RIVER SYSTEMS INSTITUTE
TEXAS STATE UNIVERSITY-SAN MARCOS

INTEGRATED ASSESSEMENT OF THE PEDERNALES WATERSHED

Year 1 Final Report

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Introduction

The purpose of the Integrated Assessment of the Pedernales Watershed project is to provide current watershed data for the development of a conservation plan for the Pedernales river basin, from its headwaters in Kimble County to its confluence with the Colorado River. A secondary purpose is to make a contribution to the development of data sets needed to inform the Texas Instream Flows Program framework for the Pedernales River that will rigorously evaluate future water management projects.

Texas State University researchers implemented a multi-disciplinary approach to address key data gaps, evaluate impacts of land management, and develop strategies for integrated watershed management. The four research areas and lead investigators include:

1. Integrated Assessment of the Pedernales Watershed – Dr. Vicente Lopes
2. Spatial and Temporal Patterns in the Pedernales River Drainage Fish Assemblage – Dr. Tim Bonner
3. Water Chemistry and Water Quality in the Pedernales River Watershed – Dr. Alan Groeger
4. Hydraulic Geometry of the Pedernales River – Dr. Joanna Curran

Due to the relatively rainy summer in 2007, researchers requested an extension through the 2008 summer to gather data during a dry season and have a more robust study. In addition, several students used this project as part of their masters' work. The final report presented here provides an overview on work completed during the first year of study and findings in each of these research areas as required in the Pedernales River Project Agreement with The Nature Conservancy.

PEDERNALES RIVER WATERSHED ANALYSIS

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INTRODUCTION

Traditional water resource management has focused on establishing water quality targets and the use of dams and diversions to maintain a target level of supply to meet the demands of agriculture, industry and municipalities. However, while this method establishes a minimum standard of integrity for the aquatic ecosystem, it ignores the health of the linked riverine-terrestrial ecosystem as a whole. There is increasing evidence that the success of managing a target variable, such as water, for sustained production has often resulted in inflexible management practices, producing less resilient systems that are increasingly dependent on human manipulation for regulation (Holling 2004; Berkes and Folke 2000).

The alteration of in-stream flow regimes as a result of dams and diversions has been identified as one of the leading causes of the degradation of aquatic habitats (Pringle et al. 2000). In addition, ecosystem functions and services provided by freshwater systems have also been compromised (Postel and Carpenter 1997; Vorosmarty et al. 2005). There has been increased interest in determining and maintaining the flow regime necessary to ensure sustainable aquatic ecosystems and to maintain the desired level of ecosystem services provided by river systems (Richter et al. 2003; Mallard et al. 2005).

Maintaining adequate water supplies, however, has been a serious issue for decades. Moreover, global climate change, population growth and increasing urban development are likely to amplify the problems facing water resources management in the near future. In 1997, recognizing the need for more integrated management of water systems in Texas, the state legislature passed Senate Bill 1, creating 16 Regional Water Planning Groups. This bill requires each Regional Planning Group and the Texas Water Development Board (TWDB) to provide new water management plans every 5 years.

In 2001, the 77th Texas Legislature amended state water law further to enhance regionally-based water management in the state and to encourage conjunctive planning for surface and groundwater usage. In addition, the new legislation included provisions for protecting environmental needs, including in-stream flows, freshwater inflows to bays and estuaries, and fish and wildlife habitats.

Combining science and policy into an effective water management program, however, is a challenge that requires detailed knowledge of both the historical and current social, political, and economic systems in which management decisions are imbedded. Integrated Water Resources Management (IWRM) has gained recognition in recent years as an approach that recognizes the complex and integrated nature of social-ecological systems.

IWRM is based on a perspective that explicitly includes humans and social systems within ecosystems, as linked social-ecological systems. IWRM can be defined as “a process which promotes the coordinated development and management of water, land and related resources, in order to [maximize] the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP 2000).

This approach holds promise for managing river systems such as the Pedernales River Watershed, which are experiencing multiple conflicting demands on limited resources and where conflicts can only be expected to increase in the future. The Pedernales River is one of Texas' most pristine and beautiful rivers - vast stretches of the river are lined by privately owned ranches and remain largely free of development, making the watershed a top priority conservation area.

However, the projected level of population growth in Texas and the associated increase in water demand, particularly for the municipal needs of growing urban centers, creates a conflict with the ecological and legislative imperative to ensure environmental flows in the Pedernales River Watershed. A further complication arises from the multiple and still relatively poorly understood linkages between surface water flows and cross-cutting subsurface aquifers in the region.

The implementation of an integrated approach to water planning and management in the Pedernales River Watershed will require an integration of both human and ecosystem needs. This means recognizing that although in-stream flow programs are based upon a scientific foundation, they must be implemented in a legal, social, political, and economic context. This context is furthermore constrained by its historical trajectory, or how it has evolved throughout its history.

The purpose of this study is to investigate the Pedernales River Watershed's current structure and function to enable evaluation of the likely effects of future land and water use change on water quality and quantity. We envision that planners and communities will use the information gained from this study to construct scenarios that depict likely consequences of development patterns and land and livestock management in the watershed. Our guiding principal is to examine the way rain is divided into interception, direct runoff, soil water and base flows during the period of record. The manipulation of this distribution is considered one of the main ways humans affect the greater ecosystem. Furthermore, Dunne and Leopold (1978) maintain that understanding where water goes and what it does is fundamental to solving many environmental problems.

The study will proceed in two interrelated phases. Phase I will involve gathering hydro-geomorphic data to analyze historical and current watershed conditions. The generally recognized factors of particular consequence to watershed management and those that affect the division of rainfall into its various flows and storages are physiography, land use/land cover, the character of precipitation, and water use. These parameters will be studied in conjunction with hydrologic parameters to determine causal relationships and associations. We have taken special care with characterizing land cover, because of its relatively fast changing state, and the urgent need to develop a baseline record for analysis of future changes.

In Phase II we will investigate through watershed modeling and scenario development, the likely effects of future land and water use change on water quality and quantity in the watershed. Our focus will be on the development of a comprehensive watershed-scale model to be used as a tool to assist stakeholders to evaluate the impacts of increasing water demands and land cover changes on water quantity and quality. This report describes the methods and results of Phase I.

If integrated water resource management is to succeed in the Pedernales River Watershed, it will require a firm grounding in both the environmental science aspects of hydrology, in-stream flows, and aquatic ecology, as well as the social science aspects of human interactions, institutions, values and priorities that shape the co-evolution of social-ecological systems. By providing a framework for understanding the hydrologic context of water management in the Pedernales River Watershed, this study will fulfill a vital role in the successful implementation of strategies for water resources planning and development in the future.

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

The Pedernales River Watershed is a tributary of the Colorado River, approximately 106 miles (171 km) long, in central Texas. It drains an area of the Edwards Plateau, flowing west to east across the Texas Hill County west of Austin. The river rises from springs in southeastern Kimble County, approximately 25 miles (40 km) southeast of Junction. It flows generally east into Gillespie County, past Fredericksburg, and into Blanco County, passing north of Johnson City. It joins the Colorado from the southwest in Lake Travis, approximately 10 miles (16 km) west of Austin.

There are two long-term stream flow gauges and five gauges with 5 years of quality controlled data in the Pedernales River Watershed. These data allowed us to evaluate spatial variations in runoff ratios and determine the structural characteristics that correspond with hydrologic variation between seven selected sub-watersheds. The watersheds were identified using advanced Geographical Information System (GIS) techniques in watershed delineation and various quality controls.

A GIS database was compiled to store and catalog available geographical information and to maintain spatial continuity throughout this study. Since most of this data was not originally collected with watersheds in mind, a great deal of work has been done with ArcGIS, ArcHydro, and various specialist tools and scripts. The following is a list of products generated from this work.

Geology - we have mapped and described the surface geology of the Pedernales River Watershed, and the specific geology of selected sub-watersheds and incremental watersheds. We describe briefly the geologic history of the Pedernales River Watershed, how it was likely to have formed, and spatial variation as a function of period of deposition, tectonic events, and erosion. These factors have created considerable stratographic and textural variation across the Watershed. Rock types range from underlying limestone to sand, and the age of the rock ranges from unfaulted Cretaceous (114 to 65 mya) to highly faulted Paleozoic (543-248 mya) rock. We discuss the likely hydrologic consequences of this variability.
Soils - we have mapped and described the soil characteristics of the Pedernales River Watershed, and the specific soil characteristics of selected sub-watersheds and incremental watersheds. We used SSURGO soil polygons, the highest resolution soil data features, from the National Resources Conservation Service (NRCS). Data was compiled from the seven soil surveys that overlay the Pedernales River Watershed. The US Geological Survey (USGS) Soil Data Viewer was used to spatially arrange the vast data base of soil characteristics.

We analyzed spatially the following factors for water quantity: soil texture, hydrologic soil group, soil profile average hydraulic conductivity, and depth to any restrictive layer. Furthermore, we analyzed the fallowing factors for potential land use change: quality of soils for cultivation, potential water quality, and land degradation with the NRCS qualitative erosion evaluations.

In general there is a strong association between soil type and geology, though different topography in the southeast and far west contributes to different soils types under somewhat similar geology. The most striking variation in the Pedernales River Watershed is the contrast between the uplands and two bowl-like flood plains. The largest of the bowls is a flat sandy area that sits in the shared flood plain of Live Oak, Barons, and Palo Alto Creeks, while the Southeastern upland of the Watershed is a steep Adobe with thin clay soils.

Precipitation - we studied the spatial variation of rainfall and the ability to model rainfall patterns across the watershed. This was an extensive study that involved aggregation and manipulation of over 50 rain gauges with five years of 15 minute data each. Over 675 interpolative surfaces were created and analyzed. A full report of methods and results has been completed. Significant findings are that gauge density of rain gauge networks in the watershed is not at a resolution sufficient to explain the spatial variation of rainfall. Also, we found that using the highest resolution of gauges possible with the Kriging method, regardless of parameterization, was the most reliable technique for estimating areal rainfall. Monthly areal rainfall estimates were created for each studied sub-watershed for the five year study period (water years 2003- 2007).

Land cover - we conducted interviews with expert community members in the Pedernales River Watershed to develop an historical narrative of the land cover change and current trends in the watershed. We used this information along with geographic information collected from interviews and locally maintained data bases, to create preliminary maps of land cover in the watershed. We then classified Digital Orthophotography to map the watershed from 1996 and 2004. The classification process greatly benefitted from contextual information obtained during the interview process. This study is an ongoing study. So far land cover classification in the Pedernales River Watershed in Gillespie County is complete for 1996 and 2004. A data layer of buildings present in 1996 and 2004 has also been completed for Gillespie County.

Surface water use and discharge - we have studied the legal and social context of water use and discharges in the watershed. We calculated the effect of surface water withdraws and wastewater discharges relative to annual average flows. We found both to be insignificant to annual flows. Withdraws could become a larger factor if LCRA rewards firm water contracts within the watershed; otherwise almost all the flow in the Pedernales River Watershed is appropriated to down stream users. Currently in-stream flows in the Pedernales River Watershed are appropriated to downstream users, primarily Lake Travis (LCRA service area), the City of Austin, the four major Lower Colorado River irrigation districts (Garwood, Lakeside, Pierce Ranch, and Gulf Coast).

Hydrologic variation - we studied the watershed's spatial variation of runoff per unit area using the two longest records of stream flow in the watershed. We calculated drainage area ratios and created linear relationships to determine comparative runoff ratios for sub-watersheds. We found that the watershed does not exhibit proportional drainage area runoff. We analyzed water use, rainfall patterns, land use, and physiography to determine factors that significantly contribute to the disparity between drainage area ratios and runoff to runoff ratios. As stated above we found surface water withdraws and discharges to be insignificant relative to the disparity. Rainfall-runoff relationships were created to account for variation in rainfall patterns.

The five year rainfall runoff relationships for both sub-watersheds with long term stream flow records were above acceptable levels of “goodness of fit”. We found that a gradient of rainfall is likely the source of disparity between drainage area ratios and runoff to runoff ratios in the Pedernales River Watershed. This is consistent with the generally south-easterly increase in precipitation across the state, and the same trend seen on a larger scale in adjacent basins like the Brazos.

We have also studied the five year rainfall runoff relationship of selected sub-watersheds in the Basin. Having only five years of data for these relationships and the relative extremes of those five years to the longer record obscured the findings in these smaller watersheds. A base flow-separating computation was used to ameliorate some the variation not due to rainfall in a particular month. Relationships of acceptable fit (R^2 = 0.6 or higher) were created for most of the studied sub-watersheds, and the one with the lowest fit exhibited effects convincingly attributable to low head dams and small head reservoirs. Of considerable interest was the variation proportional base flow throughout the basin. The interpretation of these results is still ongoing.

GEOLOGY OF THE PEDERNALES WATERSHED

INTRODUCTION

Geology plays a major role in determining watershed function and structure. Over the long term geology influences the creation of soil, the character and structure of vegetation, erosion process, topography, etc. Of considerable concern to water resource managers is geology's role in determining where water goes, and what it is doing while it is there. As discussed by Dunne and Leopold (1978), understanding where water goes and what it does is fundamental to solving many environmental problems.

Geology influences the division of rainfall into its various flows and storages in many ways. For example, surface water-ground water interactions are directly affected by the relative connectivity between water sources due to the particulars of geology. Faults may lead transfers of water from one area to another, out-cropping may produce high levels of communication between ground water and surface water, and impervious surface geology may lead to uncommon runoff generation mechanisms such as saturation excess and interflow.

"Interflow" or "subsurface flow" is the flow of water in a lateral direction though the soil horizons, and is normally associated with a soil horizon of relative high conductivity overlaying a relatively impervious layer. So it is readily evident that because geology dictates where water goes before eventually discharging into a stream, natural resources studies concerned with water quantity, quality and associated effects on environmental and social welfare should pay considerable attention to geologic context. The geology of the Pedernales Watershed as it relates to water resources requires special study, due to its highly heterogeneous nature and the potentially tight linkages between surface and ground water in the area. For this reason our study is intended to inform stakeholders about the variation in geology across the Pedernales River Watershed, generally by region, and more specifically by areas of selected sub-watersheds and incremental watersheds.

However, it is impractical to propose a description without first offering a conceptual model of how and why the geology of the Pedernales Watershed came into being. Thus the watershed as a whole is first described relative to spatial variation of geology and history associated with periods of deposition, tectonic events, and erosion under the heading "Description of the Pedernales Watershed and Its Geologic History." Then geology is described generally by region, and then by specific sub-watershed and incremental watershed under the headings "Geological Description of Major Sections of the Pedernales Watershed," and "Surface Geology by Sub-Watershed and Incremental Watershed."

Following the descriptions, a brief summary of the potential hydrologic consequences of some of the more significant geologic forms in the Perdernales River Watershed is provided. Preceding the descriptions is a brief discussion of methods that illustrates how the descriptions were developed from existing sources and expert opinion.

METHODS

The groundwork for compiling this reference of the Pedernales River Watershed geology was constructed from consultations with community members (local experts) in reference to the Geologic Atlas of Texas (BEG 1981). These community members included employees of the Ground Water District in Gillespie and Blanco counties (HCUWCD 2008; BPGWCD 2008). To support the community-based information, the University of California Berkley's "Web Geological Time Machine" was used to understand the orientation of stratigraphy relative to geologic time (WGTMA 2008). Also the reader is referred to several works specific to the geology and hydrogeology of Pedernales Area (Preston et al. 1996; Bluntzer 1992; Ashworth 1983). These works have also been summarized in more recent reports (LCRA 2002; HCUWCD 2007). All this information was used in interpretation of Geologic Atlas of Texas.

Geologic descriptions were created by viewing a geo-referenced digital version of the GAT and observing the location and position of surface geology relative to other watershed features. For clarity, the maps included with this report only show the GAT overlayed with watershed boundaries. However, several analyses of the GAT maps were made to assist in interpreting the geological data of the Pedernales River Watershed. For example, locating a geologic feature relative to stream valleys and ridge lines was accomplished by toggling on and off other GIS layers such as "hill shades" and stream lines, and then double checking interpretations regarding relief by projecting the GAT over a three-dimensional surface using the soft ware program ArcScene.

All of the above information was combined to illustrate several descriptive levels of the geology of the Pedernales River Watershed. First, the geologic history of the area and a general description of the Watershed are discussed briefly to aid the reader in conceptualizing the overall geologic setting. Next, the major sections of the Watershed moving from west to east are described. Finally, depictions are listed for selected sub-watersheds and incremental watersheds. Maps are included and referenced by these descriptions

RESULTS

Description of the Pedernales Watershed and Its Geologic History

The geology of the Pedernales Watershed is best understood by examining when the stratigraphic layers were deposited, covered up, up-lifted, then weathered and dissected. The majority of the surface geology throughout the Pedernales River Watershed was deposited in the Cretaceous period (114 to 65 mya). The Cretaceous strata in the Pedernales River Watershed has not experienced any major faulting events since its deposition (Preston et al 1996).

Cretaceous deposition occurred after the tectonic event (200 mya) that faulted the watershed's Paleozoic strata. The Pedernales River Watershed currently lies west of a series of faults that occurred during the Cenozoic period (65 mya to today), known as the Balcones fault zone. The Cretaceous layers dip gradually to the southeast following underlying Paleozoic elevation. With increasing down-dip the Cretaceous layers increase in variety, with most notably the lower Glen Rose of the Cretaceous increasing in presence.

Cretaceous layers, present only at lower elevations, are absent from higher elevations because periods of inundation that deposited those layers did not cover the higher elevations to the west. Dissection by water has since removed younger Cretaceous layers and exposed older Cretaceous strata; in some areas the Cretaceous layers have been removed completely, exposing the faulted and highly irregular Paleozoic rock. The magnitude of dissection and consequential out-cropping of older strata generally increases from west to east across the Watershed, until about the middle of Blanco County where the Paleozoic rocks dip back below the Cretaceous strata. The river valley then cuts deep into the older Cretaceous rock not present in the western parts of the Watershed, creating a canyon (Preston et al 1996). The resulting geology of the Pedernales is discussed below, first by general area of the Watershed (western, middle, and eastern), and then in greater detail in the context of a selected study group of sub-watersheds and incremental watersheds.

Geological Description of Major Sections of the Pedernales Watershed

Far Western Portion near Harper

In the western portion of the Watershed the Edwards Group, the youngest of the Cretaceous Groups that is significantly present in the Watershed, is observed in the uplands as the Segovia (Ks) member and the Fort Terrett member (Kft). This is shown as light brown and light green on the Geology Atlas Map (Map 1, Appendix A). Both members consist primarily of limestone. The Edwards Group comprises almost all of the surface geology in the west near Harper, with the exception of stream channels where the older Cretaceous Upper Glen Rose (Kgr(u)) is exposed and Quaternary (1.8 mya) Alluvium is deposited. The Upper Glen Rose consists mainly of dolomite and limestone with some clay and marl. The Quaternary alluvium is a thin layer of eroded material from the Edwards and Upper Glen Rose formations. The Quaternary Alluvium consists of clay, silt, sand and gravel.

Middle Portion near Fredericksburg

Moving east through the Watershed, the older Cretaceous Hensel Sand (Kh) is exposed in the middle of the Watershed near Fredericksburg. The Hensel (Kh) is shown as yellow-green on the Geologic Atlas (Map 1, Appendix A). Hensel Sand comprises the majority of surface geology in this portion of the Watershed. The younger Upper Glen Rose (Kgr(u)) formation is significantly present along southern uplands that overlay the Hensel Sand (Kh), but it outcrops only slightly in the north where it is mainly overlaid by the Edwards (Kft and Ks). Moving east toward the Blanco County line the exposure of Hensel Sand dissipates as the valley narrows and deepens. Here the Hensel is overlaid by Glen Rose in the uplands and is eroded down to Paleozoic strata in the river valley.

Eastern Portion

The eastern portion of the Pedernales River Watershed begins with a north and south line of demarcation that coincides with the headwaters of North Grape Creek in Gillespie County. In this portion of the Watershed, the main stem of Pedernales River and its tributaries to the north have large areas of Paleozoic rock exposed: the limestone and dolomite Honey Cut Formation (Oh); the limestone and dolomite Gorman Formation (Og); the limestone and dolomite Tanyard Formation (Ot); the dolomitic, aphanitic, and calacitic San Saba Member

(Ɛws); the limestone Points Peak Member(Ɛwpp); the Morgan Creek Limestone Member (Ɛwm); the Welge Sandstone Member (Ɛww); the Lion Mountain Sandstone Member (Ɛrl); the Cap Mountain Limestone Member (Ɛrc); the Hickory Sandstone Member (Ɛrh); and the Town Mountain Granite (pƐtm).

Though there are large outcrops of Palezoic strata in the eastern portion, the predominant surface geology is still Cretaceous. In fact, the uplands to the south of the Pedernales River have no exposed Paleozoic rock. Of the Cretaceous layers, outcropping in the eastern portion the Upper Glen Rose predominates. The Fort Terret (Kft) member of the Edwards formation is only present as hills near the southern boundary of the watershed. The Lower Glen Rose (Kgr(l)) and the Hensel Sand (Kh) are present in significant bands along contours where the Upper Glen Rose (Kgr(u)) has been eroded.

Surface Geology by Sub-Watershed and Incremental Watershed

Fredericksburg Sub-Watershed

The Fredericksburg Sub-Watershed (FBSW), which outlets to USGS gage 8152900, is the farthest western sub-watershed and includes the Harper area. The surface geology in this sub-watershed is primarily the Segovia (Ks) member and the Fort Terrett member (Kft) of the Edwards Group (in the west and on the eastern uplands) and exposed Hensel sand (in the east near the outlet). A small but significant portion of the Upper Glen Rose is present along with Quaternary Alluvium (Qa) in the stream channels (Map 2, Appendix A).

The Stone Wall Incremental Watershed

The Stone Wall gauge was recently established between USGS 8152900 and 8153500; the area draining to it is the Stone Wall Sub-Watershed (SWSW). The Fredericksburg Sub-Watershed and South Grape Creek Watershed (SGCW) are nested inside of the SWSW. The segment exclusive of the other nested watershed will be referred to as the Stone Wall Incremental Watershed (SWIW). The SWIW is covered primarily by Hensel Sand (Kh) with a significant amount of Upper Glen Rose (Kgr(u)) in the southern uplands, a thin strip of the Edwards Group's Fort Terrett member (Kft) along the watershed perimeter, as well as a few small outcrops of Paleozoic rocks (Ɛrc, Ɛrc, Ɛwp, Og, and Ot) and Quaternary Alluvium (Qa) in the main channel of the river and the ungauged portion of South Grape Creek (Map 3, Appendix A).

The Johnson City Incremental Watershed

The Johnson City Sub-Watershed (JCSW) has its outlet at the USGS 8153500 stream flow gauge. Several of the other sub-watersheds are nested inside of the JCSW. These include FBSW, SGCW, North Grape Creek Watershed (NGCW), and SWIW. The Johnson City Incremental Watershed (JCIW) is the final segment of the JCSW that is gauged only by the Johnson City gauge.

The JCIW has very diverse geology. A thin strip of the Edwards Group's Fort Terrett member (Kft) is present on the watershed's southern perimeter and in patches along the watershed's northern perimeter. The Upper Glen Rose (Kgr (u)) is the primary Cretaceous strata (543-248 mya). It covers almost the entire southern portion of the JCIW, and is present in northern uplands. The Upper Glen Rose (Kgr (u)) is noticeably eroded away along the river valley and in the middle of the northern portion. The Lower Glen Rose is present in a thin strip along the river valley's southern terrace.

The Hensel Sand (Kh) is also present along the Pedernales River valley's southern terrace and in patches along the flood plain. Paleozoic rocks make up the majority of the northern portion of the watershed. Valleys of area tributaries (North Grape Creek, Hickory Creek, and Buffalo Creek) are primarily Town Mountain Granite (pЄtm) and Hickory Sandstone Member (Єrc). Paleozoic limestone and dolomites cover the river's flood plain in this segment. They consist primarily of the Cap Mountain Limestone Member (Єrc), the San Saba Member (Єws), and the Morgan Creek Limestone Member (Єwm). Toward the outlet Paleozoic Ordovician (490 to 443 mya) limestone dolomites become the prominent surface geology in the river valley. The predominate Ordovician strata present are the Gorman Formation (Og) and the Tanyard Formation (Ot) (Map 4, Appendix A).

South Grape Creek Sub-Watershed
The South Grape Creek Sub-Watershed (SGSW) outlets to the LCRA South Grape Creek stream flow gage. The surface geology of the South Grape Creek watershed is primarily Upper Glen Rose (Kgr(u)) with a significant amount of the younger Edwards Group's Fort Terrett Member (Kft) in the upland and Quaternary Alluvium (Qa) in the stream channel (Map 5, Appendix A).

Miller Creek Sub-Watershed
The Miller Creek Sub-Watershed (MCSW) has its outlet at the LCRA Miller Creek stream flow gauge. The surface is primarily covered by the Upper Glen Rose (Kgr(u)). The Edwards Group's Fort Terrett member (Kft) is present in a thin strip along the perimeter of the watershed's head waters. The Lower Glen Rose (Kgr(l)) is present along the river valley terrace from the outlet to about the middle of the watershed. Quaternary alluvium (Qa) is present in almost all the stream channels of Miller Creek. Hensel Sand is present on the flood plain near the outlet (Map 6, Appendix A).

Flat Creek Sub-Watershed
The Flat Creek Sub-Watershed (FCSW) has its outlet at the LCRA Flat Creek stream flow gauge. The surface is primarily covered by the Upper Glen Rose (Kgr(u)). The Lower Glen Rose (Kgr(l)) is present along the river valley terraces. The Hensel Sand (Kh) is present in stream channels and on the flood plain near the watershed outlet (Map 7, Appendix A).

North Grape Creek Sub-Watershed
The North Grape Creek Sub-Watershed (NGSW) outlets to the LCRA North Grape Creek stream flow gauge. The surface geology of NGSW is very diverse. The watershed is covered by both a significant portion Cretaceous strata (144 to 65 mya) along with exposed Paleozoic strata (543-248 mya). The Cretaceous strata outcropped or present in the NGSW consists of equal area of Edwards Group's Fort Terrett Member (Kft) in the upland, Upper Glen Rose (Kgr(u)), and Hensel Sand (Kh). Exposed Paleozoic rocks in the upstream portion of Willow Creek, the largest tributary of North Grape Creek, are the Cap Mountain Limestone Member (Єrc), the Hickory

Sandstone Member (Єrh), and the Town Mountain Granite (pЄtm).

The oldest rocks are the highest here due to faulting. Though Paleozoic-Precambrian (4,530 to 543 mya) Town Mountain Granite (pЄtm) is exposed at higher elevations, it exists elsewhere below the Paleozoic-Cambrian (543 to 490 mya) Cap Mountain Limestone Member. In the middle of Willow Creek the Hensel Sand (Kh) is not eroded away and is present along with Quaternary Alluvium (Qa). Near the confluence of Willow Creek and Cypress Creek the Paleozoic rock exposure begins again. The largest outcrops of Town Mountain Granite (pЄtm) in the NGSW are here, though the ungauged increment of North Grape Creek does include some larger outcrops.

Moving towards the outlet of the NGSW, Paleozoic rocks include primarily limestone and dolomites from the Gorman Formation (Og), Tanyard Formation (Ot), the San Saba Member (Єws), the Morgan Creek Limestone Member (Єwm), and the Cap Mountain Limestone Member (Єrc). The presence of granite outcrops in this watershed along with the other Paleozoic rocks may significantly alter both surface and groundwater hydrology compared to the other sub-watersheds (Map 8, Appendix A).

Cypress Creek Sub-Watershed

The Cypress Creek Sub-Watershed (CYSW) has its outlet at the LCRA Cypress Creek stream flow gauge. The perimeter of Cypress Creek is covered by Cretaceous strata (144 to 65 mya) while the center of the watershed is eroded down to Paleozoic limestone (543 to 248 mya) and dolomite. The Edwards Group's Fort Terrett Formation (Kft) is present in a very small strip along the top of the watershed's perimeter. The Upper Glen Rose is present in large proportion in uplands and along the perimeter of the watershed near the outlet.

The Lower Glen Rose (Kgr(l)) is present along the terrace and uplands near the watershed outlet. The exposed Paleozoic rocks are primarily limestone and dolomite, the Honey Cut Formation (Oh), Gorman Formation (Og), the Tanyard Formation (Ot). Also present are the dolomitic, aphanitic, and calacitic San Saba Member (Єws), and the Morgan Creek Limestone Member (Єwm) (Map 9, Appendix A).

The contrasting of geologic features in the Pedernales River Watershed reveals specific concerns shared and not shared between sub-watersheds and incremental watersheds. For instance, highly faulted Paleozoic rock outcrops figure significantly in three of the studied sub-watersheds and incremental watersheds (NGSW, CYSW, JCIW). Since the outcropping Paleozoic layers were exposed by water, it seems logical to assume that these areas lay in and along major stream channels, thus stream flow will interact directly with these layers. Consequently, relating ground water interaction with stream flow may be very difficult since fault lines may transfer water to and from stream channels. To put it in another context, the main hydrologic characteristics shared between areas with Paleozoic outcrops may be that each is unique and complex.

Another prominent geologic feature of hydrologic relevance in the Pedernales River Watershed relates to those sub-watersheds that have substantial amounts of their area overlain by Hensel sand. These areas are expected to have considerable interaction with ground water, because of the high permeability of Hensel sand. It is expected that, in these areas, stream flow will likely be lost as recharge, gained from outflow, or even run as subsurface flow, depending on the height of the water table.

Though three sub-watersheds have substantial outcrops of the Hensel sand, the most significant is SWIW (see also SGSW and FBSW). The City of Fredericksburg and its well fields are in SWIW. Recently the consulting firm LBG Guyton Associates conducted a study in this area and concluded that future demand on the Ellenburger aquifer would be sustainable, but may cause a 50 ft draw down in dry years. (HCUWCD, 2008) The implications of how a 50 ft draw down would affect the river's ability to meet environmental in-stream flow requirements is unclear, but because this area is primarily overlain by Hensel sand, it is reasonable to assume that there may be significant effects. Further study is need in this area.

As the above examples demonstrate, the geologic context of the Pedernales River Watershed is important to understanding its unique hydrologic regime, and potential outcomes of water resource management strategies. The above descriptions are an attempt to bring the geologic context of the Watershed within closer reach of this interdisciplinary study and stakeholder groups. Ongoing studies by the various ground water districts in the area will no doubt eclipse this analysis over the coming years. It appears that facilitating these entities in this task would be of considerable benefit to develop sustainable programs in the Pedernales River Watershed.

SOILS OF THE PEDERNALES WATERSHED

INTRODUCTION

Soil composition is of considerable importance in assessing several factors related to watershed management. Soils in so many ways affect the division of water into its various flows, along with what water carries with it. They also play a large role in land use. For these reasons, the Natural Resources Conservation Service (NRCS) maintains a database of soil characteristics that have major implications on hydrologic regime, land use suitability, and potential erosion, among many other factors. However, this database is maintained by county survey, and is not framed in a hydrologic context.(SDM 2008) For example (as described in the methods below) the Pedernales River Watershed falls across seven soil surveys.

This study has developed a reference to inform stakeholders about the variation in soil across the Pedernales River Watershed, and specifically to frame the consequence of soils patterns in a hydrologic context by analysis of selected sub-watersheds and incremental watersheds associated with hydrologic data (stream flow). First, a description of soil texture across the watershed is offered to inform watershed workers about spatial associations of soils between sub-watersheds and incremental watersheds. Next, more detailed descriptions are offered for each sub-watershed and incremental watershed of Pedernales River Watershed.

The more detailed descriptions address six characteristics of soils. First, the following factors are analyzed spatially for hydrologic implications: surface soil texture, hydrologic soil group, saturated hydraulic conductivity, and depth to restrictive layer. Each is discussed under its respective heading, i.e., “Hydrologic Soil Group.” The next factor addresses potential land use implication, specifically quality of soils for cultivation, under the heading “Potential Farm Land.” Finally, potential water quality and potential land degradation are addressed, with the NRCS qualitative erosion evaluation, under the heading “Potential Erosion.” This paper concludes with a summary that illustrates how the descriptions may be used by stakeholders to uncover unrealized information by comparing and contrasting the sub-watersheds. Three examples are offered. Preceding the descriptions is a brief methods section of how the descriptions were created.

METHODS:

Descriptions concerning the spatial arrangement of soils characteristics were produced by manipulating SURGO soil survey data with GIS (SDM 2008). The USGS Soil data viewer was used to create soil shape files for the seven soil surveys that intersect the Pedernales River Watershed (SDV 2008). Six types (texture, hydrologic soil group, hydraulic conductivity, depth to a restrictive layer, potential farm land, and potential erosion risk) of soil shape files were created for each survey area, the shape files were merged by type and clipped to the Pedernales River Watershed boundary and unified and clipped to a selected group of sub-watersheds and incremental watersheds.

Area was calculated for the polygons for each categorical data type and is reported as a summary table. All manipulations of digital geographical data were performed in geographical information system using the software platform ArcInfo. The aggregation of data into tables was performed in a Microsoft Excel spread sheet environment. No tables were created for continuous data types like soil depth to a restrictive layer, but these are described in reference to their spatial arrangement, as are the other data types. Soil descriptions were created by observing the location and position of soil characteristics relative to other watershed features. Maps are included and referenced by the descriptions.

For clarity only the soil shape files are shown with the sub-watershed and incremental watershed boundaries super imposed, however descriptions were written by toggling on and off other GIS layers such as geology, “hill shades”, slope grids, and stream lines. Also, to double check interpretations of soil arrangement regarding relief, the ESRI software program ArcScene was used to project the soil shape files into three dimensions masked by the Pedernales River Watershed and the selected group of sub-watersheds and incremental watersheds.

RESULTS

Description of Soil Textures across the Watershed

The Pedernales River Watershed has a diversity of soils ranging from clays to sands, with several silts and loams in between (Table 1; Map 10, Appendix A). Much of the soil is gravelly, cobbly or stony. The description that follows describes the soils of the Pedernales River Watershed moving from west to east. On the upland in the west near the town of Harper the soils are primarily clays, with patches of clay loam and silty clay. Soil texture varies from clay, through very cobbly, to stony. In the western stream channels, the soils are primarily very gravelly loam, with patches of silty clay loam in the flood plains. Moving east, patches of silty clay loam and clay loam become more prominent in the flood plain along the Pedernales River. This trend continues into the southern tributaries in the middle of the watershed. However, the uplands in the middle of the Watershed are primarily clays.

Closer to the Pedernales River, in the middle of the Watershed, there is a large area of loamy fine Sand. This loamy fine sand is primarily deposited along the converging flood plains of Live Oak Creek, Barons Creek, Palo Alto Creek, and the Pedernales River. Moving east, the presence of loamy fine sand continues along the flood plain but begins to dissipate in concert with a decrease in area draining from the North. The North Grape Creek Sub-watershed (NGSW) routes the northern drainage area further east before its confluence with the Pedernales River further downstream. Consequently, at North Grape Creek’s confluence, the flood plains of several tributaries converge again, creating a large coverage of fine sandy loam. As the Pedernales River moves east beyond the NGSW confluence the flood plains become primarily covered by loam, and further up slope the soils are clays.

In the eastern section of Pedernales River Watershed the soil arrangement changes significantly to clay loams on the upland instead of the clays observed on the western uplands, this is primarily due to a shift in major surface geology from Edwards to the Upper and Lower Glen Rose formations (see geologic descriptions in this report). In the south east uplands the soils are primarily clay loam. In the channels the soils are primarily clay with runs of loam and small patches of silty clay. In the North East upland (exclusive of North Grape creek and it’s the area where it has its confluence with the Pedernales River) the soils display a similar pattern to those in the south, however the flood plains are significantly larger creating a larger area covered by loam and clay. Also the Northern flood plains have patches of fine sandy loam. The distribution of soils is described in greater detail below for selected sub-watersheds and incremental-watersheds. Also, additional attributes (hydrologic soil group, saturated hydrologic conductivity, depth to a restrictive layer, potential farm land, and potential for water erosion) are discussed.

Description of Soils by Sub-Watershed and Incremental Watershed

Fredericksburg Sub-Watershed (FBSW)

Soil Texture
The soil surface texture of the Fredericksburg Sub-Watershed (FBSW) is primarily clay (64% of the area), which occurs primarily in the uplands. Significant patches of clay loam and silty clay are also present (22% of the area), they occur near stream channels and become more prominent moving downstream (Table 1). The soil texture along stream channels is primarily loam (10% of the area), which gives way to sandy loam to loamy sand near the outlet of the watershed (4% of area) and very small patches of sand (Map 11, Appendix A).

Hydrologic Soil Group
Soils in FBSW are primarily classified as soil group D (76% of the area), the soil group associated with the highest runoff (Table 2). In the river channels the soils have higher infiltration and are classified as soil group B (11% of the area). Moving toward the outlet the flood plain widens and class C soils become more prominent (11% of the area) near streams. Also, class A soils are present in small patches near stream channels (1% of the area) (Map 12, Appendix A).

Saturated Hydraulic Conductivity
The saturated hydraulic conductivity (weighted average of horizons) is below 8 µm/s and closer to 3 µm/s in the majority of the FBSW, but it ranges between 8 and 92 µm/s in the stream channels. Thus, water moves more easily though the soils in the river, and can be readily gained or lost, depending on the level of the water table (Map 13, Appendix A).

Depth to Restrictive Layer
The depth to a restrictive layer is greatest in the stream channels and the large flood plains near the outlet of the FBSW and ranges from a considerable depth of 143 to 201 inches. The depth to a restrictive layer in the uplands near the head waters in the gradually sloping west is between 30 to 60 inches on average, while the uplands in the more incised east have a much shallower restrictive layer which is 0 to 30 inches from the surface on average (Map 14,Appendix A).

Potential Farmland

The majority of FBSW is not considered prime farm land based on soil composition (84% of the area) (Table 3). Areas suitable for cultivation (16% of the area) are primarily around the stream channels and in the flood plains near the outlet of the watershed (Map 15,Appendix A).

Potential Erosion

Potential water erosion is predominantly moderate in the upland plains and the majority of the FBSW (53% of the area) (Table 4). There is low potential (32% of the area) to very low potential erosion (9% of the area) near and along most channels and in the flood plains near the outlet of the watershed. Soils with high potential for erosion occur only in patches long the steep terrace near upland stream channels in the more incised East part of the watershed (Map 16, Appendix A).

Stone Wall Incremental Watershed (SWIW)

Soil Texture

Soil surface texture of the Stone Wall Incremental Watershed is diverse (Table 1). It includes uplands which are situated on the Edwards and the Glen Rose formations in the north and south, and Pedernales River valley in the middle. Here the valley is a large eroded bowl like structure; it is relatively flat and overlays the Henzel sand. In the uplands in the North and South the surface soil texture consists primarily of clays (26% of the area). Also, there are significant patches, of silty clay to clay loam, near stream channels (29% of the area), with the south having significantly lager patches. Loam is deposited along stream channel terraces in the uplands and in the stream channel though out the watershed increment (19% of the area). The largest deposit of loamy sand to sand in the Pedernales River Watershed is in the middle of the Stone Wall Incremental Watershed (26% of area). These sandy soils spread across the converging flood plains of Live Oak Creek , Barons Creek, Palo Alto Creek, and the Pedernales River. This area is the most heavily cultivated in the Pedernales River Watershed (see section on Land Cover Analysis in this report). Note that Live Oak Creek is just outside of the Stone Wall Increment (Map 17, Appendix A).

Hydrologic Soil Group

Soil group D has the greatest presence in the SWIW (45% of the area), but is primarily located in the uplands (Table 2). Soil group C is found in very significant patches along stream channel terraces (31% of the area). Soil group B is present in and along most of the larger stream channels (14% of the area). Soil group A, which generates least runoff amongst the hydrologic soils groups, is found in significant patches in the flood plains (9% of the area) (Map 18, Appendix A).

Saturated Hydraulic Conductivity

Saturated hydraulic conductivity in the SWIW is very patchy. In general the upland soils have lower saturated hydraulic conductivity (about 3 to 6 µm/s), while patches in and along stream channels have the highest (about 8 to 92 µm/s) (Map 19, Appendix A). SWIW has the largest area with high saturated conductivity among all the sub-watersheds and incremental watersheds examined in this study.

Depth to Restrictive Layer
The uplands in the Far North and to a lesser extent in the Far South have a very shallow restrictive layer (0 to 30 inches). The restrictive layer runs deeper as the upland nears the stream channels (31 to 66 inches), and in some patches. In the middle of the watershed increment there is a very large area were the restrict layers is very deep (143 to 203 inches) with some shallower patches (67 to 142 inches). This area is the aforementioned converging flood plains of Live Oak Creek, Barons Creek, and the Pedernales River. In the stream channels the restrictive layer is also deep (143 to 203 inches) (Map 20, Appendix A).

Potential Farmland
The majority of the SWIW is not consider prime farm land (65% of the area), yet more than 35% of the Stone Wall Increment is considered suitable for cultivation, which is the most of amongst the selected study sub-watersheds in the Pedernales River Watershed (Table 3). The land suitable for cultivation is located near streams and primarily in the large areas where the flood plains of several creeks converge as mentioned above (Map 21, Appendix A).

Potential Erosion
The majority of soils in SWIW are classified as having low to very low potential for water erosion (53% of the area) (Table 4). This large area of low potential erosion is primarily found in the gently slopping flood plains and valleys overlaying the Henzel sand. The small areas of high potential erosion are along upland terraces that overlay the Edwards and the deeper Glen Rose formations. In general, the upland plains exhibit moderate potential for water erosion (29% of the area) (Map 22, Appendix A).

Johnson City Incremental Watershed (JCIW)

Soil Texture
The soils in Johnson City Incremental Watershed (JCIW) are similar to SWIW and NGSW (Table 1). This is possibility to the fact that all three areas have relatively large, gradually sloping valleys. As discussed in the geology section of this report, the JCIW features an eroded bowl like structure, that is similar to the one found in SWIW. The flood plains of the Northern tributaries converge with the Pedernales valley in this area, because the uplands have been eroded away in this area. The relatively flat topography and parent geology have allowed for loam to loamy sand to be deposited along the flood plains and in the Pedernales valley as it stretches through JCIW (42% of the area). Yet on what remains of the northern upland slopes, clays and clay loam preside (Map 23, Appendix A).

In the southern half of this increment, clay loam dominates the uplands, though there are significant patches of silty clay, and clay. The clays are predominately found near and in the stream channels. The headwaters area of Williams Creek (the most south western tributary in this increment) is an exception to the soil pattern observed in the rest of JCIW. Instead of clay or clay loam, loams dominate here. In total, clays to clay loam textures cover 58% of JCIW (Table 1).

Hydrologic Soil Group
The hydrologic soil groups in JCIW change in relation to proximity to stream channels. Soil group C is predominant in the uplands in the north and south near the watershed boundary and patches throughout the JCIW (36% of JCIW) (Table 2). Moving down slope toward the stream channels of JCIW, the soils become primarily of the hydrologic group D (56% JCIW). However, in and along several of the larger stream channels of JCIW, there are significant patches of soil group B (6% JCIW) and to a lesser extent, soil group A (2% JCIW). This arrangement of soils may have interesting hydrologic consequences.

During small rainfall events this incremental watershed may produce very little runoff due to high infiltration within the streams associated with the presence of soils of groups B and A. On the other hand, intermediate events, in which the uplands begin to contribute runoff, may exhibit relatively high level of runoff production due to the presence of soils of group D near the streams. Finally, larger events may be muted in JCIW relative to some of the other sub-watershed and incremental watershed studied, because the most upland slope and plains will contribute less runoff due to a predominance of group C soils, rather than soils of group D (Map 24, Appendix A).

Saturated Hydraulic Conductivity
Saturated hydraulic conductivity (8 to 94 µm/s) is greatest in JCIW in the bowl like area in the north where the northern tributaries and their flood plains converge with the Pedernales valley. The Pedernales valley has another smaller area of high saturated hydraulic conductivity (about 9 to 94 µm/s), upstream to the west along the Pedernales River. In the south, soils near Williams Creek have higher saturated hydraulic conductivity. The soils in the uplands also have high saturated hydraulic conductivity (about 4 to 8 µm/s) relative to the uplands of the selected sub-watersheds and watershed increments in the Pedernales River Watershed. However, the upland slopes near streams and stream terraces that overlay the Upper and Lower Glen rose have the lowest hydraulic conductivity in JCIW (1.22 to 3.86 µm/s) (Map 25, Appendix A).
Depth to Restrictive Layer
The depth to restrictive layer is perhaps the most significant difference between the bowl in the Johnson City Increment and the deep loamy sand bowl in the Stone Wall Increment. Underlying the majority of the bowl is Paleozoic bedrock of granite and limestone, and the loamy sands are not very deep here (31-41 inches) (see Geology Descriptions in this report). However, there are patches where the restrictive layer is between 67-201 inches, mainly over the hickory sand stone. Near the Pedernales River valley the restrictive layer is vary shallow (0-31 inches). In the south the restrictive layer is relatively shallow in the uplands (31-41 inches) and still shallower in some patches near the watershed boundary. However, in the streams channels in the south, the restrictive layer is relatively deep (143 to 201 inches) (Map 26, Appendix A).

Potential Farmland
The majority of JCIW is not prime farmland (78% of the area) (Table 3). However, 22% of the JCIW is prime farm land which is relatively moderate to high amongst the selected sub-watersheds and incremental watershed of this study. Prime farm land in JCIW is found primarily

in a few large patches in the north, and in along stream channels in the south (Map 27, Appendix A).

Potential Erosion

In JCIW the soils that lay over what remains of the Edwards formation and other Cretaceous strata in northern uplands have very high potential for water erosion (Table 4). The soils along the Pedernales River valley have very high potential erosion, while in the bowl like valley in the north; there is a large area where the soils have moderate potential for erosion. However, within this area, there are many soil patches with low potential for erosion.

In the south, the potential for erosion changes from high to moderate down slope and down stream. There is considerable area of high potential erosion in the southern uplands. This arrangement gives way moving towards streams channels to patches of moderate potential erosion, and then low potential erosion, until the potential for erosion reduces to very low along the stream channels (Map 28, Appendix A). In the JCIW, potential for water erosion is roughly normally distributed around a moderate potential for erosion. There is a large potion with moderate potential (27% of the area), a large portion with high potential (32% of the area), and a larger portion with low potential for soil erosion (26% of the area). Then moving to the extremes there is equal portions of soils with both very high potential for erosion (7% of the area) and very low potential for erosion (7% of the area). When compared to other selected sub-watersheds and incremental watersheds, the JCIW falls in the middle in terms of overall potential for erosion.

South Grape Creek Sub-Watershed (SGSW)

Soil Texture

The South Grape Creek Sub-Watershed (SGSW) is primarily situated in the southern uplands near the middle of the Pedernales River Watershed, and consequently the soils resemble those of the adjacent sub-watersheds and incremental watersheds' uplands. The soils of the SGSW are primarily clays (52% of the area), which prevail on the upland plains (Table 1). Along the stream channels, there are large patches of silty clays (26% of the area), silty clay loam (5% of the area), clay loam (2% of the area), and loams (14% of the area) (Map 29, Appendix A).

Hydrologic Soil Group

The majority of the soils in the SGSW are of the highest runoff generating soil group, soil group D (78% of the area) (Table 2). There are some patches of soil Group C (14% of the area) near and along tributaries with relative small drainage areas. In the more defined stream channels with larger drainage areas, soil group B (8% of the area) is in and along the channels. The arrangement of soils could lead to great extremes in runoff production. During light rainfall events, only areas near a stream contribute because the soils have low runoff generation characteristics, which would lead to very little or no runoff from small rainfall events. During heavy rainfall events, however, the upland plains would contribute more and at lower threshold than the plains with a lower hydrologic soil group (Map 30, Appendix A).

Saturated Hydraulic Conductivity

The soils with the highest saturated hydraulic conductive in the SGWS are located in the bottom lands of the canyons formed in the Fort Terret member of the Edwards formation and also in the larger channels of SGSW (about 25 µm/s). These soils are primarily very stoney clays in the canyon bottoms and loams in and along the stream channels. The soils with the next highest saturated hydraulic conductivity are silty clay loams that are deposited along the river channel and channel terraces (about 9 µm/s). The majority of the remaining soils are below 6.5 µm/s, with significant portions below 3.0 µm/s and some small patches even below 1.22 µum/s (Map 31, Appendix A).

Depth to Restrictive Layer

Depth to restrictive layer follows topography closely in the SGSW as it increases from uplands toward the channels. Generally the depth to a restrictive layer starts at 0-30 inches, and then changes down gradient progressively through areas where the depth is 31-41 inches, 42-66 inches, and 67-142 inches, until finally reaching areas of 143-201 inches, in and along stream channels. There is a significant exception to above stated trend. The depth to a restrictive layer in the very southern uplands near the top of the watershed boundary is greater (42-86 inches) than the next down gradient contour where the soils are 0-30 inches. Also, the depth to a restrictive layer is below 66 inches in the vast majority of the watershed and is even below 41 and 30 inches in large portions of the watershed (Map 32, Appendix A).

Potential Farmland

Areas considered prime farm land (22% of the area), of any sort, are on the narrow flood plains near stream channels (Table 3). To illustrate, the widest areas of prime farmland spans only 0.84 km (0.52 miles) and are centered on the South Grape Creek stream channel. In SGWS, the majority of land is not considered prime farm land (78% of the area) (Map 33, Appendix A). However, SGWS has relatively high to moderate amounts of prime farm land relative to the other studied sub-watersheds and incremental watersheds of the Pedernales River.

Potential Erosion

The soils covering the majority of SGSW have low to very low potential for erosion (57% of the area) (Table 4). Soils with moderate potential erosion are primarily on low stony hills or on moderate slopes (22% of the area). Soils with high potential for erosion (20% of the area) are located primarily on steep slopes or in high gradient stream channels. There are no soils rated for very high potential erosion in the SGSW (Map 34, Appendix A).

Miller Creek Sub-Watershed (MCSW)

Soil Texture

The vast majority of the Miller Creek Sub-Watershed (MCSW) is covered by clay loam (70% of the area). This is a change from the western sub-watersheds and incremental watersheds that are primarily clays (Table 1). However, there is still a large portion of clay soils (26% of the area), which is located primarily in and along stream channels, but also on some upland slopes. There are small patches of silty clay (3% of the area) on hillslopes, and there are narrow stretches of loams (1% of the area) along small portions of the stream channels (Map 35,

Appendix A).

Hydrologic Soil Group
The vast majority of the MCSW is covered by soil group C (69% of the area) (Table 2). However, along the stream channels, the predominant soil type is of the group D (29% of the area). There are also significant patches of soil group B (2% of the area) in the main stem of Miller Creek. In contrast to SGSW, the distribution of soil groups throughout the watershed suggest (based solely on soil types) that during light rainfall events, when only the areas near the streams are contributing, MCSW should generate more runoff than South Grape because of the predominance of soils of the group D along the streams. This relationship should reverse (again based solely on soil group) during heavier rainfall events, when the uplands of the watersheds are more likely to contribute runoff. In this situation MCSW's uplands should generate less runoff than SGSW due to the predominance of soils of the group C on MCSW uplands (Map 36, Appendix A).

Saturated Hydraulic Conductivity
The majority of MCSW is covered by soils with relatively low to moderate saturated hydraulic conductivity. The greater part of MCSW is covered by soils with saturated hydraulic conductivity around 7.78 µm/s. There are some significant patches where saturated hydraulic conductivity is about 4.73 µm/s. The saturated hydraulic conductivity is below 3.01 µm/s in the stream channels with exception of some wide patches where saturated hydraulic conductivity is between 3.01 and 3.86 µm/s, and where loam is present in the channel, saturated hydraulic conductivity is about 28 µm/s (Map 37, Appendix A).

Depth to Restrictive Layer
In the MCSW, depth to a restrictive layer increases down gradient; though there are primarily three dominate groups. For the majority of the watershed, the depth to a restrictive layer is on average between 31- 41 inches with the exception of soils near and along stream channels. The depth to a restrictive layer is relatively very deep along most of the stream channels of Miller Creek (201 inches), primarily where clays occur. There are some areas along the stream channels where the depth to a restrictive layer is between 31 and 41 inches (Map 38, Appendix A). There are also some small patches where depth to a restrictive layer is less than 30 inches, but they are located only in the far south western uplands.

Potential Farmland
The vast majority of the MCSW is not prime farmland of any sort (87% of the area), ranking second to last amongst the selected sub-watersheds and incremental watersheds, just ahead of the adjacent Flat Creek Sub-Watershed (FCSW) (Table 3). The only area that is considered prime farm land (13% of the area) is located in narrow strips along the stream channels (Map 39, Appendix A).

Potential Erosion
The majority of the soils covering MCSW have high potential for erosion (68% of the area) (Table 4). Exceptions are in small patches in the uplands and in narrow strips along stream

channels, and near the outlet of the watershed where the potential for erosion ranges from moderate to very low. This is in contrast to many of the western sub-watersheds where potential erosion is lower on the uplands relative to streams and potential for erosion is lower in general (Map 40, Appendix A).

Flat Creek Sub-Watershed (FCSW)

Soil Texture

The majority of Flat Creek Sub-Watershed (FCSW) area is covered by clay loam (71% of the area), similar to its neighboring sub-watershed MCSW (Table 1). Also, there are significant patches of clay (16% of the area), silty clay (4% of the area), and loam (7% of the area). The majority of the clay soils are located along stream channels and ridge lines in Blanco County, while the majority of loam soils are located on hillslopes in Hays County. Silty clays are deposited on hill tops and slopes and along the main stem channel near the outlet of the sub-watershed. Note: Blanco and Hays counties are not in the same soil survey. It appears that there may be a discrepancy between the two surveys (Map 41, Appendix A).

Hydrologic Soil Group

In the Blanco County portion of the FCSW, soil group D is found along ridge lines and in the stream channels, while in the Hays County in the smaller eastern potions of the watershed soil group D predominates (Table 2). Over 49% of the soils in the sub-watershed are of the soil group D with the majority of those occurring in Hays County. Soil group C is predominant in the Blanco County portion of the sub-watershed and is located only in patches on ridge lines and in a few small stream channels. Over 50% of the soils in the FSCW are of the group C, and those soils are located primarily in the Blanco County portion of the sub-watershed (Map 42, Appendix A).

Saturated Hydraulic Conductivity

In the Blanco County portion of the FCSW, the saturated hydraulic conductivity is the lowest along ridge lines (about 3.2 µm/s) and in the stream channels (about 2.7 µm/s), while along the majority of the FCSW slopes, the saturated hydraulic conductivity is higher (about 7.8 µm/s). In Hays County (note discrepancy between surveys), the soils with the lowest saturated hydraulic conductivity (3.8 and 5.8 µm/s) are located in small patches on ridge lines and slopes. The saturated hydraulic conductivity of the soils in the majority of FCSW in Hays County, is primarily between 22 µm/s and 28 µm/s, and with some narrow soil patches with saturated hydraulic conductivity of about 8.9 µm/s in a few stream channels (Map 43, Appendix A).

Depth to Restrictive Layer

For the vast majority of the FCWS, the depth to restrictive layer is between 31-46 inches. The main exceptions are in the channels of Flat Creek, and Calohan Creek, where the depth to restrictive layer is 201 inches, and along an unnamed tributary and Sycamore Creek, where the depth to the restrictive layer is 71 inches. Upstream of the above confluence for the additional 5.5 km of Sycamore Creek, the depth to restrictive layer is about 31-41 inches. Also, there are significant patches on ridge lines and hill tops in the Hays county portion of the watershed where the restrictive layer is very shallow (0-31 inches). Finally, the depth to a restrictive layer is 31-41 inches at the outlet of the FCWS (Map 44, Appendix A).

Potential Farmland
The percent area of potential farm land in FCWS is the lowest (9% of the area) amongst the selected sub-watershed and incremental watershed areas in the Pedernales River Watershed (Table 3). The areas of prime farm land that are present are located in a similar fashion to soils in FCWS where the depth to restrictive layer is deeper than 71 inches as discussed above. Thus, prime farm land is found almost exclusively along the channels of Flat Creek, and Calohan Creek where the depth to restrictive layer is 201 inches, and along an unnamed tributary and Sycamore Creek (Map 45, Appendix A).

Potential Erosion
The majority of the soils in the FCWS have high potential for water erosion (77% of the area) (Table 4). The soils with moderate (16% of the area) or less (7% of the area) potential for water erosion are found along the channels of Flat Creek, and Calohan Creek, the ridge line between Flat Creek and Calohan Creek, along an unnamed tributary and Sycamore Creek, and in patches along ridge lines and slopes throughout FCWS (Map 46, Appendix A).

North Grape Creek Sub-Watershed

Soil Texture
Soil texture in North Grape Creek Sub-Watershed (NGSW) is very diverse (Table 1). There are two vary different areas of the sub-watershed, one around Willow Creek and the other around the main stem of North Grape Creek and Dry Hallow Creek. The area around Willow Creek has large deposits of sandy loams and loams. Clays are present on the slopes near first order stream channel flow lines, but quickly give way to sandy loams. In the center of the stream channel loam is present, while the area around North Grape Creek and Dry Hallow Creek is primarily covered in clay and clay loams (Map 47, Appendix A). In total, the NGWS is covered by soil textures of approximately 56% clay to silty clay, 8% clay loam, and 36% loam to find sand.

Hydrologic Soil Group
The majority of NGSW is covered by soil Group D (72% of the area), which is the third highest percentage of soil group D amongst the studied sub-watersheds and watershed increments in the Pedernales River Watershed, following only SGSW (1st), and FBSW (2nd)(Table 2). Soil group B (6% of the area) is present in the majority of the length of the major stream channels (North Grape Creek, Dry Hallow Creek, and Willow Creek), and reaches up to several unnamed small tributaries. Soil group A (1% of the area) is present throughout the watershed in small patches near streams. The majority of group A soils are in two separate patches which are located on gradually sloping terrains and overlay granite. Soil group C (21% of the area) is present in small patches along the hillslopes that drain into North Grape Creek and Dry Hallow. The majority of Group C soils are deposited on the hillslopes (down hill of group D soils) and flood plains that drain to Willow Creek. After the confluence of the three major streams in NGSW, the vast majority of the area around North Grape Creek stream channel is soil groups D,

except in a few small patches (Map 48, Appendix A).

Saturated Hydraulic Conductivity

The soils in the sub-watershed are primarily a mosaic of hydraulic conductivity ranging from 8.7 µm/s to almost zero (impermeable surfaces) with most of the soils being closer to around 3 µm/s. The few exceptions here are in and along stream valleys where the hydraulic conductivity ranges from about 9 to 90 µm/s (Map 49, Appendix A).

Depth to Restrictive Layer

Before the confluence of the three major stream channels of NGSW (North Grape Creek, Dry Hallow Creek, and Willow Creek), there is a general trend of the depth to a restrictive layer changing from moderate on the uplands (42-66 inches) with several patches of shallower soils (0-41 inches), to deep in the three major stream valleys (67 – 201 inches). The area draining to Willow Creek in particular has large areas in the stream valleys where the depth to a restrictive layer is greater than 67 inches and very often greater than 201 inches.

After the confluence of three major streams the depth to restrictive layer of the remaining upland drainage to North Grape Creek, changes from moderate to very shallow moving toward the outlet. The exception here is a deep restrictive layer located in the immediate stream channel (74-86 inches) near the Northern watershed boundary overlaying the remaining Cretaceous geology (Glen Rose and Hensel Sands) (Map 50, Appendix A).

Potential Farmland

When prime farmland is considered, NGSW ranks second behind the SWIW for percentage of area considered potential farm land (24% of the area) (Table 3). The area considered potential farmland is located almost exclusively upstream of the confluence of the three major stream channels in the sub-watershed, with the exception of a patch near the Northern watershed boundary overlaying the remaining Cretaceous geology (Glen Rose and Hensel Sands). Potential farmland is also located almost exclusively along stream channel valleys. The area draining to Willow Creek contains the majority of land considered prime farmland (Map 51, Appendix A).

Potential Erosion

The majority of the NGSW has moderate to very low potential for water erosion (77% of the area) (Table 4). Soils with moderate potential (34% of the area) are located primarily on the uplands, while soil with low (29% of the area) and very low (14% of the area) potential for erosion are located in and along the gradually sloping stream channels and channel valleys. Areas of high potential erosion (16% of the area) are located primarily on slopes near stream channels. Soils with very high potential erosion (7% of the area) are located primarily in one large patch near the outlet of the watershed. NGSW and the JCIW are tied for a distant first for the greatest percentage of area with a very high potential for water erosion (Map 52, Appendix A).

Cypress Creek Sub-Watershed (CYSW)

Soil Texture

The soils in the Cypress Creek Sub-Watershed (CYSW) are diverse in terms of land form association (uplands, hill slopes, stream channels, etc.) (Table 1). This is due mainly to the change in geology across CYSW moving down stream as the Cretaceous layer are eroded away exposing the highly faulted Paleozoic rock. In the uplands where the Cretaceous rock is not eroded the soils are primarily clay loams, and the soils in and along the stream and the stream channels are clays with small patches of silty clays. There are also clay deposits on ridge lines where the Fort Terret member of the Edwards formation is still present. Moving further down stream there are significant patches of silty clay and loamy sand, where the Hensel Sand and Welge Sandstone member outcrop.

Again moving down stream, the Cypress Creek valley widens over an outcrop of Paleozoic rock. Here the soils are primarily loams, but they give way to clays as the valley narrows and the surface geology returns to Cretaceous age strata. Soils near the boundary between the Paleozoic valley and the Cretaceous slopes and tributaries are a patch work of sandy loams, silty clays, and clays, while the uplands overlaying the upper Glen Rose are primarily clay loams (Map 53, Appendix A). In total, the CYSW is covered by 47% clay loam to silty clay, 32% clay to silty clay, and 21% loam to fine sandy loam.

Hydrologic Soil Group

Soils of the hydrologic group C cover 50% of the CYSW and are primarily deposited along the watershed boundary and around a large deposit of soil group D (48% of the area) that lies along the center line of the sub watershed (Table 2). Small patches of soil group A (less than 1% of the area) and soil group B (1% of the area) can be found along steam channels and stream valleys (Map 54, Appendix A).

Saturated Hydraulic Conductivity

The soils in CYSW fall within two primary groups in regards to saturated hydraulic conductivity. The first group includes soils with a saturated hydraulic conductivity of 6-12 µm/s in the uplands and hillslopes. The second group includes more restrictive soils with saturated hydraulic conductivity of 0-3 µm/s located in the wide stream valley of Cypress Creek and along stream channels throughout CYSW. There are also significant patches of soil with saturated hydraulic conductivity of about 3-6 µm/s buffering the junction of the primary two groups, and there are also some small patches in stream channels where the saturated hydraulic conductivity is about 12 to 85 µm/s (Map 55, Appendix A)

Depth to Restrictive Layer

For the majority of the soils in the CYSW, the depth to restrictive layer is between about 25 and 50 inches. The most significant exceptions are patches of very deep soils (201 inches to a restrictive layer) that are present in and along the stream channels that overlay Cretaceous geology or spill out over Paleozoic layers. Also, on some hill tops, there are patches of soils with a depth to restrictive layer between 0 and 30 inches (Map 56, Appendix A).

Potential Farmland

Cypress Creek Sub-Watershed ranks third highest amongst the studied sub-watersheds and watershed increments in the Pedernales River Watershed for the percentage of area considered prime farm land (22% of the area) (Table 3). The majority of prime farm land is located along stream channels and terrace that overlay Cretaceous geology (Map 57, Appendix A).

Potential Erosion

The majority of soils in the CYSW have high potential for water erosion (55% of the area) (Table 4). Soils with moderate potential for soil erosion make 22% of the sub-watershed area and are primarily associated with deposits that overlay Cretaceous geology either on ridge lines on the Fort Terret formation, along stream channels in the Upper Glen Rose, or on slope overlaying the lower Glen Rose formation and Henzel Sand. Soils with low and very low potential for erosion cover 21% of the sub-watershed area and are found almost exclusively overlaying patches of Hensel Sand. The largest patches of soils with low to very low potential for erosion are found primarily in stream channels in the western portion of the CYSW and in its flood plains and low lying hills to the north of Cypress Creek in the eastern portion of the CYSW (Map 58, Appendix A).

SUMMARY

The descriptions presented above have the potential to yield many previously unrealized associations, because an inquiring mind could quickly cross reference soils information in a hydrologic context. For the purpose of illustration, three examples are offered below.

Example 1

Sub-watersheds and incremental watersheds of the Pedernales River Watershed fall into three groups with respect to hydrologic soil groups (Table 2). The first group includes NGSW, FBSW, and SGSW. These sub-watersheds are characterized by having at least 72% of their areas covered by soils of hydrologic group D, with significant amount of soils of hydrologic groups C and B in their stream channels. Therefore, one should expect that these sub-watersheds may generate less runoff relative to the other studied sub-watersheds during periods of small rainfall events when only the soils near the stream channels contribute runoff.

On the other hand, one should expect that during periods of large rainfall events, these sub-watersheds could contribute more often and in greater magnitudes because of the larger proportions of soils of hydrologic group D. The second group includes MCSW, FCSW, and CYSW. These sub-watersheds are characterized by having no more than 49% of their respective areas covered by soil of hydrologic group D and almost the rest of their respective areas covered by soils of hydrologic group C. Therefore, one should expect that this group may generate more runoff relative to the other studied sub-watershed during periods of small rainfall events when only the soils near the stream channels contribute runoff.

Though as with the first group there may be a switch during larger event. To illustrate, during periods of large rainfall events, this group’s uplands may contribute less often and in lower magnitudes, because their upland areas are covered primarily by soils of hydrologic group C.

With that said, no sub-watershed in this group has more than 2 % of their respective areas covered by soils of hydrologic groups B or C. Therefore, these sub-watersheds are expected to have high runoff potential under any type of event.

The third group, including SWIW and JCIW, is likely to have the lowest runoff potential. These incremental watersheds are characterized by having less then 56% of their areas covered by soils of hydrologic group D, and they have also significant amounts of soils of hydrologic groups A and B near and in their stream channels. Following what has been already discuss above, it is expected that this group may generate less runoff relative to the other studied sub-watersheds during periods of small rainfall events when only the soils near the stream channels contribute runoff. Also it is expected that this group will generate less relatively runoff during larger events, because of the lower proportions of soils of hydrologic group D in their upland areas.

Thus, based on soils properties alone, there appears to be distinctly different runoff-generating potentials for the studied sub-watersheds and incremental watersheds in the Pedernales River Watershed. Therefore, future studies should address this important question. Perhaps it would be appropriate to consider the hydrologic implications of soil characteristics in these sub-watersheds, including spatial patterns of soil texture, saturated hydraulic conductivity, and depth to soil layer.

Example 2

The studied sub-watersheds and incremental watersheds also fall into three groups of potential farm land (Table 3). The first group includes FBSW, MCSW, and FCSW. This group is characterized by having no more than 16% of their respective areas classified as prime farm land. The second group includes NGSW, CYSW, JCIW, and SGSW. This group is characterized by having between 22 to 24% of their respective areas classified as prime farm land. The third group is represented by the SWIW. This sub-watershed has the most potential farm land (35% of its area). Future studies should incorporate this information in the analysis of the hydrologic implications of land use change in the sub-watersheds.

Example 3

The studied sub-watersheds and incremental watersheds also fall into three groups with respect to potential erosion risks (Table 4). The first group, which includes CYSW, MCSW, FCSW, is characterized by the fact that each sub-watershed has at least 55% of its area covered by soils with a high potential for erosion. The second group, which includes FBSW, NGSW, SWIW, and SGSW, is characterized by the fact that each sub-watershed has more than 23% of its area considered to have high or very high potential for erosion. The last group, which includes the JCIW, falls between the other previously mentioned groups in terms of potential erosion risk, given that 38% of its area is classified as having high to very high potential for erosion. This information has important implications for soil conservation (erosion control) and water quality management in the Pedernales River Watershed.

CURRENT AND HISTORICAL LAND COVER CHANGES IN THE PERDENALES WATERSHED

INTRODUCTION

Human manipulation of land cover and land use has profoundly affected riverine systems. Molnar et al (2002) have pointed out the inadequacy of the traditional approach of studying riverine systems that focuses only on the river reach scale and regards stream flow as a steady driving force. They remark that it is incomplete to study the role of stream flow in the river ecosystem without studying the watershed processes that are responsible for stream flow variability and water quality. They explain that a vision of river management relative to the watershed is critical for the evaluation of conservation projects and potential anthropogenic impacts. This view represents a growing world-wide opinion in the field of water resources management concerning landscape change and its effects on river systems. Land use and land cover changes at the watershed scale are the primary way that humans affect water resources and aquatic ecosystems (Dunne and Leopold 1978; Faulkenmark and Folke 2002, Froney et al. 2001). It is clear that the community of experts regards the effects of land use/ land cover on river ecosystems like the Pedernales River Watershed as an essential element to any conservation efforts.

Land cover in the Pedernales River Watershed has been studied in the past, although only two publications have concentrated on the watershed context (LCRA 2002; TNC 2007). The two watershed-based studies only extracted or cobbled together existing land cover data from varying sources into a picture that spans the Pedernales River Watershed. Most of these data sources were created and intended for analysis at a much larger scale such as the state or regional scale. For example, vegetation maps such as that shown in Map 1, Appendix B and used in the referenced Pedernales River Watershed studies, do not show any of the cultivation or development in the watershed where very little natural vegetation is present. One of the studies even notes that the classification scheme used to create the available land cover maps obviously changed at the boundary between Gillespie and Blanco Counties (LCRA 2002). It is important to note that the future of land cover analysis points to satellite data products. However, current products, such as the NLCD, are at an inadequate resolution and have not standardized their classification scheme between their limited years of availability. Other higher quality satellite products are available, but at very high prices.

A higher quality data set is needed to be able to analyze the effects of current and historical land cover in order to evaluate the potential effects of land cover change on the riverine system and prevent land degradation. One failing of the current data products in addition to those discussed above are that the data cannot be easily updated or edited by secondary users. For example, satellite images used in remote sensing are expensive and manipulation of the product is beyond the expertise of the typical stakeholder. Also, the resolution and delineation of more readily available data products are so low that Common Land Units are not mutually exclusive or do not have boundaries related to real physical features on the landscape, thus making them unsuitable for division into subclasses. For example the National Land Cover Dataset, was found to grossly differ from Digital Othrophotography.

Creating a data set based on Digital Orthophotography Quarter Quadrants (DOQQs) addresses many of the limitations of the other available data. DOQQs resemble photographic images and therefore are easily interpreted by the casual user. Also DOQQs show the landscape at a higher resolution (1 meter) to clearly identify tillage patterns, houses, and even individual peach trees in the case of the Pedernales River Watershed. The versatility of these data sets has created high demand for DOQQs, and consequently several years of data developments are becoming increasingly available, and there is a commitment by state agencies to provide and continue to add to these data sets. These data sets are readily available and often free or at very affordable prices from state digital information clearing houses like Texas Natural Resources Information System, or collaborative county level organizations like the Capitol Area Council of Governments, which includes the Eastern counties of the Pedernales River Watershed.

Finally, these data sets are used by the US Natural Resource Conservation Service (NRCS) to catalog their county level agricultural projects and to help them delineate areas into common land units at the farm and often to the individual cultivated field level. The NRCS does not release their information because it would hinder their ability to work with producers; however, they do distribute the boundaries data as a GIS layer. The amalgamation of the NRCS data with available DOQQs is a combination of data that provides the basis for the creation of a high quality data set which is easily updated by the secondary user. With that said, the use of digital photography in land cover classification, even at the 1 meter resolution, requires understanding of local land use practices. Any well-planned land cover classification should first consult with local experts and community members.

For the aforementioned reasons, this study attempts to describe current and historical land cover as well as land cover change by conducting two primary initiatives. First, a brief historical narrative of land cover in the watershed was developed by conducting interviews with community members and local experts. Second, a new land cover data set for the years 1996 and 2004 was created and used to identify current spatial patterns of land cover and recent trends in land cover change using DOQQs.

METHODS

Historical Narrative of Land Cover Change

Background and supplemental data were gathered from the community. This process proceeded by arranging meetings with local county officials and workers, federal and state natural resources workers, and consulting engineers. A historical narrative was developed from the interviews and conversations that occurred during this process. Questions were asked and data sets obtained regarding land cover or other landscape features that might affect the hydrologic regime of the Pedernales River Watershed. The interview process structured around the identification of land cover and landscape features on five large 3 ft by 4 ft DOQQ maps that clearly showed individual cultivated fields. Sub-watersheds, roads, and county boundaries were superimposed to aid in orientation for those interviewed. When deemed appropriate, features were drawn on the map and other general information was recorded in field notebooks and used to guide classification in a GIS environment. The interview process produced several leads to additional expert opinion and informative data sets.

After the interview process was completed, the gathered information was reviewed and a working protocol was developed for the heads up classification of NRCS common land units using DOQQs. It was determined from preliminary review of geographical information gathered on subdivisions that it was reasonable to classify them in terms of the greater matrix of range land in which they occurred. It was reasoned that this would adequately represent the hydrologic responses due to sparse development as observed in subdivision locales in the 2004 DOQQs. As explained in the historical narrative, most were very low density developments of one house per 5 to 25 acres which did not preclude the common land unit from being classified under one of the already proposed classification types. Furthermore, many subdivisions were incomplete as of 2004. In addition to the brief historical narrative, subdivisions are discussed in the "Results" section under "Evaluation and Limitation of the Data."

Analysis of Mapping Resources

DOQQ coverages of the years 1996 and 2004 were chosen because they were the only years readily available at the 1 meter resolution from TNRIS at the time of this study. It should be noted that additional years of DOOQ coverage have recently become available but were not classified for this study. Classifications were chosen as a result of the review process regarding land cover types that might be relevant to the hydrologic process or that might be of special interest to water quality. The classification is structured in a hierarchal order with family classes: cultivated, abandoned, cleared, rangeland, developed (urban or roads), and water. "Cleared" was used to classify land that was not distinguishable between range land and cultivated land. Cultivated land, abandoned land, and rangeland were further classified into subclasses: cultivated land (tilled, contoured, orchards, vineyards, cultivated no visible tillage), range land (high, medium, and low density of trees or canopy coverage), and abandoned land (the abandoned subclasses all have a direct counter part within the cultivated land subclasses). After development of this classification system, a heads up classification of the DOQQs was conducted.

The heads up classification process occurred in a GIS environment and employed the ESRI software Package ArcGIS 9.2. The NRCS "common land unit" polygons were superimposed over a full watershed coverage of the 1996 and 2004 DOQQS. The polygons were classified one by one for 1996 and then the same for 2004 by toggling between the coverages. Polygons were further delineated using the "Cut Tool" as needed to better represent one classification type and additional polygons were added as need. It is important to emphasize that the classifying process proceeded by classifying one polygon for both 1996 and 2004 before moving on to another polygon. This procession of the classification procedure was considered a crucial step in developing reliable indications of land cover change. Additionally, the one to one procession improved the overall classification process because the two perspectives bolstered greater discernment of obscured features.

After completion of the classification process, ArcGIS was used to calculate areas for each polygon and then the attribute table was exported to Microsoft Excel for manipulation in a spreadsheet environment. Quality control was conducted in an iterative process by tabling the data and using filters and pivot tables to identify inconsistencies and then addressing those concerns in the GIS environment. An evaluation of the data set is discussed in the “Results” section under “Evaluation and Limitation of the Data.” This section also includes suggested improvements in future runs of the process. The quality-controlled data was then summarized in tables for analysis of land cover spatial distribution and land cover change in regards to family classes and subclasses. These elements were summarized by the Pedernales River Watershed total gauged area, and by the gauged sub-watersheds and watershed increments. Sub-watersheds are areas that include all of the drainage upstream of a specific streamflow gauge. Incremental watersheds are similar to sub-watersheds but do not include any drainage area that drains past an upstream gauge, consequently all incremental watersheds in this study included segments of the main stem of the Pedernales River. Maps were also created to enable the visualization of land cover association with other landscape features like stream channels and upland plains.

RESULTS

A Brief History of Land Cover Change in the Pedernales River Watershed

Declarative Statement

The following historical description of the Pedernales River Watershed’s land cover change over the past century is taken from the observations and opinions of citizens and natural resource workers and government officials living in the watershed. This account is not meant to serve as the definitive account of historical land cover in the Pedernales River Watershed, but instead to record current views of the past and to serve as a platform to provide direction for the classification of common land units into land cover, to foster debate, and above all to provoke further interest and study of the Pedernales River Watershed.

History

At the beginning of the 20th century agricultural practices were well established in the Pedernales River Watershed area. Most of the populations lived on farms or ranches and subsisted off of home gardens that were maintained in addition to cash crops. Ranches were managed for livestock production by clearing brush with fire. Most oak trees at this time where between 50 to 70 years old because fire kept out new growth. Cultivation continued to intensify each decade as mechanized farm equipment and artificial fertilizers became more available. By the 1950s, row crops such as corn, maze, and milo were prevalent but the main cash crop was cotton. In the 1960s there was a major reconfiguration of the social and economic system that had major impacts on land use practice in the watershed.

Large portions of the population moved out of the watershed, cultivation declined, and fire suppression became prevalent. It is possible that many factors contributed to this shift, but those most recognized by interviewees are mentioned here. Cotton root rot decimated the primary cash crop in the area and severely affected the economy. The cotton root rot effects were compounded by the already fragile state of the economy due to having just suffered through a record drought in the 1950s. The cost of cultivating food crops rose due to increased fuel prices. Also, an increase in white-tailed deer population, the result of screw worm irradiation, increased the cost of cultivation by requiring the construction of high fences. It was noted that most people left for the city in search of steady pay. In the aftermath, neighbors began to complain about burning, so fire was routinely suppressed and oak and mesquite trees became more prevalent.

Cedar was mainly suppressed by the browsing of mohair goats until the recent repeal of mohair subsidies circa 2002. Now in Blanco County, which comprises the most western portion of the watershed, cultivation is almost exclusively forage or improved grass for livestock and very few if any fields grow cash crops other than hay. Currently in Gillespie County, in the western portion of the watershed where historically a large majority of the cultivation of cotton took place, the row crop agriculture (18 inch tillage) that is still practiced is mainly food crops which is cycled with drill crops (9 inch tillage) or left fallow. Since the late 1980s and early 1990s, several boutique farms have been established, and though they do not represent a large portion of the cultivated land, they are becoming more prevalent. Of the boutique farms, vineyards and peach orchards are by far the most common, however peach orchards were actually more numerous in the past. Current range land management is focused on suppressing new growth cedar and reestablishing grass lands. It was noted by members of the NRCS that they had seen grass take back well-managed areas that were thought to be unsuitable for quality grass production.

Analysis of Mapping Resources

Evaluation and Limitation of the Data

The classification procedure resulted in a data set of 15,088 classified polygons representing 99.84% of the total study area (688,455 acres). A total of 659 polygons were left unclassified representing 0.15% of the total study area. Also no one sub-watershed or incremental watershed had less than 99.66% of its total area classified (Table 1).

Most land cover fit well within the classifications scheme, however, driveways and farm houses were not considered in the classification of the larger polygons. In all of these cases, the features were thought to represent a very insignificant portion of the polygons. Also, the vast majority of farm houses were very near major roads which were classified as developed and therefore are partially represented, if by surrogate.

The classification of range lands as categorical densities was somewhat problematic. Most of these issues were do to the unit area problem where classification of an area as high or medium density depends on the size or placement of the frame. This effect on determination of land use change should be minimal because the years 1996 and 2004 were classified within the same frame. Care was also taken to routinely revisit already classified polygons to maintain consistency as the process proceeded. In future runs of the process, range land area once delineated from more fine resolution features may be adequately sampled by low resolution satellite data, which would allow for greater consistency in the data. The efficacy of this approach must first be studied relative to a “gold standard” data set, such as classifying range land polygons with a fine grid superimposed over a coverage of DOQQs. Future runs will give focus to improving estimates of range land density, because reducing the density of rangeland is goal of several management activities in the watershed, which view high density rangeland as excess evapo-transpiration and lost grassing land.

Land Cover Change from 1996 to 2004

In general, land cover changed very little from 1996 to 2004. Rangeland (84.33%) and cultivated land (12.05%) were predominant family classifications in 2004 and these proportions were very similar in 1996. (Table 2). No family class of land cover changed by more than 0.28% of the total study area (Table 2). The percentage of abandoned cultivation, cleared land, and developed land increased while the percentage of range land or land under cultivation decreased. It should be noted that orchards, vineyards, and abandoned land classes increased substantially relative to their own size. Of the total area classified as range land, no class changed by more than 1%. Of the small changes observed, one visible shift was a 0.33% swap between high density and medium density rangeland. Though land cover change was detected between family classes and the sub classes, the changes were very small relative to the total study area.

The general finding that land cover changed very little from 1996 to 2004 is also supported at the scale of the individual sub-watersheds and watershed increments (Map 2, Appendix B). No sub-watershed or incremental watershed experienced a change of more than 1% of its individual area in any one family class of land cover (Table 3). Also, there was very little change in how the sub-watersheds and watershed increments ranked relative to percentage of their area under a particular family class of land cover (Table 4 and Table 5). In fact, the only change in rank at the family class level besides the relatively insignificant “other class” was cleared land.

Even this change was minimal, as it was caused by Flat Creek sub-watershed moving from second to fourth in the percentage of individual area classified as cleared land. The change only represented a 0.04% change over the Flat Creek sub-watershed area. At the sub class level the percentage of change relative to each watershed was slightly higher than the family class, because change within a particular family class’s subclasses cancelled each other out and were not seen at the family class level (Table 6). This occurred most notably in the Flat Creek sub watershed with low density range land increasing by 3.95% as a direct result of a decrease in high and medium range land size, and in the North Grape Creek sub-watershed with medium rangeland size increasing by 2.63% as a direct result of a decrease in low and medium density rangeland. With these two instances noted, the general findings were that almost all of the changes in sub-class coverage were very small relative to each individual watershed and did not amount to more than 1 percent in the vast majority of cases.

Land Cover Variation in Sub-Watersheds

In the study area as a whole, range land and to a lesser extent cultivated land predominates. All of the sub-watersheds and watershed increments exhibit this characteristic, however, they distinctly vary from one another across a spectrum that moves from higher percentages of range land to increased percentages of cleared, cultivated, and developed land. Within this spectrum there are four distinct groups. The first includes the eastern sub-watersheds consisting of Miller Creek, Cypress Creek, and Flat Creek. The main characteristic of this group is that over 96% of the area is covered in range land (Table 7 and Table 8). The majority of what is not range land in this group is under cultivation, and almost all cultivated land is contoured or without tillage (Table 9). There were no noticeable vineyards or orchards in these sub-watersheds.

The second group includes the Johnson City incremental watershed and the Fredericksburg sub-watershed. For clarity it is appropriate here to note that the major development in the study area is the City of Fredericksburg, which is in the Stone Wall incremental watershed and not the sub-watershed of the same name. Though separated by considerable geographic space, the Johnson City incremental watershed and the Fredericksburg sub-watershed are similar. They are both primarily covered in range land (about 85% to 88%) but have substantially more land under cultivation than the eastern group (about 10% to 11%). Also, both have about 1.5% of their area covered by development. The Johnson City incremental watershed and the Fredericksburg sub-watershed do vary in that Fredericksburg has a considerably higher proportion of its cultivated land under tillage rather than contoured (3.41%), however, the highest portion of cultivated land in both areas is contoured (Fred. 5.34% and John 7.52%).
North Grape Creek sub-watershed and South Grape Creek sub-watershed make up the third group. Though this group sits on opposite sides of the Pedernales River they are still very similar. This group, too, is mainly range land but has more cultivated land than group two (15% to 16%). This group, however, has less developed land than group two (about 0.5%). The majority of cultivated land in both sub-watersheds is contoured with very little under tillage (less than 1.26%). In fact, North Grape Creek has the highest percentage of contoured land (12.54%). The group three sub-watersheds differ amongst themselves in that the South Grape Creek sub-watershed has a considerably higher percentage of cultivated land with no tillage or contours (4.97% versus 1.67%). In this regard, South Grape Creek is the only watershed similar to the Stone Wall incremental watershed. Also, while South Grape Creek has no observable orchards or vineyards, North Grape Creek has a small amount of orchards and the largest percentage of land cover in vineyard, though it was only 0.04%.
The fourth group is exclusively occupied by the Stone Wall incremental watershed. This increment of the Pedernales River Watershed, though primarily range land (70.98%), has the largest proportion of developed and cultivated land amongst the sub-watersheds studied. About 23% of this incremental watershed's area is under cultivation and about 4% percent is developed land. Also the Stone Wall incremental watershed has the highest percentage of tilled land and cultivated land with no contours or observable tillage. Plus Stone Wall has the highest percentage of land covered by orchards and the second highest percentage of land covered by vineyards.

CONCLUSION

The spatial arrangement of land use amongst the sub-watersheds and incremental watersheds of this study has important implications for management. Since at least 70% of all of the study group is range land, careful consideration of management practices occurring in range land areas must be considered in regards to water quantity and quality throughout the watershed. Regarding cultivation practice, though land is cultivated throughout the study area, special attention should be paid to the segment of the Pedernales River that runs through the Stone Wall incremental watershed.   This segment has by far the highest percentage of developed land and land under cultivation.

We recommend focusing monitoring resources and water quality studies for impacts on the river ecosystem in this area. This area is likely to have considerably more nutrient loading discharging into the river than any other portion of the watershed. Changes in aquatic species assemblages in this area may serve as an example for changes that the ecosystem of the entire river may undergo under a scenario of increased nutrient loading throughout the watershed. Consideration should also be given at the confluence of North Grape Creek, as this segment may represent an area where nutrient loading from cultivation may spike after having dissipated through the Johnson City incremental watershed. Furthermore, specific loadings from vineyards may be present here.

Generally, very little land cover change occurred between 1996 and 2004 in the Pedernales River Watershed. This period may be suitable as a benchmark for the effects of land cover change in the future, and variation in hydrologic and water quality data during this period may be considered as a range of variation reasonably expected during a period of relatively consistent land cover conditions.

In regards to the success of this effort, the methodology of creating the data set did deliver a satisfactory product that allows for a fine resolution of characterization at the watershed scale (less than a million acres) and that adequately differentiates between features of value relevant to hydrologic and water quality analysis. It is recognized that improvements could be made to insure better standardization in the estimation of range land tree and shrub densities. Also, methods need to be developed to reconcile residential subdivisions within the classification system, especially since their spread is observably more prevalent in preliminary analyses of 2006 DOQQs.

These issues can easily be resolved in updates of the process, due to the flexibility of the classification scheme and the user-friendly nature of the data structure. The main limitation of the process is the amount of work needed to create a quality product, however, the simplicity and intuitiveness of this process may be its greatest strength. For example, in future studies this process could serve as a catalyst for community involvement if stakeholders were incorporated into a classification project. Not only would research cost be reduced, but a well of community know-how could be tapped, and previously unrealized associations could be made.

PRECIPITATION ANALYSIS

Introduction

As communities of the Texas Hill Country continue to experience rapid growth, the Pedernales River Watershed faces increased human pressure and threats to its aquatic systems. Human modification of land and water resources, and as well as other problems that confront landuse planners, can be analyzed by considering the path that water takes, and what water is doing at various stages along its path. This requires knowing where and in what quantity water enters the system (Dune and Leopold 1978). Therefore, accurate estimates of areal precipitation are needed at the scale at which water is to be traced. The identification of a method to accurately estimate areal distribution of precipitation is needed in order to create a dataset for hydrologic analysis in the Pedernales River Watershed.

Purpose

There are several methods of estimating areal rainfall. The accuracy of each method depends on the context in which each is used. The purpose of this study is to assess and compare several interpolation techniques for estimating monthly areal precipitation in the Pedernales River Watershed across a range of scenarios. The objective was to find a “best” technique that out performed other techniques consistently. To determine the “best” technique,” this study addresses the questions below, and then evaluates each technique before picking a winner.

Does “best” technique vary depending on the resolution of the rain gauge network used as input data?
Does “best” technique vary relative to the magnitude of monthly rain?
Does “best” technique vary due to parameterization or “fine tuning” of applicable interpolation techniques?

Background

The National Climatic Data Center (NCDC) maintains a data base of climatic data that includes a network of rain gauges in and around the Pedernales River Watershed. These data are readily available and often long term. Rainfall monitoring in the majority of Texas is conducted with the spatial density of the NCDC. Many watershed studies conducted in Texas have depended solely on the NCDC data; however, little has effort has been made to examine and correct the possible occurrence of errors in precipitation estimates. In fact, often only one rain gauge is used such as in the Lower Colorado River Authority LCRA watershed assessment report (LCRA 2002).

Recently, the LCRA installed an additional rainfall network primarily for daily operational level management of their reservoir systems. The resulting increase in rain gauge density provides a unique opportunity to evaluate the Pedernales River Watershed at a higher scale of hydrological resolution than has ever been accomplished in the past. Thus, determining the technique that can best transform point data of combined networks into areal estimates of precipitation has promising implications for hydrologic analysis and management.

Methods and Materials

Study Design

Five spatial interpolation techniques and one ready-made product were evaluated and compared regarding their accuracy in estimating monthly areal precipitation in the Pedernales River Watershed. They were chosen because each has been used by hydrologists in other studies (Ahrens 2005; LCRA 2002; Zheng and Basher 1995). Each technique is readily available in a format compatible with GIS applications, such as the ESRI product ArcGIS 9.2, or may be easily accomplished in a spreadsheet computational environment. The one "ready-made" product, PRISM, was included, because it represents a compelling "one-stop shop" alternative. The selected interpolation techniques are discussed in greater detail below under "*Interpolation Techniques*". The methodology behind the creation of the PRISM dataset is also discussed.

The primary statistics used to evaluate best techniques is discussed below under statistical evaluation of *"Best Technique"*. Discussion of how the study addressed the consideration regarding the identification of one best technique is discussed separately under *Analyzing "Best Techniques" Across Conditions of Varying Density of Precipitation Gauges*; *Analyzing "Best Techniques" Across Varying Monthly Magnitudes of Precipitation*; and *Analyzing Variation in "Best Techniques" Relative to the Parameterization of Applicable Techniques*. Finally, information relative to the data set used in this study is discussed under "*Precipitation Datasets.*"

Statistical Evaluation of Best Techniques

Root mean square was the summary statistic used to evaluate the overall prediction error of a surface. The difference between the predicted and observed monthly precipitation at each validation point is referred to in the study as prediction error. Root mean square error (RMSE) is the standard summary static used in ArcGIS to evaluate the prediction error of an interpolated surface. Root mean square error was the only summary statistic used because in preliminary review of surfaces created for five months, in which five different statistics were used, all where found to be redundant. In all instances, all five techniques selected the same "best technique." Figure 1 further illustrates the covariation between prediction error statistics.

In a plot of maximum prediction error against the root mean square error of over 100 surfaces, regression analysis yields a strong linear relationship between the two summary statistics (R^2= 0.8). These findings give creditability to using only root mean square which dramatically reduced the labor cost of extracting and processing data. Root mean square error is calculated using the equation below.

$$\sqrt{\frac{\sum (f(x_i) - y_i)^2}{n}}$$

The difference between the predicted (Y_i) and observed (X_i) monthly precipitation at each validation gauge represents the prediction error at that gauge. Root mean square is calculated by taking the sum of squared prediction errors, then dividing by the number of validation gauges (n) before finally taking the square root.

Analyzing "Best Techniques" Across Conditions of Varying Density of Precipitation Gauges.

Using the combined resolution of the NCDC and the LCRA rain gauge network to estimate areal rainfall allows for a much finer understanding of rainfall variation within the Pedernales River Watershed than using only one network. On the other hand, increased resolution of climatic measurement does not necessarily equate to increased realism (Daly 2006). If a higher density of gauges cannot decrease prediction error, then the inclusion of additional gauges in the analysis is not justifiable.

Furthermore, maintaining a network of climatic monitoring stations requires substantial resources, and should therefore demand much more than a marginal reduction in prediction error. For the purpose of the analysis performed here, if increased resolution equated to increased accuracy, then the techniques were run using three orders of gauge density. The first order density included only the National Climatic Data Center network, and the second and third orders represented increasing densities that were accomplished by incrementally adding LCRA rain gauges to the predicative data set of gauges (see Map 1, Appendix C).

Analyzing "Best Technique" Across Varying Monthly Magnitudes of Precipitation
To analyze the effect that varying magnitudes of precipitation might have on "best techniques," months were chosen for the study that represented five distinct groupings of rainfall magnitude. To accomplish this, all months from the study data set (October 2002 to July 2007) were ranked by the mean of precipitation values from the 23 NCDC study gauges. Then 15 months were systematically chosen at quintile interval, occurring between October 2002 and July 2007.

% = rank of month (precipitation) / total # of months

In reference to the above relation, the months selected for this study were equal or adjacent in rank to the following: the lowest month of record, the monthly value exceeded 75% of the time, 50% of the time, 25% of the time, and the lowest month of record. Three months were chosen for the five intervals to add replication in order to allow for a more robust interpretation of results.

Analyzing Variation in "Best Techniques" Relative to the Parameterization of Applicable Techniques

The following interpolation techniques all have varying options by which they can be parameterized: Inverse Distance Weighted (IDW), Kriging, and Spline. Variation of each one of these technique was compared across the other factors considered in this study (density of precipitation gauges, and magnitude of precipitation), to analyze variation in "best technique" relative to parameterization. This was accomplished by creating surfaces that represent a logical spectrum of values for a selected parameter from each technique. The parameters used are discussed in the description of each technique, below.

Interpolation Techniques

Inverse Distance Weighted (IDW)

Inverse Distance Weighted (IDW), as used in this study, executes Tobler's first law of geography: all things are related, but closer things are more related than things that are further apart (Tobler 1970). IDW is a deterministic interpolation method, which uses a weighted average of measure to determine the interpolated value of a non-measured point. IDW assigns weights to neighboring observed values based on distance to the interpolation location, giving greater weight inverse to distance. (Ahrens 2005). In this study IDW was calculated as the weighted average of the five nearest NCDC monthly values using the equations below to determine the weighting factor or W(D):

$U= 1/D^2$
$W(D)= U / U \text{ total}$

where D = distance of an observation from the interpolation location, U =
and U total = the sum of all considered U's. The power of distance was set at 2, because it is often used as the assumed or default value in IDW calculation (Ahrens 2005). All IDW surfaces used in this study were created with the Arc GIS spatial analyst. The parameter manipulated to evaluate the effects of parameterization on IDW was the number of neighboring rain gauges used in the calculation. Increasing this parameter smoothes the data to a global value as more neighbors are included, decreasing this number makes estimations more localized. The values for this parameter used in this study were 10, 8, and 5.

Ordinary Kriging

Kriging is a statistical interpolation method historically introduced by Krige (Krige 1962; Reubel and Hantel 2001). Kriging has several variations, but the most common definition of Kriging is recommended over other Kriging methods unless there is a good reason to wander (Johnson et al. 2001). Ordinary Kriging uses a weighted average similar to IDW but the weighting factor is determined by a statistical model (circular, polynomial, etc). The type of model to be used is determined graphically by visually determining the model that best fits a semi-variogram plot between semi-variance of a value and geographical distance.

The semi-variogram used for September 2003 (the monthly precipitation value exceed only 25% of the time) is shown in Figure 2. The ArcGIS Geo-statistical Analyst was used to create the entire Kriging surface in this study. The spherical function was used for every surface. The nugget was set at zero for models in months where the fit of semi-variance to distance relationship benefited. To evaluate the effects of parameterization on Kriging, the number of neighboring rain gauges used to calculate a cell was manipulated. Increasing this parameter smoothes the data to a global value as more neighbors are included, decreasing this number makes estimations more localized. The values for this parameter used in this study were 10, 8, and 5.

Voronoi Diagrams or Thiessen's Polygons

Voronoi Diagrams, also known as Thiessen's Polygons or Dirichlet Tessellations, is a deterministic method of interpolation often applied to precipitation data. The interpolated location is assigned the value of the nearest measured value. (DeMers 2005). The method is normally applied cartographically by drawing polygons that represent the area in which all points are proximal to a certain measured value. In this study, ArcGIS was used to draw the polygons and the validation gauges that fell within a certain polygon were assigned a prediction value that was exactly the value of the prediction dataset gauge the polygon represented.

One Gauge

The simplest method of interpolation is to apply the value of one gauge to an entire study area. This has been the practice of studies previously conducted on the Pedernales River Watershed (i.e. LCRA 2002). This method does not **c**apture the variability between the gauges, so it was used as a null value. To increase the nullifying power of this study, two one-gauge prediction data sets were created (one for the Johnson City gauge and one for the Fredericksburg gauge, both of which are available through the NCDC).

Spline

Spline is commonly referred to as a rubber sheet method. Conceptually, Spline represents a surface with inherent tension that is pulled down or up by the values of point data.
The Spline function uses the following formula for the surface interpolation used in ArcGIS:

$$S(x,y) + \sum_{j=1}^{N} \lambda i R(rj)$$

where j = 1, 2, ..., N (the number of points), λ_j are coefficients found by the solution of a system of linear equations; R is the regularization parameter, and r_j is the distance from the point (x,y) to the j^{th} point. To evaluate the effects of parameterization on Spline, the regularization factor was manipulated. The "regularize" option is conceptually like increasing the tension of the rubber sheet surface represented by Spline. Higher values lead a tighter surface. The most commonly used variations of the regularized parameter were used in this study (0.0001, 0.001,0.01,0.5). (Franke, 1982; Mitas and Mitasova 1988, as sited by Johnston et al. 2001)

PRISM Data Product

The PRISM data set developed by Dr. Christopher Daly of Oregon State is considered a "knowledge-based system" that uses point measurements of precipitation, temperature, and other climatic factors to produce continuous, digital grid estimates of monthly, yearly, and event-based precipitation. (PRISM GROUP 2007) It incorporates point data, a digital elevation model, and expert knowledge of complex climatic extremes, including rain shadows, coastal effects, and temperature inversions.

Since this data can be downloaded already as a surface, valuable hours in processing time can be saved. However, since the dataset does not incorporate the LCRA's hydromet (short for hydrological – meteorological data acquisition system) rain gauge network, advantages of incorporating rain shadows and other features may be of negligible benefit toward creating accurate estimates at the scale of the Pedernales River Watershed.

Data

Precipitation data and latitudes and longitudes of respective rain gauges were obtained from both the NCDC and the LCRA's hydromet. All rain data were aggregated to monthly totals in a spread sheet environment. The Pedernales River Watershed boundary used for orientation within the watershed was obtained from the Environmental Protection Agencies, Better Assessment Science Integrating Point and Nonpoint Sources (**BASINS)** Data archives. Estimates of monthly precipitation were obtained from the PRISM data base using the Prism Group's latitude longitude extraction tool located on their website. (PRISM GROUP 2007)

Results and Discussion:

The results are organized into two parts. The first part discusses the suitability of the LCRA or NCDC rain gauge network to capture spatial patterns of monthly rainfall, called quality of resolution. The second part addresses factors affecting the "best" interpolation method, or factors that may affect which interpolation method has the lowest root mean square error (RMSE).

Effects of increasing gauge density (resolution)

The presentation of results and discussion of best methods is restricted to factors affecting best methods within the finest resolutions. Resolution appears to be the most important factor affecting RMSE, and trumps or retards the other factors so much that it is irrelevant to discuss finding the best technique for this dataset, based on the effects of the other considered factors at coarser resolutions. In most cases increased resolution was accompanied by a decrease in RMSE that was significant enough to cause interpolation methods to overlap in their range of RMSE. (see Figure 2 and 3).

Therefore, the variation in Figure 2 is grouped more by an interaction between resolution and type than any one factor. Notice that in February 2007, IDW is both the worst and best technique depending on resolution. Therefore, resolution can change the best fit method, and cause methods that were the worst performing to become the "best," as was the case in February 2007 (see Figure 2). Since the best method in a month is almost always a third order (an estimate that used the highest density of gauges) then using just the third order data seems appropriate.

Effect of magnitude

The relative performance rank of techniques was not observed to change relative to precipitation magnitude. Magnitude's main effect, relative to the comparison of techniques, is that the difference in performance was amplified. As can be seen in Figure 4, the months are organized from left to right in order of average measured rainfall, and thus because of how the months were originally selected they represent quintile intervals of the average monthly rainfall from January 2002 to August 2007 (lowest, exceeded 75% of time, exceeded 50% of time, exceeded 25% of the time, and the highest). Reading from left to right, RMSE generally increases with magnitude and the separation between techniques increases, culminating in widely separated RMSE values in July of 2002. Thus, though magnitude does not have an effect on which technique performs best, it does cause those techniques that perform badly to perform even worse.

Effect of parameterization (Kriging, IDW, Spline)

Type determines the "best" technique despite changes in parameter, for those applicable techniques. In Figure 5, the range of RMSE for Kriging, IDW, and Spline rarely overlapped. RMSE within their parameterized variants, though all the Kriging variants in a month are lower than Spline variants. The lowest Spline and the highest Kriging are closer than the lowest and highest Spline. This is mainly attributed to high relative variation between Splines (ex: July 2002). Based on these results, the best method can be determined independent of parameterization of the parameters manipulated. Naturally, the winning method can be fine tuned since the difference in root mean square will not be on the order of a change in technique. In conclusion, the effects of parameterization are not relevant when picking a winning technique.

EVALUATION OF TECHNIQUES

One Gauge

The one gauge method performed the worst in predicting areal precipitation in the Pedernales River Watershed. To illustrate, the highest root mean square error in eight out of the fifteen months was held by a "one gauge method"(see Table 1). Also, the one gauge method is often widely separated from the general grouping of RMSE values in a month (Figure 4). The relatively poor performance of the one-gauge method is further demonstrated in that on average its RMSE was 50% to 65% larger than the RMSE of the best technique in a month, when December of 2005 is not considered (Table1). This was by far the highest average difference from the best RMSE in a month. It can also be seen in Table 1 that the median and maximum RMSE also confirm the one gauge technique as the least accurate. December 2005 was removed from the above comparison and those to follow, because several gauges reported zero rainfall, which can confound a comparison of percentages. In conclusion, the above results suggest that the one-gauge method is the least accurate prediction method included in this study.

Voronoi Diagrams (Thiessen's Polygons)

Voronoi Diagrams performed the second worst relative to the other techniques in predicting areal rainfall. The average RMSE in a month was 148% of the best technique - which is again the highest, second only to the one gauge method (see Table 1). In Figure 6 the one-gauge method was removed so that it can be more clearly seen that the Voronoi Diagrams RMSE in general are consistently higher than the other methods. The other statistics in Table 1 also reinforce Voronoi Diagrams as the second worst technique in this study. The Voronoi Diagram technique was the worst method in 4 months, and in one month its RMSE was 217% of the best technique analyzed in this study. In conclusion, the above results suggest that the Voronoi Diagrams technique is not amongst the more accurate methods.

PRISM

The data obtained from the PRISM website did not perform well relative to IDW and Kringing, and at times performed exceptionally badly. The PRISM product usually performed within the range of statistics of the variants of Spline. However, at times it performed exceptionally badly, in one case recording an RMSE that was 250% of the best technique (Table 1). PRISM's high separations from the more accurate techniques can be seen in Figure 4 for July of 2002 and June of 2004**.** In conclusion, the PRISM data did not perform well relative to the more accurate IDW and Kriging techniques.

Spline

None of the variants of Spline performed better than any IDW or Kriging Variant. In Figure 5, only variants of Spline, IDW, and Kriging are shown to contrast clearly the three types. Spline can be seen to vary greatly between its variants, but in general none of the variants cause Spline to move up in ranking relative to IDW or Kriging. This conclusion is supported by the data shown in Table 1. Spline's best performing variant has an RMSE that is on average 126% of the RMSE of the best technique. The highest corresponding values related to IDW and Kriging respectively are 118% and 112%. Also, in two months out of the fifteen months used in the study, Spline techniques had the highest RMSE amongst all techniques including the one-gauge method. In conclusion, though Spline performed better than the more basic techniques used in this study, it was relatively out-classed by IDW and Kriging.

IDW

As can be seen in Figures 4-6, the variants of IDW performed very well relative to the other techniques included in this study. This is supported by the data shown in Table 1 and most notably by the fact that in none of the months did a variant of IDW have the highest RMSE. In fact, on average, IDW's worst performing variant had on average a RMSE that was only 118% of the RMSE of the best technique in a month, while its best performing variant was 115%. These values are the lowest second only to Kriging, however the median performance RMSE area is taken in to consideration IDW does perform the best (see table 1). Also IDW had the lowest RMSE in 5 months out of the 15. On the other hand, in Figure 5 it can be seen that in some cases IDW performed badly relative to Kriging, most noticeably in July of 2004, where the best performing IDW was over 161% of the RMSE of the best technique. In conclusion, IDW performed much better than any other technique with the exception of Kriging.

Kriging
Kriging clearly out performed all the other techniques included in this study with exeption of IDW. Kriging was only second in the number of months that it ranked as the best technique (4 times), but its best performing variant on average had an RMSE that was only 109% of the best techniques with in a month. Also, in no month, excluding December of 2005, was the RMSE of any variant of Kriging more than 126% of the RMSE of the best technique. As can be seen in Figures 4-6, although Kriging is not always the best technique, it is consistently close to the best. In conclusion, Kriging performed much better than any other technique in this study, other than IDW, and had a consistently lower RMSE than IDW.

Picking a winner:
Since magnitude does not appear to affect the selection of methods amongst IDW, Kriging, and Spline, and parameterization does not seem to interfere with a choice being based on technique alone, Kriging was chosen as the winner based on the following criteria that relate to any variant of Kriging used in this study. At the third resolution IDW and Kriging out-performed Spline 11 out of 15 times (see Figure 5) and are relatively close to one another most of the time. IDW has the lowest root mean square error more often than Kriging, but those "wins" are by a relatively small difference in RMSE. Kriging's wins come with a much greater separation in root mean square errors. Also, Kriging is consistently close to a best technique under almost all scenarios, while IDW sometimes has a RMSE of more than 161% of the total of the "best" techniques in a month. Therefore, Kriging appears to be the most appropriate method for estimating areal rainfall in the Pedernales River Watershed when the finest resolution of gauge is used.

Conclusions
This study found that the density of rain gauges, and the technique selected can lead to a considerable increase in the accuracy of areal rainfall estimation. The highest resolution was found to decrease considerably prediction error across methods that could incorporate more gauges. Kriging was found consistently to estimate areal rainfall as the best or close to the best estimate of a month, and was declared the "winning technique". So it is suggested that Kriging be used for estimating areal precipitation for hydrologic studies in the Pedernales River Watershed.

Also, it was observed that spatial patterns of areal rainfall are occurring at a finer scale than the observation density of either the NCDC rain gauge network or the LCRA rain gauge network alone. The improvements in estimation gained by combining the networks suggest that hydrologic studies occurring in other watersheds near the Pedernales River Watershed could benefit from supplementing their local NCDC network, by adding rain gauges, or incorporating other networks like the LCRA hydromet.

Finally the increased performance of estimating monthly precipitation in the Pedernales River Watershed, due to the use of an increased network and a more complex methods of interpolation speaks to the variability occurring between the sub-watersheds in terms of monthly precipitation. Since the monthly rainfall within the watershed is spatially diverse enough to create the large disparity between simple methods like Voronoi's diagrams and more complex methods such as Kriging.

The implications are that tracing pollutants or ground water to its source will require carefully applied areal rainfall estimates because runoff may not be considered uniform within a monthly time step. Thus, the identification of a method to create accurate estimates of areal rainfall at a finer hydrologic scales is essential to properly analyze where water goes in the Pederanales River Watershed system, in addition to analyzing how human activities may be affecting the Watershed's landscapes and water resources.

SURFACE FLOW ANALYSIS

INTRODUCTION

An evaluation of hydrologic variability within the Pedernales River Watershed is needed so that planners can create scenarios that represent reasonable outcomes and consequences associated with the implementation of various “best management practices,” conservation plans, and water resource regulation. A primary question that is fundamental to hydrologic scenario development is analyzing what areas in a watershed generate more or less runoff than other areas of the watershed, and why (Dunn and Leopold 1978).

Many water resource efforts in general benefit by answering this question. For example, best management practice implemented at the watershed scale may more efficiently use resources by addressing critical areas that account for a higher portion of flow in the river, or higher loadings of pollutants. Also, with an understanding of what areas generate more runoff, conservation initiatives may be able to identify areas where the watershed has been degraded, because watershed degradation is often associated with increased runoff.

Finally, water resource regulators may be able to allocate water use more efficiently, by identifying in what areas increased consumptive use of water poses larger marginal effects on the environment or water rights, and in what areas increased consumptive use of water may pose significant effects on the environment or vested water rights. Thus the answer to this basic question of hydrology is of considerable importance to implementing ecologically minded sustainable development in the Pedernales River Watershed, because the population is expected to increase considerably, and development of more land is inevitable (LCRA 2002).

In a recent Texas Nature Conservancy Report, it was noted that little is known about the hydrology of the Pedernales River Watershed, and there is a need to study and model the function and capacity of the river to create estimates of water resources and help determine if current use trends are sustainable (TNC 2007). Thus, the basic question of what areas generate more or less runoff and why is of considerable importance in the Pedernales River Watershed. Currently, the available stream flow gauges in the Pedernales River Watershed present two potential opportunities to address this question. The first, an opportunity for identifying hydrologic variation, contrasts two large areas of the watershed over 20 years and is examined in this study. The second opportunity would contrast seven areas, and is discussed under future research opportunities at the end of the ”Conclusions” section.

Long Term Analysis of Hydrologic Variation

A comparison of the Fredericksburg Sub-Watershed (FBSW) and the Johnson City Sub-Watershed (JCSW) present an opportunity to address what areas of the Pedernales River Watershed generate more runoff and why. These sub-watersheds share a concurrent record of stream flow measurement over 22 years, and also represent different landscape types. For example, the FBSW falls within a group of sub-watersheds that have the second highest percentage of range land, while the JCSW is composed of sub-watersheds and watershed increments that all fall within a land cover group that either has the highest proportion of cultivated or developed land, or at least no more range land than the FBSW (Map 1, Appendix D).

It is of special interest that the Stone Wall Incremental Watershed, which has the highest portion of developed and cultivated land falls within the JCSW exclusive of the FBSW. This presents an opportunity to contrast a watershed with relatively low land cover modification against another with relatively high land cover modification, and therefore potentially contrast their ability to absorb land cover modification. However, if a difference in average stream flow is observed, then factors unrelated to watershed processes must be ruled out to determine if the stream flow is representative of runoff. The most common alterations to stream flow are consumptive withdrawals and discharges of effluent. These must be accounted for to determine if stream flow measurements are representative of the total runoff. Differences in rainfall must be accounted for to determine if they are isolated to a combination of land cover and physiographic differences or are a product of long-term trends in precipitation. The implications of variation in runoff due to climatic characteristics and those due to landscape features are different, but awareness of either can foster considerable insight when developing management plans. So, for the above reasons, this study proposes to answer the following questions in order to evaluate hydrologic variation between the Fredericksburg Sub-watershed and Johnson City Sub-watershed, so that planners may make informed decisions regarding the steering of development and water resource issues in the Pedernales River Watershed.

Questions 1: Is there an observable runoff difference (stream flow) between the Fredericksburg Sub-watershed and the Johnson City Sub-watershed?

Question 2: Do withdrawals and discharges from the Pedernales River affect variation in long term stream flow that might explain perceived runoff differences between the Fredericksburg Sub-watershed and the Johnson City Sub-watershed?

Question 3: Can observable differences in runoff between the Fredericksburg Sub-watershed and the Johnson City Sub-watershed be explained by difference in average precipitation?
The methods and hypotheses generated to answer these questions are presented in the following section.

METHODS

The three questions posed in the introduction are discussed individually here, under the headings Question 1, Question 2, and Question 3. More conceptual background is given, for each question along with the procedures used to answer them. The results related to each question are also discussed individually in the Result and Discussion section.
Question 1: Is there an observable difference in runoff per unit area (stream flow) between the Fredericksburg Sub-watershed and the Johnson City Sub-watershed?
Homogenous watersheds generally are observed to have proportional runoff. This trait has led to the engineering standard of applying the drainage area ratio method to estimate flows at ungauged points in a watershed, as shown below (TNRCC (a) 2001):

$$Da = WA1 \div WA2$$
$$R1 = Da \times R2$$

where Da is the drainage area ratio, WA1 is the area of watershed 1, WA2 is the area of watershed 2, R1 is the predicted runoff from watershed 1, and R2 is the observed runoff from watershed 2.

However, it has been observed that, everything else being equal, larger watersheds may have slightly diminished stream flows, presumably due to greater losses associated with evaporation from the stream channel. (Goodrich et al. 1997) With this noted, if two watersheds have the same runoff per unit area, then it is expected that any relationship between runoff would be close to a drainage area ratio, and that any other difference could be attributed to evaporative losses of flow in the larger watershed. On the other hand, if the smaller watershed runs off considerably less proportionally to the drainage area ratio, then the watersheds can be considered to have dissimilar hydrologic character (exclusive of the additional questions addressed later in this study). Consequently, to test for hydrologic variation between the FBSW and the JCSW the following hypotheses were created.

Null Hypothesis: The Fredericksburg sub-watershed and the Johnson City sub-watershed are not dissimilar in hydrologic character. Therefore, if a period that represents the typical range of hydrologic conditions in the Pedernales River Watershed is considered and a linear relationship exists between the average annual runoff rate (cfs) of the Fredericksburg sub-watershed and the Johnson City sub-watershed, then that relationship will not be different from the drainage area ratio, when evaporative losses from the larger watershed are considered.

Alternative Hypothesis: The Fredericksburg sub-watershed and the Johnson City sub-watershed are dissimilar in hydrologic character. Therefore, if a period that represents the typical range of hydrologic conditions in the Pedernales River Watershed is considered and a linear relationship exists between the average annual runoff rate (cfs) of the Fredericksburg sub-watershed and the Johnson City sub-watershed, then that relationship will not be different from the drainage area ratio when evaporative losses from the larger watershed are considered.

To test the null hypothesis above, the annual flow values for the FBSW and the JCSW were plotted against each other and regression was used to create a linear equation and R^2 statistics. The linear equation was forced to a y intercept of zero so that the slope coefficient was the equivalent of a runoff ratio. Annual flows were used for the following reasons: hydrologic events are highly random and complex, and longer time steps are more likely to smooth the noise of natural variationOn the other hand, using an annual time step still produced an adequate sample size to obtain statistical power. The average calendar year was used to compute annual flows (cfs) from 1980-1992 and 1999-2007, rather than water year, because the calendar year provided a longer record of concurrent measurement.
To compare the runoff relationship (slope of the linear equation) to predicted flows derived from the drainage area ratio method, trend lines representing both were plotted together. The drainage area ratio trend line was created by estimating runoff from the FBSW by applying the drainage area ratio to the annual runoff from the JCSW. The drainage area ratio trend line was used as a proxy to visually compare how the measured values of FBSW varied from the drainage area ratio. To further determine if runoff per unit area was dissimilar from that predicted by the drainage area ratio, a flow frequency distribution curve was created for observed annual runoff ratios. Annual runoff ratios were computed as follows.

$$R1 \div R2 = RATn$$

where R1 is the runoff from watershed 1, R2 is runoff from watershed 2, RAT is the runoff ratio for year = n. A frequency distribution curve was created by plotting the annual runoff ratio for each study year against the percent of the time that ratio was exceeded, and a curve was fit to the data. The curve was used to calculate percentile statistics regarding the years that the yearly runoff ratio approached the drainage area ratio.

To further analyze the results from the analysis above a frequency distribution curve of annual flow was created including all the years of record for the JCSW (1940 to 2007). This was done so that flow conditionsrepresenting years when the drainage area ratio was similar to an annual runoff ratio could be evaluated in terms of their frequency in a longer period of record. In this way conclusion regarding the disparity between the runoff ratio and the drainage area ratio could be supported relative to a longer period of record.

The results and discussion of this analysis is presented in the Results and Discussion section under "Question 1"

Question 2: Do withdrawals and discharges form the Pedernales River considerably affect variation in long-term stream flow that might explain any perceived differences in runoff per unit area between the FBSW and the JCSW?

Human manipulation of a water course can significantly change the natural hydrology. In the Pedernales River, water is diverted from the river for human uses (irrigation, etc.) and discharged to the river as waste water effluent. The Fredericksburg gauge generally measures less stream flow than predicted by the drainage area ratio. The possibility that this is due to known withdrawals or discharges is examined here. Since the Colorado Basin is manipulated greatly (TCEQ 2008) and very little of the water is not appropriated for some type of use, it is important here to account for the most obvious and measurable alterations of natural flow. So discharges and withdrawals are discussed below.

EFFLUENT DISCHARGES

The City of Fredericksburg (FB) discharges waste water effluent into Baron's Creek. The Baron's Creek confluence with the Pedernales River is downstream of the FB stream flow gauge (USGS 8152900). Any stream flow gains from effluent produced by FB would be measured at the Johnson City (JC) gauge, but not at the FB gauge (See Map 1, Appendix D). The question at hand is the following: Is FB's waste water discharge significant enough to account for the disparity between the drainage area ratio and the runoff ratio between the FBSW and the JCSW? The discharge from FB's waste water treatment plant was the only effluent considered in this analysis, because the only other equivalent source of effluent in the Pedernales River is in Johnson City and discharges downstream of the JC stream flow gauge.
For discharges to be the primary cause for disparity between predicted runoff derived by the drainage area ratio and the observed runoff ratio, then it must make up for the disparity in the ratios. The disparity was 0.137 and was calculated as shown below, using a drainage ratio of 0.4 and a runoff ratio of 0.27. The disparity in ratios is equivalent to 32.5% of the Johnson City flow ratio on average, this was derived as shown below.

$$Dis = RATt - Da$$

and

$$RJC\% = 100 - \frac{RATt}{Da}$$

where Dis is the disparity in ratios, RATt is the observed runoff ratio derived from linear regression,Da is the drainage area ratio, and RJC% is the percentage of JCSW measured runoff that would be in excess of the predicted runoff derived by drainage area ratio and FBSW observed runoff, RATt is the observed runoff ratio derived from linear regression, and Da is the drainage area ratio. This is the amount of flow at JC that is not accounted for by FB in terms of the drainage area ratio method. This led to the construction of the following hypotheses:

Null Hypothesis: Waste water discharges from the FB waste water treatment plant are the primary cause of the disparity between the flow ratio and the drainage area ratio. In other words, discharges from the FB waste water treatment plant are an order of magnitude larger than 0.137 that is required to account for the disparity ratio.

Alternative Hypothesis: Waste water discharges from the FB waste water treatment plant are not the primary cause of disparity between the flow ratio and the area drainage ratio. In other words, discharges from the FB waste water treatment plant are much smaller than 0.137 that is required to account for the disparity ratio.

To test the null hypothesis the following was done. Effluent records were acquired from the FB waste water treatment plant. The data were transcribed from hand written to digital form for data manipulation and analysis. The data then were converted from gallons per day to daily average cubic feet per second and aggregated to annual averages.

The hypothesis was tested by examining the frequency of years in which the disparity between flow and drainage ratios could be accounted for by adjusting for FB waste water effluent. JC annual flows were adjusted by subtracting a 120% of the maximum annual waste water discharge from 2004-2007. The maximum annual effluent was used by a factor of 1.2 to add power to any conclusion that would rule effluent out as a major contributor. Next, the adjusted and measured flow ratio (FB/JC) was calculated for each year of the record. Next the disparity between the adjusted flow ratio and drainage ratio was calculated for each year ((Area FB/Area JC)-(Flow FB/Flow JC Adjusted)). Then the disparity between the measured flow ratio and drainage ratio was calculated for each year ((Area FB/Area JC)-(Flow FB/Flow JC)). The percent of the measured disparity accounted for by the adjustment was calculated using the formula below:

%Add = (Disa-Dis)/ Da

where %Add is the percent of the measured disparity accounted for by the adjustment, Dis is the disparity between the measured flow ratio of a year and drainage ratio, and Disa is the disparity between the adjusted flow ratio and the drainage ratio. The frequency that the percent of disparity attributable to FB waste water was exceeded was plotted as a frequency distribution curve for the study period (1980-1992 and 1999-2006).

Using the curve, it was determined in what percentage of years waste water effluent would account for the disparity between the runoff ratio and the drainage area ratio, and thus what relative effect discharges of waste water effluent might have on the perceived runoff relationship between the FBSW and the JCSW. The results of this analysis are discussed in the Results and Discussion section.

SURFACE WATER WITHDRAWALS

Diversions of surface water can have a dramatic effect on the amount of water that passes a stream flow gauge. On the main stem of the Colorado, much of the flow is determined by scheduled releases by reservoirs and diversions (LCRA 1989). While the Pedernales River has no major releasing reservoirs, it does have several permitted diversions (TNRCC (b) 2001). It is important to account for these diversions when analyzing the runoff ratio between the FBSW and the JCSW, especially when that the Colorado River Basin has very little water that is not appropriated (TCEQ Website). Some additional background on Texas water law is given here to illustrate the context of water appropriation in Texas. The state of Texas entrusts the surface water of Texas for the people of Texas and allows its use on a prior appropriations basis. If water is available, the State is obliged to allow it to be diverted from the river. A junior water right (a certificate assigned or a permit granted at a later date) is not allowed to divert water that belongs to a senior water right downstream.

The Colorado Basin, to which the Pedernales River is a tributary, is classified as having very little to no water that is not appropriated (TCEQ website). That does not mean that any particular stream or river of the basin is often altered greatly from its natural flow. The reason for this is that a senior water right down in Matagorda Bay can call on a junior right in the Pedernales River to stop diverting. Also, the state of Texas grants permits in the Pedernales River Watershed not on the basis of physically available flow, but on unappropriated flow relative to the entire Colorado Basin.

This leads to the following question: Are the diversions from stream flow in FBSW large enough to account for the difference between the flow ratio and the area ratio? For withdrawals to account for the disparity between flow ratio and drainage area ratio the stream flow depletions above FB would have to be greater than the stream flow depletions in JC exclusive of FB, and enough to return a 0.407 ratio from FB adjusted flow over JC adjusted flow. This allows for the construction of the following hypotheses:

Null hypothesis: Withdrawals are the primary cause of the disparity between the flow ratio and the drainage area ratio. In other words, withdrawal adjusted flows would exhibit a ratio that is within an order of magnitude closer to 0.407. Thus, an adjustment for withdrawals from the stream does account for a major portion of the disparity (0.137) between the area ratio (0.407) and the flow ratio (0.27) in a majority of the years.

Alternative Hypothesis: Withdrawals are not the primary cause of the disparity between the flow ratio and the drainage area ratio. In other words, stream-depletion adjustment does not account for a major portion of the disparity (0.137) between the area ratio (0.407) and the flow ratio (0.27) in a majority of the years.

The null hypothesis was tested using the following data and analysis. The Texas Commission on Environmental Quality (TCEQ) maintains a database of all of the water appropriated throughout the Pedernales River Watershed. This database was used with Mircosoft Excel to account for all of the legal diversions in FB and JC. From the database, water rights were filtered for the Pedernales River Watershed then by the respective streams that lie within FB and those that lie within JC exclusive of FB. The diversion amounts for FB and JC exclusive of FB were totaled.

The diversions in JC were totaled to account for diversions that would negate FB diversions from accounting for the disparity between the flow ratio and drainage ratio. The diversions from FB were used to adjust the annual flow record of FB. Then the adjusted and measured flow ratio (FB/JC) was calculated for each year of the record. Next the disparity between the adjusted flow ratio and drainage ratio was calculated for each year. Then the disparity between the measured flow ratio and drainage ratio was calculated for each year. The percent of the measured disparity accounted for by the adjustment was calculated using the formula below:

$$\%ADD = (Dis - Disa / DIS)$$

where %Add is the percent of the measured disparity accounted for by the adjustment, Dis is the disparity between the measured flow ratio of a year and drainage ratio, and Disa is the disparity between the adjusted flow ratio and the drainage ratio.

A frequency distribution curve was plotted showing the percent of disparity from stream flow in the FBSW attributable to withdrawals for the study period (1980-1992 and 1999-2006). Using the curve it was determined in what percentage of years permitted withdrawals from stream flow would account for the disparity between the runoff ratio and the drainage area ratio, and thus what relative effect

withdrawals from stream flow might have on the perceived runoff relationship between the FBSW and the JCSW. The results of this analysis are discussed in the Results and Discussion Section.
Question 3: Can observable differences in runoff between the Fredericksburg Sub-watershed and the Johnson City Sub-watershed, be explained by difference in average precipitation?

Proportionally small variation in precipitation can cause large changes in runoff in the hydrologic systems of Texas, since the threshold level of rain needed to create runoff often represents a large portion of the annual rainfall received. This is seen in the Brazos River Basin as the percentage of rain running off increases considerably with incremental increase in rainfall (see Table 1). For example, the San Jacinto-Brazos basin has twice as much rainfall as the lower section of the Brazos River Basin, but has 15 times the amount of average annual runoff (TNRCC (a) 2001).

Thus long term trends in average annual rainfall can amount to large amounts of variation in average annual runoff. The regional trend observed in the Brazos River Basin is generally thought to occur throughout Texas. The state precipitation maps shows that the average annual rainfall decreases across a gradient from east to west and south to north (see Map 2, Appendix D). Since the Pedernales River stretches 122 km (75 miles) from its head waters in the West to its confluence with the Colorado River at Lake Travis Reservoir in the East, it possibly crosses though several rainfall isoclines.

Thus, it is possible that the disparity between predicted runoff derived from the drainage area ratio and the observed runoff is due to a gradient of increasing rainfall across the basin from east to west, and a difference in landscape features. On the other hand, state-wide trends in precipitation may not be observable at the scale of the Pedernales River Watershed. Furthermore, even if state-wide spatial trends in precipitation are observable at the scale of the Pedernales River Watershed they may still not account for the disparity between the runoff predicted by the drainage area ratio and the observed runoff ratio. Thus, the watershed must be compared based on the relative proportions of rainfall runoff. Rainfall- runoff relationships computed with linear regression can be used to compare sub-watersheds based on their hydrologic response to a given unit of rainfall. However, to be meaningful, rainfall- runoff relationships must predict runoff with an acceptable means of fit relevant to the field of hydrologic science (TNRCC (a) 2001). Furthermore if runoff is normalized by area and converted to inches of runoff, then the sub-watershed can be compared, based on the portion of rainfall converted to runoff. If the flow is not normalized by flow area then a ratio of the resulting portion can be compared to the area drainage ratio. The drainage area ratio in this instance represents the ratio by which both watersheds would runoff the same proportion of precipitation depth. These methods enable the testing of the following hypothesizes.

Null Hypothesis: Spatial trends in precipitation are not the cause of the disparity between the predicted runoff computed by the drainage area ratio (0.407) and the observed runoff ratio (0.27).
If a relationship between runoff and precipitation can be modeled in both sub-watersheds with an acceptable degree of fit, then the proportion of rainfall that runs off from each sub-watershed can be determined, as the coefficient of slope. Consequently, if the null hypothesis is false then the ratio between the proportion of the rainfall running off from the two sub-watershed (ratio between slope coefficients), if computed in cubic feet per second, will be closer to the drainage area ratio (0.407) than the runoff ratio (0.27).

Furthermore, if the rainfall-runoff relationships are computed in inches of runoff, then the FBSW proportion of rainfall running off (slope coefficient) will be similar to the JCSW. Furthermore if values from the two sub-watershed are compared on a plot of rainfall (inches) against runoff (inches) then the scatter of data will have the same distribution, or range.

RAINFALL-RUNOFF RELATIONSHIPS

Linear regression was used to create monthly rainfall runoff relationships for the FBSW and JCSW. The monthly time step was chosen for the following two reasons. Longer time steps better capture rainfall and related runoff in one time interval. However, this study had only five years of high resolution precipitation data, so monthly time step was used to increase the sample size in order to increase statistical power. Goodness of fit was determined to be acceptable if the R^2 value was greater than or equal to 0.6, which was used by HDR engineering to accept relationships between gauge flows in the Brazos River Basin (TNRCC (a) 2001). Rainfall estimates were created as described below under "Creating Areal Rainfall Estimates". Daily flows values were obtained from the USGS and converted to monthly cfs and runoff depth.

Areal Rainfall Estimates

As determined in the Precipitation Analysis portion in this report, precipitation spatial patterns occur at scales not fully captured by either the NDCD or the LCRA gauge networks. To enable greater accuracy in estimates of spatial precipitation patterns, all the gauges reporting in a month without detectable error were used from both networks. This increased accuracy limited the study to time periods of available data for the largest number of gages, which are water years 2003-2007. Using the Geographical Information System created for the Estimating Areal Precipitation Analysis Section of this report, areal estimates of monthly precipitation were created using Kriging as recommended in this report. Then the zonal summary tool in ArcGIS Spatial Analyst extension was used to extract average rainfall depth by watershed shape file from the monthly rainfall surfaces. The extracted monthly averages were exported for data manipulation and analysis.

RESULTS AND DISCUSSION

Question 1

It appears that the FBSW runoff is considerably less per unit area than the JCSW. In Figure 1, annual runoff values from the two sub-watersheds are plotted against each other and a linear equation representing the runoff ratio is shown with an R^2 statistic. The R^2 statistic is 0.94 which indicates a very strong relationship with regards to hydrologic data (TNRCC (a) 2001). Thus, the linear equation acceptably represents the runoff ratio, which is about 0.27. The JCSW is 2.45 times larger than the nested FBSW; however the JCSW produces 3.68 times more runoff. The area ratio is 0.407 to 1, while the runoff ratio is 0.27 to 1.

The FBSW would have to be 1.5 times or 50% larger than JCSW to produce the same runoff, that is, it runs off only 2/3 the amount of JCSW per unit area. Furthermore, since the FBSW is nested inside of the JCSW, it means that the rest of the JCSW exclusive of the FBSW runs off 1.84 times more flow than the FBSW to make up the difference. To illustrate, if the JCSW produced 368 cfs, then the linear runoff relationship dictates that the FBSW would produce 100 cfs. Accordingly, 268 cfs would have to be made up by an area 1.45 times than that of the FBSW. Thus, the JCSW (exclusive of the FBSW) runoff rate per unit area would equal 268 cfs divided by the additional area of the JCSW which is 1.45 times that of FBSW. Thus, 268cfs/1.45 = 184 cfs/ per unit area, which is 1.84 times more runoff than per unit area than the FBSW. Thus the JCSW appears to runoff considerably more than the FBSW.

It should be noted that in years when the JCSW average annual flow was below 100 cfs the drainage area ratio method predicts FBSW flow reasonably well. In Figure 2 it is shown that in 20% of years the yearly runoff ratio approached or exceeded the drainage area ratio. However in all of these years runoff did not exceed 100 cfs. In Figure 3 it is shown that only 33% of the JCSW's longer record (1940-2007) did not exceed 100 cfs (Figure 2). Thus, the runoff ratio of 1.8 to 1 may be considered the norm, because runoff exceeded 100 cfs in 67% of the years in the longer JCSW record.

Therefore it has been demonstrated that a linear relationship does exist between the annual average stream flows of FBSW and JCSW, and that the relationship is considerably different from the drainage area ratio, which cannot be explained in terms of evaporative losses from the larger watershed since the smaller watershed runs off less. Furthermore, it was determined that the runoff relationship was representative of the typical range of hydrologic conditions in the Pedernales River Watershed when considered against the longer record of the JCSW. Thus the null hypothesis was rejected and it was determined that FBSW and JCSW appear to have dissimilar hydrologic characteristics, exclusive of the other questions to be answered in this study.

Question 2

Discharges of effluent from the City of Fredericksburg waste water treatment facility were determined to not have a considerable effect on the runoff ratio between the FBSW and the JCSW. The maximum annual waste water discharge was 392 million gallons from 2004 to 2007. That is the equivalent of an average discharge of about 52.4 million cubic feet, which is the equivalent of an average discharge of 1.66 cubic feet per second (cfs). In the analysis of the effect of waste water discharge on the runoff ratio, the possibility of discharge having an effect was given even more weight by rounding the average discharge to 2 cfs (120% of the maximum).

The adjustment of 2 cfs accounted for no more than 35% of the difference in flow ratio and drainage area ratio (DFRDAR) in any year (1980-1992 and 1999-2006). The percent of the disparity in ratios attributable to FB waste water effluent exceeded 10% only in one very dry year. Figure 4 shows the frequency distribution of the percent difference in flow ratio and drainage area ratio attributable to FB waste water discharge during the study period (1980-1992 and 1999-2006). The max of any one day was the equivalent of about 16 cfs, and much of that potential is due to storm water running through the treatment plant.

Thus, in the majority of years the percent of disparity explained by discharges of effluent from the FB waste water treatment plant is very small relative to the total disparity. In addition, permitted diversions from stream flow in the JCSW downstream of the FBSW are large enough to negate totally any effect that discharges of waste water effluent may have on the flow ratio. This is especially true in a low flow year, which represents the only year that diversions from FBSW represented more than 10% of the disparity between the drainage area ratio and the runoff ratio. Since the disparity is most pronounced in medium and high flow years, the plausibility that diversion accounts for the disparity is not congruent with the magnitude by which stream-flows exceed the magnitude of effluent.
It should be noted here, that though discharges of waste water effluent seemed inconsequential in relation to water quantity at the scale of the Basin, waste water effluent may still account for a significant amount of the base flow in Baron's Creek. In addition discharges of effluent from the FB waste water treatment plant might also be significant on the basin scale in terms of water quality. However, though some aspects of FB waste water effluent require further examination, the relative effect on water quantity at the scale of FBSW and JCSW is marginal. Thus the alternative hypothesis can be accepted that waste water discharges from the FB waste water treatment plant are not the primary cause of disparity between the flow ratio and the area drainage ratio.

Question 3

Permitted withdrawals from stream flow were determined to not have a considerable effect on the runoff ratio between the FBSW and the JCSW. Permitted withdrawals in the FBSW amount to a total of 1,299 acre-feet per year which is the equivalent to a 1.7 cfs average annual flow rate. The total sum of permitted diversions in the FBSW accounts for more than 25 percent of the disparity only once, as can be seen in the flow frequency distribution curve (see Figure 5). Also, diversions account for 10% or more of the disparity in only 35% percent of the years, and in 65% percent of the years diversions account for less than 10% of the disparity. Additionally, the years with the highest percentage of disparity accounted for by the adjustment are low flow years when the JCSW ran off less than 100 cfs (see Figure 3). Finally, diversions from the Pedernales River between the FB stream flow gauge and the JC gauge could negate any disparity caused by diversions in FB. Thus, the alternative hypothesis can be accepted that withdraws are not the primary cause of the disparity between the flow ratio and the drainage area ratio.

Precipitation effects

Spatial trends in precipitation can account for the disparity between the predicted runoff computed by the drainage area ratio (0.407) and the observed runoff ratio (0.27). This conclusion is demonstrated rather resoundingly by Figure 6. This figure shows the runoff depth plotted against precipitation for both sub-watersheds. The scatter clouds of data are overlapping and appear coincident, and the relationships have identical slope coefficient, and have acceptable goodness of fit. In addition, the ratio between the proportion of the rainfall running off from the two sub-watershed, when computed in cubic feet per second, was almost identical to the drainage area ratio (0.406). (see Figure 7) Thus the null hypothesis can be rejected and it can be accepted that the proportion of rainfall that runs off from both watersheds is the same, although the JCSW receives more rain.

CONCLUSIONS

It was observed that the Johnson City sub-watershed runs off considerably more rainfall per unit area than the Fredericksburg sub-watershed. This was affirmed by the determination that known withdraws from stream flow or discharges of waste water effluent represent only a marginal portion of annual average flows. Finally there was strong evidence that variation in runoff was the result of higher annual rainfall in the eastern portion of the JCSW exclusive of the FBSW. These results have important management implications. A few are noted below.

First, soil erosion from hillslopes is facilitated by detachment of soil particles by raindrop impact (RUSLE 2002). Thus the hillslopes in the eastern portion of the JCSW may be more vulnerable to soil erosion because more rain falls on this area. Thus, sediment control and soil remediation projects, with limited resources, may achieve greater effects if they are focused in the eastern portion of the watershed.

Next, there is less runoff to wash nutrients into the stream channels of the FBSW relative to the eastern portion of the JCSW. Consequently, the aquatic system in the FBSW may be more limited by specific nutrients. This may have effects on the specific aquatic species assemblages found in the stream channels of the FBSW compared to those found in the eastern portion of the JCSW.

Furthermore, brush control management projects aimed at producing more surface water may have higher yields if they are concentrated in the eastern portion of the JCSW due to more water entering the system via rainfall. Finally, an equivalent stream flow withdrawal from a headwater tributary in the eastern portion of the watershed may have considerably less impact on the river environment than it would have in the FBSW, since there is more water running off to the stream channels of the eastern portion of the JCSW.

In conclusion, answering the fundamental hydrologic question of what areas in a watershed generate more or less runoff and why, produces valuable information that can be used in the development of management plans and future studies. However, considerably more insights can be gained if this question is asked with increased resolution, in order that the effects of specific land cover and physiographic characteristics could be considered. Potential future studies are addressed below.

FUTURE RESEARCH

An analysis of stream flow that includes records from every working flow gauge in the Pedernales River Watershed with more than six years of record may provide an opportunity to answer the question "What areas generate more or less runoff and why?" at a finer scale, that can more precisely relate hydrologic response to local landscape traits. Currently there are eight working flow gauges in the watershed. Seven of the gauges have records of at least five consecutive years.

Consequently these gauges measure the runoff from eight sub-watersheds, or seven with records over five years. Also, as discussed in the "Land Cover Analysis" section of this report, these sub-watersheds represent four distinct groups relative to land cover that can be contrasted across and within groups. However, since the hydrologic period of record is short, it represents only a snapshot of the full range of hydrological variability, and following the findings from the "Estimating Areal Precipitation," there is considerable spatial variation in monthly rainfall across the Pedernales River Watershed.

Thus, the relationship between rainfall and runoff from these watersheds must be calculated in order to account for short term variation in rainfall. A preliminary review of the data suggests that use of simple linear relationships may be sufficient to develop adequate seasonal or monthly rainfall estimates after more data are available. Currently the relationships do not show an acceptable fit, primarily due to difficulties in estimating data from a long dry period in 2006. During this period the occasional months of high rainfall produced almost no measurable runoff.

Therefore, a longer dataset would allow the development of separate relationships for different climatic conditions. However, it is also recommended that a more complex computer modeling scheme, such as the Hydrologic Simulation Program Fortran (HSPF), be used in order to address issues that are not well accommodated by linear regression models, such as rainfall-runoff thresholds, effects of antecedent soil moisture conditions on runoff generation, base flow contributions, subsurface flow, and delayed rainfall-runoff responses. Furthermore, a more comprehensive hydrologic model would allow for considerably more utility in scenario development and analysis. In conclusion it is suggested here that a great amount of relevant insight could be gained by continuing to ask the question "What areas generate more or less runoff and why," in conjunction with a more complex hydrologic model.

REFERENCES

Aherns B. (2005) Distance in spatial interpolation of daily rain gauge data. Hydrology and Earth System Sciences Discussions 2, 1893-1923

Ashworth, J. B. 1983. Ground-water availability of the lower Cretaceous formations in the Hill Country of south centralTexas. Texas Department of Water Resources Report 273, Austin, Texas.

Berkes, F. and C. Folke eds.(2000). Linking social and ecological systems: management practices and social mechanisms for building resilience. Cambridge, Cambridge University Press.

Blanco-Pedernales Ground Water Conservation District, BPGWCD (2008). Ron Fieseler, http://www.blancocountygroundwater.org/

Bluntzer, B. L. (1992). Evaluation of the ground-water resources of the Paleozoic and Cretaceous aquifers in the Hill Country of central Texas. Texas Water Development Board Report 339, Austin, Texas.

Bureau of Economic Geology, BEG (1981). Geologic atlas of Texas, Llano sheet.University of Texas at Austin, Austin, Texas.

Daly, C. (2006). Guidelines for Assessing the Suitability of Spatial Climate Data Sets International Journal of Climatology 26, 707-721

DeMers M. N. (2005). Fundamentals of Geographic Information Systems. John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ

Dunne, T., and Leopold, L.B. (1978). Water in Environmental Planning. W.H. Freeman Company. New York, New York

Faulkenmark, M. and Folke, C. (2002). The ethics of socio-ecohydrological catchment management: toward hydrosolidarity. Hydrology and Earth System Sciences 6(1), 1-9

Forney, W., Richards, L., Adams, K. D., Minor, T. B., Rowe, G., Smith, J. L. and Raumann, C. G. (2001). USGS Open-File Report 01-418.

Franke, R. (1982). Smooth Interpolation of Scattered Data by Local Thin Plate Splines. Comp.& Maths. with Appls. vol. 8, 4. pp. 237–281. Great Britain.

Goodrich, D,.C., Lane, L.J., Shillito, R. M. and Miller, S. N. (1997). Linearity of basin response as a function of scale in a semiarid watershed.Water Resources Research, vol. 33, 12, 2951-2965

GWP (2000). Integrated water resources management. TAC Background Papers No 4. Global Water Partnership, Stockholm, Sweden.

Hill Country Underground Water Conservation District, HCUWCD (2008). Paul Tybor and Margret Ratilif, [online]: www.hcuwcd.org

Hill Country Underground Water Conservation District, HCUWCD (2007). Groundwater Availability Model fro the Ellenburger Aquifer in Southeast Gillespie County, Texas. LBG-Guyton Associates

Holling, C.S. (2004). From complex regions to complex worlds. Ecology and Society 9(1): 11. [online]: http://www.ecologyandsociety.org/vol9/iss1/art11/print.pdf

Johnston K, Ver Hoef J. M., Krivoruchko, L. N (2001). Using ArcGIS Geostatistical Analyst. ESRI, Redlands, CA

Krige D.G. (1962) Statistical applications in mine valuation. J. Inst. Min. Survey of S Afr 12(2): 45-84; 12(3): 95-136

Lower Colorado River Authority, LCRA (2002). Pederanles River Watershed brush control and feasibility study. Austin, Texas

Lower Colorado River Authority, LCRA (1989). Water Management Plan For the Lower Colorado River

Basin. Texas Austin (TCEQ 2008) water availability maps
Mallard, G. E., K. Dickson, et al. (2005). The Science of Instream Flows: A Review of the Texas Instream Flow Program. The National Academies Press, Washington DC: 126.
Mitas, L., and H. Mitasova (1988) General Variational Approach to the Interpolation Problem, Comput. Math. Applic. vol. 16, 12, 983–992. Great Britain.
Molnar, P., Burlando, P., and Ruf, W. (2002). Integrated catchment assessment of riverine landscape dynamics, Aquatic Sciences, 64(2), 129-140.
Postel, S., and S. Carpenter. (1997). Freshwater ecosystem services. Pages 195–214 in G. C. Daily, editor. Nature's services: societal dependence on natural ecosystems. Island Press, Washington, D.C., USA.
Preston, R. D., Pavelicek, D. J. and Bluntzer, R. L. (1996). The Paleozoic and related aquifers of central Texas. TexasWater Development Board Report 346, Austin, Texas.
Pringle, C. M., M. C. Freeman, and B. J. Freeman. (2000). Regional effects of hydrologic alterations on riverine macrobiota in the New World: tropical–temperate comparisons. BioScience 50:807–823.
PRISM GROUP (2007). PRISM GROUP, Oregon State Unversity, 6 May 2007 [online]: http://www.prism.oregonstate.edu/

Reubel F. and Hantel M .(2001). Baltex 1/6-degree daily precipitation climatology 1996-1998. Meteorology and Atmospheric Physics 77, 155-166
Richter, B. D., R. Mathews, et al. (2003). "Ecologically sustainable water management: managing river flows for ecological integrity." Ecological Applications 13(1): 206-224.
RUSLE (2002), RUSSLE Online soil Assessment Tool, [online]: http://www.iwr.msu.edu/rusle/about.htm
Soil Data Mart, SDM (2008), Soil Surveys Intersecting the Pedernales Watershed. Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. [online]: http://soildatamart.nrcs.usda.gov/Survey.aspx?State=MT .
Soil Data Viewer, SDV (2008), Natural Resources Conservation Service, United States Department of Agriculture. [online]: http://soildataviewer.nrcs.usda.gov/
Texas Commission on Environmental Quality, TCEQ (2008). Water Availability Models [online] http://www.tceq.state.tx.us/permitting/water_supply/water_rights/wam.html
Texas Natural Resources Conservation Commission, TNRCC(a) (2001). Water availability in the Brazos River Basin and the San Jacinto-Brazos Coastal Basin. HDR Engineering Inc. Texas, Austin.
Texas Natural Resources Conservation Commission, TNRCC(b) (2001). Water availability for the Colorado River Basin and the Colorado/Brazos-Colorado
Texas Water Development Board. (2002). Water for Texas – 2002. State Water Plan.
The Nature Conservancy, TNC (2007). Conservation Plan for the Pedernales River Watershed. Dallas, Texas
Tobler W. (1970). A computer movie simulating urban growth in the Detroit region. Economic Geography, 46, 234-240
Vorosmarty, C. J., C. Leveque and C. Revenga (2005), Chapter 7: Fresh Water, In: Millennium Ecosystem Assessment, Volume 1: Conditions and Trends Working Group Report, Island Press
WEB Geologic Time Machine, WGTMA, 2008. University of California Museum of Palentology. .R. Palmer and J. Geissman -- S. Rieboldt, Nov. 2002 http://www.ucmp.berkeley.edu/help/timeform.html

Zheng X. and R. Basher, (1995) Thin-plate smoothing Spline modeling of spatial climate data and its application to mapping South Pacific rainfalls. Monthly weather review, 123, 3086-3102

Appendices

Please see attached for Appendix A-D and Tables and Figures

Spatial and Temporal Patterns in the Pedernales River Drainage

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The Pedernales River is a dynamic and unique hydrological feature of the Edwards Plateau region of central Texas, which supports a number of endemic aquatic taxa. The fish assemblage includes species with large distributions as well as those finding their entire range limited within the Edwards Plateau (Conner and Suttkus 1986; Bowles and Arsuffi 1993). The habitat-faunal relationships within the region are threatened by a number of anthropogenic modifications, including urbanization, dewatering, and lowhead dams (Arsuffi and Bowles 1993, Bean et al. 2007). As abiotic disturbances have helped shape much of the Edwards Plateau landscape and are known to structure aquatic communities across biological regions, it is important to understand how the fish assemblage will react with both natural and induced environmental change (Harrell 1978; Matthews 1988; Poff and Allan 1995; Higgins 2005). Although a system of importance recreationally, commercially, and environmentally (Bowles and Arsuffi 1993; Leopold 2001), relatively little work has been conducted on the Pedernales River main-stem.

Much of the previous focus for fish and macroinvertebrates in the Pedernales River has resided within the tributaries and on water quality in the mainstem. Birnbaum (2005) assessed the effect of Ashe juniper (*Juniperus ashei*) cover on the physicochemical patterns and faunal assemblages in the tributaries of the Pedernales River and found differences in fish and macroinvertebrate abundances related to physical habitat and season. However, the author stated that more temporal work is necessary to further understand connectivity between tributaries and the mainstem. Important linkages exist in these connections by way of: hydrological input, disturbance refugia, and source populations for obligate tributary, or in many cases, spring-associated taxa (Rice et al. 2001; Franssen et al. 2006). Higgins (2005) explored spatiotemporal variation of fish assemblages using functional groups in three tributaries of the Colorado River, including the mainstem Pedernales River. Though this information is valuable by revealing large-scale mechanisms, the habitat-faunal associations in the Pedernales River were not explored for macroinvertebrates and the associations for fish were analyzed at a more principle level.

Study Objectives:

Objectives of this study were to determine occurrence and abundance of the Pedernales River drainage fish assemblage and to assess spatial and temporal habitat associations of fish assemblages in the mainstem and tributaries of the Pedernales River.

Methods

Nine sites in the Pedernales River basin were sampled four times from February 2007 through November 2007 with five Pedernales River mainstem sites (P1-P5) and four tributary sites: Barons Creek (B1), Cypress Creek (C1), Live Oak Creek (L1), and North Grape Creek (G1). Exploratory sampling was conducted in portions of the Pedernales River (P-1, P0, P1.5, P3.5) outside of the regularly sampled sites as well as in Miller Creek (M1) and Flat Creek (F1), to collect specimens and record habitat unlikely to be found in other portions of the river (Figure 1).

Sites were sampled exhaustively for fish, and effort was proportional among geomorphic unit levels (i.e., pool, riffle, run, backwater). For each geomorphic unit, current velocity, water depth, percent substrate (Cummins 1962), and overhead cover were taken from a representative transect. In addition, temperature (°C), specific conductance (uS/cm), pH, dissolved oxygen (mg/l), and turbidity (NTU) were measured with a YSI Model 660 meter at each site.

Fish were collected with multiple passes using a 2.4 x 1.8 m seine (mesh size = 3.2 mm) and a Smith-Root backpack electroshocker. Fish were identified to species and enumerated according to Hubbs et al. (1991) and measured to the nearest millimeter up to 30 fish of each species, after which the remainder was enumerated. All fish were released on site except for voucher individuals, which were anesthetized in a lethal dose of MS-222 and preserved in buffered 10% formalin.

Patterns in species occurrence, abundance, and habitat associations were assessed with Principal Component Analysis (PCA) and Canonical Correspondence Analysis (CCA). PCA was used to assess changes in the habitat structure of each site spatially and temporally, and to detect differences among sites throughout the Pedernales River basin based upon habitat and environmental parameters. CCA was used to show spatiotemporal patterns and habitat associations of the fish assemblage with regard to habitat variation. Variance partitioning was performed on the CCA model to show the amount of variation explained by variation type and the significance, if any, of that variation. In both multivariate tests, temperature-dependent data were excluded (e.g. dissolved oxygen, conductivity, pH) to reduce variation seen in diel sampling. In PCA for trajectory plots utilizing environmental data, geomorphic units were averaged within season, and for CCA analyses rare species (less than two individuals) were removed and the abundance for one anomalous sample of *I. punctatus* (482 individuals) was averaged.

Results

A total of 109 geomorphic units were sampled through four seasons for all sites in the Pedernales River basin from February 2007 through November 2007. Within this period of sampling, environmental parameters varied considerably through time and among sites. Pedernales site 3 had the highest turbidity, followed by downstream Pedernales sites 2 and 1. Additionally Pedernales site 3, as well as Barons Creek, had high values for dissolved oxygen and conductivity. The headwater (Pedernales site 4, Pedernales site 5) and tributary sites (Cypress Creek, North Grape Creek, Live Oak Creek) had similar ranges in environmental variation, but Cypress Creek and North Grape Creek showed the least amount of variation, typical of spring-influenced systems (Table 1).

The first two axes in PCA of habitat explained 21.1% of the variation from 22 environmental parameters. Principal component axis I described a current velocity and depth gradient with high negative loadings for average current velocity (-1.99), riffles (-1.69), cobble (-1.12), and bedrock (-0.92) and high positive loadings for sand (1.75), pools (1.38), submerged vegetation (1.34), and average depth (1.26). Principal component axis II described a substrate and geomorphic unit size gradient with high negative loadings for cobble (-1.97), riffles (-1.53), gravel (-1.11), and average current velocity (-0.50) and high positive loadings for bedrock (2.29), geomorphic unit width (1.47), turbidity (1.46), and geomorphic unit length (1.05). Pedernales sites 1 and 2 grouped similarly on principal component axis I with more cobble, riffles and higher current velocities. Pedernales sites 4 and 5 grouped similarly as well but in contrast to Pedernales sites 1 and 2 with more bedrock, wider and longer geomorphic units, and higher turbidity. Pedernales site 3 exhibited data points plotting at the negative ends of both axes with larger substrates, higher current velocities, and riffles. Little similarity was seen in the tributary plots between Live Oak Creek, Barons Creek, North Grape Creek, and Cypress Creek. Live Oak Creek and Barons Creek had more sand, submerged vegetation, higher turbidities, and larger geomorphic units. North Grape Creek varied on principal component axis II with large geomorphic units, more bedrock and higher turbidities, while Cypress Creek occupied only a small multivariate space with little variation.

To show groupings between sites based on season PCA was used in a trajectory style plot for data encompassing nine sites through four seasons using five environmental variables (i.e. temperature, dissolved oxygen, conductivity, pH, turbidity). In the analyses, 45.1% of the variation was explained on the first two axes and general trends in seasonality were apparent (Figure 4 and Figure 5). Principal component axis I described a temperature and dissolved oxygen gradient with high negative loadings for temperature (-1.07) and high positive loadings for dissolved oxygen (1.38). Principal component axis II described a conductivity and turbidity gradient with high negative loadings for turbidity (-1.81) and high positive loadings for conductivity (1.19). PCA of mainstem sites in the basin again grouped Pedernales sites 1 and 2 and Pedernales sites 4 and 5 similarly in their trajectories through the year, while Pedernales site 3 was different with high winter scores for temperature and turbidity. In the tributaries, little variation was seen through the season for all sites with the exception of Barons Creek, which was shown to have high winter scores for conductivity and temperature.

A total of 12,547 fish and 35 species were collected from the Pedernales River mainstem and tributaries (Table 2). Among these, blacktail shiner *Cyprinella venusta* and red shiner *Cyprinella lutrensis* were the most abundant fishes comprising 39% and 20% of the fish assemblage, respectively. These two species were also prevalent throughout the basin found at all nine regularly sampled sites. There seemed to be clear divisions with regard to distributions of other species throughout the basin with many either being found in the headwaters (Pedernales sites 4 and 5) and tributaries and absent elsewhere, or found in the lower mainstem (Pedernales sites 1, 2, and 3) and absent upstream.

Species presence and abundance data was incorporated with environmental and habitat data in a CCA model. The CCA model showed that 64.2% of the variation could be explained by the model, Total Inertia (TI) = 4.085, Sum of All Eigenvalues (SAE) = 2.624. The first canonical axis described a spatial and habitat type gradient with scores of high negative values for Pedernales site 3 (-0.69), turbidity (-0.53), dissolved oxygen (-0.48), and side channel (-0.45) and high positive values for Pedernales site 5 (0.60), cobble (0.40), riffle (0.37) and average depth (0.33). The second canonical axis described a habitat type and site type gradient with scores of high negative values for sand (-0.43), submerged vegetation (-0.32), Barons Creek (-0.31), and average depth (-0.27) and high positive values for Pedernales site 5 (0.58), cobble (0.47), Pedernales site 3 (0.42) and average current velocity (0.40). Higher loadings in the CCA model were shown for: sites P3 and P5 (Figure 6), corresponding with higher loadings for turbidity and dissolved oxygen, and cobble respectively (Figure 7). The tributaries (Barons Creek, Cypress Creek, Live Oak Creek) clustered closely and corresponded with sand, gravel, submerged vegetation, and riffles. Season did not show much variation explained and subsequently had low loadings (Figure 6), while many species scores followed closely to expected habitats and corresponded well with site and habitat (Figure 8).

Species that were negatively associated with the first canonical axis were *Cyprinella* sp. (-1.20), red shiner *Cyprinella lutrensis* (-1.00), western mosquitofish *Gambusia affinis* (-0.87), and species that were positively associated were Texas shiner *Notropis amabilis* (2.09), mimic shiner *Notropis volucellus* (1.81), and redear sunfish *Lepomis microlophus* (1.00). Species that were negatively associated with the second canonical axis were dusky dater *Percina sciera* (-1.47), yellow bullhead *Ameirus natalis* (-1.26), orangethroat darter *Etheostoma spectabile* (-1.13), and species that were positively associated were Texas shiner *Notropis amabilis* (2.07), mimic shiner *Notropis volucellus* (1.79), and Texas logperch *Percina carbonaria* (0.68).

Using variance partitioning, 45.2% of the variation could be explained by environment, site, and season pure effects (Figure 9), and all were found to be significant at 95% confidence intervals (environmental: F = 1.603, P = 0.0001, SAE = 1.030, 25.2% explained, site: F = 2.112, P = 0.0001, SAE = 0.555, 13.6% explained, season: F = 2.233, P = 0.0002, SAE = 0.261, 6.4% explained). Variation accounted for by two and three-way effects was 19.0%, with the remainder unexplained by the CCA model.

Discussion

The large amount of significant variation explained in the CCA model suggests a strong association between species and habitat. Pedernales site 3 is the first main-stem site downstream of the wastewater treatment plant in Fredericksburg and it showed correspondence with high loadings for dissolved oxygen, turbidity, pH, and associated tolerant taxa (Figure 6, Figure 7, and Figure 8). It was also a site that consistently differed from other sites in the Pedernales River basin in PCA plots looking at spatial and temporal differences (Figure 2 and Figure 4). These data help in explaining how the fish assemblage is structured and what habitat and environmental parameters seem to be important in showing species affinities. The fishes that showed an affinity for the Pedernales site 3 were also more tolerant taxa (i.e. *Gambusia affinis*, *Cyprinella lutrensis*, and possible hybrids of *C. lutrensis* X *C. venusta*).

Though season did not explain a large portion of the variation seen in the fish assemblage, it appeared that it did structure habitat and environmental variables evenly in PCA plots. Most sites exhibited a general pattern in multivariate space that followed through the seasons and was similar between nearby sites. This may aid in understanding on why certain fish species were found during portions of the year and not at others (e.g. spring associated taxa). Spring-flow oriented fishes showed affinities for tributaries, gravel, cobble, and riffles (i.e. *Etheostoma lepidum*, *Dionda episcopa*, *Micropterus treculii*, and *Etheostoma spectabile*). Notable headwater species were *Notropis amabilis*, *Notropis volucellus*, and *Percina carbonaria*. Generalist species were fairly predictable as well, with *Micropterus salmoides*, *Lepomis auritus*, *Lepomis macrochirus* and *Cyprinella venusta* showing little association with a specific habitat type, site or season (Figure 8).

Acknowledgments--We thank Rivers Systems Institute at Texas State University, Nature Conservancy of Texas, Texas Parks and Wildlife Division, Lower Colorado River Authority, and many students and professionals who helped in the lab, field, and in planning.

Literature Cited

Bean, P.T. 2006. Spatial and temporal patterns in the fish assemblage of the Blanco River, Texas, and reproductive ecology and diet of the gray redhorse, Moxostoma congestum. Master's thesis. Texas State University, San Marcos.

Bean, P.T., T.H. Bonner, and B.M. Littrell. 2007. Spatial and temporal patterns in the fish assemblage of the Blanco River, Texas. Texas Journal of Science, 59(3):179-200.

Birnbaum, J.S. 2005. Associations of watershed and instream environmental factors with aquatic macrofauna in tributaries of the Pedernales River, Texas. Master's thesis. Texas A & M University, College Station.

Blum, M.D., and S. Valastro, Jr. 1989. Response of the Pedernales River of Central Texas to late Holocene climatic change. Annals of the Association of American Geographers, 79(3):435-456.

Bowles, D.E., and T.L. Arsuffi. 1993. Karst aquatic ecosystems of the Edwards Plateau region of central Texas, USA: A consideration of their importance, threats to their existence, and efforts for their conservation. Aquatic Conservation: Marine and Freshwater Ecosystems, 3(4):317-329.

Conner, J.V., and R.D. Suttkus. 1986. Zoogeography of freshwater fishes of the western Gulf Slope of North America. Pages 413-456 *in* C.H. Hocutt and E.O. Wiley, editors. The zoogeography of North American freshwater fishes. Wiley, New York.

Cummins, K.W. 1962. An evaluation of some techniques for the collection and analysis of benthic samples with special emphasis on lotic waters. American Midland Naturalist, 67(2):477-504.

Franssen, N.R., K.B. Gido, C.S. Guy, J.A. Tripe, S.J. Shrank, T.R. Strakosh, K.N. Bertrand, C.M. Franssen, K.L. Pitts, and C.P. Paukert. 2006. Effects of floods on fish assemblages in an intermittent prairie stream. Freshwater Biology, 51:2072-2086.

Harrell, H.L. 1978. Response of the Devil's River (Texas) fish community to flooding. Copeia, 1978(1):60-68.

Higgins, C.L. 2005. Functional groupings of stream fishes: spatiotemporal variation, predictability, and patterns of diversity. Doctoral dissertation. Texas Tech University, Lubbock.

Hubbs, C., R.J. Edwards, and G.P. Garrett. 1991. An annotated checklist of the freshwater fishes of Texas, with keys to identification of species. Texas Journal of Science, Supplement 43(4):1-56.

Leopold, A.F. 2001. Recolonization mechanisms of macroinvertebrates of Barton Creek, Travis Co., Texas. Doctoral dissertation. Clemson University, Clemson.

Matthews, W.J. 1988. North American prairie streams as systems for ecological study. Journal of the North American Benthological Society, 7(4):387-409.

Poff, N.L., and J.D. Allan. 1995. Functional organization of stream fish assemblages in relation to hydrological variability. Ecology, 76(2):606-627.

Rice, S.P., M.T. Greenwood, and C.B. Joyce. 2001. Tributaries, sediment sources, and the longitudinal organization of macroinvertebrate fauna along river systems. Canadian Journal of Fisheries and Aquatic Sciences, 58:824-840.

Table 1. Environmental ranges recorded from all sites in the Pedernales River basin from February 2007 through November 2007.

Mainstem Site	P1	P2	P3	P4	P5
Temperature (°C)	10.27 - 25.70	9.30 - 29.73	10.60 - 28.88	11.00 - 26.49	10.75 - 25.97
Dissolved Oxygen (mg/l)	7.43 - 12.20	7.74 - 12.76	7.74 - 18.25	4.45 - 13.50	4.24 - 12.29
Conductivity (µS/cm)	0.470 - 0.594	0.540 - 0.702	0.594 - 0.730	0.568 - 0.666	0.539 - 0.653
pH	8.23 - 8.59	8.16 - 8.42	8.30 - 8.82	8.24 - 8.45	8.20 - 8.43
Turbidity (NTU)	0.0 - 12.1	1.5 - 13.2	3.3 - 17.3	0.0 - 7.2	0.0 - 3.1
Average Depth (cm)	36.20 - 161.83	23.60 - 68.40	7.33 - 34.80	21.00 - 79.60	17.50 - 85.60
Average Current Velocity (m/s)	0.076 - 0.874	0.006 - 0.492	0.000 - 0.764	0.104 - 1.193	0.055 - 0.580
Tributary Site	**B1**	**C1**	**G1**	**L1**	
Temperature (°C)	9.11 - 28.71	13.24 - 23.95	14.57 - 27.78	7.57 - 25.82	
Dissolved Oxygen (mg/l)	4.72 - 18.21	0.45 - 10.68	0.90 - 9.49	3.98 - 12.24	
Conductivity (µS/cm)	0.821 - 1.160	0.529 - 0.605	0.540 - 0.615	0.591 - 0.650	
pH	8.20 - 8.99	7.94 - 8.45	8.09 - 8.54	7.98 - 8.28	
Turbidity (NTU)	0.0 - 3.6	0.0 - 0.8	0.0 - 1.1	0.0 - 1.0	
Average Depth (cm)	21.57 - 76.80	17.60 - 90.60	9.00 - 68.00	13.60 - 41.60	
Average Current Velocity (m/s)	0.012 - 0.488	0.000 - 0.518	0.018 - 0.682	0.099 - 0.342	

Table 2. Absolute abundances of fish species sampled from all sites in the Pedernales River basin.

Scientific Name	Common Name	Abundance
Lepisosteus osseus	longnose gar	1
Dorosoma cepedianum	gizzard shad	59
Campostoma anomalum	central stoneroller	622
Cyprinella lutrensis	red shiner	2522
Cyprinella venusta	blacktail shiner	4837
Cyprinella sp.	(*lutrensis* x *venusta* hybrid)	21
Cyprinus carpio	common carp	2
Dionda episcopa	roundnose minnow	14
Notropis amabilis	Texas shiner	528
Notropis stramineus	sand shiner	17
Notropis volucellus	mimic shiner	124
Pimephales vigilax	bullhead minnow	288
Carpiodes carpio	river carpsucker	15
Moxostoma congestum	gray redhorse	17
Ameiurus melas	black bullhead	10
Ameiurus natalis	yellow bullhead	12
Ictalurus furcatus	blue catfish	1
Ictalurus punctatus	channel catfish	581
Pylodictis olivaris	flathead catfish	16
Menidia beryllina	Inland silverside	21
Gambusia affinis	western mosquitofish	582
Lepomis auritus	redbreast sunfish	586
Lepomis cyanellus	green sunfish	131
Lepomis gulosus	warmouth	13
Lepomis humilis	orangespotted sunfish	68
Lepomis macrochirus	bluegill	370
Lepomis megalotis	longear sunfish	507
Lepomis microlophus	redear sunfish	60
Lepomis sp.	hybrid	2
Micropterus salmoides	largemouth bass	85
Micropterus treculii	Guadalupe bass	141
Pomoxis nigromaculatus	black crappie	1
Etheostoma lepidum	greenthroat darter	108
Etheostoma spectabile	orangethroat darter	59
Percina carbonaria	Texas logperch	93
Percina sciera	dusky darter	3
Cichlasoma cyanoguttatum	Rio Grande cichlid	30
	Total number of fish	12547

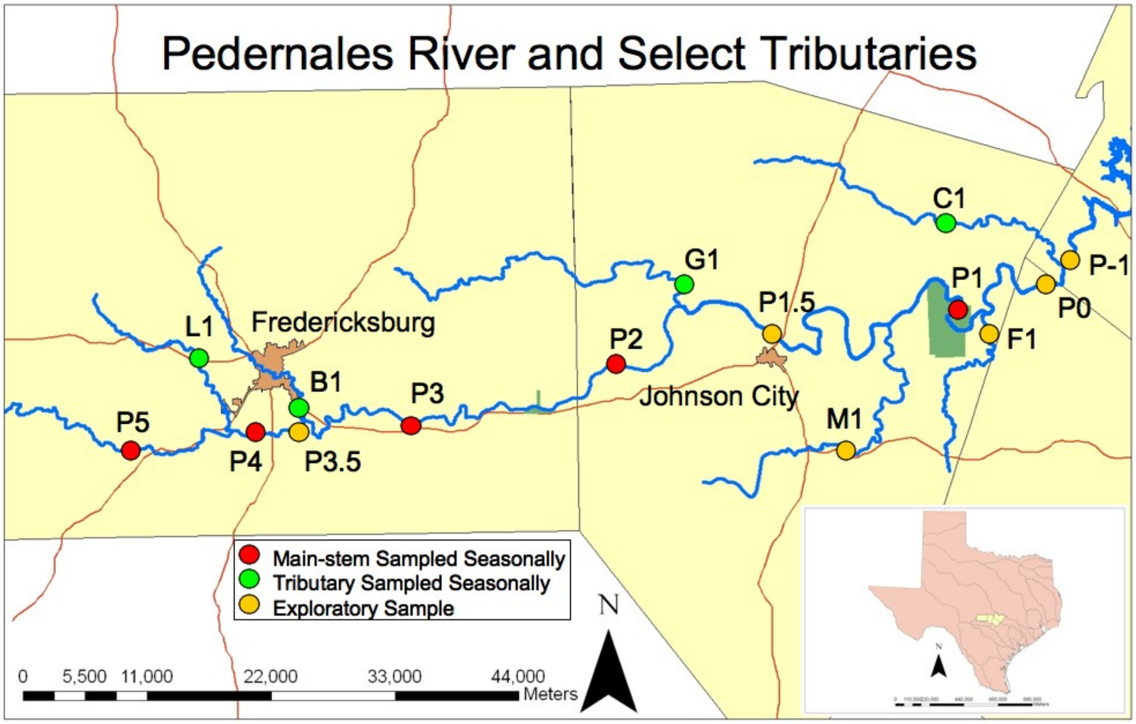

Figure 1. Sampling sites in the Pedernales River basin separated by sites sampled regularly (seasonally) and sites sampled in exploration.

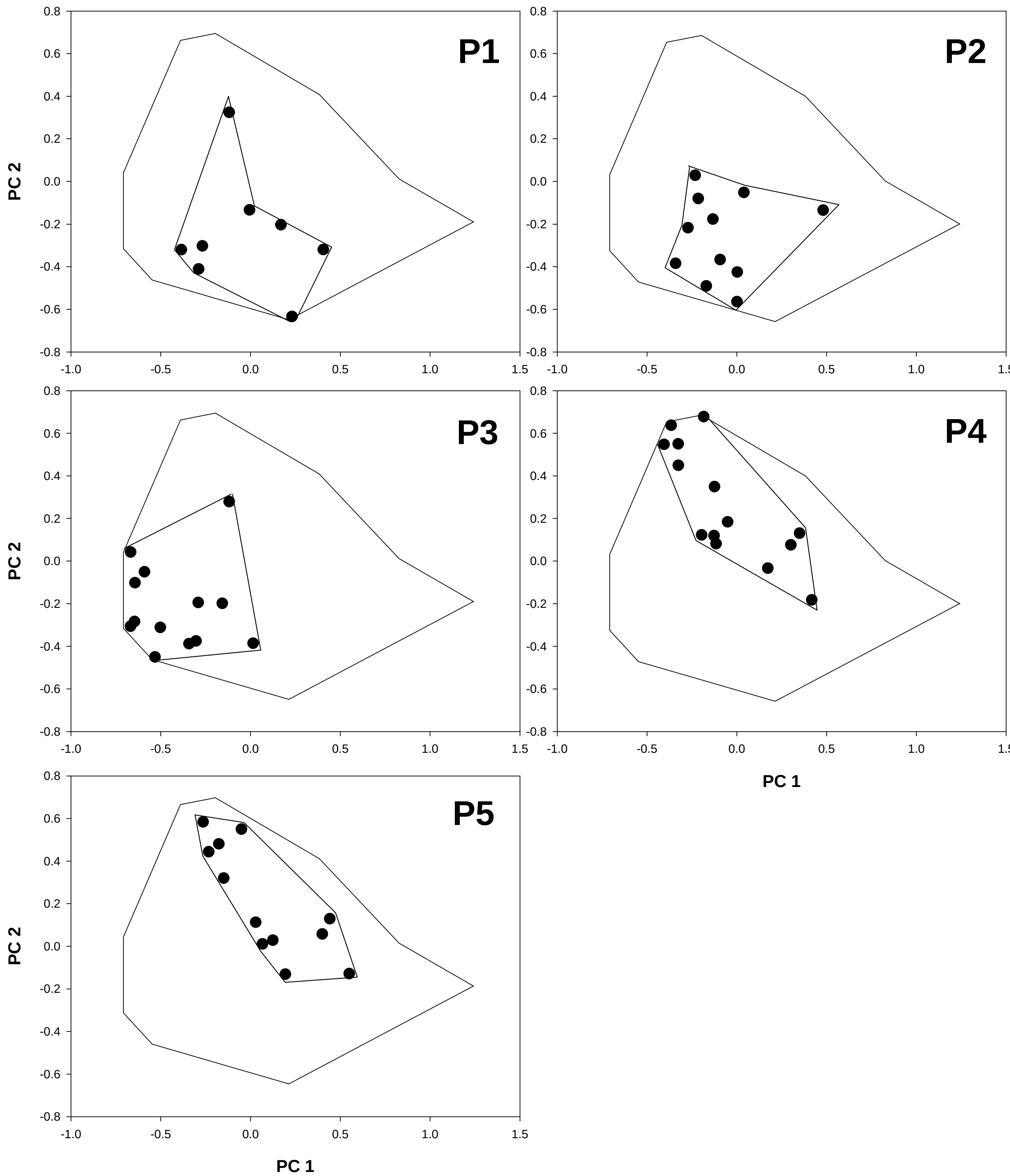

Figure 2. Principal Component Analysis of all 99 habitat samples for the Pedernales River with mainstem sites separated individually by site and partitioned within all available multivariate space.

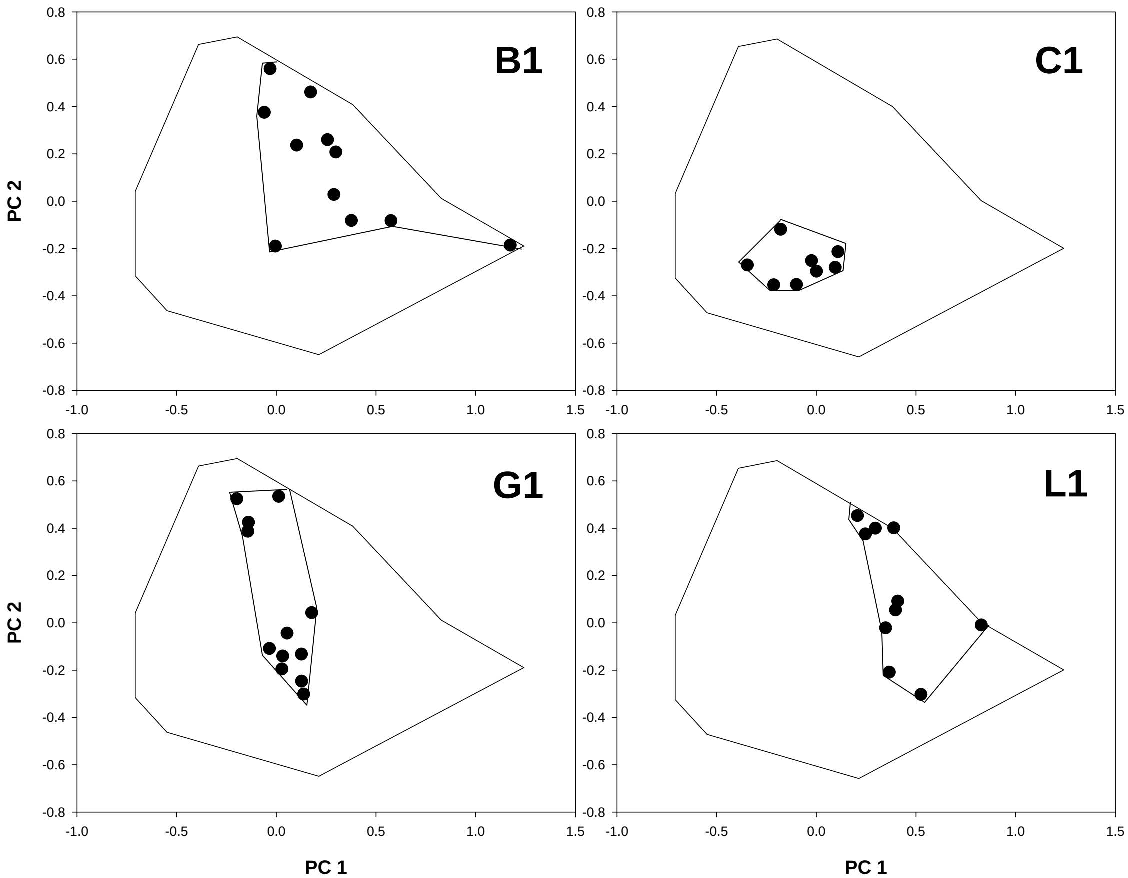

Figure 3. Principal Component Analysis of 99 habitat samples for the Pedernales River with tributary sites separated individually by site and partitioned within all available multivariate space.

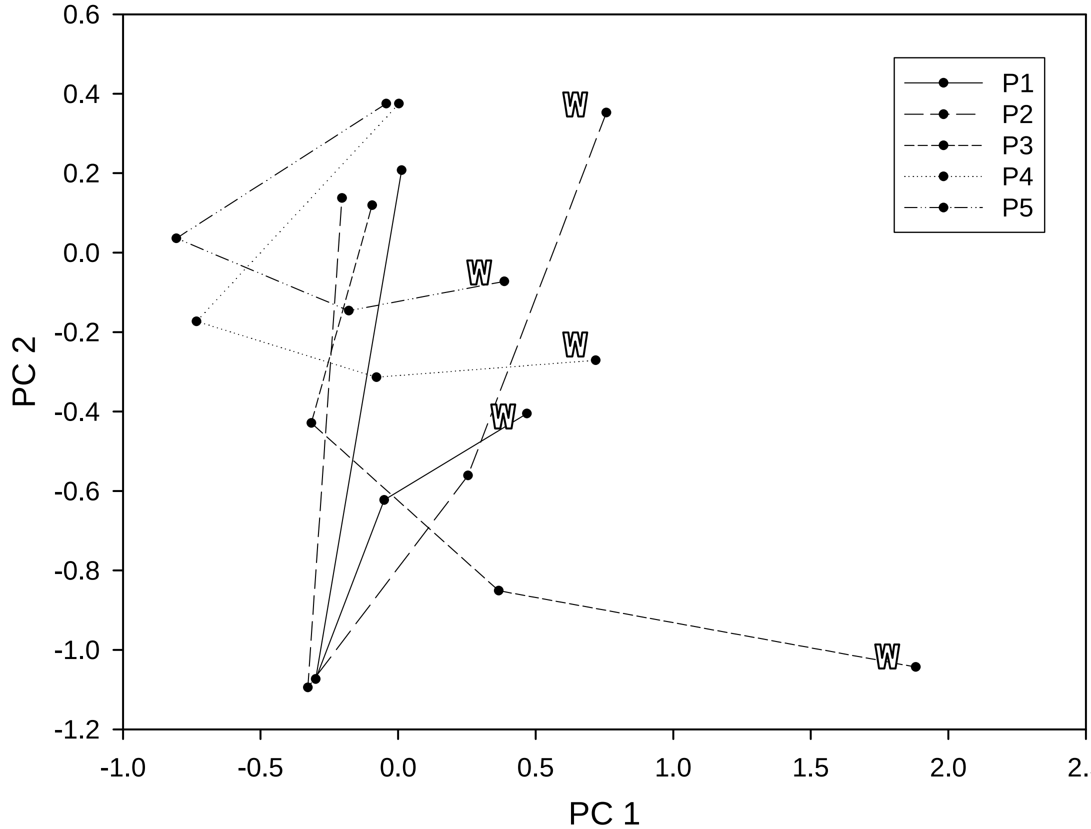

Figure 4. Principal Component Analysis using a trajectory plot of averaged environmental samples by season (winter, spring, summer, fall), with "W" designating winter followed by subsequent seasons for the Pedernales River mainstem sites.

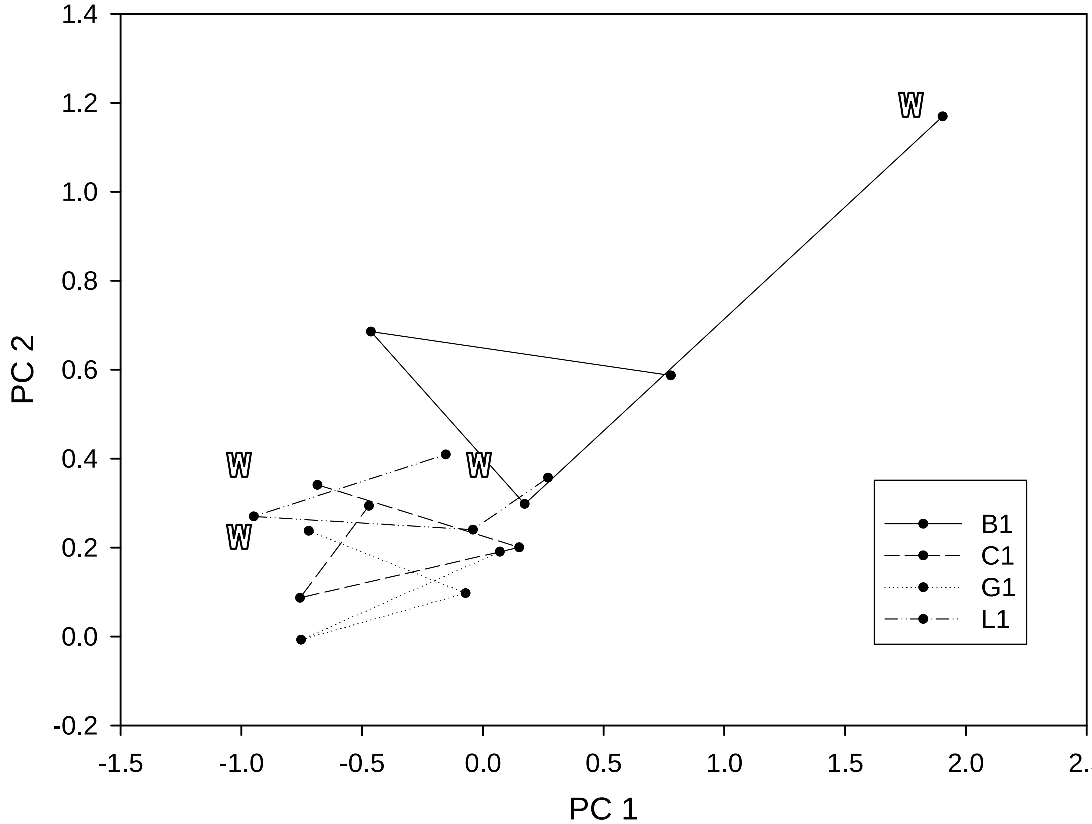

Figure 5. Principal Component Analysis using a trajectory plot of averaged environmental samples by season (winter, spring, summer, fall), with "W" designating winter followed by subsequent seasons for the Pedernales River tributary sites.

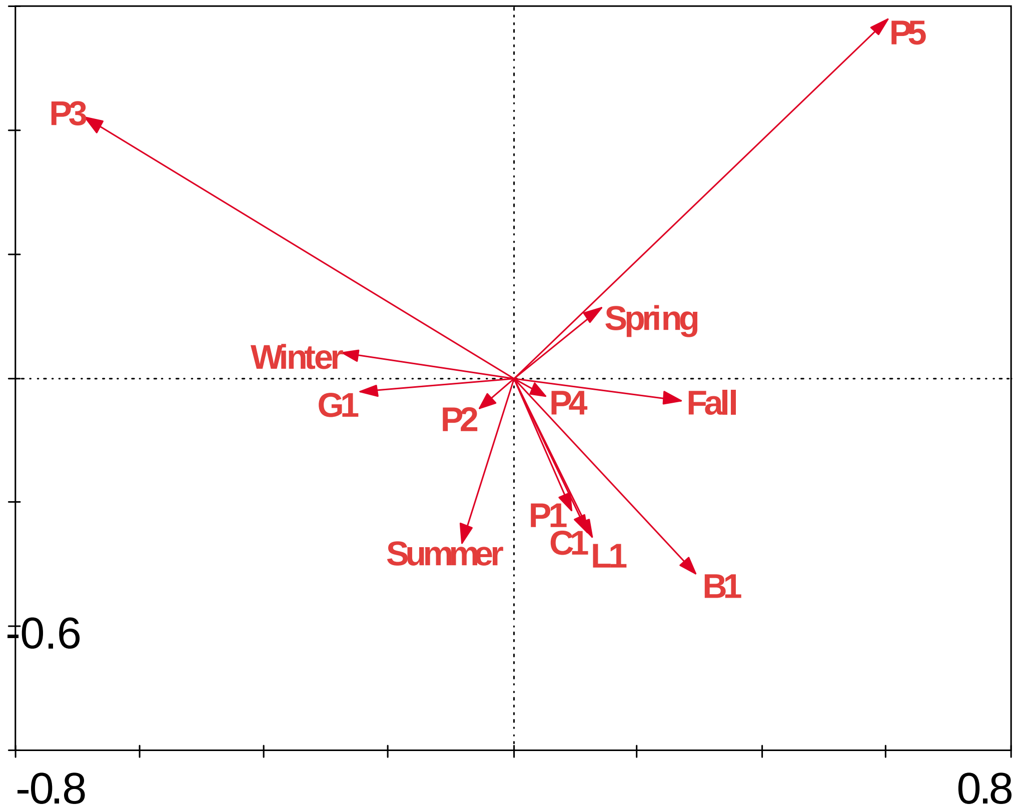

Figure 6. Canonical Correspondence Analysis scores for season and site, the complete CCA model explained 64.2% of the variation seen (TI = 4.085, SAE = 2.624).

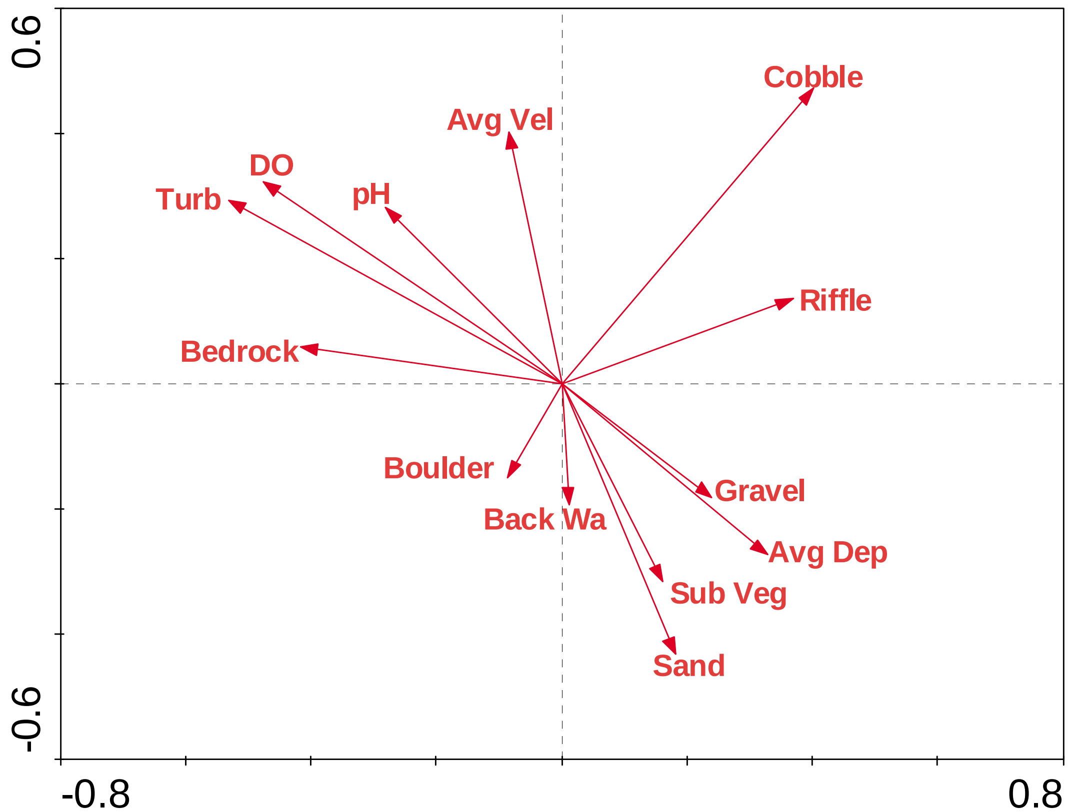

Figure 7. Canonical Correspondence Analysis scores for habitat, the complete CCA model explained 64.2% of the variation seen (TI = 4.085, SAE = 2.624).

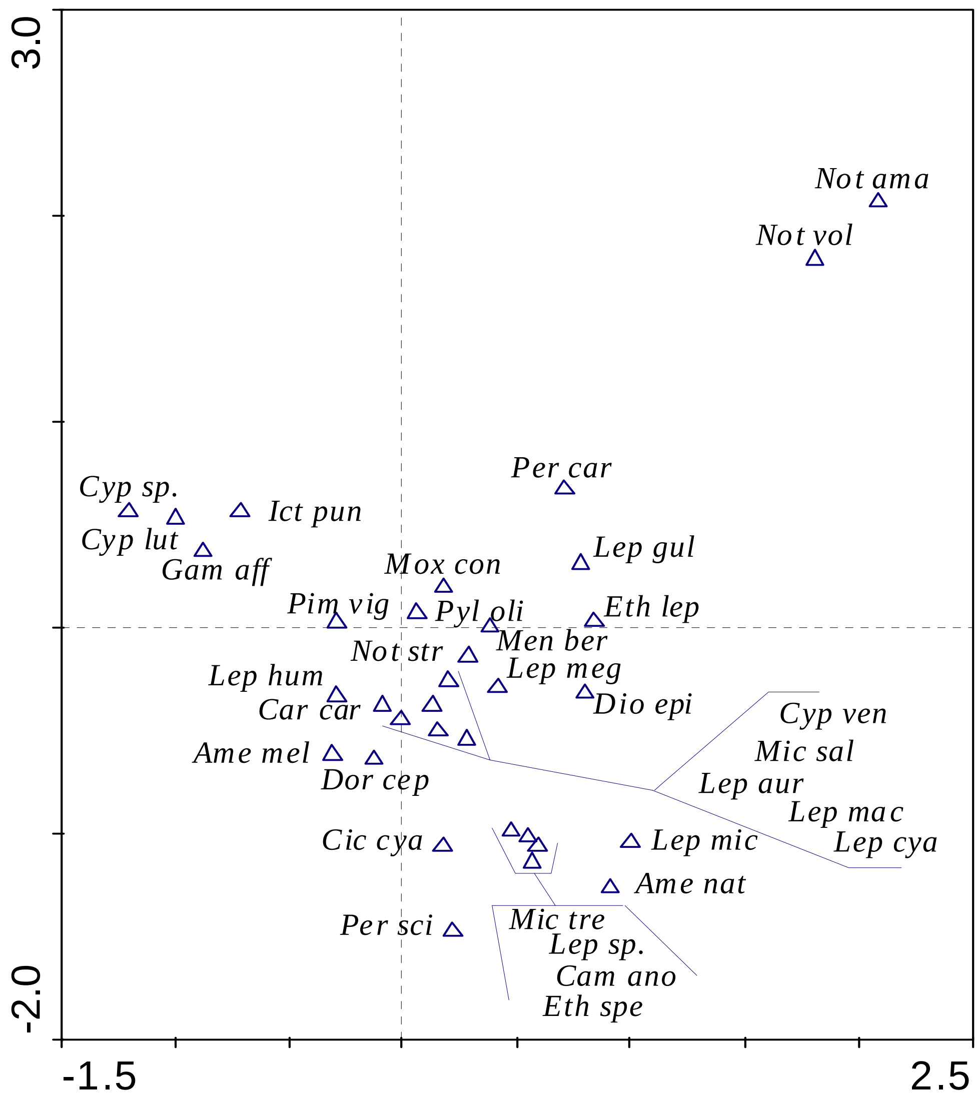

Figure 8. Canonical Correspondence Analysis scores for fish species, the complete CCA model explained 64.2% of the variation seen (TI = 4.085, SAE = 2.624).

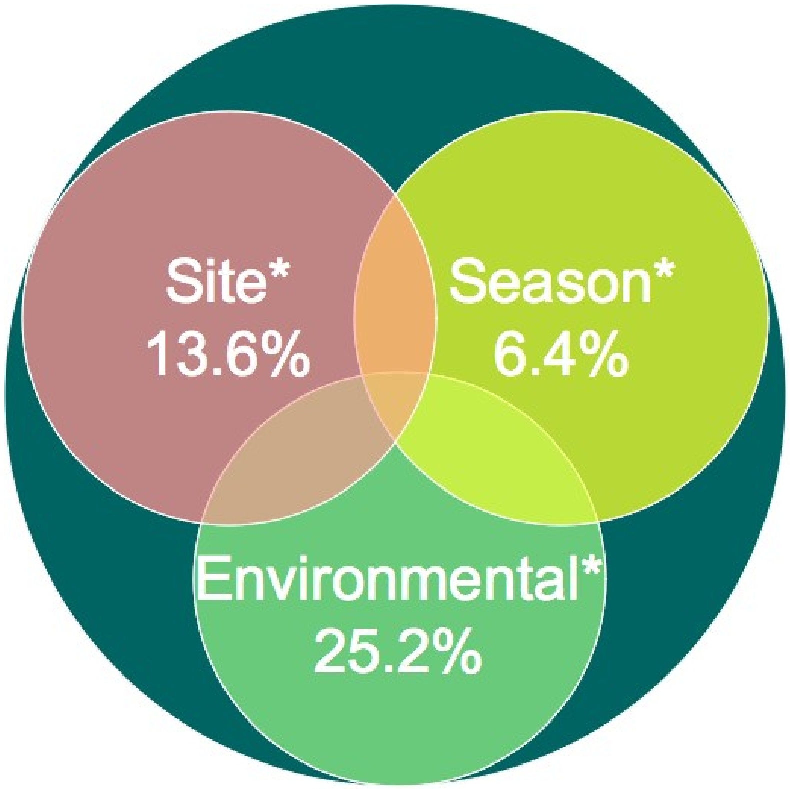

Figure 9. Variance partitioning of Canonical Correspondence Analysis with a total of 45.2% variance explained by environmental, site, and season pure effects (*all effects were found to be significant α = 0.05) with 19.0% variance explained in the two and three-way effects.

Water Quality Analysis of the Pedernales River, Texas

Project Final Report

August 2008

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INTRODUCTION

The Pedernales River is located in the Edwards Plateau ecoregion, and exhibits the characteristics of karst geology. Chemical weathering of karst rock creates conditions conducive for the formation of aquifers, a unique ecosystem with a high degree of connectivity between surface waters and groundwater (Cave, 2006). The Edwards Plateau is characterized by geologically distinct subregions with the Balcones Canyonlands located between the Llano Uplift and the Balcones Escarpment forming its southeastern boundary. The Balcones Canyonlands are generally referred to as the Texas Hill Country and have many distinguishing characteristics, including: high gradient streams, steep canyons, extreme hydrologic variability, and endemic aquatic organisms (LCRA, 2000 and Cave, 2006). The Pedernales River watershed is the northernmost watershed of this subregion, with boundaries defined by the of U. S. Geological Survey (USGS) hydrologic unit 12090206. The watershed is approximately 815,000 acres (3,300 km^2) of central Texas, mostly located within Blanco and Gillespie counties, but also includes Burnet, Hays, Kendall, Kerr, Kimble, and Travis counties. Headwater springs are located in Kimble County with the termination point being the confluence with Lake Travis near the Colorado Rivers confluence in Travis County (LCRA, 2000). The Pedernales River watershed is directly bounded Llano Uplift to the north, which provides a unique geologic aspect to the rivers water chemistry.

The Pedernales River watershed is characterized by a subtropical climate, with typically wetter summers and dry winters. Precipitation is highly variable, and rainfall is dominated by short-term high intensity events (LCRA, 2000). The local climate in coordination the local geology creates conditions conducive for rapid runoff creating flash flood events. This hydrologic variability in combination with the aquifer system are the driving forces for the unique habitat with which many endemic aquatic organisms persist.

The Pedernales River watershed has many distinguishing characteristics, which offer an opportunity to study and analyze important unique aquatic chemical and physical properties. The purpose of this study is to characterize the water quality of the Pedernales River, and analyze results to determine current conditions and identify potential significant water quality trends. These possible trends include: spatial trends (i.e., variations in concentrations along the length of the river), and temporal trends (i.e., variations in concentrations through time at a single monitoring site). Groundwater and tributary influences may also be identified as important.

STUDY VARIABLES

The primary focus of this study was to determine the water quality of the Pedernales River and the influence of the contributing watershed. The selected variables were chosen as they are primary indicators of the chemical and physical status of an aquatic system. Many of these variables are biological response variables to each other, as affecting one will in turn affect the other. Under Section 305(b) of the Clean Water Act the U. S. Environmental Protection Agency (USEPA) has designated five types of water quality monitoring data. For the purpose of the study, three types of data were collected: physical data, chemical data, and biological data. The selected constituents used to make assessments of the water quality of the Pedernales River included:

- Physical Data
    - Temperature
    - Specific Conductance
    - Turbidity
- Chemical Data
    - pH

- Dissolved Oxygen (DO)
    - Alkalinity
    - Nitrate (N-NO_3)
    - Total Phosphorus (TP)
    - Soluble Reactive Phosphorus (SRP)
- Biological Data
    - Chlorophyll a

Physical Data and Water Quality Implications

Specific conductance

Specific conductance measurements give an indication of ions or dissolved-solid concentrations in an aquatic system (Kalff, 2001). Primary factors influencing conductivity include: local geology, climate, and anthropogenic inputs. The Edwards Plateau is largely dominated by sedimentary carbonate rock including limestone, dolomite, sandstone, and shale. These rock types have a higher degree of solubility, which lead to higher concentrations of ions in the water column. Higher conductivity readings near urban areas can be a result of industrial pollution or urban runoff, particularly areas receiving wastewater effluent. Wastewater effluent can be characterized by high levels Na^+ and Cl^- ions, increased phosphorus, and moderately increased levels of nitrogen.

Turbidity

Turbidity is a measurement of the suspended solids in the water. Increased turbidity can decrease light penetration into the water column, which adversely effects primary productivity, photosynthesis, and can cause variations in pH and dissolved oxygen concentrations (Ebbert, 2002).

Chemical Data and Water Quality Implications

Dissolved Oxygen (DO) and pH

Many of these constituents are covariates, in that they directly affect the relationship of other variables. The DO levels in an aquatic system can often provide more insight in the metabolism of that system than any other single measurement (Kalff, 2001). Low DO levels not only affect the distribution and growth of the biological community, but also have major effects on the uptake or release of nutrients from sediments (Kalff, 2001). Several factors can affect DO levels in an aquatic system. Warmer water temperatures hold less DO, and can provide conditions for increased bacterial respiration. These forces working together can serious negative impacts, such as creating anoxic conditions. Anoxic conditions can lead to algal blooms, decrease species diversity or richness, and potential fish kills. Extreme temperatures, anoxic conditions, and high nutrient levels can lead to extremely high or low pH levels, which can also directly affect species diversity or richness.

Alkalinity

Alkalinity refers the acid neutralizing capacity, or the sum of the weak acid ions (Kalff, 2001). As the Pedernales River is a limestone rock dominated system, its alkalinity is quite high.

Nutrients: N and P

The most recent USEPA report on the conditions the national waters has listed nutrients as the fifth leading pollutant in rivers and streams (USEPA, 2002). Nutrients can be defined as chemical compounds that contain nitrogen (N) or phosphorus (P) (Mueller and Spahr, 2006). These compounds are essential to primary productivity, but in high numbers can lead to eutrophication of freshwater systems. Additionally, "Nutrient compounds are affected by chemical and biological processes that can change their form and can transfer them to or from water, soil, biological organisms, and the atmosphere" (Mueller and Spahr, 2006). During low oxygen conditions, toxic compounds may be created. Rapidly growing algae remove carbon dioxide from the water during photosynthesis, which can result in a significant increase in pH levels.

Biological Data and Water Quality Implications

Chlorophyll a

Chlorophyll a concentrations are an indicator of phytoplankton abundance and biomass in an aquatic system. Excessive quantities of chlorophyll a can be an indictor of the presence of algal blooms, and/or excessive nutrient concentrations.

METHODS

Sampling included seven monitoring sites along the length of the Pedernales River, and six sites on five major contributing perennial tributaries (Figure 1). The tributaries incorporated in the survey included: Live Oak Creek, Barons Creek, North Grape Creek, Cypress Creek, and Miller Creek. All sites were located off public road-crossing, except P6 which was located within Pedernales State Park. Sampling events were conducted on a monthly basis from July 2007 to July 2008, with readings and discrete samples taken from the bank in areas where there was visible stream flow.

Abiotic variables assessed included: temperature, pH, DO, and specific conductivity with a Hydrolab™ Minisonde that was calibrated one day prior to the sampling event (Hydrolab Corporation, Austin, Texas, USA). Turbidity was measured using a Fisher Scientific Turbidometer. Water samples were also collected at each site location in acid-washed high-density polyethylene (HDPE) bottles, stored on ice, and transported back to the lab where all necessary preparations for more permanent storage were conducted until analysis could be performed. From the collected water samples the following analysis were conducted: SRP, TP, $N\text{-}NO_3$, alkalinity, and chlorophyll a. Storage and analysis of nutrients were conducted in accordance with standard methods approved by the USEPA. Alkalinity was measured by potentiometric titration to pH 4.8 using 0.02 N H_2SO_4 (Wetzel and Likens, 2000). Chlorophyll a was measured using fluorometeric analysis. SRP was determined using the ascorbic acid method (Murphy and Riley, 1962). $N\text{-}NO_3$ was measured by second-derivative UV spectroscopy (Crumpton *et al*., 1992).

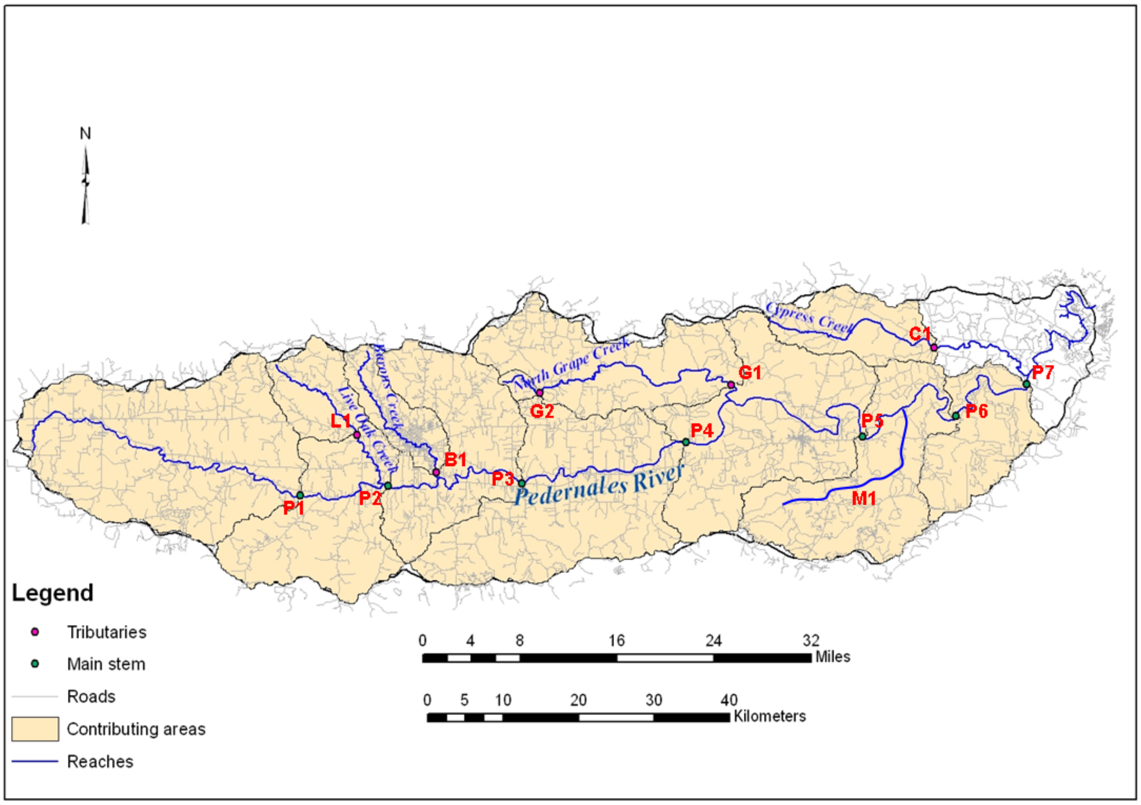

Figure 1. Monitoring site location map.

RESULTS and DISCUSSION

Temperature (^{o}C), pH, and Alkalinity (meq/L)

Median water temperatures varied by site between 19 and 26 ºC. There appeared to be a warming trend from upstream to downstream (Table 1.1). Headwaters are more heavily driven by spring and groundwater, therefore colder upstream temperatures are expected. Live Oak Creek was found to have a lower median temperature than the Pedernales (Table 1.2). Tributaries in the Pedernales watershed are characterized by strong spring water influence. Lower more consistent water temperatures are expected in spring-fed systems. These characteristics were most apparent at Live Oak and Cypress Creek monitoring sites (Table 1.2). Median alkalinity values were generally higher at tributary sites than at Pedernales sites (Table 1.2). However, Miller Creek was found to have a lower median alkalinity than the Pedernales. This is likely due to differing geology as Miller Creek was the only tributary monitored south of the river.

	P1	P2	P3	P4	P5	P6	P7
Temperature (°C)	**20.81**	**20.91**	**22.55**	**22.42**	**25.59**	**25.58**	**24.24**
	SD = 7.38	*SD = 7.63*	*SD = 7.43*	*SD = 7.75*	*SD = 6.88*	*SD = 6.50*	*SD = 7.28*
pH	**8.06**	**8.16**	**8.31**	**8.31**	**8.39**	**8.38**	**8.41**
	SD = 0.27	*SD = 0.20*	*SD = 0.22*	*SD = 0.19*	*SD = 0.19*	*SD = 0.11*	*SD = 0.41*
Alkalinity (meq/L)	**4.72**	**4.88**	**5.04**	**4.80**	**4.48**	**4.44**	**4.36**
	SD = 0.40	*SD = 0.34*	*SD = 0.52*	*SD = 0.38*	*SD = 0.28*	*SD = 0.29*	*SD = 1.38*

Table 1.1. Median water temperature (ºC) and standard deviation from the monitoring stations on the Pedernales River.

	Live Oak Creek	Barons Creek	North Grape Creek (G1)	North Grape Creek (G2)	Miller Creek	Cypress Creek
Temperature (°C)	**19.78**	**21.21**	**23.22**	**24.59**	**22.05**	**21.04**
	SD = 7.04	*SD = 7.53*	*SD = 6.94*	*SD = 8.41*	*SD = 7.05*	*SD = 5.75*
pH	**8.12**	**8.23**	**8.29**	**8.19**	**8.22**	**8.15**
	SD = 0.18	*SD = 0.32*	*SD = 0.28*	*SD = 0.21*	*SD = 0.26*	*SD = 0.12*
Alkalinity (meq/L)	**5.52**	**6.08**	**4.84**	**6.40**	**4.16**	**5.52**
	SD = 0.31	*SD = 0.38*	*SD = 0.42*	*SD = 0.82*	*SD = 0.57*	*SD = 0.28*

Table 1.2. Median water temperature (ºC) and standard deviation from the monitoring stations on the sampled tributaries.

Specific Conductance (uS/cm)

A total of 169 specific conductivity measurements were taken, with the mean across all sites being approximately 650 uS/cm. There was a decreased trend in specific conductance from upstream to downstream (Figure 2). However, there was a slight increase at P3 and P4. The Fredericksburg wastewater treatment facility is located on Barons Creek. The P3 monitoring station is located directly downstream of the confluence of Barons Creek into the Pedernales. This slight increase in conductivity is likely the effect of wastewater effluent. There were two high peaks in the dataset: B1 (i.e., Barons Creek) and G2 (i.e., upstream site at North Grape Creek). The input of Na^+ and Cl^- ions and excessive nutrients from the wastewater treatment facility is causing a spike in conductance relative to the other tributary sites. North Grape Creek is predominately located in the Llano Uplift, which is dominated largely by Precambrian rock versus the soft sedimentary Cambrian rock of the Texas Hill Country ecoregion. This change in geology is likely cause of the increase in specific conductivity, as there were no notable differences in the other parameters measured.

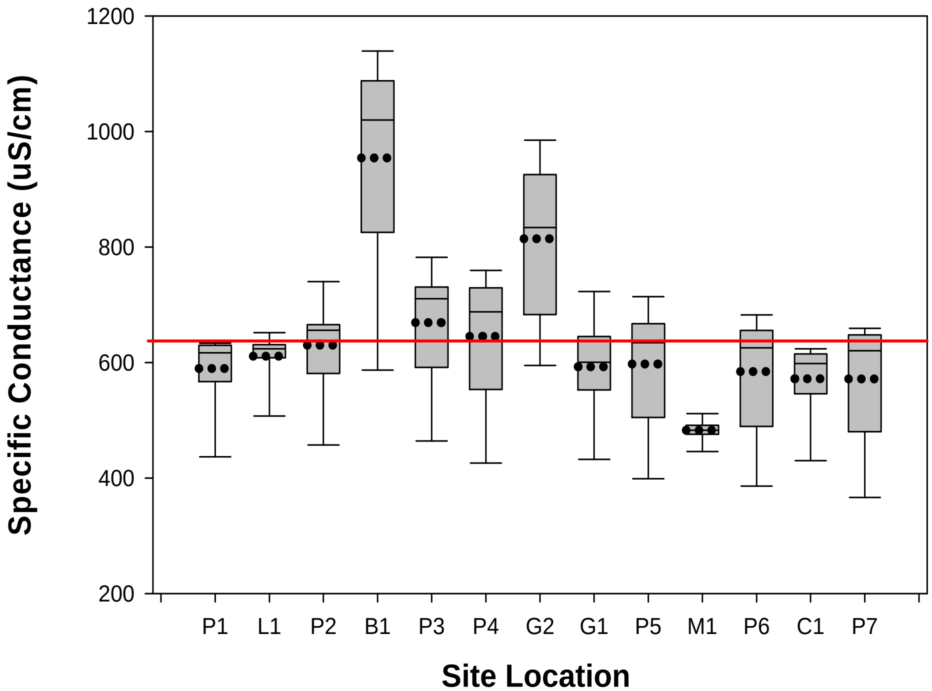

Figure 2. Box-plot diagrams of specific conductance (uS/cm) by site location. The red line represents the grand mean.

Dissolved Oxygen (mg/L)

Dissolved oxygen concentrations were normally between 8 and 10 mg/L for all sites, and were generally near saturation with the atmosphere. Some samples did fall below 80% saturation. Those samples were identified to be winter samples taken early in the morning, and likely before photosynthetic activities had the chance to compensate for nightly respiration. At the B1 and P3 monitoring sites, DO concentrations were found to be consistently supersaturated. The high nutrient input by the wastewater treatment facility at Barons Creek could be causing an increase in photosynthesis, and the supersaturated DO conditions.

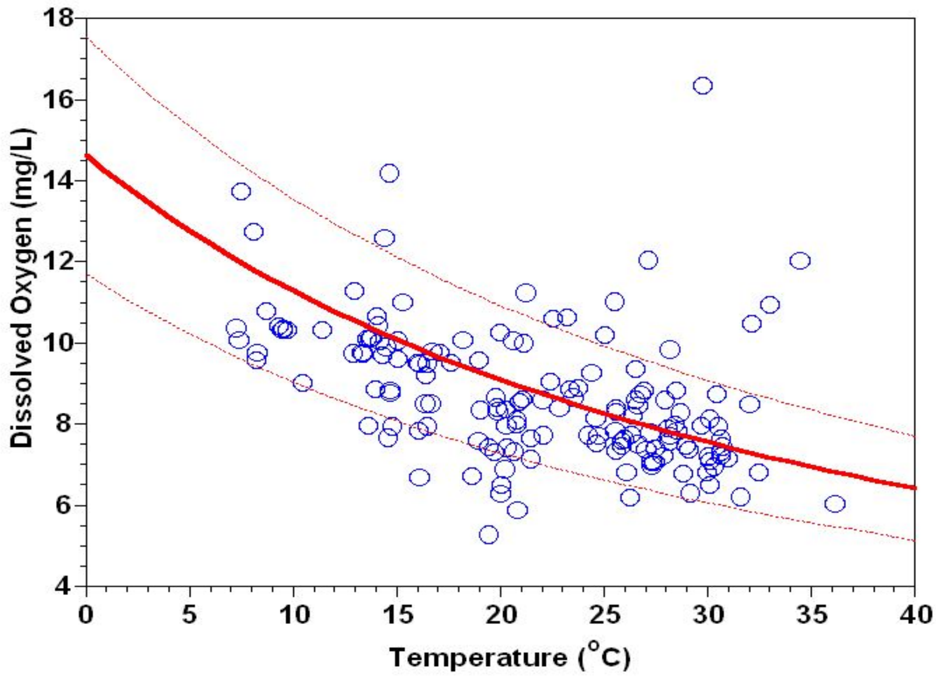

Figure 3. Dissolved oxygen and water temperature from all monitoring stations. The solid line represents 100% saturation, and the upper and lower dashed lines represent 120 and 80% saturation, respectively.

Turbidity (NTU)

Turbidity values generally ranged between 2 and 5 NTU, with the exception of summer 2007 samples. Extreme runoff from heavy precipitation during the summer months dramatically increased turbidity values, particularly at the downstream monitoring stations. There was a notable increase in turbidity at the downstream river monitoring sites (Figure 4.1). This is likely due to headwater stations being more spring and groundwater driven, whereas downstream surface flow is additive at each site location. Tributary turbidity was usually very low, even during the rainy season (Figure 4.2).

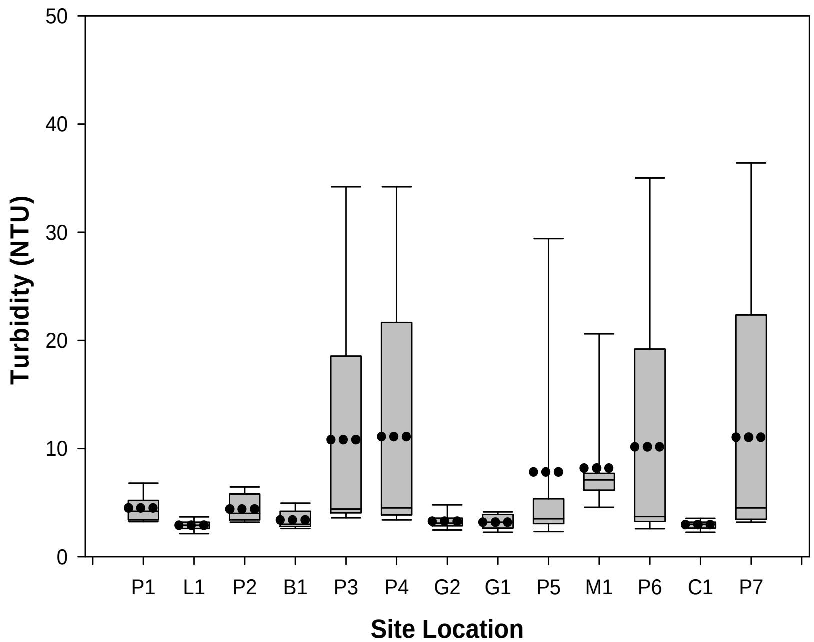

Figure 4.1. Box-plot diagrams of turbidity (NTU) from all monitoring stations.

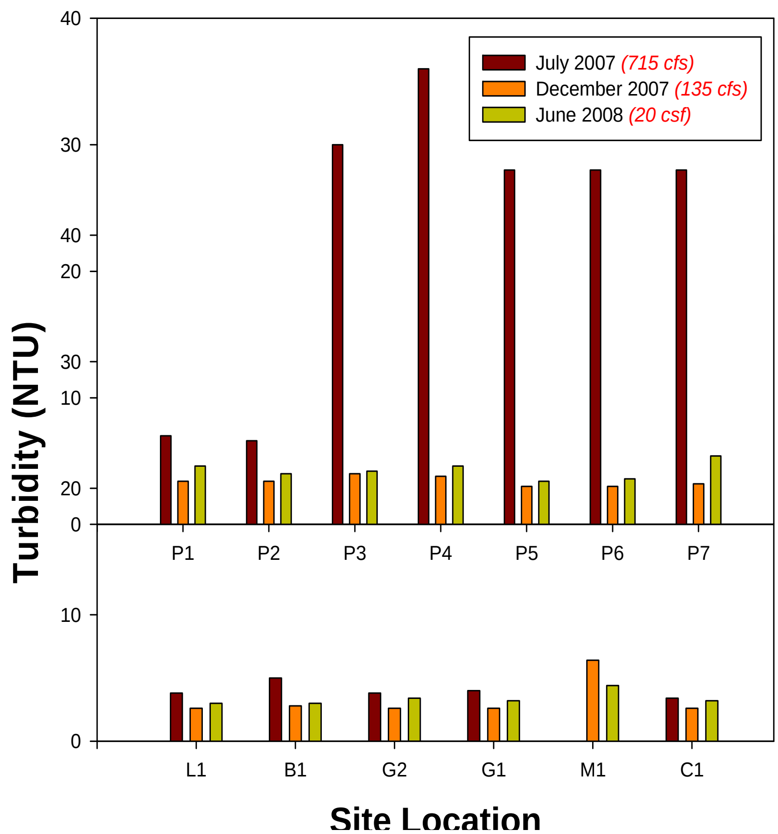

Figure 4.2. Turbidity by monitoring stations at three varying flow regimes.

Phosphorus (ug/L)

Median TP values from Pedernales monitoring stations varied by site between 6 and 10 mg/L (Figure 5.1). TP concentrations appeared to be greatly influenced by the input of nutrients from the wastewater treatment facility. Barons Creek monitoring station (B1) nutrient levels were on average 200 times greater than any other site location (Figure 5.2). This increased nutrient input was also noticeable within the Pedernales River downstream of B1, particularly at the most immediate downstream (P3) monitoring station. Increases in nutrient loading can cause increases in primary productivity at these site locations, which was noted in the chlorophyll a samples taken.

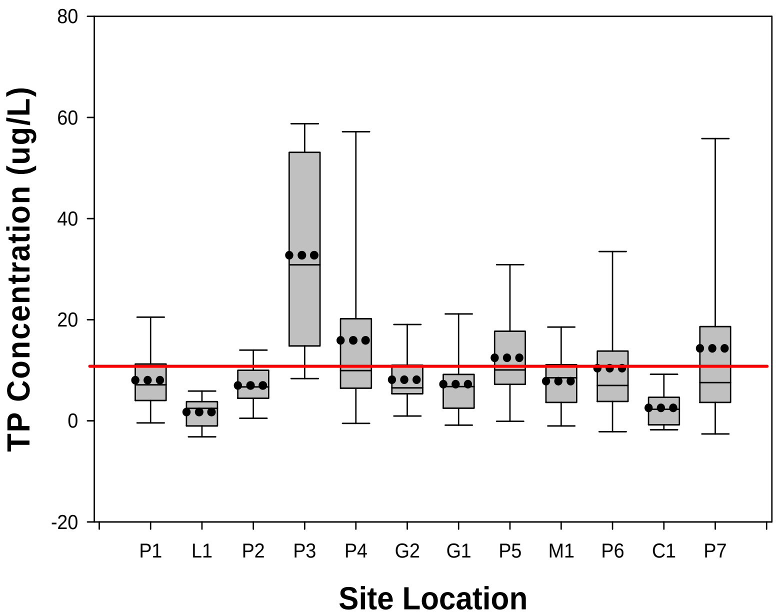

Figure 5.1. Box-plot diagrams of TP (ug/L) at all monitoring stations excluding Barons Creek.

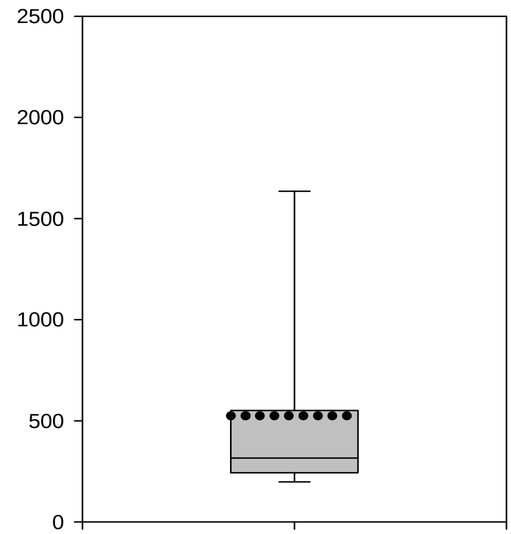

Figure 5.2. Box-plot diagram of TP (ug/L) at the Barons Creek monitoring station.

Nitrates (ug/L)

Median nitrate values from all monitoring stations varied by site between 90 and 900 mg/L (Figure 6). There was a downward trend in nitrate concentration from upstream to downstream. Higher nitrates are expected upstream in this system due to strong spring and groundwater influence. Groundwater often contains higher concentrations of dissolved solids, nitrogen, and other ionic species especially in karst river systems (Barrett, 1996). Agricultural land use practices upstream are also higher than downstream, and include more row crop cultivation which would result in higher nutrient loadings through fertilizers and irrigation return flows. However, there was a slight increase at P3 and P4. This is likely due to the increase nutrients from the wastewater effluent.

Lower nitrate values at the downstream monitoring stations could be due to either dilution through increased flows or through biological uptake (Kalff, 2001).

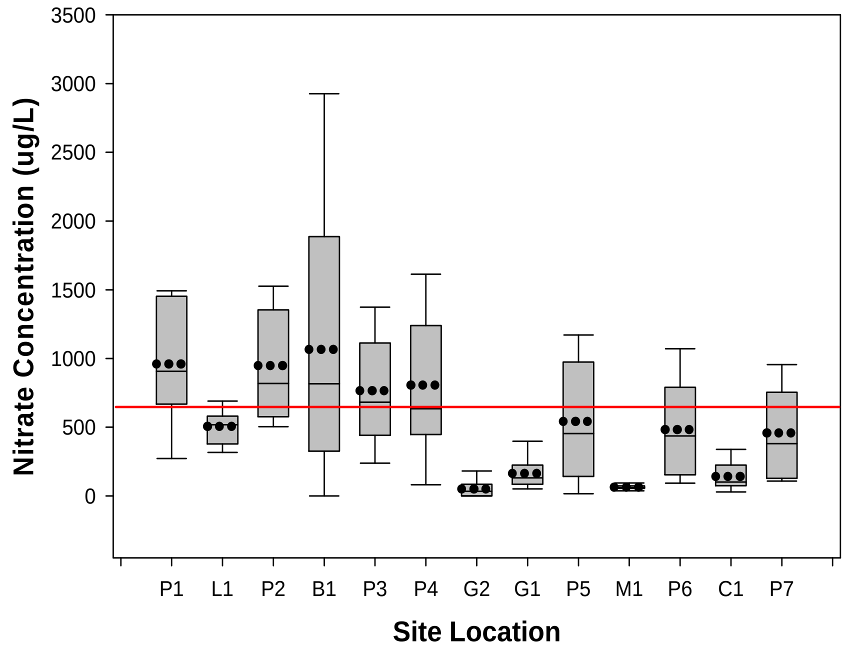

Figure 6. Box-plot diagrams of nitrate concentration (ug/L) at all monitoring stations. The red line represents the grand mean.

Chlorophyll a

Chlorophyll a values generally ranged between 1 and 3 ug/L, with the exception of Barons Creek and P3 samples. B1 and P3 chlorophyll a concentrations were found to be consistently higher than the other monitoring stations. The high nutrient input by the wastewater treatment facility at Barons Creek is likely causing an increase in photosynthesis in the water column.

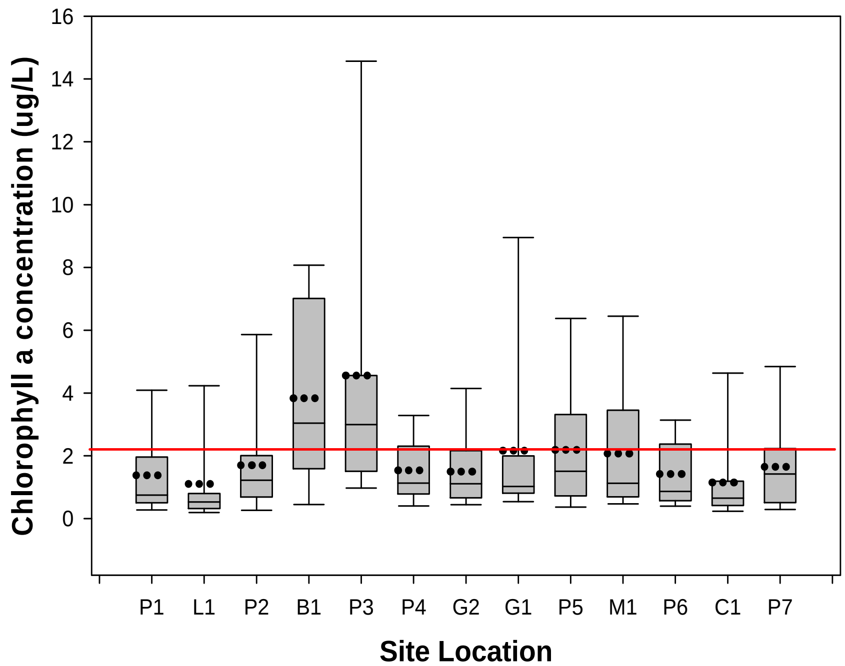

Figure 7. Box-plot diagrams of Chlorophyll a concentrations (ug/L) at all monitoring stations.

FUTURE STUDIES

Future studies should focus on pinpointing the cause of higher nitrate concentrations upstream versus downstream. Evaluating surrounding land use practices could help separate natural base flow concentrations from anthropogenic loading. Since nutrients are a constituent of concern for the watershed, discerning the nitrate sources is essential for conserving the biological integrity of this river system. Additionally, the effects of excess nutrients from the major point-source pollutant of the Pedernales River (i.e., Fredericksburg wastewater treatment facility) should be evaluated.

LITERATURE CITED

Barrett, M.E. 1998. Analysis of Pedernales River water quality. Report to the Lower Colorado River Authority.

Brune, G. 1981. Springs of Texas. Volume I. Branch Smith, Inc. Fort worth, Texas, USA.

Cave, M. S. 2006. Effects of surface and groundwater interactions on the solution chemistry of a subtropical karst stream. Masters Thesis to Texas State University.

Crumpton, W. G., T. Isenhart, and P. Mitchell. 1992. Nitrate and organic N analyses with second-derivative spectroscopy. Limnology and Oceanography 37:907-913.

Ebbert, J. C. 2003. Water Temperature, Specific Conductance, pH, and Dissolved-Oxygen Concentrations in the Lower White River and the Puyallup River Estuary, Washington, August-October 2002: USGS Water-Resources Investigations Report 03-4177.

Groeger, A. W., P. F. Brown, T. E. Tietjen, and T. C. Kelsey. 1997. Water quality of the San Marcos River. Texas Journal of Science 49(4):279-294.

Hydrolab. 1985. Minsonde Surveyor II operating manual. Hydrolab Corp., Austin, Texas, USA.

Kalff, J. 2001. Limnology: Inland water ecosystems. Prentice Hall, Upper Saddle River, New Jersey, USA.

Lower Colorado River Authority. 2000. The Pedernales River watershed: brush control assessment and feasibility study: Lower Colorado River Authority.

Lower Colorado River Authority. Water Quality Data. Available at: http://waterquality.lcra.org/. Accessed January 2008.

Lower Colorado River Authority. River Operations Center Hydrologic Data. Available at: http://hydromet.lcra.org/. Accessed January 2008.

Mueller, D. K., and N. E. Spahr. 2006. Nutrients in streams across the Nation – 1992- 2001: USGS National Water-Quality Assessment Program Report 2006-5107.

Murphy, J., and J. Riley. 1962. A modified single solution for the determination of phosphate in natural waters. Analytica Chimica Acta 27:31-36.

The Nature Conservancy. 2007. Conservation plan for the Pedernales River watershed: The Nature Conservancy, San Antonio, Texas, USA.

Riskind, D.H. and D.D. Diamond. 1988. An Introduction to Environments and Vegetation. Baylor Univ. Press, Waco, Texas, USA.

Texas State Soil and Water Conservation Board 1991. A comprehensive study of Texas watersheds and their impacts on water quality and water quantity: Texas State Soil and Water Conservation Board, Temple, Texas, USA.

U.S. Environmental Protection Agency. 2002. National water quality inventory - 2000 report: U.S. Environmental Protection Agency Office of Water Report EPA–841–R–02–001, 207 p. Available online at: *http://www.epa.gov/305b/2000report/*. Accessed January 2008.

United States Geological Survey. Water Resources Data-Texas. Available at: http://waterdata.usgs.gov/tx/nwis/rt. Accessed January 2008.

Wetzel, R. G., and G. E. Likens. 1991. Limnological analysis. Second Edition. Springer-Verlag, New York, NewYork, USA.

Hydraulic Geometry of the Pedernales River

Dr. Joanna Curran
Benjamin Warden

(please see attached Thesis by Benjamin Thomas Warden, 2008)