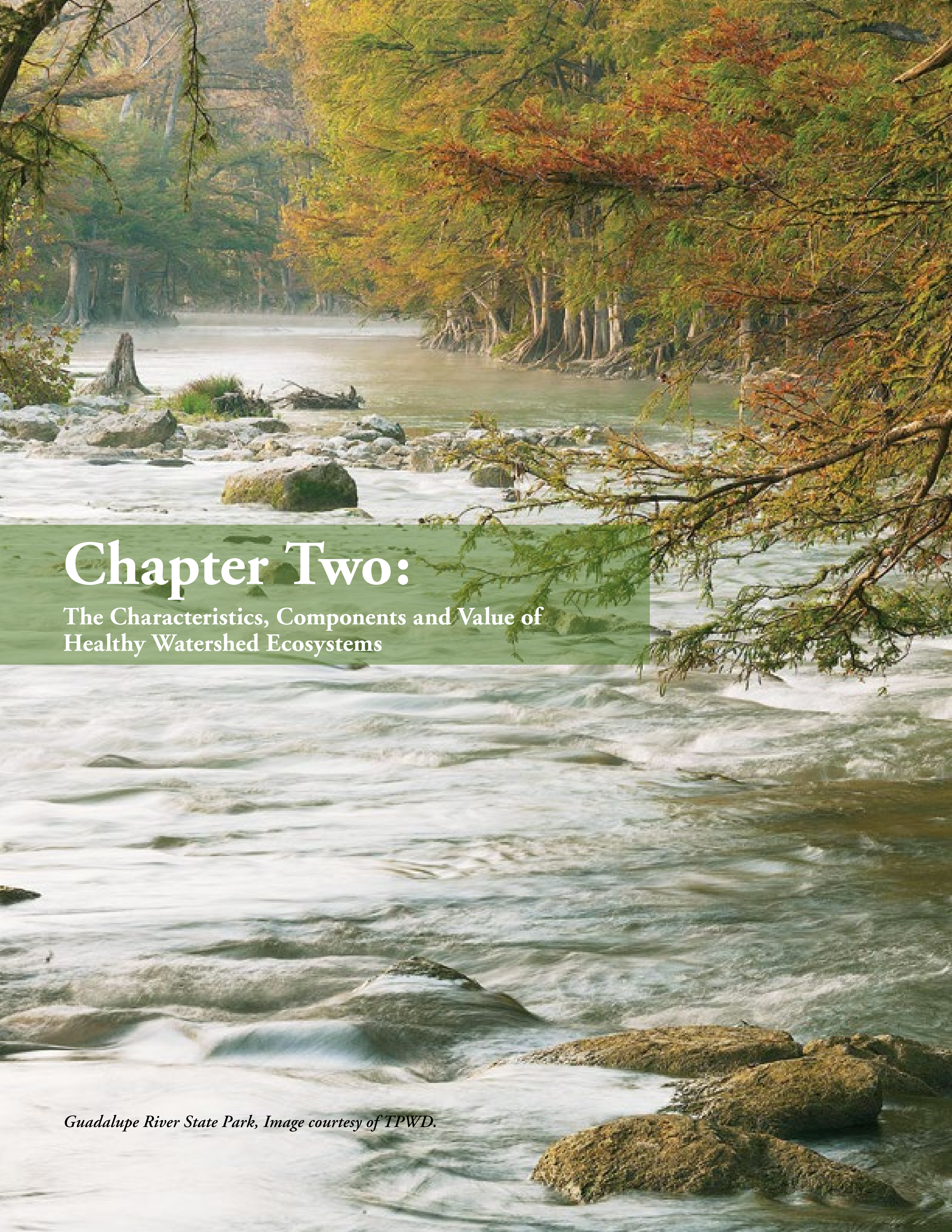
Now you know a little more about the numerous and diverse aquatic habitats in our state. You also know a bit more about the many plant and animal species these habitats support. In the next chapter, we will shift gears and learn about the characteristics, components and value of healthy Watershed Ecosystems.

Challenge

Find out more about an aquatic habitat near where you live. What impairments might it have? Is it home to any species that experiences environmental challenges? If so, what can you do to make a difference? In addition to the resources above that can shed light on your local aquatic habitat, there are fourteen river authorities in Texas. Use this link to locate yours: http://tpwd.texas.gov/landwater/water/habitats/rivers/authorities.phtml. Once on their site, search for the "Clean Rivers Program Basin Summary." Most river authorities publish a Basin Summary Report roughly every five years. In the report, you will find information about every stream segment in the basin and any water quality impairments.

References

1. (U.S. Geological Survey and Environment Canada, 2015)
2. (U.S. Geological Survey and Environment Canada, 2015)
3. (Rosen, 2013)
4. (Rosen, 2013)
5. (U.S. Geological Survey and Environment Canada, 2015)
6. (U.S. Geological Survey and Environment Canada, 2015)
7. (iNaturalist, 2016)
8. (U.S. Geological Survey and Environment Canada, 2015)
9. (Species, 2016)
10. (U.S. Geological Survey and Environment Canada, 2015)
11. (U.S. Geological Survey and Environment Canada, 2015)
12. (Edwards Aquifer Authority, 2016)
13. (Texas Parks and Wildlife, 1993)
14. (Edwards Aquifer Authority, 2016)
15. (U.S. Geological Survey and Environment Canada, 2015)
16. (U.S. Geological Survey and Environment Canada, 2015)
17. (Shields, 2016)
18. (U.S. Geological Survey and Environment Canada, 2015)
19. (U.S. Fish and Wildlife Service, 2016)
20. (U.S. Geological Survey and Environment Canada, 2015)
21. (U.S. Geological Survey and Environment Canada, 2015)
22. (U.S. Geological Survey and Environment Canada, 2015)



Chapter Two:

The Characteristics, Components and Value of Healthy Watershed Ecosystems

Guadalupe River State Park, Image courtesy of TPWD.

Chapter Two:

The Characteristics, Components and Value of Healthy Watershed Ecosystems

Questions to Consider

- What connections exist between climate, geomorphology, hydrology and healthy watershed ecosystems?
- What can the biodiversity of a given ecosystem tell us about its health?
- How does the structure of a watershed determine its plant and animal life?
- What is the significance of identifying keystone and indicator species?

Introduction

This chapter is all about watershed ecosystems. Most often, we humans are concerned with water only as it relates to our own comfort and convenience. Nevertheless, here we begin to make the case for the importance of water in the natural environment and just how vital is its role to our very existence. The interplay of living (biotic) and non-living (abiotic) components creates an ecosystem. A watershed is the land area that drains to a stream, lake, or river. To understand how a watershed works, we must first look at its abiotic components. Together, land, climate, and flowing water create the physical elements of a watershed's ecosystem. These basic building blocks, their structure, function and interaction, form the foundation of a watershed. In this chapter, we will explore not only those abiotic components, but also the biotic, or living, components that populate the watershed. Let's start with a closer look at climatology, geomorphology, and hydrology and the role they play in helping us study and understand watershed characteristics and components.

Abiotic Components

Climatology

Climatology, the science of climate and its causes, is important to understanding regional issues in watershed science. Climate varies greatly by latitude. The input of solar energy is greatest at the equator, which results in well-described global air circulation and precipitation patterns that influence regional climate. Seasonal variation is an important component of climate, and local and regional effects on climate, such as those caused by large water bodies or mountains are important. Climate is not the same as weather. Climate refers to atmospheric conditions over time, while weather is the day-to-day variation in atmospheric conditions. Atmospheric conditions include:

- temperature,
- humidity,
- precipitation (including type and amount),
- winds, and
- cloud cover.

Climatologists study these conditions and measure them over an extended period to understand climate. Long-term weather trends establish averages, which become climatic regimes.

Climate heavily influences:

- vegetation and plant communities,
- magnitude and timing of streamflow,
- water temperature, and
- many other key watershed characteristics.

For example, precipitation varies in Texas from over 50 inches annual average in the east to less than 10 inches annual average in the west, which greatly influences abiotic and biotic factors of watersheds.

The global climate is rapidly changing due to increasing concentrations of carbon dioxide and other greenhouse gases in the earth's atmosphere.

Geomorphology

Geology studies earth structures and processes. **Geomorphology** is the study the earth's surface structures and the processes that change them. **Fluvial geomorphology** focuses on the structure and dynamics of stream and river corridors. This is important to grasping:

- stream and river channel formation,
- alteration,

Figure 2.1 - Geomorphology helps explain river and watershed processes. Brazos River. Image courtesy of TPWD.

- flood plains, and
- their upland transitional zones.

Hydrology

Hydrology is the study of water, including the movement, distribution, and quality of water. The water cycle, or hydrologic cycle, (Figure 2.2) includes water in all its forms (liquid, gas, and solid) on, in, and over the land areas of the earth. This includes:

- distribution,
- circulation,
- behavior,
- chemical properties,
- physical properties, and
- the reactions of the environment (including all living things) on water itself.

This cycle, driven by our sun, is a natural process including:

- evaporation and transpiration,
- condensation,
- precipitation, and
- runoff.

The global water budget adds further insight into the water resources of our planet (Figure 2.3). Fresh-

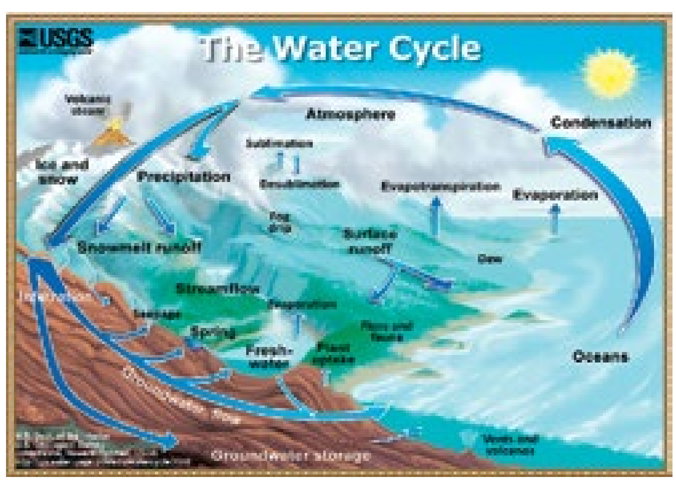


Figure 2.2 - The Hydrologic Cycle. Diagram courtesy of the USGS.

water, which is not evenly distributed, makes up only about 2.5% of all the water on the planet. The remaining water is seawater or saline (salty water). Only about 1% of the available freshwater is found on the earth's surface in lakes, rivers, and streams.

How we manage and conserve that small percentage of water is critically important to the health of aquatic ecosystems.

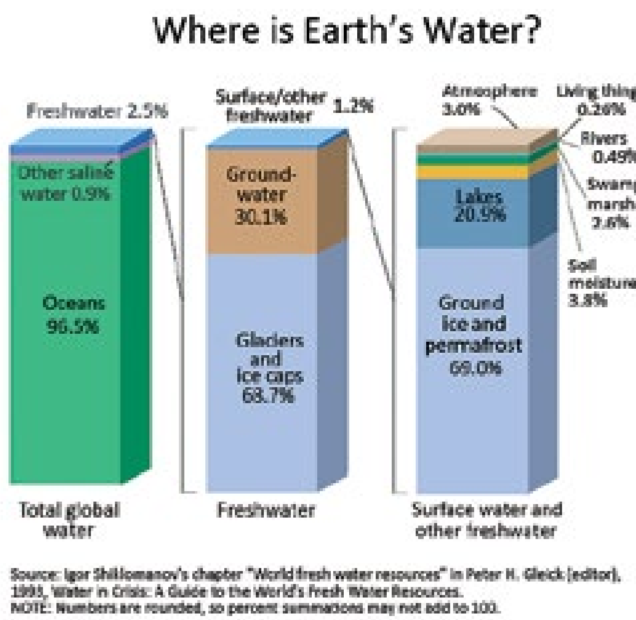


Figure 2.3 - The Global Water Budget. Diagram courtesy of the USGS.

Biotic Components
Food Webs and Trophic Ecology

Upon the template of climate, land, and water, living things thrive. These living things, the biotic component, are the fourth component of a healthy watershed ecosystem. Ecosystems have characteristic trophic (feeding) patterns hat express themselves in the form of food chains and food webs. These patterns organize the flow of energy into, through, and out of the watershed ecosystem. This supports the growth and reproduction of organisms within the system. Food "chains" are rarely linear, so we use the term food web to describe the trophic interactions of organisms within an ecosystem (Figure 2.4).

Within a food web, organisms interact with one another, directly or indirectly. Food webs can be very complex, with many interactions among land-based and water-based species. Food webs categorize the different roles species play:

- *Producers:* (plants) generate food, through photosynthesis.
- *Consumers:* exist in orders. First-order consumers are vegetarians, second-order consumers feed on first-order consumers, and so forth. Sometimes scientists call the different orders of consumers primary, secondary, tertiary, and so on.
- *Decomposers:* feed on dead tissue and return nutrients and energy to other parts of the cycle.

As we learned in **chapter one**, species with particularly far-reaching effects on an ecosystem are **keystone species**. These species differ from **dominant** (i.e., abundant) species. The effects of keystone species are much more pronounced than their abundance suggests. In other words, even though they may not be common, their presence has an important, even critical, effect on the configuration of communities and ecosystem function. A keystone species' presence is often the sole reason for the presence of other organisms and/ or the maintenance of unique ecological

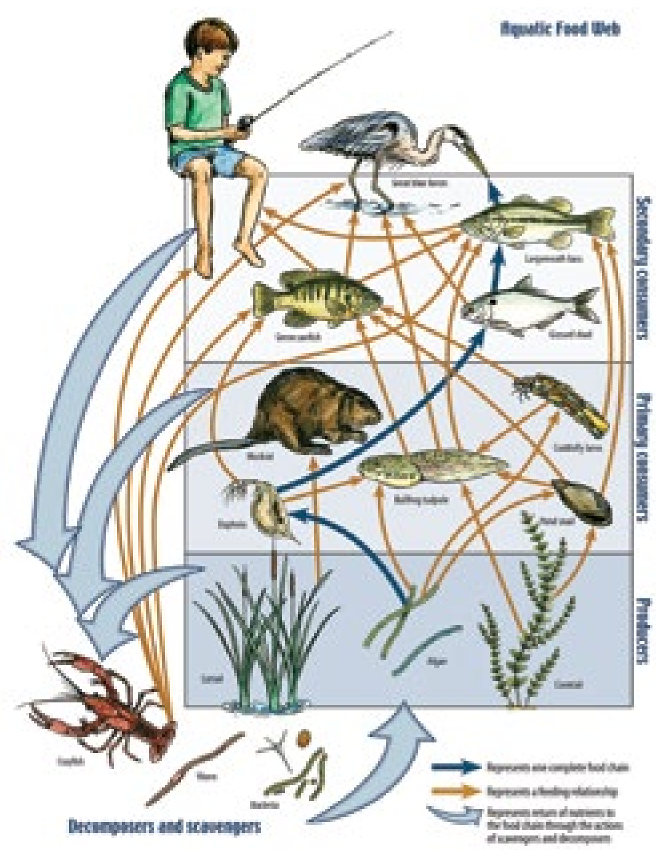


Figure 2.4 - Aquatic Food Web. Image used with permission from the Missouri Department of Conservation.

areas. The beaver is an example: it is an uncommon species, but is important since it modifies habitat structure by damming waterways and creates lakes, ponds, or flooded woodlands.

Indicator species show evidence of environmental change through their presence or absence. Nineteenth-century coal miners used to keep a caged canary with them in the mineshaft. When toxic gases were present, the canary would cease to sing before dying, thus alerting miners to danger.

The ever-aware miners could evacuate upon noticing the silent canary. Today we think of indicator species as modern-day canaries-in-a-coal mine. Watershed indicator species "intolerant" of poor water quality, such as frogs and salamanders, signal to humans that problems exist.

Figure 2.5 - Houston toad. Image courtesy of TPWD.

Amphibians often serve as indicators of human-induced global changes, since their characteristics make them particularly susceptible to environmental change. They live both in water and on land, have porous skin, and a notably omnivorous diet. Scientists studying localized **extinctions**, known as **extirpations**, or declines in amphibian populations often relate their findings to an **anthropogenic** (human caused) disturbance. For example, Houston toads are in decline in Texas due primarily to habitat loss and alteration.

Benthic macroinvertebrates are bottom dwelling organisms that one can see with the unaided eye. They lack a backbone. Stream and lake invertebrates display varying tolerances to different environmental factors. Some are more sensitive than others are to sedimentation, temperature changes, and food availability. Scientists categorize many as "intolerant" of many common pollutants. As such, many benthic macroinvertebrates are indicator species.

Biodiversity

Texas' many aquatic ecosystems are alike in that they are all aquatic homes for a variety of organisms. They are different in size, whether their hydrology is dominated by surface or groundwater, whether they are flowing or standing water, whether they are saltwater or freshwater, and whether they are inland or coastal. These characteristics help determine the organisms that can make each ecosystem its home.

Biodiversity refers to the variety and number of different organisms and populations in a community, and the way they live together. The greater the biodiversity in an ecosystem, the healthier, more sustainable and better balanced it is. Biodiversity is very important to the stability of an ecosystem. If many different species are present, then the loss of one or two species will probably not have a great effect, unless the loss includes keystone species. However, if species diversity is low, the loss of one or two species could have a major impact.

Figure 2.6 - Damselfly larva. Image courtesy of Jasper Nance, https://creativecommons.org/licenses/by-nc-nd/2.0/.

Some types of human activity can destroy habitat, the main cause of species declines, thereby reducing biodiversity. Straightening a stream speeds up erosion and cuts out curves that shelter fish and other aquatic life. Draining a swamp eliminates wetland habitat. Dams and diversions on rivers alter hydrologic flow regimes which in turn causes negative impacts to fish habitat. You will learn much more about flow regimes in **chapter four**. The term regime refers to a system where there is a heavy ecological influence by one particular factor. Protecting and restoring a wide variety of habitat helps keep species from becoming endangered or extinct, helping to maintain biodiversity for healthy ecosystems.[1]

Categories of Biodiversity

Biodiversity has several categories. In general, it applies to the relative amount of biological elements in a given area. This is critically important to the health of watershed ecosystems because it provides a robust template on which the entire food web relies.

Figure 2.7 - Whooping cranes. Image courtesy of TPWD.

Genetic biodiversity describes the total number of genotypes, or genetic material, available within a given population. For example, whooping cranes were driven to the brink of extinction; at one point, the total global population stood at 14 individuals. Today, the population has returned to a more comfortable level. Still, the current population is limited to the genetic material, contained within those 14 birds. It will take eons and many, many generations for genetic diversity to build up again. Populations with low genetic biodiversity may be more susceptible to certain diseases given the limited amount of genetic resistance available. A "genetic bottleneck" refers to the loss of valuable survival traits from a population that has shrunk to a low level and then re-expanded.

Population biodiversity refers to the total number of populations a given species has worldwide. For instance, the Guadalupe Bass lives only in Texas and is the official state fish. It is endemic to the northern and eastern Edwards Plateau and is native to the Brazos, Colorado, Guadalupe, and San Antonio River basins. Other populations exist outside of the Edwards Plateau, primarily in the lower Colorado River. Introduced populations exist in the Nueces River system.

Species biodiversity is the total number of species found in a given area. Species biodiversity is quite high in the tropical regions of the world, while the number may be lower in temperate zones. In Texas, for instance, it is common to count on one hand the total number of tree species within an acre of land. In the tropics, the number of tree species found within an acre of land may be more than 250.

Earth's Extraordinary Biodiversity

One of the most striking features of the earth's biota is its extraordinary diversity, estimated to include about 10 million different species. One of the most obvious aspects of recent global change is the rapid decline of this diversity in many ecosystems. The decline is not limited to increased rates of species extinction. Rather, it includes losses in genetic and functional diversity across:

- population,
- community,
- ecosystem,
- landscape, and
- global scales.

The term biodiversity refers collectively to all these aspects of biotic diversity. The wide-ranging decline in biodiversity results largely from:

- habitat modifications and destruction,
- increased rates of invasions by deliberately or accidentally introduced non-native species,
- over-exploitation,
- and other human-caused impacts.

On a global scale, even at the lowest estimated current extinction rate, about half of all species could be extinct within 100 years. Such an event would be similar in magnitude to the five mass extinction events in the 3.5 billion year history of life on earth. Pronounced local and regional biodiversity declines typically result from natural ecosystem conversion. These conversions include changes from native habitats to croplands, urbanization, timber plantations, aquaculture and other managed ecosystems. The diversity of managed ecosystems is often low, and species composition very different from those of the natural systems they have replaced.

Biodiversity's Impact on Ecosystem Functioning

Ecosystem functioning reflects the collective life activities of plants, animals, and microbes. It also reflects the activities and the impact their effects (feeding, growing, moving, excreting waste, etc.) have on the physical and chemical conditions of their environment.

A functioning ecosystem exhibits biological and chemical activities characteristic for its type. Critical ecosystem processes that ultimately affect human welfare influence:

- plant productivity,
- soil fertility,
- water quality,
- atmospheric chemistry, and
- many other local and global environmental conditions.

Plants, animals and microbes live in the community of aquatic ecosystems and play a critical role in the processes listed above. Human modifications to the living community in an ecosystem can alter ecological functions and services vital to our own well-being. Substantial changes, such as local and global losses of biodiversity, have already occurred.

These things we know:

- Human impacts on global biodiversity have been dramatic, resulting in unprecedented losses in global biodiversity at all levels, from genes and species to entire ecosystems;
- Local declines in biodiversity are even more dramatic than global declines, and the beneficial effects of many organisms on local processes are lost long before the species become globally extinct;
- Many ecosystem processes are sensitive to declines in biodiversity;
- Changes in the identity and abundance of species in an ecosystem can be as important as changes in biodiversity in influencing ecosystem processes.
- Current research identifies the following impacts on ecosystem functioning that often result from loss of biodiversity:
- Plant production may decline as regional and local diversity declines;
- Ecosystem resistance to environmental perturbations, such as drought, may be lessened as biodiversity is reduced;
- Ecosystem processes such as soil nitrogen levels, water use, plant productivity, and pest and disease cycles may become more variable as diversity declines.[2]

The Natural Systems Concept

So far, you have learned about the biotic and abiotic components from which watersheds develop. The physical template (Climatology, Geomorphology, and Hydrology) is the canvas upon which the painting (the biological setting) is placed. The interactions and natural processes that link these biotic and abiotic components, exhibit **system-like behavior**.

The dictionary defines a **system** as "a group of interrelated, interacting, or interdependent constituents forming a complex whole." We have seen that natural systems such as watersheds have interacting components that:

- *perform work:* (e.g., transport sediment, water, and energy), and
- *generate products:* (e.g., form new physical structures like floodplains or channels, and form biological communities and new energy outputs).

In a natural system, each of the physical and biological components of watersheds if they existed separately would not be capable of generating the work and the products that the intact watershed system can generate. In other words, these interactions make the whole greater than the sum of its parts.

The natural systems concept is key to your understanding because it emphasizes that a watershed, as a natural system, is more than just a variety of natural resources coincidentally occurring in one place. Severely degraded watersheds may have lost several of

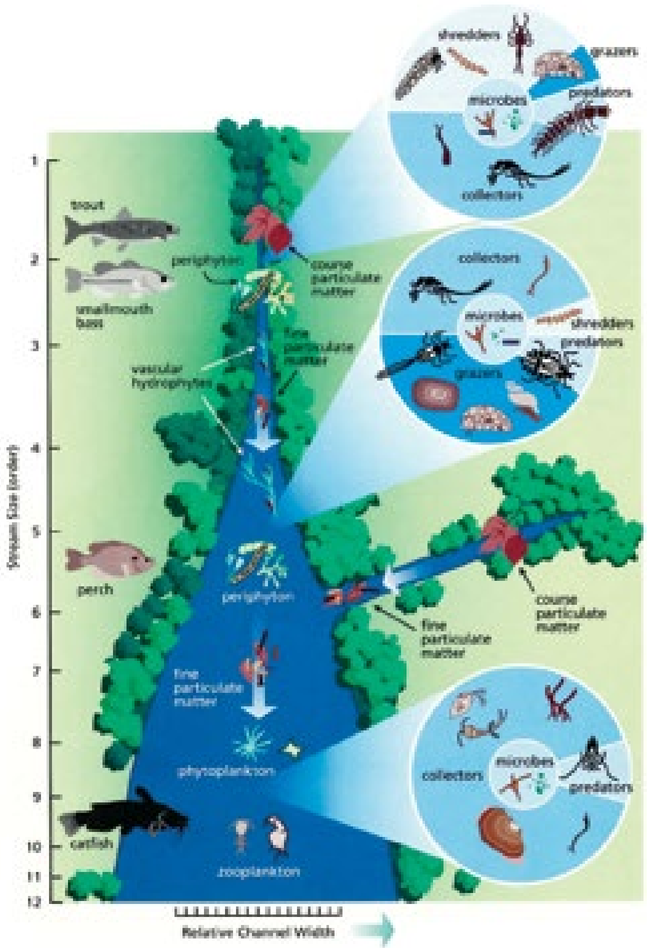


Figure 2.8 - The River Continuum Concept (Source: Vannote ET AL. 1980. © Canadian Science Publishing or its licensors. Used with permission from NRC Research Press).

Figure 2.9 - Components of watershed structure. Image used with permission from the Missouri Department of Conservation.

their components and functions, resulting in fewer benefits to human and natural communities.

The River Continuum Concept

This concept[3] is a generalization of the physical and biological patterns often seen in different zones of rivers from the headwaters to the mouth.

Conceptually, from headwaters to outlet, there exists a gradient of physical and biological conditions. Early order streams have more shredders, for example, breaking down organic matter into smaller bits. Downstream, more filter feeders are found and species richness increases.

Geomorphologists have shown that flowing water systems display patterns in the relationship of a number of physical characteristics (e.g., stream width, depth, velocity, sediment bedload) along their entire length. Biotic characteristics in each zone reflect their position in the continuum. In other words, similar natural systems often develop under similar conditions. As we move from the headwaters to a downstream reach, we see a continuum of physical conditions and a subsequent response in biota within these aquatic systems.

Watershed Structure

Now that you have reviewed the physical and biological components of watersheds and considered that together they comprise organized, functional systems, we'll now discuss watershed structure. This includes structure of **flowing waters** (mainly rivers and streams with their wetlands and **riparian zones**), **still waters** (lakes and associated basin-type wetlands and shorelands), and **upland areas** of watersheds.

Flowing Water Systems

Texas has more than 191,000 miles of rivers and streams, seven major estuaries, over 1000 public water bodies and approximately 200 major springs.

Flowing water or lotic systems commonly go through structural changes en route from their source to mouth. Three zones are usually recognized:

- *Headwaters:* where flow is usually lowest of anywhere along the system, river bed slope is often steepest, and erosion is greater than sediment deposition
- *Transfer zone:* the middle range of the stream where river bed slope usually flattens somewhat, more water flow appears, and deposition and erosion are both significant processes;
- *Lastly, the downstream end's* **depositional zone**, *where water flow is highest but river bed slope is minimal and deposition of sediment significantly exceeds erosion most of the time.*

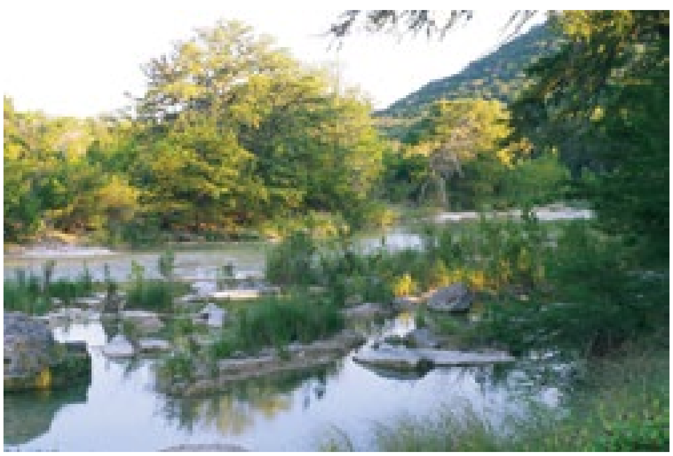


Figure 2.10 - Frio River at Garner State Park. Image courtesy of Johnnie Smith.

Watershed Form

All watersheds share a common definition: a watershed is an "area of land that drains water, sediment, and dissolved materials to a common outlet at some point along a stream channel."[4]

Drainage Patterns

One distinctive aspect of a watershed when observed in map view is its drainage pattern (the pattern of creeks, streams and rivers that represent the flow of water across the land). Drainage patterns are primarily controlled by the overall topography and underlying geologic structure of the watershed.

Drainage Density

Drainage density describes the total length of streams in a watershed divided by the total drainage area of the drainage basin. The more streams there are in a given area, the higher the drainage density. Controls on drainage density are climate and geology. Basins with a high drainage density tend to be "flashy" with a short lag time between rainfall and flood peak.

Stream Ordering

A method of classifying, or ordering, the hierarchy of natural channels within a watershed was developed by Horton.[5] Several modifications of the original stream-ordering scheme have been proposed, but the modified system of Strahler[6] is probably the most popular today and is well-known classification based on stream/tributary relationships. The uppermost channels in a drainage network (i.e., headwater channels with no upstream tributaries) are designated as first-order streams down to their first confluence. A second-order stream forms below the confluence of two first-order channels.

Third-order streams are created when two second-order channels join, and so on. Note in the figure that the intersection of a channel with another channel of lower order does not raise the order of the stream below the intersection (e.g., a fourth-order stream intersecting with a second- order stream is still a fourth- order stream below the intersection). Within a given drainage basin, stream order correlates well with other basin parameters, such as drainage area or channel length. Consequently, knowing what order a stream is can provide clues concerning other characteristics such as which longitudinal zone it resides in and relative channel size and depth.

Stream Channel Classification

Stream order plays a large part in determining the aquatic community it supports due to factors such as elevation, canopy cover, and inputs of organic material and sediments.

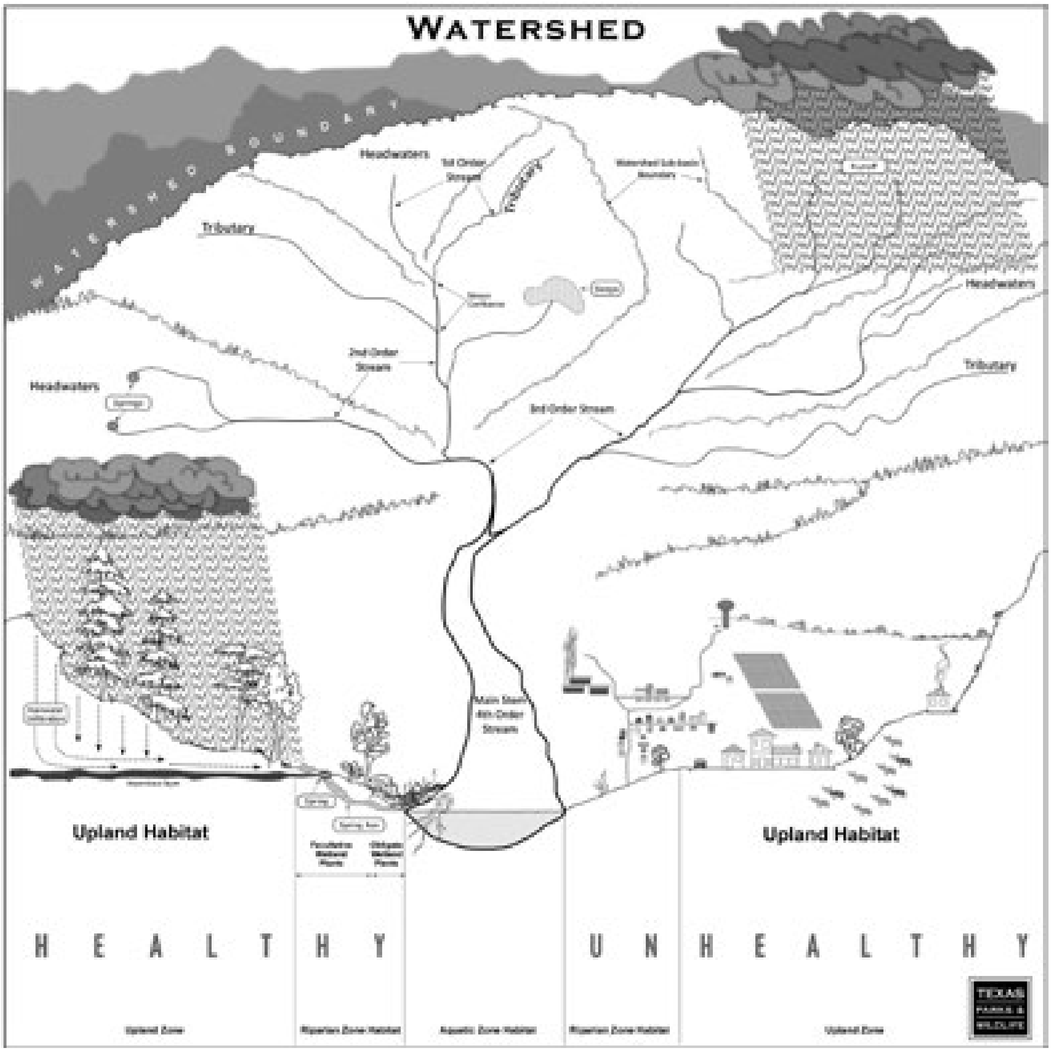


Figure 2.11 - Stream Order. Image courtesy of TPWD.

"Still" Water Systems

Still water, or lentic systems generally include lakes and ponds. A lake's structure has a significant impact on its biological, chemical, and physical features. Some lentic systems may be fresh water bodies, while others have varying levels of salinity. Most basin-type wetlands belong within lentic systems; these are areas of constant soil saturation or inundation with distinct vegetative and faunal communities. Lakes and ponds are usually connected with streams in the same watershed. The method of lake formation is the basis for classifying different lake types. Natural processes of formation most commonly include glacial, volcanic, and tectonic forces while dams, or excavation of basins, create human constructed lakes. In his classic review of lake types, Hutchinson (1957) describes 76 different types of lakes. Caddo Lake in Texas is naturally occurring. There are also many playa lakes, marsh lakes, and oxbows or resacas that are naturally occurring in Texas. The rest though, are constructed reservoirs or impoundments. Although on human time scales we may think of lakes as permanent, they are short-lived features on the landscape. They are depressions in the earth's surface in regions where water is available to fill the basin. Over time, lakes fill with sediments and organic material while outlets tend to erode the lake rim away. There are multiple types of lakes, many of which do not exist in Texas.

Glacial Lakes

Most of North America's lakes, including the Great Lakes, formed during the most recent cycle of glacial activity (approx. 10,000 to 20,000 years ago). Although glaciers can form lakes through several unique processes, glacier's weight and movement carved out most basins. Others were created when

Figure 2.12 - Stream order determines aquatic community. Image used with permission from the Missouri Department of Conservation.

Figure 2.13 - Caddo Lake. Image courtesy of TPWD.

glacial debris formed dams. Glacial moraine dams are responsible for a number of lakes in North America (e.g., Lake Mendota in Wisconsin). Melting ice blocks left by retreating glaciers create kettle lakes (e.g., Walden Pond in Massachusetts).

Tectonic Basins

These basins form or are exposed due to movements of the earth's crust. This can result from uplifting as when irregular marine surfaces that collect freshwater after elevation (e.g., Lake Okeechobee in Florida), and tilting or folding to create depressions that form lake basins. Lakes also form along faults (e.g., several lakes in California).

Other processes of lake formation are generally less common, but responsible for the wide variety of lakes that we see across North America. Examples include:

Volcanic Lakes

Several different volcanic processes can form lake basins. Craters form natural basins (Crater Lake in Oregon) well known for their clear waters and lava dams can create basins in valleys.

Landslides

Rockfalls or mudslides that dam streams or rivers can form lakes for periods as short as a year to several centuries (e.g., several lakes in the Warner Range of northeastern California).

Solution Lakes

These lakes are in areas characterized by significant limestone deposits where percolating water creates cavities. These lakes are particularly common in Florida.

Plunge Pools

Although somewhat rare, these lakes formed when ancient waterfalls scoured out deep pools. They are often associated with glacial activity that diverted river flow (examples are Falls Lake in Washington and Green Lake in New York)

Playa Lakes

Playas are shallow, circular-shaped wetlands that are primarily filled by rainfall, although some playas found in cropland settings may also receive water from irrigation runoff. Playas average slightly more than 15 acres in size. Although larger playas may exceed 800 acres, most (around 87 percent) are smaller than 30 acres. Approximately 19,300 playas are found in the Texas High Plains, giving us the highest density of playas in North America.

Oxbow Lakes

Where rivers or streams have meandered across low gradients, oxbows can often form in areas where the former channel has become isolated from the rest of the river. Several examples are along the Mississippi River and along the Rio Grande in Texas, known as resacas.

Figure 2.14 - Oxbow lake formation. Image used with permission from the Missouri Department of Conservation.

Beaver-made and Human-made Lakes

Both humans and beavers create lakes when they dam rivers and streams. The Highland Lakes system is an example of human made lakes or reservoirs on the Lower Colorado River. In addition to the many large dams, there are upwards of one million small dams impounding lakes and ponds across the lower 48 states.

Structure in Upland Areas of Watersheds

Figure 2.15 - The complexity of landscape patterns in a watershed. Image courtesy of NRCS.

The physical form of the uplands in watersheds can vary greatly. Here we focus only on the distribution of and variations in vegetation and land use. Together, they create the element of watershed structure called **landscape pattern**. Vegetation and land use patterns in watersheds have significant influences on the condition of the water bodies into which they drain.

Landscape Patterns

Landscape ecology offers a simple set of concepts and terms for identifying basic landscape patterns: **matrix**, **patch**, and **mosaic**. The ecological term **matrix** refers to the dominant land cover (> 60 percent), while a **patch** is a nonlinear area that is less abundant and different from the matrix. A **mosaic** is a collection of different patches comprising an area where there is no dominant matrix. The most obvious landscape patterns are combinations of native vegetation communities, unvegetated areas, and land use patterns.

Examples of different patch types include:

- A **disturbance patch** results from an alteration or disturbance.
- A **remnant patch** is one that survives disturbance for some extended period.
- An **environmental patch** exists due to the natural variation of the environment (such as a soil type).
- A **regenerated patch** resembles a remnant patch, except that it has regrown on a previously disturbed site.
- **Corridors** are uniquely important types of patches that link other patches in the matrix (e.g., a river channel, riparian or buffer zone).
- Finally, a human process (e.g., a clear-cut or a stand of planted trees) creates an **introduced patch**.

The individual patches in a landscape can change. In fact, the entire landscape can change in pattern and/or composition. Disturbances and various landscape processes maintain a constant dynamic, called a **shifting mosaic**. Some remain in a "**dynamic equilibrium**" and, although changing steadily from place to place, retain an important quality called **mosaic stability**. A well-managed forestry operation, for example, would exhibit over the long term a constantly shifting set of locations where mature forest occurred, but at the same time sustain the relative proportions of forested and non-forested land in the area. Alternatively, a landscape may evolve toward a new type of pattern and composition. These might include:

- timber clearcutting,
- urban and suburban sprawl,
- abandonment and succession of agricultural lands back to forest, or
- landscape change due to disease, fire, or global warming.

When analyzing landscape pattern and landscape change, remain aware that your perspective or viewpoint **may or may not be sufficient** to detect all the landscape changes of possible significance that may be occurring.

Vegetational Patterns

Upland vegetation structure varies from place to place, following patterns based on climate, geography, soils, disturbance, and their interactions. **Vegetation communities** are areas where a few species of plants domi-

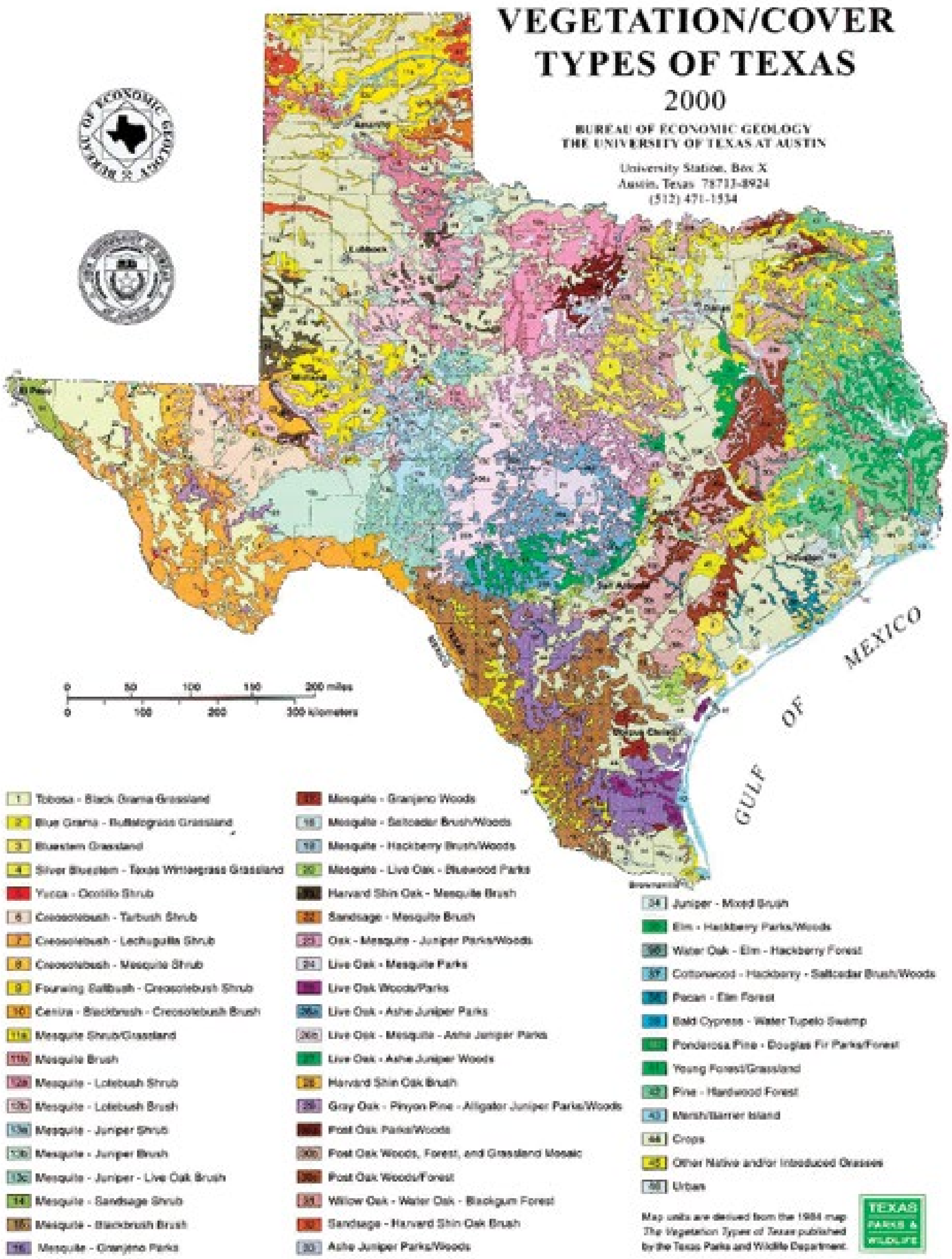


Figure 2.16 - Vegetation/cover types of Texas. Image courtesy of the Texas Bureau of Economic Geology.

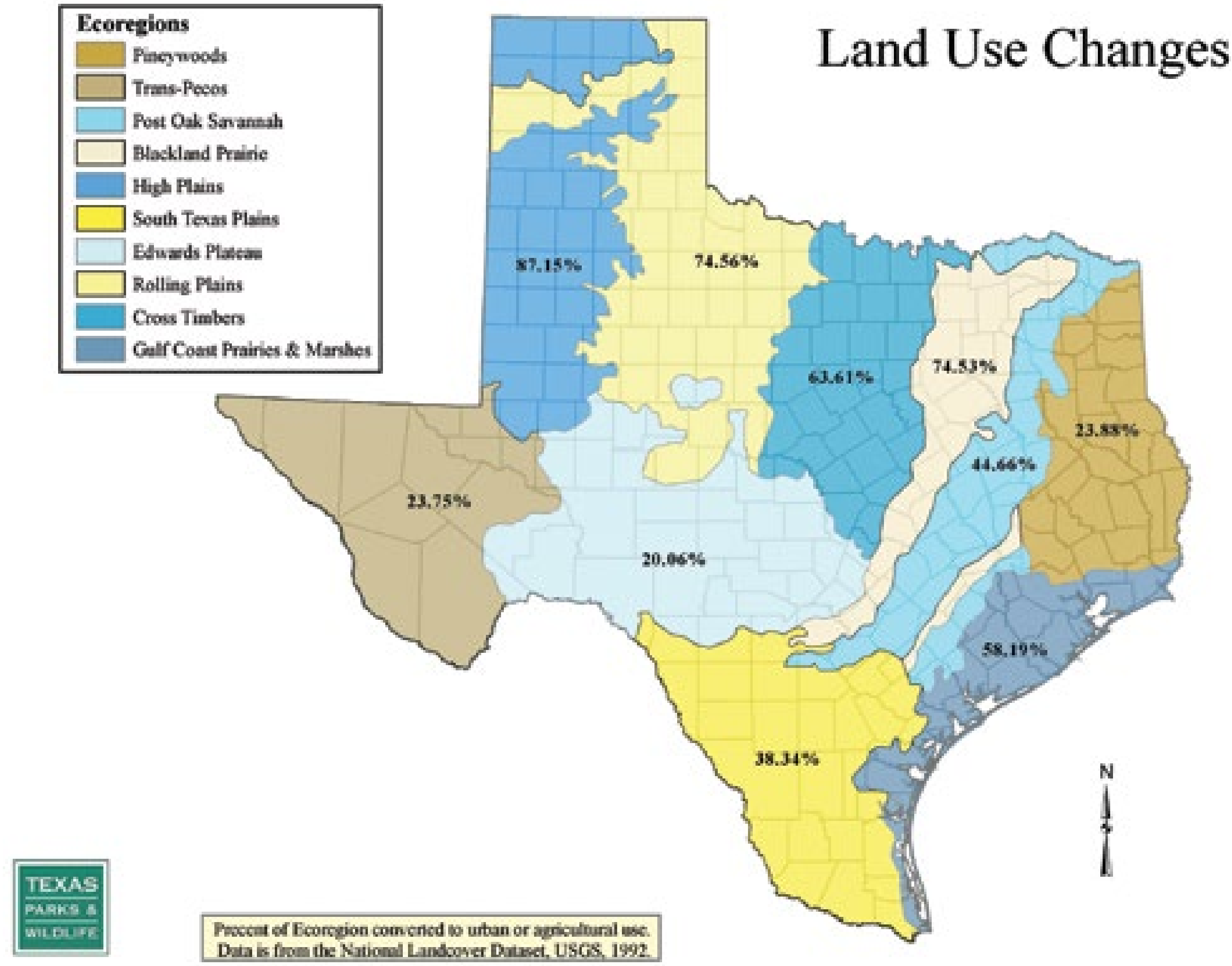


Figure 2.17 - Land Use Changes. Image courtesy of TPWD.

nate and establish a characteristic form or structure. In such a community, a potentially large number of less abundant organisms also exist. As a first step in analyzing vegetational patterns, it is easier to recognize a few generalized upland vegetation types based on their growth form, including:

- forests (deciduous, evergreen and mixed),
- shrubland,
- grassland, and
- forbs (broad-leaved herbs).

You can find these categories on land cover maps likely to be available in the Geographic Information Systems (GIS) data for most watersheds. One may consult these to give a general sense of vegetation patterns in the watershed. Human activity has carved up and fragmented many of the natural vegetation patterns that formerly covered our watersheds. Without human influence, however, vegetation patterns would not be uniform due to different vegetation communities arising from different environmental conditions (e.g., variations in moisture and temperature due to slope and aspect) and events (e.g., fire, pest outbreak).

Land-use Patterns

Increasingly, the landscape structure and pattern we see is the result of widespread human activity. Some common land cover categories (indicating land uses within the areas) include:

- urban land (residential, commercial, industrial, mixed),
- agriculture (row crops, field crops, pasture),
- transportation (roads, railroads, airports),

- rangelands,
- forestry, and
- mining/extractive areas.

Like vegetation patterns, land use patterns in a watershed are studied through GIS data or maps. Human-dominated landscapes, just as natural landscapes, are shifting mosaics that often progress through a series of changes in what is dominant.

Texas has undergone tremendous changes since human habitation began spreading across the state. We have converted lands for agriculture, for human settlement and the infrastructure that requires. Although the data in this map is dated, it reflects that as of 1992, we have converted over fifty-one percent of our lands to agricultural or urban use. Since the early 1990s, Texas' population has grown from approximately 17 million to 27 million. We are rapidly converting large privately owned farms and ranches, working lands, to subdivided and fragmented parcels.

Summary

In this chapter, you have learned about the complex relationship between water, the land and climate. You have learned how these natural forces work together to shape a watershed and shape the land. We described for you the Natural Systems Concept; further, we explained how the River Continuum Concept sets up the dynamic between flow, channel structure, the plant and animal species these dictate, and the web of their interactions. We discussed the complex mosaic of the lands that make up Texas' watersheds. From differing landscape, vegetation, and land use patterns you have learned that our watersheds face a wide range of interrelated factors that affect watershed ecosystem health. As water flows across our state through watersheds, creeks, streams, and rivers, each of the factors we have discussed play a role in water quality and watershed health. Lastly, you learned how vitally important a role biodiversity plays in the health of watersheds and the aquatic ecosystems they contain. Biodiversity is the glue that holds watershed and ecosystem structure together. In **chapter three**, we will delve deeper into the structure and function of a watershed and its role as a natural system.

Challenge

Consider the watershed in which you live. You can use Texas Parks and Wildlife's Watershed Viewer https://tpwd.maps.arcgis.com/apps/Viewer/index.html?appid=2b3604bf9ced441a98c500763b8b1048 to see your watershed and the various creeks and streams that flow into and out of it. Identify and order the different streams in your watershed and locate the primary stream channel that flows into the Gulf of Mexico.

References

1. (Johnson, 2013)
2. (Shahid Naeem, 1999)
3. (Vannote, 1980)
4. (Dunne, 1978)
5. (Horton, 1945)
6. (Strahler, 1957)

Chapter Three:

The Watershed's Role as a Natural System

Blooming Lily pads in a freshwater wetland. Image courtesy of TPWD.

Chapter Three:
The Watershed's Role as a Natural System

Questions to Consider

- What is the primary role that flowing water plays in a watershed?
- Is erosion a bad thing?
- How do watersheds use the various nutrients that pass through them, and what role do they play in trophic interactions?

Introduction

In **chapter two**, we explored how the land, climate, and flowing water work together to create a watershed ecosystem. We have described the basic building blocks of watersheds, their structure and pattern. We also learned about the Natural Systems Concept, meaning that each of the physical and biological components of watersheds if they existed separately would not be capable of generating the work and the products that the intact watershed system can generate. In other words, these interactions make the whole greater than the sum of its parts. Now, let's consider the watershed's role as a natural system as we dive into a discussion of a few of the essential functions that occur in most healthy watersheds. These include:

- transport and storage,
- cycling and transformation, and
- ecological succession.

Thus far, we have gradually added layer upon layer of information about watersheds. Here we explore how watersheds as natural systems are capable of performing many complex functions. Along the way, recall the elements of the physical template, the biological setting, the characteristics of natural systems, and our discussion of watershed structure.

Watershed Functions
Transport and Storage

Since a watershed drains to a common body of water, one of its main functions is to store and transport water. It does this from the land surface to the water body and onward to the ocean. In addition, watersheds transport sediment and other materials (including pollutants), energy, and many types of organisms.

These terms are useful in describing the movement of matter through the watershed:

1. **Availability** is not just the presence of an element in a system, but also its usability. For instance, nitrogen gas may be plentiful in and around dam spillways, but nitrogen gas is not a usable form of nitrogen for most aquatic organisms.
2. **Detachment** refers to the release of matter from an anchoring point, and its ensuing movement.
3. **Transport**, a process most evident in stream channels, involves the movement of material through a system.
4. **Deposition** is the settling or dropping out of sediments and particulates.
5. **Integration** is the assimilation of matter into a site or organism following deposition.[1]

Water

A watershed is simply a huge water collecting and routing device. However, these key processes involve a complex mix of many smaller processes.

1. Before **precipitation** reaches the ground, it interacts with vegetation. Trees and other vegetation are responsible for **interception** and **detention** of some of the rainfall. This leads to some degree of **evaporation**. **Throughfall** (precipitation passing through the leaves, stems and branches of vegetation) slows the water that reaches the ground.
2. This allows time for better **infiltration** to groundwater (one form of **storage**). **Saturation** of soils leads to **overland flow** and, over longer periods, development of a **drainage network**.
3. The consistent flow of water in channels affects and shapes **channel development and**

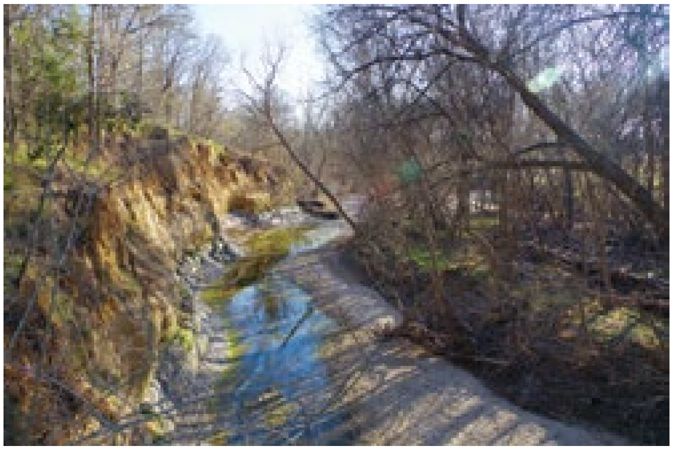


Figure 3.1 - Erosion on Williamson Creek. Image courtesy of Johnnie Smith.

morphology in ways that seek **dynamic equilibrium**. Recall our earlier discussion of the channel development of rivers and streams. Upper, middle and lower zones of streams generally have very different forms in order to handle different sets of functions. Many of these relate to the transport and storage of water.

Sediment

Another major function of watersheds is to collect and transport sediments. Sediment transport and storage is also a complex network of smaller watershed processes and is inseparable from water transport and storage. Sediment related processes mostly involve **erosion** and **deposition**, but sediment transport and storage also play a longer-term role in **soil development**.

At first glance, the dominant process in **drainage network development** and **channel development** discussed above appears to be erosion, but the redepositing of sediments on floodplains is an equally important function. It rejuvenates soils and influences the productivity and diversity of stream corridor ecosystems.

Seston

Watersheds also transport and store **seston** (suspended particulate matter). It is an important food source for key aquatic organisms. Seston includes all particulates: plankton, organic **detritus**, and inorganic material. For example, attached algae begin to grow on rocks and submerged surfaces (**availability**). During growth and maturation, algal cells begin to slough off from the rocks and logs (**detachment**) and the current carries these cells, rich in **chlorophyll**, downstream (**transport**). Caddisfly larvae, which feed on seston, spin elaborate nets (much like a spider's web), anchoring these nets on cobble substrates or other submerged features. These nets catch the suspended particulates as they drift with the current (**deposition**). The caddisfly larvae then feed off particles captured in the net (**integration**); algal cells represent high quality food for these organisms, which in turn become available food to other organisms. In this way, watershed function enables the first trophic level of a food chain.

Cycling and Transformation

Cycling and **transformation** are another broad class of natural functions in watersheds. Various elements and materials (including water) are in constant cycle through watersheds. Their interactions drive countless other watershed functions. Elements like carbon, nitrogen, and phosphorus make up the watershed's most important biogeochemical cycles.

Nutrient Spiraling

The flow of energy and nutrients in ecosystems are cyclic, but open-ended. True systems, in both an environmental and energetic context, are either "open" (meaning that there is some external input and/or output to the loop) or "closed" (meaning that the system is self-contained). In watersheds, streams and rivers represent an open-system situation where energy and matter cycles, but due to the one-way flow, the matter does not return to the spot from whence it came. In addition, nutrients "spiral" back and forth in:

- the water column,
- the bodies of terrestrial and aquatic organisms, and
- the soil of the stream corridor on their way downstream.

Hence, the concept of nutrient "spiraling" implies both movement downstream and multiple exchanges between the terrestrial and aquatic environment, as well as between **biotic** and **abiotic** components of the watershed.

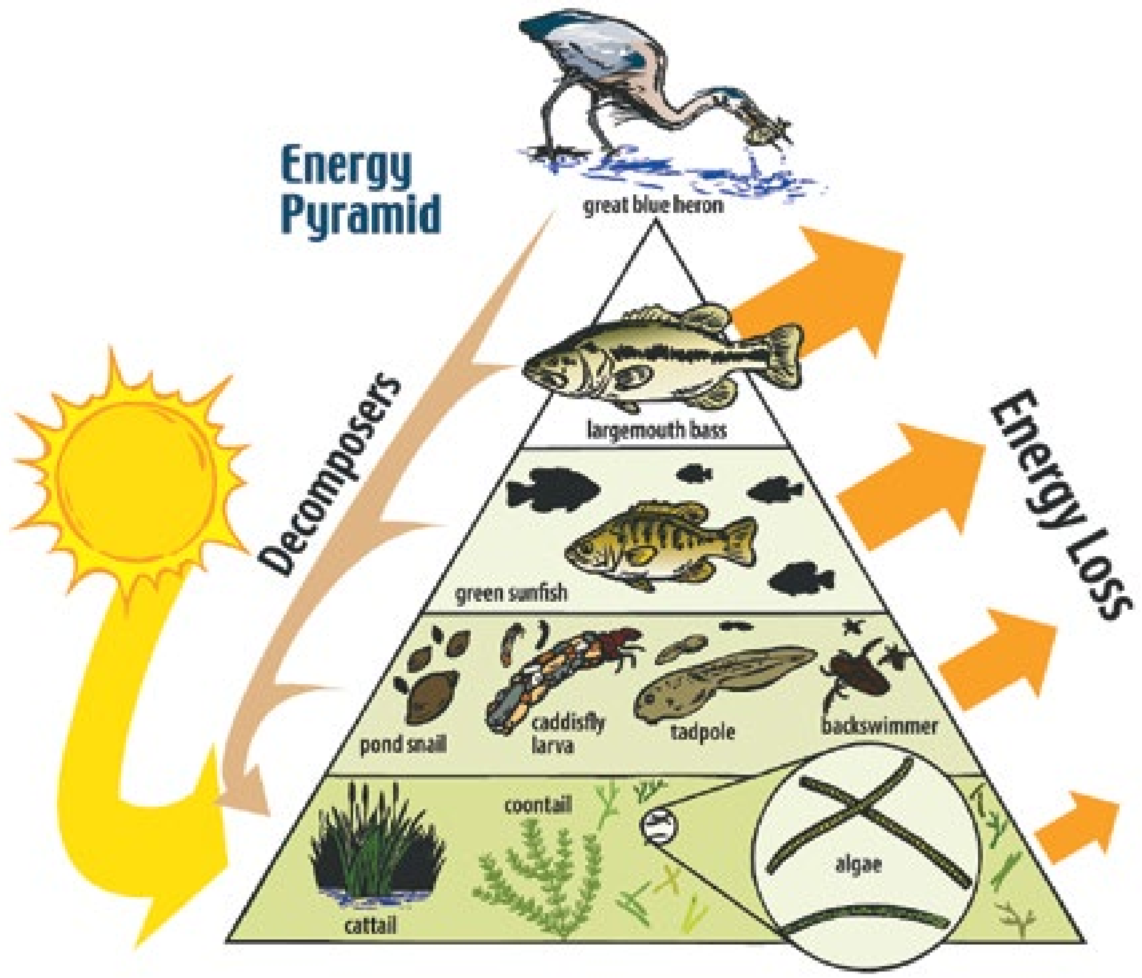


Figure 3.2 - Energy Transfer and Losses. Image used with permission from the Missouri Department of Conservation.

Cycling of Carbon and Energy

In food webs, carbon and the energy it produces cycle through trophic levels. Energy transfer is inefficient, though, with about a ninety percent loss of energy from one trophic level to the next. Since producers (plants) are the beginning of aquatic food webs and provide food and energy to aquatic animals, it is important to understand how they get their nutrients.

Nitrogen (N)

N_2 (gaseous state of nitrogen) is not usable by plants and most algae. N-fixing bacteria or blue-green algae transform it into nitrite (NO^2) or ammonia (NH^4). N-fixation, precipitation, surface water runoff , and groundwater are all sources of nitrogen. Nitrogen inputs from human activities such as application of industrially fixed nitrogen in fertilizers and planting of legume crops is now greater than natural inputs on land.

Phosphorus (P)

Phosphorus in unpolluted watersheds results from dust in precipitation, or via the weathering of rock. Phosphorus is normally present in watersheds in extremely small amounts.

Nitrogen and Phosphorus Limitation

Watershed systems have nutrient requirements similar to garden soil. Both require nutrients in the right balance in order to produce plant growth. Most watershed systems are either N- or P-limited, in that these are the required elements present at the lowest availability relative to primary producers' need for them.

As a rule, the N:P ratio should be 15-16:1. A lower ratio would indicate that N is limiting, a higher ratio places P in that role. In freshwater ecosystems, commonly P is the limiting factor, but co-limitation can occur. Often, the slightest increase in P can trigger

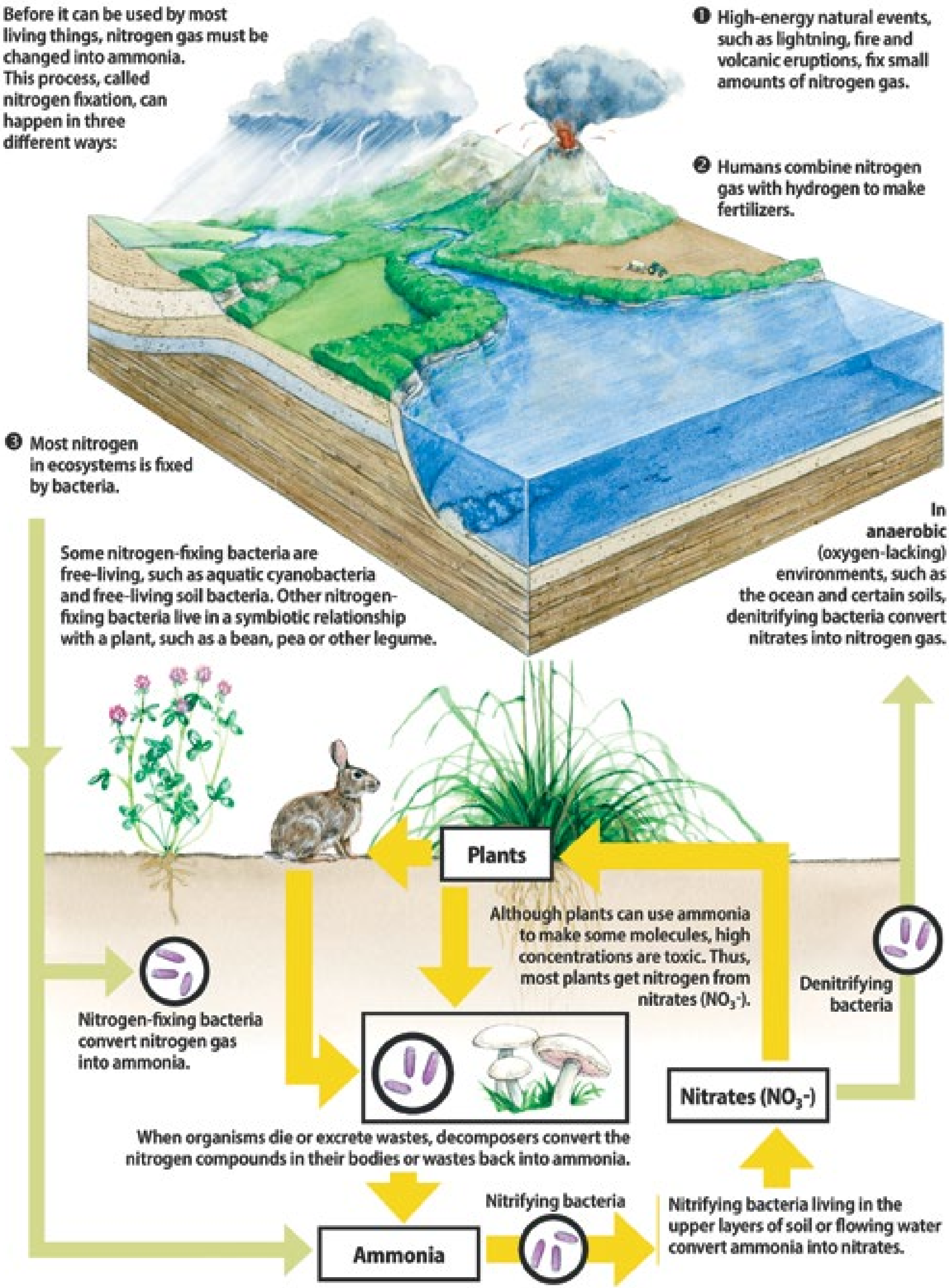


Figure 3.3 - Physical and biological components of the nitrogen cycle. Image used with permission from the Missouri Department of Conservation.

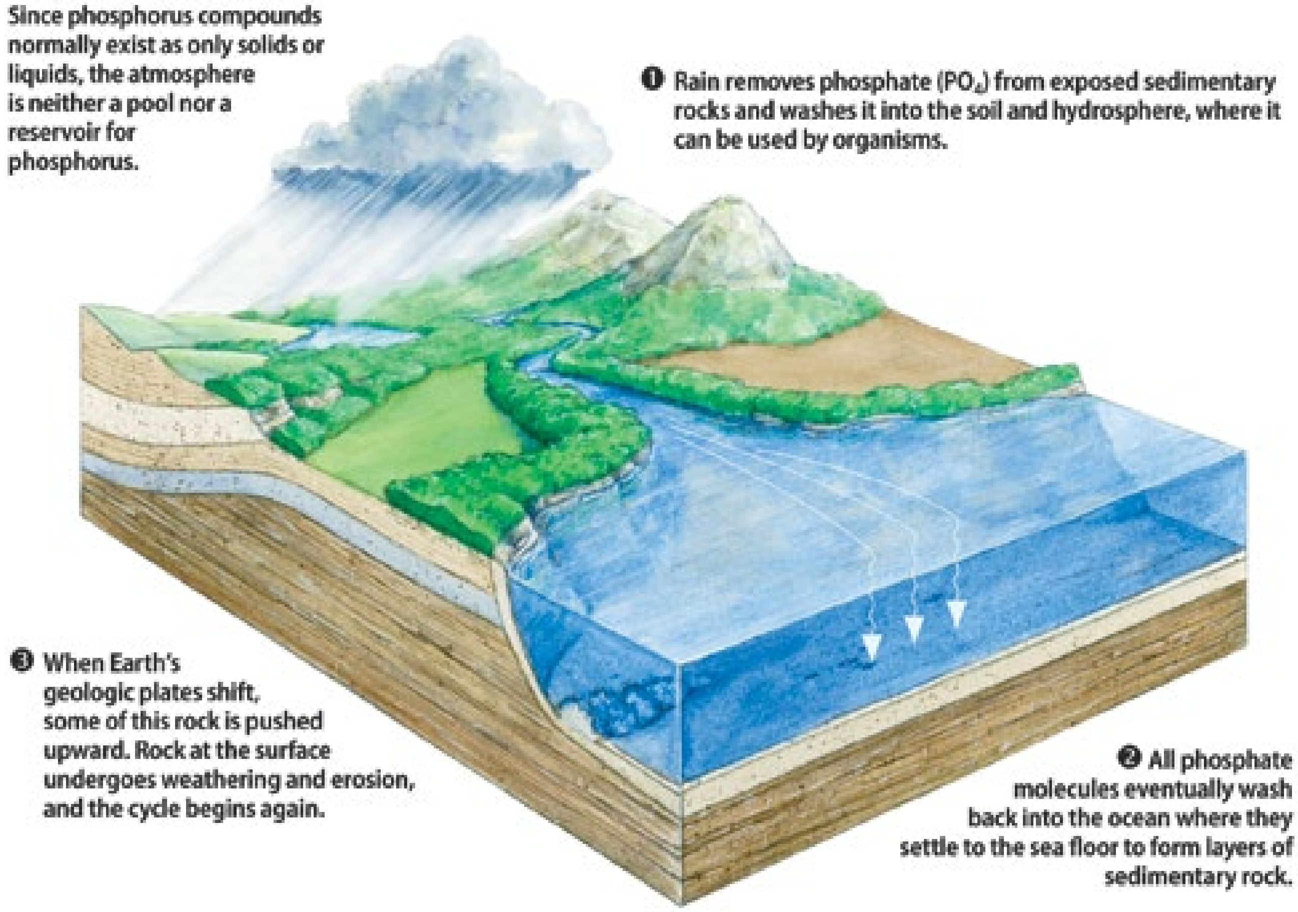


Figure 3.4 - Phosphorus cycle. Image used with permission from the Missouri Department of Conservation.

growth, as in algal blooms in an aquatic setting. In N- and P-limited systems, an input of either element above normal, "natural" levels may lead to **eutrophication** (excessive nutrient input in a body of water that causes excessive plant and algae growth).

The stream corridor is often a mediator of upland–terrestrial nutrient exchanges. As N and P move down through groundwater flow, **riparian zone** root systems often filter and utilize N and P, leaving less to reach the stream. This has a positive influence on bodies of water already nutrient overloaded, but a negative influence on organisms struggling to find food in very clean, nutrient-limited headwaters streams.

Decomposition

Mostly as the result of differences in rates of decomposition, the rates at which nutrients cycle in ecosystems can vary greatly. Decomposition involves the reduction of energy-rich organic matter (detritus), mostly by microorganisms (fungi, bacteria, and protozoa) to CO^2 , H_2O and inorganic nutrients.

Through this process, they perform two functions:

1. They release nutrients, making them available for other organisms.
2. They transform organic material into energy usable by other organisms.

In the headwater reaches of streams, external sources of carbon from upland forests (leaves, stems, etc.) are a particularly important source of organic material. The decomposition of microscopic particles occurs very rapidly. Bacteria and fungi decompose the organic material and make it an important food source for invertebrate and vertebrate **detritivores**. In this way, they reinsert these nutrients and materials into the watershed's aquatic and terrestrial food webs.

Influential factors in decomposition are:

- moisture,
- temperature,
- exposure,
- type of microbial substrate, and
- vegetation, etc.

Specifically, temperature and moisture affect the rate of decomposition. Nutritional value (as well as palatability) of the organic matter will also affect the time involved in complete breakdown and mineralization.

Decomposition involves the following processes:

- the leaching of soluble compounds from dead organic matter,
- fragmentation,
- bacterial and fungal breakdown,
- consumption of bacterial and fungal organisms by animals,
- excretion of organic and inorganic compounds by animals, and
- clustering of organic matter into larger particles.

The processes of death and consumption, along with the leaching of soluble nutrients from the decomposing matter, release minerals contained in the biomass. This is the process of mineralization.

Ecological Succession

The traditional definition of plant succession involves a predictable set of vegetative changes. These changes happen through a series of stages. Within the watershed, succession varies with spatial scale, elevation, and topography. Rather than being a static situation, the riparian landscape is in **dynamic equilibrium**, in that various patches make up a shifting mosaic of successional stages.

In watershed terms, succession is a process that circulates significant amounts of the watershed's energy, water, and materials from the abiotic environment back into the biotic, and up and down the energy pyramid. Succession builds and gradually changes vegetational structure. This structure serves many critical functions such as maintaining varied habitat, providing food sources, and reestablishing renewable resources for human use, like woodlots.

Example: Riparian Succession

Stages

1. The **early** successional stage in a riparian area displays bare stream banks with little vegetative cover. The stream flow is relatively unrestricted.
2. In **mid**-successional stage areas, one sees deposition along the stream bank with herbaceous and woody cover developing.
3. The **late** successional stage shows deposition of sediment along the stream banks, good woody and herbaceous cover, and woody debris in the floodplain and stream.

Along the stream, riparian vegetation experiences periodic spates of flooding, erosion and redeposition. As such, the life history patterns and physical adaptations of different tree, shrub and herbaceous species will enable them to dominate in different stages of riparian succession. As natural variations such as flood events and drought conditions occur, vegetation in riparian zones can experience wide swings in successional stages. Areas with high rates of disturbance may never vegetate much past the early and mid-successional stages.

Plant Strategies

The following are some common plant strategies for survival in the riparian corridor:

- *Invaders:* for instance, are typically the first trees to establish themselves following a landscape disturbance such as a flood or landslide. Examples of invaders are box elder and willow.
- *Resisters:* are those species, which are adapted to resist the stress of their environment. In riparian corridors, these are species that can withstand the force of intense floods. The flexible, "whippy" stems of willow trees serve as an example of a resister-like adaptation.
- *Endurers:* are species that endure floods by timing or mode of reproduction. Cottonwood, willow, and dogwood may reproduce

by sprouting from a severed and deposited branch.

- *Evaders:* reproductively "wait out" the process of disturbance by producing seeds that are capable of experiencing dormancy through the given disturbance. Riparian trees do not exhibit this strategy, but many riparian understory species do.
- *Avoiders:* find a way to survive disturbances by not growing in regions of frequent perturbation. In general, conifers take root and exist in riparian systems only in areas where the intensity and frequency of disturbances are low.
- *What results is a mosaic of patch types on a small scale within the riparian zone.* Protected areas and those that experience frequent erosion and deposition, create a patchwork of various soil types and successional stages within the stream corridor. Woody debris, large enough and decay-resistant enough to withstand fluvial processes, can create "islands" of refuge where conifers may eventually be able to take root again near the stream channel. This "process loop" between woody debris deposition, early to mid-stage vegetation establishment, and eventual late stage establishment (and the prospect of recurring woody debris deposition) represents an example of a riparian successional process.

Summary

As a follow-up to chapter two, this chapter further defines the watershed's role. Here you have learned about the transport and storage roles and that they are not limited to water, but include sediment, nutrients, energy, and even organisms. As in your vegetable garden, aquatic habitats require a balance of nutrients. With a balance usually maintained through natural processes, human-caused change in a watershed may produce imbalance. This can result in system-wide problems as different areas of the food web are impacted. We will learn much more about changes in a watershed in **chapter seven** and **chapter eight**. Lastly, you learned about the various stages of succession that occur within a watershed and how they perform critical functions such as maintaining varied habitat, providing food sources, and reestablishing renewable resources.

Challenge

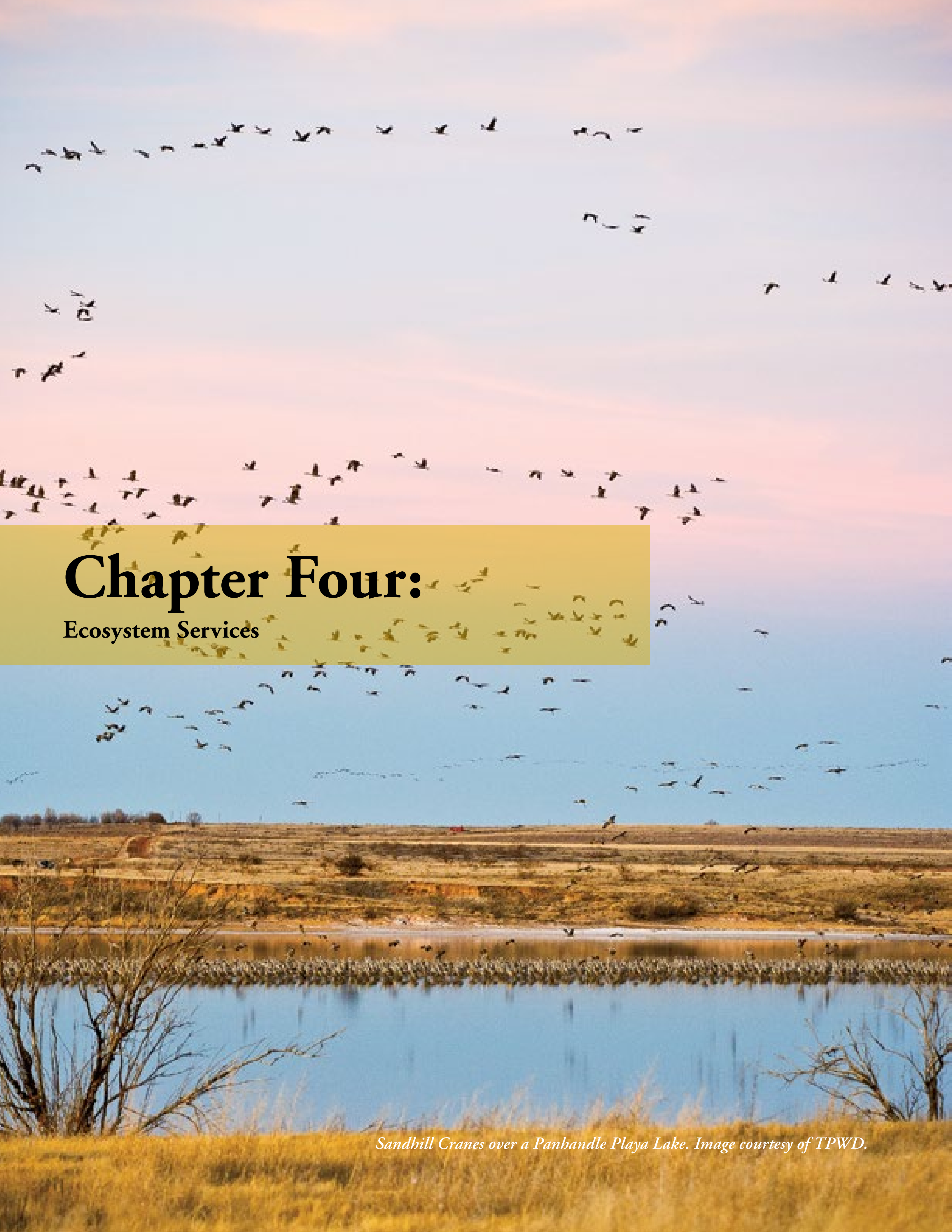
Look around the area where you live for signs of the transportation and storage roles water plays. Do they represent natural functions or are they reflective of human-caused changes in the landscape and watershed?

References

1. (Naiman, 1998)

Chapter Four:

Ecosystem Services



Sandhill Cranes over a Panhandle Playa Lake. Image courtesy of TPWD.

Chapter Four:
Ecosystem Services

Questions to Consider

- What are ecosystem services?
- What natural systems protect human settlements from flood and drought?
- What does soil do for humanity?
- What other ecosystem services are happening all around me, without my notice?

Introduction

An ecosystem is a dynamic system of plants, animals, and microorganism communities which interact with each other and the nonliving environment as a functional unit. Humans are an integral component of these systems and are in fact often the dominant organism. However, like all species, humans depend on a functioning ecosystem and on the network of interactions among organisms in an ecosystem and within and among multiple ecosystems. The values or benefits that humans derive from the interactions within and between ecosystems are called **ecosystem services**.

The term ecosystem services refers to a wide range of conditions and processes through which natural ecosystems and the species that are part of them, help sustain and fulfill human life. Ecosystem services can be categorized in a number of different ways, including:

- *Supporting services:* nutrient cycling, soil formation, primary production (i.e., the resources used for agriculture and farming)
- *Provisioning services:* food, fresh water, wood and fiber, fuel, e.g.
- *Regulating services:* climate regulation, food regulation, water purification
- *Cultural services:* aesthetic, recreational, educational, and spiritual

Ecosystem services generally encompasses both the tangible and intangible benefits humans obtain from ecosystems—these are sometimes separated into "goods" and "services", respectively. Ecosystem goods, which are the tangible benefits to humans, include:

- seafood,
- wild game,
- fruits & vegetables
- timber,
- biomass fuels,
- natural fibers,
- many pharmaceuticals, and
- industrial products.

The harvest and trade of these goods represent important and familiar parts of the human economy. In addition to the production of goods, ecosystem services support life through:[1,2]

- purification of air and water,
- mitigation of droughts and floods,
- generation and preservation of soils and renewal of their fertility,
- detoxification and decomposition of wastes,
- pollination of crops and natural vegetation,
- dispersal of seeds,
- cycling and movement of nutrients,
- control of the vast majority of potential agricultural pests,
- maintenance of biodiversity,
- protection of coastal shores from erosion by waves,
- protection from the sun's harmful
- ultraviolet rays,
- partial stabilization of climate,
- moderation of weather extremes and their impacts,
- places to recreate, and
- provision of aesthetic beauty and intellectual stimulation that lift the human spirit.

This chapter discusses ecosystem goods and services, the ways in which humans utilize those services, the inherent difficulty in their valuation, and potential threats to their continued use. In particular, this chapter emphasizes the following three points:

1. The services flowing from natural ecosystems are greatly undervalued by society. For the most part, they are not traded in formal markets and so do not send price signals that warn of changes in their supply or condition. The process of waste disposal, for example, involves the life cycles of bacteria and the planet-wide cycles of major chemical elements such as carbon and nitrogen. Such processes are worth many trillions of dollars annually. Yet because we don't trade these benefits financially, they carry no price tags that could alert society to changes in their supply or deterioration of underlying ecological systems that generate them. Because threats to these systems are increasing, there is a critical need to identify and monitor them both locally and globally, and for us to incorporate their value into our decision-making processes; otherwise, there will be a continued conversion of natural ecosystems to human-dominated systems (e.g., wheatlands or oil palm fields), whose economic value can be expressed, at least in part, in standard currency.
2. Many human-initiated disruptions of these systems—such as introductions of exotic species, extinctions of native species, and increased production of greenhouse gases through fossil fuel burning—are difficult or impossible to reverse on any time scale relevant to society.
3. If awareness is not increased and current trends continue, humanity wil dramatically--and, in some cases, permanently--alter Earth's remaining natural ecosystems within a few decades.[3]

Taken for Granted

The lack of attention to the vital role of natural ecosystem services is easy to understand. Humanity came into being after most ecosystem services had been in operation for hundreds of millions to billions of years. These services are so fundamental to life that they are easy to take for granted, and so large in scale that it is hard to imagine that human activities could irreparably disrupt them.

An Experiment

Perhaps a thought experiment that removes these services from the familiar backdrop of the Earth is the best way to illustrate both the importance and complexity of ecosystem services, as well as how ill-equipped humans are to recreate them. Imagine, for example, human beings trying to colonize the moon. Assume for the sake of argument that the moon had already miraculously acquired some of the basic conditions for supporting human life, such as an atmosphere, a climate, and a physical soil structure similar to those on Earth. The big question facing human colonists would then be which of Earth's millions of species would they need to transport to the moon to make that sterile surface habitable?

One could tackle that question systematically by first choosing from among all the species exploited directly for food, drink, spices, fiber, timber, pharmaceuticals, and industrial products such as waxes, rubber, and oils. Even if one were highly selective, the list could amount to hundreds or even thousands of species. That would only be a start. One would then need to consider which species are crucial to supporting those used directly:

- the bacteria, fungi, and invertebrates that help make soil fertile and break down wastes and organic matter,
- the insects, bats, and birds that pollinate flowers, and
- the grasses, herbs, and trees that hold soil in place, regulate the water cycle, and supply food for animals.

The clear message of this exercise is that no one knows which combinations of species -- or even approximately how many -- are required to sustain human life.

Rather than selecting species directly, one might try another approach: Listing the ecosystem services needed by a lunar colony and then guessing at the types and numbers of species required to perform each. Yet determining which species are critical to the functioning of a particular ecosystem service is no simple task. Let's take soil fertility as an example. As we learned in

chapter three, soil organisms are crucial to the chemical conversion and physical transfer of essential nutrients to higher plants. However, the abundance of soil organisms is staggering.

Under a typical square-yard of pasture, for instance, roughly 50,000 small earthworms and their relatives, 50,000 insects and mites, and nearly 12 million roundworms inhabit the soil. In addition, that tally is only the beginning. The number of soil animals is tiny compared to the number of soil microorganisms: a pinch of fertile soil may contain over 30,000 protozoa, 50,000 algae, 400,000 fungi, and billions of individual bacteria.[4,5,6] Which must colonists bring to the moon to assure lush and continuing plant growth, soil renewal, waste disposal, and so on? We give little thought to these soil-dwelling species, yet the sobering fact is, as E. O. Wilson put it: they don't need us, but we need them.[7]

Moving our attention from the moon back to Earth, let us look more closely at the services nature performs on the only planet we know that is habitable. Ecosystem services and the systems that supply them are **interconnected**; so much so, that any classification of them is necessarily rather arbitrary. Here we briefly explore a suite of overarching services that operate in ecosystems worldwide.

Habitat for People, Plants, and Animals

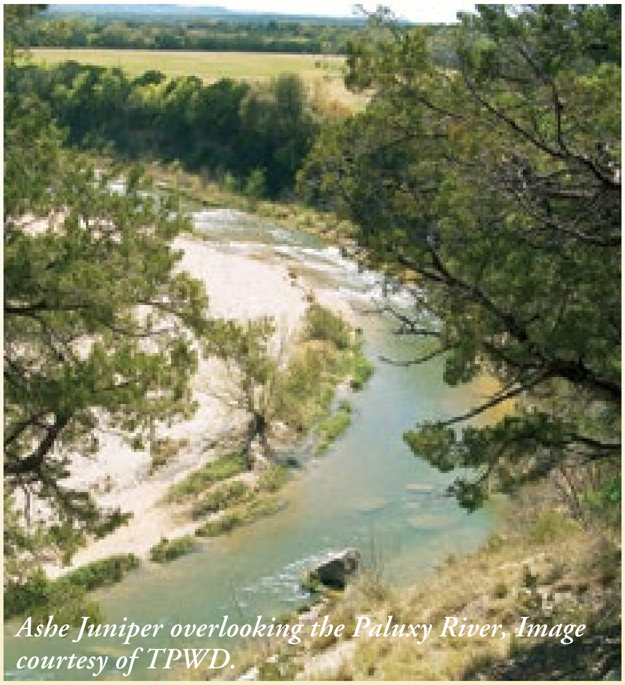
Humanity obtains an array of ecosystem goods from natural ecosystems. These are the organisms, and their parts and products, which grow in the wild. We use them directly for human benefit. We commonly trade many of these, such as fishes and animal products, in economic markets. Without sufficient and healthy habitats and ecosystems, human dependence on many of the following products would lead to disaster.

Fish and Aquatic Habitats

The annual world fish catch, for example, amounts to over 150 million metric tons. Worldwide fishery exports totaled US$129.2 billion in 2012. Fish accounts for about 17 percent of the global population's intake of animal protein.[8]

In the United States in 2011, the total fishing-related recreational expenditures totaled 47.6 billion US dollars.[9]

The Ashe-juniper in Texas



Ashe Juniper overlooking the Paluxy River, Image courtesy of TPWD.

The Ashe juniper, commonly called cedar, gets very little love in Texas. Its unpopularity partially stems from the wicked allergies triggered by its pollen and the grief this causes many Texans. The Ashe- juniper also has a bad reputation for being a water intensive tree. If you shake a cedar a day or two after a rain, you are probably going to get a shower. The needlelike scale leaves have a large leaf area and create a lot of precipitation interception. This can have a negative impact on the water budget when that intercepted water is not allowed to runoff into streams or recharge groundwater. The spatial scale of Ashe juniper in Texas, before European settlers arrived, is often debated. It is not uncommon to hear people incorrectly describe the tree as a non-native. We know through the accounts of early explorers that there were dense "cedar brakes" in areas around the Edwards Plateau. We also know that poor agriculture and fire suppression practices have created a situation over the last 100 years where the Ashe juniper has thrived and has outcompeted native grasses.

The tree may create headaches for allergy sufferers and water managers, but one very important bird loves them. The Golden Cheek Warbler is a listed endangered species that builds its nest in central Texas from the bark of mature Ashe juniper. Large scale clearing of cedar for development has caused the bird to become endangered. Juniper berries are also forage for many birds and small animals. Thoughtful management practices are required to control the species in an ecologically sound way that negates the negative impacts to the water budget while maximizing the ecological services provided by the tree.

In Texas, freshwater and saltwater systems provide huge economic impact:

- In 2011, the U.S. Fish and Wildlife Service estimated that expenditures for wildlife-related activities in Texas were $6.2 billion; such activities are dependent on healthy estuaries with adequate freshwater inflows.
- Citing the groundbreaking ecosystem serviceswork of economist Robert Costanza[10], Dr Andrew Sansom, in his expert report for "The Aransas Project" concluded that the total value of ecosystem services provided by healthy estuaries is $11,000 per acre per year.[11]

By comparison, the net value of auto sales in Texas for 2011, was $44.2 billion.[12]

Grasses and Grasslands

Turning our attention to the land, grasslands are an important source of marketable goods, including animals used for labor (horses, mules, asses, camels, bullocks, etc.) and those whose parts or products are consumed (as meat, milk, wool, and leather). Grasslands were also important as the original source habitat for most domestic animals such as cattle, goats, sheep, and horses, as well as many crops, such as wheat, barley, rye, oats, and other grasses.[13]

In a wide variety of terrestrial habitats, people hunt game animals such as waterfowl, upland birds, deer, moose, elk, fox, boar and other wild pigs, and rabbits. In many countries, game meat forms an important part of local diets and, in many places, hunting is an economically and culturally important sport.

Figure 4.1 - Grasslands. Image courtesy of TPWD.

Wood and Forests

Natural ecosystems also produce vegetation used directly by humans as food, timber, fuelwood, fiber, pharmaceuticals, and industrial products. We extract fruits, nuts, mushrooms, honey, other foods, and spices from many forest species. Humanity uses wood and other plant materials in the construction of homes and other buildings, as well as for the manufacture of furniture, farming implements, paper, cloth, thatching, rope, and so on. Wood is humankind's very first source of energy and today accounts for over 9% of the global total primary energy supply.

More than two billion people depend on wood energy for cooking and/or heating, particularly in households in developing countries. In many countries, it represents the only domestically available and affordable source of energy. Private households cooking and heating with wood fuels represents one third of the global renewable energy consumption, making wood the most decentralized energy source in the world.

Wood fuels arise from multiple sources including:

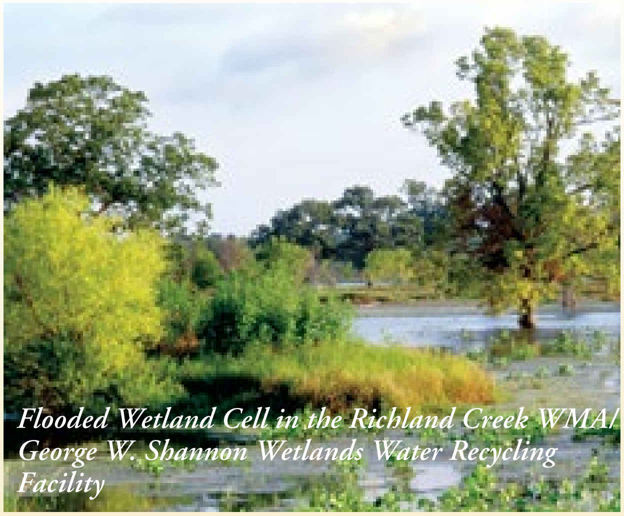
- forests,
- other wooded land and trees outside forests,
- co-products from wood processing,
- post-consumer recovered wood, and
- processed wood-based fuels.

Wood energy is also an important emergency backup fuel. Societies at any socio-economic level will switch easily back to wood energy when encountering economic difficulties, natural disasters, conflict situations or fossil energy supply shortages.a

Today wood energy has entered into a new phase of high importance and visibility with climate change and energy security concerns. Many consider wood energy to be a climate neutral and socially viable source of renewable energy, but only when meeting the following conditions:

- wood arising from sustainably managed resources (forests, trees outside forests, etc.),
- appropriate fuel parameters (water content, calorific value, shape, etc.),

Richland Creek Wildlife Management Area



Flooded Wetland Cell in the Richland Creek WMA/ George W. Shannon Wetlands Water Recycling Facility

The Richland Creek Wildlife Management Area and George W. Shannon Wetlands Water Reuse Facility produce clean water for the Fort Worth region while providing habitat for wildlife while providing vital ecosystem services.

In the January 2009 Texas Wetland News, TPWD Wildlife Biologist Matt Symmank reported that Texans are faced with the problem of supplying water to a growing population while avoiding adverse impacts to remaining bottomland hardwood habitat throughout the state. As a solution to the problem, Texas Parks and Wildlife Department partnered with Tarrant Regional Water District (TRWD) on a project designed to provide a reliable water supply to the Dallas-Fort Worth Metroplex without construction of a new reservoir. According to a *Fort Worth Star Telegram* article from June of 2014, the George W. Shannon Wetlands Water Reuse Facility supplies about 17 percent of the water supply for the Tarrant Regional Water District, about 55 million gallons of water daily. This water is made available by cleaning nutrient rich Trinity River water using the natural filtering process of wetlands. This project has harnessed the ecological function of wetlands for the benefit of mankind by helping to meet our needs for clean water. Not only is this project an innovative, environmentally friendly method of water supply, it is also cost effective. An economic analysis by TRWD shows that the development of wetlands for water filtration costs half as much as new reservoir construction would.

- efficient incineration or gasification minimizing indoor and outdoor emissions, or
- cascade use of wood fibers – favoring material use, re-use and recycling before energy use.[14]

Generation and Maintenance of Biodiversity

Biological diversity ("biodiversity" for short) refers to the variety of life forms at all levels of organization, from the molecular to the landscape level. Natural ecosystems generate and maintain biodiversity. In natural ecosystems, organisms encounter a wide variety of living conditions and chance events that shape their evolution in unique ways. Out of convenience or necessity, we tend to talk about biodiversity in terms of numbers of species, and this perspective has greatly influenced conservation goals. It is important to remember, however, that biodiversity supplies benefits to humanity through the populations of species residing in living communities. For example, microbes, insects, worms, and mammals interact to produce nutrient-rich soil that humans use for agriculture.[15]

Regional Biodiversity

Generally, ecosystem services occur regionally. The type, spatial layout, extent, and proximity of the ecosystems determine the flow of ecosystem goods and services in a region. Preserving only one minimum viable population of each non-human species on Earth in zoos, botanical gardens, and the world's legally protected areas would not sustain life as we know it. Indeed, such a strategy, taken to extreme, would lead to collapse of the biosphere, along with its life support services.

Biodiversity's Support of Agriculture and Pharmaceuticals

As described in the previous section, biodiversity is a direct source of ecosystem goods. It also supplies the genetic and biochemical resources that underpin our current agricultural and pharmaceutical enterprises and may allow us to adapt these vital enterprises to global change. Our ability to increase crop productivity in the face of new pests, diseases, and other stressors has depended heavily upon the transfer of genes from wild crop relatives to our crops.. In addition to sustaining the production of conventional crops, the biodiversity in natural ecosystems may include many potential new foods. Human beings have utilized around 7,000 plant species for food over the course of history and we know of another 70,000 plants that have edible parts.[16]

According to Professor Ciddi Veeresham, in the *Journal of Advanced Pharmaceutical Technology and Research*:

> "Until recently, plants were an important source of novel pharmacologically active compounds with many blockbuster drugs being derived directly or indirectly from plants. Despite the current preoccupation with synthetic chemistry as a vehicle to discover and manufacture drugs, the contribution of plants to disease treatment and prevention is still enormous. Even at the dawn of 21st century, 11% of the 252 drugs considered as basic and essential by the World Health Organization were exclusively of flowering plant origin. Obviously natural products will continue to be extremely important as sources of medicinal agents. In addition to the natural products which have found direct medicinal application as drug entities, many others can serve as chemical models or templates for the design, synthesis, and semi synthesis of novel substances for treating humankind's diseases. Although there are some new approaches to drug discovery, such as combinatorial chemistry and computer-based molecular modeling design, and many drugs are made by synthetic chemistry, none of them can replaced the important role of natural products in drug discovery and development as most of the core structures or scaffolds for synthetic chemicals are based upon natural products."[17]

Mitigation of Floods and Droughts

Vegetation

An enormous amount of water, about 119,000 cubic kilometers, rains annually onto the Earth's land surface, enough to cover the land to an average depth of 1 meter.[18] Much of this water soaks into soils and gradually percolates to plant roots or into aquifers and surface streams. Plants and plant litter shield the soil from the full, destructive force of raindrops and hold it in place. When landscapes are denuded, rain compacts the surface and rapidly turns soil to mud (especially if it has been loosened by tillage); mud clogs surface cavities in the soil, reduces infiltration of water, increases runoff, and further enhances clogging. Detached soil particles are splashed downslope and carried off by running water.[19] Also, it is believed that for every mile of robust coastal wetland vegetation, storm surge (associated with tropical storms and hurricanes) is reduced by one foot.

Erosion results in impacts not only at the site where soil is lost but also in aquatic systems, natural and human-made, where sediment accumulates. You will learn more about this in **chapter five** and **chapter seven**. Local impacts of erosion include losses of production potential, diminished infiltration and water availability, and losses of nutrients. Downstream costs may include:

- disrupted or lower quality water supplies;
- siltation that impairs drainage and maintenance of navigable river channels, harbors, and irrigation systems;
- increased frequency and severity of floods; and
- decreased storage potential for hydroelectric power and/or water supply as reservoirs fill with silt.[20]

Worldwide, the replacement cost of reservoir capacity lost to siltation is estimated at $6 billion per year.

Wetlands

Healthy wetlands can often reduce the need to construct flood control structures. Floodplain forests and high salt marshes, for example, slow the flow of floodwaters and allow sediments to be deposited within the floodplain rather than washed into downstream bays or oceans. In addition, isolated wetlands, such as playa lakes and prairie potholes, serve as detention areas during times of high rainfall. They delay saturation of upland soils and overland flows into rivers and thereby damping peak flows. Retaining the integrity of these wetlands by leaving vegetation, soils, and natural water regimes intact can reduce the severity and duration of flooding along rivers.[21]

Services Supplied by Soil

Soil represents an important component of a nation's assets, one that takes hundreds to hundreds of thou-

Figure 4.2 - This ten-foot root system of the Big Bluestem shows how deep the fibrous roots of native grasses reach and help rainwater soak down, recharge underground aquifers, and stabilize the soil. Image courtesy of Tom Harvey.

sands of years to build up and yet very few years to be lost. Some civilizations have drawn great strength from fertile soil; conversely, the loss of productivity through mismanagement ushered many once flourishing societies to their ruin.[22]

Today, soil degradation induced by human activities afflicts nearly 20 percent of the Earth's vegetated land surface.[23]

In addition to moderating the water cycle, as described above, soil provides five other interrelated services.[24]

Seed Shelter

Soil shelters seeds and provides physical support as they sprout and mature into adult plants. The cost of packaging and storing seeds and of anchoring plant roots would be enormous without soil.

Nutrient Delivery

Soil retains and delivers nutrients to plants. Tiny soil particles (less than 2 microns in diameter), primarily bits of humus and clay, carry a surface electrical charge that is generally negative. This holds positively charged nutrients such as calcium and magnesium near the surface, in proximity to plant roots, allowing plants to take them up gradually. Otherwise, these nutrients would leach away. Soil also acts as a buffer in the application of fertilizers, holding onto the fertilizer ions until plants need them. Hydroponic systems supply water and nutrients to plants without need of soil, but the margin for error is much smaller. Even small excesses of nutrients applied hydroponically can be lethal to plants. Indeed, it is a complex undertaking to regulate the nutrient concentrations, pH, and salinity of the nutrient solution in hydroponic systems, as well as the air and solution temperature, humidity, light, pests, and plant diseases.

Waste Decomposition

Soil plays a central role in the decomposition of dead organic matter and wastes, and this decomposition process renders harmless many potential human pathogens. People generate a tremendous amount of waste, including household garbage, industrial waste, crop and forestry residues, and sewage from their own populations and their billions of domesticated animals. Fortunately, there is a wide array of organisms capable of decomposing many types of waste. These range from vultures to tiny bacteria that extract energy from the large, complex organic molecules. Like assembly-line workers, diverse microbial species process the particular compounds by separating their chemical bonds. Then they pass along the products of their specialized reactions to other species. Many industrial wastes, including soaps, detergents, pesticides, oil, acids, and paper, are detoxified and decomposed by organisms in natural ecosystems. Some modern wastes, such as plastics however, are virtually indestructible.

The simple inorganic chemicals that result from natural decomposition return to plants as nutrients. Thus, the decomposition of wastes and the recycling of nutrients is the fourth service soils provide (Figure 4.3). They are two aspects of the same process. The fertility of soils, that is, their ability to supply nutrients to plants, is largely the result of the activities of diverse species of bacteria, fungi, algae, crustaceans, mites, termites, springtails, millipedes, and worms, all of which, as groups, play important roles.

Some bacteria are responsible for fixing nitrogen, a key element in proteins, by drawing it out of the atmosphere and converting it to forms usable by plants and, ultimately, human beings and other animals. Certain types of fungi play extremely important roles in supplying nutrients to many kinds of trees. Earthworms and ants act as .mechanical blenders, breaking up and mixing plant and microbial material and other

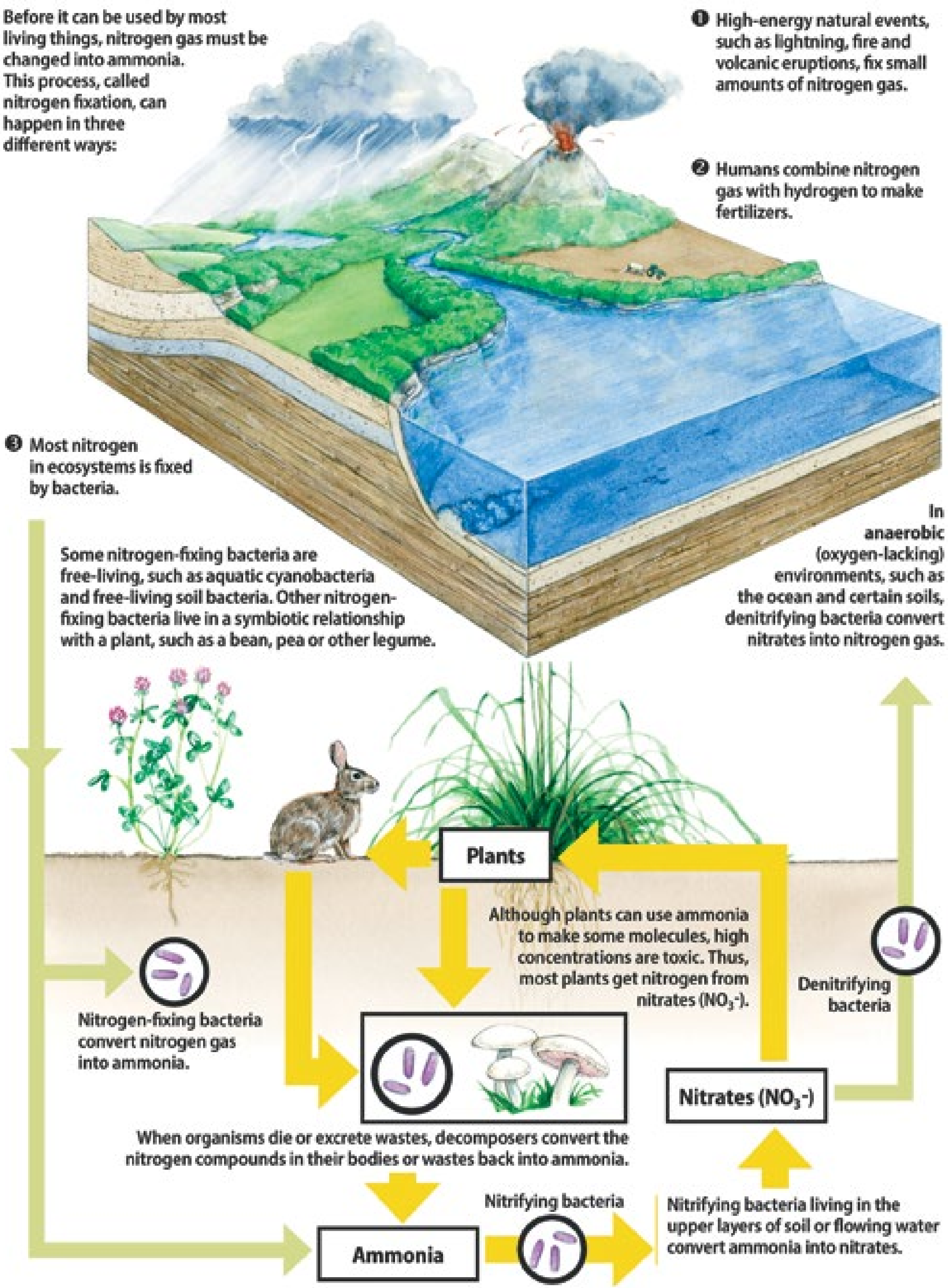


Figure 4.3 - This graphic, introduced in chapter 3, is shown here again to show the important role that decomposers like bacteria, fungi, microbes, and more play in the nitrogen cycle. Image used with permission from the Missouri Department of Conservation.

matter.[25] For example, as much as 10 metric tons of material may pass through the bodies of earthworms on a hectare of land each year, resulting in nutrient rich casts that enhance soil stability, aeration, and drainage.[26]

Biochemical Cycle Regulation

Finally, soils are a key factor in regulating the Earth's major element cycles; those of carbon Figures 4.4 and 4.5), nitrogen, and sulfur. The amount of carbon and nitrogen stored in soils dwarfs that in vegetation, for example.

Carbon in soils is nearly double (1.8 times) that in plant matter, and nitrogen in soils is about 18 times greater.[27] Alterations in the carbon and nitrogen cycles may be costly over the long term, and in many cases, irreversible on a time scale of interest to society. Increased fluxes of carbon to the atmosphere, such as occur when land is converted to agricultural use or when wetlands are drained, contribute to the buildup of key greenhouse gases, namely carbon dioxide and methane, in the atmosphere.[28] Changes in nitrogen fluxes caused by production and use of fertilizer, burning of wood and other biomass fuels, and clearing of tropical land lead to increasing atmospheric concentrations of nitrous oxide, another potent greenhouse gas that is also involved in the destruction of the stratospheric ozone shield. These and other changes in the nitrogen cycle also result in acid rain and excess nutrient inputs to freshwater systems, estuaries, and coastal marine waters. This nutrient influx causes **eutrophication** of aquatic ecosystems and contamination of drinking water sources, both

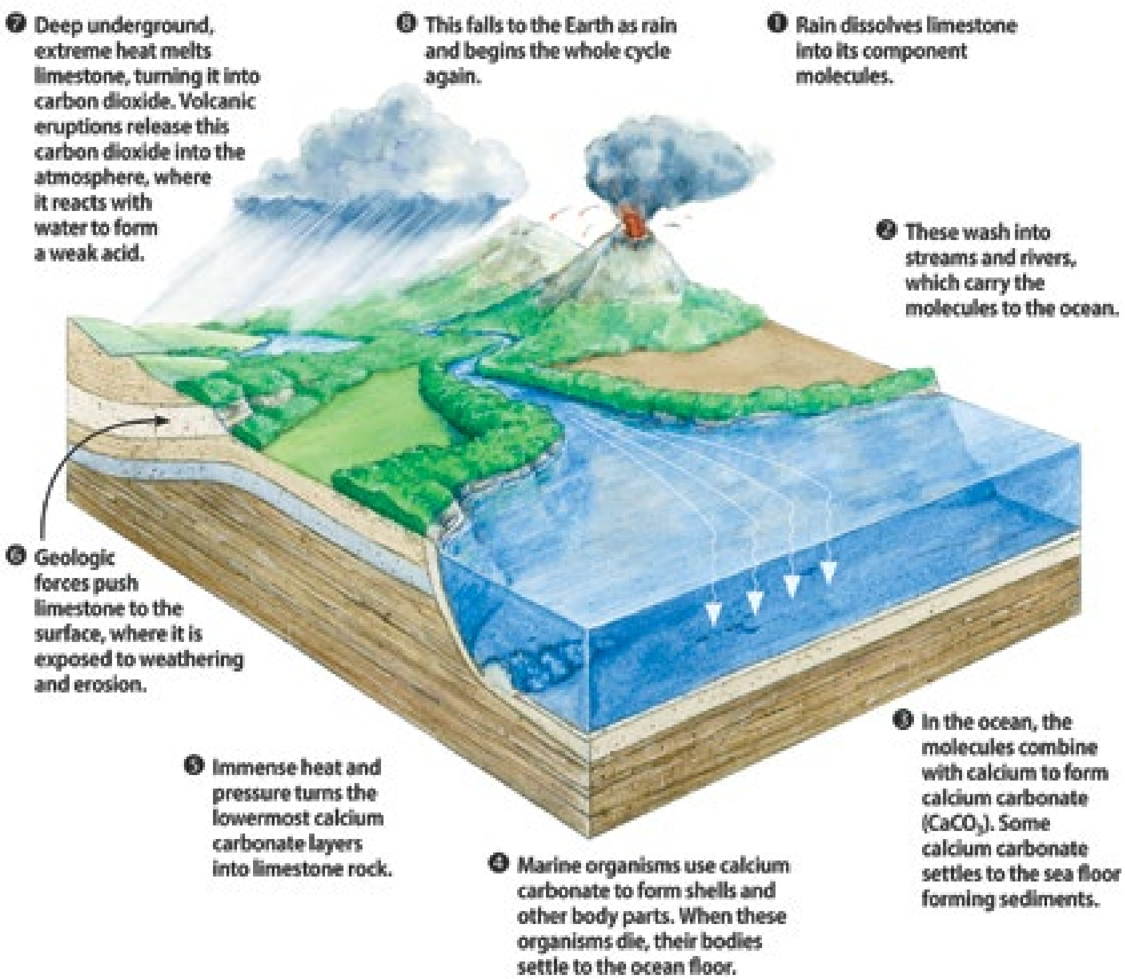


Figure 4.4 - Geological Carbon Cycle. Image used with permission from the Missouri Department of Conservation.

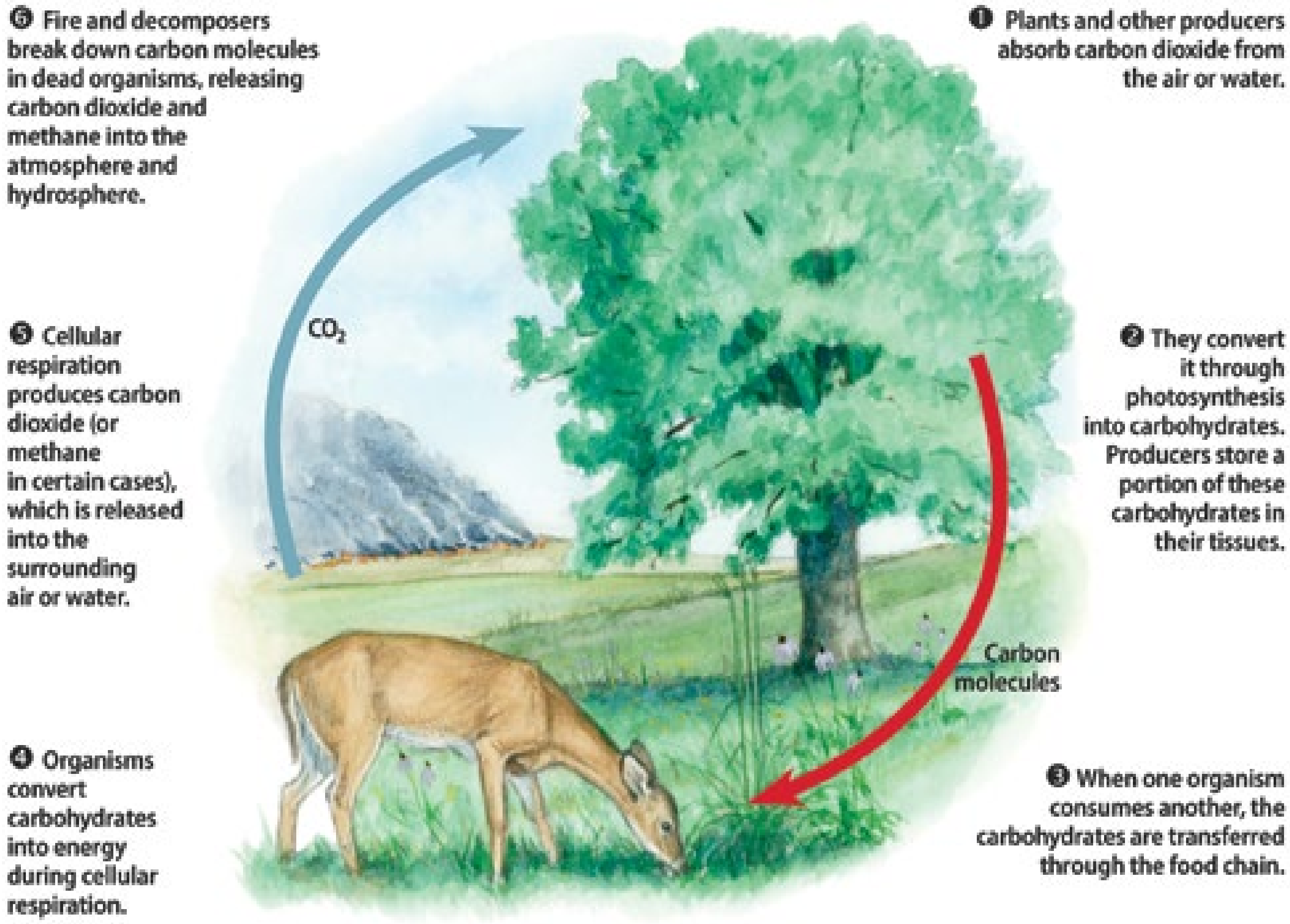


Figure 4.5 - Biological Carbon Cycle. Image used with permission from the Missouri Department of Conservation.

surface and ground water, by high levels of nitrate-nitrogen.[29]

Pollination

Animal pollination is required for the successful reproduction of most flowering plants. About 220,000 out of an estimated 240,000 species of plants (or 92 percent) require an animal such as a bee or hummingbird to accomplish this vital task. This includes both wild plants and about 70 percent of the agricultural crop species that feed the world. Over 100,000 different animal species including bats, bees, beetles, birds, butterflies, and flies provide these free pollination services. Together, they assure the perpetuation of plants in our croplands, backyard gardens, rangelands, meadows and forests. In turn, the continued availability of these pollinators depends on the existence of a wide variety of habitat types needed for their feeding, successful breeding, and completion of their life cycles.[30]

One third of human food comes from plants pollinated by wild pollinators. Without natural pollination services, yields of important crops would rapidly decline and many wild plant species would become extinct. In the United States alone, the agricultural value of wild, native pollinators, those sustained by natural habitats adjacent to farmlands, is estimated in the billions of dollars per year. Pollination by honey bees, originally imported from Europe, is extremely important as well, but these bees are presently in decline, enhancing the importance of pollinators from natural ecosystems. Honey bee populations in the Americas are currently threatened by diseases and pesticide use. Meanwhile, the diversity of natural pollinators available to both wild and domesticated plants is diminishing: more than 60 genera of pol-

Figure 4.6 - Natural pollination at work. Image courtesy of TPWD.

linators include species now considered threatened, endangered, or extinct.[31]

Natural Pest Control Services

If a species competes with humanity for food, timber, cotton, and other fibers, we call them pests. They include numerous herbivorous insects, rodents, fungi, snails, nematodes, and viruses. These pests destroy an estimated 25 to 50 percent of the world's crops, either before or after harvest.[32] In addition, numerous weeds compete directly with crops for water, light, and soil nutrients, further limiting yields.

Figure 4.7 - We take many natural predators, such as spiders, and the role they play in nature for granted. Image courtesy of TPWD.

Chemical pesticides, and the strategies by which we apply them to fight crop pests, can have harmful unintended consequences. First, pests can develop resistance to the chemicals, which means that we must apply higher and higher doses of pesticides or develop new chemicals periodically to achieve the same level of control. Second, we decimate populations of the natural enemies of pests by heavy pesticide use. Natural predators are often more susceptible to synthetic poisons than are the pests because they have not had the same evolutionary experience with overcoming plant chemicals that the pests themselves have had. In addition, natural predators typically have much smaller population sizes than those of their prey. Destruction of predator populations leads to explosions in prey numbers, not only freeing target pests from natural controls but also promoting other non-pest species to pest status. In California in the 1970s, for instance, 24 of the 25 most important agricultural pests had been elevated to that status by the overuse of pesticides.[33]

Fortunately, natural enemies, including many birds, spiders, parasitic wasps and flies, ladybugs, fungi, viral diseases, and numerous other types of organisms, control an estimated 99 percent of potential crop pests.[34]

These natural biological control agents save farmers billions of dollars annually by protecting crops and reducing the need for chemical control.[35]

Seed Dispersal

Once a seed germinates, the resulting plant is usually rooted in place for the rest of its life. Plants move to new sites beyond the shadow of the parent through seed dispersal. Many seeds, such as those of the dandelion, spread by wind. Some spread by water, the most famous being the seafaring coconut. Many other seeds have evolved ways of getting around by using animals as their dispersal agents. Some contain sweet fruit to reward an animal for its dispersal services; some of these seeds even require passage through the gut of a bird or mammal before they can germinate. Others require burial by a forgetful jay or a squirrel, (Figures 4.8 and 4.9) which later leaves its cache uneaten, for eventual germination. Still others are equipped with sticky or sharp, spiny surfaces (Figure 4.10) designed to catch onto a passing animal and go for a long ride before dropping off. Without thousands of animal species acting as seed dispersers, many plants would fail to reproduce successfully. Animal seed dispersers play a central role in the structure and regeneration of many pine forests.[36] Disruption of these complex services may leave large areas of forest devoid of seedlings and younger age classes of trees, and thus unable to recover swiftly from human impacts such as land clearing.

Figure 4.9 - East Texas Southern Yellow Pine. Image courtesy of TPWD.

Figure 4.8 - Eastern Red Squirrel. Image courtesy of TPWD.

Aesthetic Beauty and Intellectual and Spiritual Stimulation

Many human beings have a deep appreciation of natural ecosystems. That is apparent in their artistic, religious, and cultural traditions, as well as in activities such as gardening and pet-keeping, nature photography and film-making, bird feeding and watching, hiking and camping, eco -ouring and mountaineering, river-rafting and boating, fishing and hunting, and in a wide range of other activities. For many, nature is an unparalleled source of wonderment and inspiration, peace and beauty, fulfillment and rejuvenation.[37]

Figure 4.10 - Cocklebur. Image courtesy of Dinesh Valke, https://creativecommons.org/licenses/by-nc-nd/2.0/.

Threats to Ecosystem Services

Human activities impair and destroy a wide variety of ecosystem services. Foremost among the immediate threats are the continuing destruction of natural habitats and the invasion of non-native species that often accompanies such disruption. In marine systems, overfishing is a major threat. Irreversible among human impacts on ecosystems is the loss of native biodiversity. A conservative estimate of the rate of species loss is about one per hour, which unfortunately exceeds the rate of evolution of new species by a factor of 10,000 or more.[38,39] But complete extinction of species is only the final act in the process. The rate of loss of local populations of species, the populations that generate ecosystem services in specific localities and regions, is orders of magnitude higher.[40] Destroying other life forms also disrupts the web of interactions that could help us discover the potential usefulness of specific plants and animals.[41] Once a pollinator or a predacious insect is on the brink of extinction, for instance, it would be difficult to discover its potential utility to farmers.

Other imminent threats include:

- the alteration of Earth's carbon, nitrogen, and other biogeochemical cycles through the burning of fossil fuels and heavy use of nitrogen fertilizer;
- degradation of farmland through unsustainable agricultural practices;
- mismanagement of freshwater resources;
- release of toxins onto both land and waterways; and
- overharvesting of fisheries, forests, and other theoretically renewable systems.

Two broad underlying forces ultimately drive these threats to ecosystem services: One is rapid, unsustainable growth in the scale of the human enterprise: in population size, in per-capita consumption, and also in the environmental impacts that technologies and institutions generate as they produce and supply those consumables.[42] No line can easily be drawn between the developed and developing countries in this regard. Consumption in the agriculture, forest, and fishery sectors is rising in every major world region; although at different rates. However, in the global theater, the United States stands out above the rest in terms of consumption of resources. For example, with less than 5% of the world's population, the U.S. consumes about 25% of the world's fossil fuels. While China contributes to 25% of global greenhouse gas emissions, the per-capita emissions of the U.S. are more than double than of China. The U.S. and North America lead in per-capita consumption of meat and milk products, fresh water for drinking and agriculture, and many other resources.

The other underlying driver is the frequent mismatch between short-term, individual economic incentives and long-term, societal well-being. Often, personal and policy decisions forego potential long term sustainability for short-term gains. Assessing the value of ecosystem services has been challenging for a number of reasons:

- Because these services are not traded, their value is not often quantified like other goods and services.
- Many serve the public good rather than provide direct benefits to individual landowners.
- Private property owners often have no way to benefit financially from the ecosystem services supplied to society by their land.
- Economic subsidies often encourage the conversion of such lands to other, market-valued activities.

Thus, people whose activities disrupt ecosystem services often do not pay directly for the cost of those lost services. Moreover, society often does not compensate landowners and others who do safeguard ecosystem services for the economic benefits they lose by foregoing more lucrative but destructive land uses.

Valuation of Ecosystem Services

Human society would cease to exist in the absence of ecosystem services. Thus, their immense value to humanity is unquestionable. Yet quantifying the value of ecosystem services in specific localities and measuring their worth against that of competing land uses is no simple task. Often a qualitative comparison of relative values is sufficient, that is, which is greater, the economic benefits of a particular development project or the benefits supplied by the ecosystem that would be destroyed, measured over a time period of interest to people concerned about the well-being of their grandchildren?

There are, and will remain, many cases in which ecosystem service values are highly uncertain. Yet the pace of destruction of natural ecosystems, and the irreversibility of most such destruction on a time scale of interest to humanity, warrants substantial caution. Valuing a natural ecosystem, like valuing a human life, is fraught with difficulties. Just as societies have recognized fundamental human rights, it may be prudent to establish fundamental ecosystem protections even though uncertainty over economic values remains.

Summary

The human economy depends upon the services performed free by ecosystems. The ecosystem services supplied annually are worth many trillions of dollars. Economic development that destroys habitats and impairs services can create costs to humanity over the long term that may greatly exceed the short-term economic benefits of the development. Hidden from traditional economic accounting, these costs are nonetheless real and are usually borne by society.

Historically, humanity has typically ignored the nature and value of Earth's life support until their disruption or loss highlights their importance. For example, deforestation has belatedly revealed the critical role forests serve in regulating the water cycle--in particular, in mitigating floods, droughts, the erosive forces of wind and rain, and silting of dams and irrigation canals. Today, escalating impacts of human activities on forests, wetlands, and other natural ecosystems imperil the delivery of such services. The primary threats are land use changes that cause losses in biodiversity as well as disruption of carbon, nitrogen, and other biogeochemical cycles; human-caused invasions of exotic species; overfishing of oceanic resources; pollution of land and water resources; climate change; and depletion of stratospheric ozone. Consider these truths:

- Ecosystem services are essential to human civilization.
- Technological advances are unable to replace most ecosystem services because they operate on such a grand scale and in such intricate and little-explored ways.
- Human activities are already impairing the flow of ecosystem services on a large scale.
- If current trends continue, humanity will dramatically alter virtually all of Earth's remaining natural ecosystems within a few decades.

In addition, based on growing scientific evidence, we are confident that:

- Many of the human activities that modify or destroy natural ecosystems may cause deterioration of ecological services whose value, in the long term, dwarfs the short-term economic benefits society gains from those activities.
- Considered globally, very large numbers of species and populations are required to sustain ecosystem services.
- It may be possible for humanity to restore the functioning of many ecosystems if we take appropriate actions in time. Humanity must strive to achieve a balance between sustaining vital ecosystem services and pursuing the worthy short-term goals of economic development.

Challenge

Consider the ecosystem services required to produce the food items from your last meal. Be sure to include all of the biotic and abiotic factors that contributed to producing your food. Then, consider the resources consumed in getting your food from where it grew to where you consumed it. In what ways do your personal consumption affect an ecosystem other than the one in which you live?

References

1. (Holdren, 1974)
2. (Ehrlich, 1981)
3. (Daily G. , 1997)
4. (Overgaard-Nielsen, 1955)
5. (Rouatt, 1961)
6. (Chanway, 1993)
7. (Wilson, Dec., 1987)
8. (Food and Agriculture Organization of the United Nations, 2015)
9. (Southwick, 2012)
10. (Costanza, R.,1997)
11. (Sansom, 2012)
12. (Texas Comptroller of Public Accounts, 2016)
13. (Sala, 1997)
14. (Xia, Z., 2016)
15. (Daily G., 1996)
16. (Wilson, Threats to Biodiversity, 1989)
17. (Veeresham, 2012)
18. (Shiklomanov, 1993)
19. (Hillel, 1991)
20. (Pimental, 1995)
21. (Ewel, 1997)
22. (Adams, 1981)
23. (Oldeman, L.R., 1990)
24. (Oldeman, L.R., 1990)
25. (Jenny, 1980)
26. (Lee, 1985)
27. (Schlesinger, 1991)
28. (Schlesinger, 1991)
29. (Vitousek P., 1997)
30. (Nabhan, 1997)
31. (Nabhan, 1997)
32. (Pimentel, 1989)
33. (Rational Research Council, 1989)
34. (DeBach, 1974)
35. (Naylor, 1997)
36. (Lanner, 1996)
37. (Kellert, 1993)
38. (Wilson, Threats to Biodiversity, 1989)
39. (Lawton, 1995)
40. (Daily G., 1995)
41. (Thompson, 1994)
42. (Ehrlich P., 1977)

Chapter Five:

The Ecological Significance of Natural Flow Regimes

Aerial view of the Colorado River Delta. Image courtesy of TPWD.

Chapter Five:
The Ecological Significance of Natural Flow Regimes

Questions to Consider

- What factors determine the structure of a stream corridor?
- How does a stream reach "equilibrium"?
- How does stream flow relate to groundwater?
- How do natural flow patterns affect things like sediment, organic matter, temperature, nutrient balance, and organisms' life cycles?

Introduction

Thus far, you have learned about aquatic habitats, healthy watershed ecosystems, and how they operate as a natural system. In **chapter four**, you learned about the ecosystem services that these natural systems provide to sustain life on our planet and human life, as we know it. In this chapter, you will learn about the role of natural flow regimes and their ecological significance in the overall order and function of these natural systems. Remember that the term regime refers to a system where there is a heavy ecological influence by one particular factor. We will begin with considering the structure and function of stream corridors.

The Structure and Function of Stream Corridors

Stream Corridor Structure

A stream's structure and function is constantly changing and morphing because of variations in flow. Stream corridor structure and function exist like two sides of the same coin. Natural flow variation shapes streams and rivers, creating the physical structure to convey high and low flow conditions. The physical structure of the stream corridor is one of the most ecologically and hydrologically important parts of the watershed and the environment in general. Even though streams

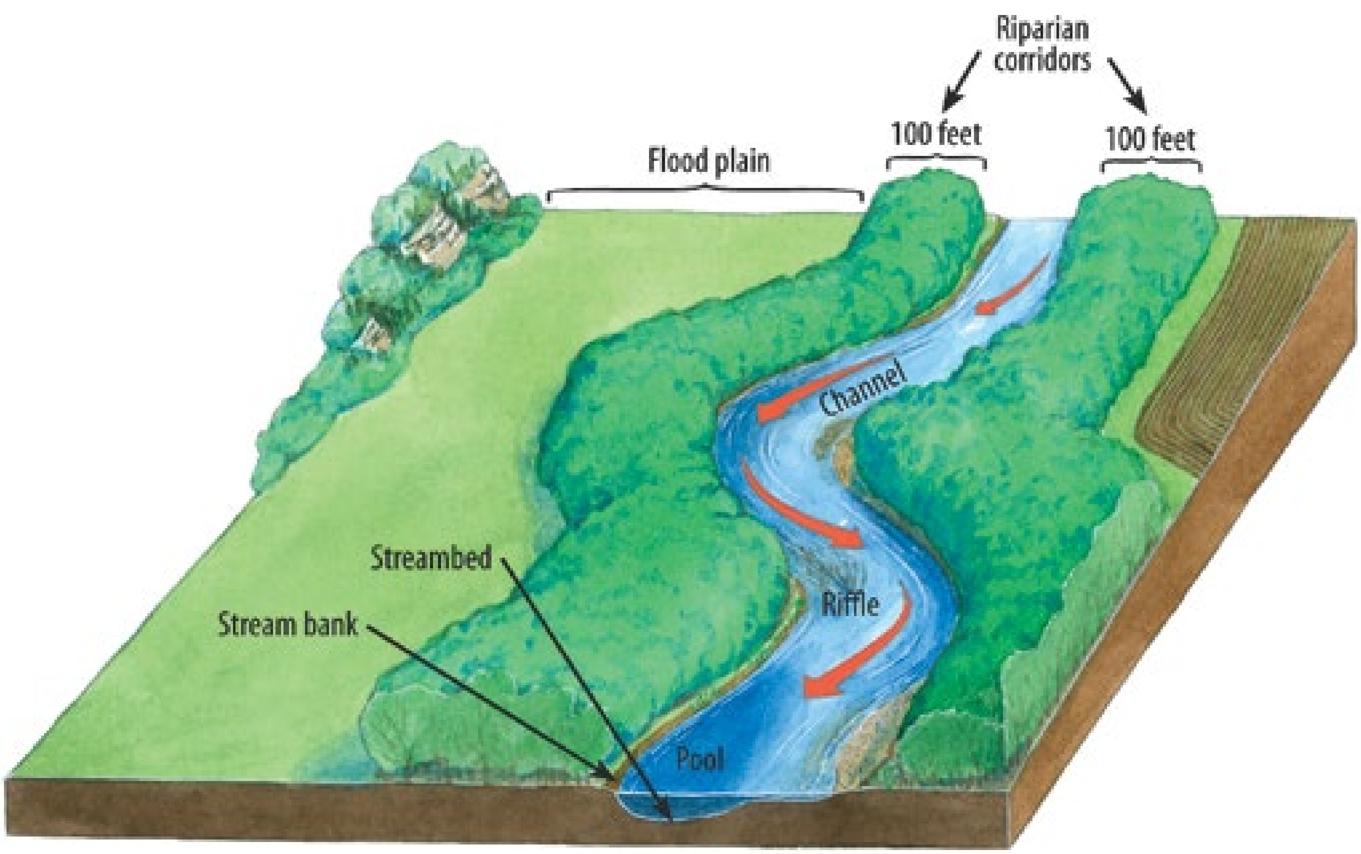


Figure 5.1 - Parts of a Stream. Image used with permission from the Missouri Department of Conservation.

vary widely, most stream corridors have four major components in cross section (Figure 5.1):

- the **stream channel**, a channel with flowing water at least part of the year,
- the **riparian corridor**, the part of the floodplain that is closest to the stream channel, it contributes nutrient input, stream shading, and bank stabilization,
- the **floodplain**, a highly variable area on one or both sides of the stream channel that is inundated by floodwaters at some interval, from frequent to rare, and
- the **transitional upland fringe**, a portion of the upland on the landward side of the floodplain that serves as a transitional zone or edge between the floodplain and the surrounding landscape.

We will explore each of these components in turn on the coming pages. Let's begin with the stream channel.

The Stream Channel

Stream channels carry water and sediment that form, maintain, and alter the physical features of the stream channel. **Channel equilibrium** and **streamflow** are two functions in river systems of interest because they influence most physical characteristics of the channel.

Channel Equilibrium[1]

Channel equilibrium involves the relationship of four basic factors:

- Sediment discharge
- Sediment particle size
- Streamflow
- Stream slope

Natural systems tend towards equilibrium. If something shifts out of normal range, other parts of the system behave differently until equilibrium, or balance, is achieved. Channel equilibrium occurs when all four of the above variables are in balance. If one variable changes, one or more of the other variables must increase or decrease in order to maintain equilibrium. For example, if channel slope is increased (e.g., by filling or dredging a part of the channel) and streamflow remains the same, either the sediment load or the size of the particles must also increase. Likewise, if flow is increased (e.g., by a significant rain event) and the slope stays the same, sediment load or sediment particle size has to increase to maintain channel equilibrium. Under these conditions, a stream seeking a new equilibrium will tend to erode more of its banks and bed, transporting larger particle sizes and a greater sediment load.

Alluvial streams, where the stream channel is made up of loose sediment, are free to adjust to changes in these four variables allowing them to easily reestablish new equilibrium conditions. Non-alluvial streams, such as bedrock or artificial, concrete channels are constrained by all factors except changes in streamflow. This results in equilibrium conditions with little to no movement.

Streamflow

A second distinguishing feature of the channel is streamflow. **Streamflow**, or discharge, is the volume of water that moves over a point during a fixed period of time. It is often expressed as cubic feet per second (cfs).

Figure 5.2 - Dry summertime streambed. Image courtesy of Johnnie Smith.

The flow of a stream is influenced by the amount of water moving through the watershed and into the stream or river channel. The pathways precipitation takes after it falls to earth affect many aspects of streamflow including its quality, quantity, and timing. Stream flow affects the concentrations of dissolved oxygen, natural substances, and pollutants in the water, as well as the temperature and turbidity. The discharge rate of a river or stream varies over time depending on factors such as precipitation, seasonal water use, and air temperature. For example, stream flow during the summer time may be much lower than in the spring or after a heavy rain event (Figure 5.2) due to lower precipitation, higher water use and increased evaporation.

The two basic components are:

- *stormflow:* also known as storm water runoff, from precipitation that reaches the channel over a short time frame through overland or underground routes, and
- *baseflow:* from precipitation that percolates to the ground water and moves slowly through substrate before reaching the channel. It sustains streamflow during periods of little or no precipitation.

Streamflow at any one time might consist of water from one or both sources. If neither source provides water to the channel, the stream goes dry.

Flow Patterns

Ecosystems have evolved and adapted to seasonal and annual cycles in flow patterns. Species have developed strategies for surviving – and often requiring – periodic hydrologic extremes caused by floods and droughts that exceed normal annual high or low in flows. Hydrological variability is critical for regulating **biological productivity** (that is, the growth of algae or phytoplankton that forms the base of aquatic food webs) and **biological diversity**, particularly for rivers.

Changes in Hydrology after Urbanization

Hydrology describes the movement, distribution, and quality of water. Impervious cover such as rooftops, roadways, parking lots, sidewalks, and driveways tends to increase storm water runoff and decrease baseflows, altering the hydrology of urban streams. Depending on the degree of watershed impervious cover, the annual volume of storm water runoff can be 16 times higher than that of natural areas.[2]

In addition, since impervious cover prevents rainfall from infiltrating into the soil, less flow is available to recharge groundwater. Therefore, during extended periods without rainfall, baseflow levels typically drop in urban streams.[3]

Storm water runoff moves more rapidly over smooth, hard pavement than over surfaces with natural vegetation cover. Consequently, streamflow velocity and magnitude increase due to increased surface runoff. The result is decreased infiltration to recharge groundwater, causing lower baseflow after stormflow has receded. You may have noticed a planned approach to a solution for this problem-detention ponds in urban areas that hold storm water runoff until it can slowly infiltrate.

The Riparian Corridor

The riparian corridor is a plant community growing nearest to the water's edge. It preserves water quality by filtering sediment from runoff before it enters rivers and streams, protects stream banks from erosion, provides the first level of storage area for flood waters, and it provides food and habitat for fish and wildlife.

The riparian corridor is also the interface between the aquatic and terrestrial habitats. The vegetation found can vary widely based on the size and order of the stream, and by streamflow variability.

The Floodplain

The floor of most stream valleys is relatively flat. This is because over time the stream moves back and forth across the valley floor in a process called lateral migration. In addition, periodic flooding causes sediments to move longitudinally. The stream deposits sediments on the valley floor near the channel. These two processes continually modify the floodplain.

Through time, the channel reworks the entire valley floor. As the channel migrates, it maintains the same average size and shape if conditions upstream remain constant and the channel stays in equilibrium. Two very general types of floodplains: (Figure 5.3)[4]

- *Hydrologic floodplain:* the land adjacent to the baseflow channel residing below bankfull elevation. It is inundated about two years out of three. Not every stream corridor has a hydrologic floodplain.
- *Topographic floodplain:* the land adjacent to the channel including the hydrologic floodplain and other lands up to an elevation

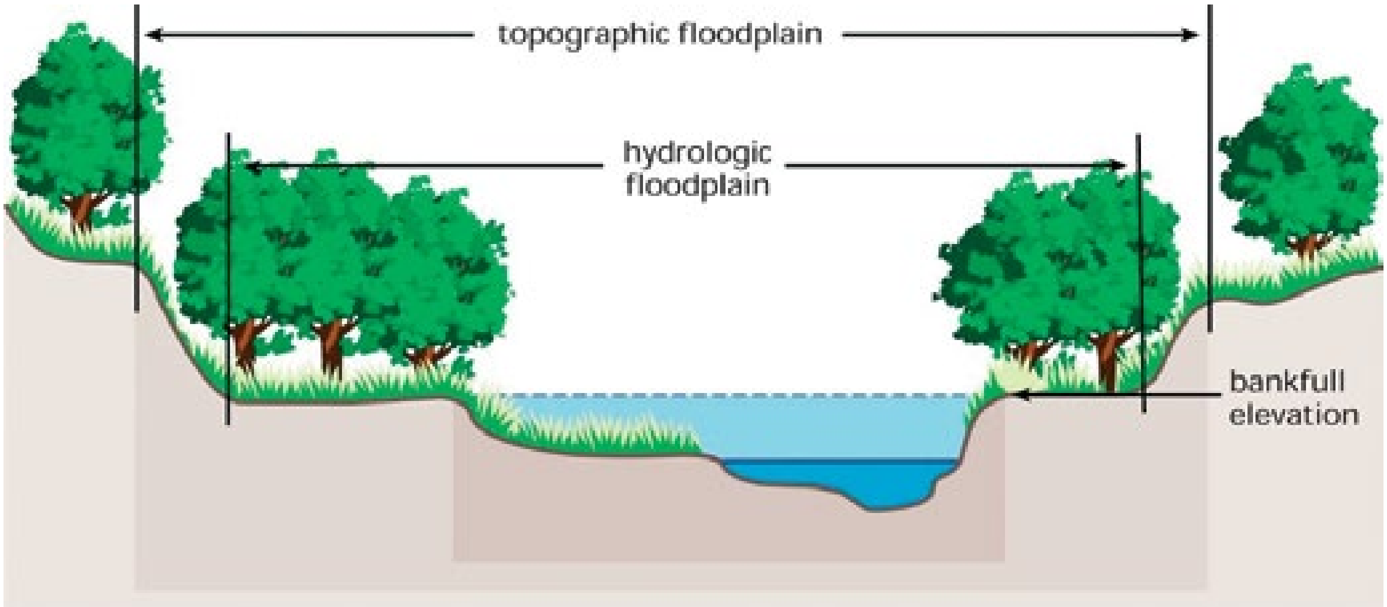


Figure 5.3 - The hydrologic floodplain is defined by bankfull elevation. The topographic floodplain includes the hydrologic floodplain and higher floodplains up to a defined elevation that corresponds to a specific flood frequency. Used with permission from the NRCS.

based on the elevation reached by a flood peak of a given frequency (for example, the 100-year floodplain).

Professionals involved with flooding issues define the boundaries of a floodplain in terms of flood frequencies (probability of recurrence, in years). Thus, we use the 100-year and 500-year floodplains in the development of planning and regulation standards.

Flood Storage

The floodplain provides temporary storage space for floodwaters and sediment produced by the watershed. This characteristic serves to add to the **lag time** of a flood--the time between the middle of the rainfall event and the runoff peak.

If a stream's capacity for moving water and sediment is diminished, or if the sediment loads produced from the watershed become too great for the stream to transport, flooding will occur more frequently and the valley floor will begin to fill. Valley filling results in the temporary storage of sediment produced by the watershed.

Landforms and Deposit

Many topographic features form on the floodplain by the lateral migration (meandering) of the channel. These features result in varying soil and moisture conditions and provide a variety of habitat niches that support plant and animal diversity.

Floodplain landforms and deposits include:

- *Meander scroll:* a sediment formation marking former channel locations.
- *Chute:* a new channel formed across the base of a meander. As it grows in size, it carries more of the flow.
- *Oxbow:* a term used to describe the severed meander after a chute forms.
- *Clay plug:* a soil deposit developed at the intersection of the oxbow and the new main channel.
- *Oxbow lake:* a body of water created after clay plugs the oxbow from the main channel.
- *Natural levees:* formations built up along the bank of some, generally low-gradient streams that flood. As sediment-laden water spills over the bank, the sudden loss of depth and velocity causes coarser-sized sediment to drop out of suspension and collect along the edge of the stream.
- *Splays:* delta-shaped deposits of coarser sediments that occur when a natural levee breaches. Natural levees and splays can prevent floodwaters from returning to the channel when floodwaters recede.

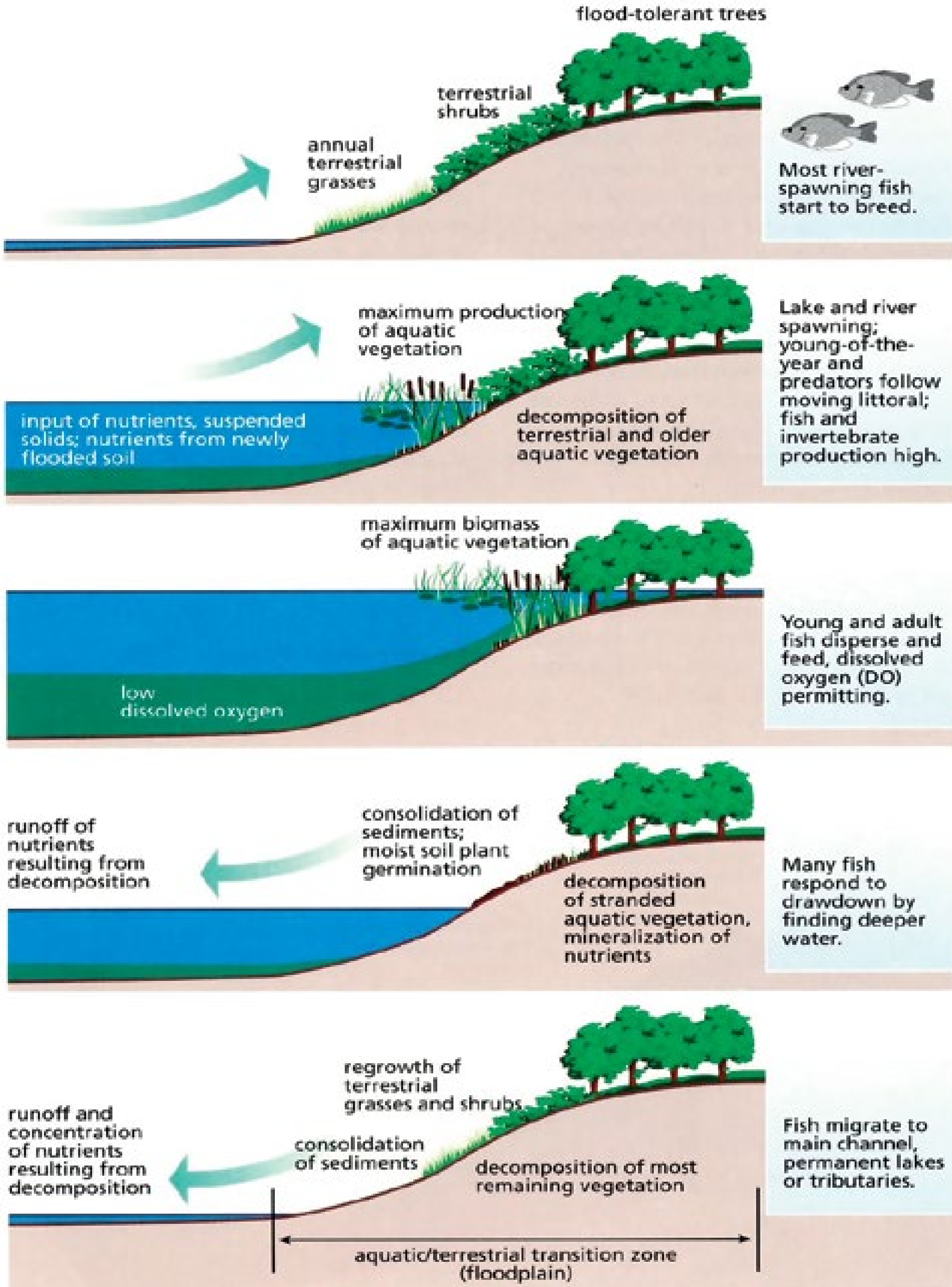


Figure 5.4 - The flood-pulse concept diagrammed in five stages of an annual hydrologic cycle. The left column describes nutrient movement, the right describes typical life history traits of fish. From Bayley, P. BioScience vol 45 no 3, p. 154, March 1995. ©1995American by permission of Oxford University Press.

- *Back swamps:* a term used to describe floodplain wetlands formed by natural levees.

Flood-Pulse Concept

The flood-pulse concept (Figure 5.4) demonstrates how flooding processes interact with plants and wildlife in all parts of the stream corridor. Floodplains serve as essential focal points for the growth of many riparian plant communities and the wildlife they support. Some riparian plant species such as willows and cottonwoods depend on flooding for regeneration. Flooding also nourishes floodplains with sediments and nutrients and provides habitat for invertebrate communities, amphibians, reptiles, and fish spawning.

The flood-pulse concept was developed to summarize how the dynamic interaction between water and land is exploited by the aquatic and terrestrial river corridor biota. Applicable primarily on larger rivers, the concept demonstrates that the predictable advance and retraction of water on the floodplain in a natural setting enhances biological productivity and maintains diversity.[5]

The Transitional Upland Fringe

The transitional upland fringe is a transitional zone between the floodplain and surrounding landscape. Its outside boundary is also the outside boundary of the stream corridor itself.

There is no typical cross-sectional structure for transitional upland fringes. They can be flat, sloping, or in cases such as ravine walls, nearly vertical. Their width may vary, and their outer boundaries are often indistinct. They can incorporate features such as hillslopes, bluffs, forests, and prairies. All transitional upland fringes have one thing in common: they are recognizably different from the surrounding landscape because of their connection to the floodplain and stream. For example, they will typically have similar vegetation partway up the hillslopes or on the edges of upland terraces.

Figure 5.5 - Terrace formation can be seen here on the Pecos River near Comstock, Texas. Image courtesy of TPWD.

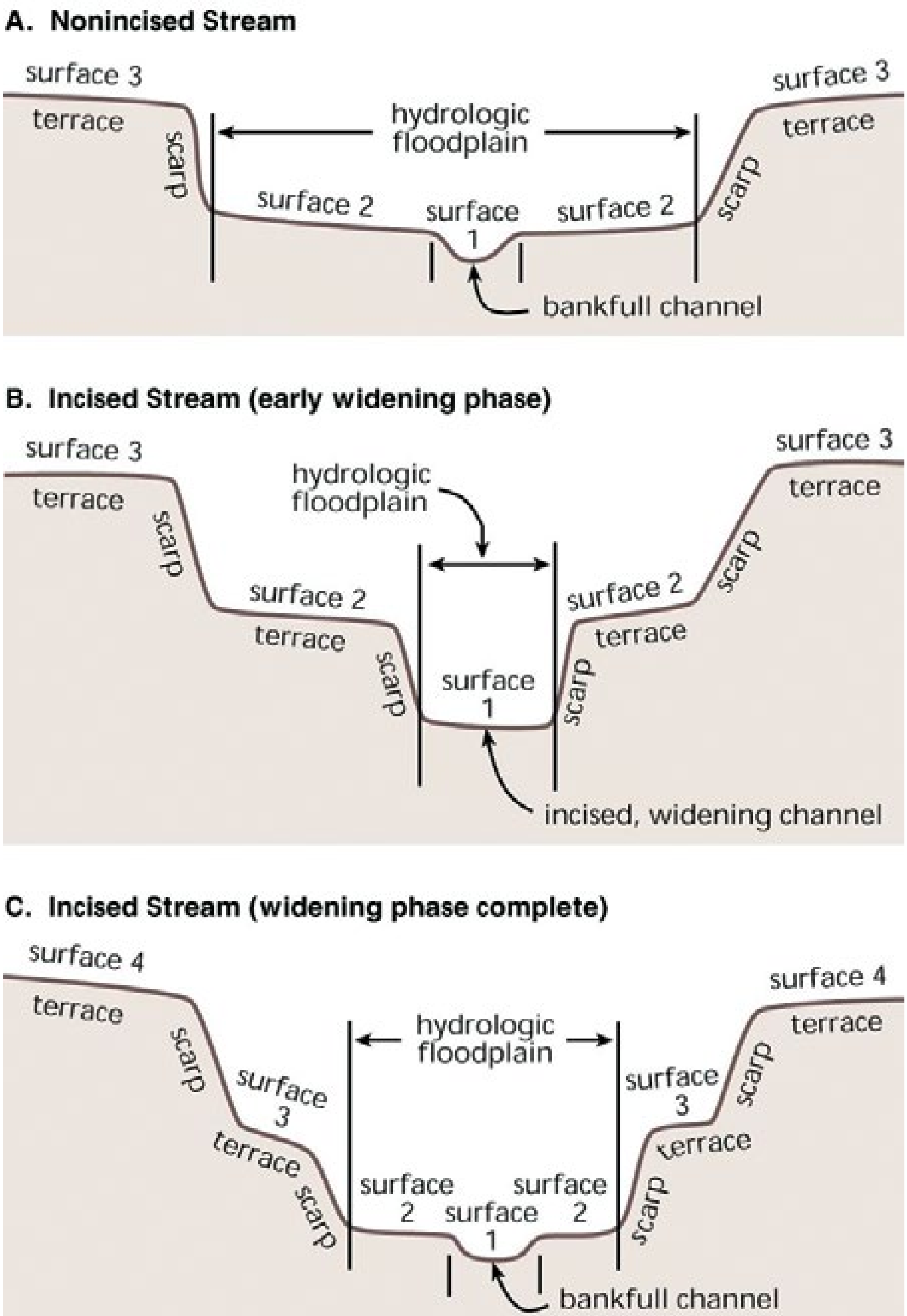


Figure 5.6 - Terrace formation by incising or widening floodplains, Used with permission from the NRCS.

An examination of the floodplain side of the transitional upland fringe often reveals one or more flat-topped benches. These landforms are terraces. (Figure 5.5) They form in response to new patterns of streamflow, changes in sediment size or load, or changes in watershed base level--the elevation at the watershed outlet. Although many terraces were formerly active floodplains, most have become isolated from periodic flooding by the stream in recent years. In some regions of the country, some of the higher, older terraces formed by glaciation.

We explain terrace formation using stream equilibrium, which we discussed earlier. When one or more variables in a system change, equilibrium is lost, and either erosion or deposition of sediments occurs.

Figure 5.6 presents an example of terrace formation by channel incision. Cross section A represents a non-incised channel. Due to changes in streamflow or sediment delivery, equilibrium is lost and the channel degrades and widens. The original floodplain is abandoned and becomes a terrace (cross section B). The widening phase is completed when a floodplain evolves within the widened channel (cross section C)

Vegetation across the Stream Corridor

The vegetation that responds to changes in the stream corridor and variations in flow is itself dynamic. Vegetation is an important and highly variable element in the stream corridor. In some minimally disturbed stream corridors, a series of plant communities might extend uninterrupted across the entire corridor. In smaller streams, the riparian vegetation might even form a closed canopy above the channel.

Submerged aquatic plants will grow in many types of channels if the substrate and stream velocity allow for rooting. Plants requiring submerged or saturated conditions, including floating rooted, free floating, and emergent herbaceous and shrub species can become established on the edges of slow-flowing waters of shallow-gradient rivers and deeper streams. Examples may include coontail, duckweed, pond lily, and cattail.

Gravel bars, shores and active floodplains within the bankfull channel may support stands of herbaceous plants and small shrubs or tree seedlings temporarily, but moderate flooding almost yearly displaces these communities. These plants are often somewhat water-tolerant but are not necessarily aquatic; examples include stargrass, smartweed, and seedlings of cottonwood, alder, and willow.

In the absence of land use disturbances, the transitional upland fringe will often consist of forested terraces and hillslopes. In desert and grassland regions, however, the fringe may mark the end of riparian woodlands or shrubs and the beginning of dry grasslands or desert scrub.

Channel and Ground Water Relationships

Interactions between groundwater and the channel vary throughout the watershed. There are two types of water movement between streams and ground water. Streams either gain or lose water to/from groundwater based on the depth of the water table and the amount of rainfall their area receives. We categorize streams based on the balance and timing of their stormflow and baseflow components.

There are three main categories:

Ephemeral streams (Figure 5.7) flow only during or immediately after periods of precipitation. They generally flow less than 30 days per year. You may be familiar with these streams if you live in drier parts of the state.**Intermittent streams** flow only during certain times of the year. Seasonal flow in an intermittent stream usually lasts longer than 30 days per year.

Perennial streams flow continuously during both wet and dry conditions. Baseflow occurs reliably from the movement of ground water into the channel.

Channel Form along the Corridor Longitudinal Zones

The form of the channel can change as it moves through longitudinal zones. This term, “longitudinal zones” refers to zones along the length of an entire river basin. These zones can be described as follows:

- Zone 1 typically includes 1st and 2nd order streams, flow swiftly, are V-shaped, with waterfalls and runs of rapids commonly occurring. There may be a high percentage of canopy cover and there is little to no floodplain present.
- Zone 2 typically includes 3rd order streams, occur at lower elevations, and on gentle slopes. There is less canopy covering the

Figure 5.7 - Ephemeral Creek near Saucedo Ranch. Image courtesy of TPWD.

streambed, and there may be more occurrence of meandering.

- Zone 3 occurs at even lower elevations and includes 4th order streams, or the main channel of the river that flows to the sea. This zone usually occurs in a broad flat valley and may exist in braided form with high amounts of deposition.

Channel form is typically described by two main characteristics--thread (single or multiple) and sinuosity. Single-thread (one-channel) streams are most common, but multiple-thread streams occur in some landscapes. Most multiple-thread streams are **braided streams**.

Braided streams typically get their start when a central sediment bar begins to form in a channel due to reduced streamflow or an increase in sediment load. The central bar causes water to flow into the two smaller cross sections on either side. The smaller cross sections result in higher velocity flow causing the channels to widen as banks erode. After this occurs, flow velocity decreases allowing another central bar to form in the newly created channels. The process is then repeated and more channels are created.

In landscapes where braided streams occur naturally, the plant and animal communities have adapted to frequent and rapid changes in the channel riparian area. In cases where disturbances trigger the braiding process, however, physical conditions might be too dynamic for many species.

Vegetation along the Stream Corridor

Riparian vegetation is an important and highly variable element in both the longitudinal and the lateral view of the stream corridor. Floodplains are narrow or nonexistent in Zone 1 (headwaters) of the longitudinal profile; thus, flood-dependent or flood-tolerant plant communities tend to be limited in distribution, except where wetland plants may dominate at or near the stream's source. Many upland plant communities bordering the stream create a canopy that leaves little open sky visible from the channel. Headwaters in flat

Figure 5.8 - Zone 1 vegetation seen here, Honey Creek SNA. Image courtesy of Johnnie Smith.

Luna Leopold relished the opportunity to do field work. Courtesy of the Aldo Leopold Foundation, aldoleopold.org.

Luna Leopold

Luna Leopold's contributions to the fields of Geomorphology and Hydrology were many. Son of famed ecologist and author Aldo Leopold, he was educated in many fields of science, including meteorology, engineering, and geology. He would combine his knowledge of all these fields into his study of water in general and rivers in particular.

Over his career as the first Chief Hydrologist at the USGS, Leopold developed our understanding of the connections between groundwater and surface water. His ideas would become the foundation of the water science programs that he would lead at the United States Geological Survey (USGS). His quantitative approach to the study of river processes and how they influence (and are influenced by) the surrounding landscape would revolutionize the field of fluvial geomorphology. He made important observations into the relationships between river depths, velocity, vegetation, and sediment load. Leopold combined his observations into books and articles, over 200 in total, including *Water: A Primer and View of a River.*

Luna Leopold's integrative approach toward Earth science continues to influence the field of geomorphology. He furthered the understanding of ecosystems through his thoughtful insights into the relationships between land use, channel engineering, flooding, and channel planform. In 1991, hisefforts were recognized in a Rose Garden ceremony at the White House, where he was awarded the National Medal of Science by President George H. W. Bush.

terrain may support plant communities dominated by grasses and broad-leaved herbs, shrubs, or planted vegetation.

Despite the variation in plant community type, many headwaters areas provide organic matter from vegetation along with the sediment they export to Zones 2 and 3 downstream. For example, logs and woody debris from headwaters forests are among the most ecologically important features supporting food chains and instream habitat structure in Pacific Northwest rivers from the mountains to the sea.[6]

Zone 2 has a wider and more complex floodplain and larger channel than Zone 1. Plant communities associated with floodplains at different elevations might vary due to differences in soil type, flooding frequency, and soil moisture. Localized differences in erosion and deposition of sediment add complexity and diversity to the types of plant communities that become established.

The lower gradient, larger stream size, and less steep terrain commonly found in Zone 2 often attract more agricultural or residential development than in the headwaters zone. This phenomenon frequently counteracts the natural tendency to form broad and diverse stream corridor plant communities in the middle and lower reaches. This is especially true when land uses involve clearing the native vegetation and narrowing the vegetated corridor.

Often, a planted vegetation community such as agricultural crops or residential lawns replaces a native plant community. In such cases these significant alterations can occur:

- stream processes involving flooding, erosion/deposition,
- import or export of organic matter and sediment,
- stream corridor habitat diversity, and
- water quality characteristics.

The lower gradient, increased sediment deposition, broader floodplains, and greater water volume in Zone 3 all set the stage for plant communities different from those found in either upstream zone. (Figure 5.9) Large floodplain wetlands become prevalent because of the generally flatter terrain. Highly productive and diverse biological communities, such as bottomland hardwoods, establish themselves in the deep, rich alluvial soils of the floodplain. The slower flow in the channel allows emergent marsh vegetation, rooted floating or free-floating plants, and submerged aquatic beds to thrive.

Figure 5.9 - Zone 3 vegetation seen here, Lower Colorado River. Image courtesy of Johnnie Smith.

The changing sequence of plant communities along streams from source to mouth is an important source of biodiversity and resiliency to change. Although many, or perhaps most, of a stream corridor's plant communities might be fragmented, a continuous corridor of native plant communities is desirable. Restoring vegetative connectivity in even a portion of a stream will usually improve conditions and increase its beneficial functions.

Sinuosity

Natural channels are rarely straight. Sinuosity is a term indicating the amount of curvature in the channel. The **sinuosity** of a reach is computed by dividing the channel centerline length by the length of the valley centerline. If the channel length/valley length ratio is more than about 1.3, the stream can be considered meandering in form. Generally, less sinuosity occurs near the headwaters and more occurs as the river widens and reaches flatter terrain.

Pools and Riffles

No matter the channel form, most streams share a similar attribute of alternating, regularly spaced, deep and shallow areas called **pools** and **riffles**. The pools and riffles are associated with the thalweg (or deepest part of the channel), which meanders within the channel. Pools typically form in the thalweg near the outside bank of bends. Riffle areas usually form between two bends at the point where the thalweg crosses over from one side of the channel to the other.

The makeup of the streambed plays a role in determining pool and riffle characteristics. Gravel and cobble-bed streams typically have regularly spaced pools and riffles that help maintain channel stability in a high-energy environment. Coarser sediment particles are found in riffle areas while smaller particles occur in pools. The pool-to-pool or riffle-to-riffle spacing is normally about 5 to 7 times the channel width at bankfull discharge.[7]

Sand-bed streams, on the other hand, do not form true riffles since the grain size distribution in the

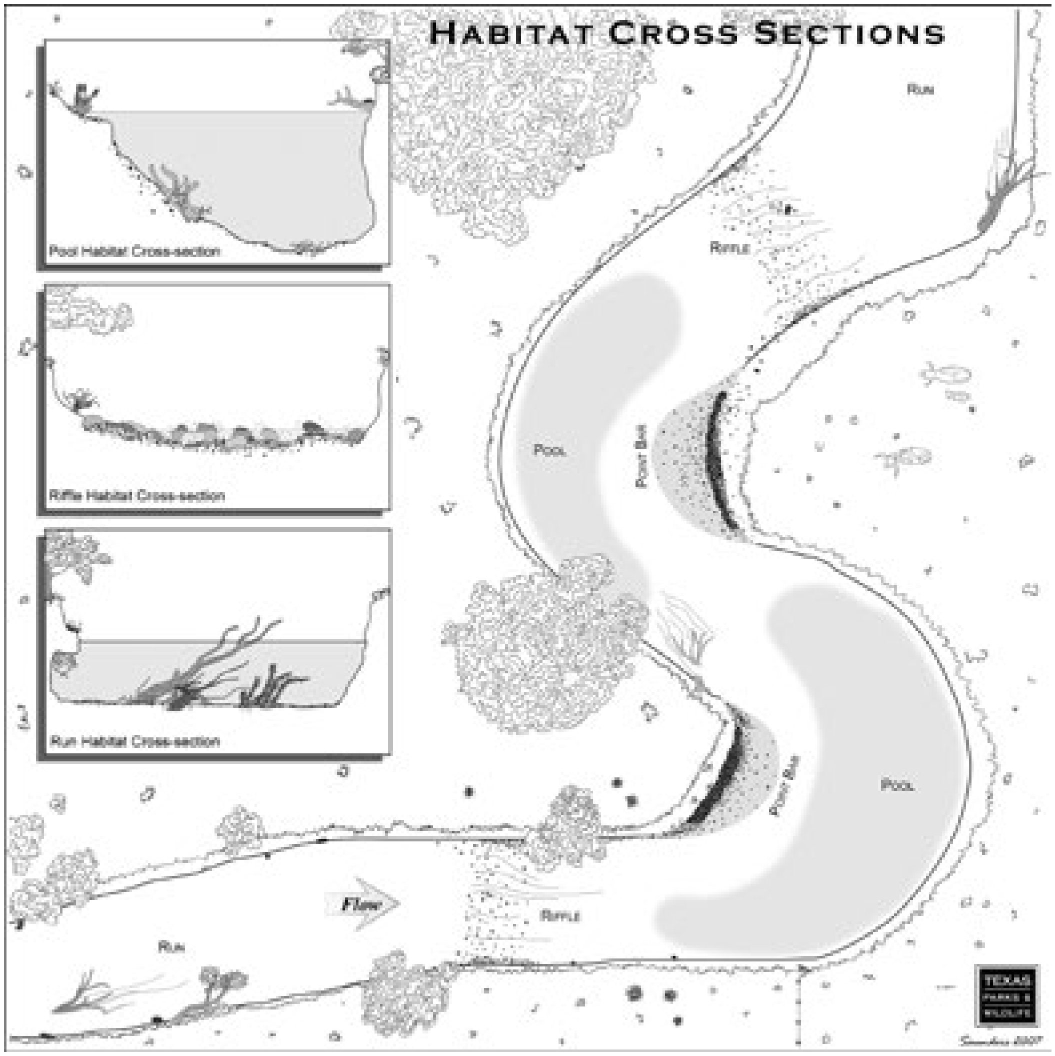


Figure 5.10 - Stream channel cross sections showing separate and distinct habitats. Image courtesy of TPWD.

riffle area is similar to that in the pools. However, sand-bed streams do have evenly spaced pools. High-gradient streams usually have pools but often lack riffles because water moves from pool to pool in a stair step fashion.

The River Continuum Concept

As we introduced in **chapter two**, the River Continuum Concept is an attempt to generalize and explain longitudinal changes in stream ecosystems.[8]

This conceptual model shown again here in Figure 5.11 not only helps to identify connections between the watershed, floodplain, and stream systems, but it also describes how biological communities develop and change from the headwaters to the mouth. The River Continuum Concept can place a site or reach in context within a larger watershed or landscape and thus help natural resource managers define and focus restoration goals.

The River Continuum Concept hypothesizes that many first- to third-order headwater streams are shaded by the riparian forest canopy. This shading, in turn, limits the growth of algae, periphyton, and other aquatic plants.

Since energy can't occur through photosynthesis in the stream channel, the aquatic biota in these small streams is dependent on materials coming from outside the channel such as leaves and twigs. These biological communities are uniquely adapted to use externally derived organic inputs. Temperature regimes are also relatively stable due to the influence of ground water recharge, which tends to reduce biological diversity to those species with relatively narrow thermal niches.

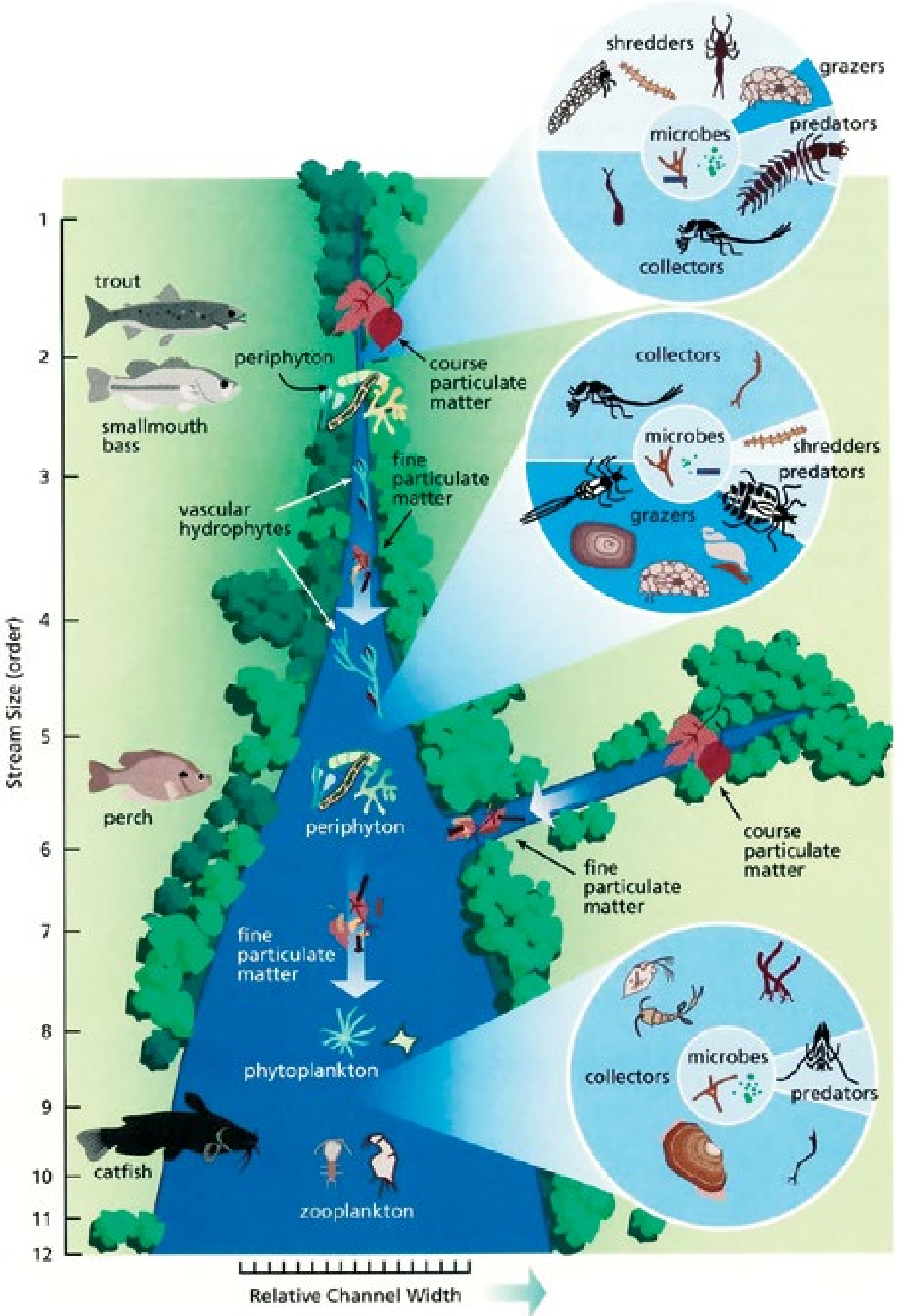


Figure 5.11 - The River Continuum Concept (Source: Vannote, 1980). © Canadian Science Publishing or its licensors. Used with permission of NRC Research Press).

Predictable changes occur as one proceeds downstream to fourth-, fifth-, and sixth-order streams. The channel widens, which increases the amount of incident sunlight and average temperatures. Levels of primary production increase in response to increases in light, which shifts many streams to a dependence on materials coming from inside the channel.[9]

In addition, smaller, preprocessed organic particles flow from upstream sections, which serve to balance plant and animal life within the stream. Species richness of the invertebrate community increases as a variety of new habitat and food resources appear. Invertebrate functional groups, such as the grazers and collectors, increase in abundance as they adapt to using both internal and external food resources. Mid-sized streams also decrease in thermal stability as temperature fluctuations increase, which further tends to increase biotic diversity by increasing the number of thermal niches.

Larger streams and rivers of seventh to twelfth order tend to increase in physical stability, but undergo significant changes in structure and biological function. Larger streams develop increased reliance on primary productivity by phytoplankton, but continue to receive heavy inputs of dissolved and ultra-fine organic particles from upstream. Fine-particle collectors (i.e., zooplankton) dominate invertebrate populations.

The influence of storm events and thermal fluctuations decrease in frequency and magnitude, which increases the overall physical stability of the stream. This stability increases the strength of biological interactions, such as competition and predation.

Sustaining Natural Freshwater Ecosystems[10]

Because freshwater ecosystems are dynamic, all require a range of natural variation or disturbance to maintain viability or resilience. To maintain natural habitat dynamics that support production and survival of species, plant and animal communities need water flows that vary both season-to-season and year-to-year. Variability in the timing and rate of water flow strongly influences:

- the sizes of native plant and animal populations and their age structures,
- the presence of rare or highly specialized species,
- the interactions of species with each other and with their environments, and
- many ecosystem processes.

Periodic and episodic water flow patterns also influence water quality, physical habitat conditions, and energy sources in aquatic ecosystems. Freshwater ecosystems, therefore, have evolved to the rhythms of natural hydrologic variability. As we learned in **chapter two**, the structure and functioning of freshwater ecosystems are also tightly linked to the watersheds of which they are a part. Water flowing through the landscape moves in three dimensions, linking:

- upstream to downstream,
- stream channels to floodplains and riparian wetlands, and
- surface waters to ground water.

Materials generated across the landscape ultimately make their way into rivers, lakes, and other freshwater ecosystems. Thus, what happens on the land, including human activities, greatly influences these systems.

Five dynamic environmental factors regulate much of the structure and functioning of any aquatic ecosystem, although their relative importance varies among aquatic ecosystem types. The interaction of these drivers in space and time defines the dynamic nature of freshwater ecosystems:

1. The *flow pattern* defines the rates and pathways by which rainfall enters and circulates within river channels, lakes, wetlands, and connecting ground waters. It also determines how long water is stored in these ecosystems.
2. *Sediment and organic matter inputs* provide raw materials that create physical habitat structure, **refugia**, substrates, and spawning grounds; sediment also supplies and stores nutrients that sustain aquatic plants and animals.
3. *Temperature, dissolved oxygen and light characteristics* regulate the metabolic processes, activity levels, and productivity of aquatic organisms.
4. *Nutrient and chemical conditions* regulate plant and animal productivity, and water quality.

5. *The plant and animal assemblage* influences ecosystem process rates and community structure.

In naturally functioning freshwater ecosystems, all five of these factors vary within defined ranges throughout the year, tracking seasonal changes in climate and day length.

Focusing on one factor at a time will not yield a true picture of ecosystem functioning. To evaluate freshwater ecosystem integrity, we must integrate and consider all five of these dynamic environmental factors jointly.

Sediment and Organic Matter Inputs

As we learned in **chapter three**, the movement of sediments and influxes of organic matter are important components of habitat structure and stream dynamics. Natural organic matter inputs include seasonal runoff and debris such as leaves and decaying plant material from land-based communities in the watershed. In smaller rivers and streams, the organic matter that arrives from the land is a particularly important source of energy and nutrients. Tree trunks and other woody materials that fall into the water provide important substrates and habitats for aquatic organisms. Natural sediment movements are those that accompany variations in water flows. In lakes and wetlands, all but the finest inflowing sediment falls permanently to the bottom, so that over time these systems fill. The invertebrates, algae, **bryophytes**, vascular plants, and bacteria that populate the bottom of freshwater systems are highly adapted to the specific sediment and organic matter conditions of their environment. They, as well as many fish species, cannot survive if changes in the type, size, or frequency of sediment inputs occur. The fate of these organisms is critical to sustaining freshwater ecosystems since they are responsible for much of the work of water purification, decomposition, and nutrient cycling.

Humans have severely altered the natural rates of sediment and organic matter supply to aquatic systems by increasing or decreasing sediment loads. Poor agricultural, logging, or construction practices, for example, promote high rates of soil erosion that can enter these systems. In some areas, development has eliminated many small streams or wetlands through filling, paving, or re-routing into artificial channels. The U.S. Environmental Protection Agency (EPA) reports that in one quarter of all lakes with sub-standard water quality, the cause of impairment is sediment loading from agricultural, urban, construction, and other non-point sources.

Dams alter sediment flows by retaining silt in the reservoirs behind them and starving streams below. By one estimate, 1.2 billion cubic meters of sediment builds up each year in U. S. reservoirs.[11]

This sediment capture in turn reduces normal sand, silt, and gravel supplies to downstream reaches, causing streambed erosion and downcutting (incision) that both degrades in-channel habitat and isolates floodplain and riparian wetlands from the channel during rejuvenating high flows. Channel straightening, overgrazing of river and stream banks, and clearing of streamside vegetation reduce organic matter inputs and often increase erosion.

Temperature, Dissolved Oxygen and Light

Water temperature directly regulates oxygen concentrations, the metabolic rate of aquatic organisms, and associated life processes such as growth, maturation, and reproduction. The temperature cycle greatly influences the fitness of aquatic plants and animals. By extension, it can determine species distribution in the system. It also influences how the living community in a body of water varies from season to season. In lakes particularly, the absorption of solar energy and its dissipation as heat are critical to developing temperature gradients between the surface and bottom water layers. These temperature gradients in turn influence nutrient cycling, distribution of dissolved oxygen, and the distribution and behavior of organisms, including game fishes.

Nutrient and Chemical Conditions

Natural nutrient and chemical conditions are those that reflect the:

- local climate,
- substrate composition,
- vegetation type, and
- topography.

Natural water conditions can range from clear, nutrient-poor rivers and lakes on crystalline bedrock to much more chemically enriched and algae-producing

Figure 5.12 - Eutrophication on Onion Creek in McKinney Falls State Park results from miles of passage through urban and suburban neighborhoods, parks, and golf courses. Image courtesy of Johnnie Smith.

freshwaters in watersheds with organic matter-rich soils or limestone bedrock. This natural regional diversity in watershed characteristics sustains high biodiversity. **Eutrophication** occurs when additional nutrients, chiefly nitrogen and phosphorus, from human activities enter freshwater ecosystems. This affects water quality for all users of water and aquatic habitats.

Plant and Animal Assemblages

The community of species that lives in any given aquatic ecosystem reflects both the pool of species available in the region and the abilities of individual species to colonize and survive in that water body. The suitability of a freshwater ecosystem for any particular species is dictated by the environmental conditions – for example, water flow, sediment, temperature, light, and nutrient patterns—and the presence of, and interactions among, other species in the system. Thus, both the habitat and the biotic community provide controls and feedbacks that maintain a diverse range of species. A high degree of natural variation in environmental conditions in fresh waters promotes high biological diversity. In fact, North American freshwater habitats are virtually unrivaled in diversity of fish, mussel, crayfish, amphibian, and aquatic reptile species compared with anywhere else in the world. The biota, in turn, is involved in shaping the critical ecological processes of primary production, decomposition, and nutrient cycling.

Within a body of water, species often perform overlapping, apparently redundant roles in these processes, a factor that helps provide local ecosystems with a greater capacity to adapt to future environmental variation. High apparent redundancy affords a kind of insurance that ecological functions will continue during environmental stress. Critical to this is connectivity among water bodies, which allows species to move to more suitable habitat as environmental conditions change. Human activities that alter freshwater environmental conditions can greatly change both the identity of the species in the community and the functioning of the ecosystem. Excessive stress or simplification of natural complexity has the potential to push functionally intact freshwater ecosystems beyond the bounds of resilience or sustainability, threatening their ability to provide important goods and services (**chapter four**) on both short and long term scales. Further, introduction of non-native species that can thrive under the existing or altered range of environmental variation can contribute to the **extinction** or **extirpation** of native species, severely modify food webs, and alter ecological processes such as nutrient cycling. Exotic species are often successful in modified systems, where they can be difficult to eradicate.

We can best sustain aquatic ecosystems by maintaining:

- naturally variable flows,
- adequate sediment and organic matter inputs,
- natural fluctuations in heat, light, and clean water, and
- a naturally diverse plant and animal community.

If we fail to provide for these essential requirements, the results may be loss or degradation of species and ecosystem services in wetlands, rivers, and lakes. We can protect and/or restore aquatic ecosystems by recognizing the following:

1. More than simply isolated bodies or conduits, aquatic ecosystems are tightly connected to terrestrial environments. Connected to one another, aquatic ecosystems provide essential migration routes for species.
2. Dynamic patterns of flow within the historical range of variation will promote the integrity and sustainability of freshwater systems.
3. Aquatic ecosystems require that sediment loads, heat and light conditions, chemical and nutrient inputs, and plant and animal populations fluctuate within their natural ranges.

In Texas, the Texas Commission on Environmental Quality (TCEQ) and the Texas Parks and Wildlife Department (TPWD) work together to monitor and ensure the health of aquatic habitats in naturally flowing streams and rivers and those that are dammed alike. In dammed reaches that hold water for human use, other issues related to sedimentation, dissolved oxygen, temperature etc. require specialized monitoring and inclusion of engineered solutions to provide flows that most closely resemble those of natural flows. These considerations provide compliance with the Clean Water Act and the Aquatic Life Use designations of those reaches. Examples include:

- aeration to improve dissolved oxygen levels in the water released out of Lake Travis into Lake Austin at Mansfield Dam,
- dissolved oxygen and temperature triggers that regulate the flow out of Lake Livingston,
- dissolved oxygen concentrations in the

Figure 5.13 - Exotic Invasive Blue tilapia. Image courtesy of TPWD.

Figure 5.14 - Frio River. Image courtesy of TPWD.

Tenaha Creek Arm of the Toledo Bend Reservoir, and

- many, many more examples.

Summary

Natural flow regimes reflect the conditions under which aquatic plants and animals evolved and adapted to their place in aquatic ecosystems. Simply put, once natural flow variability changes, the aquatic life that relies on it begins to suffer. Because of this, humanity struggles with balancing the needs of those aquatic and riparian habitats with its own needs. Science clearly states the evidence for maintaining or restoring natural flow regimes. Wherever possible, we must hope that we make wise conservation decisions and ensure that we save enough water for wildlife and for people.

Challenge

Look at a map of the watershed in which you live. Look for any evidence of human impact on the natural flow regime. Recall your newfound knowledge about stream order, ecological succession in riparian areas, and vegetation along the stream corridor. Build an image in your mind of your local riparian area. What stream order is your local flowing water? What vegetation zone should you expect to find? Is there a specific stage of ecological succession you would expect to see?

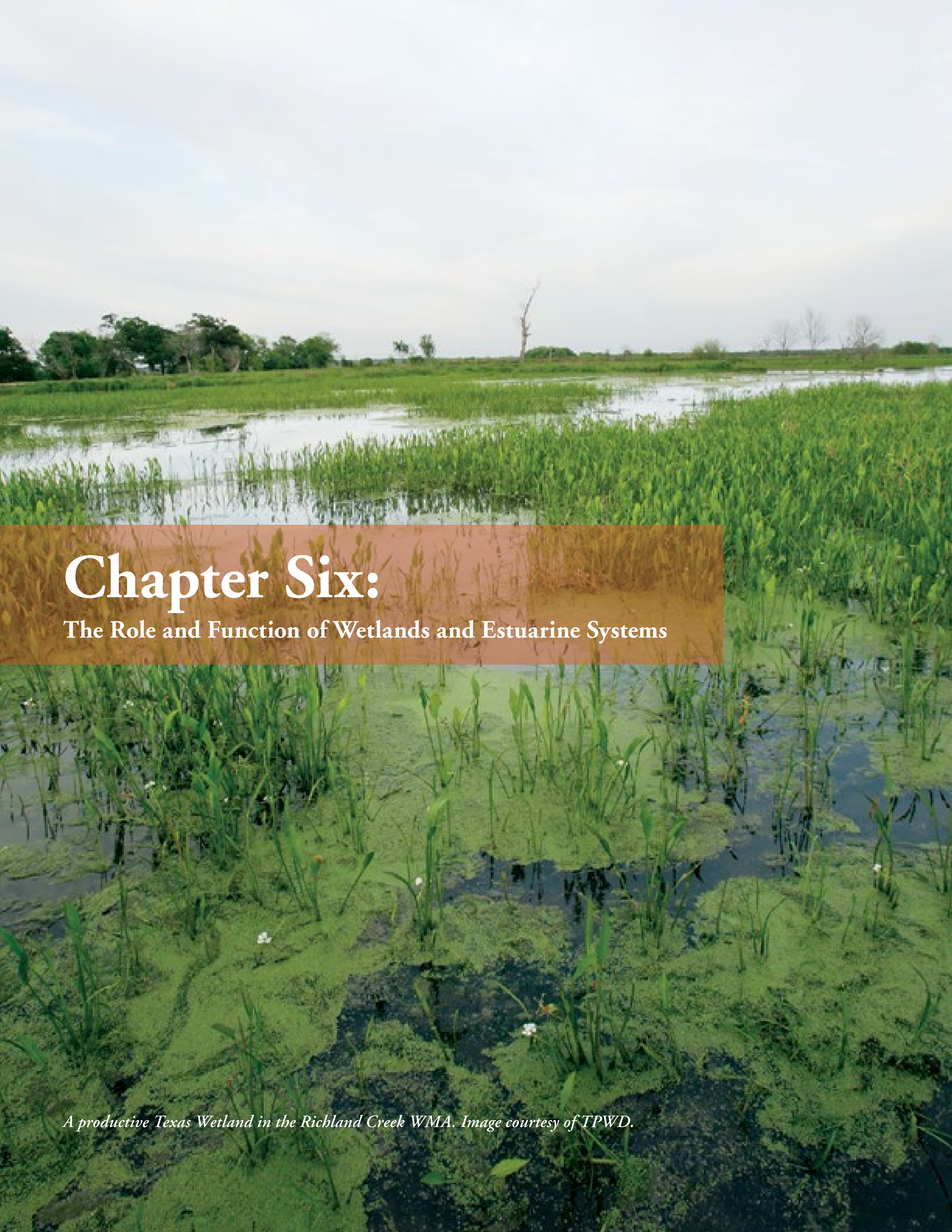
Armed with this knowledge and the mental image of your local riparian area, take a field trip! Do your observations agree with your expectations?

References

1. (Lane, 1955)
2. (Schueler)
3. (Simmons, 1982)
4. (Federal Interagency Stream Restoration Working Group, 1998)
5. (Bayley, 1995)
6. (Maser, 1994)
7. (Leopold, 1964)
8. (Vannote, 1980)
9. (Minshall, 1978)
10. (Baron, J. 2003)
11. (Stallard, 1998)

Chapter Six:

The Role and Function of Wetlands and Estuarine Systems



A productive Texas Wetland in the Richland Creek WMA. Image courtesy of TPWD.

Chapter Six:
The Role and Function of Wetlands and Estuarine Systems

Questions to Consider

- What functions do wetlands perform?
- How do wetlands affect water quality?
- Can wetlands help to mitigate floodwaters?

Introduction

Wetlands are among the most productive ecosystems in the world, comparable to rain forests and coral reefs. They also are a **source of substantial biodiversity** in supporting species from all of the major groups of organisms – from microbes to mammals – and various stages of organisms' life cycles. Wetlands also provide essential roles in water and air quality.

Although the basic functions of wetlands are similar, all wetlands are not alike. Wetlands in Texas, North Carolina, and Alaska, for example, differ substantially from one another because of their varying physical and biotic nature. Physical and chemical features such as climate, topography, geology, nutrients, and hydrology help to determine the plants and animals that inhabit various wetlands.

Wetland Functions and Values

Support for the Aquatic Food Web

Think of wetlands as "biological supermarkets." They **produce great quantities of food** that attract many animal species (Figure 6.1). As we learned in previous chapters, food webs are complex, dynamic feeding relationships.

Wetlands provide shallow water, high levels of inorganic nutrients, and high rates of primary plant productivity. These conditions are ideal for a healthy aquatic food web. Dead plant leaves and stems break down in the water to form small, nutrient-enriched particles of organic material called detritus. Bacteria, fungus and protozoa break down plant material into smaller particles, enriching it and feeding organisms that form the base of the food web such as many species of insects, mollusks, and crustaceans. This enriched material, including the various microbes that colonize it, feeds many small aquatic invertebrates and small fish. Many of these invertebrates and fish then serve as food for larger predatory amphibians, reptiles, fish, birds, and mammals.

Biochemical Cycling

The diversity of habitats in a watershed or larger landscape unit is also important for biogeochemical cycling. Biogeochemical cycling involves the biologic, physical or geological, and chemical processes that move essential elements from the biotic to the abiotic world and back again. That is, it helps transfer various nutrients within the biota, soils, water, and air. Wetlands are very important in the chemical transformation of nitrogen, sulfur, and phosphorous. A good example of this occurs in anaerobic (non-oxygenated) and chemically reduced wetland soils and muddy sediments. Through decomposition, soil microbes convert organic nitrogen and sulfur into inorganic forms. This is called mineralization. Much of this transforms into gaseous forms and releases into the atmosphere, where it once again becomes available to certain plants and nitrogen-fixing bacteria in the soil. On the other hand, phosphorous does not have a gaseous form, but vascular plants in wetlands transform inorganic forms of phosphorus into organic forms in their biomass as they grow. Otherwise, undesirable algal blooms may result. Thus, wetlands provide the conditions needed for the removal of both nitrogen and phosphorus from surface water. Scientists also point out that atmospheric maintenance is an additional wetland function. Wetlands store carbon within their live and preserved plant biomass (peat) instead of releasing it to the atmosphere as carbon dioxide. Carbon dioxide is a greenhouse gas affecting global climates. Therefore, wetlands worldwide help to moderate global climatic conditions. Wetlands also play an important role in the water cycle. Wetlands receive, store, and release water in various ways—physically through ground water and surface water, as well as biologically through transpiration by vegetation—and therefore function in this very important global cycle.

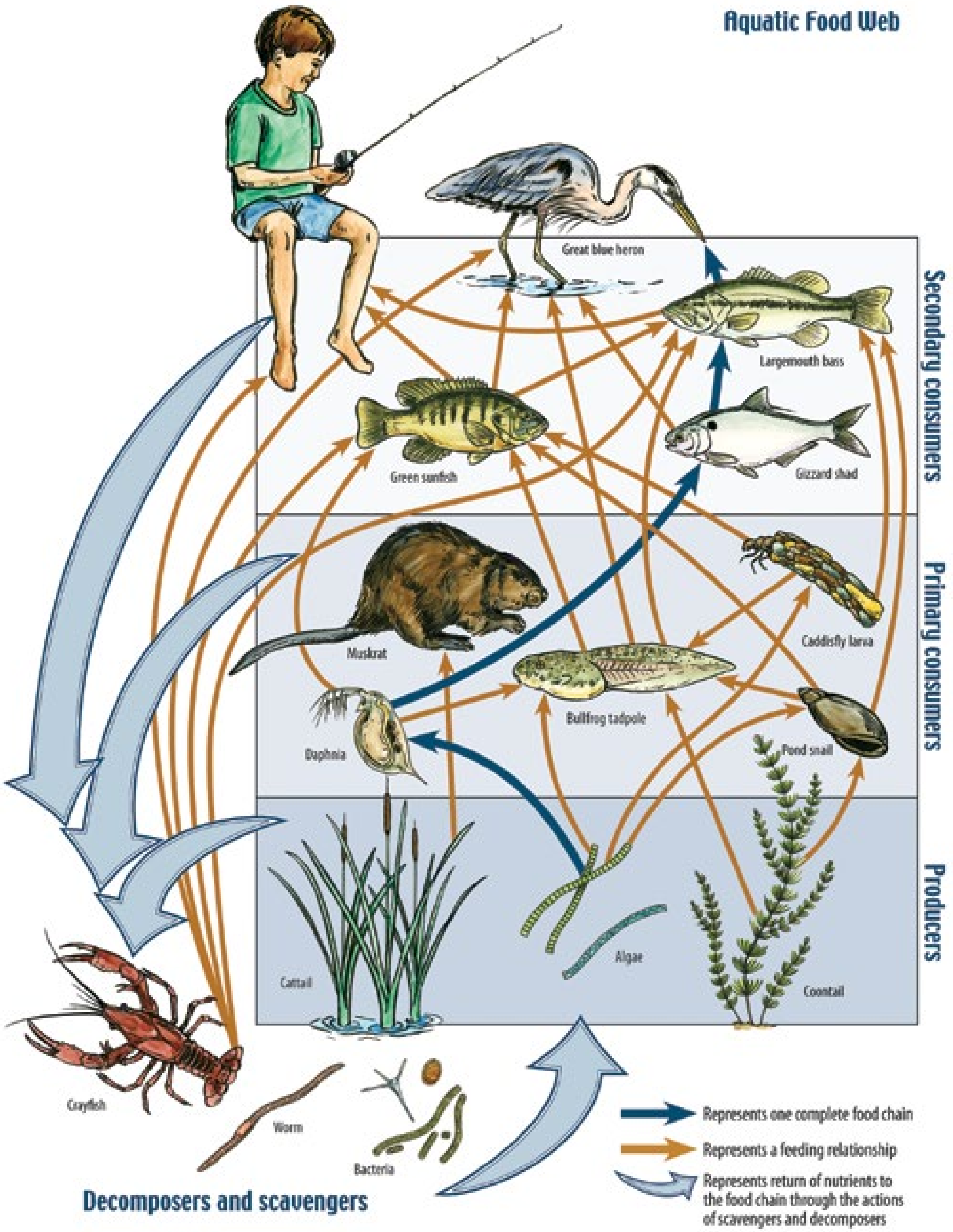


Figure 6.1 - Remember this food web diagram from Chapter 2? The tremendous capacity of wetlands to produce plant growth supports a great diversity of consumers. Image used with permission from the Missouri Department of Conservation.

Habitat for Fish, Wildlife, and Plants

Many animals need wetlands for part or all of their life cycles. Some live only in wetlands for their entire lives; others require wetland habitat for at least part of their life cycle; still others use wetlands much less frequently, generally for feeding. Numerous species of birds and mammals rely on wetlands for food, water, and shelter, especially while migrating and breeding. In other words, for many species wetlands are primary habitats, meaning that these species depend on them for survival; for others, wetlands provide important seasonal habitats, where food, water, and cover are plentiful.

Figure 6.2 - Beaver. Image courtesy of TPWD.

For example, wetlands are essentially the permanent habitat of the beaver, muskrat, wood duck, Wild-rice, cattail, broadleaf arrowhead and swamp rose. However, some species such as the tiger salamander,

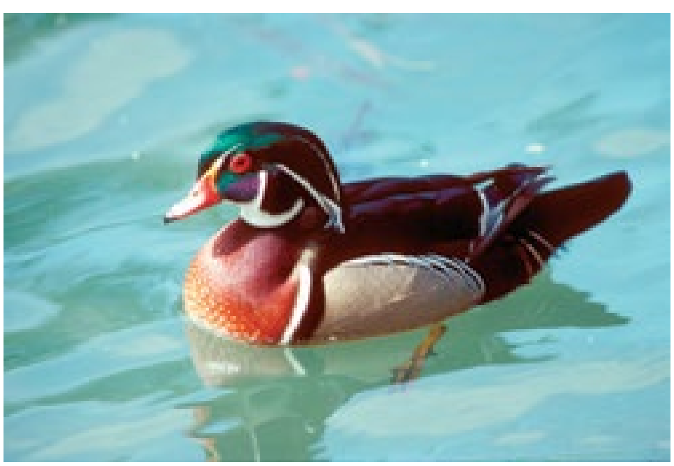


Figure 6.3 - Wood Duck. Image courtesy of TPWD.

rely on wetlands for just certain periods in its life cycle. For other species, such as largemouth bass, great blue heron, ibis, spoonbill, otter, and raccoon, wetlands provide important food, water, shelter, or nesting habitat.

Numerous birds -- including certain shorebirds, wading birds, and raptors, and many songbirds -- feed, nest, and/or raise their young in wetlands. Migratory waterfowl, including ducks, geese, cranes and swans, use coastal and inland wetlands as resting, feeding, breeding, or nesting grounds for at least part of the year. The U.S. Fish and Wildlife Service estimates that up to 43% of the federally threatened and endangered species rely directly or indirectly on wetlands for their survival.

Figure 6.4 - White Ibis. Image courtesy of Johnnie Smith.

Figure 6.5 - Roseate Spoonbill. Image courtesy of Johnnie Smith.

Wetlands Nursery

Because they produce so much plant biomass and invertebrate life, estuaries and coastal marshes serve as important nursery areas for the young of many recreational and commercial fish and shellfish.

Figure 6.6 - Great Blue Heron. Image courtesy of Johnnie Smith.

Menhaden, flounder, sea trout, spot, croaker, and striped bass are among the more familiar fish that depend on coastal wetlands. Such areas are also critical nursery habitat for young commercial shrimp along the Southeast and Gulf Coasts. Freshwater fish, such as the alligator gar, use well-flooded or ponded wetlands as breeding and nursery areas. Some fish, like the Brown Bullhead and Gulf Killifish, even subsist in wetlands that have naturally low dissolved oxygen concentrations that unadapted species cannot endure. In late winter and early spring, adult tiger salamanders migrate from uplands to vernal pools to breed and deposit their eggs. The fertilized eggs hatch into gilled larvae. As they develop lungs, they must leave the vernal pools for adjacent upland, generally forested, habitat. As adults, they are mainly subterranean. In this instance, a matrix of wetlands within a forest supports the reproductive and early stages of the tiger salamanders' life cycle.

Figure 6.7 - Wild-rice. Image courtesy of TPWD.

Figure 6.8 - Texas Coastal Wetlands. Image courtesy of TPWD, artwork by Clemente Guzman.

Improving Water Quality and Hydrology

Wetlands are valuable to us because they greatly influence the flow and quality of water. They help improve water quality, including that of drinking water, by intercepting surface runoff and removing or retaining inorganic nutrients, processing organic wastes, and reducing suspended sediments before they reach open water. As runoff water passes through wetlands, vegetation and soils retain or process excess nitrogen and phosphorus, decompose organic pollutants, and trap suspended sediments that would otherwise clog waterways and affect fish and amphibian egg development.

In performing this filtering function, wetlands save us a great deal of money. Wetlands efficiently remove pollutants and excess nutrients. Many areas across our state are realizing the benefits of these natural processes, even using constructed wetlands as a step in wastewater treatment. This produces critical habitat for a myriad of aquatic and aquatic dependent species.

Wetlands also reduce environmental problems, such as algal blooms, dead zones, and fish kills, that are generally associated with excess nutrient loadings. However, the capacity of wetlands to function this way is limited, and too much runoff carrying sediments, nutrients, and other pollutants can degrade wetlands and thus the societal services they provide.

Flood Protection

Figure 6.9 - Lower Colorado River Delta. Image courtesy of TPWD.

Because of their low topographic position relative to uplands (e.g., isolated depressions, floodplains), wetlands store and slowly release surface water, rain, groundwater and flood waters. Trees and other wetland vegetation also impede the movement of floodwaters and distribute them more slowly over floodplains. This combined water storage and slowing action lowers flood heights and reduces erosion downstream and on adjacent lands. It also helps reduce floods and prevents waterlogging of agricultural lands. Wetlands within and downstream of urban areas are particularly valuable in this regard, counteracting the greatly increased rate and volume of surface-water runoff from impervious cover. In coastal areas, researchers believe that each mile of robust coastal wetlands can reduce the height of storm surge by one foot.

Preserving and restoring wetlands, together with other water retention practices, can often provide the level of flood protection otherwise provided by expensive dredging operations and levee construction.

Therefore, in addition to the ecological value provided to fish and wildlife, wetlands reduce the likelihood of flood damage to homes, businesses, and crops in agricultural areas. They also help control increases in the rate and volume of runoff in urban areas. This protection results in less monetary flood damage (and related insurance costs), as well as protection of human health, safety, and welfare.

Shoreline Erosion

Because of their position on the landscape, wetlands at the margins of lakes, rivers, bays, and the ocean help protect shorelines and stream banks against erosion. Wetland plants hold the soil in place with their roots, absorb the energy of waves, and break up the flow of stream or river currents. The ability of wetlands to control erosion is so valuable that some states are restoring wetlands in coastal areas to buffer the storm surges from hurricanes and tropical storms by dissipating wave energy before it affects roads, houses, and other man-made structures.

Summary

In this chapter, you have learned how wetlands are among the most productive ecosystems in the world, comparable to rain forests and coral reefs. Earth's amazing biodiversity is due in large part to wetlands. You have learned that they support species from all of the major groups of organisms – from microbes to mammals. Lastly, you discovered how abiotic features like climate, topography, geology, nutrients, and hydrology all work together to produce the unique life that exists in each type of wetland.

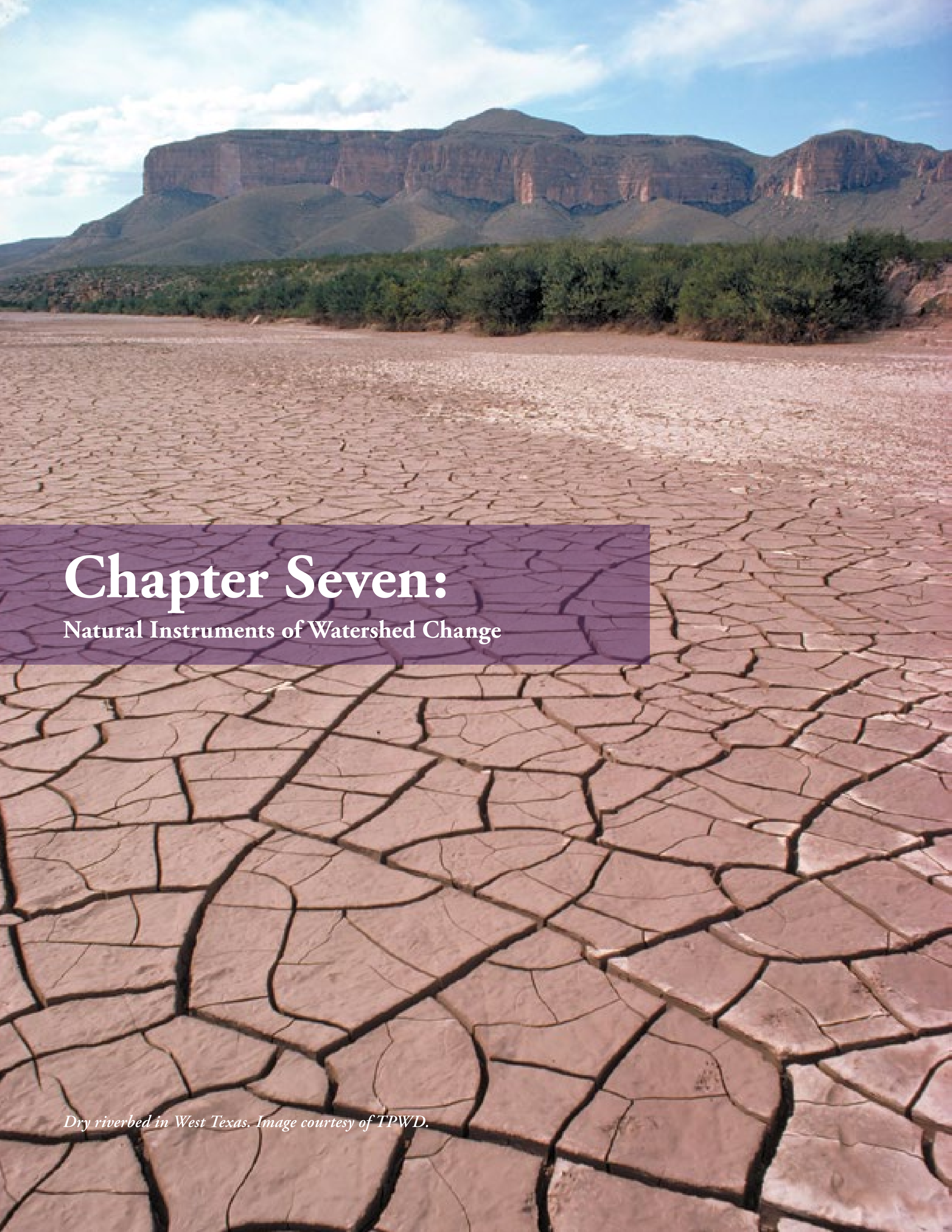
Challenge

What is the closest wetland to where you live? What is its value in the community? In what ways, if any, has the community affected the wetland?

Links:

TPWD's Texas Treasures: Wetlands publication. Search for the title on tpwd.texas.gov.

TCEQ's Field Guide to Water Education publication. Search for the title on tceq.texas.gov/.



Chapter Seven:

Natural Instruments of Watershed Change

Dry riverbed in West Texas. Image courtesy of TPWD.

Chapter Seven:
Natural Instruments of Watershed Change

Questions to Consider

- What naturally occurring change processes have you witnessed in your watershed?
- What has been the result of natural change processes in your watershed?
- To what extent should people attempt to control naturally occurring change?

Introduction

Agents of change may be naturally occurring or human caused. In many cases, change involves interactions between human and natural processes. In this chapter, we will provide brief descriptions of several agents of natural change processes, along with their general effects on watersheds. Then, in the next chapter, we will discuss a series of human caused agents of change.

Natural Change Processes

Natural agents of change directly affect watershed ecosystems and their evolution. As constant sources of change, they have shaped watersheds over countless centuries. There are many additional natural change agents beyond those listed and discussed here.

- Flooding
- Drought
- Fire
- Windstorms
- Erosion/Sediment Deposition

Flooding

In rivers and streams, floods are critical for several reasons. They redistribute organic material and living organisms downstream, create an opportunity for exchange of sediment and nutrients with the floodplains, and they help maintain healthy native plant diversity. Through the processes of erosion and deposition, floods redistribute major structural elements of the channel and expose new surfaces. Particularly intense floods can form entirely new channels, displace riparian forests, and trigger major landslides and debris torrents. This creates a new mosaic of deposited sediments, seeds, and plants that can lead to a more extensive ecological recolonization and recovery period. However, when highly invasive plants are present, intense floods can spread their propagules (seeds or other reproductive parts) into freshly disturbed habitats where they are able to rapidly recolonize, outcompeting native vegetation.

Figure 7.1 - Floodwaters of the San Marcos River in Palmetto State Park. Image courtesy of TPWD.

Seasonal and year-to-year variation in flow is a primary selective force for organisms living in rivers and their associated watersheds. Floodwaters also play a major role in shaping the physical environment of the stream channel and floodplains. For example, the bankfull flood stage is the primary force in determining the shape of the channel and the location of its floodplains. A bankfull flood fills the main channel and just begins to spill onto the floodplain. These occur about every 1.5 years on average. The amount and velocity of streamflow and the shape of the channel affect the size of materials transported and the stability of the streambed. These in turn, affect the density and composition of benthic organisms like freshwater clams, mussels, crayfish, and plants. Higher streamflow velocity during bankfull flood events is also important for preventing deposition of invasive

Figure 7.2 - Erosion on Williamson Creek in McKinney Falls State Park. Image courtesy of Johnnie Smith.

plant fragments from upstream sources. In Texas, floods generally occur during extreme weather events such as hurricanes (southeast coastal areas) or periods of extended rain.

Drought

Figure 7.3 - Drought can severely affect lake levels. Image courtesy of TPWD.

In addition to its obvious adverse effect of reducing overall water volume or flow, drought can have a major impact on water chemistry by altering the contribution of groundwater versus surface water. This can result in changes in the water chemistry, transparency, light regime, and the thermal characteristics of lakes and rivers. Drought also may totally dry up temporary water bodies such as woodland ephemeral pools, small streams with marginal flow, or seasonal, pothole-type wetlands. Many organisms are uniquely dependent upon the ephemeral waters that are absent from the landscape during periods of drought. For several species of birds and amphibians, the disappearance of seasonal water bodies can have a negative effect on the population due to temporary elimination of breeding or feeding grounds. Many years of depressed population numbers in these species can follow droughts. Some species, including most microcrustaceans, many amphibians, and even some species of fish can wait out periods of drought by going through a stage of dormancy that, in the case of some crustaceans, can last hundreds of years.

Beyond affecting the water body and its aquatic organisms, drought affects upland areas of watersheds. Severe drought can cause dieback of less-tolerant tree and shrub species and can lead to shifts in dominant vegetation. Crop failures from sustained droughts can eventually lead to abandonment of some areas' agricultural land uses and communities. As witnessed during the Ddust Bowl period in the 1930s, droughts can also liberate huge volumes of topsoil no longer stabilized by crops or natural vegetation. This may have severe effects on water quality and on productivity of the topsoil-deprived lands.

Fire

Fire frequencies and intensities are controlled by soil moisture, ignition sources (e.g., lightning) and fuel buildup (i.e., amounts and combustibility of litter). In Texas, wildfires typically occur during dry summer periods, and dry upland areas are generally more prone to fire than riparian areas. Longer intervals between fires cause greater fuel buildups and more intense fires when they do occur. A specific distinction exists between surface fires, which tend to occur at frequent intervals (1 to 10 years) and burn at low intensities, and crown fires, which occur less frequently (100 to 1,000 years) and burn at high intensities. Crown fires tend to do more damage to trees and are more likely to initiate stand replacement by other, pioneer species.

The Bastrop County Complex fire ignited on September 4, 2011. This crown fire was the most destructive wildfire in state history. The 32,000-acre inferno destroyed over 1,600 homes and killed two people. Again, in 2015, the "Hidden Pines" fire erupted. This fire affected 684 acres of parkland, including most of the scenic Park Road 1C corridor, 10 acres at Bastrop State Park, and more than half of Buescher State

Figure 7.4 - Bastrop County Complex Fire. Image courtesy of TPWD.

Park. In total, this blaze affected almost 5,000 acres with about 35 percent having reached extreme intensity, indicating that all trees died. By comparison, the 2011 Bastrop County Complex wildfire covered 34,000 acres, of which 75 percent saw extreme fire intensity levels.

"Fire is and can be a good thing, since it is required for maintaining and sustaining the pine forests," said Jamie Creacy, superintendent at Buescher and Bastrop State Parks. "However, fire had been suppressed in these forested habitats for the past several decades, allowing incredible accumulation of 'fuel,' which supported catastrophic wildfire – negatively impacting communities and natural resources."[1]

Frequent low-intensity fires play an important role in shaping various forest associations. Species such as lodgepole pine and jack pine rely on heat from fires to open cones and allow seeds to disperse, while exposed mineral soils following fire encourages germination of pine seeds. In some areas, fire resistance adaptations (e.g., thick bark, dropping of lower limbs to prevent fire ladder effects) allow species like ponderosa pine and red pine to withstand periodic low-intensity fires, maintaining open stands with minimal shading and competition for soil resources from other species. More intense fires kill off mature trees, creating open conditions for early successional species like sweet gum and persimmon. Small, patchy fires help maintain a mosaic of different communities within a given watershed, thereby increasing habitat complexity and diversity. Some invasive riparian plants (e.g., giant reed and salt cedar) create an extraordinarily high "fuel load" that results in more frequent, high-intensity fires that kill off mature trees, allowing the invader to rapidly sprout and dominate.

Wildfire effects on water quality can vary widely. Large-scale fires in a watershed with steep slopes can accelerate erosion and runoff, raise water temperatures due to removal of riparian cover, and leave a watershed more vulnerable to other disturbances for a period of years.

Windstorms

Figure 7.5 - Regrowth after the Bastrop County Complex fire. Image courtesy of Julia Gregory.

Windstorms are one of the many factors responsible for maintaining the spatial mosaic of different vegetation communities across the landscape. Extreme windstorms, such as tornadoes and hurricanes, occur regularly.

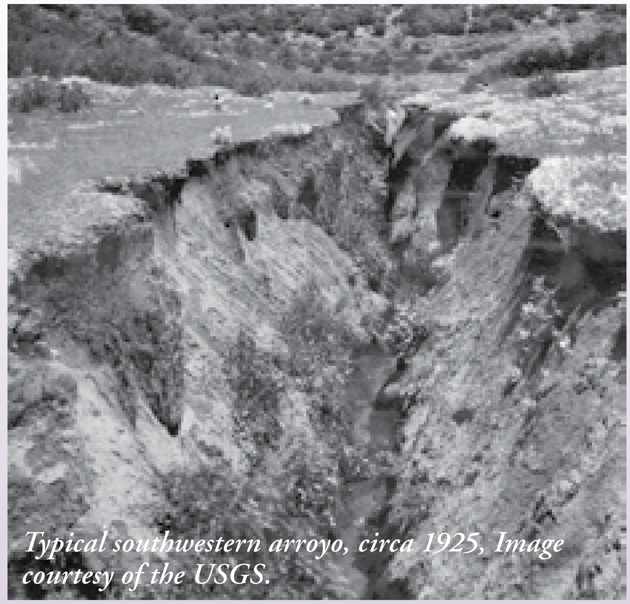
The effects of a windstorm can depend greatly on the local topography and the vegetation present. Disturbance associated with wind can thus be

Figure 7.6 - Hurricane Ike approaching the Texas coast, September 12, 2008. Image courtesy of NOAA Environmental Visualization Laboratory.

quite patchy. The ability of a given tree to withstand a windstorm depends on not only the energy of the wind, but the exposed surface area of the tree, its root mass, and the characteristics of the soil in which it is rooted. Small groves of old-growth trees found in second growth forests can be especially susceptible to windstorms. Blowdown patches form open areas that become habitat for edge-preferring plant and animal species. Synergy between windstorms and pest outbreaks is evident when a disease weakens a stand of trees that later become victims of high winds. There can also be interactions between human land use and the effects of windstorms, as when removing natural windbreaks makes remaining vegetation more susceptible to windthrow.

Figure 7.7 - Lower Colorado River Delta. Image courtesy of TPWD.

Arroyos



Typical southwestern arroyo, circa 1925, Image courtesy of the USGS.

Between the years 1860 and1920, the southwest United States witnessed an episode of arroyo cutting. Arroyos have flat bottoms and steep vertical sides and are formed in unconsolidated materials. Upstream migration of head cuts (erosional features usually involving a short cliff or bluff) and the consolidation (or joining) of separate gullies, causes them to form. These channels typically only flow in response to a rainfall event and can cause severe damage to agricultural land, causing farmers in some cases to abandon their farms. They also lower the water table locally, making water supplies less reliable.

The development of arroyos has been linked to climate, land-use change, and rainfall intensity. The extent each plays a role is up for debate. The period of erosion that began in the 1800s coincides with an increase in livestock populations in the southwest. Cattle, goats, and horses put pressure on the vegetation and caused soil compaction, creating conditions conducive to runoff and erosion. There is evidence of arroyo cutting cycles occurring around 2000 years ago. This would indicate that the introduction of livestock and overgrazing is not the only cause of arroyo cutting. There was also heavy rainfall and flooding in parts of the southwest during this same time period. Heavy rainfall events preceded by a drier than normal period where the vegetation is thin can initiate erosion and gully formation. Another explanation is that periods of heavy rains can cause upward erosion of tributaries and an increase in available sediment. Over time the increase in sediment load can steepen the slope of the streambed. At a critical gradient entrenchment is triggered and the down cutting stream will form an arroyo.

Wind can affect water quality and aquatic ecosystem health, for example, by adding significant quantities of windblown soil to the water. Wind events are often responsible for transporting debris and in some cases organisms to different areas of a lake. The timing of a lake's turnover in the fall, for example, depends on the relative strengths of wind energy and the water's buoyant resistance to mixing.

Erosion and Sediment Deposition

Despite the fact that erosion can dramatically affect water quality, it is a natural process. Sediment erosion, transport, and redeposition are among the most essential natural processes occurring in watersheds. In fact, cutting off sediment supply can lead to dramatic shifts in streambed composition and stream downcutting, among other effects. This can occur when an **impoundment** intercepts cobbles, gravels and smaller particle sizes normally transported downstream as a stream's bedload.

Although sediment may enter a river from adjacent banks, most comes from upstream sources. Sediment supply can be a major factor in determining channel morphology, which in turn determines many of the primary physical and biological characteristics of a river. Sediment transport depends on the interaction between upland topography (which represents the source of sediments), and discharge regime (which supplies the kinetic energy for distribution in the river channel). Several factors influence the location and nature of erosion:

- vegetation cover,
- climate,
- soil type, and
- slope gradient.

Dramatic changes can occur, for example, when intense rainstorms cause landslides or when a stand-replacing fire changes the vegetation cover on a hill slope. It is important to note that in most parts of the watershed, erosion, transport, and deposition do not occur at constant rates, but are highly active during events such as flooding, windstorms, and seasonal or drought-induced exposure of soils.

Figure 7.8 - Floods in Bastrop followed the fires. Rain soaked soils laid bare by the fire quickly eroded and washed out waterways. Here the earthen dam was washed out on Copperas Creek, draining the lake in Bastrop State Park. Image courtesy of TPWD.

The relationship of transport capacity to sediment supply determines the channel response to inputs of sediment. Widening and aggradation of the channel (rise in elevation due to sediment deposition), pool filling, and braiding can all occur when sediment supply overwhelms the ability of the river to transport it. Channels with too-high sediment supply tend to be unstable and have multiple active channels separated by bars.

Summary

Watersheds and their riparian areas are in a constant state of dynamic equilibrium. Natural change processes are at the heart of how watershed systems function. Understanding naturally occurring change processes will help you to better understand the effects of human caused change, which we will cover in the **chapter eight**.

Challenge

Look around your watershed. What natural change processes do you see in action? Learn more in your community about preventive measures your community has in place or corrective actions they are taking.

References

1. (Salinas, 2015)

Chapter Eight:

Human Caused Instruments of Watershed Change

Non-point source pollution, an oil slick on flowing water. Image courtesy of TPWD.

Chapter Eight:
Human Caused Instruments of Watershed Change

Questions to Consider

- Since many instruments of watershed change are natural, could human-induced changes really be that harmful, or would ecosystems simply adapt to our modifications?
- What are the distinguishing factors that result from the difference between natural change processes and those that are human caused?
- Many human caused change processes have resulted from our attempts to control or manage natural change. How many of these can you name?

Introduction

As we saw in **chapter seven**, agents of change may be naturally occurring or human caused. Let's look now at a series of human caused agents of change and their effect on watersheds.

Human Caused Change

Change through human caused factors is often closely tied to, and interactive with, natural change. In the following discussion, you will notice that human-caused changes drive many of the same effects on the ecosystem but at magnitudes or frequencies that outpace watershed ecosystems' adaptations. When these intensified changes exceed certain thresholds, recovery is no longer certain and significant loss of natural resources, goods and services can result, to the detriment of human and ecological communities alike.

Since some change is natural, could human-induced changes really be that harmful, or would ecosystems simply adapt to our modifications? Human influence on the rate of biological species extinctions best illustrates the human capacity to affect the natural environment adversely. In 1999, a working group of the world's leading evolutionary biologists ranked the brief period of human presence on Earth as among the top four sources of mass biological extinctions in the planet's history. Recovery from the previous mass extinction period did take place, but required 10 million years to occur.

In this section, we will discuss the following major human-made agents of change:

- Modification of river flow
- Agriculture
- Timber harvest
- Urbanization
- Fire suppression
- Mining
- Harvesting of fish and wildlife
- Introduction of exotic species
- Accelerated climate change
- Human population and development
- Nonpoint source pollution

Modification of River Flow

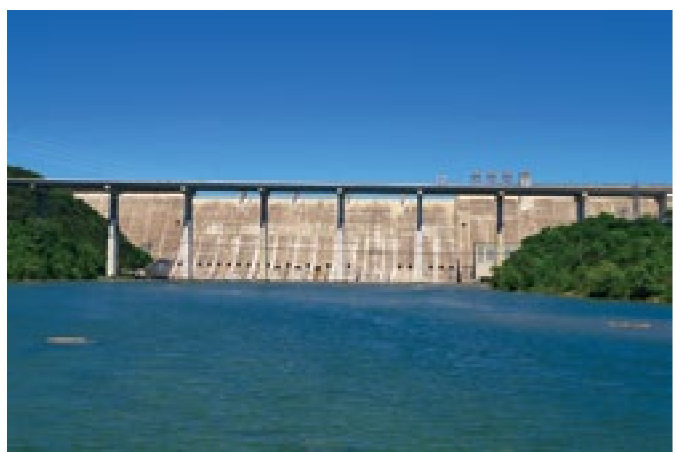


Figure 8.1 - Mansfield Dam in Austin, Texas.. Image courtesy of Johnnie Smith.

Land uses such as urbanization, agriculture, and timber harvest in watersheds change runoff and flow in significant indirect ways, but this section specifically addresses modification of river flow on impounded or diverted water. In many cases, impoundment and water withdrawal occur together resulting in reduced flow amplitude, increased baseflow variation, alteration

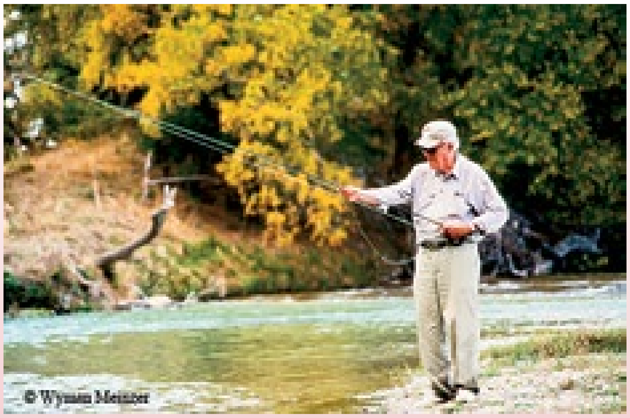


Image: Goodbye to a River: TPWD, October 2013.

John Graves

In the late 1950s John Graves (1920-2013) set off on a canoe trip down a section of the Brazos River that he had come to know well as a child. His desire was to see the river as he had known it, before a planned series of dams altered the river and the landscape. Keeping him company in his canvas canoe was a dachshund dog only referred to as "the passenger." Mr. Graves's trip would be documented in his memoir;'*Goodbye to a River*. In the book he illuminates the connection between people, culture, community, and rivers. He explores our unique connection to rivers and the ways we place value on them. The book was a critical success and is partially credited for the dams not getting built. John Graves wrote four major books in total and a variety of articles on conservation. His writings are a reliable reminder that while we shape the landscape, it also shapes us.

of temperature regime, and declines in mass transport of materials. The result is compromised connectivity between upstream and downstream reaches and between the river and its floodplain. This has a detrimental effect on biodiversity and ecological processes.

Natural flow regimes include variations in the magnitude, frequency, duration, timing, and rate of change in flow conditions. These natural variations:

- move sediment, woody debris, and other materials downstream,
- scour out vegetation,
- transport seeds and plants,
- provide breeding conditions to which aquatic organisms are adapted, and
- define and organize the river ecosystem's physical structure and environment.[1]

The possibility exists for dam operations that more closely mimic natural flow regimes. Although it is unlikely that it will be possible or desirable to operate a dam in a manner *entirely* consistent with a natural flow regime; practices that both stabilize base flows and ensure flows necessary to reconfigure channels and transport and exchange sediment go far to sustaining more natural conditions. For more on this topic, follow the work of the Caddo Lake Institute's Environmental Flows Project at www.caddolakeinstitute.us.

A 2008 report on the life history of alligator gar[2] suggests that alligator gar depend on floodplains as spawning and nursery areas. Juvenile alligator gar will remain in the backwater habitats as they develop. The prehistoric alligator gar is the largest freshwater fish in Texas and in the past received little respect from fishery managers. The fish's population has been threatened as a result. Attitudes toward alligator gar have been changing over recent years and conservation of the species and its habitat has become a new goal. The spawning period for alligator gar is between April and June and coincides with seasonal flooding. Construction of dams on rivers can alter the natural flow regime, particularly timing and magnitude, and break the lateral connectivity between stream and backwater habitat. Once a river is managed it is challenging to provide the recommended overbank flows necessary for alligator gar to reach their spawning areas due to liability and potential harm to public safety. Ongoing efforts are underway to collect the data necessary to understand the effects of an altered flow regime on alligator gar and develop better management practices for the conservation of the species.

Flow regime, however, is not the only aspect of a river affected by dams. Dissolved oxygen, sediment transport, and habitat are also affected. Downstream temperature can also experience significant changes in response to dam operation. Reservoirs in temperate latitudes typically stratify, with a warm surface layer and a cold, dense layer in the depths. Dams that release surface water tend to increase annual temperature variation whereas dams that release deep water will tend to decrease annual temperature variation. Substantial biological consequences can result from altered temperature regimes and related changes in dissolved oxygen. Dams also act as sediment traps that limit downstream sediment delivery, with mixed effects on downstream habitat.

Agriculture

Agricultural practices can affect watersheds in several different ways. Primary changes of concern result from:

- removal of streamside vegetation,
- soil tillage,
- application of fertilizers and pesticides and their subsequent export into water,
- grazing practices that can shift grassland vegetation to dominance by inedible species, and
- irrigation practices that dewater streams to levels that harm aquatic communities.

Figure 8.2 - Application of fertilizers can increase runoff of dissolved nutrients. Image courtesy of NRCS.

The clearing of forested watersheds for crop and pasture lands has often resulted in degraded water quality and modification of natural flow regimes (i.e., increased erosion, turbidity, fluctuations in discharge and temperature), compounded by such practices as soil tillage and application of fertilizers and pesticides. Under agricultural development, crops generally represent sparser ground cover than indigenous vegetation, allowing greater erosion and soil loss. Farming practices generally include plowing and smoothing to create planting surfaces, while use of heavy machinery for tilling and threshing compacts soil. In temperate watersheds, farmers often plow soils in fall for spring planting, and leave them bare throughout the winter and spring months during peak flow season. This practice increases the possibility of runoff and vulnerability to surface erosion.

In addition to altered hydrologic regimes, streams through agricultural lands typically feature high exports of dissolved nutrients (e.g., NO^3, PO^4) because of fertilizer applications and loss of forest cover. A typical result in agricultural streams and lakes is increased primary production (i.e., eutrophication) and depletion of dissolved oxygen as excess organic matter decomposes. Although pesticides typically occur during a limited spray season, some compounds persist long enough in soils to load continually throughout the year via suspended sediments in surface runoff. In many cases, toxic effects may persist for several years after pesticide use has stopped. For example, the federal government banned the pesticide DDT in 1972 for most uses in the United States, but it persists in trace amounts in soil, sediment, and tissue samples from agricultural watersheds across North America.

Figure 8.3 - Cattle obtaining water directly from streams can increase bacteria levels due to direct deposition. Image courtesy of the Lone Star Healthy Streams program.

In some areas of the United States, particularly in the arid and semi-arid lands of the West, livestock grazing with unlimited access to the stream channel and banks can cause degraded water quality and is one of the most significant rural sources of non-industrial pollution. Although they often make up a small percentage of grazing areas by surface area, riparian zones (vegetated stream corridors) are particularly attractive to cattle that prefer the cooler environment and lush vegetation found alongside rivers and streams. This can result in increased sediment and debris input into streams due to “hoof shear,” trampling of bank vegetation (Figure 8.4) causing disturbance that can allow invasive species to gain a foothold, downcutting by the destabilized stream with resultant drop in the water table, loss of fisheries, and direct deposition of wastes into waterways. Ironically, despite livestock's preference for frequent water access, farm veterinarians have reported that cows whose stream access is limited are healthier.

Figure 8.4 - Steam bank destruction caused by uncontrolled access by cattle. Image courtesy of the Lone Star Healthy Streams program.

While the most protective Best Management Practice (BMP) is full exclusion from riparian areas, it is not always feasible (Fig. 8.5). One of the most common sources of fecal bacteria entering waterways is the direct deposition of feces into the stream while cattle are drinking or loafing in the water. When cattle ranchers totally exclude cattle from the riparian area, significantly reduced bacteria levels result.[3]

Figure 8.5 - One method for limiting cattle access and streamside damage. Image courtesy of the Lone Star Healthy Streams program.

If cattle have full access, they may spend a lot of time loafing in sensitive streamside areas for shade and water. These areas are often overgrazed, making the forage plants less able to filter out bacteria, sediment, nutrients, and pesticides that enter the waterway after a rain. In addition, cattle trails can degrade stream banks, leading to increased runoff and erosion.[4]

Irrigation of agricultural fields has had dramatic impacts on watershed hydrology through the diversion and detention of running waters and overutilization of groundwater reserves. In many cases, impacts occur over broad regions encompassing several watersheds.

There are countless opportunities for reducing the adverse effects on aquatic systems from agriculture and grazing by following well-documented and publicized BMPs. Probably the best-known and most widely useful category of BMP is the retention of naturally vegetated buffer strips along streams (Figure 8.6). Streamside buffers serve many functions including

Figure 8.6 - Multiple rows of trees and shrubs, as well as a native grass strip, combine in a riparian buffer to protect this riparian area.. Image courtesy of NRCS.

nutrient filtering, bank stabilization, reduction of soil loss and land loss, moderating water temperature (which helps dissolved oxygen and hence fisheries), improving habitat for aquatic wildlife, and creating terrestrial wildlife habitat and corridors for movement. However, in order to be effective for erosion control and protection of aquatic life, buffers must be a *minimum* of 30 feet wide on each bank; terrestrial wildlife using riparian areas as movement corridors may need a buffer width closer to 300 feet on each bank.

Timber Harvest

Many watershed effects of timber harvest are similar to agriculture's effects. Aquatic impacts such as altered runoff and streamflow, increased sedimentation, and addition of nutrients can result from timber operations. The most obvious terrestrial change associated with timber harvest is that of removal of vegetation, but other common changes involve habitat alteration, altered species diversity and stand age. There are also numerous indirect effects.

Figure 8.7 - Mixed age timber on a lodging truck. Image courtesy of TPWD.

Under commercial forestry, young monoculture stands of commercially valuable species typically replace mature, multi-aged, mixed-species forests. Forestry practices at times denude harvested lands of live vegetation for long periods. These changes in forest habitat have different effects on different species. Species that rely on old growth conditions for parts of their life cycle (e.g., red cockaded woodpecker) suffer adverse impacts, whereas species that use edge habitats (e.g., white-tailed deer) may increase in population. Accordingly, we must draw a distinction between clearcutting, in which all trees harvested from a given area and replaced with an even-aged stand, and selective harvesting (i.e., some trees removed, others remain, resulting in a mixed-age stand). Whereas clearcutting results in drastic change over large areas of forest habitat, selective harvesting may also produce significant impacts, as rotation lengths are typically shorter, and sites are therefore disturbed more frequently.

In addition to terrestrial impacts, timber harvesting may have significant effects on stream discharge and water quality. Loss of mature vegetative cover leads to decreased interception of rainfall by vegetation, reduced evapotranspiration and correspondingly increased peak flows. Road construction compounds these effects, which creates permanently bare surfaces and compacts soil, resulting in decreased infiltration and increased surface runoff. Logging roads also fragment and isolate habitat patches from smaller, less mobile animals such as salamander species, and roads' stream crossings and culverts sometimes become barriers to fish passage.

Road construction on steep slopes often results in slope failure and excess sediment delivery to streams. Overall effects can also include elevated and more variable water temperature, increased turbidity, and higher uniformity of substrates, which generally impair habitat for a number of fish and invertebrate species.

Riparian buffers are required in many jurisdictions, but these have not always been successful in mitigating effects on streams. Texas Forestry BMPs are state-of-the-art, non-regulatory (voluntary) methods designed to prevent erosion and protect water quality during and after forest management activities. Perhaps the most effective and beneficial practice is the Streamside Management Zone (SMZ). An SMZ is a forested buffer, with a minimum recommended width of 50 feet on each bank, surrounding perennial and intermittent streams managed with specific attention given to protecting water quality. One way that SMZs protect water quality is by reducing the amount of sediment that enters streams from forest management activities. SMZs achieve this function by maintaining the stability of the soil around waterways, slowing down overland flow from areas adjacent to the SMZ, minimizing soil disturbance around waterways, and by reducing rainfall impact by intercepting precipitation. Another function of SMZs is to provide shade for streams, preventing increases in water temperature. This is important because high water temperatures can result in reduced dissolved oxygen in the water, negatively affecting aquatic organisms. In addition to protecting waterways, SMZs benefit wildlife by providing habitat diversity, travel corridors, and food.[5]

Urbanization

Urbanization often has more severe hydrologic effects than timber harvesting or agriculture, replacing watershed vegetation with impervious surfaces in the form of paved roads and parking lots. Urbanization results in increased surface runoff and correspondingly earlier and higher peak flows following storms. Flooding frequency also increases. Channelization of small streams and the use of storm sewers designed for rapid downstream transport of drainage waters only compound these effects. Both are intended as flood control measures but in fact can contribute to rapid water rise and flooding downstream, often still within the urban area. There is a direct relationship between urbanization (watershed imperviousness) and the number of bankfull flows occurring annually.[6] Researchers estimate that a watershed with 25% impervious surfaces experiences an event of peak volume equivalent to the 100-year storm (under completely forested conditions) once every five years. At 38% imperviousness, this same event occurs every 2.5 years, and at 65% imperviousness, it occurs annually.[7]

Bank scour from frequent high flow events tends to enlarge urban streams and result in increased turbidity and uniformity of substrates. Planners try to reduce structural complexity by bank armoring, and by channelization. Intended to limit the damage to streamside property resulting from increased flooding and erosion, channelization often results in increased flow velocities, increased flooding, and erosive power downstream.

Contaminant inputs from a variety of sources compound the physical impacts of urbanization. Urban contaminants may be loaded directly to streams and lakes from point sources (e.g., sewage, industrial effluents), or they may originate from nonpoint sourc-

Figure 8.8 - Waller Creek in downtown Austin, Texas, is a great example of a channelized urban stream.. Image courtesy of Johnnie Smith.

Figure 8.9 - Automobile oil and gas contaminants are common in urban and suburban settings.. Image courtesy of Johnnie Smith.

es (e.g., atmospheric deposition and/ or street litter washed off impervious surfaces and incorporated in storm runoff). Individual nonpoint source loadings are generally of small volumes, but these tend to be so common in urban watersheds that they collectively represent an important contribution to overall pollution. Whereas quantification of point source pollution is relatively straightforward, assessment and control of nonpoint source loadings is not. The difficulty resides in the fact that contaminants originate over broad areas and the distribution processes are hard to model or measure.

Because of these effects, a direct inverse relationship exists between the diversity of stream communities and the degree of urbanization. Klein (1979) reported reduced fish and invertebrate diversity at 12% watershed imperviousness, and severe degradation in the form of reduced benthic populations and absence of fish life at 30% imperviousness. The presence of an intact riparian buffer and/or wetlands, lost in most urbanized areas, or replaced/dominated by invasive plants, can lessen these impacts.

In many cases, the effects of urbanization extend far beyond the urbanized watershed. As urban growth increases, we require water delivery from increasingly great distances to meet sewage and drinking water requirements of urban populations.

Figure 8.10 - Bastrop fire, 2012.. Image courtesy of TPWD.

Fire Suppression

In the years following European settlement of Texas, forest management policies related to fire suppression have had a profound impact on forest community structure. Since the turn of the twentieth century, suppression has been the primary goal of fire policy. The overall effect of this policy has been an increase in fuel accumulation.[8,9] Effects have generally been more profound in areas where fires were historically frequent as opposed to where fires occurred at longer return intervals. In many parts of Texas, fire suppression has caused native grasslands, savannahs, and open woodlands to become overgrown with thickets of woody species.

These changes increase potential for high-intensity crown fires, (such as the Bastrop fire in 2012, Figure 8.10) not only by providing more available energy but also by creating pathways for flames to reach the forest canopy. Such crown fires usually exceed our control and kill all species present, including those resistant to fires of moderate to low intensities. The accumulation of fuel is one of the biggest concerns of land managers today, who now fear that when fires occur they will be extremely difficult to control, although the implications of fire suppression extend beyond increased potential for catastrophic fires. Fire represents an important component of forest ecology, as fires increase the availability of soil nutrients, while periodic disturbance results in a mixture of successional stages and increased biodiversity.

In trying to determine the effects of fire or fire suppression on forest community composition, note that plant succession is not always predictable. In addition to variables such as many species' responses to disturbance or life history traits which affect patterns of vegetation change, random factors may come into play. This presents difficulties in determining whether people should suppress fires on public lands. Such decisions are further complicated by the fact that forest conservation has become a management imperative to many, given the decline of forested lands in North

Figure 8.11 - A prescribed burn is the planned and deliberate application of fire as a management tool for land stewardship.. Image courtesy of TPWD.

America and worldwide. If people allow forest fires to burn without intervention, entire regions may lose forest resources for long periods. When making local management decisions, managers must weigh long-term goals related to the preservation of ecological processes and relationships against shorter-term goals of resource use, aesthetics, and recreation.

Mining

A series of environmental changes results from mining and mineral development. These may occur over several decades. The actual mine site is just one point in a long line of activity before and after the digging starts. A mine is also at the center of a geographical web of transportation routes (e.g., roads, barges, air access routes) and energy infrastructure (e.g., dams, power lines), as well as processing plants, tailings ponds and waste rock piles. The basic stages of mineral development are: (1) preliminary and advanced exploration, (2) mining and milling, (3) smelting and refining, and (4) mine closure. Each of these stages entails specific activities and environmental impacts.

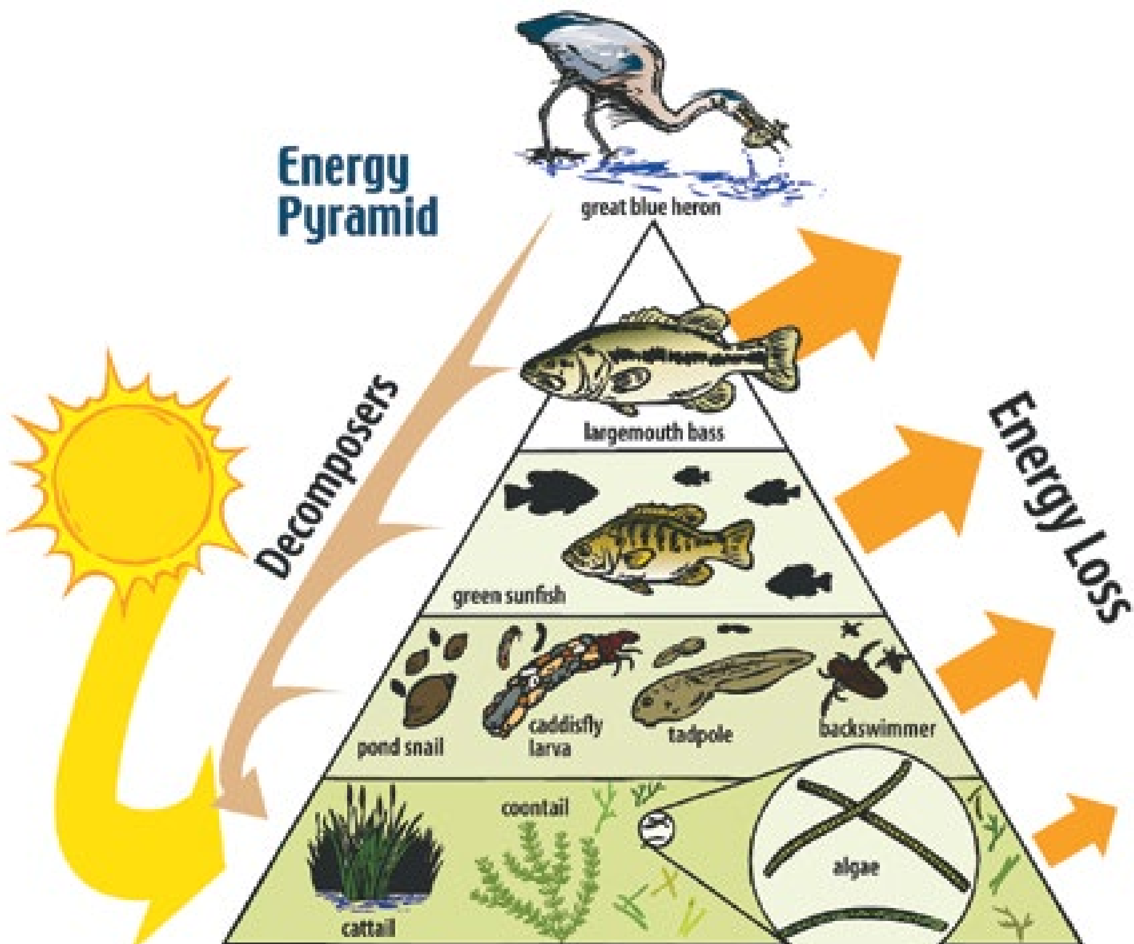


Figure 8.12 - Energy Pyramid,.Image used with permission from the Missouri Department of Conservation.

Activities and impacts also vary with different mining procedures and environmental settings. Historically, mining left a legacy of severe impacts on watersheds and the rivers and streams of western federal lands, as well as in eastern coal mining areas. Restoration after mining remains a significant challenge in many parts of the US.

After removal, waste rock is usually stored above ground in freestanding piles. When these rocks contain sulfide minerals, they react with water and oxygen to form sulfuric acid. The resulting leachate is known as acid mine drainage (AMD). AMD leaching continues in source rock exposed to air and water until all of the sulfides leach out, a process that can last hundreds and even thousands of years. During this process, there is a constant risk of water pollution, as surface drainage transports AMD from mine sites to receiving streams, lakes and groundwater.

Further effects stem from extraction of the ore itself and from disposal of tailings (i.e., residues from ore concentration). Up to 90 percent of metal ore ends up as tailings, large piles or ponds stored near the mine. Tailings usually contain residues of toxic organic chemicals used in ore concentrators (e.g., toluene, a solvent damaging to human respiratory, circulatory and nervous systems). The finely ground tailings material makes metals that were formerly bound up in solid rock (e.g., arsenic, cadmium, copper, lead and zinc) accessible to water, increasing potential for heavy metal contamination in aquatic communities. These effects worsen when AMD, which creates low pH conditions, mobilizes heavy metals.

Smelting can produce significant quantities of air pollutants. Worldwide, smelting of copper and other non-ferrous metals releases large quantities of metals such as lead and cadmium, as well as sulfur dioxide, into the atmosphere each year. Mining and smelting operations also consume significant amounts of energy.

Harvesting of Fish and Wildlife

Commercial harvesting of fish and wildlife may have significant impacts on community composition and trophic (food web) interactions, well beyond the removal of the target species. Commercial fishing practices, where harvest pressures have resulted in a gradual shift from large, long-lived, high trophic level species to smaller, shorter-lived, lower trophic level species, demonstrate these effects clearly.

Figure 8.13 - Lunker Largemouth Bass.. Image courtesy of TPWD.

Changes in decreased abundance of one trophic level can lead to trophic cascades where changes at higher trophic levels cascade down to lower trophic levels. This is because consumers highest on the food pyramid determine the size and species composition of those who appear at lower levels, which in turn affect the zooplankton community composition that determines the kinds of phytoplankton that compete for nutrients.[10]

In terms of recreational fisheries, Texas Parks and Wildlife fisheries managers constantly monitor the balance of the food chains in the various fisheries around the State. Their management maintains healthy trophic interactions. Changes in harvest regulations such as size, daily bag limits, and possession regulations all work together to shape the populations in our aquatic ecosystems and ensure their healthy balance.

Introduction of Exotic Species

Human mobility has resulted in significant exchanges of biota, occurring at global and local scales. Exotic species introduced outside their range often have

Figure 8.14 - Zebra Mussels. Image courtesy of TPWD.

Figure 8.15 - Giant Salvinia (salvinia molesta) Damages aquatic ecosystems by outgrowing and replacing native plants that provide food and habitat for native animals and waterfowl. Image courtesy of TPWD.

Figure 8.16 - Heavenly bamboo spreads readily in riparian zones through water transport. Image courtesy of Johnnie Smith.

Figure 8.17 - Ligustrum japonicum and chinese tallow both produce floating berries that riparian waterways readily transport downstream. Images courtesy of Johnnie Smith and TPWD respectively.

Figure 8.18 - Water Hyacinth, Eichornia crassipes, and elephant ear, colocasia antiquorum, respectively. Image courtesy of TPWD.

harmful impacts on the ecosystem, economy, or even human health and quality of life. Exotic species having, or likely to have, deleterious impacts are considered "invasive." People sometimes intentionally introduce exotic species, such as ornamental plants, popular game, and aquarium or bait fish species to areas or watersheds outside their native range, but in many cases, the transport and introduction is unintentional. For example, zebra mussels (Figure 8.14) (abundant in the aquatic ecosystems of the Great Lakes presently and spreading in Texas), hitched a ride in ballast waters and likely also on the anchors of large ships arriving from Europe. When established near a river or stream, the flowing water in streams and rivers, the contiguity of river corridors, and periodic flood events help to spread larvae, seeds, and fragments of invasive species that create new infestations. As human global mobility has increased, introductions of exotic

Figure 8.19 - Saltcedar (top) and giant reed (bottom). Images courtesy of Monica McGarrity.

species have also increased, and major transportation pathways have been linked to transfer of exotic species.

In some cases, introduced species are unable to thrive in the new environment, but in some cases, introduced plants and animals outcompete native species, aided by opportunistic tendencies, prolific reproduction, and a lack of natural predators or parasites. Establishment of invasive species often results in significant changes in food webs and community composition.

The effects of exotic species have been particularly devastating to the Great Lakes Basin, which is a site of several invasions and a source for the spread of invaders across North America. Transported by human activity, at least 139 nonindigenous species now inhabit the Great Lakes. These reported exotics are mostly fish, vascular plants, and some of the larger (> 0.5 mm) plankton species. Intensive and costly management efforts have been directed toward controlling the most pervasive exotics (e.g., sea lamprey).

In Texas, examples of invasive species include salt cedar, giant reed, Chinese tallow, Chinaberry, privet, K-R bluestem (also known as Mediterranean bluestem) and other introduced grasses, Japanese honeysuckle, bighead carp, blue tilapia, and zebra mussels. If left unchecked, invasive plants often dominate and displace native vegetation, changing Texas' diverse habitats into practical monocultures, reducing habitat quality for native plants and animals. Riparian areas dominated by invasive species such as giant reed and salt cedar have lower plant diversity, the shape of the stream is altered, and instream habitat diversity suffers as well. These monocultures are often devoid of quality wildlife forage with limited useful habitat for ground-nesting game birds such as turkeys. Similarly, dense stands of introduced turf-type grasses provide limited useful habitat for burrowing small mammals and ground dwelling birds. It can also create a barrier to animal movement, functionally fragmenting their habitat. Through improved land management techniques, invasive plants can be significantly reduced or controlled to benefit water quality and quantity as well as wildlife habitat. Invasive aquatic plants, such as giant salvinia, water hyacinth, water lettuce, and hydrilla, exert similar impacts on aquatic habitats and native freshwater communities and can impede boater access. Control of aquatic and riparian invasive species requires great effort and expenditure of financial resources.

Figure 8.20 - Blue Tilapia, Oreochromus aureus. Image courtesy of TPWD.

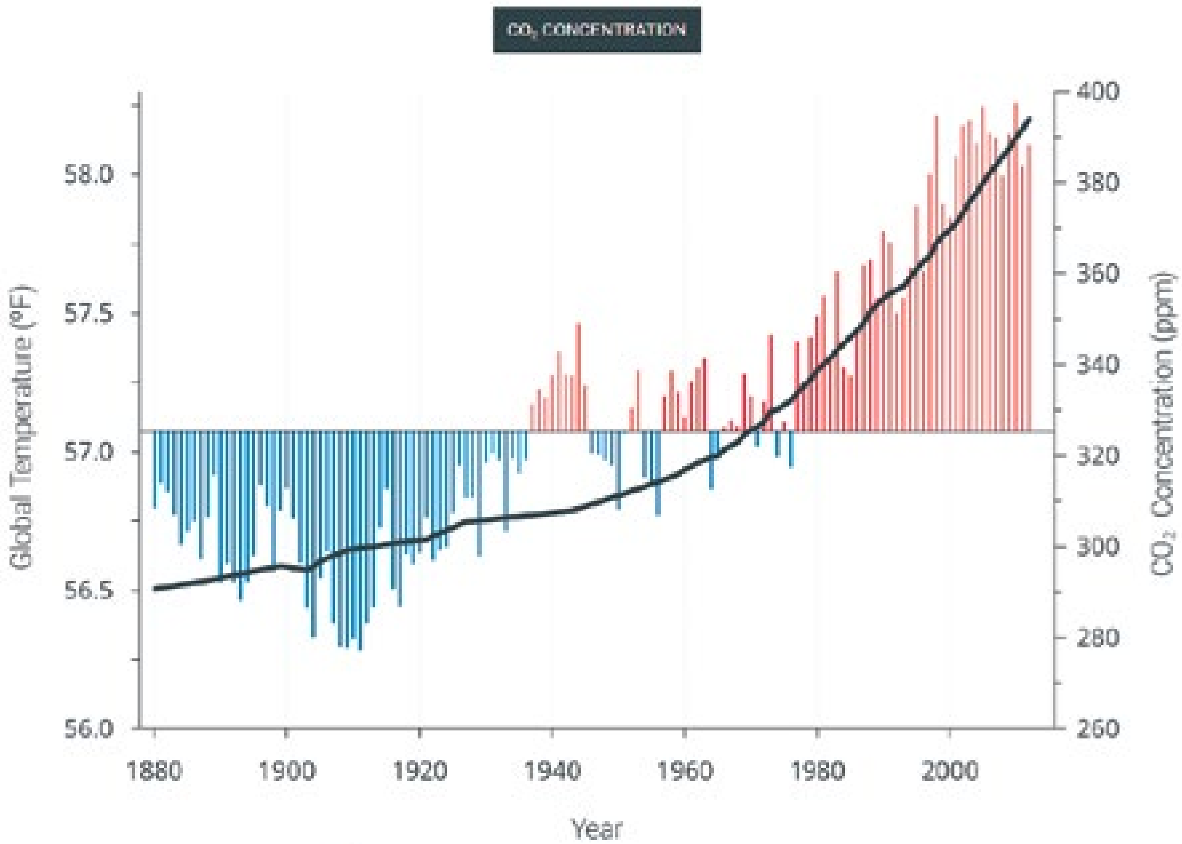


Figure 8.21 - Global temperature and carbon dioxide concentration. Image courtesy of the National Climate Assessment report 2014.

Another species that has had significant negative impact is imported the red fire ant. They have had profound, adverse impacts on many wildlife species, particularly ground-nesting birds and reptiles. Efforts to prevent the spread of these carnivorous ants has resulted in quarantines with economic impacts on the nursery, grass sod, and baled-hay industries. Many non-native fish species (e.g., invasive blue tilapia; Figure 8.20) have been documented in Texas as well as a number of snail and bivalve species.

Accelerated Climate Change

A major difference between natural and human caused climate change is the rate at which it occurs. With industrialization and population growth proceeding at a rapid pace over the last century, greenhouse gases from human activities have consistently increased in the atmosphere. Global annual average temperature (as measured over both land and oceans) has increased by more than 1.5°F (0.8°C) since 1880 (through 2012). Red bars show temperatures above the long-term average, and blue bars indicate temperatures below the long-term average. The black line shows atmospheric carbon dioxide (CO_2) concentration in parts per million (ppm). Although it is not the only greenhouse gas, CO_2 clearly illustrates the trend where levels since 1860 have increased from 280 ppm to 360 ppm. Measurements from ice cores extending back 160,000 years show that CO_2 levels and global temperature strongly correlate. If current emissions trends continue, CO_2 and temperature will rise to their highest levels in the past 50 million years. Current predictions indicate that we can expect an increase of 3.5°F over the next century with this continued release of CO_2 into the atmosphere.

While there is a clear long-term global warming trend, some years do not show a temperature increase relative to the previous year, and some years show greater changes than others do. These year-to-year fluctuations in temperature are due to natural processes, such as the effects of recurring weather systems (like El Niños and La Niñas), and volcanic eruptions.[11] Fluctuations in temperature within years have also become more extreme and frequent, resulting in negative impacts on wildlife.

Over the last century, the average surface temperature of the earth has warmed by approximately 1.0°F. The higher latitudes have warmed more than equatorial regions. These changes may seem small and some have argued that over geologic time our planet has experienced changes in global temperature For example, during the Cretaceous period (from about 145 million years ago to 66 million years ago) the average global temperature is estimated to have been 8.5°F higher than at present.

With these apparently small increases in temperature, however, we can expect major impacts on the global hydrologic cycle and other natural processes. When air temperature increases just 1°F, the air can hold 6% more water. This warming trend tends to speed up the exchange of water among oceans, land, and atmosphere. Longer droughts punctuated by heavy bursts of rain and flash flooding are a consequence. These effects can determine the water supply available to plants and the hydrologic regime of streams and rivers. Species composition of upland plant communities will also undergo major changes.

In a study linking global climate and temperature variability to widespread amphibian declines, researchers found "that changes to temperature variability associated with climate change might be as significant to biodiversity losses and disease emergence as changes to mean temperature."[12]

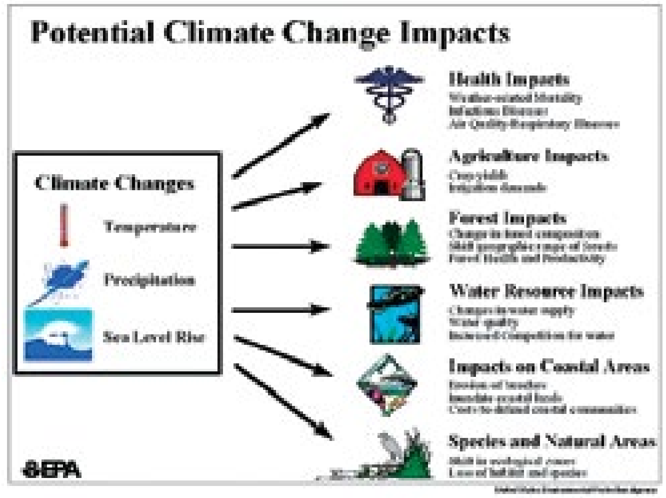


Figure 8.22 - Potential Climate Change Impacts. Image courtesy of The US EPA.

Excerpted from the 2014 National Climate Assessment[13]

(See the full regional report here: http://nca2014.globalchange.gov/highlights/regions/great-plains.)

Texas is a diverse state where climate and water are woven into the fabric of life. Day-to-day, month-to-month, and year-to-year changes in the weather can be dramatic and challenging for communities and their commerce. The state experiences multiple climate and weather hazards, including floods, droughts, severe storms, tornadoes, hurricanes, and winter storms. In much of the Great Plains, too little precipitation falls to replace that needed by humans, plants, and animals. These variable conditions already stress communities and cause billions of dollars in damage; climate change will add to both stress and costs.

The people of Texas historically have adapted to this challenging climate. Although projections suggest more frequent and more intense droughts, severe rainfall events, and heat waves, communities and individuals can reduce vulnerabilities through the use of new technologies, community-driven policies, and the judicious use of resources. Adaptation (means of coping with changed conditions) and mitigation (reducing emissions of heat-trapping gases to reduce the speed and amount of climate change) choices can be locally driven, cost effective, and beneficial for local economies and ecosystem services.

Significant climate-related challenges are expected to involve 1) resolving increasing competition among land, water, and energy resources; 2) developing and maintaining sustainable agricultural systems; 3) conserving vibrant and diverse ecological systems; and 4) enhancing the resilience of the region's people to the impacts of climate extremes. These growing challenges will unfold against a changing backdrop that includes a growing urban population and declining rural population, new economic factors that drive incentives for crop and energy production, advances in technology, and shifting policies such as those related to farm and energy subsidies.

Residents already must contend with weather challenges from winter storms, extreme heat and cold, severe thunderstorms, drought, and flood-producing rainfall. Texas' Gulf Coast averages about three tropical storms or hurricanes every four years,[14] generating coastal storm surge and sometimes bringing heavy rainfall and damaging winds hundreds of miles inland. The expected rise in sea level will result in the potential for greater damage from storm surge along the Gulf Coast of Texas.

Energy, water, and land use are inherently interconnected,[15] and climate change is creating a new set of challenges for these critical sectors.[16,17,18] Texas is rich with energy resources, primarily from coal, oil, and natural gas with growing wind and biofuel industries.[19] Texas produces 16% of U.S. energy, mostly from crude oil and natural gas. Texas leads the Great Plains region in wind generation capacity.[20]

Significant amounts of water are used to produce energy[21,22] and to cool power plants.[23] Electricity is consumed to collect, purify, and pump water. Although hydraulic fracturing to release oil and natural gas is a small component of total water use,[24] it can be a significant proportion of water use in local and rural groundwater systems. Energy facilities, transmission lines, and wind turbines can fragment both natural habitats and agriculture lands.[25]

The trend toward more dry days and higher temperatures will increase evaporation, decrease water supplies, reduce electricity transmission capacity, and increase cooling demands. These changes will add stress to limited water resources and affect management choices related to irrigation, municipal use, and energy generation.[26]

Changing extremes in precipitation are projected across all seasons, including higher likelihoods of both increasing heavy rain and snow events[27] and more intense droughts. Winter and spring precipitation and very heavy precipitation events are both projected to increase in the northern portions of the area, leading to increased runoff and flooding that will reduce water quality and erode soils. Increased snowfall, rapid spring warming, and intense rainfall can combine to produce devastating floods, as is already common. More intense rains will also contribute to urban flooding.

Increased drought frequency and intensity can turn marginal lands into deserts. Reduced per capita water storage will continue to increase vulnerability to water shortages.[28] Federal and state legal requirements mandating water allocations for ecosystems and endangered species add further competition for water resources.

Diminishing water supplies and rapid population growth are critical issues in Texas. Because reservoirs are limited and have high evaporation rates, San Antonio has turned to the Edwards Aquifer as a major source of groundwater storage. Nineteen water districts joined to form a Regional Water Alliance for sustainable water development through 2060. The alliance creates a competitive market for buying and selling water rights and simplifies transfer of water rights.

Over the past century, average temperatures in Texas and other southern states have risen much less than elsewhere in North America, from a 0°F rise in East Texas to up to 2°F in Far West Texas. But, researchers believe this anomaly is temporary, and in coming decades Texas temperatures could rise by 3 to 7°F in summer, with increases in the July heat index of 10 to 25°F.

Precipitation projections through 2100 for Texas are highly uncertain. Some models show increased precipitation over parts of the state, but other models project more arid conditions like those we are experiencing presently. It is likely that future precipitation patterns will differ either seasonally or geographically from historical patterns.

Texas bay waters have warmed by an average of nearly 3°F over the past 25 years. This mostly reflects warmer winters, not warmer summers.

Texas coastal sea level is rising. At a continued subsidence rate of four inches per century, Gulf coast sea levels could be 17 inches higher by 2100. This will mean more frequent and longer flooding of marshes that could convert to open water. Seagrass beds will appear and disappear with changing water depths, tidal flats will spread inland and bays and estuaries will expand. Coastal plains ecosystems may be threatened by saltwater intrusion.

Climate Change and the Risk to Texas Biodiversity

Texas has a rich natural heritage, which raises the stakes for risks from climate change and other factors. For example, Texas ranks third in the nation for endemic vertebrate species, with 126 such species found nowhere else on the globe. However, Texas has a total of nearly 180 threatened or endangered animals and plants and an additional 58 vertebrates that are accorded high priority in the Texas Wildlife Action Plan. These species would be the most vulnerable to climate change and complicating factors such as habitat loss and fragmentation.

Impacts on Texas' Plants, Fish and Wildlife

Climate is the key determining variable of species distributions.

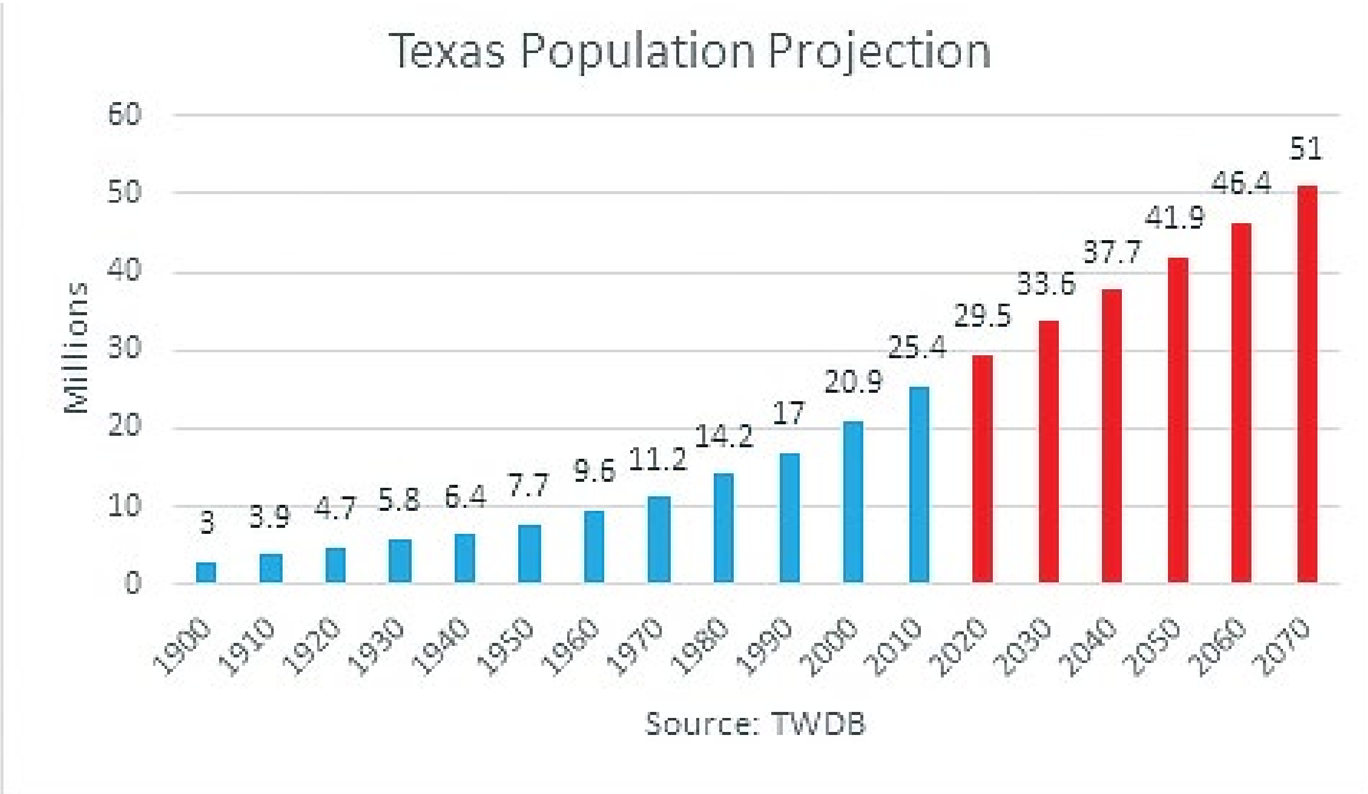


Figure 8.23 - TWDB population projection data.

As the Earth warms, species tend to shift to northern latitudes and higher altitudes. Rising temperatures are lengthening growing seasons and changing migration patterns of birds and butterflies. More than 70 species of South Texas birds have ranged north and east, and some scientists believe this is due to climate change.

Pests and diseases are increasing in range because warmer winters reduce die-off, and parasite development rates and infectivity increase with temperature. Woody shrubs invading prairie grasslands are favored by increases in concentrations of CO^2, changes in soil moisture cycles, fire suppression, and soil disturbances. TPWD biologists have for decades been tracking the expanding northward range of Whitewing Dove, originally confined to the Lower Rio Grande Valley, now common in Central Texas.

South Texas bird species are expanding northward, including the least grebe, great kiskadee, green jay and buff-bellied hummingbird, although their range expansions are likely due also to habitat change including fire suppression and resulting brush encroachment.

Gray snapper have been ranging farther north since the 1990s; once found only in the lower Laguna Madre and off the extreme southern shore of Texas, they are now migrating all the way up to Sabine Lake near Port Arthur. Snook, a large game fish that favors warmer water, have also been appearing more frequently in Texas waters.

Plant community changes are occurring, possibly due to climate change and other factors, and these changes will in turn affect fish and wildlife and people. In Texas, as elsewhere across the U.S., the growing season is lengthening; plants are greening up sooner and dying back later. For example, cold-sensitive plant species such as the red mangrove are moving north up the Texas coast. Early maps showed no red mangrove north of the Rio Grande estuary, and today they are appearing as far north as the edge of Matagorda Bay.[29]

Human Population and Development

Natural environmental influences and the activities of humans together determine the quality and quantity of our water resources. In this section, you will learn about the ways human actions can impair water quality and quantity. In later sections, we will focus on ways people can benefit the land by implementing various watershed management and protection strategies.

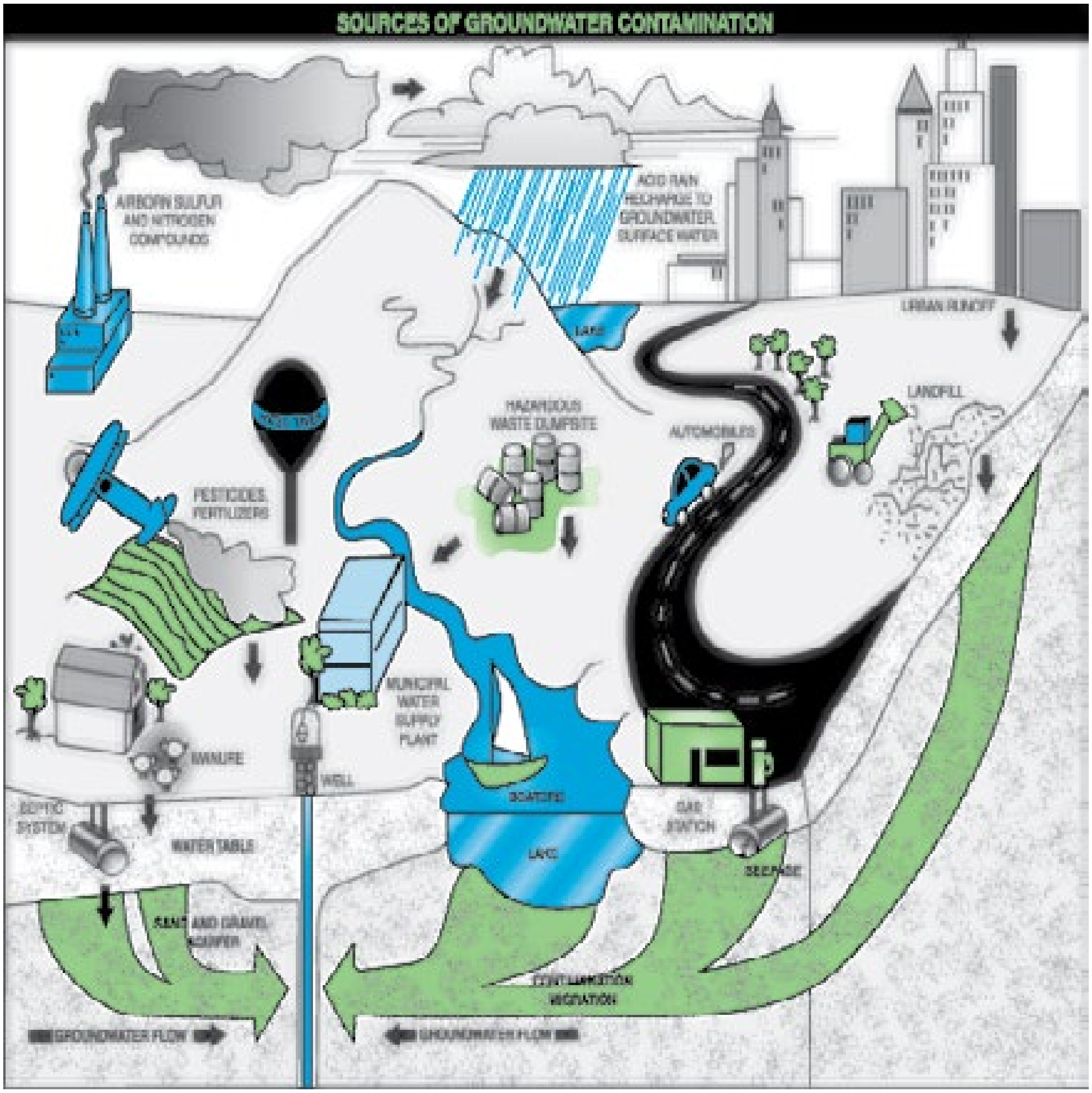


Figure 8.24 - The effect of human activity on groundwater. Image courtesy of The Groundwater Foundation (www .groundwater.org).

Different types of land cover and our land use decisions affect water quality and quantity. Specific land use categories include agriculture, industry, recreation, residential, and urban. Most of the ways people use lands have the potential to generate pollutants that can impair water quality and/or reduce water quantity.

Land cover refers to the biological or physical features of the land surface. Types of land cover include forests, agricultural fields, lakes, rivers, and even parking lots. When people change land use in a watershed, they usually alter the land cover at the same time. For example, when developers build a new housing development, land cover like roofs and pavement replace forests and fields.

Here are some activities that can affect both water quantity and water quality:

- Urban and agricultural irrigation
- Using fertilizers and pesticides
- Mining and resource extraction
- Construction of roads and buildings
- Disposing of municipal and industrial wastes and wasteawater

Unless done carefully, the effects of these land use activities can be severe. Such activities can alter the natural hydrology of a system, alter the land cover, create pollution, increase erosion and sedimentation, allow exotic species to invade at the expense of native vegetation, and harm biodiversity.

Adequate supplies of good quality water are vital to the health and social and economic well-being of all Texans. Yet water quality and quantity are at risk in many areas of the state because our population is growing and our use of the land is changing so rapidly. We must ensure the safety of our water resources for generations to come.

Urbanization has enormous effects on water quality and quantity because the amounts of wastewater, industrial contaminants and solid waste per unit area generated in urban areas is dramatically greater than in rural areas.

Urbanization also changes the hydrology of an area because of increases in impermeable surfaces like houses, parking lots and roads. The conversion of permeable soil to impermeable surfaces reduces the amount of infiltration and increases the amount of runoff and sedimentation. Excess sediments and pollutants become concentrated in streams and rivers, altering the quality of the water. Stream channels widen as banks erode to accommodate the large volumes of water. To control increased peak flows and runoff, streams and rivers are often **channelized** (straightening a section of a stream, building retention walls along the streambanks, and sometimes making the streambanks and bottoms concrete), which alters stream composition and flow.

As little as 10% impervious cover in a watershed can result in stream degradation. Heavily urbanized places like cities and downtown areas can have as much as 90% impervious surface cover.

The decrease in water infiltration caused by urbanization also reduces the amount of **groundwater** recharge—the downward replenishing flow of rainfall through the soil profile to an underground aquifer. This is a concern since 60% of Texans rely on groundwater aquifers for their water supply. The extraction of water for growing populations also puts increased demands on local water resources, both above and below ground, and can leave streams, rivers, and wetlands with insufficient water to function properly.

Construction sites usually remove habitat for native plants and animals and expose the soil surface to wind and rain. This increases erosion and sedimentation and makes it possible for invasive species to outcompete native vegetation for resources. The loss of native vegetation further reduces wildlife habitat and valuable shading along the shoreline.

We often focus on the effects of pollution rather than the causes of pollution. People can cause serious impairment to water quality and quantity when they change the land use or land cover type in a watershed. The effects of these changes can indirectly alter the entire ecological system.

Human population growth and resulting land fragmentation, or the division of single ownership properties into two or more parcels, have had profound effects on the Texas landscape. Changing land use and fragmentation alters natural habitats, which can threaten the viability of those habitats and sustainability of wildlife populations. Such changes will increase pressures on natural resources throughout the state, especially near growing metropolitan areas.[30]

Point and Nonpoint Source Pollution

What causes the chemical, physical and biological quality of water to become impaired? The Environmental Protection Agency has defined two major sources of pollution: point and nonpoint.

Point source pollution is pollution discharged from a clearly defined, fixed point such as a pipe, ditch, channel, sewer, or tunnel (Fig. 8.25). In Texas, one major type of point source pollution is the millions of gallons of wastewater discharged by industrial facilities and municipal sewage plants into the surrounding waters every day.

Discharged wastewater, whether treated or not, can contain substances harmful both to aquatic and human life. Untreated or partially treated wastewater can also lower the amount of dissolved oxygen in streams and rivers, reducing the quality of the water as habitat for aquatic plants and animals.

Nonpoint source pollution (NPS) is pollution that does not originate from a clearly defined, fixed location. NPS pollution originates from many different places across the landscape, most of which cannot be readily identified. For this reason, NPS monitoring is extremely difficult because the contaminants are not easily traceable to an exact source or point of origin. Runoff from storm water or excess irrigation carries NPS pollutants off the land. As the runoff moves over the land, it picks up and carries away natural and man-made pollutants, finally depositing them in surface water and even in underground sources of drinking water.

To some degree, both point and nonpoint sources of pollution have affected all of Texas' 15 inland river basins and eight coastal basins, many of its reservoirs, and all of its estuaries, coastal wetlands and bays. Nonpoint source pollution is the leading cause of the nation's water quality problems. **The U.S. Environmental Protection Agency (EPA)** estimates that more than half of all water pollution in the U.S. originates from nonpoint sources! In Texas alone, nonpoint sources of pollution affect 92 percent of the state's water bodies (Fig. 32). There are four categories of nonpoint source pollutants: bacteria, nutrients, sediment, and toxic/hazardous substances.

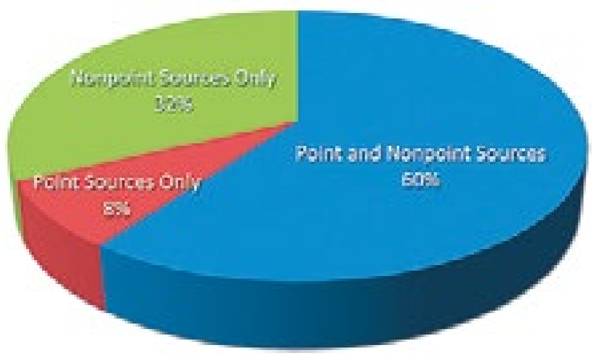


Figure 8.25 - Rivers, streams, reservoirs, and bays affected by nonpoint source pollution. (Source: TCEQ, Clean Water for Texas: Working Together for Water Quality, 2003.)

Bacteria

Most **bacteria** are harmless to healthy people, but some bacteria can be pathogenic, meaning they can cause disease. Disease-causing bacteria and viruses can enter bodies of water from many sources, including failed septic systems, boat discharges, livestock, waterfowl, and even the family pet. For example, runoff from agricultural areas (where manure is deposited by livestock or collected and spread on fields) can be a source of bacteria and viruses. Urban areas also can be a source of pathogenic bacteria and viruses, especially where the concentration of dogs and other family pets is high or where sanitation facilities are inadequate. Bacteria carried in storm water runoff are a major issue because they can pose severe health and environmental risks and can have major economic impact. In Texas, more than half of the evaluated water bodies are impaired because of excess bacterial levels!

As they decompose organic matter, bacteria compete with other aquatic life for limited dissolved oxygen. As bacteria levels rise, their oxygen consumption increases and the concentration of dissolved oxygen in the water drops. In addition, elevated levels of bacteria indicate that water quality is impaired and the water is probably unsuitable for drinking and other domestic uses. Its suitability for recreation and its ability to sustain aquatic life also may be impaired. Waterborne diseases such as hepatitis, cholera, and salmonella can result from elevated bacteria levels and can pose severe risks to human health. Because bacteria can come from many sources, identifying the sources and controlling bacteria levels can be extremely difficult and expensive.

Nutrient Pollution

Nutrients themselves are not pollutants–they are vital to plants and animals and are necessary to sustain life in general. However, when the levels of nutrients in water become too high, they are considered pollutants and can threaten the surrounding ecosystem.

Two main nutrients of concern are nitrogen and phosphorus. Nitrogen is highly soluble. Leaching of nitrogen through the soil profile and into groundwater is also a concern. Phosphorus is less soluble and mobile than nitrogen, but can attach to soil particles and runoff. Nitrogen and phosphorus are components of manure and other animal wastes, and of the fertilizers used in urban, suburban, rural and agricultural areas. When excess nitrogen and phosphorus run off the land into streams and lakes after a storm, these nutrients stimulate plant growth, but not necessarily

Figure 8.26 - Eutrophication on Onion Creek in McKinney Falls State Park. Onion Creek flows through an urban landscape, neighborhoods, ball fields, and golf courses before reaching this point. Image courtesy of Johnnie Smith.

the kind of plant growth that is beneficial. An overabundance of aquatic plant life can lead to eutrophication and make water unsuitable for habitat, recreation, fishing and other important uses.

Researchers estimate about 12 million tons of nitrogen and 4 million tons of phosphorus are applied each year as inorganic fertilizer in the United States. Another 7 million tons of nitrogen and 2 million tons of phosphorus are applied as manure. If not applied properly and in the correct amounts, these important plant nutrients can become pollutants.

Nitrogen and phosphorus also can originate from the atmosphere. Scientists believe that the combustion of fossil fuels such as oil and coal by power plants, large industries and automobiles is a major source of nutrients in the atmosphere.

Sediments

One of the most important nonpoint source pollutants is sediment (Fig. 8.27). Sediment is composed of the loose particles of clay, silt, and sand found in soil that erodes off the land by wind and water. Most sediment comes from agricultural fields, surface-mined lands and construction sites. These areas are at especially high risk of increased erosion because they generally lack sturdy vegetation to help keep soil in place and to block the surface movement of wind and water. Eventually, sediment finds its way to bodies of water and settles to the bottom.

Sediment is always present in water bodies, but in excessive amounts, it can create harmful conditions for

Figure 8.27 - Sediment runs off an agricultural field and into nearby waterways after a heavy rain, Photo courtesy of USDA Natural Resources Conservation Service.

plants and animals living in or near the water. Sediment can cloud the water, preventing light from penetrating to the leaves and stems of aquatic vegetation. Excessive sediment can also smother benthic macroinvertebrates and can clog waterways and ports.

Hazardous Substances

Hazardous substances include any material that can be harmful to humans and/or the environment. Pesticides and toxic chemicals are common examples. Pesticides include insecticides, fungicides, herbicides, and other materials designed to eliminate or control pests. They are used extensively to control insects, weeds and other unwanted pests by homeowners, municipalities, agriculture, businesses, and others.

Pesticides can enter a body of water through surface water runoff, wind and water erosion, leaching and "spray drift," which occurs when wind blows a pesticide into a body of water as it is being sprayed over an area of land. Once in a body of water, pesticides often decompose into compounds that are more toxic and increase the threat to the surrounding environment. Although people use pesticides to control only certain target species, they often unintentionally harm surrounding organisms. Furthermore, some pesticides decompose rather slowly. Because of this, they can build up in the food chain and have a cascading effect throughout the system.

People use over 1 billion pounds of pesticides in the U.S. each year at a cost of about $12 billion. Currently, the agricultural sector accounts for 60 to 70 percent of total pesticide use. In Texas alone, the Texas Agricultural Statistics Service estimated that farm and ranch operators spent $345 million on pesticides in 2002. Researchers do not know the exact cost and amount of pesticides used in Texas for nonagricultural purposes, including use by homeowners, parks departments, golf course managers, and others.

Toxic chemicals, such as spilled oils and fuels found on city streets (Fig. 8.28), are examples of harmful substances that can run off the land surface and wash into surrounding bodies of water. Combustion of fuel from automobiles and factories can introduce hydrocarbons and metals into the atmosphere. These can eventually end up in water through atmospheric deposition or runoff. Industrial facilities without the proper means to control runoff also can contribute toxic chemicals to the environment. Various businesses and even homeowners may use chemicals such as solvents, paints and cleaning solutions that can harm aquatic environments. The effects of toxic chemicals are usually greatest near urban areas where there is lots of business, industry and transportation activity is higher.

Toxic chemicals can have detrimental effects on drinking water quality, water used for recreation, aquatic plant and animal life, and the pipes and pumps associated with industrial and other facilities. Cleaning up water contaminated by toxic chemicals can be very difficult and quite expensive.

Figure 8.28 - Oils are washed off roadways into waterways. Image courtesy of Johnnie Smith.

Summary

In this chapter we have learned that human activity often exacerbates these natural change processes by increasing the magnitude or frequency of these occurrences. Looking back over the many changes that can occur in a watershed, those driven by human caused change often come at a price. The very people who inhabit these areas and those who live downstream bear the cost. These costs include reduced water quality, loss of habitat, reduced real estate values, and the cost of infrastructure improvements, to mention just a few. In the **chapter nine**, we explore Texas Water Law, planning, and the nexus between water and energy production.

Challenge

Look around your watershed. What human caused change processes do you see in action? Learn more in your community about preventive measures your community has in place or corrective actions they are taking.

References

1. (Poff, 1997)
2. (Buckmeier, 2008)
3. (Redmon, 2011)
4. (Redmon, 2011)
5. (Service, 2015)
6. (Leopold L. B., 1968)
7. (Klein, 1979)
8. (Huff, 1995)
9. (Kimmins, 1997)
10. (Carpenter, 1993)
11. (Richmond, 2014)
12. (Rohr, 2010)
13. (Shafer, 2014)
14. (Roth, 2010)
15. (Barry, 1983)
16. (Averyt, 2013)
17. (Ojima D. S., 2002)
18. (Strzepek, 2010)
19. (Brekke, 2009)
20. (Department of Education, 2013)
21. (Averyt, 2013)
22. (Foti, 2009)
23. (Barber, 2009)
24. (Nicot, 2012)
25. (Ojima D., 2013)
26. (Colby, 2011)
27. (Kunkel, 2013)
28. (Texas Water Development Board), 2012 State Water Plan: Water for Texas, 2012)
29. (Texas Parks and Wildlife, 2016)
30. (Texas Parks and Wildlife, 2016)

Chapter Nine:
Texas Water Law and Planning

The Texas Capitol. Image courtesy of Johnnie Smith.

Chapter Nine:
Texas Water Law and Planning[1]

Questions to Consider

- What is the difference between surface water and groundwater rights?
- What is the "Rule of Capture?"
- How does the "Prior Appropriations Doctrine" dictate how surface water rights are handled?
- What regional planning group covers your geographic area?
- What is the connection between water and energy?
- Who makes decisions about water use near you?

Introduction

Texas water law combines public and private interests, comprising a complex system steeped in history and change. This chapter will provide some basic information on water law and management. We will then cover ways in which citizens get involved in water issues. There will be links to more detailed information throughout the chapter. We encourage you to explore these topics in more detail.

The Evolution of Water Law in Texas

In Texas, water rights depend on whether the water is groundwater or surface water. Surface water flowing in a clearly defined water course (i.e., river or stream) is considered state property; groundwater is water found beneath the land's surface and is considered the property of the landowner. Diffused surface water occurs when rainfall or snowmelt flows across land before reaching a defined water course.

Over time, the Texas Legislature has modified the Texas Water Code in order to keeps pace with the needs of a growing and changing state. The Texas Water Code will continue to evolve as the state grows and changes. Let's take a brief look at this evolution. Settlement during the Spanish Colonial, Mexican, and Anglo-American periods in Texas influenced how Texas dealt with water rights.

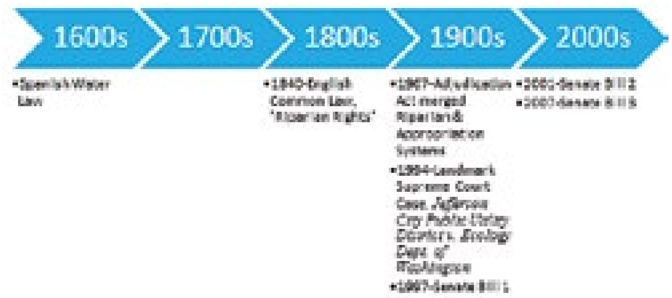


Figure 9.1 - Texas Water Law Timeline, Graphic courtesy of Johnnie Smith.

Early Spanish settlers in the 1600s built missions and presidios where water was available for irrigation. Spanish water law at that time encouraged the formation of community irrigation ditches, or acequias.

Under Mexican rule (1821-1836), law established under Spanish rule continued in the Spanish system. Land was classified as irrigable, temporarily irrigable, or suitable for grazing, then apportioned by government grant, but not always with specific rights for water access.

The Republic of Texas (1836-1846) adopted English common law in 1840, including the doctrine of riparian rights. These rights applied to land which bordered streams and was granted by the Republic. These landowners were allowed to use the ordinary flows of the streams for domestic, livestock, and irrigation purposes. A base stream-flow was still required to be passed downstream for other potential users. Meanwhile, the state continued to recognize the legality of any rights to use water on lands granted from Spain and Mexico.

The State of Texas (1846-present), starting in the mid-1800s, began a system that authorized the appropriation of water rights from the state. During their early development, western states failed to control rivers and streams, and water was treated as though it belonged to no one. In the absence of any rules, people simply took water from streams and used it; that is, they appropriated it. When this practice became legalized, it became known as the Doctrine of Prior Appropriation, which is discussed in more detail later. In 1895, the Texas Legislature declared that lands patented from the state after July 1, 1895, did not include

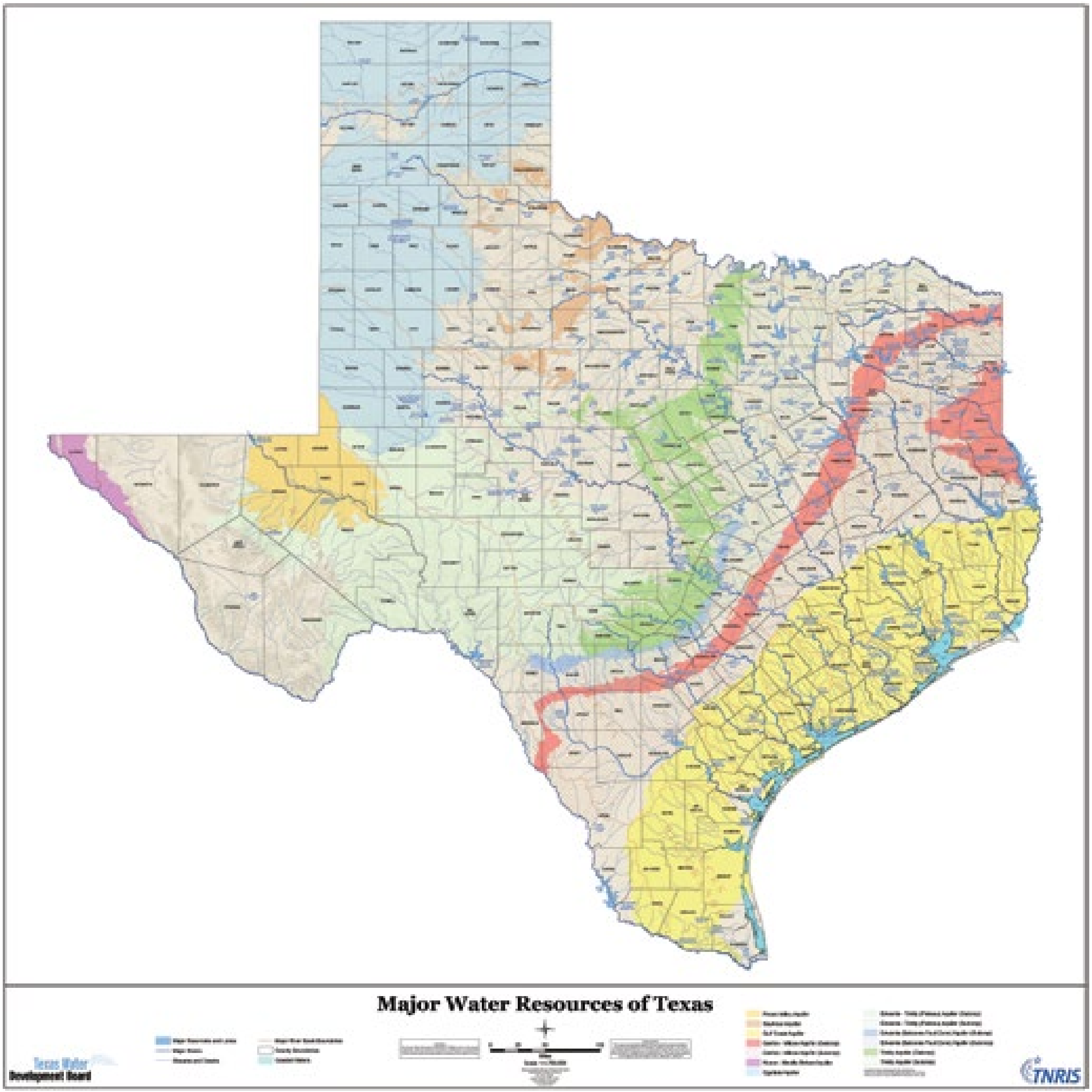


Figure 9.2 - Map courtesy of TWDB.

riparian rights, thus making the appropriation system the only means to acquire water rights on later patented lands.

The riparian and appropriation system continued to co-exist in Texas; however, the nature of riparian rights made it difficult to determine the extent of such rights, and to manage the streams of Texas. When claimed water rights exceeded water available in the Rio Grande Valley during the drought of the 1950s, an extensive lawsuit brought by the state resulted in an adjudication of the all rights to the Rio Grande. In 1967 the Texas Legislature merged the riparian rights system into the prior appropriation system with passage of the Water Rights Adjudication Act. The act required any person claiming a riparian water right to file a claim for the right by 1969 with the Texas Water Commission. With passage of the 1967 act, Texas consolidated the allocation of surface water into a unified water permit system. Anyone wishing to use surface water (exclusive of drainage water) must receive permission from the state in the form of a "water right." Awarding permits for these "water rights" is a task of the Texas Commission on Environmental Quality.

Meanwhile, the state treated groundwater differently. Texas courts adopted the common law rule that a landowner has a right to take for use or sale all the water that he can capture from below his land. The Texas Supreme Court explicitly adopted the rule of capture in 1904 in *Houston Texas & Central Railroad Co. v. East*, where the courts favored the pumping of water by the railroad over the landowner whose well went dry as a consequence.

The rule of capture has undergone several reviews and changed over the years. The Texas Supreme Court stated that the legislature has the authority to regulate groundwater if it chooses to do so. Droughts in 1910 and 1917 prompted the Conservation Amendment declaring that natural resources, including water, "are each and all hereby declared public rights and duties; and the Legislature shall pass all such laws as may be appropriate thereto." In 1949, the Texas Legislature passed the Texas Groundwater Act, which authorized the formation of groundwater districts with limited power to regulate withdrawals.

In 1955, the Texas Supreme Court affirmed the rule of capture and in its decision stated that, "percolating waters are regarded as the property of the owner of the surface who may, 'in the absence of malice,' intercept, impede, and appropriate such waters while they are on their premises, and make whatever use of them they please, regardless of the fact that use cuts off the flow of such waters to adjoining land, and deprives the adjoining owner of their use."

The Texas Legislature acknowledged private ownership of percolating groundwater in legislation passed in 1949 and again in 1985, when it authorized the establishment of underground water conservation districts.

Recent legislation strengthened conservation of water through Texas Senate Bills 1, 2, and 3.

- Senate Bill 1, enacted in 1997, explicitly recognized groundwater districts as the state's preferred method for managing groundwater resources in Texas. Senate Bill 1 also established the regional water planning process, creating 16 regional water planning groups who are directed to prepare regional water plans that form the basis for the State Water Plan. It also allowed for the designation of unique reservoir sites and stream segments of unique ecological value.
- Senate Bill 2, enacted in 2001, addressed the importance of balancing human and environmental water needs. It directed the Texas Parks and Wildlife Department (TPWD), the Texas Commission on Environmental Quality (TCEQ) and the Texas Water Development Board (TWDB), in cooperation with other appropriate agencies, to " . . . jointly establish and continuously maintain an instream flow data collection and evaluation program . . . " The Legislature also directed the agencies to "conduct studies and analyses to determine appropriate methodologies for determining flow conditions in the state rivers and streams necessary to support a sound ecological environment."
- Senate Bill 3, enacted in 2007, established a stakeholder process to recommend state action to protect instream flows and freshwater inflows on a basin-by-basin basis, environmental flow standards for new and amended water right applications and to establish an amount of unappropriated water, if available, to be set aside for the environment.

Texas Water Rights Highlights[2]

This section is used with permission from Ronald Kaiser, TAMU.

Surface Water Laws

Two legal doctrines of surface water law are recognized in Texas today: the Riparian Doctrine and the Prior Appropriation Doctrine.

Riparian Doctrine. The Riparian Doctrine is based on English common law. These court-developed rules are used in deciding cases that involve water use conflicts. The basic concept is that private water rights are tied to the ownership of land bordering a natural river or stream. Thus, water rights are controlled by land ownership.

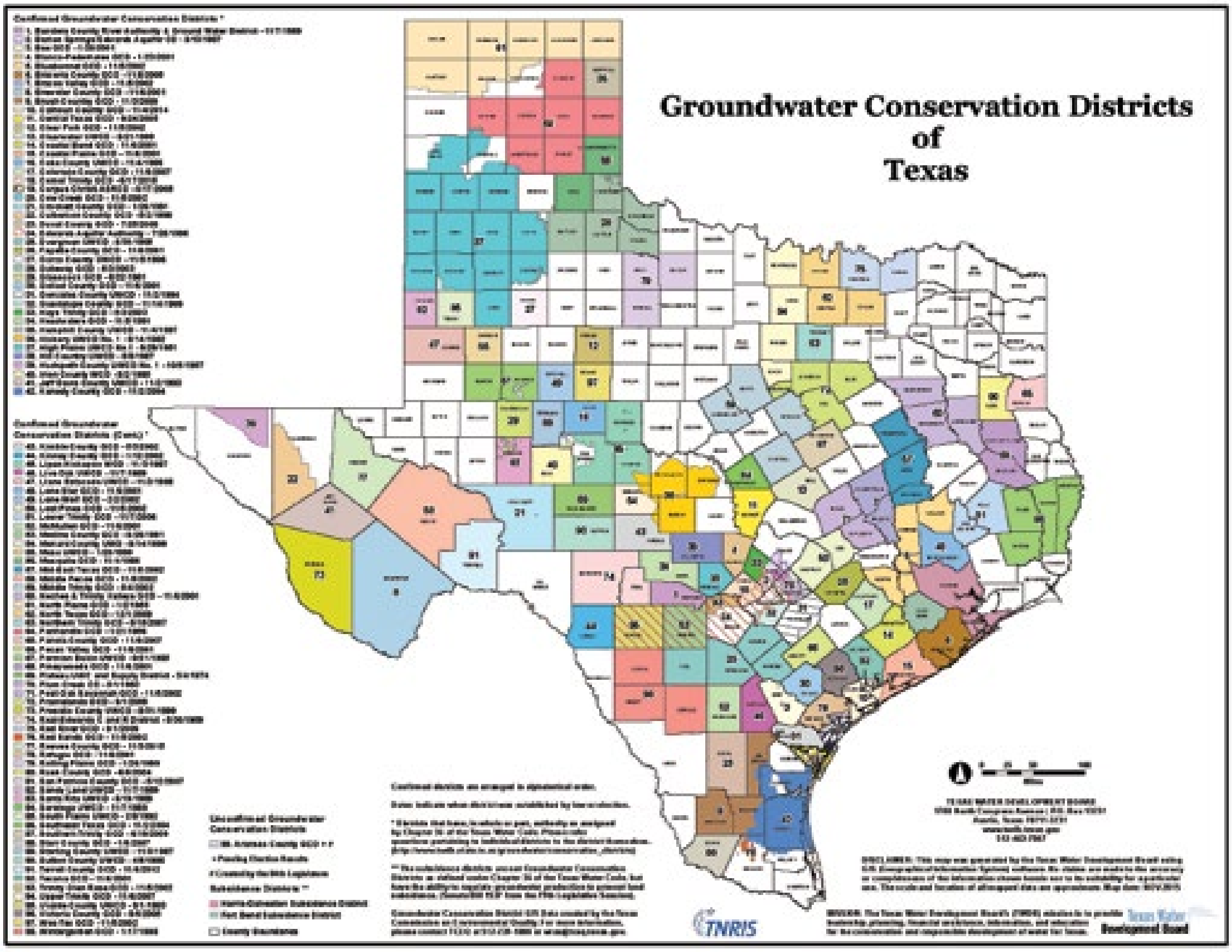


Figure 9.3 - Map courtesy of TWDB.

Riparian landowners have a right to use the water, provided that the use is reasonable in relation to the needs of all other riparian owners. Riparian owners retain the right to use water so long as they own the land adjacent to the water.

Prior Appropriation Doctrine. This doctrine, on the other hand, is controlled by statute. Applied in the western states, prior appropriation is not related to land ownership; instead water rights are acquired by compliance with statutory requirements. While the principles of riparian rights were appropriate in areas of England and the United States where rainfall averages 30 inches or more a year, these rights were not suited to the arid West.

Drainage Water

Diffused surface water, in its natural state, occurs after rainfall or snowmelt and flows across land from high elevations to lower elevations. This diffused water is often called stormwater, drainage water, or surface runoff.

Once the water flows into a clearly defined watercourse, it is claimed by the state and is subject to appropriation. On its way to the watercourse, drainage water often flows across privately owned lands. In such cases the water does not automatically become the property of the landowners, although they may capture and use it. Legal problems arise when a landowner interferes with the natural flow of drainage water by capturing and holding the flow or by diverting or increasing it. There are three general rules of law that apply when diffused surface water is captured or diverted:

Common Enemy Rule. One is called the "common enemy rule." Under this rule, drainage water is regarded as an enemy common to all landowners. The law allows every owner to take any measure to protect property, regardless of the consequences to other neighbors.

Natural Flow or Civil Law Rule. This rule recognizes that each landowner is entitled to rely upon continuation of the natural flow. Under this rule a landowner who increases runoff, thereby causing flooding, is liable for damages.

Reasonable Flow. This rule allows landowners to divert or change drainage water, even to the extent of harming adjoining neighbors, so land as the diverter's actions are "reasonable" considering all circumstances.

Groundwater Rights

Water found below the earth's surface in the crevices of soil and rocks is called percolating water, or more commonly groundwater. Texas groundwater law is judge-made law, derived from the English common law rule of "absolute ownership." Groundwater belongs to the owners of the land above it and may be used or sold as private property. This "Rule of Capture" allows landowners to withdraw water under their property with little regard to other groundwater users, as long as the water is beneficially used and is not intentionally wasted or negligently used resulting in the subsidence of neighboring lands.

Because of the seemingly absolute nature of this right, Texas water law has often been called the "law of the biggest pump." Texas courts have consistently ruled that a landowner has a right to pump all the water that he can from beneath his land regardless of the effect on wells of adjacent owners. The legal presumption in Texas is that all sources of groundwater are percolating waters as opposed to subterranean rivers. Consequently, the landowner is presumed to own underground water until it is conclusively shown that the source of supply is a subterranean river.

The state of the law with respect to ownership of subterranean rivers is not settled in Texas. Both stream underflow and subterranean rivers have been expressly excluded from the definition of underground water in Section 52.001 of the Texas Water Code.

The practical effect of Texas groundwater law is that one landowner can dry up an adjoining landowner's well and the landowner with the dry well is without a legal remedy. Texas courts have not adopted the American rule of "reasonable use" with respect to groundwater.

Exceptions to Absolute Owner Rule. There are five situations in which a Texas landowner can take legal action for interference with his groundwater rights:

- If an adjoining neighbor trespasses on the land to remove water either by drilling a well directly on the landowner's property or by drilling a "slant" well on adjoining property so that it crosses the subterranean property line, the injured landowner can sue for trespass.
- There is malicious or wanton conduct in pumping water for the sole purpose of injuring an adjoining landowner.
- Landowners waste artesian well water by allowing it to run off their land or to percolate back into the water table.
- There is contamination of water in a landowner's well. No one is allowed to unlawfully pollute groundwater.
- Land subsidence and surface injury result from negligent over-pumping from adjoining lands.

Limited Regulation of Groundwater. Authorized by the state, underground water conservation districts generally have the authority to promulgate rules for conserving, protecting, recharging, and preventing waste of underground water.

The Texas Legislature has significantly expanded the powers of groundwater districts, particularly in the late 1990s. There are approximately 100 groundwater districts covering more than half the state's land area that regulate a great percentage of water withdrawn from Texas' nine major and 20 minor aquifers (Figure 9.3). The powers exercised by these districts vary, but in general, consist of regulations to prevent the depletion of water tables, the loss of artesian pressure, waste, and subsidence. These regulations often take the form of rules that may restrict pumping, require permits for wells, delineate well spacing, establish maximum rates of water use, and define out-of-district export requirements.

What rights do landowners have to use groundwater?

From an ownership perspective, Texas groundwater law is simple and straightforward: Groundwater is the

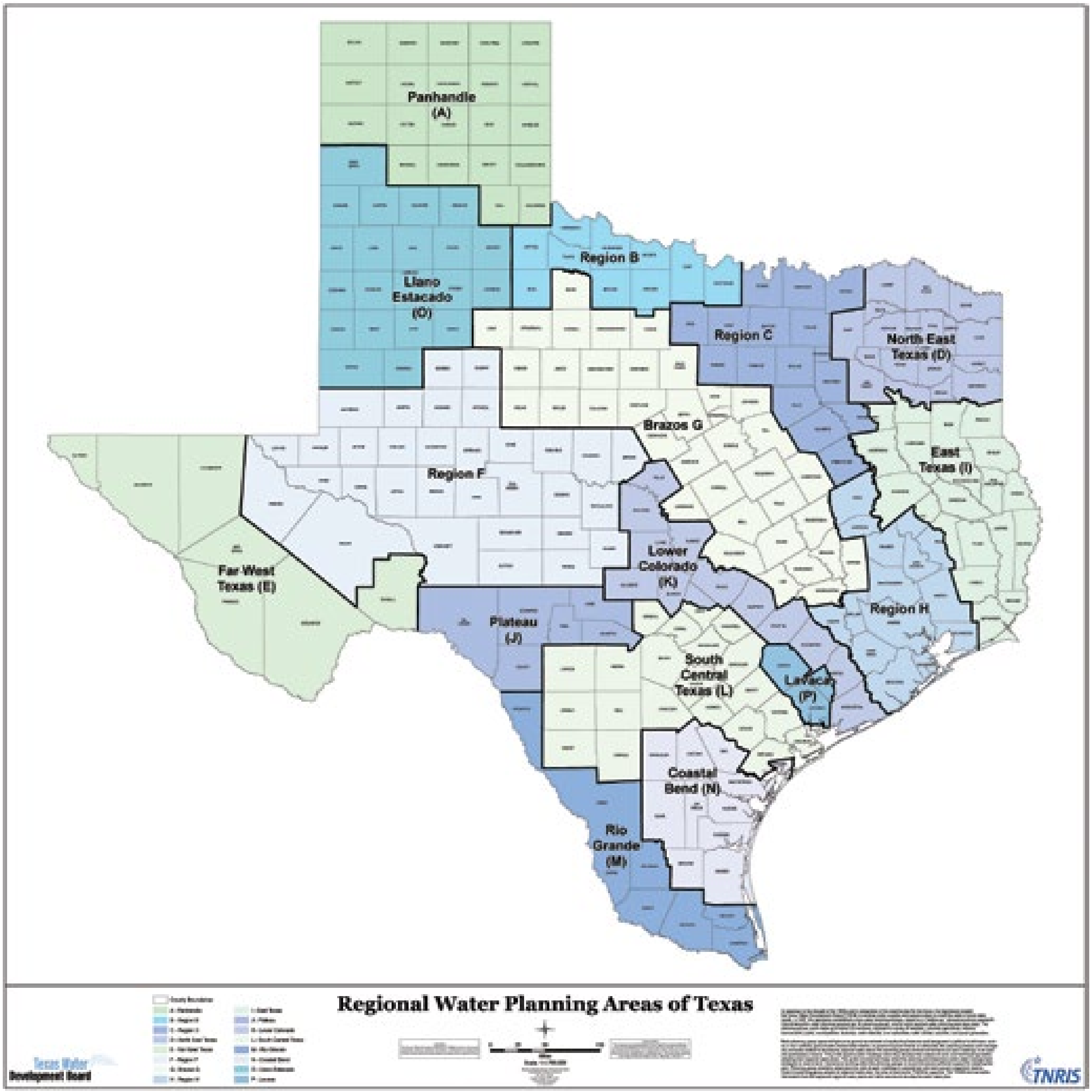


Figure 9.4 - Regional Water Planning Areas of Texas. Image courtesy of the TWDB.

private property of the owner of the overlying land. The owners of the land have the right to capture the groundwater beneath their land. However, the adjoining landowners have the same right to pump water from beneath their properties. Pumping water sometimes causes the groundwater beneath one property to move to an adjoining property and cause the nearby landowner's wells to go dry. The rule of capture was adopted by the Texas Supreme Court in 1904 in Houston & T.C. Ry. Co. v East, 81 S.W. 279 (Texas 1904). This rule allows landowners to pump as much water as they chose, as long as the water is not wasted, without liability to surrounding landowners who might claim that the pumping has depleted their wells. The rule of capture has been followed by the courts ever since that 1904 decision.

Texas groundwater law has often been called the "law of the biggest pump."

Senate Bill 1: Water Planning

The creation of resource management agencies, along with the collection of rainfall and streamflow data, began a new era of water management in the state. When reviewing the history of weather events, it is easy to see that the major policy changes in the management of Texas' water resources have largely corresponded to cycles of droughts and floods. Droughts are unique among climate phenomena in that they develop slowly but can ultimately have consequences as economically devastating as hurricanes, tornadoes, and floods.[3]

In each decade of the past century, at least some part of the state has experienced a severe drought. In September 2011, 99 percent of the state was experiencing severe, extreme, or exceptional drought conditions. The majority of Texas counties had outdoor burn bans, 902 public water supply systems were imposing voluntary or mandatory restrictions on their customers, and the Texas Commission on Environmental Quality had suspended the use of certain water rights in several of the state's river basins. The 2011 drought ranks as the worst one-year drought in Texas' history.

Regional Water Planning

Senate Bill 1 outlined an entirely new process for consensus-based regional plans to meet water needs during times of drought.

- TWDB develops a comprehensive state water plan based on the regional water plans every five years.
- TWDB designated 16 regional water-planning areas (Figure 9.4), taking into consideration river basin and aquifer delineations, water utility development patterns, socioeconomic characteristics, existing regional water planning areas, state political subdivision boundaries, public comments, and other factors. TWDB is required to review and update the planning area boundaries at least once every five years, but no changes have been made to date.
- TWDB may provide financial assistance for water supply projects consistent with the regional water plans and the state water plan.
- TCEQ-issued water right permits must also be consistent with the state water plan.

Regional water planning groups have at least one representative from each of the following interest groups: the public, counties, municipalities, industries, agriculture, environment, small businesses, electric-generating utilities, river authorities, water districts, and water utilities. Planning groups can designate representatives for other interests that are important to the planning area. Planning groups also have non-voting members from state and local agencies and have members that serve as liaisons with planning groups in adjacent areas. Each planning group approves bylaws to govern its methods of conducting business and designates a political subdivision of the state.

The regional water planning process consists of the following tasks:

- describe the regional water planning area;
- quantify current and projected population and water demand over a 50-year planning horizon;
- evaluate and quantify current water supplies;
- identify surpluses and needs;
- evaluate water management strategies and prepare plans to meet the needs;
- evaluate impacts of water management strategies on water quality;
- describe how the plan is consistent with long-term protection of the state's water, agricultural, and natural resources;
- recommend regulatory, administrative, and legislative changes;
- describe how sponsors of water management strategies will finance projects; and
- adopt the plan, including the required level of public participation.

Once the planning group adopts its regional water plan, the plan is sent to the TWDB for approval. The TWDB then compiles information from the approved regional water plans and other sources to develop the state water plan. For example, the state water plan summarizes the dedicated efforts of about 450 planning group members, numerous technical experts, the public, and several state agencies (TWDB, TPWD, TDA, and TCEQ). This process resulted in greater public participation, public education, and public awareness, underscoring the benefits of directly involving local and regional decision makers and the public in water planning.

Designation of Ecologically Unique River and Stream Segments

As part of the planning process, each regional water planning group (RWPG) may recommend designation of ecologically unique river and stream segments to the Texas Legislature. RWPGs must submit a description, maps, photographs, literature citations, and data pertaining to each candidate stream segment. The designation criteria is outlined on the TWDB website, and includes biological function, hydrologic function, riparian conservation areas, unique or critical habitats and exceptional aquatic life or threatened or endangered species/unique communities. This is a powerful tool in protecting river and stream segments in our State. Find more information about ecologically significant stream segments at http://tpwd.texas.gov/landwater/water/conservation/water_resources/water_quantity/sigsegs/.

Water Management Strategies

To address identified future water needs, the regional water planning groups recommend water management strategies for inclusion in regional plans, and ultimately the state water plan. Water management strategies include water conservation, water reuse, desalination of brackish groundwater or sea water, brush control, and new reservoir construction (on channel or off-channel). Some areas of the state also consider interbasin transfer of water from water-rich basins to those with less available water. Evaluation of water management strategies are required to include environmental factors such as environmental water needs, wildlife habitat, cultural resources, and effects of development on bays and estuaries.

Water Conservation

Water conservation, the most environmentally-friendly strategy for meeting future water needs, is predicted to comprise about 28 percent of future water management strategies, with the percentage increasing to 41 percent if reuse of treated wastewater is included. If all the recommended municipal conservation strategies are implemented, the projected statewide municipal average gallons per capita per day (gpcd) will be approximately 133 gpcd by 2070, surpassing the 140 gpcd goal recommended by the Water Conservation Implementation Task Force. The recently approved 2017 State Water Plan is the first state water plan to project meeting the statewide water conservation goal within the planning horizon.

Reuse Supplies

Reuse refers to the use of groundwater or surface water that has already been beneficially used. The terms “reclaimed water,” “reused water,” and “recycled water” are used interchangeably in the water industry. As defined in the Texas Water Code, reclaimed water is domestic or municipal wastewater that has been treated to a quality suitable for beneficial use. Reuse or reclaimed water is not the same as graywater, that is, untreated household water from sinks, showers, and baths.

There are two types of water reuse: direct reuse and indirect reuse. Direct reuse refers to the introduction of reclaimed water via pipelines, storage tanks, and other necessary infrastructure directly from a water reclamation plant to a distribution system. For example, treating wastewater and then piping it to an industrial center or a golf course would be considered direct reuse. Indirect reuse is the use of water, usually treated effluent, which is placed back into a water supply source such as a lake, river, or aquifer, and then retrieved to be used again. Indirect reuse projects that involve a watercourse require a “bed and banks” permit from the state, which authorizes the permit holder to convey and subsequently divert water in a watercourse or stream. Both direct and indirect reuse can be applied for potable—suitable for drinking—and non-potable—suitable for uses other than drinking—purposes.

Water reuse has been growing steadily in Texas over the past two decades. A recent survey of Texas water producers revealed that in 2010 approximately 62,000 acre-feet per year of water was used as direct reuse and 76,000 acre-feet per year of water was used as bed and banks permitted indirect reuse. The number of entities receiving permits from TCEQ for direct non-potable water reuse rose from 1 in 1990 to 187 by June 2010. Evidence of the increasing interest and application of indirect reuse is also illustrated by several large and successful projects that have been implemented by the Tarrant Regional Water District and the Trinity River Authority in the Dallas-Fort Worth area.

Like surface water and groundwater, the amount of existing water reuse supplies is based on the amount of water that can be produced with current permits and existing infrastructure. The planning groups estimated that the existing supplies in 2010 were approximately 482,000 acre-feet per year. Reuse supplies will increase to about 1,107,000 acre-feet per year by 2070.

Desalination

Texas has access to vast quantities of brackish groundwater and seawater. To be useable as future water supplies, these sources require desalination. Desalination requires energy to remove salt, also known as brine concentrate, which in turn must be disposed of properly to avoid environmental impacts.

Brush Control

Brush control, the removal of certain species of invasive plants, can help increase local water supplies in certain situations. Successful brush control efforts take into account factors including type of brush, local rainfall patterns, soil types and slopes and presence of sensitive habitats. In addition, successful brush control efforts include measures to manage landscapes to prevent reestablishment of invasive plants.

Reservoirs

Surface water reservoirs, both on main stems of rivers and off channel near reservoirs, are among the more environmentally-impacting water management strategies. Impacts to fish and wildlife can be minimized by careful reservoir placement that avoids sensitive habitat types. Mitigation is typically required to address impacts that cannot be avoided. In addition, reservoir management should be designed to provide adequate environmental flow regimes downstream of the reservoir.

Interbasin Transfer of Surface Water

Water is moved from one water basin to another through an interbasin transfer. Senate Bill 1 imposed additional requirements on new interbasin transfers of surface water, requiring economic, environmental and water-right analyses. TCEQ may grant an interbasin transfer, in whole or in part, but must consider whether 1) detriments to the basin of origin are less than the benefits to the receiving basin, and 2) the applicant has prepared drought and water conservation plans that will result in the highest level of water conservation and efficiency. In addition, a permit amendment for an interbasin transfer would result in the assignment of a junior priority date to the surface water right to be transferred from the basin of origin.

Water Marketing

In addition to conservation measures, the legislature recommends exploring market approaches, both public and private, to deal with water needs. These negotiated water transactions can include:

Sale of a Surface Water Right

The sale of a surface water right may be conducted between a willing seller and a willing buyer by arranging a contract for sale or a condemnation through the right of eminent domain. To the best of our knowledge, no municipality in Texas has exercised the condemnation and eminent domain authority to arrange the sale of a surface water right.

Contract Sale of Surface Water

In Texas, vast quantities of water are sold through wholesale contract. These sales are made separately, and apart from the transfer of any interest in the water right itself. Typically, one or more entities that own underlying water rights develop a water supply and then sell the water to others. Obvious examples are the development of reservoirs and well fields by regional entities such as river authorities and large municipalities who subsequently lease the developed water, but not the underlying water right, to contracting parties.

Lease of a Surface Water Right

Lease of a surface water right is a transaction in which a willing lessor and willing lessee agree to a short or long term transfer of a surface water right for financial or other considerations. During the term of the lease the lessee would get the use of the water right.

Dry-Year Option Contracts—Surface Water

Dry-year option contracts are used by municipalities to secure reliable sources of additional water to augment their existing supplies during times of drought. A municipality does this by negotiating an agreement with a water right holder (generally an irrigator) to acquire the use of the water right holder's water, during and only during, a specified dry-year period.

Transfers of Conserved Water—Surface Water or Groundwater

Municipalities or industries acquire water by financing the modernization of irrigation systems in exchange for the right to use all or part of the water that is conserved. In the Lower Rio Grande Valley, for example, irrigation districts have utilized this approach to finance improvements that both conserve water and improve canal distribution efficiencies.

Sale/Lease of Groundwater

Rights to groundwater may be severed from the land and made available for sale. Likewise, it is possible to purchase a lease for the right to withdraw groundwater. Historically, however, it has been much easier for prospective groundwater users to merely purchase a parcel of land and mine the groundwater available there, than to purchase groundwater via contract with an existing landowner.

Texas Water Bank

The Texas water bank was created in 1993 by the Texas Legislature in order to facilitate the voluntary transfer of water and/or water rights, either surface or groundwater, between willing buyers and sellers. The water bank, as administered by the TWDB, maintains registries of water and water rights for potential buyers and sellers, as well as a listing of deposits. It operates primarily as a bulletin board, similar to a real estate listing service, and also is an information clearing-house for water marketing information, although transaction details, such as pricing, are limited. Additional information concerning the water bank, as well as the registries and deposit listing can be obtained at the TWDB Internet website at: http://www.twdb.texas.gov/.

Texas Water Trust

In 1997 the Texas Legislature created the Texas water trust within the Texas water bank for the protection of aquatic and riparian habitats. The trust is to hold water rights dedicated to environmental needs, including instream flows, water quality, fish and wildlife habitat, or bay and estuary inflows. No water right may be placed into the trust without review and approval of TCEQ after appropriate consultation with TWDB and TPWD. Water rights may be placed in the trust for a term of years or in perpetuity. By statute, all deposits to the trust are protected from possible cancellation for as long as they remain in the trust.

The Nexus Between Water and Energy Production

The connection between water and energy is one that many do not consider. Water is used in the production, storage, delivery, use, and disposal of the overwhelming majority of products and goods that people take for granted. Water literally touches every area of our lives. Energy production is no exception. It takes water to make energy and it takes energy to make water useable. This paradigm is known as the "Energy-Water Nexus." Approximately 157,000 million gallons of water annually are consumed for cooling power plants in Texas.[4] In addition, approximately 0.8-1.3% of electricity generated in Texas goes to the treatment, transportation and heating of water for human use.

Along with Texas' increasing population comes increasing demand for water and electricity. The Texas Water Development Board (TWDB) predicts that steam electric (power generation) demand is expected to increase in greater proportion than any other water use category, from 953,000 acre-feet per year in 2020 to 1.7 million in 2070. They also predict that existing water supplies will not be enough to meet the growing overall water demand. To make matters worse, competition for limited water supplies is heating up, especially during drought. In some cases, water supplies are overcommitted, risking the potential for economic loss and ecosystem damage. Water planning at the state, regional and local level helps to address the conflicts

Figure 9.5 - Fayette Lake, a power station cooling reservoir near La Grange. Image courtesy of TPWD.

but when drought intensifies, planning assumptions might not hold.

Without natural lakes, reservoirs are the state's primary means of water storage. Levels fluctuate drastically based on rainfall and usage. Many of these reservoirs serve as cooling water for thermoelectric power plants, which account for 85 to 90% of Texas' power generation. Times of lower water levels are cause for concern, because if "cooling" water reservoirs are abnormally hot (i.e., the record heat experienced in 2012) power plants have to work harder to generate electricity.

Thermal power plants—those that use fuels such as biomass, coal, oil, natural gas or uranium to generate electricity—often use water for cooling. Doing so improves their performance and efficiency. However, that means the water has to be available. If there is water scarcity from droughts, or if the water temperature is too high from heat waves, then enough water might not be available or effective as a coolant. That means the power sector is vulnerable to water constraints, according to Dr. Michael E. Webber, Associate Professor of Mechanical Engineering at the University of Texas.

During the summer of 2011, demand for electricity in Texas was so great the Electric Reliability Council of Texas (ERCOT), issued consumer warnings, asking users to raise their thermostats and otherwise limit electricity use, because our demand was exceeding the state's electrical grid capacity. Fortunately, Texas consumers responded, conditions moderated, and the crisis was averted.

Even though renewable energy sources like wind and solar need much less water to generate electricity when compared to conventional fuels, they do require water to manufacture turbine blades and solar panels. In fact, every product we consume requires water and energy to produce. This concept, when applied to every product we consume, is known as the "Water Footprint." Tackling the Energy-Water Nexus may seem like a daunting, even impossible challenge but there is a positive side: saving water saves energy and saving energy saves water. Individuals can conserve energy. Individuals can also consider using alternative energy as a means to reducing their water footprint. Texas leads the nation in wind energy production. Wind energy is a low carbon source of dependable energy that has a low water footprint. Saving water delays the need for building new water supply projects that also impact fish and wildlife habitat.

Figure 9.6 - Wind energy production in West Texas. Image courtesy of Johnnie Smith.

Senate Bill 2: Texas Instream Flow Program

The Texas Instream Flow Program in its 2008 Report described four components of a Natural Flow Regime which are (Figures 9.7-9.10):

- *Subsistence Flows:*
- *Base Flows:*
- *High Flow Pulses:* and
- *Overbank Flows:*

Subsistence Flows are infrequent periods of low flow that occur less than 5% of the time in most rivers across the state. These flows are usually adequate to support aquatic communities for a limited period of time during periods of drought. (Figure 9.7). **Base**

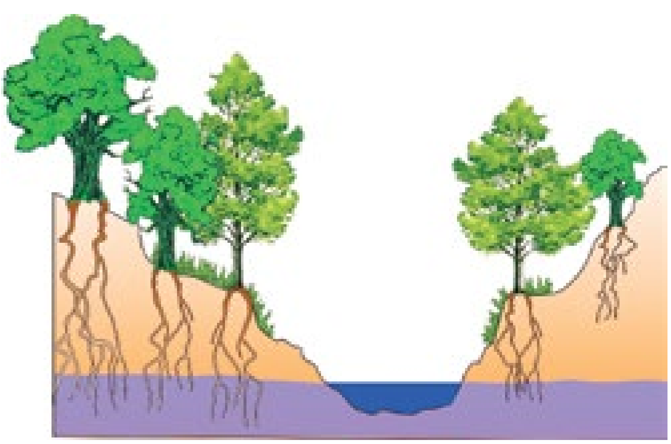


Figure 9.7 - Subsistence Flow. Image courtesy of the Texas Instream Flow Program (TIFP), 2008.

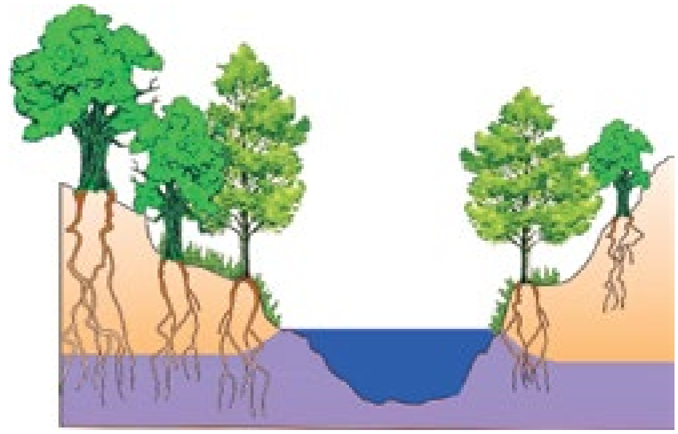


Figure 9.8 - Base Flow. Image courtesy of the Texas Instream Flow Program (TIFP), 2008.

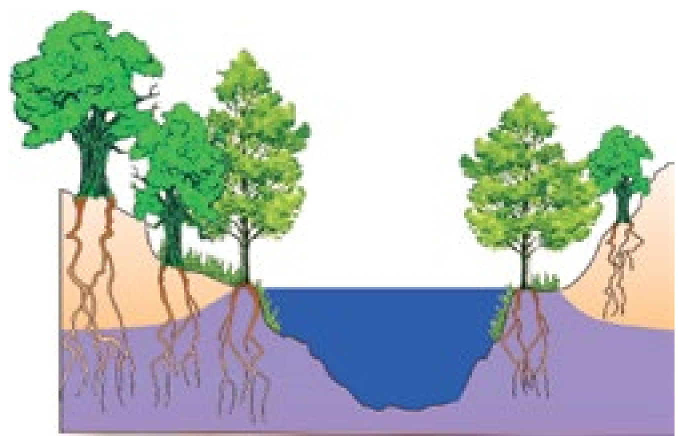


Figure 9.9 - High Pulse Flow. Image courtesy of the Texas Instream Flow Program (TIFP), 2008.

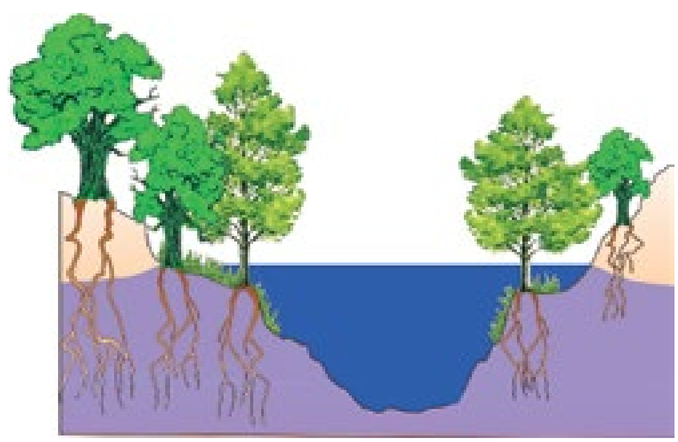


Figure 9.10 - Overbank Flow. Image courtesy of the Texas Instream Flow Program (TIFP), 2008.

Flows are "normal" flow conditions that exist between high flow events and are often classified as either wet, average or dry base flow (Figure 9.8). **High Flow Pulses** are of short duration, contained within the bankfull channel, and usually occur following storm events (Figure 9.9). Lastly, **Overbank Flows** are high flow events that exceed the normal stream channel (Figure 9.10). Each flow type has ecological benefits and is a part of the natural flow regime. Species are adapted and dependent on the fluctuations. Human activity such as dam construction and over-utilization of water resources can alter natural flow regimes, thereby compromising the health of the ecosystem.

Senate Bill 3 Environmental Flow Protection in Texas[5]

Environmental Flows in Texas[6]

The population of Texas is expected to increase 82 percent between the years 2010 and 2060, growing from 25.4 million to 46.3 million people. In addition, forecasts predict that cities will grow most rapidly.[7] Integrated watershed-based planning and conservation are key to the future health of Texas' aquatic ecosystems. Meeting the water needs for this burgeoning population is the subject of great debate among regional water planning groups. One of the many challenges the regional planning group members face is the consideration of environmental flows.[8]

Environmental flows are worthy of consideration by water managers for a multitude of reasons.[9] Recreational fishing has a $115 billion impact on the nation's economy and supports more than 828,000 jobs.[10] Environmental flows are also critical for maintaining the value of our commercial fishery. Commercial fishing along the Texas coast generates over $3 billion annually. During droughts in 2011, reduced freshwater inflows led to record high salinity levels in Texas estuaries that contributed to a coast-wide red tide harmful algal bloom event. Red tides, a type of harmful algal bloom that kills fish and contaminates oysters, most commonly occur during drought years, as the organism that causes red tide does not tolerate low salinity. The 2011 bloom started in September and lasted into 2012, killing an estimated 4.4 million fish. The state closed the commercial oyster season and issued disaster declarations. The total economic loss was estimated at $7.5 million.

Figure 9.11 - High flow pulse on the Pedernales River. Image courtesy of TPWD.

Figure 9.12 - Base flow on the Frio River. Image courtesy of Johnnie Smith.

Prior to 1985, there was no explicit recognition of environmental flows under the law in Texas. The 69th Texas Legislature amended both the Texas Parks and Wildlife Code and the Texas Water Code, creating for the first time in Texas an opportunity to address environmental flow issues within the context of water regulation and management.

Added to the Parks and Wildlife Code, Section 12.0011 reinforced that Texas Parks and Wildlife is the state agency with primary responsibility for protecting the state's fish and wildlife resources. Section 12.0011 also explicitly states that the department's resource protection activities include providing recommendations to the Texas Department of Water Resources (predecessor agency of the Texas Water Development Board and Texas Water Commission) on scheduling of instream flows and freshwater inflows to Texas estuaries for the management of fish and wildlife resources.

In addition, the 69th Texas Legislature amended Chapter 11 of the Texas Water Code, recognizing the importance of environmental flows. The Legislature also added Section 11.147, Effects of Permit on Bays and Estuaries and Instream Uses, defining what is meant by the term beneficial freshwater inflows:

> "a salinity, nutrient, and sediment loading regime adequate to maintain an ecologically sound environment in the receiving bay and estuary system that is necessary for the maintenance of productivity of economically important and ecologically characteristic sport or commercial fish and shellfish species and estuarine life upon which such fish and shellfish are dependent."

Section 11.147 of the Texas Water Code directed the Texas Water Commission (now the Texas Commis-

Figure 9.13 - Subsistence flow on the Rio Grande. Image courtesy of TPWD.

Figure 9.14 - Overbank flow on the San Marcos River in Palmetto State Park. Image courtesy of TPWD.

sion on Environmental Quality or TCEQ) to consider freshwater inflows to bays and estuaries and impacts to instream uses, water quality and fish and wildlife habitat when granting or amending water rights. For permits issued within an area that is 200 river miles of the coast, to commence from the mouth of the river thence inland, the Commission was directed to include in the permit, to the extent practicable when considering all public interests, those conditions considered necessary to maintain beneficial inflows to any affected bay and estuary system. The Texas Water Code allows TCEQ to suspend environmental flow special conditions in emergency situations and is required to allow TPWD 72 hours to provide comments before issuing a suspension order.

Special conditions to protect freshwater inflows to estuaries have been incorporated into a number of water right permits, including those for several major reservoirs: Lake Texana, Choke Canyon Reservoir, and the Highland Lake system managed by the Lower Colorado River Authority (LCRA). LCRA manages the Highland Lake System, which includes Lakes Travis and Buchanan, to provide instream flows in the Colorado River and freshwater inflows to Matagorda Bay at the mouth of the Colorado River.

Unfortunately, these revisions to the Texas Water Code came years after the granting of most major water rights in Texas. Of the existing water rights issued by the state, the vast majority were granted prior to 1985, and subsequently do not contain provisions for instream use or freshwater inflow maintenance. By today's estimates, many river basins in Texas are fully or over-appropriated and environmental flows in these segments are dependent on non-use of water rights and return flows. In these areas, currently permitted diversions have the capacity to reduce streamflows significantly below levels necessary to maintain instream

Figure 9.15 - Frio River Springs. Image courtesy of TPWD.

Figure 9.16 - Freshwater inflows are critical to bay and estuary systems such as the Colorado River Delta. Image courtesy of TPWD.

uses. Streamflow restrictions on junior permits alone cannot protect environmental flows.

Other benefits are more indirect, but no less important. Maintaining instream flow levels sufficient to ensure good water quality in our rivers and lakes reduces the cost of treating to drinkable standards. Likewise, healthy estuaries provide millions of dollars in wastewater treatment each year saving expenditures of treatment facilities.[11]

With the passage of Senate Bill 3, the Texas Legislature formally recognized that "maintaining the biological soundness of the state's rivers, lakes, bays, and estuaries is of great importance to the public's economic health and general well-being."

The Legislature acknowledged that a process with specific timelines and deliverables would be required to address environmental flow issues in the state's major basin and bay systems, especially those systems in which unappropriated water is still available. Furthermore, in those basins in which water was available for appropriation, TCEQ should establish an environmental set-aside below which water should not be available for appropriation. For those basins in which the unappropriated water to be set aside for instream flow and freshwater inflow protection is not sufficient to fully satisfy the environmental flow standards established by the commission, the legislature recommended that a variety of market approaches, both public and private, for filling the gap should be explored and pursued. To oversee the process, an Environmental Flows Advisory Group established boundaries for the basin and bay areas (figure 9.17). A Science Advisory Committee provided direction and consistency to existing environmental flow methodologies and programs at TPWD, TCEQ, and TWDB. Stakeholder Committees composed of balanced interests ranging from agricultural water users to commercial anglers in turn appointed an expert science team to recommend local environmental flow regimes.

Senate Bill 3 defined an environmental flow regime as "a schedule of flow quantities that reflects seasonal and yearly fluctuations that typically would vary geographically, by a specific location in a watershed, and that are shown to be adequate to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats in and along the affected water bodies." Fortunately most rivers, streams and estuaries in Texas were considered "ecologically sound" by the science teams but there were a few exceptions. For example, the Nueces Estuary was deemed "unsound" due to substantial alteration of the historic flow regime.[12]

Flow regimes dictate many ecological processes in rivers influencing chemical, physical and biological characteristics.[13] For this reason, streamflow has been called the "master variable" in relation to riverine ecosystem function.[14] Since life cycles of plant and animal species have evolved and adapted to a range of streamflow patterns, a favorable environmental flow regime should emulate the historical duration, frequency, and magnitude of hydrologic events and include flood pulses as well as droughts. For example, certain fish species rely on flood events to successfully reproduce and nesting colonial waterbirds benefit from prey concentration during spring drought conditions. Flood pulses are also critically important to estuaries in the form of freshwater inflows that moderate salinities, provide nutrients and deliver sediments.[15] Each science committee and stakeholder committee (with one exception) also recommended freshwater inflow regimes to protect ecologically sounds bays and estuaries within their basin. For example, salinity models help ensure suitable habitat for organisms such as oysters and clams.

The end result of the formal rulemaking process was a set of adopted environmental flow standards for each of the locations shown in figure 9.18. TCEQ may not issue new water right permits or amend water right permits if the issuance of the permit will impair environmental flows as established by rule. More information about the process including Science Advisory Committee guidance documents, Science and Stakeholder Committee recommendation reports, and the environmental flow standards rules themselves may be found at: tceq.texas.gov/permitting/water_rights/wr_technical-resources/eflows/group.html.

Senate Bill 3 sets out that at the conclusion of the development of flow standards for all of the river basins in the state, the Environmental Flows Advisory Group, the Science Advisory Committee and all stakeholder and science teams are to be abolished. Since environmental flow standards have only been adopted for those basins specifically identified in Senate Bill 3, not for every basin in the state, it is not clear when the various groups and committees will be abolished or who will oversee the assessment and adjustment of standards if these groups cease to exist. Another critical step in the Senate Bill 3 process is to identify voluntary strategies to meet environmental flow standards, especially in fully appropriated basins. More work is needed to identify ways to manage streamflows through timing of downstream water deliveries and through voluntary leases and/or acquisition of existing water rights.

Summary

In this chapter, you have learned a lot about the nuances of groundwater and surface water law and water management in Texas. It is a challenging topic and one that will become increasingly more important as the Texas population grows. You know now that Texas manages groundwater and surface water differently. You also have a better understanding of how water rights have evolved over time. We have covered, in fact, a variety of methods and strategies that municipalities, irrigators, industry and others in Texas may utilize to meet their current and future demands for water. You have discovered the many and complex connections between water and energy in our state. You have also learned about environmental flows and the importance of protecting instream flows and freshwater inflows to Texas bays and estuaries.

Challenge

Determine which regional water planning group covers your area. Plan to attend a meeting to learn about and provide input regarding your water future.

Determine where your water comes from. If your community's water supply comes from surface water, research and determine your community's water right as it relates to others upstream and downstream.

Track your water consumption and water conservation. See if you can improve your gallons per capita per day (GPCD) over time.

Identify the energy-water nexus in your community. What conservation measures are taking place? Who in your community advocates for them? Now that you understand more about these issues, what will you do differently?

For additional information please see:

Texas State Historical Association https://tshaonline.org/handbook/online/articles/gyw01

Texas Water Law http://texaswater.tamu.edu/water-law

Handbook of Texas Water Law: Problems and Needs, by Ronald A. Kaiser, Texas Water Resources Institute, Texas A&M University https://www.tshaonline.org/home/

More Publications and Links

Questions about Groundwater Conservation Districts in Texas, Ronald A. Kaiser. Bruce J. Lesikar, Valeen Silvy

Who Owns the Water?, Ronald A. Kaiser. Reproduced with permission from the July 2005 issue of Texas Parks & Wildlife magazine.

A Texan's Guide to Water and Water Rights Marketing, http://www.twdb.texas.gov/publications/reports/infosheets/doc/WaterRightsMarketingBrochure.pdf

The Handbook of Texas Online-Search for this title on https://www.tshaonline.org/home/

Texas Statutes Related to Water https://www.twdb.texas.gov/waterplanning/index.asp

Texas Water Foundation Facts About Your Water Supply (Discovering Who Provides and Makes Decisions About Your Water in Texas) – Search for this title on the Texas Sierra Club website.

2017 Texas State Water Plan:

https://sierraclub.org/texas

http://www.twdb.texas.gov/waterplanning/index.asp

References

1. (Texas Water Development Board, 2016)
2. (Kaiser, 2016)
3. (Texas Board of Water Engineers), Texas Water Resources Planning at the End of the Year 1858, A Progress Report to the Fifty-Sixth Legislature, 1958)
4. Stillwell, A.S., King, C.W., Webber M.E., Duncan, I.J. and Hardberger, A. 2009. Energy- Water Nexus in Texas. The University of Texas at Austin and the Environmental Defense Fund.
5. (Loeffler, 2015)

6. (Loeffler C. , 2016)
7. (Texas Water Development Board), 2012 State Water Plan: Water for Texas, 2012)
8. (Loeffler, 2015)
9. (Loeffler, 2015)
10. (Southwick, 2012)
11. (Loeffler, 2015)
12. (Team, Environmental Flows Recommendations Report. Final Submission to the Environmental Flows Advisory Group, Nueces River and Corpus Christi and Baffin Bays Basin and Bay Expert Science Team, and Texas Commission on Environmental Quality, 2011)
13. (Annear, 2004)
14. (Poff, 1997)
15. (Longley, 1994)

Next Steps

Along the way in this Texas Waters curriculum, you have learned how climate, land, and water work together and become the physical template on which the living plant and animal mosaic thrives. You learned about the watershed as a system, about the rich ecosystem services that healthy ecosystems provide to humanity, and the significance of natural flow regimes. You discovered the role and function of wetlands and estuarine systems, and the ways natural and human-caused change affect watersheds. Lastly, you explored water law and planning and learned about the nexus between water and energy. Now that you have worked your way through this curriculum, your mind is brimming with new knowledge, but knowledge without action is fruitless. We ask you to thoughtfully consider how your new understanding may translate into action.

What can YOU do?

Texas Parks and Wildlife uses three organizing principals to guide our actions, decisions, and path. They are:

- Life's Better Outside
- Everything's Connected, and
- Everyone Plays a Role

With these three principals in mind, we want you to be committed to taking responsible action in your future choices with regard to Texas water and watersheds. Here are just a few ways in which you can take an active role and make wise choices for future generations of Texans.

Share Your Appreciation of Texas Water Resources

For you, this may mean taking a kid fishing, or sharing outdoor experiences with your family. The outdoors provides a great setting for meetings or other professional gatherings as well.

Conserve Water

Water conservation is something everyone can do, regardless of your age, income, or where you live! Your help in conserving this increasingly limited resource will help maintain reservoir and aquifer water levels and help more water reach our rivers, springs and bays. These resources are critical to wildlife survival and outdoor recreation. It will also help you save money on your water bills.

Plant Native Plants

When you prepare for planting, choose native plants that provide food and shelter for birds, butterflies and other native wildlife. They provide colorful additions to your yard or balcony and require less water than non- native plants. Learn more about wildscapes for the best plants for your region.

Take Only Your Share

Texas Parks and Wildlife designs hunting and fishing regulations to keep native Texas wildlife populations healthy. We take into account cycles of drought and other challenges and adjust as necessary to preserve our native wildlife. Check daily bag limits and other regulations.

Wildlife: Feed or Don't Feed?

You can plant native plants that are part of wildlife's diet. If you do provide food, use caution to prevent attracting rodents, spreading disease and creating an unhealthy increase in animal populations. Be aware that feeding wild animals such as raccoons or opossums can contribute to eventual human-animal conflicts as wild animals lose their fear of humans.

Tread Lightly on Our Planet

When in nature, follow this simple rule: Take nothing but photos, leave nothing but footprints. For example, when on our beautiful Texas coast, avoid disturbing shorebirds. Human and dog disturbance causes unnecessary expenses of their energy, causing them to work harder to survive. Remember, nature isn't just some far off place you travel to; it's where you find it! Nature is in your own backyard. It's in a city or State park or greenspace, at the lake or river, or wherever you find a minimized footprint of human development. Here, we allow natural patterns of wildlife and vegetation to thrive. Do your part to protect and preserve our wild and natural spaces so that future Texans will have places to explore and our native plants and wildlife have room to grow.

Invasive Species

Do not contribute to the spread of exotic invasive species. Plant only native plant species. Don't release non- native aquatic or terrestrial species into nature. They only belong where they are native and may disrupt the natural balance of native plants, animals, and ecosystems.

Get Involved

You can put your new learning to work in so many ways. Here is a short list of groups with which you may get involved. Each has a unique role to play in our state and in your community.

Agency	Description/Type of Opportunity	Contact Link
Texas Water Development Board	Water Conservation	https://www.twdb.texas.gov/conservation/index.asp
	Water Planning	https://www.twdb.texas.gov/waterplanning/index.asp
	Groundwater Management, modeling, Management Areas and Conservation Districts	https://www.twdb.texas.gov/groundwater/index.asp
	Report summarizing the 9 major aquifers and 21 minor aquifers, their extent, estimated extent, demand, and water quality	http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R380_AquifersofTexas.pdf
	Interactive Submitted Well Drillers Reports Map	https://gisweb.tceq.texas.gov/waterwellpublic/

Agency	Description/Type of Opportunity	Contact Link
Texas Commission on Environmental Quality	Water Quality monitoring, program successes, drought information, conservation	https://www.tceq.texas.gov/about/organization/water.html
Texas Water Resources Institute	Water Conservation, Education, and Aquatic Habitat/Riparian Restoration	http://twri.tamu.edu/what-we-do/
Texas Alliance of Groundwater Districts	A consortium of Groundwater Conservation Districts (GCDs) that facilitates information sharing between GCDs that provides a great summary of general statistics for each GCD.	http://www.texasgroundwater.org
Texas Stream Team	Education, citizen science, water quality monitoring	http://www.meadowscenter.txstate.edu/Service/TexasStreamTeam.html
Texas Master Naturalist	The mission of the program is to develop a corps of well-informed volunteers to provide education, outreach, and service dedicated to the beneficial management of natural resources and natural areas within their communities for the state of Texas.	https://txmn.org/
Texas Parks and Wildlife Department	Texas Aquatic Science curriculum (Grades 6-12)	http://tpwd.texas.gov/education/resources/aquatic-science
	TPWD Habitat Conservation Branch: River Studies; Environmental Assessment, Response, and Restoration; Aquatic Invasive Species Management; and Watershed Conservation and Management	http://tpwd.texas.gov/landwater/
	TPWD Water Resources Branch: Water Quality and Quantity; Habitat Conservation, Restoration and Management; Freshwater Inflows to Estuaries; Seagrass Conservation	http://tpwd.texas.gov/landwater/
	Texas River Guide: Publications, studies, significant river stream segments	http://tpwd.texas.gov/landwater/water/habitats/rivers/index.phtml
	Wetlands Assistance Guide for Landowners	http://tpwd.texas.gov/landwater/water/habitats/wetland/publications

We at the Texas Parks and Wildlife Department value your interest in and concerns about water, watersheds, and aquatic habitats in Texas. We thank you for working through this curriculum and believe that knowledge is the first step toward stewardship. As an involved member of the public, you can help Texas Parks and Wildlife fulfill its mission: To manage and conserve the natural and cultural resources of Texas and to provide hunting, fishing, and outdoor recreation opportunities for the use and enjoyment of present and future generations.

For more information about how to get involved or for more information about this curriculum, please contact education@tpwd.texas.gov.

Glossary

Term	Definition
Abiotic	Nonliving; not derived from living organisms; inorganic.
Acid rain	Rain or other precipitation containing a high amount of acidity.
Acre-feet	A unit volume used to describe large water resources; the amount of water that would cover an acre of land one foot deep (325,851 gallons). It is estimated that on average an acre-foot of water can support the annual indoor and outdoor needs of between one and two urban households.
Adaptation	A behavior or physical trait that evolved by natural selection and increases an organism's ability to survive and reproduce in a specific environment.
Aeration	The process of exposing water to air, allowing air and water to mix and water to absorb the gasses in air.
Aerobic	Occurring or living in the presence of oxygen.
Aerobic decomposition	The decomposition of organic matter in the presence of oxygen; decomposition by bacteria that require oxygen.
Algae	A group of aquatic organisms ranging from single cell to multicellular that generally possess chlorophyll and are photosynthetic, but that lack true roots, stems and leaves characteristic of terrestrial plants.
Algae bloom	A rapid increase in the population and biomass of algae (phytoplankton) in an aquatic system.
Anaerobic	Occurring or living in the absence of oxygen.
Angler	A person who fishes using a rod, reel, hook, and line.
Anthropogenic	Human caused.
Aphotic zone	The deep part of a lake which doesn't receive enough light to support photosynthesis.
Aquatic corridor	An area of land and water which is important to the integrity and quality of a stream, river, lake, wetland, or other body of water. An aquatic corridor usually consists of the actual body of water ("corridor" usually connotes a river or stream), the adjacent buffer, and a fringe of adjacent upland areas.
Aquatic ecosystem	A community of organisms together with their physical environment organized around a body of water.
Aquatic organism	Any living thing that is part of an ecosystem in water.
Aquatic resource	Water and all things that live in or around water.

Term	Definition
Aquifer	An underground reservoir of water that rests in a layer of sand, gravel, or rock that holds the water in pores or crevices.
Arid	Regions of the country characterized by a severe lack of water hindering or preventing the growth and development of plant and animal life.
Artesian aquifer	A confined aquifer containing groundwater under pressure.
Atmosphere	The gaseous envelope surrounding the Earth; the air.
Autotroph(y)	An autotroph is an organism capable of producing its own energy.
Bacteria	A very large group of microorganisms that are called prokaryotic because their cells lack a nucleus and many other organelles, such as mitochondria.
Barrier island	A long narrow island of sand that runs parallel to the mainland.
Base Flows	"Normal" flow conditions that exist between storm events.
Bay	A body of water partially enclosed by land that is directly open or connected to the ocean.
Behavioral trait	How an organism acts and reacts in response to its environment, distinguishing one individual or species from another. Behaviors may be inherited or learned, examples are courtship dances in birds and sounds made by many animals.
Beneficial use	Use of the amount of water which is economically necessary for a purpose authorized by a permit, when reasonable intelligence and reasonable diligence are used in applying the water to that purpose and shall include conserved water.
Benthic community, benthos	The community of organisms that live on or in the floor of a body of water, including rivers, lakes, estuaries, and oceans.
Benthic zone	The bottom substrate of aquatic ecosystems.
Benthic macroinvertebrates	Invertebrates visible without the aid of a microscope that live on or in the bottom substrate.
Biodiversity	The number and variety of living things in an environment.
Biofilter	Living material or an organism that captures and biologically degrades pollutants.
Biosphere	The part of the world in which life can exist; living organisms and their environment.
Biotic	Of or having to do with life or living organisms; organic.
BMPs (Best Management Practices)	Methods that have been determined to be the most effective, practical means of preventing or reducing pollution from non-point sources, such as pollutants carried by urban runoff.

Term	Definition
Bottomland hardwoods	Wetlands found along rivers and streams of the southeast and south central United States where the streams or rivers at least occasionally flood beyond their channels into hardwood forested floodplains.
Brackish water	Water that has more salinity than freshwater, but not as much as saltwater; often a result of mixing of freshwater and saltwater in estuaries.
Bryophytes (aquatic)	Small, herbaceous plants that grow closely packed together in mats or cushions on rocks or other submerged substrate.
Brush control	The selective control, removal, or reduction of noxious brush such as mesquite, prickly pear, salt cedar, or other phreatophytes that consume water to a degree that is detrimental to water conservation; and the revegetation of land on which this brush has been controlled.
Buffer(n)	An area adjacent to a lake or estuarine shoreline, wetland edge, or streambank, where a) critically important ecological processes and water pollution control functions take place, and b) development may be restricted or prohibited for these reasons.
Buffer(v)	To serve as a protective barrier to reduce or absorb the impact of other influences; something that buffers.
Carnivores	Animals that kill and eat other animals.
Carrying capacity	An ecosystem's resource limit; the maximum number of individuals in a population that the ecosystem can support.
Cartilaginous fish	Fish with skeletons made of cartilage (a tough, flexible tissue, which is softer than bone) rather than bone; sharks and rays.
Cetaceans	Marine mammals known as whales, dolphins, and porpoises.
Channel	The part of the stream where water collects to flow downstream, including the streambed, gravel bars and stream banks; also, a dredged passageway within a coastal bay that allows maritime navigation.
Channelize	Create an artificial channel through which a stream or river flows using engineered structures to straighten a stream and eliminate its natural tendency to meander.
Chemoreceptors	Cells that can be scattered along the outside surface of fish that function as taste receptors.
Chemosynthetic organisms	Organisms in dark regions of the ocean that get energy for production and growth from chemical reactions, such as the oxidation of substances such as hydrogen sulfide or ammonia, as opposed to using energy from sunlight and photosynthesis.
Chlorophyll	A green pigment found in algae, plants and other organisms that carry on photosynthesis; enables plants to absorb energy from light.

Term	Definition
Ciénegas	A type of spring-fed wetland that occurs on the desert floor.
Clean Water Act	Primary federal law in the United States governing water pollution, first passed by Congress in 1972.
Climatology	The science of climate and its causes.
Cluster or Open Space Development	The use of designs which incorporate open space into a development site; these areas can be used for either passive or active recreational activity or preserved as naturally vegetated land
Coastal basin	These basins include the areas of coastal plains, peninsulas and islands that lie adjacent to and between the main river basins for which the coastal basin is named.
Cold seep, cold vent	A place where hydrogen sulfide, methane, or other hydrocarbon-rich fluid seeps from the ocean floor.
Collector	An aquatic invertebrate that feeds on fine material; examples include caddis fly larvae and mayfly nymphs.
Combined Sewer Overflow	Discharge of a mixture of storm water and domestic waste, occurring when the flow capacity of a sewer system is exceeded during rainstorms.
Community	A group of plants and animals living and interacting with one another in a particular place.
Community Fishing Lake	In Texas, public lakes 75 acres or smaller located totally within a city, in a public park, or within the boundaries of a state park.
Compete	The act of actively seeking after and using an environmental resource (such as food) in limited supply by two or more plants or animals or kinds of plants or animals.
Competition	This term refers to two or more species or organisms which are engaged in an active or passive struggle for resources. Intraspecific competition refers to competition within a species (e.g., two chipmunks quarreling over a cache of acorns). Interspecific competition refers to competition between species (e.g., a female chum salmon fighting with a female pink salmon for access to a spawning redd).
Condense	To change a gas or vapor to liquid.
Confined aquifer	An underground reservoir of water contained within saturated layers of pervious rock material bounded above and below by largely impervious rocks.

Term	Definition
Conservation easements	A practice used to apply and enforce restrictions to preserve natural resources. Typically, a landowner will grant very specific rights concerning a parcel of land to a qualified recipient (e.g., public agency or nonprofit land conservancy organization). The easement gives the recipient the right to enforce the restrictions. The recipient does not assume ownership but does assume long-term responsibility for enforcement and stewardship of the easement. For example, a wildlife management agency may obtain easements in forested floodplains from private landowners that help them manage wildlife and fish.
Conservation; to conserve	The wise use of natural resources such that their use is sustainable long term; includes protection, preservation, management, restoration and harvest of natural resources; prevents exploitation, pollution, destruction, neglect and waste of natural resources.
Conserved water	That amount of water saved by a holder of an existing permit, certified filing, or certificate of adjudication through practices, techniques, and technologies that would otherwise be irretrievably lost to all consumptive beneficial uses arising from storage, transportation, distribution, or application.
Consumer	An organism that feeds on other organisms in a food chain. First- order consumers are vegetarians, second-order consumers feed on first-order, etc.).
Contaminants	Impurities, including pollution or pollutants, in a substance such as water; harmful substances in water that can make it unfit for drinking or for supporting aquatic resources.
Current	The part of a body of water continuously moving in a certain direction.
Dam	A barrier or structure, natural or made by humans or animals, that is places across a stream or river to hold water back from flowing downstream.
Decompose	To decay or rot; to break down or separate into smaller or simpler components.
Decomposer	An organism such as a bacterium or fungus that feeds on and breaks down dead plant or animal matter, making essential components available to plants and other organisms in the ecosystem.
Decomposition	The process of decaying or rotting; breaking down or separating a substance into smaller or simpler components.
Delta; river delta	A low-lying landform created by the deposition of sediment carried by a river where it flows into an ocean, lake, or reservoir; often forming a wetlands in freshwater and an estuary in saltwater.
Denitrifying bacteria	Microorganisms whose action results in the conversion of nitrates in soil to free atmospheric nitrogen.
Desalination	Specific treatment processes to demineralize seawater or brackish (saline) water.
Detritus	Loose material that results from natural breakdown; material in the early stages of decay.

Term	Definition
Detritivores	Organisms that consume detritus.
Developed water	New waters added to a stream or other source of water supply through artificial means.
Diatom	A type of algae encased within a cell wall made of silica; most are single-cell, but many can form colonies.
Diffused surface water	Water which, in its natural state, occurs on the surface of the ground prior to its entry into a watercourse, lake or pond.
Dissolved oxygen	Oxygen gas absorbed by and mixed into water.
Dredging	An excavation or digging activity carried out at least partly underwater in shallow water areas to move bottom materials from one place to another; often used to keep waterways deep enough for boat passage.
Drought	An extended period of below normal rainfall or other deficiency in water supply.
Dual doctrine	Two principles or bodies of principles covering the same matter.
Dynamic Equilibrium	A state in which the parts of a system may be in a constant state of change but the relative overall status of the system remains unchanged.
Ebb tide	The outgoing or receding tide.
Echinoderm	Radially symmetrical animal, where the body is like a hub with arms or spines coming out of it; all have rough skin or spines; found only in marine waters; common examples are starfish, sea urchin, and sand dollar.
Echolocation	Biological sonar used by several kinds of animals where the animal makes sounds and listens to the echoes of those sounds that return from bouncing off objects near them. These echoes can be used to locate and identify prey and objects, and be used in navigating through their environment. Bats, whales and dolphins are examples of animals that echolocate.
Ecology	Study of the relationships living organisms have with each other and with their environment.
Ecosystem	A community of organisms together with their physical environment and the relationships between them.
Ecosystem services	Resources and processes that are supplied by ecosystems, generally grouped into four broad categories
Ecotone	An ecotone is a boundary ecosystem, specifically the ecosystem which forms as a transition between two adjacent systems. It may possess characteristics of both bordering ecosystems, while developing a suite of its own characteristics.

Term	Definition
Ectotherm	Organisms that have internal body temperatures at or near the same temperature as the environment in which it lives; internal physiological sources of heat are relatively small and not sufficient to control body temperature.
Endemic	Species that are found naturally occurring; native.
Energy pyramid	A graphical representation designed to show the relationship between energy and trophic levels of a given ecosystem.
Environmental flow	An amount of freshwater left in a river, estuary, or other water body adequate to support an ecologically sound aquatic environment.
Ephemeral stream	A stream that flows, dries up and flows again at different times of the year.
Epilimnion	Warm surface waters of a lake.
Erosion	The wearing away of land surface materials, especially rocks, sediments, and soils, by the action of water, wind, or ice; usually includes the movement of such materials from their original location.
Estuary	A partly enclosed body of water along the coast where one or more streams or rivers enter and mix freshwater with saltwater.
Ethical	Following the rules of good conduct governing behavior of an individual or group following the rules of good conduct governing behavior of an individual or group.
Euphotic zone	The the upper layer of water in a lake or ocean that is exposed to sufficient sunlight for photosynthesis to occur; also called the photic zone.
Eutrophication	Excessive nutrient input in a body of water that causes excessive plant and algae growth.
Evaporation	To change from a liquid state into vapor.
Exoskeleton	The external skeleton or covering that supports and protects an animal's body.
Extinction	The end of a species.
Extirpation	Species are extirpated when they are no longer found in an area they used to inhabit.
Fault	A fracture or crack in rock in the land surface, across which there has been significant displacement along the fracture as a result of Earth movement.
Filter feeder	An aquatic animal, such as an oyster and some species of fish, that feed by filtering tiny organisms or fine particles of organic matter from water that passes through it.
Fin	A wing- or paddle-like part of a fish used for propelling, steering, or balancing in the water.
First-order stream	A small stream with no tributaries coming into it.

Term	Definition
Flood tide	The incoming or rising tide.
Floodplain	A generally flat, low-lying area adjacent to a stream or river that is subjected to inundation during high flows. The relative elevation of different floodplains determines their frequency of flooding, ranging from rare, and severe storm events to flows experienced several times a year. For example, a "100-year floodplain" would include the area of inundation that has a frequency of occurring, on average, once every 100 years.
Fluvial	Referring to the structure and dynamics of stream and river corridors.
Food chain	A series of plants and animals linked by their feeding relationships and showing the transfer of food energy from one organism to another.
Food web	This term used to describe the trophic interactions of organisms within an ecosystem. Food webs consist of many interconnected food chains within an ecological community.
Freshwater	Water with a salt content lower than about 0.05%; for comparison, sea water has a salt content of about 3.5%.
Freshwater inflow	Less saline water that flows downstream in streams and rivers, or as runoff, that enters estuaries and bays.
Fry	Newly hatched fish.
Fungi	Members of a large group of organisms that include microorganisms such as yeasts and molds, as well as mushrooms; classified separate from plants, animals, and bacteria.
Geomorphology	The study of the landforms on the earth and the processes that change them over time.
Geosphere	The solid part of the Earth consisting of the crust and outer mantle.
Gill	A respiratory organ that enables aquatic animals to take oxygen from water and to excrete carbon dioxide.
Grazer	An aquatic invertebrate such as a snail or water penny that eats aquatic plants, especially algae growing on surfaces.
Groundwater	Water occurring under the surface of the land, in saturated soil or aquifers, other than underflow of a surface water river or stream.
Habitat	A habitat is an area where a specific animal or plant is capable of living and growing; usually characterized by physical features, or the presence of certain animals or plants.
Halophyte	A plant that grows in waters of high salinity.

Term	Definition
Headwaters	The high ground where precipitation first collects and flows downhill in tiny trickles too small to create a permanent channel; where spring water flows from an aquifer and starts streams.
Herbivore	An animal that eats plants.
Heterotroph(y)	A heterotroph is an organism that gets its energy from consuming other organisms.
High Flow Pulses	Short duration flows, within the stream channel, that usually occur following storm events.
Hydrologic cycle	The natural process of evaporation and condensation, driven by solar energy and gravity, that distributes the Earth's water as it evaporates from bodies of water, condenses, precipitates and returns to those bodies of water.
Hydrology	The science of water in all its forms (liquid, gas, and solid) on, in and over the land areas of the earth, including its distribution, circulation and behavior, its chemical and physical properties, together with the reaction of the environment (including all living things) on water itself.
Hydroperiod	Seasonal fluctuations in water levels.
Hydrosphere	All of the Earth's water, including surface water, groundwater, and water vapor.
Hypersaline	Water with salt levels surpassing that of normal ocean water (more than 3.5% salts).
Hypolimnion	The cold dense bottom waters of a lake.
Hypoxia	The condition in water where dissolved oxygen is less than 2-3 milligrams per liter.
Hypoxic zone	An area in which the water contains low or no dissolved oxygen causing a condition known as hypoxia.
Impacted stream	A very general, watershed imperviousness-based classification category for a subwatershed with 11 to 25% impervious cover. Urbanization is generally expected to lead to some impacts on stream quality, but the type and magnitude of these effects can vary significantly among different watersheds at similar levels of imperviousness.
Impervious	Not permitting penetration or passage; impenetrable.
Impervious cover	Any surface in the urban landscape that cannot effectively absorb or infiltrate rainfall; for example, sidewalks, rooftops, roads, and parking lots.
Imperviousness	The percentage of impervious cover by area within a development site or watershed, often calculated by identifying impervious surfaces from aerial photographs or maps.
Impoundment; impound	Reservoirs created in river valleys by placement of a dam across the river.

Term	Definition
Indicator species	A species that defines a trait or characteristic of the environment, including an environmental condition such as pollution or a disease outbreak.
Inorganic	Composed of matter that does not come from plants or animals either dead or alive; abiotic.
Interbasin transfer	Transfers of water from one river basin to another.
Intermittent stream	A stream that flows, dries up and flows again at different times of the year.
Invasive species	A species that has been introduced by human action to a location where it did not previously occur naturally, and has become capable of establishing a breeding population in the new location without further intervention by humans and has spread widely throughout the new location and competes with native species.
Invertebrate	Any animal without a spinal column; for example, insects, worms, mollusks and crustaceans.
Irrigation	The application of water to the land or soil to assist in the growing of agricultural crops, watering of lawns, and promoting plant growth in dry areas and during periods of inadequate rainfall.
Karst aquifer	An underground reservoir of water contained in limestone and marble rocks that are filled with numerous small channels and, in some cases, large underground caverns and streams.
Keystone Species	Species with especially far-reaching effects on an ecosystem. These species differ from dominant (i.e., Abundant) species in that their effects are much larger than would be predicted from their abundance. They have a disproportionate effect on the composition of communities and ecosystem function.
Lagoon	A body of saltwater separated from the ocean by a coral reef, sandbar, or barrier island.
Lake	A large body of standing water.
Larva	
Lateral line	An organ running lengthwise down the sides of fish, used for detecting vibrations and pressure changes.
Lentic	Water that is not flowing; a pond or lake.
Life History Strategies	The term life-history strategy in ecology refers to the selective processes involved in achieving fitness by certain organisms. Such processes involve, among other things, fecundity and survivorship; physiological adaptations; and modes of reproduction.

Term	Definition
Limestone	A sedimentary rock composed largely of calcium carbonate; often composed from skeletal fragments of marine organisms such as coral. Limestone is slightly soluble in water and weak acid solutions which leads to karst landscapes, in which water erodes the limestone over millions of years creating underground cave systems.
Limnetic zone	The part of a lake that is too deep to support rooted aquatic plants.
Littoral zone	Th part of a lake that is shallow enough to support rooted aquatic plants.
Macroinvertebrate	An invertebrate large enough to be seen without the use of a microscope.
Mainland	A large land mass, located near smaller land masses such as islands.
Marble	A hard crystalline metamorphic form of limestone rock.
Marsh	A wetland dominated by reeds and other grass-like plants.
Metamorphosis	The process of transformation from an immature form to an adult form in two or more distinct stages. For insects, complete metamorphosis is where there is little resemblance between the larva and adult; incomplete metamorphosis is where larva resemble the adult.
Microorganism	Very tiny organisms, such as one-celled bacteria and fungi, that can only be seen using a microscope.
Migratory; migration; to migrate	The regular seasonal journey undertaken by many species of birds.
Milt	The seminal fluid containing sperm of male fish and aquatic mollusks that reproduce by releasing this fluid onto nests containing eggs or into water containing eggs.
Mussel	A mollusk that attach to objects or to each other, often in dense clusters, and has two shells that close on each other, similar to a clam.
National Pollutant Discharge Elimination System (NPDES)	Established by Section 402 of the Clean Water Act, this federally mandated permit system is used for regulating point sources, which include discharges from industrial and municipal facilities and also stormwater discharges from discrete conveyances such as pipes or channels.
Natural physiographic region	Pertaining to physical geography and natural features; relating to the surface features of terrain and habitats.
Natural resource	Something that is found in nature that is useful to humans.
Natural selection	The natural process in which those organisms best adapted to the conditions under which they live survive and poorly adapted forms are eliminated.
Neotropical migratory bird	A bird that breeds in Canada or the United States during the summer and spends the winter in Mexico, Central America, South America or the Caribbean islands.

Glossary

Term	Definition
Niche	This term applies to an organism's physical location and, most importantly, functional role (much like an occupation; what the organism specifically does) within an ecosystem.
Nitrates	A salt of nitric acid; produced for use as fertilizers in agriculture. The main nitrates are ammonium, sodium, potassium, and calcium salts.
Nonindigenous species	An organism that has been introduced to an area to which it is not native; exotic or non-native.
Non-point source water pollution	Water pollution that comes from a combination of many sources rather than a single outlet.
Non-stormwater flows	Runoff which occur from sources other than rainwater; for example, personal car washing, lawn watering overspray, street cleaning, or pressure-washing of restaurant waste disposal facilities.
Non-supporting stream	A very general, watershed imperviousness-based classification category for a stream or subwatershed with more than 25% total impervious cover. Urbanization is generally expected to lead to some impacts on stream quality, but the type and magnitude of these effects can vary significantly among different watersheds at similar levels of imperviousness. These non-supporting streams are usually not candidates for restoration of relatively healthy aquatic ecosystems, but often can benefit from some physical rehabilitation designed to reduce additional degradation for example, excessive erosion and siltation that affects downstream areas.
Nutrient	A chemical that an organism needs to live and grow that is taken from the environment; it can be an organic or inorganic compound.
Nymph	The juvenile stage of development of certain insects; nymphs look generally like the adult except they are smaller, have no wings and cannot reproduce.
Ocean Basin	Large depression below sea level containing salt water.
Omnivores	Animals that eat both plants and animals.
Open Space	A portion of a site which is permanently set aside for public or private use and will not be developed. The space may be used for passive or active recreation, or may be reserved to protect or buffer natural areas.
Organic matter	Material that comes from plants or animals either dead or alive that is capable of decay; important in the transfer of nutrients from land to water.
Osmoregulation	A physiological adaptation of many organisms that allows them to regulate their intake of salts or fresh water to keep their fluids, such as blood, from becoming too salty or too dilute.
Overbank Flows	High flow events that exceed the normal stream channel.

Term	Definition
Oxbow lake	Crescent-shaped lake formed when a bend of a stream is cut off from the main channel.
Package Treatment Plant	A small, onsite waste treatment facility designed to handle the specific needs of a specialized, small, or remotely located waste generator; for example, a treatment plant that services a trailer park.
Parasite	An organism that lives on or in the living body of another species, known as the host, from which it obtains nutrients.
Pelagic fish	Fish that live near the surface or in the water column that almost constantly move about; not associated with the bottom.
Perennial stream	A stream that flows for most or all of the year.
Periphyton	A complex mixture of algae, detritus, bacteria, and microbes that are attached to submerged objects in most aquatic ecosystems.
Permeable	Having pores or openings that permit liquids or gases to pass through.
Pervious	Allowing water to pass through.
Photic zone	The upper part of a lake where enough light penetrates the water to allow photosynthesis to occur.
Photosynthesis	A process used by plants, algae, and many species of bacteria to convert energy captured from the sun into chemical energy that can be used to fuel the organism's activities; photosynthesis uses carbon dioxide and water, releasing oxygen as a waste product; sugars or carbohydrates are a byproduct of photosynthesis.
Physiographic	Pertaining to physical geography; relating to the surface features of terrain.
Phytoplankton	Algae and plant plankton, including single-celled protozoans and bacteria.
Plankton	Microscopic free-floating living organisms not attached to the bottom or able to swim effectively against most currents.
Playa lake	Round hollows in the ground in the Southern High Plains of the United States that fill with water when it rains forming shallow temporary lakes or wetlands.
Pocosin	A boggy wetland with deep, acidic, sandy peat soils. They are usually nutrient deficient.
Point source pollution	Water pollution that comes from a single source or outlet.
Pollutant	A substance that contaminates the water, air, or soil.
Pollution; to pollute	The contamination of air, water, or soil by substances that are harmful to living organisms, especially environmental contamination with man-made waste or chemicals; also the harmful substances themselves.
Polychaetes	Marine worms, where each body segment has a pair of protrusions called parapodia that bear bristles made of chitin; sometimes called bristle worms.

Term	Definition
Pond	A body of standing water small enough that sunlight can reach the bottom across the entire diameter.
Pond succession	The natural process by which sediment and organic material gradually replace the water volume of a pond ultimately resulting in the area becoming dry land.
Pool	Part of a stream where the water slows down, often with water deeper than the surrounding areas, which is usable by fish for resting and cover.
Population	This term applies to organisms of the same species which inhabit a specific area.
Porous	Full of pores, holes or openings allowing the passage of liquid or gas.ear
Precipitation	A form of water such as rain, snow or sleet that condenses from the atmosphere and falls to Earth's surface.
Predator	An animal that lives by capturing and eating other animals.
Prey	An animal that is eaten by a predator.
Primary Consumer	An animal that eats plants; an herbivore.
Producer, primary producer	An organism that is able to produce its own food from non-living materials, and which serves as a food source for other organisms in a food chain; green plants, algae, and chemosynthetic organisms.
Protozoa	A group of microscopic single celled organisms that are called eukaryotic because their cells are organized into complex structures by internal membranes, the most characteristic of which is the nucleus.
Rapid	An area of very turbulent flow; a part of a stream where the current is moving at much higher velocities than in surrounding areas and the surface water is greatly disturbed by obstructions that reach above the surface, or nearly so.
Recharge	Water that soaks into and refills an aquifer.
Refugia	An area in which a population of organisms can survive through a period of unfavorable conditions.
Resacas	Former channels of the Rio Grande River that have been cut off from the river, that have filled in with silt and water creating shallow marshes and ponds.
Reservoir	An artificial or natural lake built by placing a dam across a stream or river and used to store and often regulate discharge of water; underground storage area of water, such as in an aquifer.
Riffle	A relatively shallow part of a stream in which the water flows faster and the water surface is broken into waves by obstructions that are completely or partially underwater.
Riparian vegetation	The plant community next to the stream, starting at the water's edge and extending up the bank and beyond on either side of the stream.

Term	Definition
Riparian zone	Land next to the stream, starting at the top of the bank and containing vegetation on either side.
River	A large stream.
River basin	A drainage area, generally made up of many smaller units called watersheds; area of land drained to form a river.
Rooftop runoff	Rainwater which falls on rooftops, does not infiltrate into soil, and runs off the land.
Rule of capture	A landowners legal right to pump and capture groundwater or runoff before it enters a stream.
Run	A portion of a stream that has a fairly uniform flow and generally smooth surface water, with the slope of the water surface generally parallel to the overall slope of the section of stream.
Runoff	Precipitation, snow melt, or other water that flows onto the land but is not absorbed into the soil.
Saltwater	Water with about 3.5% salt content; ocean water or seawater.
Sand sheet wetlands	Small isolated depressions found in places where wind erodes away topsoil, exposing clay soils underneath that trap and hold water when it rains.
Saturated	Soaked with moisture; having no pores or spaces not filled with water.
Scale	Any of the small, stiff, flat plates that form the outer body covering of most fish.
Scavengers	Animals that eat the organic material of dead plants and animals.
Scraper	An aquatic invertebrate that has special mouth parts they can use to remove algae or other food material growing on the surface of plants or solid objects; the mouth parts act like a sharp scraper blade.
Seafood	Any sea life used by humans as food; includes fish and shellfish.
Seagrass	Submerged rooted aquatic plants that tolerate salinity.
Sedges	Perennial herbaceous plants of the widely distributed genus Carex, mostly occurring in saturated or inundated soil conditions.
Sediment	Silt, sand, rocks and other matter carried and deposited by moving water.
Sedimentation	The process of particles carried in water falling out of suspension; deposition of silt, sand, rock, and other matter carried by water.
Seeps	Places where water oozes from springs in the ground.

Term	Definition
Sensitive stream	A very general, watershed imperviousness-based classification category for a stream or a subwatershed with less than 10% impervious cover, that is potentially still capable of supporting stable channels and good to excellent biodiversity. Urbanization is generally expected to lead to some impacts on stream quality, but the type and magnitude of these effects can vary significantly among different watersheds at similar levels of imperviousness.
Seston	The particulate matter suspended in bodies of water. It applies to all particulates, including plankton, organic detritus, and inorganic material.
Shellfish	Aquatic invertebrates with exoskeletons used as food, including various species of mollusks and crustaceans, such as crabs, shrimp, clams, and oysters.
Shipping lane	Regular routes used by ocean going ships.
Shredder	An aquatic invertebrate such as a stonefly nymph that feeds by cutting and tearing organic matter.
Silt	Tiny specs of dirt, sized between sand and clay particles, that can be suspended in water or fall out of suspension to cover plants and the bottom of lakes or pool sections of rivers and streams.
Slough	A backwater or secondary channel of a stream.
Spawn	The process of releasing eggs and sperm, usually into water by aquatic animals, including fish.
Species	A group of related individuals sharing common characteristics or qualities that interbreed and produce fertile offspring having the same common characteristics and qualities as the parents.
Species (organism level)	An organism which has certain characteristics of a given population and is potentially capable of breeding with the same population defines a member of a species. This definition does not apply to asexually reproducing forms of life such as Monera, Protista, etc. Species can be considered the lowest (most specific) area of biological classification, but lower groupings are sometimes employed (e.g., subspecies, variety, race).
Sport fisherman	An angler who catches fish for personal use or recreation, rather than to make a living.
Spring	A place where groundwater flows to the surface of the Earth; where an aquifer meets the ground surface.
Stakeholder	An individual, group of people, or organization that has an interest, concern, or will be affected by an action or issue.
Stock, stocking	Introduction of fish to a water that have been produced elsewhere; to add a new species to a water body or increase the number of individuals of a fish species already present in a water body.

Term	Definition
Storm surge	A rise in the height of ocean water associated with high storm winds pushing against the ocean water; flooding caused by high ocean waters in coastal areas.
Stormwater best management practice	A structural or nonstructural technique designed to temporarily store or treat stormwater runoff in order to mitigate flooding, reduce pollution, and provide other amenities
Stormwater hotspots	Land uses or activities that generate highly contaminated runoff. Examples include fueling stations and airport de-icing facilities.
Stormwater runoff	Rainwater which does not infiltrate into the soil and runs off the land
Stream	A body of flowing water.
Stream bank	The shoulder-like sides of the stream channel from the water's edge to the higher ground nearby.
Stream flow	Water flow in streams.
Streambed	The bottom of a stream or river channel.
Structural trait	How an organism is built; the internal and external physical features that make up an organism. These features include shape, body covering and internal organs and can determine how an organism interacts with its environment.
Stygobite	An aquatic species that lives totally in groundwater ecosystems and do not exist in waters above the ground surface; an aquatic troglobite.
Stygophile	An aquatic species that can live in aquatic environments above and below ground; an aquatic troglophile.
Stygoxene	An aquatic species that uses underground waters for temporary purposes or that accidently gets swept underground; an aquatic trogloxene.
Subsistence Flows	Infrequent periods of low flow, those frequently seen during periods of prolonged drought.
Subsidence	A lowering, compaction, or collapse of the ground surface caused when large amounts of groundwater are withdrawn from an aquifer.
Subwatershed	A smaller geographic section of a larger watershed unit with a drainage area between 2 to 15 square miles and whose boundaries include all the land area draining to a point where two second order streams combine to form a third order stream

Term	Definition
Surface water	Also known as “public” or “state” water. Water of the ordinary flow, underflow, and tides of every flowing river, natural stream, and lake, and of every bay or arm of the Gulf of Mexico. Also includes water that is imported from any source outside the boundaries of the state for use in the state and that is transported through the bed and banks of any navigable stream within the state or by utilizing any facilities owned or operated by the state. Additionally, state water injected into the ground for an aquifer storage and recovery project remains state water. State water does not include percolating groundwater; nor does it include diffuse surface rainfall runoff, groundwater seepage, or spring water before it reaches a watercourse.
Surface water	Precipitation that runs off the land surface and is collected in ponds, lakes, streams, rivers, and wetlands.
Swamp	A wetland in which trees or woody shrubs predominate.
Swim bladder	An air-filled sac near the spinal column in many fish species that helps maintain the fishes’ position in the water column.
Symbiosis	Literally means “living together.” This term has several subcategories. Mutualism refers to an interaction between two organisms in which both organisms benefit (e.g., mycorrhizae). Commensalism, another form of symbiosis, implies a relationship where one species benefits, while the other experiences no effect (e.g., Spanish moss). Amensalism is a situation where one party is negatively affected while the other experiences no effect (examples are difficult to find in nature). Parasitism and predation are symbiotic types whereby one species benefits and one is adversely affected.
Tardigrade	Also known as waterbears, they are small (about 1 mm long), water- dwelling, segmented animals with eight legs; they are known for being able to survive in extreme environments.
Thermocline	The part of a lake’s water column where water temperature changes rapidly from warm to cold; the layer of water in between a lake’s epilimnion and hypolimnion.
Third-party impacts	Direct and indirect economic, social or environmental effects of a water transfer to a party other than the seller or buyer including other water rights holders.
Tides, tidal	The rise and fall of sea levels caused by the rotation of the Earth and the gravitational forces exerted by the Earth, moon and sun on the ocean.
Toxic algae bloom	An algal bloom that causes negative impacts to other organisms due to production of natural toxins by some species of algae.
Transferable Development Rights (TDRS)	A form of incentive for developers in which the developer purchases the rights to an undeveloped piece of property in exchange for the right to increase the number of dwelling units on another site. Often used to concentrate development density in certain land areas.

Term	Definition
Transmission rate	Speed at which water can move through or into an aquifer.
Transpiration	The passage of water through a plant to the atmosphere.
Tributary	A stream that flows into a larger stream or other body of water.
Troglobite	A species that lives in caves and can't live anywhere else.
Troglophile	A cave-dwelling species that may complete its life cycle in a cave, but can also survive in above ground habitats.
Trogloxene	A species that uses caves for temporary purposes or that accidently gets swept underground.
Trophic level	A group of organisms that occupy the same position in a food chain; each step of an energy pyramid.
Tunicate	A group of marine filter-feeding organisms that have a sac-like body; most species attach to rocks or other hard structures on the ocean floor, while some are pelagic (free-swiming); commonly called sea squirts.
Turbid	Water that is so full of small particles, such as silt, that the water is no longer transparent but instead appears cloudy.
Turbulent flow	Water flow where water at any point is moving in many different directions at once and at differing velocities.
Turnover	Where nutrient rich water from a lake's bottom rises to the surface and oxygen rich water from the surface sinks to the bottom, and mixing of all layers occurs in spring and fall in lakes in cold climates due to water temperature changes.
Unconfined aquifer	An underground reservoir of water that is directly connected to the surface and has water levels dependent on relatively constant recharge.
Unicellular	An organism that consists of just a single cell; this includes most life on Earth, with bacteria being the most abundant.
Unpigmented	Without color; appearing transparent, translucent or white
Wastewater treatment facility	A place that treats waste water from homes and businesses, such as toilet or sewage water.
Water pollution	An excess of natural or man-made substances in a body of water; especially, the contamination of water by substances that are harmful to living things.
Water quality	The fitness of a water source for a given use, such as drinking, fishing or swimming.
Water table	The surface of the subsurface materials that are saturated with groundwater in a given vicinity.

Term	Definition
Watercourse	The definition of a watercourse comes from case law. In Hoefs v. Short (1925) the Texas Supreme Court approved the following principles as to the legal requirements for a watercourse
Waterfowl	Ducks, geese and swans.
Watershed	An area of land that drains water, sediment and dissolved materials to a common receiving body or outlet. The term is not restricted to surface water runoff and includes interactions with subsurface water. Watersheds vary from the largest river basins to just acres or less in size. In urban watershed management, a watershed is seen as all the land which contributes runoff to a particular water body.
Wetland	A low-lying area where the soil is saturated with water at least seasonally, and supports plants adapted to saturated soils.
Zoning	A set of local government regulations and requirements that govern the use, placement, spacing and size of buildings and lots (as well as other types of land uses) within specific areas designated as zones primarily dedicated to certain land use types or patterns.
Zooplankton	Animal plankton, including single-celled and complex multicellular organisms.

Bibliography

Adams, M. T. (1981). The effects of agronomy on the carbon and nitrogen contained in the soil biomass. Journal of the Agricultural Society #97, 319-327.

Annear, T. I. (2004). Instream flows for riverine resource stewardship, Revised Edition. Cheyenne, WY: Instream.

Averyt, K. J. (2013). Water use for electricity in the United States: An analysis of reported and calculated water use information for 2008. Environmental Research Letters, 8, 015001, doi:10.1088/1748-9326/8/1/015001.

Barber, N. L. (2009). Summary of Estimated Water Use in the United States in 2005. U.S. Geological Survey Circular 1344.

Baron, J. (2003). Sustaining Healthy Freshwater Ecosystems. Issues in Ecology Number 10, 1-18.

Barry, R. G. (1983). Climatic environment of the Great Plains, Past and present. In Symposium: Man and the Changing Environments in the Great Plains Transactions of the Nebraska Academy of Sciences and Affiliated Societies Volume XI-Special Issue. Transactions of the Nebraska Academy of Sciences and Affiliated Societies Volume XI-Special Issue, 45-55.

Bayley, P. (1995). Understanding large river-floodplain ecosystems. BioScience, 45(3): 154.

Brekke, L. D. (2009). Climate change and water resources management: A federal perspective, U.S. Geological Survey Circular 1331978–1–4113–2325–4. Reston, VA: U.S. Geological Survey.

Buckmeier, D. (2008). Life History and Status of Alligator Gar Atractosteus spatula, with Recommendations for Management. Mountain Home, TX: Texas Parks and Wildlife.

Carpenter, S. J. (1993). The trophic cascade in lakes. Cambridge: Cambridge University Press.

Chanway, C. (1993). Biodiversity at risk: soil microflor In E. H. M. Fenger, Our Living Legacy: Proceedings of a Symposium on Biological Diversity. (p. Biodiversity at risk: soil microflora). Victoria, Canada: Royal British Columbia Museum.

Colby, B. (2011). Using climate information to improve electric utility load forecasting. Adaptation and Resilience. In G. B. G. Colby, The Economics of Climate-Water-Energy Challenges in the Arid Southwest (pp. 207-228). RFF Press.

Costanza, R. (1997). The value of the world's ecosystem services and natural capital. Nature 387, 253-260.

Daily, G. (1995). Population diversity and the biodiversity crisis. In K. M. Perrings, Biodiversity Conservation: Problems and Policies (pp. 41-51). Dordrecht: Kluwer Academic Press.

Daily, G. (1996). Socioeconomic Equity, Sustainability, and Earth's Carrying Capacity. Ecological Applications, 991-1001.

Daily, G. (1997). Nature's Services: Societal Dependence on. Washington DC: Island Press.

DeBach, P. (1974). Biological Control by Natural Enemies. London: Cambridge University Press.

Dunne, T. (1978). Water in environmental planning. San Francisco: W.H. Freeman Co.

Edwards Aquifer Authority (2016, Mar 4). Endangered and Threatened Species. Retrieved from Edwards Aquifer Habitat Conservation Plan: http://www.eahcp.org/index.php/about_eahcp/covered_species/fountain_darter2

Ehrlich, P. (1977). Ecoscience: Population, San Francisco: Freeman and Co.

Ehrlich, P. (1981). Extinction: The Causes and Consequences of the. New York: Random House.

Ewel, K. (1997). Water quality improvement by wetlands. In E. G.C. Daily, Nature's Services: Societal Dependence on Natural. Washington DC: Island Press.

Federal Interagency Stream Restoration Working Group (1998, Oct). Stream Corridor Cross Section. Stream Corridor Restoration: Principles, Processes, and Practices. Washington DC: NRCS.

Food and Agriculture Organization of the United Nations (2015). Food and Agriculture Organization of the United Nations. Retrieved from Food and Agriculture Organization of the United Nations: http://www.fao.org/publications/en/

Foti, R. (2009). Vulnerability of U.S. Water Supply to Shortage: A Technical Document Supporting the Forest Service 2010 RPA Assessment. RMRS-GTR-295. Washington DC: U.S. Forest Service.

Hillel, D. (1991). Out of the earth: Civilization and the life of the soil. New York: The Free Press.

Horton, R. (1945). Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. Geological Society of America Bulletin 56, 275-370.

Huff, M. (1995). Historical and current forest landscapes in eastern Oregon and Washington. Portland, OR: USFS.

iNaturalist. (2016). Cascade Caverns Salamander. Retrieved from iNaturalist: http://www.inaturalist.org/taxa/27109-Eurycea-latitans

Jenny, H. (1980). The soil resource: Origin and Behavior. Ecological Studies Volume 37, p. 377.

Johnson, S. (2013). Texas Parks and Wildlife Texas Aquatic Science. Retrieved from Texas Parks and Wildlife: http://tpwd.texas.gov/education/resources/aquatic-science

Kaiser, R. (2016, May). Texas Water Law. Retrieved from Texas Water: http://texaswater.tamu.edu/water-law.html

Kellert, S. (1993). The Biophilia Hypothesis. Washington, D.C.: Island Press.

Kimmins, J. (1997). Forest ecology: A foundation for sustainable management. Second edition. Upper Saddle River, NJ: Prentice-Hall.

Klein, R. (1979). Urbanization and Stream Quality Impairment. Water Resources Bulletin of the American Water Resources Association, 948-963.

Kunkel, K. (2013). Climate Trends and Scenarios for the U.S. National Climate Assessment: Part 4. Climate of the U.S. Great Plains. Washington DC: National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service.

Lane, E. (1955). The Importance of Fluvial Morphology in Hydraulic Engineering. American Society of Civil Engineering, Proceedings, 81, paper 745, 1-17.

Lanner, R. (1996). Made for Eachother: A Symbiosis of Birds and Pines. New York: Oxford University Press.

Lawton, J. (1995). Extinction Rates. Oxford University Press: Oxford.

Lee, K. (1985). Earthworms: Their Ecology and Relationships. Sydney: Academic Press.

Leopold, L. (1964). Fluvial processes in geomorphology. San Francisco: W. H. Freeman and Company.

Leopold, L. (1968). Hydrology for Urban Land Planning-A Guidebook on the Hydrologic Effects of Urban Land Use. Washington DC: United States Department of the Interior.

Loeffler, C. (2015). A Brief History of Environmental Flows in Texas. Austin.

Loeffler, C. (2016). Chapter I.14, Sustainable Water Management (Volume I). In C. L. Leslie Hartman, Water, Energy and Ecosystem Sustainability (p. Chapter I.14). Boca Raton, FL: Taylor & Francis/CRC Press.

Longley, W. (1994). Freshwater inflows to Texas bays and estuaries: ecological relationships and methods for determination of needs. Austin: Texas Water Development Board and Texas Parks and Wildlife Department.

Maser, C. (1994). From the forest to the sea: the ecology of wood in streams, rivers, estuaries, and oceans. Delray Beach, Florida: St. Lucie Press.

Minshall, G. (1978). Autotrophy in stream ecosystems. BioScience 28, 767-771.

Nabhan, G. (1997). Pollination services: Biodiversity's direct link to world food stability. In e. G. Daily, Nature's Services: Societal Dependence on Natural Ecosystems (pp. 133-150). Washington DC: Island Press.

Naiman, R. B. (1998). River Ecology and Management. New York: Springer-Verlag.

Naylor, R. (1997). The value of natural pest control services in agriculture. In e. G. Daily, Nature's Services: Societal Dependence on Natural Ecosystems (pp. 151-174). Washington DC: Island Press.

Nicot, J. (2012). Water use for shale gas production in Texas. U.S. Environmental Science and Technology, 46, 3580-3586, doi:10.1021/es204602t.

Nueces River and Corpus Christi and Baffin Bays Basin and Bay Expert Science Team (2011). Environmental Flows Recommendations Report. Final Submission to the Environmental Flows Advisory Group, Nueces River and Corpus Christi and Baffin Bays Basin and Bay Area Stakeholders Committee, and Texas Commission on Environmental Quality. Austin: Nueces River and Corpus Christi and Baffin Bays Basin and Bay Area Stakeholders Committee, and Texas Commission on Environmental Quality.

Ojima, D. (2002). Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change - Central Great Plains. Fort Collins, CO: U.S. Global Change Research Program, Central Great Plains Steering Committee and Assessment Team, Colorado State University.

Ojima, D. (2013). Great Plains Regional Climate Assessment Technical Report, National Climate Assessment 2013. Washington DC: Island Press.

Oldeman, L. R. (1990). World map of the status of human-induced soil degradation. Wageningen: ISRIC/UNEP.

Overgaard-Nielsen, C. (1955). Studies on enchytraeidae 2: Field studies. Natura Jutlandica 4, 5-58.

Pimental, D. (1995). Environmental and economic costs of soils erosion and conservation benefits. Science, 1117-1123.

Pimentel, D. (1989). Environmental and economic impacts of reducing U.S. agricultural pesticide use. In Handbook of Pest Management in Agriculture (pp. 4: 223-278).

Poff, N. (1997). The natural flow regime: a paradigm for river conservation and restoration. BioScience, 47 (11), 769-784. Doi:10.2307/1313099.

Rational Research Council (1989). NRC Annual Report. NRC.

Redmon, L. (2011). Lone Star Healthy Streams. College Station, TX: Department of Soil and Crop Sciences and AgriLife Communications, The Texas A&M System.

Richmond, (2014). National Climate Assessment Report Chapter 2 Our Changing Climate. Washington DC: U.S. Global Change Research Program.

Rohr, J. (2010). Linking global climate and temperature variability to widespread amphibian declines putatively caused by disease. Proceedings of the National Academy of Sciences of the United States of America (pp. 8269-8274). Washington DC: National Academy of Sciences.

Rosen, R. (2013). Aquifers and Springs – Chapter 7. Retrieved from Texas Aquatic Science: http://texasaquaticscience.org/

Roth, D. (2010). Texas Hurricane History. Camp Springs, MD: National Weather Service.

Rouatt, J. (1961). A study of bacteria on the root surface and in the rhizosphere soil of crop plants. J. Applied Bacteriology, 164-171.

Sala, O. (1997). Ecosystem services in grasslands. Washington DC: Island Press.

Salinas, S. (2015). TPWD News and Media Releases. Retrieved from Texas Parks and Wildlife Department: http://tpwd.texas.gov/newsmedia/releases/?req=20151104a

Sansom, A. (2012, August 15). Report of Plaintiff's Expert Andrew Sansom, The Aransas Project v. Bryan Shaw et al. Civil Action No. 2:10-cv-00075, United States District Court for the Southern District of Texas, Corpus Christi Division. . Retrieved from The Aransas Project: http://thearansasproject.org/wp-content/uploads/2011/09/Sansom_Andrew.pdf

Schlesinger, W. (1991). Biogeochemistry, an Analysis of Global Change. New York, USA: Academic Press.

Schueler, T. (1995). The importance of imperviousness. Watershed Protection Techniques, pp. 1(3):100-111.

Shafer, M. D. (2014). Ch. 19: Great Plains. Climate Change Impacts in the United States. In J. M. Melillo, The Third National Climate Assessment (pp. 441-461). Washington DC: U.S. Global Change Research Program.

Shahid N. C. F. (1999). Biodiversity and Ecosystem Functioning: Maintaining Natural Life Support Processes. Issues in Ecology, 1-14.

Shields, M. (2016, April 19). The Birds of North America Online. Retrieved from Cornell: http://bnbirds.cornell.edu/bna/species/609/articles/introduction

Shiklomanov, I. (1993). World water resources. In P. H. (ed), Water in Crisis. New York & Oxford: Oxford University Press.

Simmons, D. (1982). Effects of urbanization on base flow of selected south shore streams, Long Island, NY. Water Resources Bulletin, pp. 18(5): 797-805.

Southwick, A. (2012). Sportfishing in America: An Economic Force for Conservation, Produced for the American Sportfishing Association (ASA) under a U.S. Fish and Wildlife Service (USFWS) Sport Fish Restoration grant (F12AP00137, VA M-26-R) awarded by the Association of Fish an. Association of Fish and Wildlife Agencies (AFWA).

Stallard, R. F. (1998). Terrestrial sedimentation and the carbon cycle: Coupling weathering and erosion to carbon burial. Global Biogeochemical Cycles, 231-257.

Stillwell, A. (2009). Energy-Water Nexus in Texas. . Austin: The University of Texas at Austin and the Environmental Defense Fund. .

Strahler, A. (1957). Quantitative analysis of watershed geomorphology. American Geophysical Union Transactions 38, 913-920.

Strzepek, K. (2010). Characterizing changes in drought risk for the United States from climate change. Environmental Research Letters, 5, 044012, doi:10.1088/1748-9326/5/4/044012.

Texas Board of Water Engineers (1958). Texas Water Resources Planning at the End of the Year 1858, A Progress Report to the Fifty-Sixth Legislature. Texas Board of Water Engineers.

Texas Comptroller of Public Accounts (2016, June). Key Economic Indicators. Retrieved from The Texas Economy: http://www.thetexaseconomy.org/economic-outlook/key-indicators/

Texas Forestry Service, (2015, Feb). Texas Forestry Best Management Practices. Retrieved from Texas A&M Forest Service: http://tfsweb.tamu.edu/water

Texas Parks and Wildlife (1993, March 12). Section 6 Grants: Habitats. Retrieved from Texas Parks and Wildlife Department: https://tpwd.texas.gov/business/grants/wildlife/section_6/projects/habitats/e1_j2.5_final_report.pdf

Texas Parks and Wildlife, (2016, April 22). Conservation Challenges. Retrieved from TPWD: http://tpwd.texas.gov/education/resources/keep-texas-wild/one-state/conservation-challenges

Texas Water Development Board (2012). 2012 State Water Plan: Water for Texas. Austin, TX: Texas Water Development Board (TWDB).

Texas Water Development Board, (2016). TWDB.texas.gov. Retrieved from TWDB: http://www.twdb.texas.gov/publications/reports/infosheets/doc/WaterRightsMarketingBrochure.pdf

The IUCN Red List of Threatened Species (2016). Retrieved from The IUCN Red List of Threatened Species: http://www.iucnredlist.org

Thompson, J. (1994). The Coevolutionary Process. Chicago: Chicago University Press.

U.S. Department of Energy (2013). Installed Wind Capacity. National Renewable Energy Lab: U.S. Department of Energy.

U.S. Fish and Wildlife Service (2016, 06 24). Quiver Retrieved from US Fish and Wildlife Service: https://www.fws.gov/refuge/Quivira/wildlife_and_habitat/whooping_crane.html

U.S. Geological Survey and Environment Canada (2015). Data from the 2011 International Piping Plover Census. Reston, Virginia: U.S. Geological Survey. Retrieved from http://tpwd.texas.gov/huntwild/wild/wildlife_diversity/nongame/listed-species/

Vannote, R. (1980). The River Continuum Concept. Canadian Journal of Fisheries - Vol. 37 - Issue 80.

Veeresham, P. (2012). Natural products derived from plants as a source of drugs. Journal of Advanced Pharmacuetical Technology and Research Oct-Dec; 3(4, 200-201.

Vitousek P., (1997). Human alteration of the global nitrogen cycle: sources and consequences. Ecological Applications, 737-750.

Wilson, E. O. (1989). Threats to Biodiversity. Scientific American, 108-116.

Wilson, E. O. (Dec., 1987). The Little Things That Run the World (The Importance and Conservation of Invertebrates). Conservation Biology, Vol. 1, No. 4, pp. 344-346.

Xia, Z. (2016). Wood Energy. Retrieved from Food and Agriculture Organization of the United Nations: http://www.fao.org/forestry/energy/en/

Index

SPORT FISH RESTORATION

Your angler dollars help clean up rivers and streams, restore fish populations, and create public access to waterways. Every purchase of fishing tackle carries a tax that goes from the U.S. Fish and Wildlife Service to state fish and wildlife agencies for fisheries research, habitat improvement, aquatic resource education programs and fishing and boating access.

TEXAS PARKS & WILDLIFE