Spring Lake Watershed Characterization and Management Recommendations Final Report

Nonpoint Source Protection Program CWA §319(h)

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The Meadows Center for Water and the Environment
Texas State University – San Marcos

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Contents

List of Acronyms and Abbreviations

BMPs	Best Management Practices
CAFO	Concentrated Animal Feeding Operation
CFS	Cubic Feet per Second
CWA	Clean Water Act
DO	Dissolved Oxygen
EAA	Edwards Aquifer Authority
EMC	Event Mean Concentration
EPA	Environmental Protection Agency
ET	Evapotranspiration
GBRA	Guadalupe-Blanco River Authority
GIS	Geographic Information System
IH	Interstate Highway
LOQ	Limit of Quantitation
LULC	Land Use and Land Cover
MRLC	Multi-Resolution Land Characteristics Consortium
N	Nitrogen
NCDC	National Climate Data Center
NH_4^+	Ammonium
NLCD	National Land Cover Dataset
NO_3^{2-}	Nitrate
NO_2^-	Nitrite
NOAA	National Oceanographic & Atmospheric Administration
NPS	Nonpoint Source
Ortho-P	Orthophosphate
OSSF	On-Site Sewage Facility
P	Phosphorus
PO_4^{3-}	Phosphate
SMRF	San Marcos River Foundation
SOW	Scope of Work
SpC	Specific Conductance
SWAT	Soil and Water Assessment Tool
TCEQ	Texas Commission on Environmental Quality
TDP	Total Dissolved Phosphorus
TDS	Total Dissolved Solids
TKN	Total Kjeldahl Nitrogen

TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TP	Total Phosphorus
TPWD	Texas Parks and Wildlife Department
TSS	Total Suspended Solids
TWDB	Texas Water Development Board
TXSTATE	Texas State University
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
USMR	Upper San Marcos River
USMRCG	Upper San Marcos River Coordinating Group
WPP	Watershed Protection Plan

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Executive Summary

Spring Lake in central Texas is a unique ecosystem and serves as the headwaters of the Upper San Marcos River. Artesian spring water from the Edwards Aquifer emerges into the lake from hundreds of spring openings, creating one of the most productive spring-fed systems in Texas. Spring Lake and the Upper San Marcos River are important resources in this portion of Texas in that they serve as major recreational sites, contain important cultural and archeological values, provide habitat for a number of threatened and endangered species, and are the basis for the drinking water supply for towns downstream. Thus, protecting and preserving the water quality of Spring Lake and the Upper San Marcos River is critical.

The Interstate Highway-35 (IH-35) corridor in central Texas is one of the fastest growing regions of the United States. As such, this area is facing increasing pressure from anthropogenic development in the form of changes in Land Use and Land Cover (LULC) and the extraction of groundwater resources. Recently, it has been qualitatively noted that the water quality in Spring Lake and the Upper San Marcos River have declined after storm flow events. The purpose of the Spring Lake Watershed Characterization and Management Measures Recommendations Project is fivefold:

(1) Characterize the Spring Lake/Sink Creek watershed in terms of hydrology, geology, and wildlife, evaluate spatial and temporal patterns in LULC characteristics of the Upper San Marcos River and Sink Creek watersheds, and gather existing data and present an initial watershed inventory for Spring Lake/Sink Creek.

(2) Examine NPS of nutrients, suspended solids, and bacteria (i.e., *Escherichia coli*) to the Spring Lake and determine the relative importance of surface- and groundwater during typical hydrology and stormflow events. This portion of the project will provide information on spatial and temporal variability in water quality in the Upper San Marcos River, and compare water quality to existing surface water quality standards. This comparison allows identification of times and locations at which water quality standards for particular parameters may or may not be exceeded, and provides guidance for future efforts to focus on mitigating any sources of NPS which may be contributing to water quality impairment.

(3) Calculate/model the loading of various NPS constituents including nutrients, heavy metals, and *E. coli* to Spring Lake and the local groundwater pool from the Sink Creek watershed and determine the proportional loading of these NPS constituents from the various LULC types within the Sink Creek watershed.

(4) Create a Public Participation Plan (PPP) for the project and work with stakeholders and partners to create a vision, goals, and action items that incorporate the environmental, economic, and social values of stakeholders and partners. The public participation portion of the project will also work with stakeholders and partners to reconcile

different values and viewpoints of the various participants in order to arrive at mutually acceptable management recommendations.

(5) Provide information on specific management recommendations for the Spring Lake – Sink Creek watershed, and present this information to the Upper San Marcos River Coordinating Group (USMRCG; the stakeholders), thus providing the basis for the stakeholders to determine which management measures they view as a priority for the watershed and Spring Lake.

Watershed Characterization

Watersheds serve an important function as transporters, storage sites, and transformers of water and other materials to downstream points in the landscape. Within watersheds, LULC patterns have the potential to affect a myriad of the physical, chemical, and biological processes. Understanding how LULC characteristics and changes affect these processes is critical for preservation of water quality.

There are four major subcatchments within the Upper San Marcos River Watershed: Sink Creek, Purgatory Creek, Sessom Creek, and Willow Creek. Sink Creek is the most upstream of these surface drainages and potentially plays an important role in determining nutrients and sediments loads to Spring Lake and the Upper River. Thus, determining NPS inputs to Sink Creek from the watershed are critical the maintenance of water quality for the lake and upper river. However, Spring Lake also receives substantial groundwater from both local- and regionally-derived sources within the Edwards Aquifer, with the magnitude of the different sources dependent upon regional hydrologic conditions. Thus, the high degree of surface- and ground-water connectivity likely makes any NPS loading to groundwater within the Edwards Aquifer recharge zone relevant to NPS dynamics in Spring Lake.

Currently, Spring Lake and the Upper San Marcos River meet water quality standards for most of the major water quality criteria; however the Draft 2010 Texas Integrated Report for Clean Water Act Sections 305(b) and 303(d) lists the upper San Marcos River Segment (Segment 1814) as Category 5, subcategory 5c for total dissolved solids (TDS). Based upon data from this 2010 assessment and designation, the upper San Marcos River does not meet water quality standards for TDS and additional data and information will be collected before a total maximum daily load (TMDL) will be scheduled. In addition to the 303(d) listing for TDS in the 2010 Draft Report, there are noted increases in suspended solids and decreased water clarity associated with rainfall events in the watershed. Biota in the lake and river has been actively monitored by multiple agencies and investigators due the relatively high number of endangered and threatened species in the area. Currently, the aquatic invertebrate, fish and aquatic vegetation communities in the river appear to be diverse and composed of many endemic species. However, there are a number of exotic and potentially invasive species in the lake and river that are cause for concern.

The Upper San Marcos River and Sink Creek watersheds have undergone significant LULC changes from 1992 - 2006. In particular, both of these watersheds have experienced declines in the percent cover of forest and agricultural area. These declines were accompanied by increases in developed area and grass/shrub lands. Conversion of forested and agricultural areas in the watersheds was most rapid during the 1992 – 2001 and this rate declined substantially during the 2001 – 2006 period. Reduction in forest and agricultural land cover is likely due to changes in land use patterns associated with increasing human populations in the area and aggressive programs to remove Ashe Juniper (*Juniperus ashei*) from the landscape.

Although developed land cover constitutes 11.5% and 5.0% of the land cover in the Upper San Marcos and Sink Creek watersheds, respectively, many previous studies have found that relatively small amounts developed land cover can lead to substantial impacts through increased pollutant loads and altered hydrological regimes. Currently, water quality conditions in Spring Lake and the Upper San Marcos River are reliant upon on adequate flows from the headwater springs. Decreases in aquifer levels, human development on or along aquifer recharge sites will likely lead to decreased water quality through an increased reliance on surface water inputs and NPS inputs associated with runoff from disturbed lands. Preservation of water quality and quantity in Spring Lake and the Upper San Marcos River requires an integrated management plan that incorporates both surface- and groundwater, spans agency jurisdictions, allows for stakeholder involvement, and maintains the sometimes difficult balance between natural resource management and economic development.

Water Quality Data Collection and Analysis

The Data Collection and Analysis section of the project collected data to characterize spatial and temporal properties of water quality in the Spring Lake watershed. Several approaches were used to accomplish this, and can be separated into three types of data collection and monitoring efforts: 1) Continuous monitoring of basic field parameters from spring openings and other locations within Spring Lake; 2) Routine sampling for water quality in Spring Lake and the Upper San Marcos River; and 3) Targeted sampling of water quality in Sink Creek, Spring Lake, and the Upper San Marcos River during stormflow events.

Continuous monitoring of field parameters indicates that all the monitored spring openings respond to local storms as well as regional-scale changes in aquifer level and spring discharge. This evidence suggests that the San Marcos Springs and the Edwards Aquifer are vulnerable to NPS and point source contamination from both local and distant (regional) sources.

Routine sampling in the San Marcos River and at several discrete spring openings in Spring Lake show that water quality is generally very good under baseflow conditions, with low levels and variability in concentrations of NPS nutrients and contaminants, but that stormwaters derived from urban areas in San Marcos rapidly and negatively influence water quality at all sites.

Compared to surface waters and the Slough Arm, waters from San Marcos Springs show relative temporal stability for all measured parameters. On an annual scale, the largest source of variability, as well as the highest concentrations of measured NPS pollutants, is due to stormwater entering the Spring Lake system. Targeted sampling during storms indicate that local urban runoff, which contributes to high levels of TSS, nutrients, and other contaminants, affects the Slough Arm of Spring Lake for longer periods than in the Spring Arm because sediment and nutrient rich stormwaters tend to stagnate in the Slough Arm after storm events.

Estimation of Loads from the Sink Creek Watershed

Calculated/modeled estimates of hydrological inputs, and sediment, nutrient and bacteria loadings from the Sink Creek watershed to Spring Lake indicated that magnitude of the NPS loads from the Sink Creek watershed to Spring Lake and the local groundwater from the various LULC types were a function of the proportion of each LULC type within the watershed. Thus, on a whole-watershed scale, low-impact LULC types had contributed the highest loads to Spring Lake and the groundwater pool because they composed >90% of the Sink Creek watershed area. However, higher-intensity LULC types (e.g., Residential areas), though composing a relatively small portion of the watershed, had a greater than expected contribution to the loads of several NPS constituents. In addition, the results from calculations of per acre yield from the different land use types indicate that conversion of the dominant land use types in the watershed (Undeveloped/Open and Rangeland) to more intense human impact land uses (Residential, Commercial, Cropland, and Industrial land uses) generally increase the nutrient, bacterial, and metal yields from the watershed. These findings provide a foundation for designing and implementing LULC-specific management measures to preserve or improve the current water quality of Spring Lake and the Upper San Marcos River and to reduce NPS pollutant loads from future human activities in the watershed.

Public Participation in Spring Lake NPS Planning

The Upper San Marcos Coordination Group (USMRCG) was initiated by the River Systems Institute (RSI) at Texas State University – San Marcos in 2009 to assist community stakeholders, local organizations, and various agency partners who are working collectively to bridge diverse perspectives, interests, and resources to provide input into the development of a watershed characterization and the resulting recommendations for the management of nutrients and other identified nonpoint source pollutants in the watershed. The group is comprised of members from the City of San Marcos, Hays County, the RSI, the San Marcos River Foundation, San Marcos River Rangers, San Marcos Greenbelt Alliance, Edwards Aquifer Research and Data Center, the Guadalupe Blanco River Authority, the United States Geologic Survey, and others. Overall, one of the main concerns of the group is to ensure that the long-term integrity and sustainability of the San Marcos watershed is preserved and that water quality standards are maintained for present and future generations. A core belief is that good water quality is essential to all, and that protection of water resources is an individual as well as governmental responsibility.

As a part of the stakeholder group process, the stakeholders created the following Mission Statement and Goals:

The mission of the Upper San Marcos Coordinating Group is to restore and preserve the natural integrity of the Upper San Marcos Watershed through research, education and stewardship.

Goals:

- Develop, coordinate and implement watershed protection planning activities to ensure the river meets the state's water quality standard but furthermore improve it beyond its status as of July, 2012.
- Protect water quality and optimal spring flows for current and future generations
- Safeguard healthy riparian and aquatic habitats
- Broaden and enlighten civic engagement in watershed management activities
- Increase awareness of the influence human activities have on the intricate web of biological relationships found within the watershed

A PPP was created and approved by the stakeholders in the Sink Creek/Upper San Marcos River. The group wanted to make information available for public on River Systems Institute website, create a brochure/flyer that condenses the major issues and findings from the Upper San Marcos Characterization report into a more manageable and easily understood format, conduct monthly Stakeholder Meetings, have several public meetings throughout the project, and maintain an open door policy in that anyone requesting information, meetings, and more can have an audience via email, phone or in person.

Management Measures Recommendations

Following presentation of the watershed characterization, the water quality data, and the loading estimates to the USMRCG, stakeholders were asked to identify and prioritize different management measures as priority for the Sink Creek - Spring Lake watershed. In this portion of the Spring Lake Project, we present the specific management measures that may be used to preserve or improve the current water quality of Spring Lake and the USMR and to reduce NPS pollutant loads from future human activities in the watershed.

The stakeholder group concluded that management measures associated with land conservation strategies, mitigation of the effects of urban/residential development, and watershed-level mitigation of the effects of sedimentation were the most important to maintain and improve in the watershed. Due to the low level of human development in the Sink Creek – Spring Lake watershed and the high sensitivity of the lake and the upper river to changes in LULC patterns, the stakeholder group ranked land conservation measures as the most important and most urgent management strategies for the Spring Lake – Sink Creek watershed. The specific management measures that may be used to preserve or improve the water quality of Spring Lake and the USMR depends upon future stakeholder involvement in the decision making-processes.

1.0 Spring Lake Watershed Characterization

The San Marcos River is an ecologically unique spring-fed ecosystem located along the margin of the Edwards Plateau in central Texas. Spring Lake, located in the City of San Marcos, is the headwaters of the San Marcos River where artesian spring water from the Edwards Aquifer emerges into the lake from approximately 200 openings. Water from these springs support the overwhelming majority of the annual discharge of the upper San Marcos River, but the importance of the springs has become evident during recent droughts. During portions of the 1996 drought, San Marcos Springs and nearby Comal Springs combined accounted for 70% or more of flows in the Guadalupe River reaching Victoria and nearly 40% of flows that reached the San Antonio Bay.

Spring Lake is a horseshoe-shaped water body with two main regions: the Spring Arm and the Slough Arm. Most of the hydrological inputs to Spring Lake occur from spring openings in the Spring Arm. Sink Creek, the lake's only significant surface water tributary, discharges into the Slough Arm of the lake. Due to the relatively large spring water influence, Spring Lake and the upper river reaches are characterized by clear water, abundant and productive macrophytes and a relatively large number of endemic and native species. Spring Lake and the upper sections of the river exhibit nearly constant seasonal flows and water temperatures of ~22^{o}C; this relative environmental constancy has led to a high number of endemic species in the headwaters. However, the potential sensitivity of the headwaters to environmental perturbation, and the limited geographic range of many of the spring-adapted organisms, have led to the designation of a large number of federally- and state-listed taxa in the headwaters of the San Marcos River.

In addition to the high ecological value of the San Marcos River headwaters, the area also has substantial economic and cultural value for central Texas. Spring Lake and the upper river lie within the Texas State University campus and serve as a focal point for the campus and the City of San Marcos. Thousands of people visit the upper San Marcos every year for recreational activities such as swimming, tubing and kayaking, and glass bottom boat rides in the headwaters. While the exact number of recreational users of the San Marcos River and its headwaters is unknown, approximately 125,000 people per year take part in the various programs at the Aquarena Center on Spring Lake, and the City of San Marcos also estimates that two city parks in the upper section of the river receive more than 600 recreational visitors per day on a typical summer day (e.g., not 4th of July weekend). In addition, there have been major archeological finds of prehistoric human artifacts and animal remains in Spring Lake. Further downstream from Spring Lake, the San Marcos River supplies drinking water for a number of communities in the San Marcos – Guadalupe River drainage, including the cities of San Marcos (49,000 residents) and the City of Victoria (60,000 residents). Water quality and quantity is of principle concern to communities below the San Marcos River – Guadalupe River confluence because they are highly dependent upon the San Marcos River contribution to river flows, especially during relatively dry periods.

Texas State University and the City of San Marcos have taken significant measures to protect the water quality of Spring Lake. The University, a public institution currently owns the land the lake sits on and acts as a steward to protect the lake's current state. The city has put in place special ordinances to ban swimming and boating in the lake to protect the endangered species habitat in the lake. Additionally, the city partners with the university to monitor water quality in the lake (bacterial testing). The City has acquired and will preserve 251 acres of land from a developer who had planned to build a conference facility immediately upstream of Spring Lake. The stormwater from this property flows directly into Spring Lake and Sink Creek just upstream of the lake. The most current plans for local action include a Watershed Protection Plan that will begin in the next few years. At this time, the City of San Marcos and Texas State University are funding a half-time watershed planner position.

To date, there has been a limited attempt to obtain data on nutrient inputs to Spring Lake. Despite the system's high ecological, economic and cultural value, Spring Lake and the upper San Marcos River have recently experienced increased turbidity and major algal blooms following substantial rainfall events and the associated increases in surface and subsurface flows. While there is an obvious and sometimes persistent deterioration of water quality during and after periods of high surface and ground water inputs to the lake, the relative pollutant load contributions of these sources in the watershed is unknown. Thus, determination of the relative nutrient and sediment inputs to the lake from the various hydrological sources is critical for the management and preservation of the lake. In order to determine the influence of various sources of water on algae and turbidity in the lake, storm event-based data which are collected at a high-temporal resolution and are quality-assured are required. In particular, determination of inputs of phosphorus (P) are of greatest concern because productivity of the lake is extremely phosphorus limited due to the low levels of immediately bioavailable phosphorus (<5 µg orthophosphate - P/L) relative to the high levels of bioavailable nitrogen (~1600 µg NO_3^{2-} - N/L) (Groeger et al. 1997).

Among the potential sources of nutrient perturbation to the lake, one of the most likely sources is Sink Creek. Currently, portions of the Sink Creek watershed are experiencing rapid and major land use changes or have been proposed for future development. Sink Creek was historically an ephemeral stream that drained ranching and agricultural areas. However, rapid urban development along the IH-35 Austin-San Antonio corridor has led to a substantial increase in impervious cover and urban lands in the watershed. Most of the land within the Sink Creek watershed is privately owned; however, the City of San Marcos recently purchased approximately 250 acres within the watershed as part of a "greenbelt" and the uppermost headwaters of Sink Creek are located on Freeman Ranch, a property owned by Texas State University. Because Sink Creek discharges into the relatively shallow and productive Slough Arm of Spring Lake, incidents of high precipitation and high surface waters inflows may function as a major contributor to deterioration of lake water quality because of the land use changes within the Sink Creek watershed.

The relative contribution of nutrients from the spring openings during periods of high discharge also remains unclear. During periods of low precipitation and surface flows (e.g., summer and early fall) groundwater dominates hydrological and nutrient inputs to the lake. However, groundwater discharges to the lake also increase with precipitation, but the relative contribution of these groundwater flows to nutrient loading during high flow periods is unknown. In addition, there are numerous spring openings in Spring Lake that vary in flow rate and groundwater sources. Some openings discharge water from largely local sources, while other openings can discharge water from regional sources that are much older.

Another potential nutrient source to Spring Lake and the upper San Marcos River is the Texas State University Golf Course. The golf course lies immediately adjacent to the middle portion of the Slough Arm of Spring Lake, and maintenance practices from the course may lead to nutrient and sediment inputs to the lake.

Given the recent substantial water quality issues and the ecological, economic and cultural value of the Spring Lake system, understanding the relative non-point source (NPS) contributions of nutrients and suspended materials to Spring Lake via groundwater, the Sink Creek watershed, and the Texas State Golf Course is critical to preserve the biota and water quality of the lake.

1.1 General Watershed Information

Spring Lake is the headwaters of the San Marcos River where artesian spring water emerges into the lake from >200 spring openings; this spring system is the second most hydrologically productive in the state. Water from these springs originates from the Edwards Aquifer. The Edwards Aquifer is a large, complex limestone karst aquifer spanning a substantial portion of the central Texas region. A more detailed discussion of the flow paths of Edwards Aquifer waters to Spring Lake are provided in Section 1.2.3 (Geology, Karst Features, and Groundwater Resources).

Although Spring Lake receives much of its annual hydrological inputs from springs, Sink Creek discharges into the Slough Arm of the lake. Flows from Sink Creek originate more than 15 stream miles upstream to the northwest near the city of Wimberley. Much of the time, Sink Creek is dry and experiences little to no flow. However, during strong rain events or in relatively wet years (e.g., El Niño year type of precipitation), Sink Creek flows and discharges substantial loads of sediments and nutrients into Spring Lake and the upper river. As the name implies, water in the creek also “sinks” and presumably provides some recharge to local groundwater sources (Johnson and Schindel 2008). However, the extent of this groundwater recharge from the creek is not well known. There are also several flood retention and groundwater recharge dams upstream from Spring Lake on Sink Creek, with the largest of these structures located on Freeman Ranch.

Typically, the strong spring water influence on Spring Lake and the upper San Marcos, the upper river exhibits high water quality with low turbidity, low suspended sediment loads, and low phosphorus (P) concentrations. Spring Lake and the upper San Marcos River have recently experienced increased turbidity and declines in water quality rainfall events, presumably from inputs by Sink Creek. However, the relative pollutant load contributions of these ground- and surface water sources to Spring Lake and the upper San Marcos River currently remain unknown.

The purpose of this report is to present information on the initial characterization of the Spring Lake watershed, especially the Sink Creek watershed. Specifically, the goals of the report are associated with Objective 3, Tasks 3.1 – 3.5 of the Scope of Work (SOW) for a Nonpoint Source Protection Program CWA §319(h) grant project examining nutrient and sediment inputs to Spring Lake from the Sink Creek watershed. The overall goal of this portion of the study is to gather existing data and create an initial watershed inventory for Spring Lake and generate information on the physical and natural features of the watershed, including the watershed boundaries, the surface- and the ground water sources, the hydrology, topography, and geology. This report evaluates land use and landcover (LULC) characteristics of the Upper San Marcos River, and more specifically the Sink Creek watershed. It also provides information on groundwater source regions and general flow paths to the springs within Spring Lake.

1.1.1 Watershed Definition

A watershed is an area of land that contributes water, dissolved matter and particulate materials to a downstream receiving point such as an estuary or lake. Although all watersheds serve as important transporters and transformers of water and materials to downstream points, there is a great deal of variability among watersheds in size and function. Typically, hydrological inputs to watersheds are in the form of precipitation and these inputs move downhill across the landscape surface or through belowground pathways. The Upper San Marcos River Watershed, defined as the area of the Spring Lake watershed to the confluence with the Blanco River, is located around the City of San Marcos in Hays County, central Texas. The entire Upper San Marcos River Watershed has a surface area of approximately 200 km^2 and exists predominantly within Hays County. The Upper San Marcos River Watershed is composed of several smaller sub-basins, including the Sink Creek, Purgatory Creek, Willow Creek, and Sessom Creek drainages (Figure 1.1). The Sink Creek watershed, the focal sub-catchment in this report, is approximately 100 km^2 in area and is the uppermost sub-catchment of the Upper San Marcos Watershed, extending north and west from Spring Lake (Figure 1.1).

Watersheds are primarily defined by their landscape characteristics, but anthropogenic activities and naturally-occurring processes can influence hydrologic processes and matter transport. Naturally occurring events such as flooding and drought can lead to alteration of stream geomorphology but anthropogenic activities can also have substantial effects on watershed processes and function. The San Marcos River Watershed is facing rapid population growth and will likely face increased growth in the future. The City of San Marcos (and Spring Lake) lies within the IH-35 corridor in Texas, one of the fastest growing areas in the nation. If San Marcos and Hays County grow at predicted rates, the degree of anthropogenic demand for water and the stresses on the Spring Lake and Upper San Marcos River Watersheds and the adjacent aquifer recharge and contributing zones will continue to increase.

1.1.2 Surface Water

Precipitation that is deposited onto landscapes that exhibits overland or channelized flow that is temporarily stored in surface water bodies (lakes, reservoirs and rivers). These surface waters are subject to evaporative loss to the atmosphere or can subsequently infiltrate into unsaturated soils (i.e., the vadose zone). Surface waters that percolate to saturated soils or rock strata become groundwater (Figure 1.2). Surface water-groundwater interactions occur when there is exchange between surface water and groundwater, such as the spring water discharges into Spring Lake. For the Upper San Marcos River, understanding the role of surface water flows in nutrient and sediment loading from a surface water drainage (Sink Creek) to a typically spring water dominated water body (Spring Lake) is critical for the effective management and preservation of water quantity and quality.

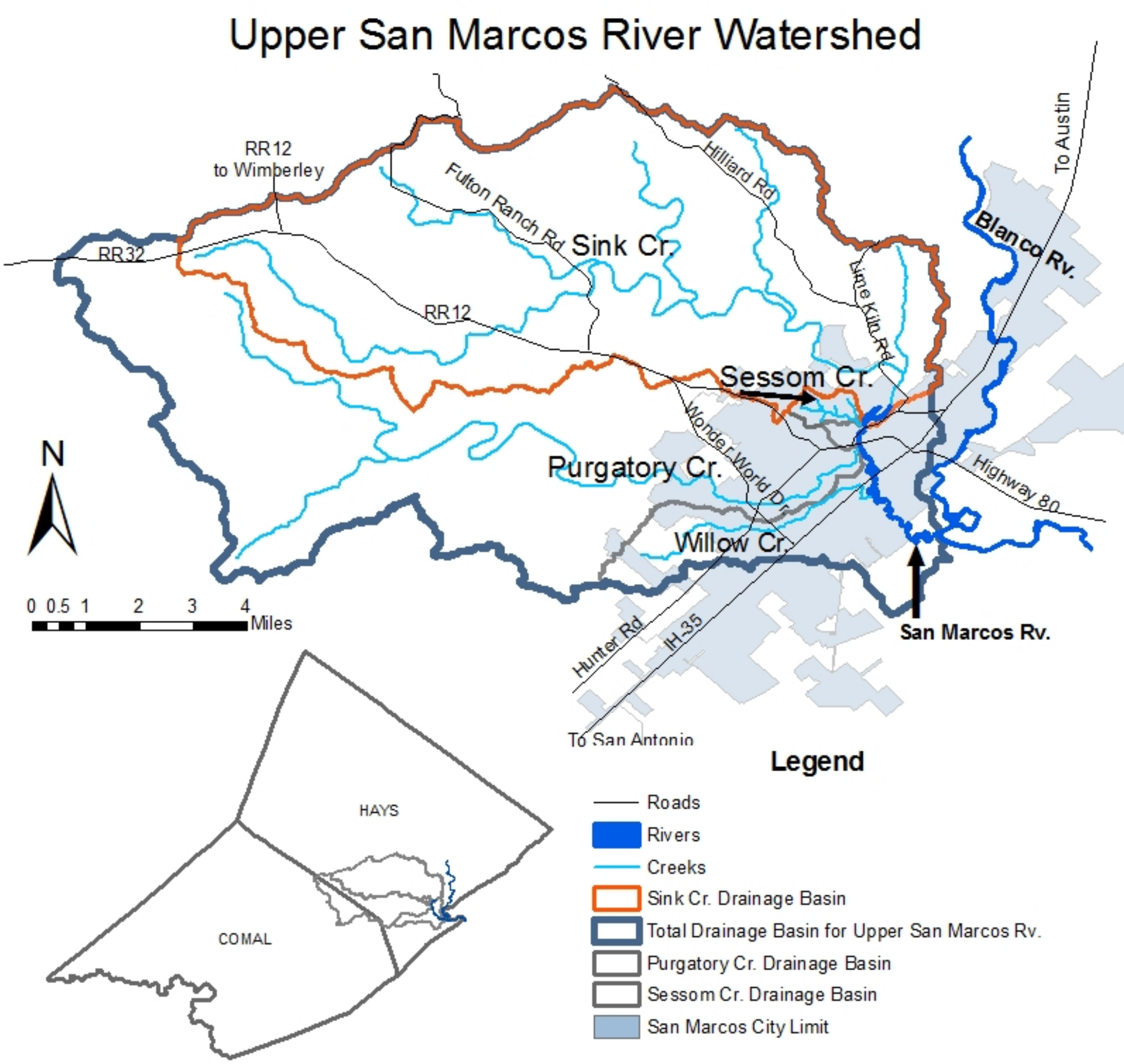


Figure 1.1. The Upper San Marcos River Watershed and its four main sub-basins - Sink Creek, Sessom Creek, Purgatory Creek, and Willow Creek. The upper most contributing sub-basin (Sink Creek) enters the San Marcos River near the headwater artesian springs located in Spring Lake. The City of San Marcos is shown in the south eastern corner of the map. Note that these watershed boundaries are only for surface drainage, and that they do not define the much larger groundwatershed contributing flow to San Marcos Springs.

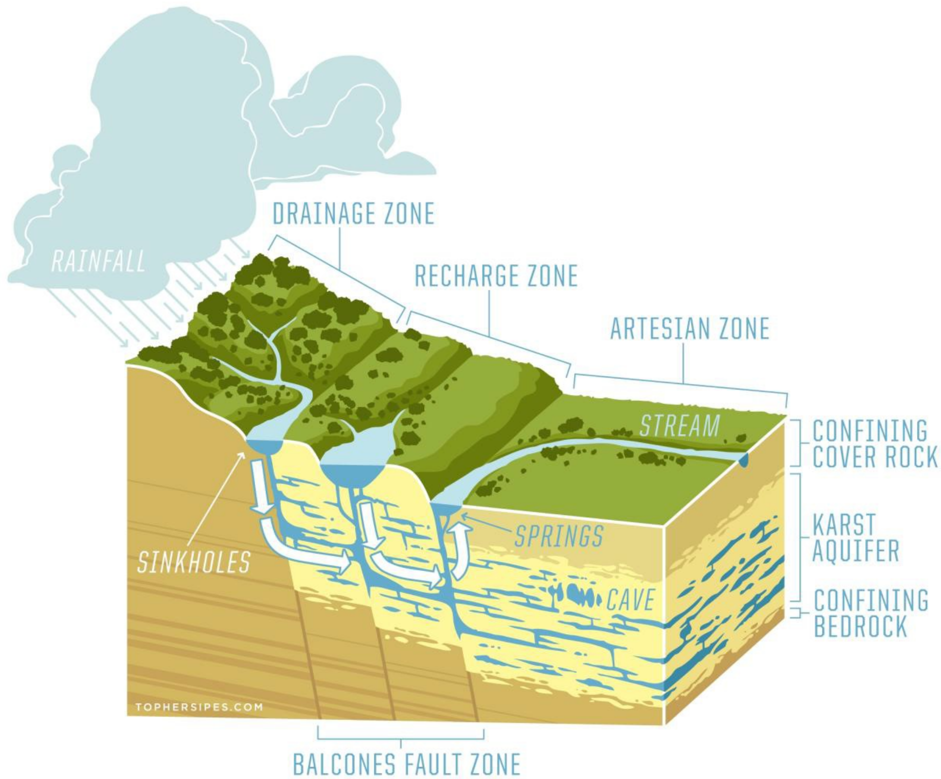


Figure 1.2. Diagram of the interaction between surface water and groundwater along the Balcones Fault Zone in central Texas. Figure courtesy of Topher Sipes.

1.1.3 Groundwater

Groundwater is water that moves through the subsurface geologic materials such as soil and/or rock strata. An aquifer is a geologic unit which contains water that has infiltrated into and through the vadose zone and reached the saturated zone where pore spaces are water-filled. In an unconfined groundwater system, groundwater is controlled by gravity and flows to 'downhill' positions through soil or rocks. However, confined aquifer systems, such as the Edwards Aquifer, are overlain by relatively impermeable strata that allow little vertical movement of the water. Movement of groundwater in a confined aquifer is controlled by differences in hydraulic head, which is a combination of water pressure and elevation. Water in a deep confined aquifer may flow under artesian pressure upward along more permeable flowpaths (such as faults and fractures) to reach discrete discharge points, such as springs. Much of the Edwards Aquifer groundwater is considered to be confined, leading to the discharge of water from several large artesian spring complexes in the landscape. The spring openings in Spring Lake in San Marcos, and Comal Springs in New Braunfels are the largest such sites associated with the Edwards Aquifer.

Within an aquifer the volume of groundwater that is stored, and its respective residence time within the aquifer, can vary considerably. Some aquifers exhibit relatively rapid flows and have groundwater residence times of a few weeks. In contrast, some aquifers have slow flows and groundwater residence times are in the 100s of years. The residence times and flow rates of aquifers are dependent upon a variety of factors including the rate of recharge from surface and up-gradient water sources, the characteristics of the discharge points from the aquifer, the geologic substrate type, substrate porosity, and the amount of conduit-facilitated transport within the aquifer. Understanding how long water is stored in the Edwards Aquifer, and what flow paths it follows between recharge (sinkholes and sinking streams, for example) and discharge at the springs, is difficult to do because of the complexity of this deep aquifer system, yet it is very important for a variety of reasons. Indeed, in many groundwater-influenced watersheds, such as Spring Lake and the upper San Marcos River, understanding the hydrology, geology, and hydrological processes in the aquifer is critical for preservation of water quality and flow required for human and ecological needs.

1.1.4 Point Source Pollution

Point source pollution to a waterbody is defined as a single, identifiable pollution source such as the effluent from a concentrated animal feeding area or the discharge from a wastewater treatment plant. Pollutant point sources are regulated under State of Texas law and the Federal Clean Water Act and are therefore subject to permit requirements. Permitted point sources have specific effluent limits, monitoring requirements, and enforcement mechanisms. The most notable point source for the Upper San Marcos River is the City of San Marcos Wastewater Treatment Plant. More specifically, there are no identified point sources in the Spring Lake (Sink Creek) watershed.

1.1.5 Nonpoint Source Pollution

Nonpoint source pollution to a waterbody is not associated with known individual sources. Rather, NPS pollution can be associated with diffuse inputs to a waterbody, such as atmospheric deposition. Pollutants associated with hydrologic inputs are the most common nonpoint sources; however, the pollutant loads to a waterbody from NPSs can exhibit substantial temporal and spatial variability. As such, NPS loads to a waterbody can be a function of human activity and/or the naturally-occurring background pollution. In the upper San Marcos River Watershed, NPS pollution creates concerns due to numerous anthropogenic activities in the watershed, including land use intensity and land use patterns, and alteration the hydrologic regime. More specifically, in the Sink Creek watershed, NPS inputs from changing land use patterns (increase in urban land use and impervious surface) and alteration of the hydrologic regime (timing and magnitude of hydrologic inputs) are likely to play an important role in determining nutrient and sediment NPS loads to Spring Lake.

Two landscape types that are frequently associated with NPS pollution are urban- and agriculture-dominated landscapes. Urban NPS pollution is linked with surface runoff containing increased suspended and dissolved solids, nutrients, metals, bacteria, biological and chemical oxygen demand, petroleum-derived hydrocarbons, herbicides, and pesticides. Nonpoint pollution sources in urban landscapes include vehicles, construction, fertilizer and pesticide application, erosion, animal wastes, and local atmospheric deposition. Nonpoint source pollutant loads from agricultural landscapes include suspended and dissolved solids, nutrients, herbicides, pesticides, and animal wastes. All of these NPS constituents can be transported in solution, suspended in surface runoff, or adsorbed on soil particles. In the Sink Creek watershed (and the Upper San Marcos River watershed), urban and agricultural NPS issues are likely to be the most relevant.

In the Spring Lake watershed, the intimate connectivity between surface- and ground-water likely makes any NPS loading to waters within the recharge zone in the Edwards Aquifer relevant to the NPS dynamics in Spring Lake. Urban and agricultural development, septic systems, irrigation systems, fertilizer, herbicide, and pesticide application, and leaking petroleum storage tanks within this larger defined area have potential to affect NPS loads to Spring Lake. Changes in the intensity and composition of LCLU practices in the larger recharge area will increase the potential for water quality impairment and may place further strain on groundwater inputs to the lake by the lowering of aquifer levels through groundwater extraction.

1.2 Geographic Setting

1.2.1 Description of Watersheds

1.2.2 Climate, Temperature, and Rainfall

The climate in the central Texas region can be categorized as semi-arid. During the period of 1946-2011, the mean annual total precipitation was 945 mm (37.2 inches) and the mean annual air temperature is 20.3^{o}C (68.5 ^{o}F) at the City of San Marcos [National Oceanic and Atmospheric Administration (NOAA) Station ID TX417983]. The annual gross lake surface evaporation in this region is estimated to be between 1524-1651 mm (60-65 inches) (TWDB 2007). Given this balance between precipitation and evaporation, this region would be considered to be prone to drought; however, this region is also known to experience a great deal of inter-annual and decadal variability in climatic conditions can affect the availability of water resources and subsequent ground water discharge from the Edwards Aquifer (Cox et al. 2009).

Seasonal variation in the climate of this area follows a pattern in which the peak rainfall periods occur in the late spring and early summer (April – June) and a secondary peak occurring in the fall (September – November (Figure 1.3). Approximately, 39% of annual precipitation falls during the April – June period and another 29% falls on the landscape during the September – November period.

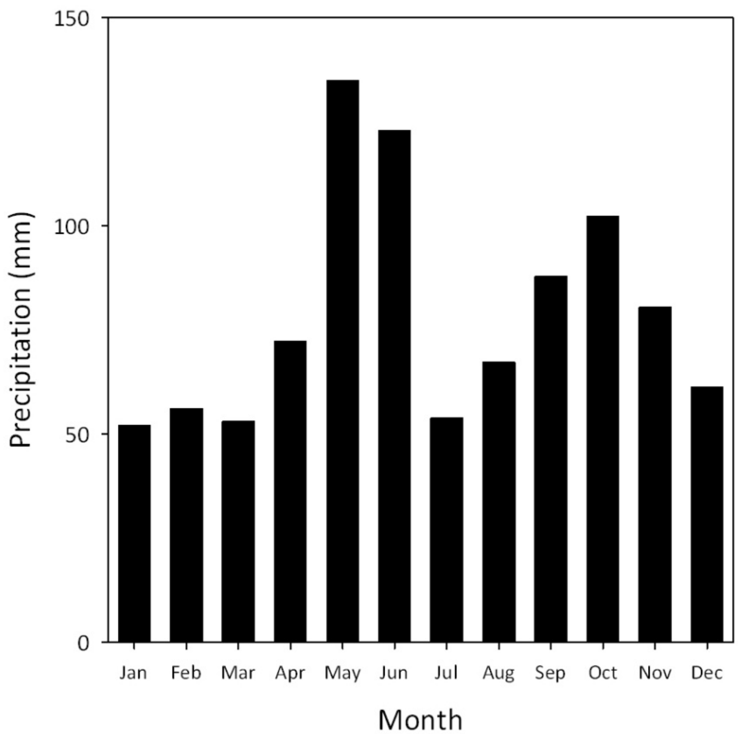


Figure 1.3. Mean monthly precipitation at the City of San Marcos (1946 – 2011).

Monthly variation in temperature follows a pattern of hot summers, with the greatest monthly minimum and maximum air temperatures in San Marcos, Texas occurring in July and August (Figure 1.4). In addition, the winter temperatures are relatively mild, with mean monthly minimum air temperatures never dropping below freezing and only reaching 3.7^{o}C in January. Provided the higher air temperatures and lower precipitation amounts (and thus lower aquifer recharge rates), it is likely that spring flows in the Spring Lake and the upper San Marcos River are likely to be at a minimum in the mid-summer and early fall. In addition, runoff from surface watersheds (which includes suspended materials and nutrients) are more likely to occur during the spring-early summer and fall periods.

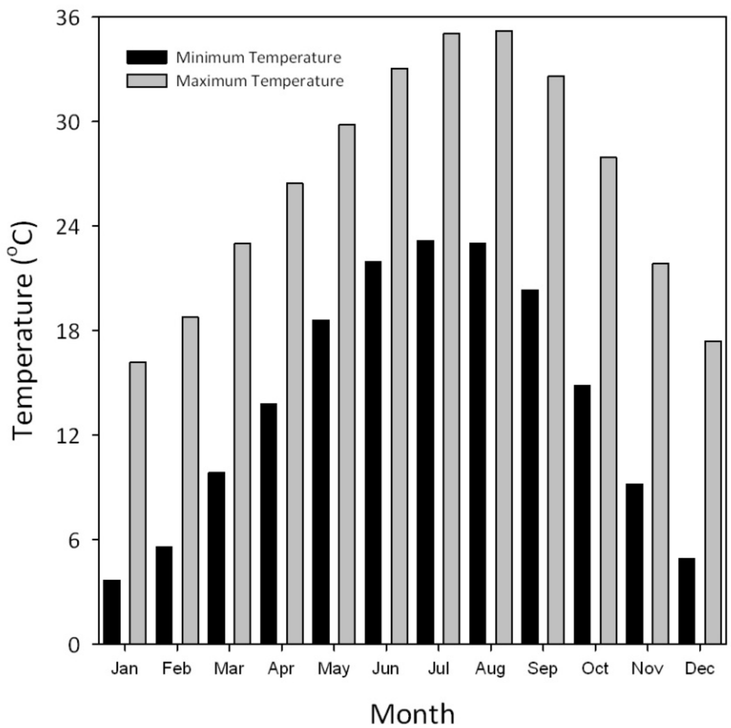


Figure 1.4. Mean monthly air temperatures at the City of San Marcos (1946 – 2011).

1.2.3 Geology, Karst Features, and Groundwater Resources

The Upper San Marcos River watershed is located upon and along the margin of the Edwards Plateau region of the Texas Hill Country. As such, the topography is hilly with karstic terrain. These karst features serve as recharge areas for the Edwards, Edwards-Trinity, and Trinity Aquifers. The Edwards Aquifer is composed of porous limestones 300-700 feet thick. The Edwards Aquifer is composed of several zones, including the contributing, recharge, transition, and artesian zones (Figure 1.5).

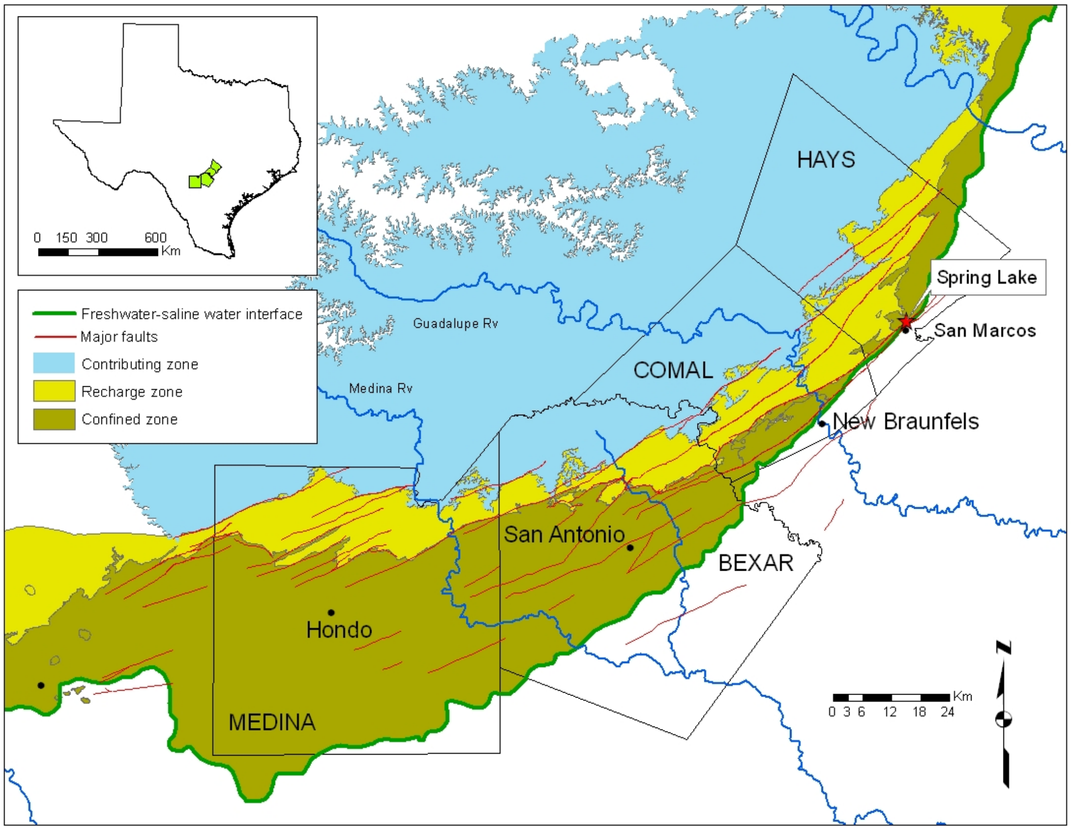


Figure 1.5. Geographic representation of the Edwards Aquifer in central Texas, showing the Contributing, Recharge, and Confined Zones. Major fault blocks are represented as well as the interface between the freshwater and saline water interfaces on the east-southeastern side of the aquifer.

The western portion of the aquifer (the San Antonio segment) forms an approximate 150 mile arc from Brackettville (Kinney County) to Kyle (Hays County). North of the San Antonio segment is a groundwater divide that separates the San Antonio segment from other segments, such as the Barton Springs segment. During drought periods or during low aquifer levels, some groundwater can be exchanged between segments (Hunt et al. 2006).

Spring Lake and San Marcos Springs is located along the Transition/Artesian zone of the aquifer. The springs within the lake are artesian in nature and are a result of confined flow within the aquifer. There are hundreds of spring “openings” in the lake, but the springs generally form “complexes” or groupings in different portions of the lake. These include Weismuller Spring, Diversion Spring, Deep Hole, Catfish Hotel, Cabomba, Salt and Pepper, Hotel, and Cream of Wheat. Due to the complex nature of the flows within the aquifer, the precise origin and age of waters emerging from the various springs is not well understood; however, there is information on the general flow paths of water emerging from the springs.

The recharge and transition zones lie on and follow the large Balcones Fault zone, which is a complex series of roughly parallel faults forming a zone between the deep artesian zone and the shallower recharge zone. Within the Balcones Fault Zone, and near San Marcos, are several major fault blocks which run in arcs that are parallel to the aquifer's position in central Texas (Figure 1.6). San Marcos Springs and the western side of Sink Creek sit at the upper end of the Hueco Springs Fault, Comal Springs Fault, and the Artesian Fault Blocks (Figure 1.7). Water within the aquifer generally follows an east-northeast direction (Thompson and Hayes 1979), with much of the water emanating from San Marcos Springs coming from flows along the Hueco Springs and Comal Springs Fault Blocks (Johnson and Schindel 2008). Water within the aquifer moves along these blocks toward Spring Lake and emerges at several other important spring systems along the way, including Comal Springs which has a much higher mean annual discharge than the San Marcos River (Comal Springs mean annual discharge = 302 cfs; USGS 08169000). However, the paths and magnitude of flows within the blocks are dependent upon the regional hydrologic conditions. For example, during times of high water, the Comal Springs Fault Block discharges at Comal Springs and Spring Lake, but these flows can largely bypass Comal Springs and primarily discharge at Spring Lake when low water conditions exist (Johnson and Schindel 2008).

The groundwater divide near the City of Kyle was once thought to impede water exchange between the northern and southern portions of the aquifer, but dye-trace studies have determined that the hydrologic conditions (drought versus wet years) greatly influence this exchange. During wet years, groundwater flow away from Onion Creek in both directions to emerge at Barton and San Marcos Springs. During drought years, this groundwater divide flattens out, moves closer to San Marcos Springs (Hunt et al. 2006), and may even disappear entirely during severe drought (HDR, 2010). Thus, San Marcos Springs receives groundwater from both local- and regionally-derived sources within the aquifer, with the magnitude of the different sources depending upon the regional hydrologic conditions.

Although water emerging from springs within Spring Lake comes from a general source, there appears to be some variation in water chemistry among some of the springs. The springs located in the southern portion of the lake (including Deep Hole and Catfish Hotel) have different temperatures, dissolved oxygen concentrations, and hardness than springs at the northern end of the lake (including Diversion, Cabomba, and Hotel) (Quick and Ogden 1985). These differences in physiochemical parameters suggest that the southern springs derive their flows from deeper, older water within the aquifer. A significant portion of this project examines the water quality and physicochemical differences among spring openings in the lake; these data are presented in the next section of this report.

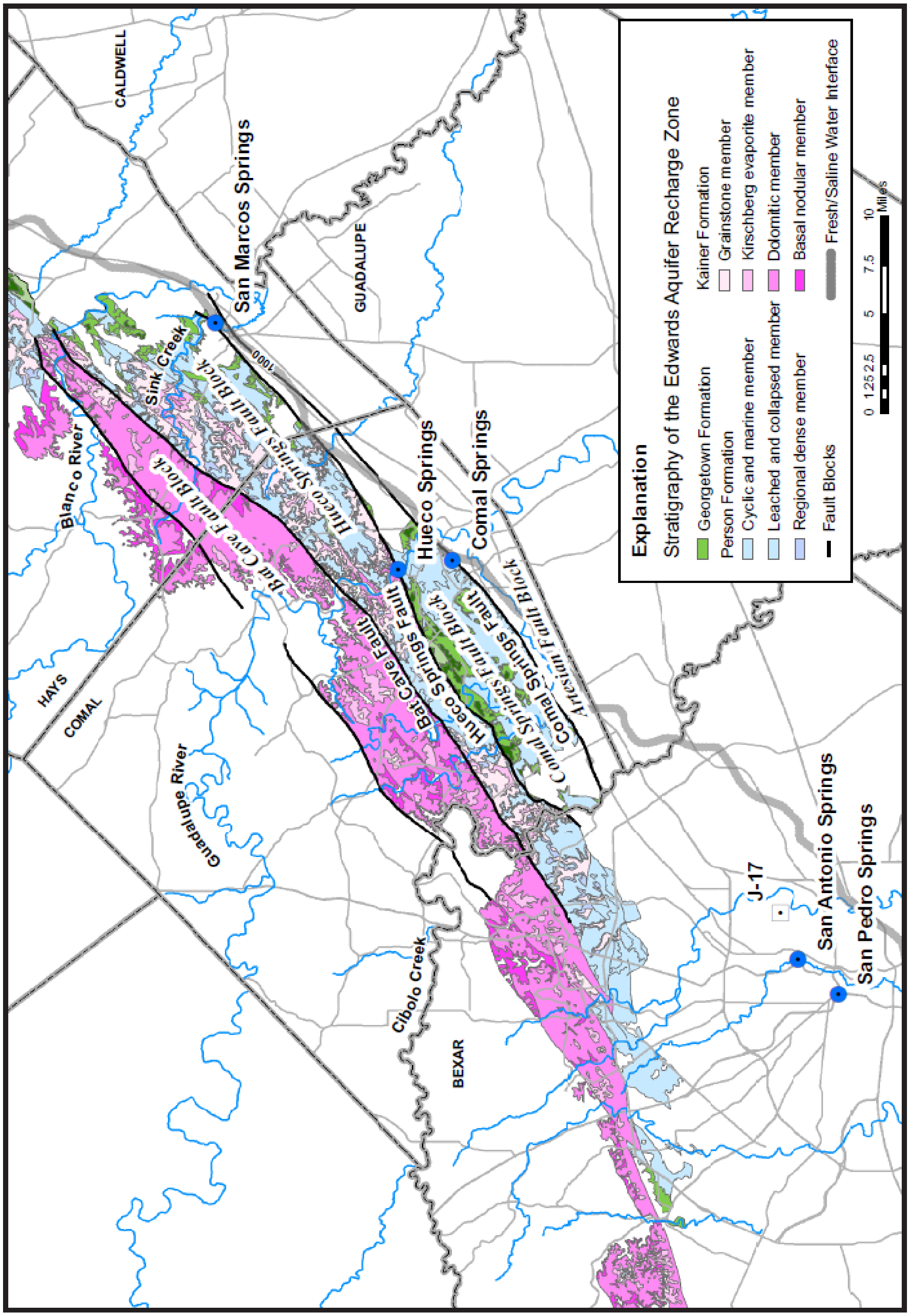


Figure 1.6. Stratigraphy of the Edwards Aquifer Recharge Zone, indicating the major fault blocks along the aquifer. Figure courtesy of Edwards Aquifer Authority.

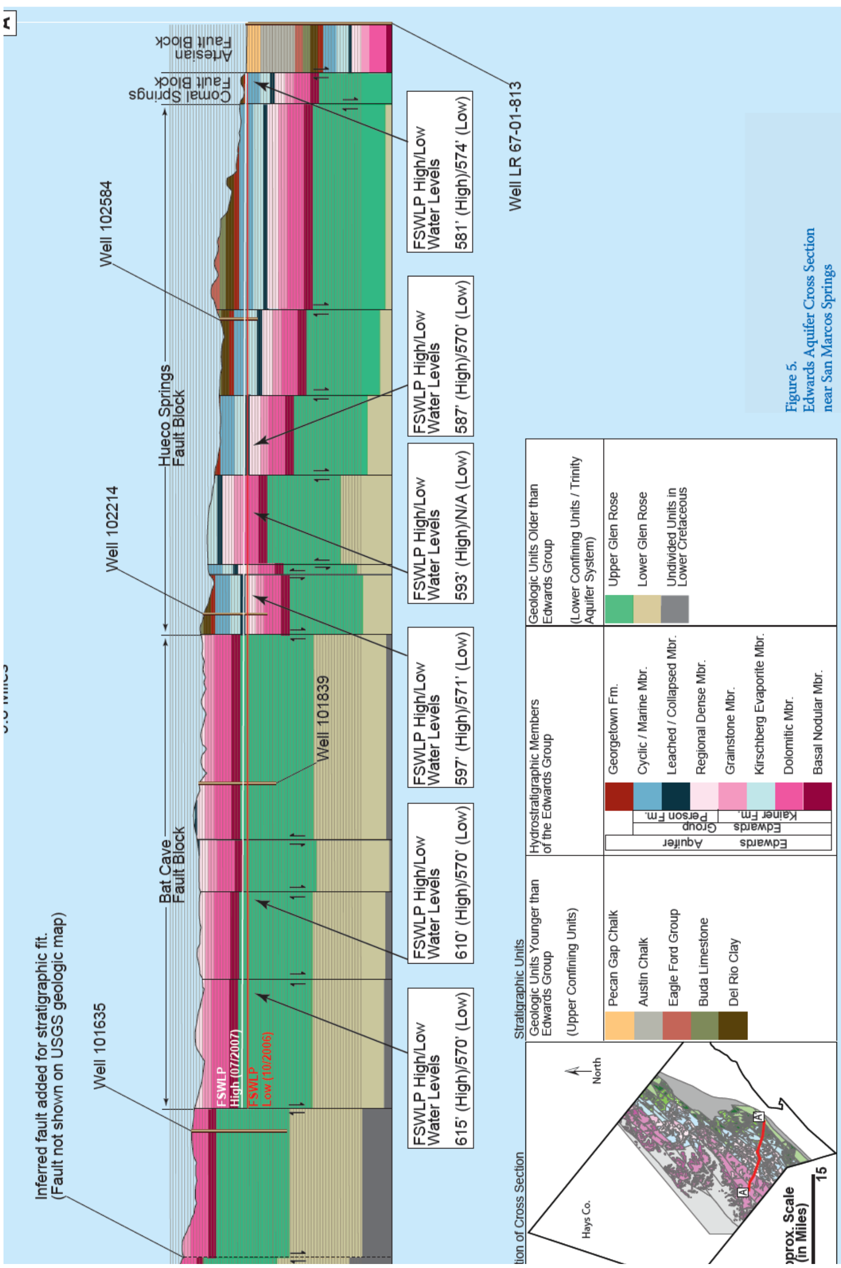


Figure 1.7. Geologic cross-section of the Edwards Aquifer near Spring Lake and San Marcos Springs. Figure courtesy of Edwards Aquifer Authority.

1.2.4 Soils

Soils in this portion of the central Texas region are composed of approximately 50 different soil units which range in their properties and coverage (Batte 1984). In Comal and Hays counties, within which the Upper San Marcos River Watershed is contained, four soils units make up 59% of the total area (Table 1.1). These soil units are the Bracket-Rock outcrop-Comfort complex (BtD), the Bracket-Rock outcrop-Real complex (BtG), the Comfort-Rock outcrop complex (CrD), and the Rumple-Comfort association (RUD). The BtD, CrD, and RUD soil units are characterized by shallow, well-drained, and stony/gravelly clayey loams that are present at 1-8% grades. The BtG unit is also well-drained gravelly clay loam, but is present on ridges of 8-30% slope. Thus, a majority of the soil units within Comal and Hays counties are classified as a part of the Comfort and Bracket series and are characterized as having shallow depths, being well-drained, having low water holding capacity, containing shallow rooting depths, and being located in more upland areas or along steep hillsides. Given these characteristics, erosion of these soils from more upland areas is a major concern (Batte 1984).

Within the Sink Creek watershed, the overwhelmingly dominant soil series are the Rumple-Comfort-Eckrant types (Figure 2.6). These series are characterized as being typical of the undulating and steep terrains of the Edwards Plateau uplands, exhibiting shallow depths, and overlying limestone parent materials. Again, the properties and characteristics of these units suggest that soil erosion is a substantial concern. Thus, development activities within the Sink Creek watershed which lead to increased erosion and transport of suspended solids and associated nutrients could have significant effects on the water quality of Spring Lake and the upper San Marcos River.

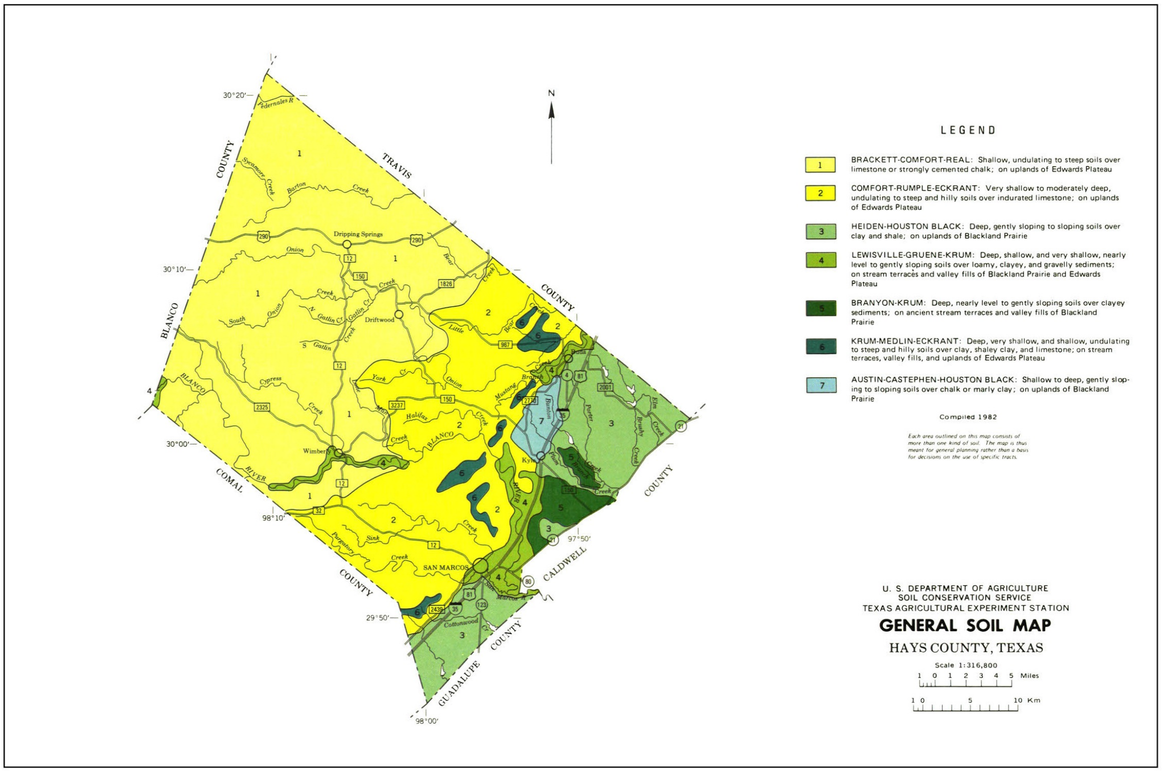


Figure 1.8. Map of the major soil unit distributions within Comal and Hays counties, including the Sink Creek watershed. Figure courtesy of the USDA and the Soil Conservation Service (Batte 1984).

Table 1.1. Soil unit distributions in Hays and Comal Counties, Texas. Data from the Natural Resources Conservation Service (http://websoilsurvey.nrcs.usda.gov).

Soil Unit	Unit Name	Acres in Area	Percent of Area
AgC3	Altoga silty clay, 2 to 5 percent slopes, eroded	2,553.80	0.30%
AgD3	Altoga silty clay, 5 to 8 percent slopes, eroded	1,441.30	0.20%
AnA	Anhalt clay, 0 to 1 percent slopes	1,094.50	0.10%
AnB	Anhalt clay, 1 to 3 percent slopes	4,369.90	0.50%
AuB	Austin-Castephen complex, 1 to 3 percent slopes	2,925.40	0.40%
AuC3	Austin-Castephen complex, 2 to 5 percent slopes, eroded	702.6	0.10%
BoB	Boerne fine sandy loam, 1 to 3 percent slopes, rarely flooded	2,947.10	0.40%
BrB 16	Bolar clay loam, 1 to 3 percent slopes	230.6	2.00%
BtD	Brackett-Rock outcrop-Comfort complex, 1 to 8 percent slopes	110,483.30	13.80%
BtG	Brackett-Rock outcrop-Real complex, 8 to 30 percent slopes	104,798.80	13.10%
ByA	Branyon clay, 0 to 1 percent slopes	13,114.50	1.60%
ByB	Branyon clay, 1 to 3 percent slopes	4,902.70	0.60%
CaC3	Castephen clay loam, 3 to 5 percent slopes, eroded	855.3	0.10%
CrD	Comfort-Rock outcrop complex, 1 to 8 percent slopes	152,712.00	19.00%
DeB	Denton silty clay, 1 to 3 percent slopes	10,581.70	1.30%
DeC3	Denton silty clay, 1 to 5 percent slopes, eroded	868.5	0.10%
DoC	Doss silty clay, 1 to 5 percent slopes	15,820.00	2.00%
ErG	Eckrant-Rock outcrop complex, 8 to 30 percent slopes	32,636.20	4.10%
FeF4	Ferris clay, 5 to 20 percent slopes, severely eroded	2,521.00	0.30%
GrC	Gruene clay, 1 to 5 percent slopes	6,109.40	0.80%
HeB	Heiden clay, 1 to 3 percent slopes	7,472.60	0.90%
HeC3	Heiden clay, 3 to 5 percent slopes, eroded	15,782.70	2.00%
HeD3	Heiden clay, 5 to 8 percent slopes, eroded	4,613.70	0.60%
HgD	Heiden gravelly clay, 3 to 8 percent slopes	2,628.40	0.30%
HoB	Houston Black clay, 1 to 3 percent slopes	20,546.50	2.60%
HvB	Houston Black gravelly clay, 1 to 3 percent slopes	3,877.80	0.50%
HvD	Houston Black gravelly clay, 3 to 8 percent slopes	4,546.30	0.60%
KrA	Krum clay, 0 to 1 percent slopes	4,211.10	0.50%
KrB	Krum clay, 1 to 3 percent slopes	12,838.30	1.60%
KrC	Krum clay, 3 to 5 percent slopes	1,452.60	0.20%
LeA	Lewisville silty clay, 0 to 1 percent slopes	4,136.80	0.50%
LeB	Lewisville silty clay, 1 to 3 percent slopes	9,053.40	1.10%
MEC	Medlin-Eckrant association, 1 to 8 percent slopes	3,764.40	0.50%
MED	Medlin-Eckrant association, 8 to 30 percent slopes	2,563.50	0.30%
Oa	Oakalla silty clay loam, 0 to 1 percent slopes, rarely flooded	2,087.00	0.30%
Ok	Oakalla soils, 0 to 2 percent slopes, frequently flooded	1,867.50	0.20%
Or	Orif soils, 0 to 1 percent slopes, frequently flooded	3,412.40	0.40%
PdB	Pedernales fine sandy loam, 1 to 5 percent slopes	299.1	<0.01%
PuC	Purves clay, 1 to 5 percent slopes	8,008.60	1.00%
RaD	Real gravelly loam, 1 to 8 percent slopes	8,546.70	1.10%
RcD	Real-Comfort-Doss complex, 1 to 8 percent slopes	44,267.00	5.50%
RUD	Rumple-Comfort association, 1 to 8 percent slopes	106,472.40	13.30%
SeB	Seawillow clay loam, 1 to 3 percent slopes	1,584.50	0.20%
SeD	Seawillow clay loam, 3 to 8 percent slopes	1,445.50	0.20%
SuA	Sunev silty clay loam, 0 to 1 percent slopes	2,502.30	0.30%
SuB	Sunev clay loam, 1 to 3 percent slopes	9,485.80	1.20%
TaB	Tarpley clay, 1 to 3 percent slopes	5,839.30	0.70%
Tn	Tinn clay, 0 to 1 percent slopes, frequently flooded	6,811.00	0.80%
	Totals for Area	**802,690.90**	**100.00%**

1.2.5 Vegetation

Vegetation within the Sink Creek watershed is characteristic of much of the Texas Hill country. Thin topsoils (10-30 cm) and semi-arid conditions lead to relatively sparse vegetation cover. Texas oak (*Quercus buckleyi*), ashe juniper (*Juniperus ashei*), and lacey oak (*Quercus laceyi*) are the dominant trees in more upland positions in the landscape. Along the San Marcos River and Sink Creek margins and in the floodplain are stands of black willow (*Salix nigra*), bald cypress (*Taxodium distichum)*, sycamore (*Platanus occidentalis*), and pecan (*Carya illinoinensis*). Grass communities within the watershed are composed of multiple species, including little bluestem (*Schizachyrium scoparium*), hairy grama (*Bouteloua hirsuta*), side oats grama (*Bouteloua curtipendula*), Texas wintergrass (*Stipa leucotricha*), white tridens (*Tridens muticus*), Texas cupgrass (*Eriochloa sericea*), tall dropseed (*Sporobolus asper*), and seep muhly (*Muhlenbergia reverchonii*) (Riskind and Diamond, 1986).

1.2.6 Aquatic Life

Monitoring and habitat assessments have been conducted for many years by Texas Parks and Wildlife (TPWD), the US Fish and Wildlife Service (USFWS), and others because of the high density of endangered and threatened species (see ENDANGERED SPECIES below). The macroinvertebrate assemblages in Spring Lake and the Upper San Marcos River are diverse, representing more than 17 orders and 68 families (P.H. Diaz, USFWS, *pers comm*). Despite the abundant and diverse macroinvertebrate communities in the river and lake, there is significant concern about non-native and invasive species of invertebrates, including the giant ramshorn snail (*Marisa comuarietis*), and the red-rimmed melania snail (*Melanoides tuburculata*). The likely source of these species is through introductions from the aquarium trade.

The fish assemblages of the lake and river have been extensively studied. Perkin and Bonner (2010) conducted a long-term assessment (1938-2006) of fish assemblages of the San Marcos River and found that from, a total of 66 fish species were reported in the river, dominated by Poeciliidae (live bearers), Cyprinidae (minnows), Centrarchidae (basses) and Percidae (darters). However, the authors determined that there were temporal changes to the fish assemblage over this interval, with a trend of replacement of endemic species with more wide-spread generalist species. They concluded that these changes were associated with changes in the hydrological regime of the river (a decrease in the number of large and small floods events) during the same period due to the construction of low-head impoundments (including Spring Lake Dam). In addition to the loss of endemic fishes, there are a number of non-native invasives that currently reside in the river including armored catfishes (*Hypostomus plecostomus*) and tilapia (*Oreochromis mossambicus*) (Pound et al 2011). Similar to the non-native invertebrates, the origin of these fishes is likely from the aquaculture and aquarium trade.

The high water clarity in the lake and Upper River also lead to abundant and diverse macrophyte communities. Lemke (1989) performed a survey of macrophytes and found a diverse aquatic plant community composed of 31 species, with 23 of the species native to the region. Of particular note, is the presence of Texas wild rice (*Zizania texana*), a native macrophyte species that only occurs in the upper San Marcos River and is listed as endangered (see ENDANGERED SPECIES below). Again, non-native and potentially invasive macrophytes are also a concern, particularly hydrilla (*Hydrilla verticillata*), elephant ear taro (*Colocasia esculenta*), and Beckett's water trumpet (*Cryptocoryne beckettii*).

1.2.7 Endangered Species

The Texas Hill country and especially the Balcones Escarpment area are habitat to many federally endangered species. Terrestrial species such as the Golden-cheeked warbler (*Dendroica chrysoparia*) and the Black-capped-vireo (*Vireo atricapilla*) occur in habitats similar to those found in the Sink Creek watershed. However, almost all of the concerns with Endangered and Threatened species come from the aquatic organisms associated with the groundwater, lake, and river. The San Marcos salamander (*Eurycea nana*), Texas wild rice (*Zizania texana*), the fountain darter (*Etheostoma fonticola*), and the Comal Springs riffle beetle (*Heterelmis comalensis*) all reside in the lake and upper river and are listed by US Fish and Wildlife Service as endangered or threatened. The fountain darter and Texas wild rice have both been used as focus organisms in restoration and mitigation actions in the Edwards Aquifer Recovery Implementation Plan (EARIP); efforts to manage river flows and optimize the availability of high-quality habitat have been centered on the requirements of these two endangered species (http://edwardsrip.org/). In particular, preservation of water quality may be critical for recovery of the fountain darter and Texas wild rice because growth and reproduction of both species is affected by temperature (Bonner et al. 1998; Trolley-Jordan and Power 2007). In addition, the Guadalupe roundnose minnow (*Dionda nigrotaeniata*) and the bigclaw river shrimp (*Macrobrachium carcinus*) also occur in the headwaters, and have been identified by the Texas Comprehensive Wildlife Conservation Strategy as species of "high priority" for conservation.

In addition to the numerous surface water-associated listed taxa, there are several listed taxa that reside within the aquifer. The Texas blind salamander (*Eurycea rathburni*), Peck's cave amphipod (*Stygobromus pecki*) and the Comal Springs dryopid beetle (*Stygoparnus comalensis*) all reside within this region of the aquifer and are listed. Two more species of phreatic fauna, the Texas trogolobitic water slater (*Lirceolus smithii*) and the Texas diving beetle (*Haedioporus texasnus*) have been petitioned for listing.

1.2.8 Water Quality

The historically high level of water quality, the unique spring-fed nature of the river, and the presence of multiple federally- and state-listed taxa has led to a great deal of water quality data collection in the river. Water quality sampling in the upper San Marcos River has been performed by a number of government entities and academic researchers. The USGS, the EAA, and TCEQ, and the Guadalupe-Blanco River Authority (GBRA) have collected water quality data in the upper San Marcos River. These various data sources are provided in Appendix 1.

Spring Lake and the Upper San Marcos River currently meet the criteria for most water quality parameters, but the Upper San Marcos River (Segment 1814) was recently listed in the Draft 2010 Texas Integrated Report for Clean Water Act Sections 305(b) and 303(d) lists as Category 5, subcategory 5c for TDS. This listing as a 5c waterbody means that the mean value of the collected TDS data (406.1 mg/L) exceeds the General Use criteria of 400 mg/L; the data used in the report and assessment span from 2001 – 2008. Total dissolved solids are defined as the total content of inorganic and organic materials dissolved in water. Generally, TDS is not considered a direct or primary pollutant, but high levels of TDS can be an indicator of contamination by dissolved organic and/or inorganic materials. The 5c designation of the upper San Marcos will lead to the collection of additional data before a TMDL is scheduled. The 5c listing spans the entire upper San Marcos segment (from section 1814_01 to 1814_04), which encompasses the river 1.0 km upstream from the confluence with the Blanco River to 0.7 km upstream of Loop 82 in the City of San Marcos.

In addition, to the concerns raised over elevated TDS concentrations in the upper river, it has been qualitatively noted that there is a great deal of spatial and temporal variability in suspended solids and water clarity associated climate-driven events. Declines of water quality in Spring Lake associated with high flows (rainfall events) are likely due to NPS pollution and/or changes in land use in the watershed. A significant portion of this project is associated with periodic grab sampling from a variety of locations within Spring Lake as well as the estimation of storm flow loads in Sink Creek to the lake. These data are still being collected and analyzed and will be presented in a later report. In addition, the USGS has performed a very limited amount of event-based water quality sampling from some of the ephemeral creeks in the upper San Marcos, including Sink Creek and Purgatory Creek (Appendix 1).

Prior to the project, there have been limited efforts to obtain high temporal resolution and storm-based data from Spring Lake and the upper San Marcos River. Much of the sampling for water quality data has occurred at regular intervals (e.g., quarterly sampling) with little integration of storm events inputs.

1.3 History and Development

1.3.1 History and Settlement

The area in and around the springs in San Marcos have been occupied by humans for at least 11,000 years, making it the oldest continually inhabited site in North America (Shiner, 1983; Bousman and Nikels 2003). Native peoples were the first human inhabitants and lived in and around the springs for most of this period. Due to the continuous habitation for this extended period of time, Spring Lake and the immediate area is an important archeological site. In addition, areas within the Sink Creek and Purgatory watersheds have also provided invaluable archaeological materials and information.

The Spanish first visited the springs in 1691 and subsequently established as an outpost (Hatcher 1932). In 1840, the Republic of Texas established Fort San Marcos at the site, which was situated near the springs, and in 1845, General Edward Burleson purchased the area around the springs and constructed a dam in 1849 (Bousman and Nikels 2003). This dam created Spring Lake; vestiges of the materials used to build the dam are still apparent today.

In 1926, A.B. Rogers purchased the tract of land associated with Spring Lake and built a hotel on the site. A.B Rogers' son purchased the area in 1949 and renamed it 'Aquarena', subsequently creating one of the most popular attractions and resorts in Texas. The resort operated for almost 50 years and Southwest Texas State purchased the property in 1991 and continued its operation until 1996. At that time, the University converted the facility and lake from a tourist attraction to location that could be used for educational purposes. Currently, most of the old Aquarena infrastructure is slated to be torn down, leaving only the old hotel which houses the Texas River Systems Institute and some offices for TPWD.

1.3.2 Populations and Growth Predictions

Based upon US Census data, the population of San Marcos increased from 34,733 in 2000 to 44,894 in 2010, a 29.3% increase in 10 years (http://quickfacts.census.gov/qfd/index.html). During this same time interval, the population of Hays County increased from 97,589 to 157,107, a remarkable 61%, indicating an even faster growth rate in areas immediately outside of San Marcos. These growth rates are greater than the entire state of Texas over this time interval (20.6%) and it far greater than the United States growth rates (9.7%). Projected growth rates for the state of Texas indicate that the state population will increase 35% over the next 20 years (from 2010 – 2030). In particular, it is projected that the population of Hays County will increase ~200% in the next 50 years, to a population of 493,320 (TWDB 2010). Indeed, the population of the entire Edwards Aquifer region will increase by 63% to nearly 1.3 million people. Given these population growth projections, the land use demands within the Spring Lake and upper San Marcos River will be much higher and the demand for Edwards Aquifer water resources will be exceptionally high.

One area with the potential of significant impact in the Spring Lake watershed is the Windmere Ranch tract, which is located adjacent to the Sink Creek stream bed at the Lime Kiln Road crossing. This area of ~230 acres is planned for conversion to a housing development. Overall, development in the Upper San Marcos watershed is expected to increase, converting from traditionally low-impact agriculture practices to more intense urban developments.

1.4 Data Collection and Analysis

The following sections describe data collections used to define and characterize land use and land cover in the Upper San Marcos and Sink Creek watersheds. These sections first provide information on the overall San Marcos River watershed and then specifically address issues related to the Sink Creek watershed. These characterization efforts include spatial delineation of the watersheds and assessment of the patterns in LULC over time. The relevant methods used for each analysis are provided at the beginning of each section.

1.4.1 Watershed and Subwatershed Delineation

The Upper San Marcos River watershed and each of the sub-basins, including Sink Creek, were delineated from digital elevation models (DEM) using standard analysis tools in ArcGIS 9.2, and included 'burning' accurate stream channels through low-gradient areas where urban infrastructure interfered with the raw DEM data, obtained from the USGS Seamless Data Warehouse (http://seamless.usgs.gov/).

1.5 Land Use and Land Cover

1.5.1 Land Cover Analysis Methods

A Land Use/Land Cover Change analysis was performed to quantify the spatial distribution trends in use, within the contributing watershed for the Upper San Marcos River and then in Sink Creek. Changes in land use, in particular, can have direct impacts on a larger watershed system, and identifying these patterns and trends in changes of land use can be useful for understanding and identifying causes for various effects that can be observed in the environment (the San Marcos River, for example).

The process of detecting changes in LULC over time involved using Remote Sensed land cover data for multiple years (1992, 2001 and 2006) and comparing classified pixel values. For this analysis, the following National Land Cover Datasets (NLCD) data was downloaded from the USGS seamless server at http://seamless.usgs.gov/nlcd.php. NLCD data for 1992, 2001, and 2006 were projected and clipped to the Upper San Marcos watershed and the Sink Creek watershed, and analyzed for the entire watershed.

Before statistics on LULC and change in LULC over the relevant time periods can be generated, data must be standardized using a re-classification scheme that allows comparison of similar land covers at each time interval. In this study, classification scheme for the data from the 1992 NLCD differed slightly from the 2001 and 2006 NLCD. Definitions for the original class coverage are provided for each of the datasets in the Appendices (Appendix 2: 1992 NLCD original class definitions; Appendix 3: 2001 and 2006 original class definitions). Reclassification consisted of converting the >30 LULC categories into one of six categories. The reclassified categories are: (1) Water, (2) Developed, (3) Barren, (4) Forest, (5) Grass/Shrub Land, and (6) Agriculture. Specifics on the reclassification schemes for each time interval are presented in Tables 1.2 and 1.3.

1.5.2 Results

Results of the LULC analyses in the Upper San Marcos River watershed for each of the three years are shown in Figure 1.9. In the Upper San Marcos River watershed, there have been substantial changes in land use over from 1992 - 2006. Forest is the dominant LULC cover type on all three dates; however, the percent cover in forested land in the San Marcos River watershed declined from 57.7% in 1992 to 49.12% in 2006. These changes in forest cover were concomitant with decreases in the percent agricultural land cover and increases in developed areas and grass/shrub land cover (Figures 1.10 and 1.11). Overall, in the Upper San Marcos River watershed, developed area accounted for 6.6% in 1992 and increased to 11.51% by 2006, indicating substantial urbanization of the Upper San Marcos River watershed over this 14-year period.

Table 1.2 1992 NLCD reclassification scheme.

Original Class	New Class	Old Value	New Value
Open Water	Water	11	1
Developed, low intensity	Developed	21	2
Developed, high intensity	Developed	22	2
Commercial/ Industrial/ Transp.	Developed	23	2
Bare Rock/Sand/Clay	Barren	31	3
Quarries/Gravel Pits	Barren	32	3
Deciduous Forest	Forest	41	4
Evergreen Forest	Forest	42	4
Shrub land	Grass/ Shrub Land	51	5
Grassland Herbaceous	Grass/ Shrub Land	71	5
Pasture/Hay	Agriculture	81	6
Row Crops	Agriculture	82	6
Small grains	Agriculture	83	6
Urban/Recreational Grasses	Agriculture	85	6
Emergent Herbaceous wetlands	Forest	92	4

Table 1.3. 2001 and 2006 NLCD reclassification scheme.

Original Class	New Class	Old Value	New Value
Open Water	Water	11	1
Developed, open space	Developed	21	2
Developed, low intensity	Developed	22	2
Developed, medium intensity	Developed	23	2
Developed, high intensity	Developed	24	2
Barren Land	Barren	31	3
Deciduous Forest	Forest	41	4
Evergreen Forest	Forest	42	4
Mixed Forest	Forest	43	4
Shrub/ Scrub	Grass/ Shrub land	52	5
Grassland/Herbaceous	Grass/ Shrub land	71	5
Pasture/Hay	Agriculture	81	6
Cultivated Crops	Agriculture	82	6
Woody Wetlands	Forest	90	4

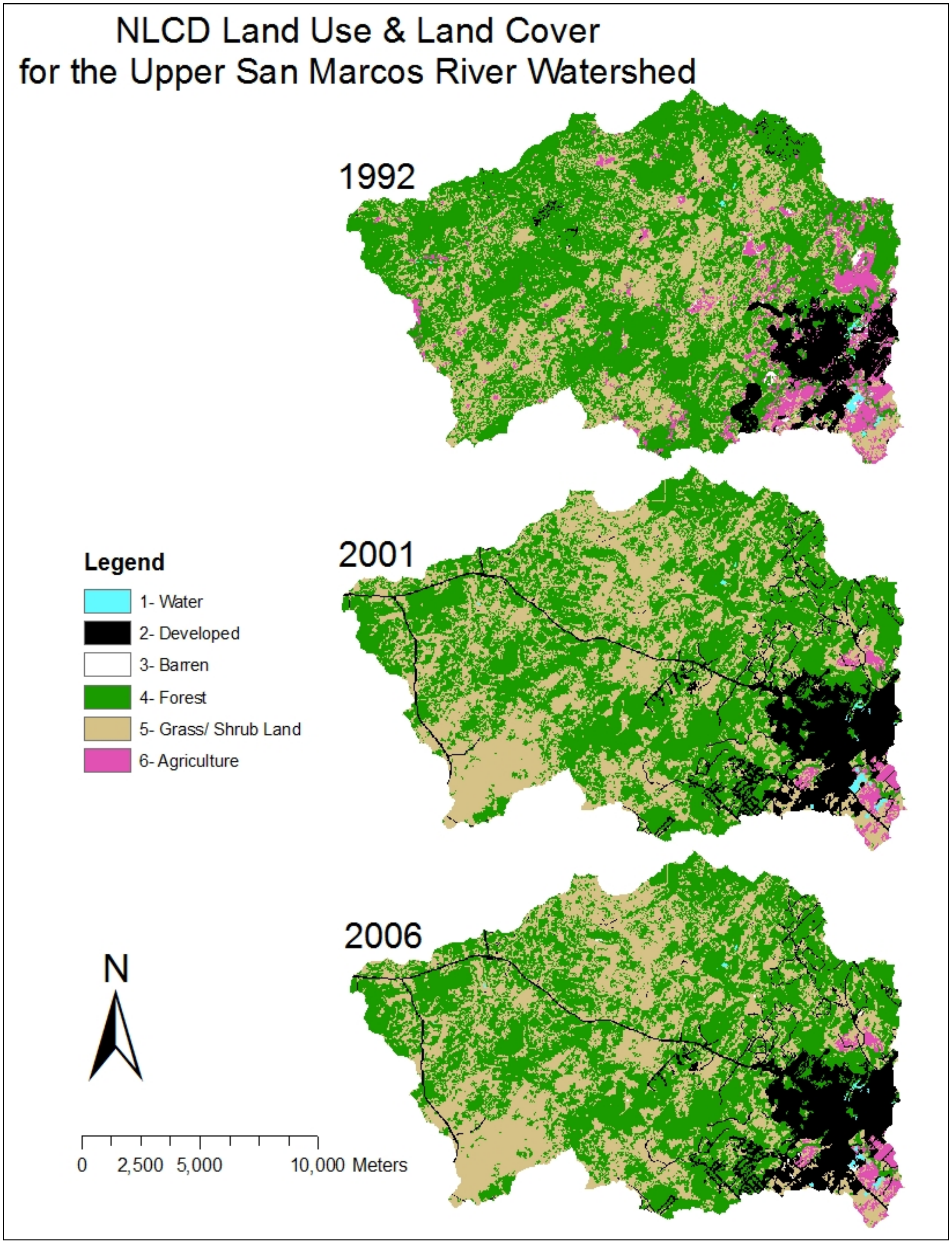


Figure 1.9. Spatial LULC patterns in the Upper San Marcos River Watershed in 1992, 2001, and 2006. Note that these watershed boundaries are only for surface drainages, and do not define the much larger groundwatershed contributing flow to San Marcos Springs.

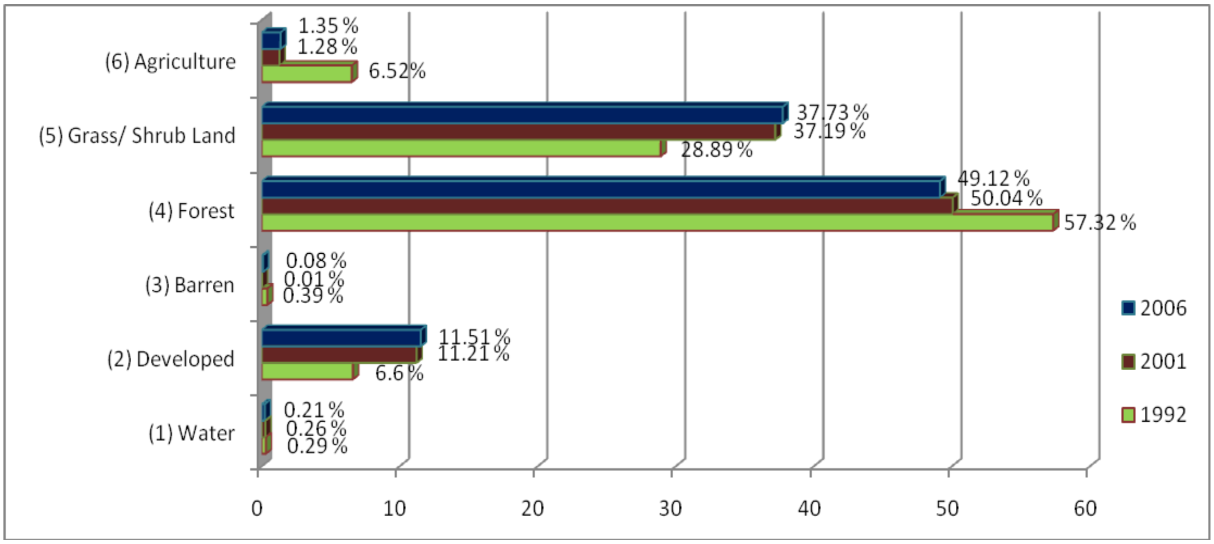


Figure 1.10. Temporal changes in the percent composition of LULC in the Upper San Marcos River watershed in 1992, 2001, and 2006.

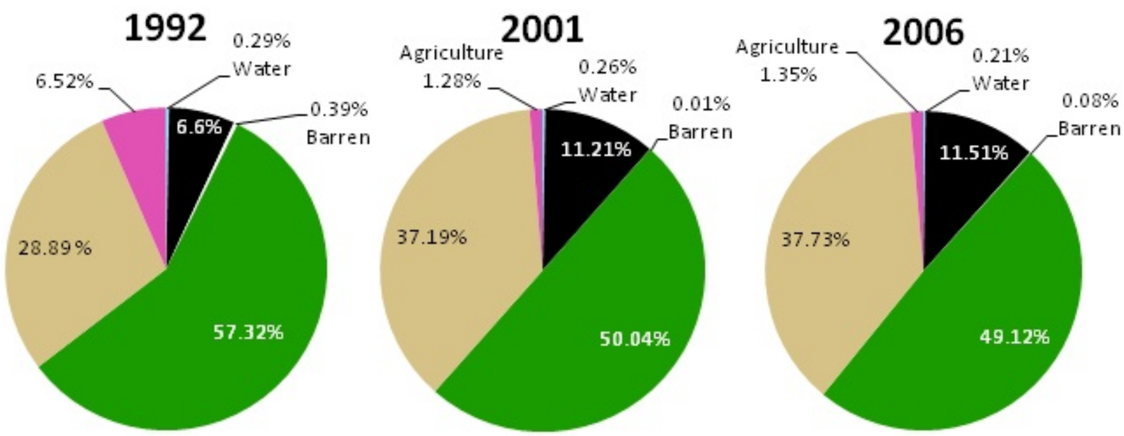


Figure 1.11. Changes in the percent composition of LULC in the Upper San Marcos River Watershed in 1992, 2001, and 2006. Colors match the legend in Figure 1.9.

Changes in the Sink Creek watershed generally followed those observed in the overall Upper San Marcos Watershed (Figure 1.12). Over the 14-year study period, most of this LULC cover change occurred from 1992 – 2001 (Figure 1.13). In the Sink Creek watershed, forest cover declined from 64.3% in 1992 to 54.9% in 2006 (Figures 1.14, and 1.15). Agricultural land cover declined (5% to <1%) and the amount of land classified as grass/shrub land also increased over this interval (28.7% to 39.5%). The percent of land cover classified as developed in the Sink Creek watershed was less than the overall Upper San Marcos River watershed, but the temporal trends were similar to the overall watershed in that the developed cover increased from 1.6% in 1992 to 5.0% in 2006.

Sink Creek NLCD LULC

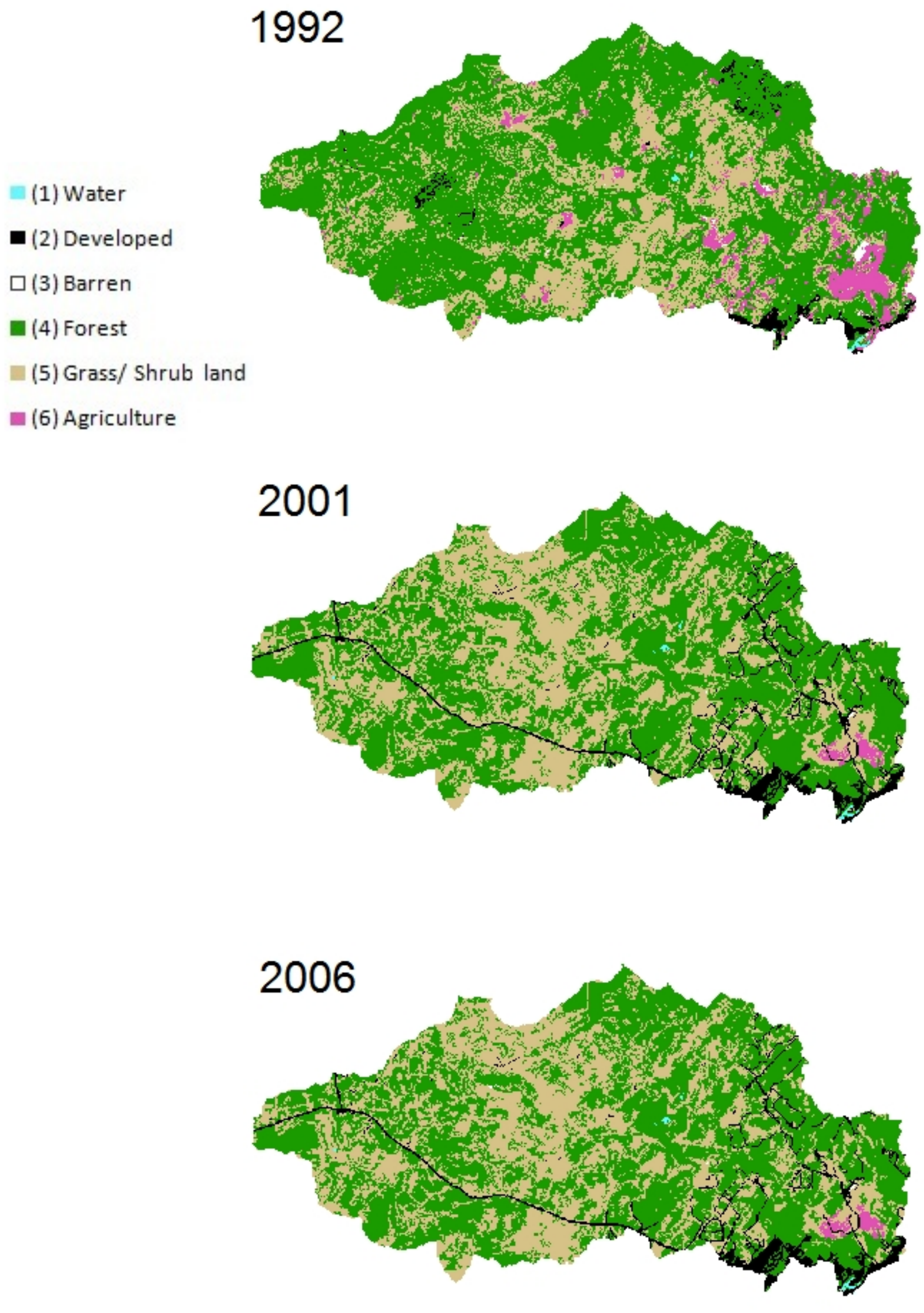


Figure 1.12. Spatial LULC patterns in the Sink Creek watershed in 1992, 2001, and 2006. Note that these watershed boundaries are only for surface drainages, and do not define the much larger groundwatershed.

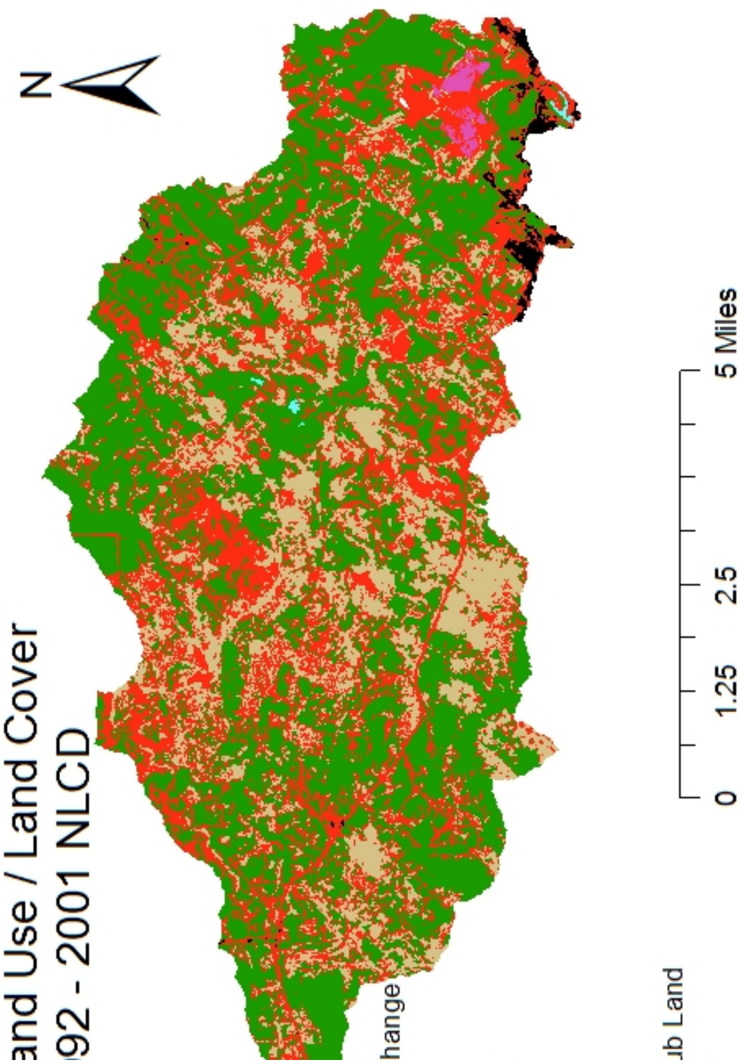


Figure 1.13. Spatial LULC change patterns in the Sink Creek watershed from 1992 to 2001. Areas that are colored red exhibited a change in land classification during this time period. All other areas on the map remained the same land classification from 1992 – 2001.

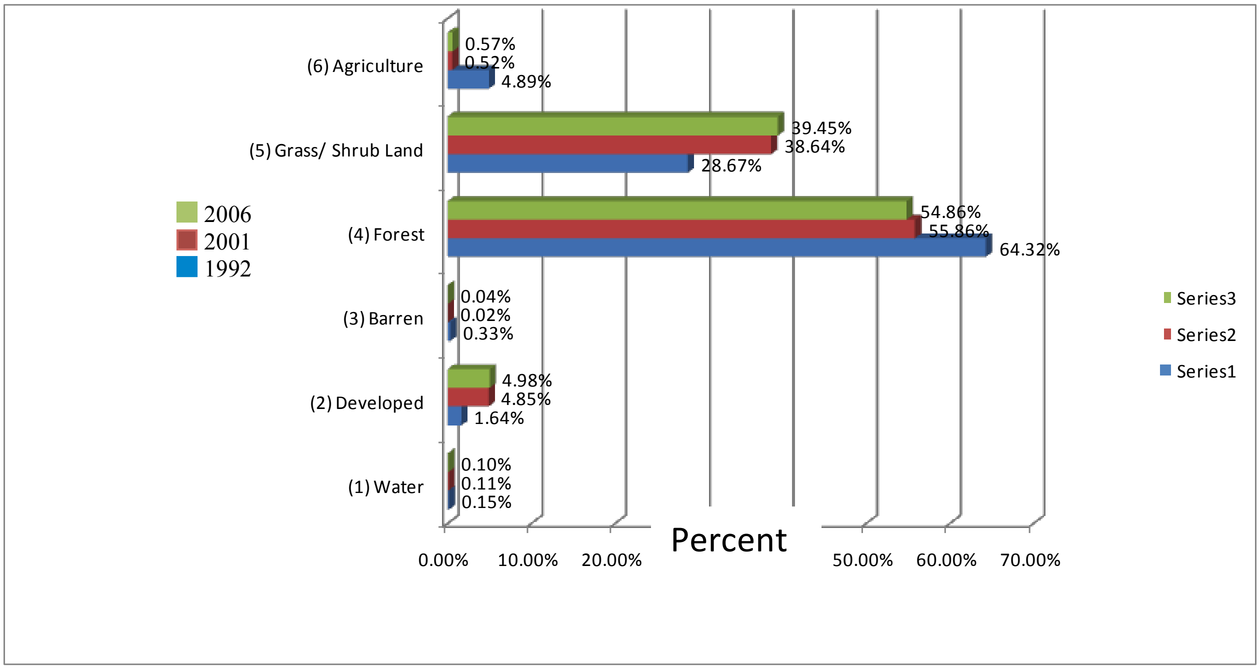


Figure 1.14. Temporal changes in the percent composition of LULC in the Sink Creek watershed in 1992, 2001, and 2006.

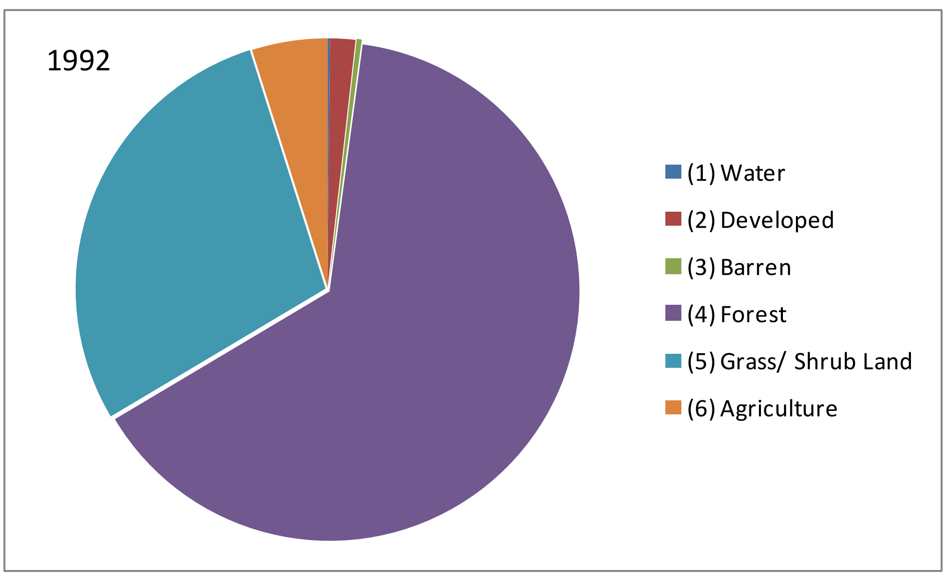
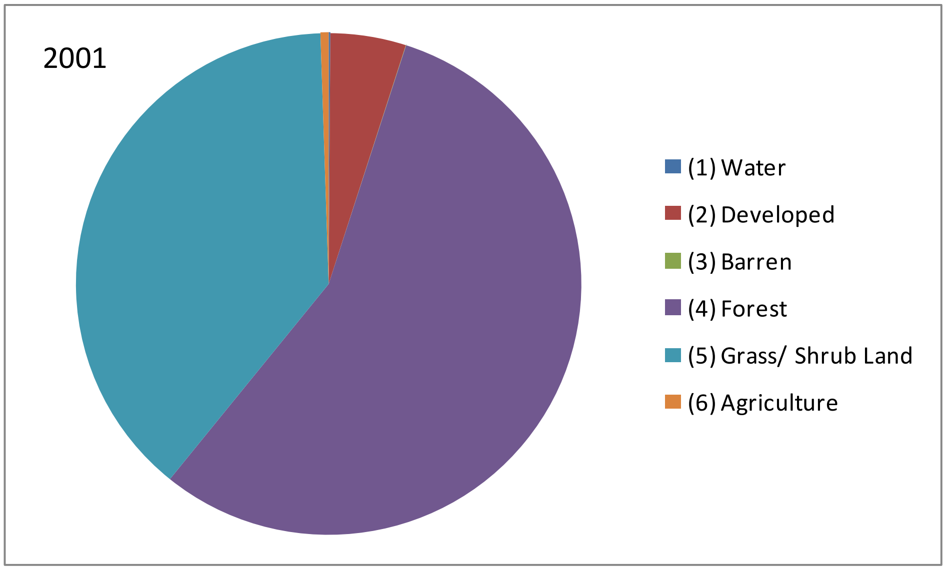


Figure 1.15. Changes in the percent composition of LULC in the Upper San Marcos River Watershed in 1992, 2001, and 2006.



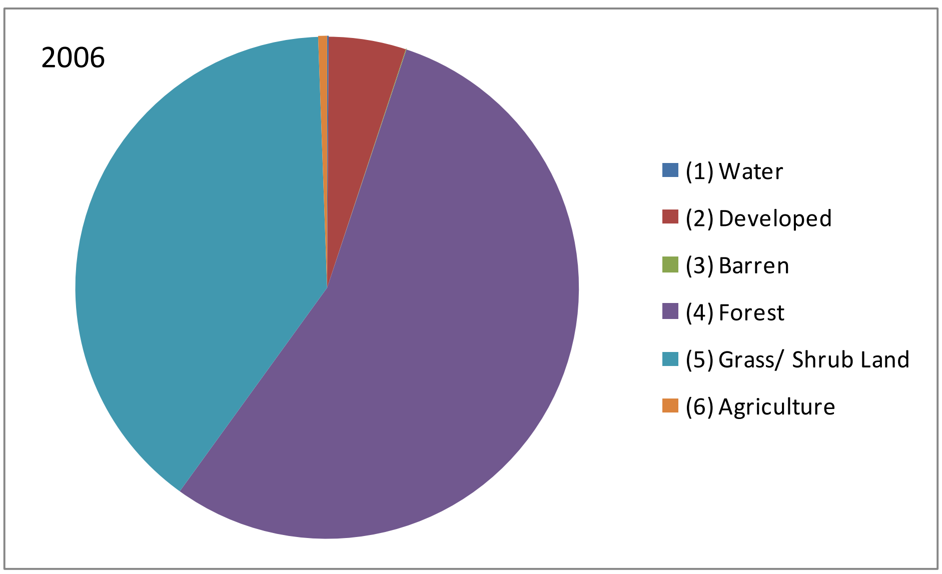


Figure 1.15 - continued. Changes in the percent composition of LULC in the Upper San Marcos River Watershed in 1992, 2001, and 2006.

These results indicate that there have been substantial LULC changes in the Upper San Marcos and Sink Creek watershed, but that between 1992 and 2006 most of this change occurred during the time interval from 1992 – 2001. Although the greatest percent conversion of LULC occurred during the 1992 – 2001, a longer time period than the 2001 – 2006 interval, when the LULC is examined as a rate (% change per year), results indicate that the rate of land use conversion proceeded at a slower rate in the 2001 – 2006 period. For example, developed land cover increased by 4.6% in the Upper San Marcos River watershed from 1992 – 2001 (6.6% to 11.21%), a rate of 0.66% per year. In contrast, developed land cover increased 0.3% in the 2001 – 2006 period (11.21% to 11.51%), an increase of 0.06% per year. This same pattern is true for the Sink Creek watershed, with much slower rates (% increase per year) of developed land cover occurring in the 2001 – 2006 time period relative to the 1991 – 2001 period.

Overall, there has been a reduction in forest and agricultural land cover and an increase in grassland and developed land cover over time in both the San Marcos and Sink Creek watersheds. The reduction in forest and agricultural land cover is due to their conversion to developed areas and grass/shrub lands. Furthermore, the conversion of forest cover to grass/shrub lands is also likely the result of extensive efforts to remove Ashe Juniper from the landscape in recent decades.

Developed land cover and associated increases in impervious cover can have a profound effect on the water quality and dynamics of aquatic ecosystems. It is critical to assess changes associated with urban development in hydrologically and ecologically sensitive watersheds in order to understand the fate and transport of materials as well as to plan future development (France, 2006). Indeed, urban land cover and associated impervious surfaces in sensitive watersheds can have profound effects on water quality and biota with even relatively modest percentage of urban land use (King et al. 2011; Nataluk and Dooley, 2003). Recently, King et al. (2011) found that as little as 1% impervious cover in a watershed can lead to declines in sensitive biota.

1.6 Summary of Initial Watershed Characterization

Spring Lake in central Texas is a unique ecosystem, serving as the headwaters of the Upper San Marcos River. Spring Lake and the Upper San Marcos River represent an invaluable recreational, educational, cultural and ecological resource for this region and clearly require protection and preservation. However, this region of Texas is rapidly growing and faces increasing pressure from anthropogenic development. Here, we presented an initial characterization of the Upper San Marcos and Sink Creek watersheds, and evaluated number of the physical, chemical, and biological aspects of these watersheds. In particular, we examined patterns in LULC characteristics of the Upper San Marcos River and Sink Creek watersheds.

Of the four major surface drainages that discharge into the Upper San Marcos River Watershed, Sink Creek is the most upstream and potentially plays an important role in determining nutrients and sediments loads to Spring Lake and the Upper River. Thus, determining NPS inputs to Sink Creek form the watershed are critical the maintenance of water quality for the lake and upper river. However, Spring Lake also receives substantial groundwater from both local- and regionally-derived sources within the Edwards Aquifer, with the magnitude of the different sources dependent upon regional hydrologic conditions. The high degree of surface- and ground-water connectivity likely makes any NPS loading to groundwater within the Edwards Aquifer recharge zone relevant to NPS dynamics in Spring Lake.

Currently, Spring Lake and the Upper San Marcos River meet most water quality standards, but the upper San Marcos River was proposed for listing under Section 5c of the 303(d) list for not meeting criteria for TDS. TDS is a composite measure of all dissolved organic and inorganic material in a sample, and it is unknown which dissolved constituents may have increased to cause TDS levels to exceed criteria for General Use. Regardless, the TCEQ will need to collect additional data and information about this issue before a TMDL is performed. In addition, a number of investigators have qualitatively noted that suspended solids have increased and associated water clarity declined after rainfall events. It is presumed that surface runoff associated with these rainfall events is the major cause of these temporally short water quality declines, but there is very little data on the role of this surface runoff in sediment and nutrient loading. Aquatic invertebrate, fish and aquatic vegetation communities in the river are relatively diverse and composed of many endemic species. However, there are a number of non-native and potentially invasive species in the lake and river that are cause for concern. In addition, increased sediment and nutrient loading from the surface watersheds, including Sink Creek can cause habitat and water quality deterioration that may lead to population- and community-level impacts.

The Upper San Marcos River and Sink Creek watersheds have undergone significant LULC changes from 1992 - 2006. In particular, both of these watersheds have experienced declines in the percent cover of forest and agricultural area. These declines were accompanied by increases in developed area and grass/shrub lands. Conversion of forested and agricultural areas in the watersheds was most rapid during the 1992 – 2001 and this rate declined substantially during the 2001 – 2006 period. Reduction in forest and agricultural land cover is likely due to changes in land use patterns associated with increasing human populations in the area and aggressive programs to remove ashe juniper from the landscape.

Although developed land cover constitutes 11.5% and 5.0% of the land cover in the Upper San Marcos and Sink Creek watersheds, respectively, many previous studies have found that relatively small amounts of developed land cover can lead to substantial impacts through increased pollutant loads and altered hydrological regimes. Currently, water quality conditions in Spring Lake and the Upper San Marcos River are reliant upon on adequate flows from the headwater springs. Decreases in aquifer levels, and/or human development on or along aquifer recharge sites will likely lead to decreased water quality through an increased reliance on surface water inputs and NPS inputs associated with runoff from disturbed lands.

It is likely that further development within the Sink Creek watershed will have implications for the water quality and biota of Spring Lake. As one example, given the presence of recharge features in the area, and the fact that Sink Creek also serves as a surface water input to Spring Lake, the Windmere Ranch Development has a high likelihood of impacting water quality in the lake and the upper river. It is recommended that future development activities in the watershed should be carefully examined and best management practices (BMPs) should be applied to minimize the effects of development on water quality in Spring Lake and the upper San Marcos River.

Preservation of water quality and quantity in Spring Lake and the Upper San Marcos River requires an integrated management plan that incorporates both surface- and groundwater, spans agency jurisdictions, allows for stakeholder involvement, and maintains the sometimes difficult balance between natural resource management and economic development. Future portions of the Spring Lake Watershed Characterization and Recommendations Project, including the periodic collection of water quality data and the determination of NPS loads associated with storm events from the Sink Creek watershed will play a vital role in initiating the generation of such a management plan.

2.0 Data Collection and Analysis Introduction

The purpose of this data collection effort is to provide information on spatial and temporal variability in water quality in the Upper San Marcos River under both baseflow and stormflow conditions, and to compare water quality under these conditions to existing surface water quality standards. This comparison allows identification of times and locations at which water quality standards for particular parameters may or may not be exceeded, and provides guidance for future efforts to focus on mitigating any sources of NPS which may be contributing to water quality impairment.

2.1 General Watershed Information

Although Spring Lake receives most of its annual hydrological inputs from groundwater sources, Sink Creek discharges into the Slough Arm of the lake. Flows from Sink Creek originate more than 15 stream miles upstream to the northwest near the city of Wimberley. Much of the time, Sink Creek is dry and experiences little to no flow. However, during strong rain events or in relatively wet years (e.g., El Niño years), Sink Creek flows and appears to discharge substantial loads of sediments and nutrients into Spring Lake and the upper river. As the name implies, water in the creek also "sinks" and presumably provides some recharge to local groundwater sources. However, the extent of this groundwater recharge from the creek is not known. There are also several flood retention structures (dams) upstream from Spring Lake on Sink Creek, with the largest of these structures located on Freeman Ranch. Presumably, these flood retention structures also provide some opportunity for surface waters to recharge the aquifer.

As a result of the strong spring water influence on Spring Lake and the upper San Marcos, the upper river typically exhibits high water quality with low turbidity, low suspended sediment loads, and low phosphorus (P) concentrations. Spring Lake and the USMR have recently experienced increased turbidity and declines in water quality after rainfall events, presumably from inputs by Sink Creek and other tributaries. However, the relative pollutant load contributions of these ground- and surface water sources to Spring Lake and the USMR currently remain unknown.

This Data Collection and Analysis portion of the report describes the data collected to characterize spatial and temporal properties of water quality in the Spring Lake watershed. Several approaches were used to accomplish this, and can be separated into three types of data collection and monitoring efforts: 1) Continuous monitoring of basic field parameters; 2) Routine sampling for water quality; and 3) Targeted sampling for water quality. A description of methods used and the results will be presented separately for each effort, and followed by a brief discussion and conclusion that integrates the major findings of all three efforts.

2.2 Sampling Sites

Locations in Spring Lake and the Sink Creek watershed where manual or automated water samples, and automated water quality data are collected, are referred to as Sampling Sites (Table 2.1). Together, these sites are part of the Continuous Monitoring, Routine Sampling, and Targeted Sampling programs, which were designed to assess existing baseline water quality as well as changes in water quality due to storm events and seasonal-scale effects. Figures 2.1, 2.2, and 2.3 illustrate the geographic locations of these sites.