A SYSTEMS APPROACH TO MODELING AND IMPACT ASSESSMENT IN AN URBANIZING WATERSHED

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A SYSTEMS APPROACH TO MODELING AND IMPACT ASSESSMENT

IN AN URBANIZING WATERSHED

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ABSTRACT

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Conflicts over water resources reflect multiple viewpoints regarding the value of preserving quality of life, protecting environmental integrity, and the need for continued urban expansion and economic growth. This has led to an increased understanding of the need for systemic and participatory approaches that address resource management from a holistic perspective. Analysis of alternative futures combined with spatially explicit watershed modeling provides a way to scope resource management problems and increase understanding of how current policies, regulations, and practices could play out in the future and impact both watershed-level hydrologic response and water quality. I propose a framework for developing a water quality decision support system (DSS) that embeds the DSS within a larger context of systemic development planning. Under this framework, the natural system is replaced with a series of analytical models and tools are provided for developing and evaluating scenarios.

In this study, a participatory modeling approach is employed to develop such a planning decision support system to assist in managing water quality in an urbanizing watershed in the central Texas Hill Country. The Cypress Creek Project Decision Support System (CCP-DSS) incorporates watershed models with high-quality local data and additional analytical modules allowing for assessment of alternative management strategies. Using the CCP-DSS, I utilize an alternative futures approach to evaluate potential impacts and interactions of continuing urban development, declining aquifer levels, and climate change on water resources in the study area.

This study also quantifies the impact that participation in DSS development had on stakeholders' perceptions of model legitimacy, buy-in, and consensus regarding priorities for effective management. The need for systemic approaches to water resources planning in central Texas is clear, given the complex nature of the problem. This study demonstrates the utility of a systemic, participatory approach for informing planning and management decisions in an urbanizing watershed.

CHAPTER I

INTRODUCTION

Background

Traditional water resource management has focused on top-down, reductionist approaches like establishing water quality targets and regulatory action 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 multi-scale linkages between human and ecological health, surface- and ground-water sources, ecological and economic well-being, in short, the integrity of the linked riverine-terrestrial ecosystem as a whole. The underlying assumption for this approach is that ecosystems exhibit stable equilibrium states that can be maintained through identifying best management practices (BMPs) or that they can be reclaimed through restoration efforts.

Management approaches based on this theoretical basis have the implicit goals of increasing efficiency and decreasing uncertainty in natural and social systems to improve control over outcomes. However, the success of managing a target variable for the sustained production of a commodity has often resulted in inflexible management practices, producing less resilient systems that are increasingly dependent on human feedback for regulation (Berkes *et al.*, 2003; Holling, 2004). In addition, although science has produced a wealth of information on the biophysical characteristics, drivers, and interactions of natural systems, it has had limited success in presenting this information in a way that is understood by resource managers and able to be incorporated effectively into planning.

In the field of water resources management, decisions about management strategies are often made within the context of development planning. It is during the planning process that many decisions regarding rules of allocation are made, as well as important infrastructure decisions that will affect to a large degree the ultimate use of the resource. Traditional development planning, as defined by Conyers and Hill (1989), is planning with the goal of attaining a fully developed society, by controlling or managing the processes of development. This approach assumes that changes in land use result from interactions between policy variables (such as infrastructure or subsidies) and exogenous parameters (such as biophysical or landscape conditions). These interactions result in the attainment of a number of previously defined goals for the developed society, such as overall welfare and equity (Sharifi, 2002).

A common criticism of traditional resource planning approaches is that in many cases unforeseen or seemingly insignificant interactions (based solely on scientific assessments) may also result in undesirable side effects such as pollution and environmental degradation (Sharifi, 2002; Walker *et al.*, 2002). In addition, environmental conflicts following policy implementation are often based on values and contrasting beliefs about the distribution of costs and benefits between individuals and groups. Often these conflicts are shunted to the judicial system, which is concerned with legal arguments rather than establishing consensus or scientific accuracy (van den Belt, 2004).

The great complexity of social-ecological systems makes it difficult to forecast future behavior in a way that is meaningful to management decisions. Key drivers to such systems are unpredictable and change nonlinearly, such as climate and technological advances. Human responses to forecasted information often changes the system in such a way that forecasts subsequently prove to be inaccurate, and during times of transition a system may change faster than the forecasting models can be recalibrated, causing unreliability in predictions when they are most needed (Walker *et al.*, 2002). This means that complex problems arising from intricate linkages in social and biophysical networks often cannot be solved for optimality, because the optimal solution will always be a moving target.

Recognition that the complex nature of water resources planning makes it an exercise in social-ecological management has led to increasing understanding of the need for systemic and participatory approaches. A systems approach addresses resource management from a holistic perspective, examining the effects of variable interactions over time. Such an approach does not seek to optimize a single variable or output to define a long-term management strategy, but rather takes into account the various biophysical, economic, legal, environmental, and other factors that impact the availability and use of the resource (Pierce, 2006). This approach would aim to identify and implement proactive strategies for adaptive management with a focus on building resilience in all levels of linked-social ecological systems (Lal *et al.*, 2001). A systems approach recognizes that no single perspective, whether proceeding from the basis of scientific inquiry and data gathering or from the personal experiences of local residents, can adequately picture the whole of the system and its component interactions. Therefore these types of systems are best understood using a multiplicity of perspectives sought through a participatory and multi-disciplinary approach (Berkes *et al.*, 2003).

In recent years, much effort has gone toward the development of new methods to address development planning through a systems approach, methods that integrate quantitative research and modeling tools with qualitative approaches. The qualitative approach is useful because it can make the planning process more participatory and incorporate considerations that may be difficult to quantify, while the quantitative and structured approach enables a more systematic method for generating management alternatives and making decisions (Mendoza and Prabhu, 2005). Participatory approaches aim to address the problem of perception and value conflicts between disparate groups, and are popular because many of their features match well with resources that are optimally managed on a community level, i.e. those that can be characterized as common pool resources (Dietz *et al.*, 2003): a) they are useful for capturing behavioral patterns and changes among stakeholders; b) they can incorporate perceptions and interpretations as well as facts; and c) they are less intimidating to stakeholders than more traditional models of “stakeholder input” (Johnson *et al.*, 2001; Mendoza and Prabhu, 2005).

Planning decision support systems are an example of such a tool that seeks to incorporate both quantitative modeling and qualitative data to aid decision-makers in the integrated evaluation of management and policy impacts on both social and ecological aspects of a system. Decision support systems are increasingly recognized as useful tools to help in the resolution of conflicts involving values, management approaches, and strategies. Decision support system (DSS) is a general term for a computer-based information system that supports decision making by providing information to assist in solving complex problems. A DSS is particularly useful in complex, semi-structured or unstructured problems by allowing an interactive dialogue between the user and the dynamic system (Pierce, 2006). The primary goal is to generate and evaluate alternative solutions in order to increase understanding of the problem structure and inherent tradeoffs.

In this study we propose a framework for developing a decision support system that embeds the DSS within a larger context of systemic development planning (Figure 1.1). In this model of systemic planning, the sum of current (or proposed) management practices, rules, climatic drivers, and social drivers combine to create scenarios. These scenarios act upon the natural system of interest (the watershed), and the resulting impacts are evaluated based on local objectives for management and decision criteria. Once the results are evaluated, management decisions may be reformulated to better achieve the specified objectives and criteria. The proposed DSS framework replaces the natural system with a series of analytical models, and includes tools for developing and evaluating scenarios. In this study a participatory modeling approach is employed to develop such a planning decision support system to assist in managing water quality in an urbanizing watershed in the central Texas Hill Country.

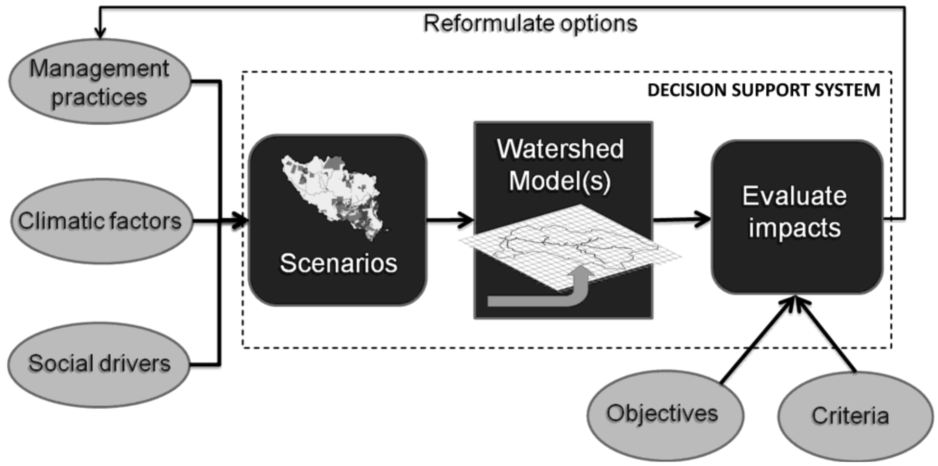

Figure 1.1. Conceptual model of decision support system within the context of systemic development planning.

In the central Texas Hill Country, rapid urbanization is occurring around major city centers interspersed with distributed, low-intensity development along major transportation corridors. The ability to manage water supply while taking into account impacts on stream ecosystems is critically important to central Texas because of the tight linkages between surface- and ground-water, and the heavy reliance on local groundwater sources for municipal and domestic supplies. Many of the area aquifers are fully or possibly over-allocated, with a legal structure that currently allows for a great deal more growth that is exempt from pumping regulation. Although State legislation supposedly encourages conjunctive use of water resources, there is a fracturing of jurisdictions that divides the responsibility for allocating and managing surface- and ground-water supplies. This division makes such cooperation difficult in practice.

Hydrologic and water quality impacts of development in karst areas such as the central Texas Hill Country will likely be mediated by spring flow inputs from regional aquifer systems. Future reductions in spring flow volumes are very likely due to the combined forces of 1) rapid development of urban areas dependent on groundwater supplies; 2) continued drilling of personal supply wells that are exempt from pumping regulation; 3) the lack of a single planning authority for surface- and ground-water quantity and quality; and 4) the lack of adequate legal jurisdiction for managing development in rural and semi-rural areas. Many small watersheds in rural and semi-rural areas are experiencing problems with regional aquifer impacts affecting local stream ecosystems, but local jurisdictions (municipalities) who are most affected by these impacts are not able to influence the patterns of growth outside of their borders effectively.

The need for systemic approaches to water resources planning in central Texas is clear, given the complex nature of the problem. Conflicts over water reflect multiple viewpoints regarding the value of preserving quality of life, protecting environmental integrity, and the need for continued urban expansion and economic growth (Pierce, 2006). Alternative futures analysis provides a way to assess how development impacts on hydrology and water quality may be mediated by concurrent declines in spring flows or changes in future climate conditions. Alternative futures describe various visions for the future and represent different pathways to get there – different management or regulatory schemes that result in different outcomes (Kepner *et al.*, 2008; Shearer, 2005). Scenario studies are based on information from the past and assumptions of possible future trajectories, and can be used to assist in setting goals, defining management options, and communicating potential future results from current management decisions (Kepner *et al.*, 2008). Analysis of alternative futures combined with spatially explicit watershed modeling provides a way to scope these problems and increase our understanding of how current policies, regulations, and practices could play out in the future and impact both watershed-level hydrologic response and water quality.

Study Approach

The approach taken in this study is to develop, through a participatory stakeholder process, tools that enable local stakeholders and decision-makers to evaluate the impacts of management decisions in and around the Cypress Creek watershed, Hays County, Texas. The Cypress Creek Project Decision Support System (CCP-DSS) incorporates watershed models with high-quality local data and additional analytical modules allowing for assessment of alternative management strategies given likely future scenarios. In addition to describing the participatory process for DSS development, this study also quantifies the impact that such participation had on stakeholders' perceptions of model legitimacy, buy-in, and consensus regarding priorities for effective management.

Using the CCP-DSS, an alternative futures approach is utilized to evaluate potential impacts and interactions of continuing urban development, declining aquifer levels, and climate change on water resources in the study area. One of the watershed models included in the CCP-DSS package (SWAT) is used to evaluate hydrologic and water quality impacts of development scenarios envisioned through the participatory process, and to assess these impacts under various scenarios of climate change and declining spring flow input. These studies demonstrate the utility of an alternative futures approach and the CCP-DSS tools for informing planning and management decisions in the watershed.

The specific objectives of this study are to:

1) Develop, through a participatory modeling process, a Decision Support System that incorporates watershed modeling, priority issues identified by stakeholder participants, a multi-criteria analysis module, and a graphical interface that allows users to evaluate potential impacts of development, land cover change, climate change, and BMPs on water quantity and quality in Cypress Creek;
2) Develop, through a participatory modeling process, scenarios that depict likely futures for the watershed, and analyze the impacts of these scenarios on water quantity and quality;
3) Evaluate the hydrologic and water quality impacts of future development under various scenarios of climate change and declining spring flow inputs; and
4) Evaluate the effectiveness of the participatory DSS development process as it impacts participants' perceptions of model legitimacy, buy-in to the participatory process, and levels of consensus regarding priorities for effective management.

To date, little work has been done attempting to link the multiple scales and processes that impact water resources in small karstic watersheds like the Cypress Creek. This study is a test case for participatory model development and implementation of a decision support framework to inform watershed management in karstic spring-fed streams, where impacts of continuing urbanization on both surface and groundwater must be considered. The following chapters detail various aspects of the study area, the participatory modeling process, and results from the alternative futures analysis.

Chapters Summary

Chapter II – Watershed Characterization. This chapter describes in detail the study area to provide the biophysical, hydrologic, and socioeconomic context for the application of the approach described above. The Cypress Creek, located in western Hays County, Texas is a prime example of a spring-run stream characteristic of the Hill Country. Springs provide a continuous supply of cold, clear water from the underlying Upper and Middle Trinity Aquifers which make up the majority of flow to the creek year-round. Because of its natural beauty and proximity to both major transportation corridors and rapidly urbanizing population centers such as Austin and San Antonio, land and water resources in the area are under increasing pressure as urban areas expand.

Chapter III – Combining participatory modeling, hydrologic simulation, and multi-criteria analysis for a water quality decision support system in an urbanizing watershed. Chapter III details the participatory process through which a water quality decision support system was developed to assist development planning in the Cypress Creek Watershed. The approach presented here incorporates participatory modeling and multi-criteria evaluation to develop decision support tools that are responsive and targeted to the needs of local decision makers.

Chapter IV – Hydrologic and water quality impacts of urbanization in a small karstic watershed, central Texas. Using the SWAT watershed model included in the CCP-DSS, this chapter demonstrates the potential impacts that various scenarios of urbanization coupled with declining spring flows could have on water quantity and quality in the creek. Understanding the potential impacts of human-induced land use and land cover changes is critical for planning and management of sustainable watersheds and water resources. Watershed processes and impacts are highly variable in time and space and so spatially explicit hydrologic modeling lends itself well as an approach to quantify potential impacts. This study combines scenario analysis with watershed modeling to: 1) develop conceptual scenarios to examine potential land use changes due to urban development; 2) model land cover change associated with each scenario in a form that is easily used as input for hydrologic simulation modeling; 3) evaluate results for scenarios relative to current (2009) conditions using the SWAT hydrologic model; and 4) evaluate scenario results using reduced spring flow inputs. This study shows that in spring-fed systems like those found throughout the Texas Hill Country, the current management framework is inadequate to ensure good water quality when such quality is so highly dependent on maintaining adequate spring flows.

Chapter V – Climate variability and the future of a rapidly urbanizing watershed in the central Texas Hill Country. Chapter V builds upon the evaluation of development scenarios described in Chapter IV, by introducing the potential for climate change in the future. Based on the results from various global climate models, central Texas is expected to see increasing temperatures and either increasing or decreasing precipitation on an annual basis over the next 30 to 100 years, accompanied by an increase in extreme weather events such as multi-year droughts and major floods. Impacts of urbanization will vary depending on future climatic conditions and so will appropriate mitigation measures. The objective of this study is to evaluate hydrologic and water quality impacts of potential climate and development futures for central Texas, using scenarios of both decreasing and increasing precipitation. This study presents the results of scenarios modeling as a sensitivity analysis of the system to a likely range of conditions. The results could be used to develop policy alternatives that are robust under a variety of likely future conditions.

Chapter VI – Assessing the impacts of stakeholder participation on the perceived legitimacy of science-based decision support models. Although much literature exists on the supposed benefits of stakeholder participation in the development of science-based planning tools, there has been very little critical evaluation of the level of effectiveness of participatory modeling processes for actually increasing stakeholder buy-in and consensus. This chapter evaluates the validity of these arguments by conducting surveys and interviews with project participants both before and after the participatory modeling process to develop the CCP-DSS. The results are analyzed to evaluate the degree of impact that participation had on stakeholder's trust, buy-in to the process, and degree of consensus regarding priority issues for watershed management, effective and appropriate management instruments, and barriers to effective long-term management. Results of this study demonstrate that stakeholder involvement in development of a decision support system for local planning increases participants' perceptions of its legitimacy and utility for local decision-making. However while the stakeholder process might have positive impacts on stakeholder understanding and consensus development in some areas, in other areas consensus may actually decrease.

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CHAPTER II

WATERSHED CHARACTERIZATION

Introduction

The Cypress Creek, located in western Hays County, Texas is a prime example of a spring-run stream characteristic of the Texas Hill Country. Springs provide a continuous supply of cold, clear water from the underlying Upper and Middle Trinity Aquifers which make up the majority of flow to the creek year-round. Because of its natural beauty and proximity to a major transportation corridor (I-35), and rapidly urbanizing population centers such as Austin (Travis County) and San Antonio (Bexar County), land and water resources in the area are under increasing pressure. Urban areas are expanding as land use is converted from low-density ranching to residential and "ranchette" home sites (usually between 2 and 10 ha). Land use in the watershed area is primarily ranching except for dense residential and commercial development in the cities of Wimberley and Woodcreek in the south. Rapid population growth and accelerated urban development are increasing the potential for impacts to wildlife habitat, groundwater and surface water resources, and aquatic habitats.

The Cypress Creek trends roughly northwest to southeast, and is a major tributary contributing flow to the Blanco River. The confluence with the Blanco River is located south of Wimberley, TX, just upstream of the Blanco River/RR 12 junction (Figure 2.1).

The watershed area contributing surface flow to Cypress Creek encompasses approximately 98 km^2. A major spring, Jacob's Well, is the largest single contributor to baseflow in the creek. Except under heavy rainfall conditions, the 10.4 km segment upstream of Jacob's Well is usually dry, while the lower 8.8 km stream that generally flows year-round is commonly referred to as Cypress Creek (Figure 2.2).

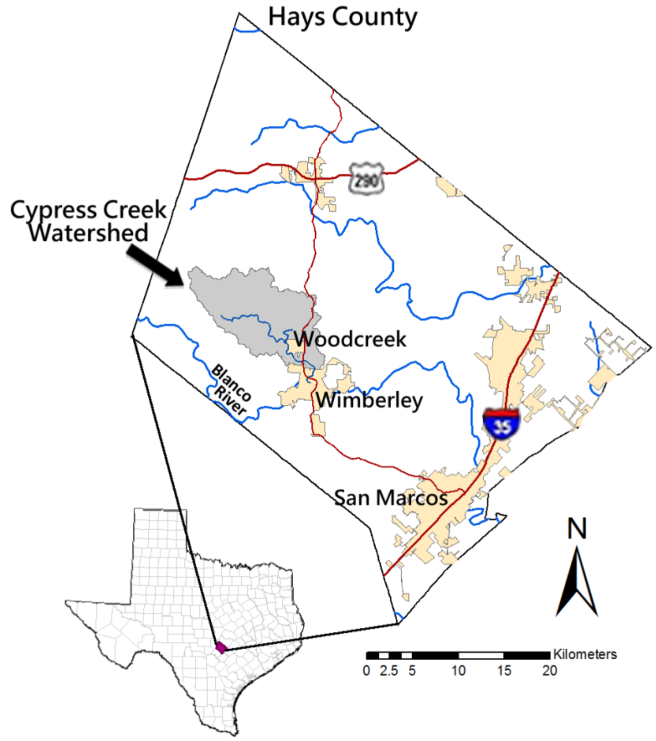

Figure 2.1. Location of study area and nearby urban areas.

The Cypress Creek watershed has a total area of 98.4 km^2, a mean elevation of 350 m, and a mean annual precipitation between 846 mm (Fischer's Store) and 944 mm (Wimberley; Figure 2.2). The watershed is located in west central Hays County, in the Edwards Plateau region of the Texas Hill Country. The topography of the Hill Country varies from hills of karstic limestone to plateaus that serve as major recharge zones to the underlying Edwards, Edwards-Trinity, and Trinity Aquifers (Longley, 1986). The hills are characterized by unstable inter-bedded limestone, shale and clays. The limestone plateaus are karstic, with the dissolved bedrock providing many conduits for recharge from rain events, and resulting in a high degree of interconnectivity between surface- and ground- water to the point where they could be considered one resource (HTGCD, 2010).

Spring fed waterways such as Cypress Creek dissect the hills and normally dry channels provide recharge to the underlying aquifers during storm events. The upper two thirds of the creek are intermittent and flow only during or immediately following precipitation events. Jacob's Well is a natural flowing artesian spring located in the bed of Cypress Creek roughly 16 km upstream of the creek's confluence with the Blanco. On average, Jacob's Well provides 92% of the flow to the perennial portion of the creek, which runs through downtown Woodcreek and Wimberley and is a major source of inflows to the Blanco River.

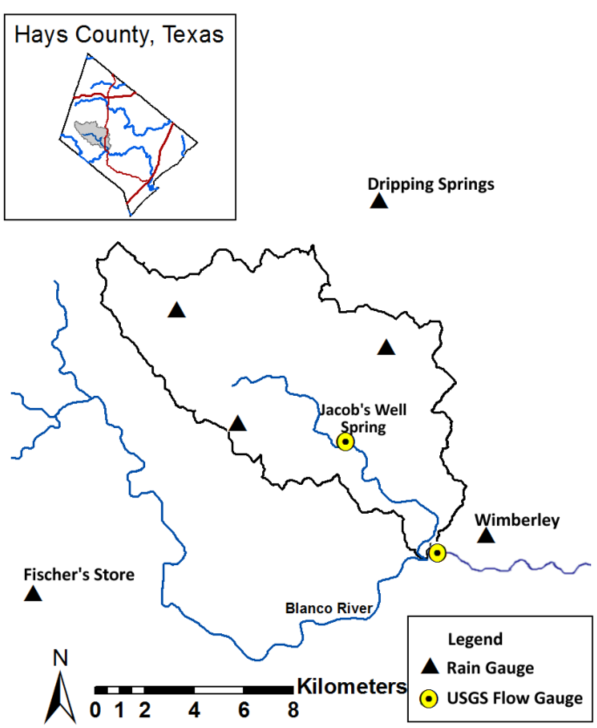

Figure 2.2. Spring and rain gauge locations in and around the watershed.

Climate

Climate in the study area is semi-arid, with relatively mild winters and hot, dry summers. The mean annual precipitation at Wimberley, located near the outlet of the watershed to the southeast, is 944 mm. At Fischer's Store (southwest of the watershed), mean annual precipitation is 846 mm. The difference in long-term statistical means at these two stations is probably due to two factors: (1) the period of record at Fischer's Store includes the drought of record in the 1950s, but Wimberley records do not extend back to the 1950's; and (2) a west-east gradient of increasing precipitation exists throughout Texas (TWDB, 2007), and the rainfall station at Fischer's Store station lies approximately 16 km west of Wimberley. In this region of TX, evapotranspiration can account for as much as 90% of the water budget (Ockerman, 2005).

Annual mean precipitation is highly variable from year to year (Figure 2.3). There is some evidence that interannual variability in rainfall has increased in the last two decades, since the autocorrelation of annual precipitation measured at Fischer's store from 1941 to 1989 is positive, while the period 1990-2009 is negative. This means that prior to 1990, if one year was wet then the next year was likely to be wet as well and vice versa. Beginning in 1990, however, a very wet year is more likely to be followed by a very dry year. If this trend continues, it could have implications for both water management and water quality in the Cypress Creek basin.

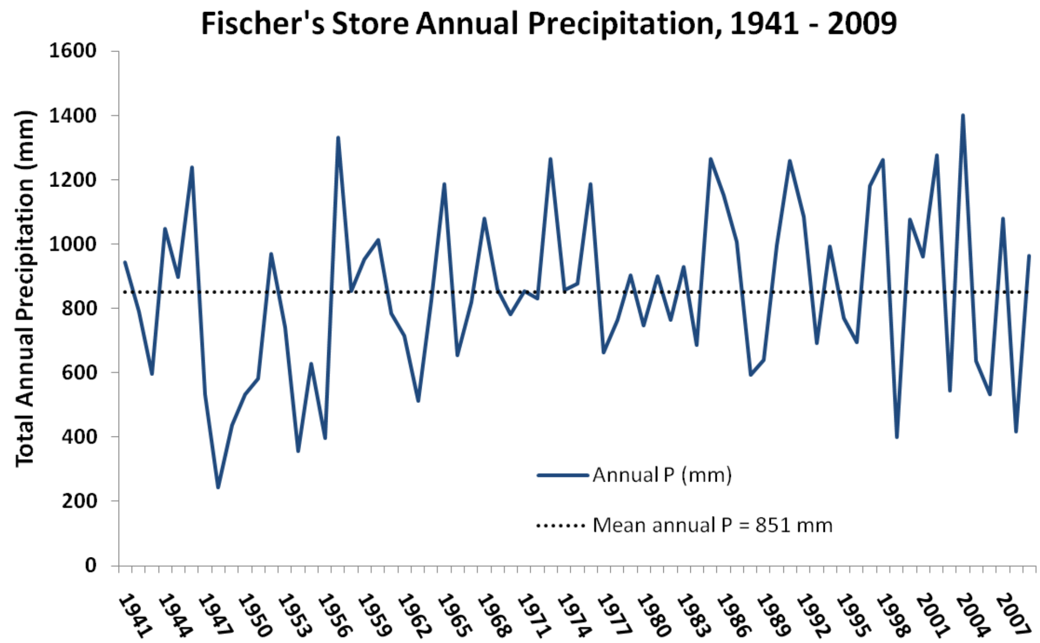

Figure 2.3. Annual precipitation and long-term mean (mm), Fischer's Store (1941-2009). Annual precipitation is highly variable year to year.

Three tipping-bucket rain gauges located inside the watershed boundary record rainfall at 0.254 mm (0.01 in) intervals, a higher resolution than is available with National Weather Service data (Figure 2.2). Rainfall data has been collected at these stations since September 2009. The results suggest that rainfall can be highly variable even within a small watershed area; for instance, one storm in January 2010 recorded 2.2 and 2.8 inches of rain at the two northern gauges, while the southern gauge recorded 0 inches. This north-south gradient is common in the data, as indicated from the results of a linear regression calculated on daily total precipitation at various weather stations. In general, the northern two gauges are similar (R^2 = 0.83) but quite different from the rain recorded at Wimberley (R^2 = 0.16 and 0.29). Data at the southern gauge are more closely correlated to rain recorded at Wimberley (R^2 = 0.37) and, within a range of variability over time, can be very different from rain data recorded at the upper two gauges.

Climate in the study area follows the general pattern of the Hill Country; peak rainfall occurs primarily in the summer and fall. About 22% of annual rainfall occurs between May and June, while 29% occurs from September to November (Figure 2.4). Temperature is highest from May to October, resulting in fairly predictable summer weather patterns. The period of July through September is often both hot and dry, with average daily temperatures above 26.7 ^{o}C and little rainfall. Since water quality in local creeks is highly dependent upon flow levels, summer months are the most likely to have water quality impairments including low dissolved oxygen, high algal density, and increased water temperature.

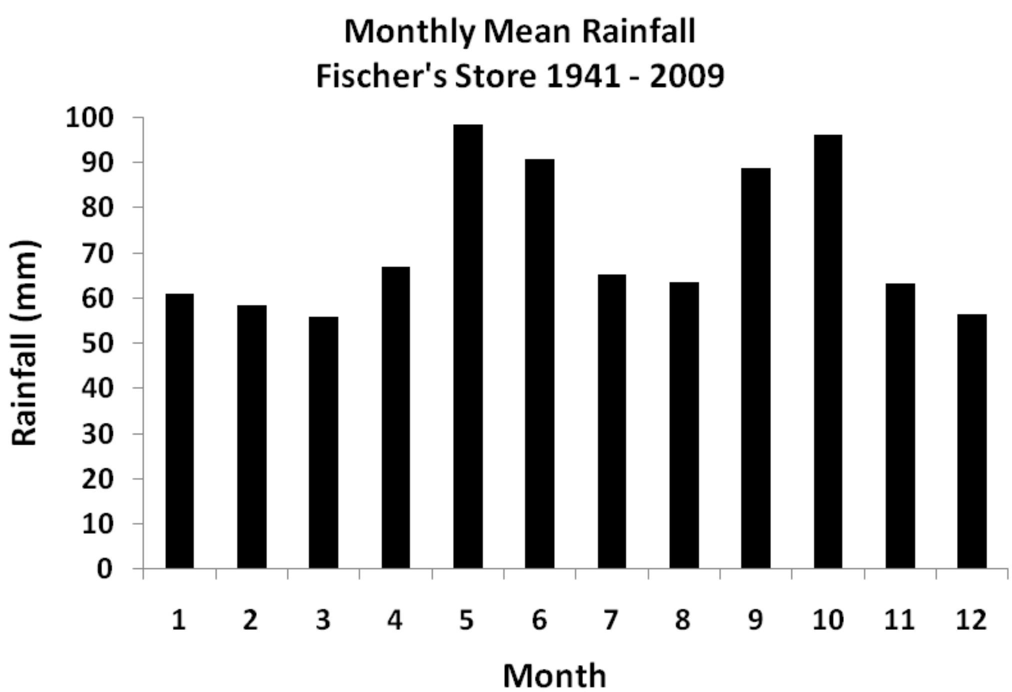

Figure 2.4. Monthly mean rainfall at Fischer’s Store (1941 – 2009).

Topography and Soils

The Cypress Creek watershed lies in the Edwards Plateau region of the Texas Hill Country. The topography of the Hill Country varies from hills of predominantly karstic limestone terrain overlain with thin, rocky soils, to plateaus that serve as major recharge zones to the underlying Edwards, Edwards-Trinity, and Trinity Aquifers (Longley, 1986). The hills are characterized by unstable inter-bedded limestone, shale and clays (Riskind and Diamond, 1986). Elevations in the study area range from 247 to 479 m above mean sea level, with approximately 232 m of topographic relief (Figure 2.5). Slopes are highest in the northern portion of the watershed, where there are many of the characteristic hills that make up the Hill Country region, and slope generally decreases toward the Village of Wimberley near the outlet (Figure 2.6).

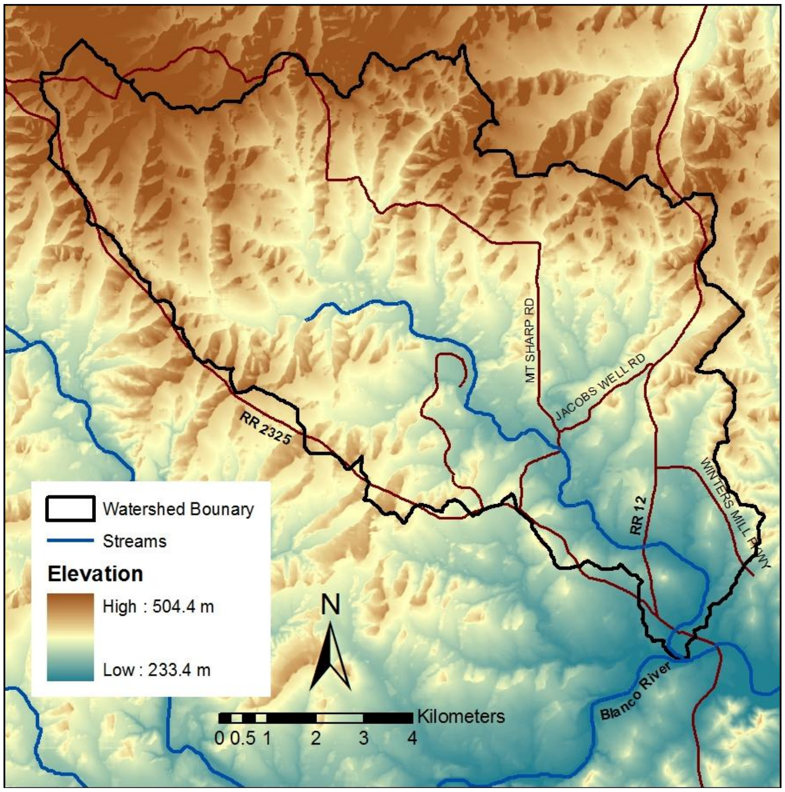

Figure 2.5. Watershed topography. Source USGS digital elevation model, 10m resolution.

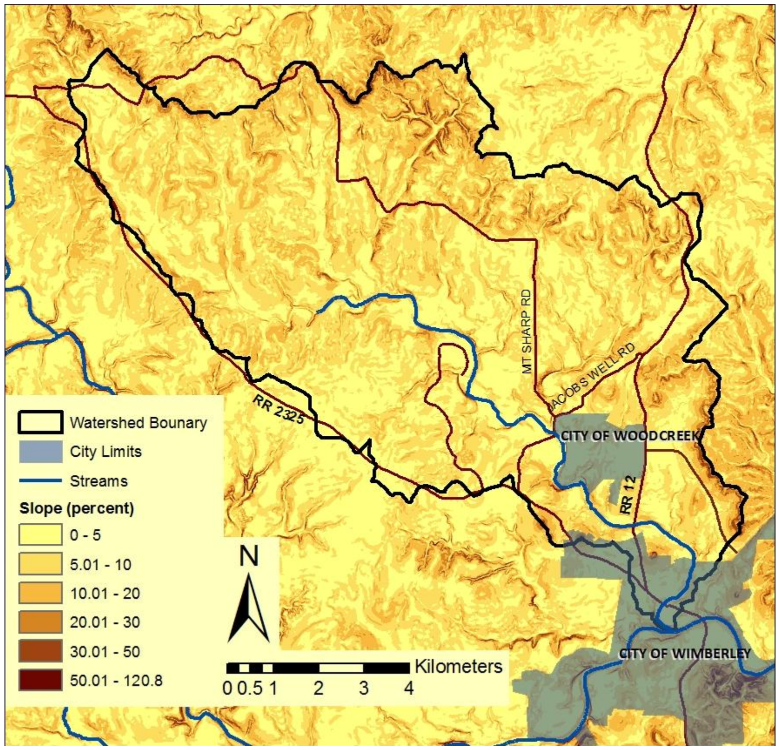

Figure 2.6. Slopes in the Cypress Creek watershed. The highest slopes are found in the northern upland portions of the watershed, as well as along stream channels in some areas where the creek has eroded into canyons.

Soils in the watershed are predominantly shallow clay loams and shallow clays such as the Brackett-Rock outcrop-Comfort complex (41.5%) and the Brackett-Rock outcrop-Real complex (15.3%) on the uplands; and shallow stony clays such as the Comfort-Rock outcrop complex (17.9%) and the Real-Comfort-Doss complex (5.6%) on hill slopes. The remaining 20% of the watershed is a mix of deep clay and clay loam uplands and hydric loamy bottomland soils along creek beds in the lower portion of the watershed (Figure 2.7). Table 2.1 gives the types and relative area of soils present in the watershed. Soil classes are based on the Natural Resources Conservation Service (NRCS) soil survey geographic database (NRCS, 2008).

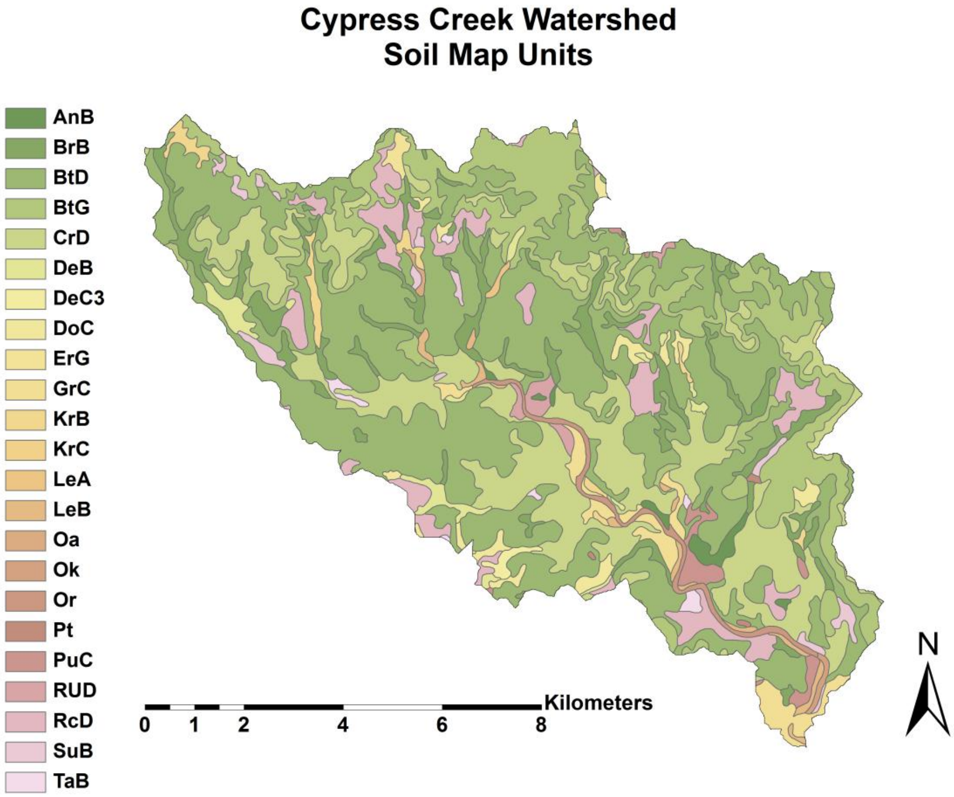

Figure 2.7. Soil units in the watershed.

Table 2.1. Soil types and their relative occurrence in the watershed. From the Natural Resources Conservation Service (NRCS) SSURGO soils database (2008).

Soil Type	Area (km^2)	% of total	Description
BtD	40.89	41.54	Brackett-Rock outcrop-Comfort complex, 1 to 8 percent slopes
CrD	17.61	17.88	Comfort-Rock outcrop complex, 1 to 8 percent slopes
BtG	15.11	15.34	Brackett-Rock outcrop-Real complex, 8 to 30 percent slopes
BrB	6.72	6.82	Bolar clay loam, 1 to 3 percent slopes
RcD	5.53	5.62	Real-Comfort-Doss complex, 1 to 8 percent slopes
GrC	2.20	2.24	Gruene clay, 1 to 5 percent slopes
DoC	1.54	1.56	Doss silty clay, 1 to 5 percent slopes
DeB	1.41	1.43	Denton silty clay, 1 to 3 percent slopes
SuB	1.09	1.11	Sunev clay loam, 1 to 3 percent slopes
Or	1.01	1.03	Orif soils, 0 to 1 percent slopes, frequently flooded
KrB	0.99	1.01	Krum clay, 1 to 3 percent slopes
PuC	0.97	0.98	Purves clay, 1 to 5 percent slopes
LeB	0.75	0.76	Lewisville silty clay, 1 to 3 percent slopes
AnB	0.67	0.68	Anhalt clay, 1 to 3 percent slopes
RUD	0.63	0.64	Rumple-Comfort association, 1 to 8 percent slopes
TaB	0.41	0.42	Tarpley clay, 1 to 3 percent slopes
ErG	0.25	0.25	Eckrant-Rock outcrop complex, 8 to 30 percent slopes
DeC3	0.24	0.25	Denton silty clay, 1 to 5 percent slopes, eroded
Ok	0.14	0.15	Oakalla soils, 0 to 2 percent slopes, frequently flooded
Oa	0.10	0.10	Oakalla silty clay loam, 0 to 1 percent slopes, rarely flooded
LeA	0.10	0.10	Lewisville silty clay, 0 to 1 percent slopes
Pt	0.08	0.08	Pits
KrC	0.002	0.002	Krum clay, 3 to 5 percent slopes

Hydrology and Hydrogeology

The hydrology and hydrogeology of the Cypress Creek watershed are shaped by the karstic limestone nature of the underlying geology. Other than a few small domestic rainwater collection systems, the area is entirely dependent on groundwater for its potable water supply. Therefore both human societies and local aquatic communities are dependent on groundwater for their existence. Aquifers underlying the study area include the Middle and Lower Trinity.

The Middle Trinity consists of the Lower Glen Rose, Hensel, and Cow Creek formations. This is the primary aquifer in the study area for residential and public water supply wells (HTCGD, 2010). The Lower Glen Rose layer is exposed at the surface along the dry Cypress Creek in the upper portions of the watershed and along the Blanco

River to the west (Figure 2.8). Where this layer is exposed, it is often faulted and fractured and contains surficial karst features that allow for rapid recharge from precipitation events. West of the watershed lies a subcrop of the Ouachita deformation front, and west of this line the relatively sandy facies of the Hensel formation allow for diffuse recharge to the underlying Cow Creek formation. East of this line and within the study area, shale and dolomite facies of the Hensel act as a semi-confining layer, causing the Cow Creek formation to act as a confined aquifer. Recharge to the Middle Trinity within the study area occurs through downward percolation of direct precipitation through exposed Upper and Lower Glen Rose rocks.

The Hammett Shale is a confining layer that separates the Middle and Lower Trinity aquifers in the study area. The Lower Trinity consists of the Sligo and Hosston formations, which is recharged through diffuse percolation through the confining layers above, and does not crop out within the study area. Groundwater flow in the Middle and Lower Trinity aquifers is approximately parallel, and generally follows the northwest to southeast structural dip of the rock formations as they dip toward the Balcones Fault Zone in eastern Hays County. Surface streams generally follow the same orientation (Figure 2.9).

Also important to the hydrogeology of the study area are the multiple faults trending northeast-southwest throughout the region. These normal faults may have downdropped the Trinity Group as much as 370 m to the southeast, juxtaposing rocks of the Edwards Group against the Trinity Group just southeast of the Cypress Creek watershed (Ryder, 1996). Jacob's Well spring occurs along one of these faults (Tom Creek Fault Zone), which restricts subsurface flow in the Cow Creek formation and redirects it to discharge at the surface.

The hydrogeologic setting in the study area results in a very strong connection between surface and groundwater, to the point where they could be considered a single resource (HTGCD, 2010). Surface streams rely on baseflow from springs and seeps, yet normally dry stream channels often provide recharge to underlying aquifers during precipitation events. Karstic conduits in Cow Creek carbonates are also an important source of discharge to springs such as Jacob's Well that provide baseflow to the Cypress Creek and the Blanco River.

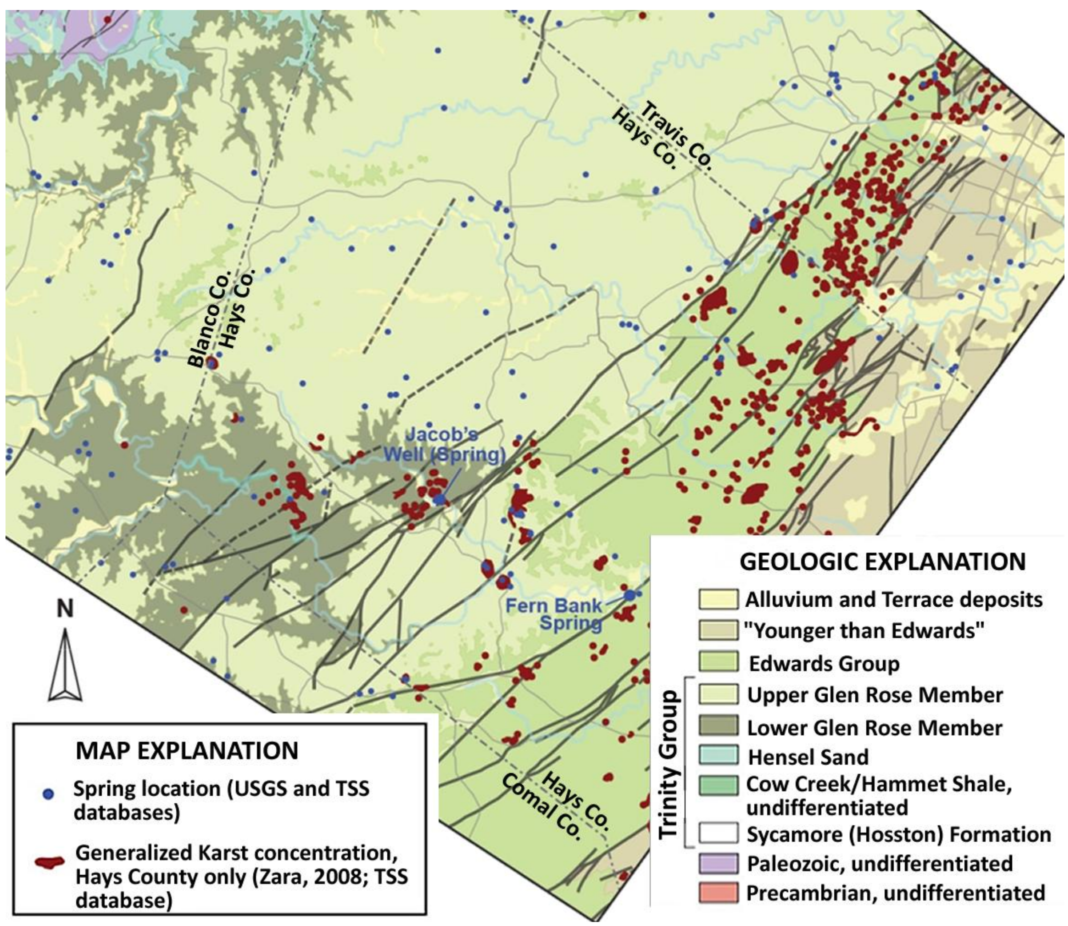

Figure 2.8. Generalized karst features, Hays County (adapted from HTGCD, 2010).

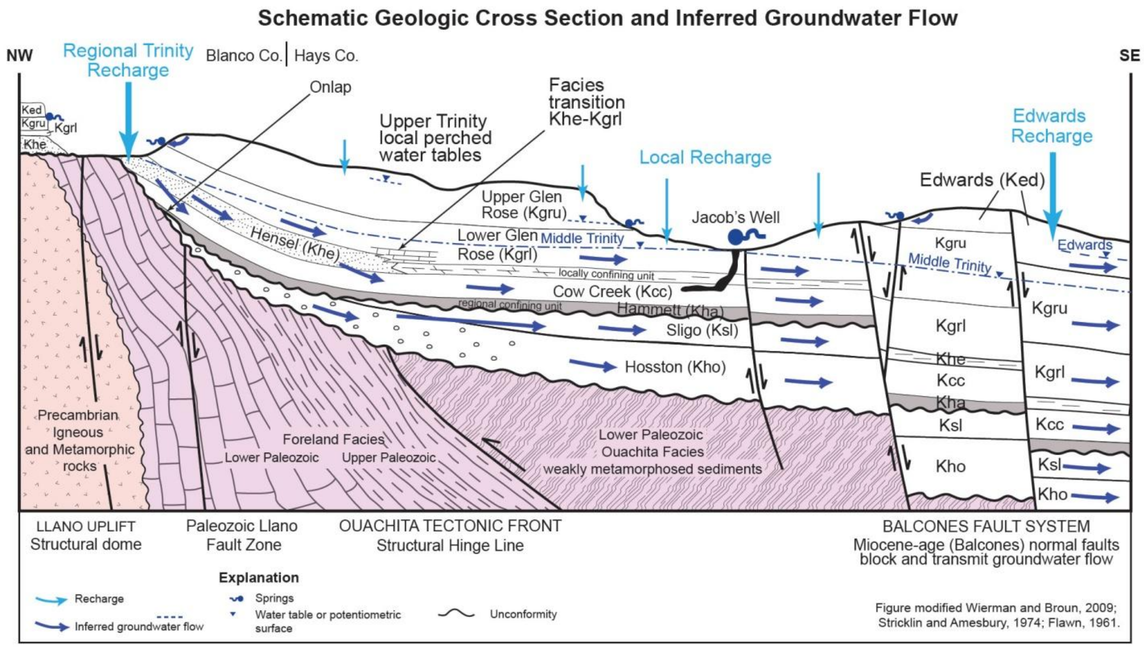

Figure 2.9. General stratigraphy and inferred groundwater movement in the Trinity Group (HTGCD, 2010).

Jacob's Well Spring provides on average approximately 92% of flow to the Cypress Creek. Blue Hole, located in Cypress Creek just upstream of Wimberley, is a swimming hole that has been enjoyed by generations of local residents and considered one of the top swimming holes in Texas (HTGCD, 2008). The opening of Jacob's Well in the bed of Cypress Creek occurs in the Lower Glen Rose unit of the Middle Trinity Aquifer (Figure 2.10). The nearly vertical shaft of Jacob's Well probably follows a former fracture or joint set that has been enlarged by chemical weathering. Approximately 21 m below the mouth of the spring is the contact between the Lower Glen Rose and Hensel Member, where two large caverns exist. At approximately 30 m lies the contact between the Hensel and Cow Creek formations. The passageway becomes roughly parallel to the horizontal bedding and continues several thousand feet in a karst zone of the Cow Creek formation (Figure 2.9). Divers have mapped over 1,500 m of passages linked to Jacob's Well, and further passages are still being explored (HTGCD, 2010).

Baseflow to Jacob's Well is primarily from groundwater under artesian conditions in the Cow Creek formation. However the flow from the spring also varies significantly with major precipitation patterns. Artesian flow maintains an average discharge of 0.08 to 0.20 $m^3 s^{-1}$, but during major precipitation events peak discharge has been measured at over 1.7 $m^3 s^{-1}$. This indicates either a local pressure surge in the Cow Creek, or direct recharge from open karst features seen locally in the Lower Glen Rose. Gunn (2004) hypothesizes that rapid increases in spring discharge like those observed at Jacob's Well may be due to rapidly filling open karst features, such as those observed in the Lower Glen Rose, which become full and exert pressure in the confined aquifer to increase spring flows.

Karst springs such as Jacob's Well provide excellent indicators of the health of local groundwater systems. Pump tests have proven that nearby public water supply wells that pump water from karst conduits in the Cow Creek formation directly influence discharge from Jacob's Well (HTGCD, 2008). Periodic droughts and increasing groundwater pumping are combining to make Jacob's Well more of a seasonal spring than a constant base flow spring (HTGCD, 2010). Flows from Jacob's Well were significantly reduced during the droughts of 2005–2006 and 2008. During dry conditions of July 2000, Jacob's Well ceased to flow for the first time in recorded history, degrading fish habitats, wildlife, and water quality in the creek. Cypress Creek also was placed on the USEPA 303(d) list for low dissolved oxygen levels for the first time during the same year.

Exactly why Jacob's Well stopped flowing is unknown; however, recent increases in groundwater demand are likely contributors. Because Jacob's Well spring continued to flow during the drought of record in the 1950s, it is thought that increased aquifer pumping and resulting water level draw-downs exacerbated dry conditions and led to the lack of flow in 2000. Due to drought conditions, the Well also ceased to flow in the summer of 2008. HTGCD Texas Water Development Board (TWDB) groundwater availability models predict an approximate 40 feet drawdown in the area around Jacob's Well by 2050 (Mace *et al.*, 2000), which if realized will have a significant impact on the water flows and quality in the creek.

Figure 2.10. Jacob's Well. Photo by Vanessa Lavender.

Surface hydrology in the Cypress Creek watershed reflects the karst conditions of the underlying rock formations. As mentioned previously, Cypress Creek is commonly divided into two segments: the 10.4 km segment above Jacob's Well is usually dry, except during major rainfall events, and is referred to as Dry Cypress Creek; the 8.8 km stream segment below Jacob's Well that consistently contains flowing water is referred to as Cypress Creek (Figure 2.2). During normal to dry conditions, baseflow in the Cypress Creek starts at Jacob's Well Spring. Continuous 15-minute spring flow data is currently collected by the USGS at Jacob's Well spring (USGS 08170990); however, flow data collected at that station represent only baseflow to the stream. USGS spring flow estimates at this gauge are based upon both stage and acoustic doppler velocity measurements. The data record from the USGS gauge does not include surface flows in that portion of the creek; when stage peaks during a storm event, flow estimates are adjusted to discount the influence of upstream surface flow to ensure that reported data represent only spring flow from the subsurface. Unadjusted stage heights at this location are available only for four storm events in 2007, and these data show that surface runoff from the upper watershed may be significant during major storm events.

Therefore storm runoff from the Dry Cypress watershed may significantly impact the timing and quality of stormflow in the perennial portions of the creek, but the magnitude of this impact is highly uncertain. Until 2009 there were no data collected on flow and water quality for the upper section of the creek to quantify any potential impact. In addition, daily mean streamflow is recorded at the Blanco River gauge just downstream of the confluence with the Cypress Creek (USGS 08171000). These values represent runoff from the Blanco River catchment of approximately 1,295 km^2, of which the Cypress Creek watershed comprises only 98 km^2.

A stream gauging project was conducted in 2005 on Cypress Creek (Dedden, 2008). The gauging program was conducted monthly during baseflow conditions between March and October 2005. Surface runoff into Cypress Creek during storm events was not measured during this study. The data indicate that Cypress Creek had very little net loss or gain in baseflow between Jacob's Well and Cypress Creek at RR12 in Wimberley. Immediately downstream of Jacob's Well, Cypress Creek flows over several major faults. The Upper Glen Rose is considerably more resistant to stream losses through the bed of the stream. Since Cypress Creek above Jacob's Well is typically dry, the majority of baseflow to Cypress Creek originates from Jacob's Well discharge, and therefore, maintaining baseflow requires maintaining flow at Jacob's Well. It must be noted, however, that this study was done during a period of drought. Annual rainfall in 2005 was only 637.5 mm, compared to an average of about 895 mm. It is likely that during wetter periods the Cypress Creek gains flow from numerous small springs and seeps throughout its course, feeding in from several major tributaries. There is a wealth of anecdotal evidence of such springs and seeps from residents and visitors to the area.

Land Use and Land Cover

Vegetation on the hill slopes is often sparse because of thin layers of topsoil. In the northern portion of the watershed, shallow or disturbed soils support evergreen shrubs and grasses. Woodlands of juniper, oak and mesquite are interspersed along the landscape with native grasses where slopes are gentle (Figure 2.11). The plateau-like uplands throughout this area support woody species such as Ashe Juniper (*Juniperus ashei*), Texas Oak (*Quercus buckleyi*), and Lacey Oak (*Quercus laceyi*) along with grasses. In the lower portion of the watershed along the floodplain and stream course of Cypress Creek, deciduous stands of Bald Cypress (*Taxodium distichum)*, Sycamore (*Platanus occidentalis*), and Black Willow (*Salix nigra*) exist (Riskind and Diamond, 1986). Commonly found grasses include Little bluestem (*Schizachyrium scoparium*), Curly mesquite (*Hilaria belangeri*), Texas wintergrass (*Stipa leucotricha*), White tridens (*Tridens muticus*), Texas cupgrass (*Eriochloa sericea*), Tall dropseed (*Sporobolus asper*), Seep muhly (*Muhlenbergia reverchonii*), Hairy grama (*Bouteloua hirsuta*), and Side oats grama (*Bouteloua curtipendula*) (Riskind and Diamond, 1986).

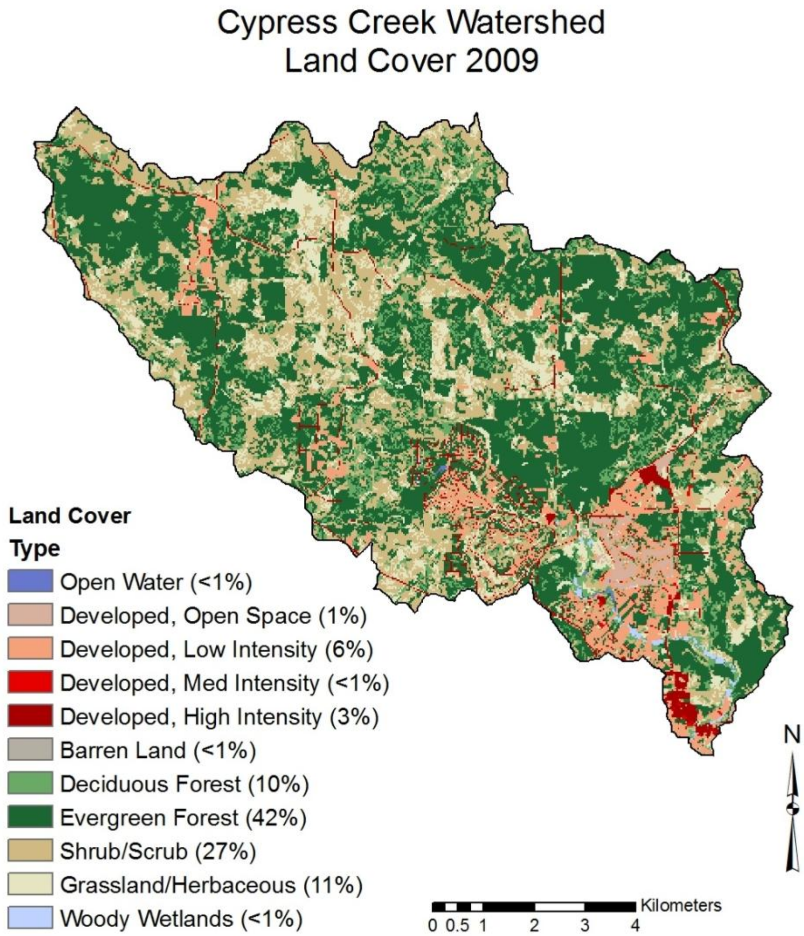

Figure 2.11. Land cover in the watershed, 2009 (RSI, 2010).

The caves, seeps, sinkholes, springs and vegetative cover in the Hill Country region provide habitat to many federally endangered species such as the Golden-cheeked warbler (*Dendroica chrysoparia*), Black-capped-vireo (*Vireo atricapilla*), San Marcos salamander (*Eurycea nana*), Texas blind salamander (*Eurycea rathbuni*), San Marcos Gambusia (*Gambusia gerogei*), Comal Springs drypoid beetle (*Stygoparnus comalensis*) and Texas wild-rice (*Zizania texana*) (TPWD, 2008). Recent sampling at Jacob's Well and nearby stream segments revealed the existence of potentially new and threatened species relying on the spring (Zara Environmental, 2010). With regard to benthic macroinvertebrate assemblages, three of the genera identified in the Zara Environmental

(2010) study have congeners that are state listed species of concern (*Elmia*, *Hyalella* and *Callibaetis*), and one genus has a congener that is endemic to the state of Texas (*Ceratopogon*). A Golden-cheeked Warbler (*Dendroica chrysoparia*) was identified by song approximately 10 meters from the spring. No federally listed aquatic species have been confirmed at the site.

Land use in the Cypress Creek watershed is predominantly Rangeland (73.9 km^2; 75%), followed by Residential (10.8 km^2; 11%), Open/ Undeveloped (9.1 km^2; 9%), and Transportation (3.2 km^2; 3%). Commercial land uses are concentrated in and around downtown Wimberley and Woodcreek, and comprise only 1.1% of the total watershed area (1.0 km^2; Table 2.2). Due to the population increases in the past two decades, land use in the Cypress Creek Watershed has changed. This is evidenced by a shift from predominantly ranching to residential land uses, as formerly large acreage holdings are subdivided for both high-density residential (<2 ha) and large lot "ranchettes" (>2 ha).

Table 2.2. Land use in the Cypress Creek watershed.

Land Use Type	**Area (km^2)**	**Percent**
Residential-Single	5.9	6%
Residential-Large lot	4.9	5%
Residential-Multi	<0.5	<1%
Undeveloped	8.8	9%
Rangeland	73.5	75%
Commercial	1.0	1%
Industrial	<0.5	<1%
Parks	1.0	1%
Transportation	2.9	3%
Total	**98.4**	

Although the combined residential, commercial, and transportation uses account for only 16% of total area, much of this percentage is impervious surface cover (ISC), and is concentrated at the southern and eastern portions of the watershed. Higher-density development is coincident with the perennial creek, making this area both the most valuable in terms of ecosystem services as well as the most vulnerable to anthropogenic impacts. Increased ISC has been shown to alter hydrologic and ecologic functioning by altering a watershed's rain-fall runoff response and concentrating runoff and infiltration into smaller areas. In karst areas this can be particularly harmful to aquifer recharge if major subsurface recharge features are paved over. In addition, landscape fragmentation caused by anthropogenic activity can have profound effects on biotic communities, ecological processes, and hydrologic functioning. Landscape fragmentation occurs as patches (relatively homogeneous areas that differ from their surroundings) become smaller and thus farther apart. A recent study of land cover change showed that ISC increased from 6.03% in 1996 to 9.04% in 2005, averaged over the watershed (Carter, 2008). This is likely to have altered watershed functioning from the previous less developed states by increasing flood peaks and potentially decreasing recharge to the underlying aquifer.

Other results from Carter (2008) show a pattern consistent with urbanizing watersheds. From 1996-2005, patch number increased for four out of six land cover types, while mean patch area decreased slightly. Cover classes associated with undeveloped land (dense canopy, woodland, dense grasses) declined as a percentage of total watershed area, while those associated with development (open park, sparse/bare soil, and ISC) increased in their relative area (Carter, 2008; Figure 2.12). Overall, an increase in ISC and decrease in average patch size for other land cover classes indicate a typical pattern of landscape fragmentation as urban development encroaches on previously open areas. The largest increases in ISC from urban development have occurred in the lower portions of the watershed around Wimberley, Woodcreek and Woodcreek North, and much projected development is expected to occur in these areas and along major transportation routes such as RR 12 and RR2325.

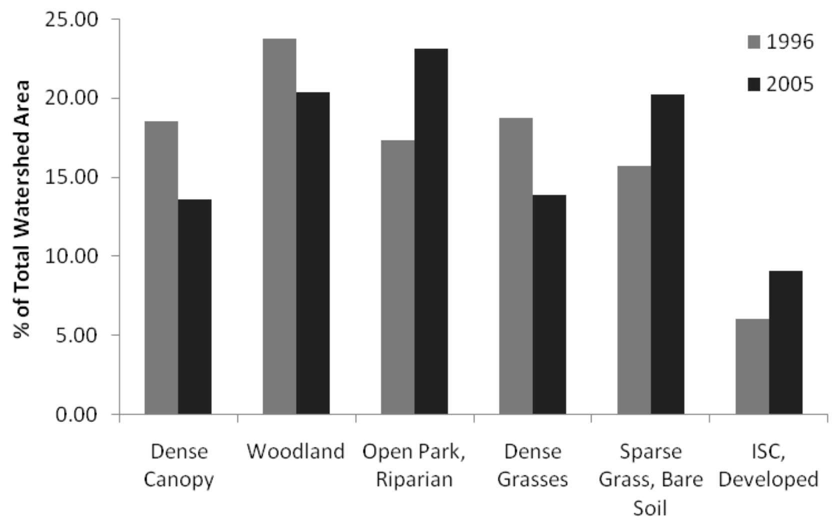

Figure 2.12. Change in relative area of six land cover classes from 1996 to 2005 (adapted from Carter, 2008). ISC = impervious surface cover.

Urban sprawl and associated increases in impervious cover can have a significant effect on watershed hydrology and landscape functioning. Urban sprawl results in increased infrastructure such as roads, fire services, utilities, buildings, storm drainage systems, and sewer services. With these changes comes the conversion of formerly rural or undeveloped lands into lands with increased ISC. In ecologically and hydrologically sensitive areas with karst topography, the effects of ISC on hydrology and water quality can be significant. Recent urbanization of karst terrains has increased the risk and frequency of water pollution with toxic pollutants and increased sediment transport through overland flow (Veni, 1999). Studies on the relationship between water quality and ISC show that adverse environmental impacts increase when ISC nears 10% to 15% land cover (Cuffney *et al.*, 2010; Veni, 1999).

Population Growth and Development

Land and water resources in the Cypress Creek watershed are under increasing demands from multiple sources. The watershed is located near the major metropolitan areas of Austin and San Antonio and the I-35 major transportation corridor. The I-35 corridor and surrounding areas are undergoing rapid urbanization. By the year 2040, population in Hays County is expected to grow from 97,589 in 2000 to over 130,000, or possibly as high as 574,000 (TSDC, 2009). The two communities of Wimberley and Woodcreek are located within the watershed and their populations are rapidly expanding as well. Between 2000 and 2009, the population of these two cities grew by approximately 21.5% (TSDC, 2010). There are over 70 approved subdivisions in the Cypress Creek watershed, several of which are only partially built out. Recent declines in the national housing market have slowed the pace of growth in the area, yet all indications are that new housing developments will continue and the pace will increase as markets recover from the current slow-down.

In the last decade, a primary limiting factor to growth in the area has been a lack of additional water sources to supply new large-scale developments. Recently the Guadalupe-Blanco River Authority (GBRA) and other local partners have been reviewing plans to provide approximately 4 million gallons per day (MGD) of surface water from the nearby Colorado or Blanco Rivers to residents in the Wimberley Valley. Assuming each household and business in the watershed uses about 350 gallons of water per day, the current total water use would be approximately 980,000 gallons per day. If 4 MGD are supplied through surface water, the number of households in the watershed could increase 400% to over 11,000 homes and businesses, an average density of just over 0.8 ha per household. Although additional surface water supplies will help to ease the strain on local groundwater resources and thus mitigate impacts on spring flows, the negative impacts of such dense residential and commercial development on watershed hydrology and nonpoint source pollutant loading may be significant.

Using public water supply pumping records and residential use estimates made by the HTGCD, the average discharge (pumping) from wells over the period of record at Jacob's Well is approximately 0.03 $m^3 s^{-1}$, or 722 acre-feet $year^{-1}$. The average baseflow over the period of record from Jacob's Well is approximately 0.20 $m^3 s^{-1}$. During periods of low flow from Jacob's Well (0.03-0.06 $m^3 s^{-1}$), the pumpage of wells may equal the discharge at Jacob's Well (HTGCD, 2008). Reductions in pumpage during drought conditions will increase the discharge of Jacob's Well and help ensure adequate baseflow to Cypress Creek. It is estimated that water levels in the Trinity aquifer near the study area are declining by 0.4 m per year (HTGCD, 2010). At the end of the drought in September 2009, groundwater levels in many areas of Hays County were below the productive zone, meaning that hundreds of wells had insufficient or no water for domestic use. From September 2008 through September 2009, flow at Jacob's Well spring rarely exceeded 0.03 $m^3 s^{-1}$ (1 cfs), the longest period of essentially zero flow ever recorded at that location.

The primary growth areas shown in Figure 2.13 are based on existing road networks, Hays County's 2025 Transportation Plan, city limits and extra-territorial jurisdiction areas (ETJs), water and wastewater service areas, and existing parcel boundaries. Major transportation corridors were defined as 150 m buffers along both sides of roadways. The primary growth areas are:

1. CR218 corridor: This area includes the Shadow Valley subdivision in the north and a swath of land to the south approximately 0.8 km (0.5 mile) wide along CR218.
2. Ledgerock subdivision: This area follows the Ledgerock subdivision boundaries.
3. Woodcreek North: This area follows the subdivision boundaries for Woodcreek Phase II, west of Jacob's Well Road.
4. Wimberley & Woodcreek: Includes the remainder of the Woodcreek subdivision east of Jacob's Well Rd. and some surrounding parcels, plus areas of northern Wimberley and its ETJ to the RR12/RR2325 intersection in downtown Wimberley.
5. Skyline Ranch subdivision: Includes the Skyline Ranch, Skyline Acres, Sagemont, and Wimberley Heights subdivisions.
6. Wimberley East: Includes downtown Wimberley along RR12 and areas to the north and east of RR12. Includes several large-lot inholdings, the Cypress Creek Acres, Ranch at Wimberley, and Pinnacle Ridge subdivisions, and areas along Winter's Mill Pkwy. Much of this area is within Wimberley and Woodcreek ETJs.

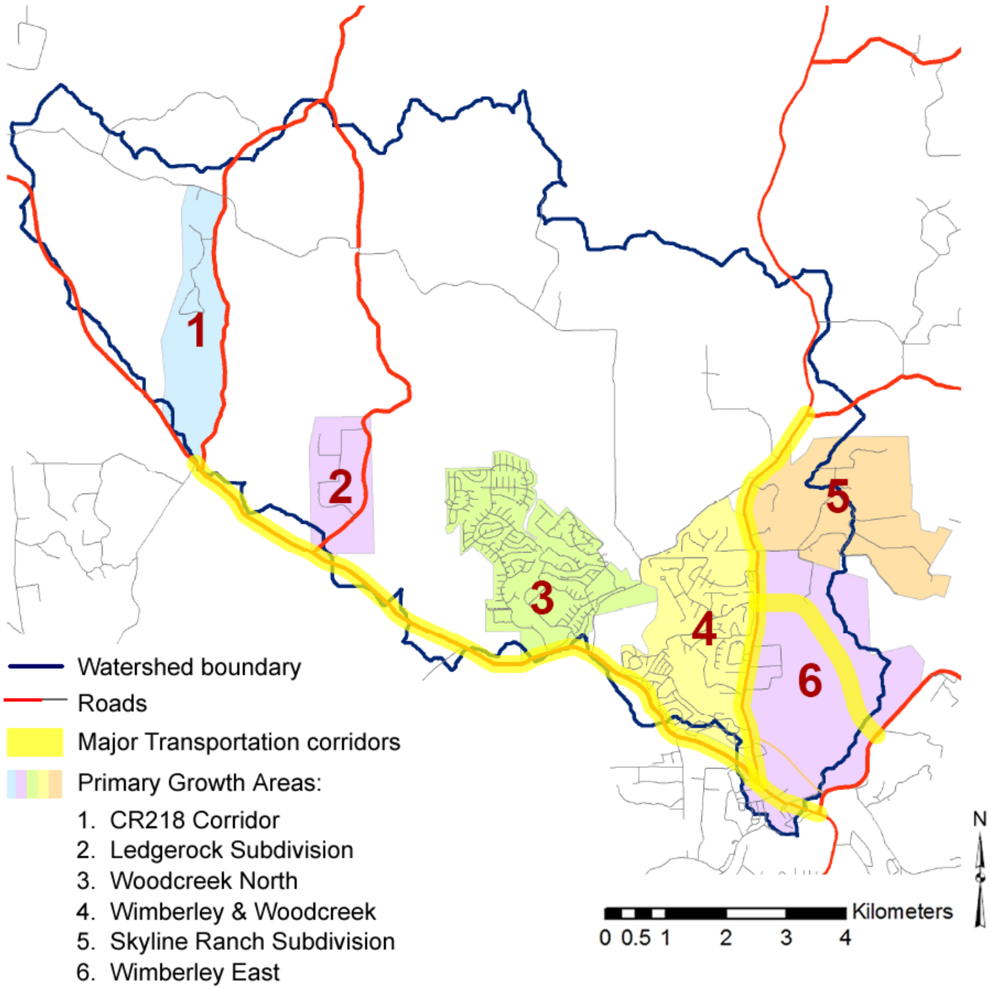

Figure 2.13. Primary growth areas in the Cypress Creek watershed.

Water Quality

Recent aquatic life monitoring and habitat assessments conducted by TCEQ between Jacob's Well and the Blanco River confluence from 2002 to 2007 classified the Cypress Creek as having intermediate to high aquatic life use based upon the index of biotic integrity (IBI) developed for the Central Texas Plateau (Linam *et al.*, 2002; Walther and Palma, 2005). Fish collections yielded a total of 22 species in eight families, including at least one species that has been shown to be sensitive to organic enrichment, the greenthroat darter (*Etheostoma lepidum*; Linam and Kleinsasser, 1998). The most numerous species collected were the green sunfish (Lepomis cyanellus), spotted sunfish (*Lepomis punctatus*), central stoneroller (*Campostoma anomalum*), Texas shiner (*Notropis amabilis*), Rio Grande cichlid (*Cichlasoma cyanoguttatum*), and western mosquitofish (*Gambusia affinis*).

Routine water quality monitoring through the Texas Commission on Environmental Quality's (TCEQ) Clean Rivers Program (CRP) is performed at five sites along the creek, from Jacob's Well to the confluence with the Blanco River (Figure 2.14). No routine water quality monitoring or flow data are collected for the dry creek above the headwaters at Jacob's Well. TCEQ site 12674 (at Ranch Road 12 in downtown Wimberley) has been sampled monthly or quarterly from 1973 to present by TCEQ and GBRA, and these data represent the best long-term record of surface water quality in the creek. The Jacob's Well CRP site (12677) has been sampled monthly from 08-08-2002 to present by CRP, and continuously (USGS site #08170990) from 04-23-2005. Additional sites on the creek include Ranch Road 12 approximately 4.5 river km downstream from Jacob's Well (12676) sampled from 02-27-2003; at Blue Hole spring (12675) approximately 6.7 river km from the Well sampled from 12-27-2005; and at the confluence with the Blanco (12673) sampled from 08-08-2002. Clean Rivers Program sites are sampled monthly or bi-monthly, and data through December 2009 were used in this study. For the following analysis, values below detection limits were replaced with 50% detection limits.

TCEQ and CRP sites include instantaneous flow data (12674 only) and the following water quality parameters: temperature (^{o}C), dissolved oxygen (mg L^{-1}), specific conductance (*u*mhos cm^{-1}), pH (SU), nitrate-nitrogen (mg L^{-1}), total phosphorous (mg L^{-1}), total suspended solids (mg L^{-1}), ammonia (mg L^{-1}), *E. coli* (mpn 100mL^{-1}; mpn = most probable number of bacteria). Ortho phosphorous (mg L^{-1}), total dissolved solids (mg L^{-1}), and fecal coliform have been sampled infrequently at various sites.

In general, ambient monitoring data are collected under baseflow conditions and occasionally following storm events when flows are elevated. Data are never collected when flows are elevated to a point that would compromise the safety of monitoring teams, nor are daily streamflow measurements routinely collected. However, proper characterization of the hydrology and water quality of the creek requires reliable data to characterize the range of streamflow and water quality under the full range of natural conditions. To help address these data gaps, two automatic stormflow monitoring devices were installed along the main creek channel in 2009 to record stage, sediment, nutrient, and bacteria concentrations during runoff events (RSI, 2010; Figure 2.14). One station draws samples from Cypress Creek near its confluence with the Blanco River, and a second station draws samples from the low water crossing at Woodacre Drive, about 180 m upstream of Jacob's Well. The stations consist of a large metal box attached to a metal platform. The sampler inside connects to plastic tubes running through electrical conduit down to the creek. An ISCO 730 bubbler flow module inside continually records the height of water ("stage") every five minutes, and triggers a pump to start collecting water samples when an increase in flow is detected, indicating that runoff has started from a rain storm. The samples are later taken to a lab and analyzed for total suspended solids (TSS), nitrate-nitrogen, total phosphorous, and *E. coli*.

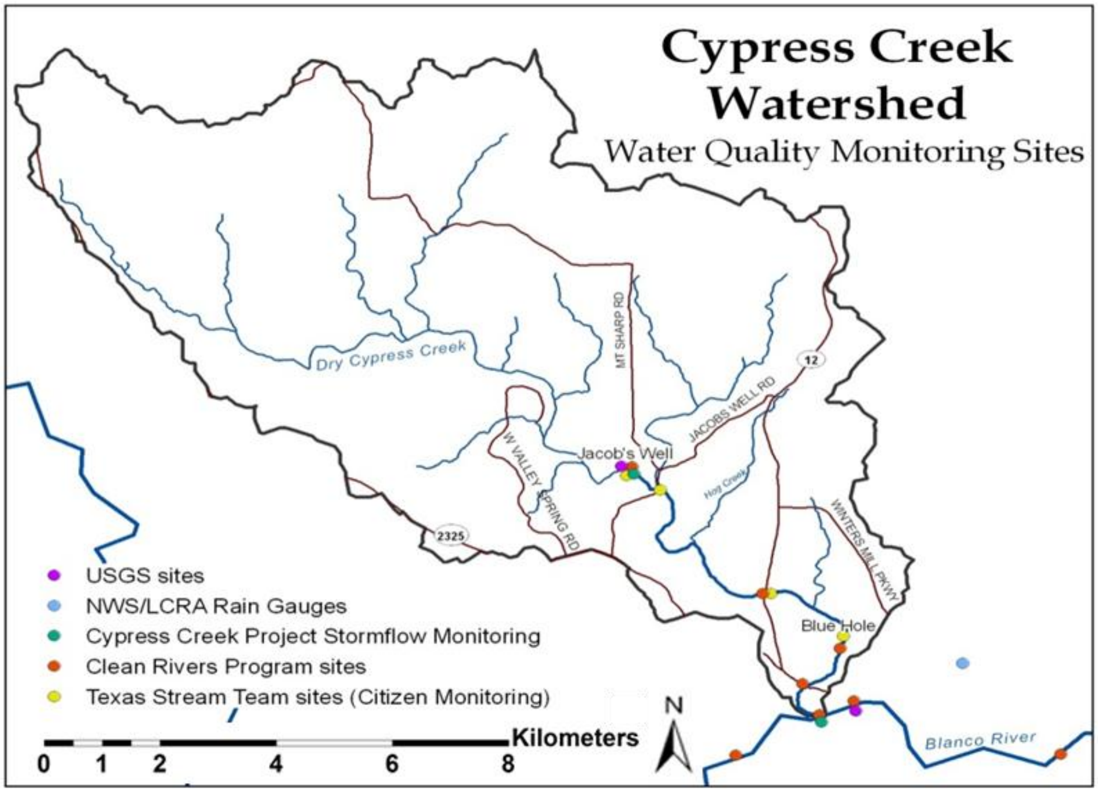

Figure 2.14. Water quality monitoring sites.

Estimating Daily Mean Flow

Since daily mean flow data are not available at the outlet of the watershed, and records of daily mean baseflow from Jacob's Well Spring are not available prior to April 2005, total flow at the outlet of the watershed must be estimated. Historical daily mean flows at the Blanco confluence were estimated based on a comparison between daily mean stage recorded at the watershed outlet and daily mean stage at the USGS Blanco River gauge (08171000), from 02/01/2010 through 07/03/2010. The relationship between the two was found to be fairly good. A linear regression using Blanco stage as the predictor and Cypress Creek stage as the response variable resulted in a goodness-of-fit (R^2) value of 0.768 ($n = 148$; $p < 0.001$):

$$S_C = 0.388ln(S_B) + 0.229 \quad [1]$$

where S_C = Stage height at Cypress Creek (m)

S_B = Stage height at Blanco River (m)

Stage estimated using equation [1] were compared to recorded stages, and the resulting error ranged from -14% to 24% with a mean error of only 0.3%. Flow velocities at the Cypress confluence are calculated using estimated stage height and Manning's equation:

$$V_t = \frac{1}{n}\left(\frac{A}{P}\right)^{\frac{2}{3}} S^{\frac{1}{2}} \quad [2]$$

where V_t = cross-sectional average velocity at time t $(m\ s^{-1})$

n = Manning coefficient

A = cross-sectional area of flow (m^2)

P = wetted perimeter (m)

S = slope of water surface $(m\ m^{-1})$

Instantaneous flow measurements were taken a few meters downstream from the bubble gauge on four occasions between 2/1/2010 and 3/17/2010. These measurements, along with data on the bank slopes and bottom width obtained from a channel cross-section, were used to estimate the Manning coefficient *n*. The resulting value (0.08) is relatively high but is within the range reported for similar watersheds in central Texas (0.016 to 0.213), and is consistent with findings that Hill Country watersheds tend to have higher observed hydraulic resistance values than are commonly estimated using methods based on physical properties alone (Conyers and Fonstad, 2005). The cross-sectional area of flow (*A*) is calculated using recorded stage height and data from the channel cross-section. Flow rates are then calculated using the discharge formula:

$$Q_t = AV_t \qquad [3]$$

where Q_t = discharge at time t ($m^3\ s^{-1}$)

A = cross-sectional area of flow (m^2)

V_t = cross-sectional average velocity at time t ($m\ s^{-1}$)

Flows estimated using the above method were compared to recorded instantaneous flows, and the resulting error ranged from -2.5% to 11.9%. This method was used to estimate historical daily mean flows for the Cypress Creek for January 2000 to March 2010 and a flow duration curve was constructed using these estimates (Figure 2.15). The resulting estimated flows are correlated very strongly with daily mean spring flow recorded at Jacob's Well starting in April 2005 (R^2 of linear regression = 0.868; n = 1,854; p<0.001).

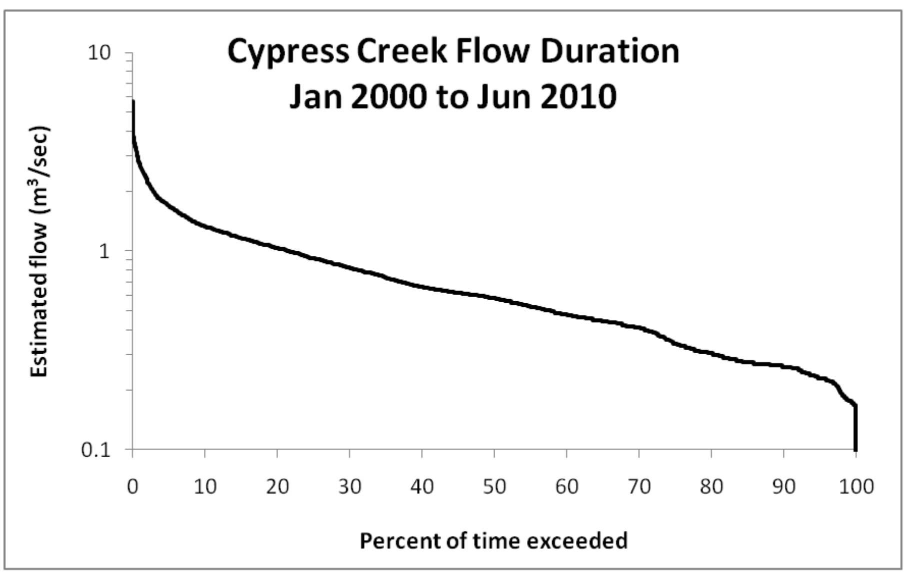

Figure 2.15. Flow duration curve for flows estimated at the Cypress Creek confluence (January 2000 to June 2010).

Table 2.3. Data sites.

Station ID	Entity	Site Description	Latitude Longitude	Start Date	End Date	Data recorded/frequency
12677	CRP	Cypress Creek at Jacob's Well	30.034 98.126	8/8/2002	12/30/2009	Temperature, DO, Conductivity, pH, Nitrate-N, Phosphorous, *E. coli*, Suspended Sediment, Ammonia
12676	CRP	Cypress Creek at RR12 (north)	30.012 98.104	2/27/2003	12/30/2009	Temperature, DO, Conductivity, pH, Nitrate-N, Phosphorous, E. coli, Suspended Sediment, Ammonia
12675	CRP	Cypress Creek at Blue Hole	30.003 98.091	12/27/05	12/30/2009	Temperature, DO, Conductivity, pH, Nitrate-N, Phosphorous, E. coli, Suspended Sediment, Ammonia
12674	TCEQ	Cypress Creek at FM12 (downtown)	29.997 98.098	12/3/1973	1/11/2010	Flow, Temperature, DO, Conductivity, pH, Nitrate-N, Phosphorous, E. coli, Suspended Sediment, Ammonia
12673	CRP	Cypress Creek at Blanco River	29.991 98.095	8/8/2002	12/30/2009	Temperature, DO, Conductivity, pH, Nitrate-N, Phosphorous, E. coli, Suspended Sediment, Ammonia
20828	RSI	Jacob's Well Stormflow #1	30.033 98.133	2/1/2010	2/5/2010	Stage height at 5 minute intervals; Suspended Sediment, Nitrate-N, Phosphorous, and E. coli – triggered by 25.4 mm (1 in) rise in water level.
12673	RSI	Confluence Stormflow #2	29.991 98.095	2/1/2010	4/15/2010	Stage height at 5 minute intervals; Suspended Sediment, Nitrate-N, Phosphorous, and E. coli – triggered by 25.4 mm (1 in) rise in water level.
08170990	USGS	Jacobs Well Spring nr Wimberley, TX	30.034 98.126	4/23/2005	3/17/2010	Stage height, Velocity, Flow, Temperature, Conductivity, Turbidity – 15 minute intervals and Daily Means
08171000	USGS	Blanco Rv at Wimberley, TX	29.994 98.089	8/6/1924	3/17/2010	Stage height, Flow – 15 minute intervals and Daily Means
CCP1	RSI	Golds Rd. Rain gauge #1	30.068 98.110	5/8/2009	3/31/2010	Rainfall at 0.254 mm (0.01 in) intervals
CCP2	RSI	Rolling Hills Rain gauge #2	30.074 98.202	6/3/2009	3/31/2010	Rainfall at 0.254 mm (0.01 in) intervals
CCP3	RSI	Ledgerock Rain gauge #3	30.039 98.175	7/3/2009	3/31/2010	Rainfall at 0.254 mm (0.01 in) intervals
419815	NCDC	Wimberley 2	29.999 98.050	3/1/1984	3/31/2010	Rainfall – daily totals
413156	NCDC	Fischers Store	29.980 98.270	2/1/1930	3/31/2010	Rainfall – daily totals
4593	LCRA	Dripping Springs 5 SSW	30.122 98.114	1/1/2000	3/31/2010	Rainfall – hourly and daily totals Temperature – daily min, max, mean
3528	LCRA	Dripping Springs 8 W	30.197 98.223	1/1/2000	3/31/2010	Rainfall – hourly and daily totals

Characterizing Water Quality

Table 2.3 lists the climate and water quality data that were utilized for the analyses described below, as well as for the studies described in the remaining chapters. Concentrations of various pollutants were analyzed in relation to one another and to available data on precipitation, temperature, and streamflow, in order to characterize the current condition of the watershed and the potential sources and loading of nonpoint source pollution in the area. Load duration curves were constructed using daily mean flow estimated at the watershed outlet and available water quality data (Table 2.3; Figure 2.14).

The Cypress Creek was placed on the 303(d) list for impaired water bodies in 2000 due to low dissolved oxygen concentrations (DO). This impairment coincided with the first time in recorded history that flow at Jacob's Well Spring was reduced to zero. Under drought conditions, spring flow again dropped to zero in 2008. The subsequent de-listing of the segment for DO in 2008 was based on data collected at the most upstream site, where Jacob's Well Spring normally provides the majority of baseflow for the stream. DO saturation levels at Jacob's Well are relatively consistent, with concentrations between 5.0 and 7.0 mg L^{-1}, and normally provide a steady flow of cold water into the creek. This indicates that DO at that location is primarily determined by the oxygen saturation of groundwater coming out of the aquifer, and not necessarily indicative of conditions across the full length of the segment.

Unlike the four other sites on segment 1815, DO actually increases at the Jacob's Well site when there are lower flow rates (such as occurred in 2008). Average flow measured at Jacob's Well when DO ≥6.0 mg L^{-1} is 0.10 $m^3 s^{-1}$, while average flow when

DO <6.0 mg L^{-1} is 0.15 $m^3 s^{-1}$. This contrasts with the most downstream site (Cypress Confluence; 12673), where the average flow when DO <6.0 mg L^{-1} is only 0.05 $m^3 s^{-1}$, versus 0.54 $m^3 s^{-1}$ when DO ≥6.0 mg L^{-1}. When spring flows are reduced, water remains in the pooled area around the spring longer and so has a longer time exposed to the air and other biological processes that increase DO locally, and could explain the adequate dissolved oxygen recorded there that was used as evidence for de-listing in 2008. Conversely, low flow has been highly correlated with depressed dissolved oxygen at three of the four remaining monitoring sites (RSI, 2010). Diurnal sampling of DO that occurred in June 2009 at the Blue Hole site (12675) showed depressed dissolved oxygen levels with a minimum of 3.7 mg L^{-1} and a maximum of 4.3 mg L^{-1}. Therefore, impaired dissolved oxygen and resulting impacts on aquatic life remain a primary issue of concern for stakeholders in the area.

Ambient water quality data show that the Cypress Creek, as a whole, remains in adequate condition when assessments are based on state water quality standards. However stakeholders and experts have agreed that meeting state water quality standards would be insufficient to maintain the desired health and historical nature of the creek as a spring-run stream. Furthermore, no state standards exist for concentrations of sediment and nitrogen for contact recreation, and both anecdotal and measurable evidence show a decline in the quality of these parameters over the last 10 years. Spatial and temporal analyses show that natural and anthropogenic activities likely impact water quality, quantity, land use, and land cover (Carter, 2008; HTGCD, 2008; RSI, 2010). Impervious cover in the Cypress Creek watershed was estimated at 6% in 1996. By 2005, total impervious cover increased to 9%. A recent study showed that healthy watershed functions are impacted at impervious cover rates as low as 10% (Cuffney *et al.*, 2010). An economic assessment conducted by business and landowner stakeholders showed that decreased water quality and quantity will not only negatively impact the creek but also land and business values, thus creating a concern among local residents and stakeholders that historic water quantity and quality be maintained (RSI, 2010).

Nitrogen is present at low concentrations at all sites under ambient conditions and is actually highest in spring flows out of Jacob's Well with a median concentration of 0.47 mg L^{-1}. Nitrogen levels at Jacob's Well track closely with a target maximum load of 0.5 mg L^{-1} (Figure 2.16). Exceedances of this level occur at higher flows and at all sites except the confluence, indicating a nonpoint source that washes nitrogen into the creek above downtown Wimberley along with high flows. High nitrate concentrations may not be strictly from natural sources and can indicate contamination from fertilizers, manure, or sewage. The fact that the confluence has the lowest maximum level recorded, only 1.13 mg L^{-1}, means that biological processes in the stream are assimilating excess nitrogen before reaching the confluence, which could explain algal blooms observed in upper portions of the perennial Cypress Creek during dry periods.

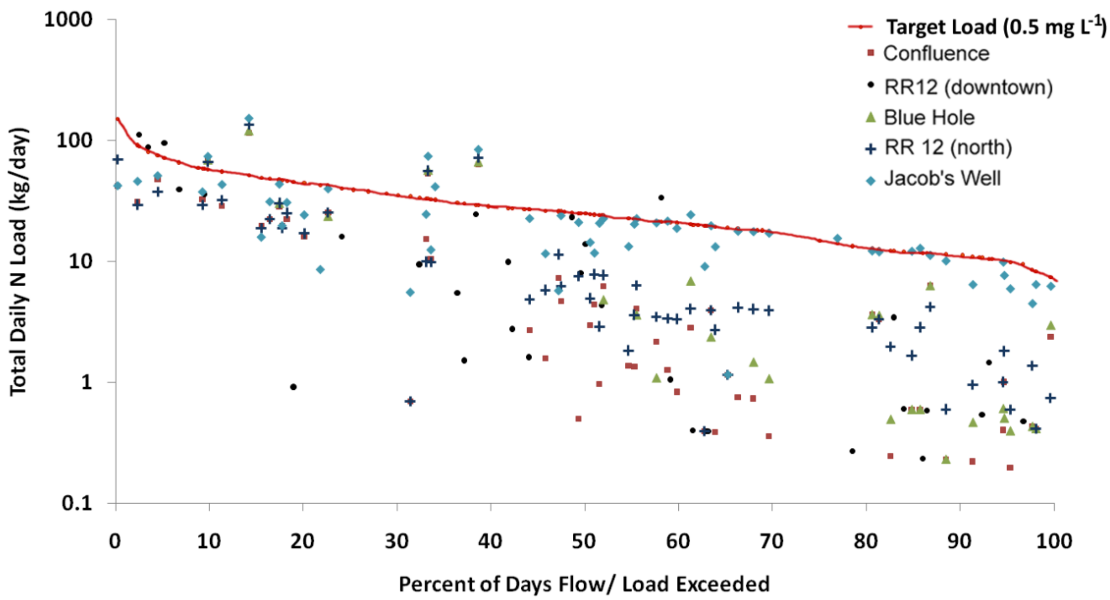

Figure 2.16. Load duration curve of nitrogen at five sites along Cypress Creek. Red dashed lines represents nitrogen loads at target concentrations of 0.1 and 0.5 mg L^{-1}, and dots represent loads calculated for observed conditions.

Nitrogen exceedances above 0.5 mg L^{-1} tend to happen at higher flows during the fall and summer months. The highest exceedances are often seen when a period of very low flow is followed by a high flow event. In particular the very dry period 2005-2006 was followed by exceedances in nitrogen targets at all sites from January through April 2007 (Figure 2.17). This evidence supports a nonpoint source of nitrogen in the contributing area, such as fertilizer or animal waste that builds up on the surface during dry periods and is washed in when rainfall is sufficiently intense to produce surface runoff.

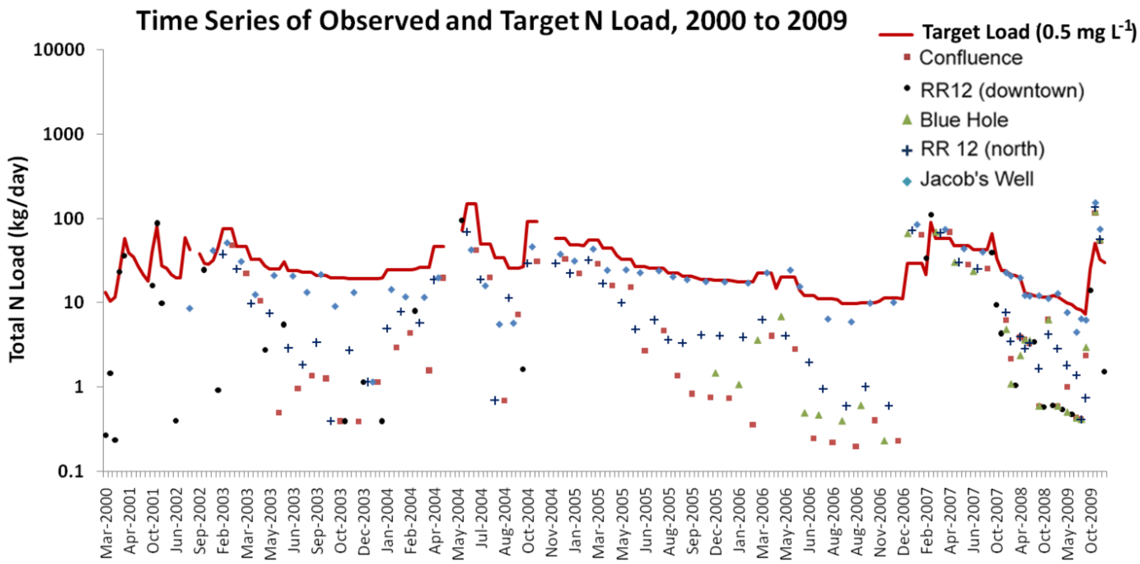

Figure 2.17. Time series of observed and target nitrogen load for five sites along Cypress Creek. The red line indicates target loads calculated based on available flow estimates and 0.5 mg L^{-1} concentration. Points above this line represent exceedances of the target load.

Sediment concentrations are highly site-specific, and the impacts on local ecosystems can be localized as well. No State standards exist for TSS concentrations relating to contact recreation. Spring-fed streams like Cypress Creek have naturally very low sediment levels, and it is natural that some sediment washes into the creek during storm events. Examining a load duration curve for TSS, it is apparent that there is a natural range of variability in sediment concentrations in the Cypress Creek from 0.5 mg L^{-1} to 5.0 mg L^{-1} (Figure 2.18). Sediment levels at the upper end of this range may still be undesirable, particularly at locations such as Jacob's Well spring, but for the purposes of characterizing and prioritizing the sources of excess loads, 5.0 mg L^{-1} is used as a maximum target. Above this level there are three distinct groups of exceedances, characterized by high, median, and low flow conditions. It is likely that three different mechanisms are operating during these times to produce excess sediment in the creek.

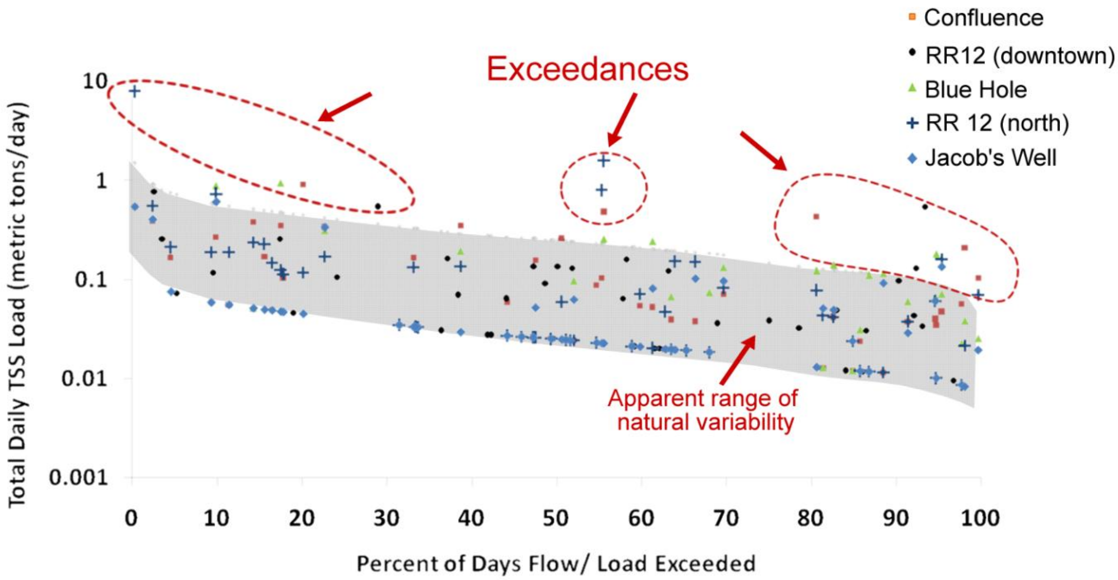

Figure 2.18. Load duration curve of total suspended solids (sediment) at five sites along Cypress Creek. There appears to be a natural range of variability between 0.5 and 5.0 mg L^{-1} across all flow levels (grey shaded area). Dots represent loads calculated for observed conditions. Values above the shaded area indicate times of excess sediment loading.

At times of low flow, exceedances are seen in all sites, and tend to be in the hottest months of the summer, July through September. This points to recreation as a major contributor to sediment, as both people and animals spend more time traveling into and out of the riparian area. Exceedances at moderate flows tend to occur earlier in the year, often in the spring (January through April) and could indicate spring showers bringing surface runoff full of sediment and particulates that have accumulated on the land surface. Very high flow exceedances represent sediment washing off the watershed from large and intense storm events, also seen in the late fall and early spring. No exceedances are recorded at Jacob's Well under moderate flow conditions; instead these tend to occur at very high flows (likely caused by runoff from the upstream Dry Cypress) and very low flows (likely caused by recreation activities at the Well). The confluence recorded only one exceedance at a high flow level, consistent with its overall low nitrogen concentrations even during higher flows.

A time series of target maximum (5.0 mg L^{-1}) and observed sediment concentrations reveals that there are a cluster of exceedances that occurred from spring 2005 through fall 2006 (Figure 2.19). A major roadway, Winters Mill Parkway, was under construction from October 2005 to July 2007 in the southeastern portion of the watershed. Some of the highest relative exceedances in the spring of 2006 may be associated with the construction of this road, although RR12 downtown and the confluence both had exceedances in the spring of 2005 before work started. In-stream dredging operations were also documented in 2005. Other construction activities along RR12 and Jacob's Well Rd. could contribute excess sediment to the creek as well.

In addition, stormflow monitoring results from 2009 for TSS indicate occasionally very high sediment loads carried in the creek during rainfall events. Samples of stormflows were taken every 30 minutes for the first three hours of each storm and every hour thereafter until flows subsided and analyzed for sediment concentrations. The maximum concentration measured during the five events was 103.0 mg L^{-1} and the minimum was 0.5 mg L^{-1}, but 38% of discrete samples registered at or above 5.0 mg L^{-1}. At the Dry Cypress site above Jacob's Well, TSS concentration for the one storm sampled started high at 10.0 mg L^{-1} and gradually dropped to 2.0 mg L^{-1}.

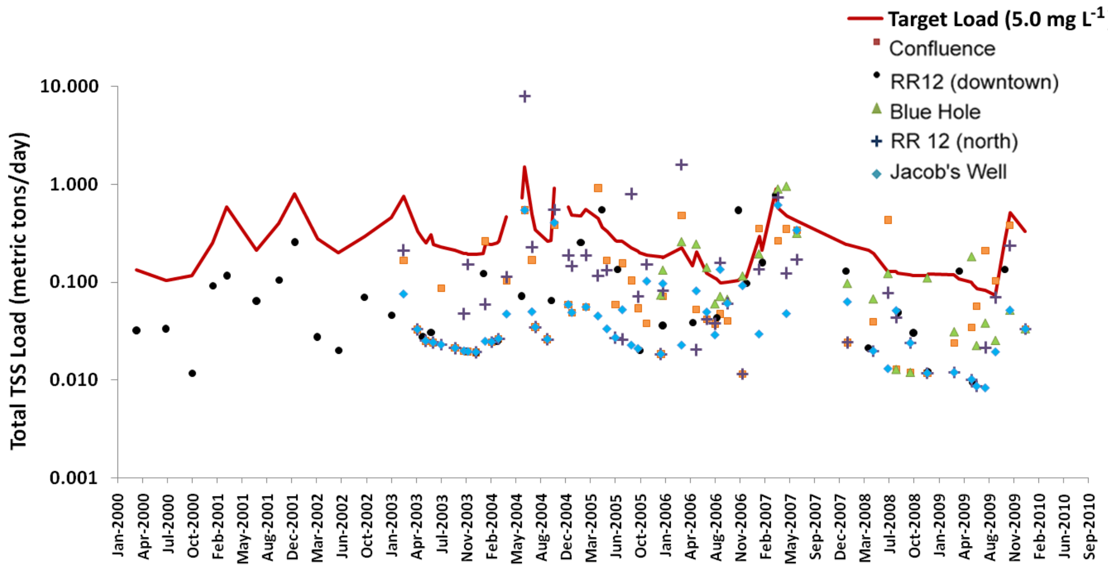

Figure 2.19. Time series of observed and target maximum sediment load for five sites along Cypress Creek. The red line indicates target loads calculated based on available flow estimates and 5.0 mg L^{-1} concentration. Points above this line represent exceedances of the target load.

Very high bacteria levels have been seen at all sites during medium to high flows (Figure 2.20). A cluster of very high values is found under the highest flow conditions, indicating a nonpoint source that washes *E. coli* down with surface or shallow sub-surface storm flows. These tend to be in the summer and fall when high temperatures favor the growth of bacteria and large flow events wash these bacteria into the creek. At median flow levels, all sites show exceedances at various times, including at Jacob's Well. These median flows tend to occur in the spring and fall, and exceedances here are often associated with elevated sediment and nitrogen levels entering the creek.

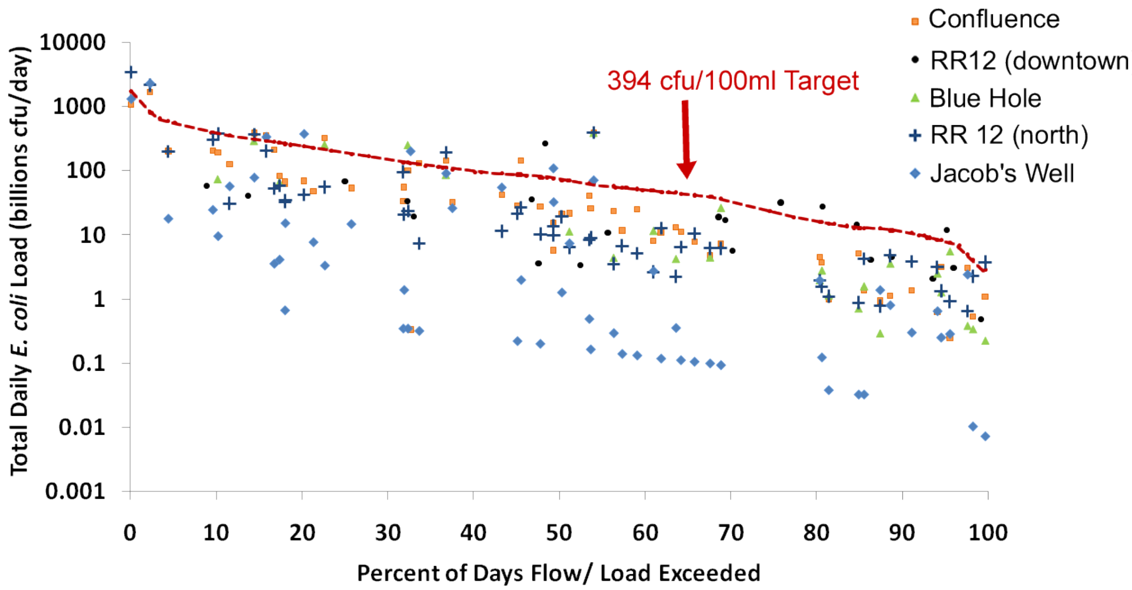

Figure 2.20. Load duration curve of *E. coli* at five sites along Cypress Creek. The red dashed line represents *E. coli* loads at a target concentration of 394 mpn 100 ml^{-1}, and dots represent loads calculated for observed conditions (mpn = most probable number of bacteria).

At lower flows (below about 0.06 $m^3 s^{-1}$), *E. coli* exceedances occur primarily at RR12 downtown. Because there would be very little surface flow during these dry periods, *E. coli* must be contributed by shallow subsurface flow from septic systems in the local area or pet/animal waste placed directly in the stream and riparian area. Two of the four low-flow *E. coli* exceedances at RR12 downtown are associated with elevated ammonia; however many times the two are not closely correlated. Higher *E. coli* values are correlated with elevated TSS levels at all sites except at Jacob's Well, which tends to have the lowest bacteria concentrations due to the influence of spring flow, but also has the greatest variability of observed concentrations.

Stormflow monitoring recorded *E. coli* levels as high as 16,000 mpn $100mL^{-1}$ at the confluence and 680 mpn $100mL^{-1}$ above Jacob's Well. For 13 storm events sampled in 2009, average peak E. coli levels were 2,400 mpn $100mL^{-1}$. Fecal coliform bacteria like *E. coli* indicate contamination due to untreated sewage, manure, or pet waste in contributing areas. High *E. coli* values during high and median flows, and their association with elevated sediment and nitrogen levels, indicate a dispersed non-point source of untreated waste that enters the creek with stormflows. High *E. coli* levels at very low flows, however, tend to indicate a problem with malfunctioning septics near the creek or animal waste deposited directly into the stream. Birds, both aquatic and otherwise, can also be a source of direct fecal matter input to the creek.

Summary

The above information on watershed characteristics, population and development, hydrology, and water quality is presented to introduce the watershed as a case study used for the analyses presented in the remaining chapters. As land use in the study area continues to shift from open space and ranching to residential and commercial, increasing adverse impacts are likely to occur as additional loadings impact water quality, and as increased pumping impacts spring flows. The lower, more densely populated portions of the watershed currently benefit from the relatively sparse development in the middle and upper portions. These large tracts of low-intensity ranching and undeveloped lands provide critical recharge and water quality protection for water that ultimately enters the creek, as well as safeguarding wildlife habitat and biodiversity.

Watershed-based management of nonpoint source pollution impacts will be important for mitigating flooding and water quality impacts of stormwater runoff in Cypress Creek. However management for aquifer levels (and thus spring flow volumes) must be addressed on a regional scale coincident with the areas of the Trinity aquifer that are contributing and recharge zones for flows at Jacob's Well and other minor springs that perennially feed the creek. These pollutants and water quality management issues cross multiple scales and agency jurisdictions. Agencies with development planning and water resource protection roles include: City of Wimberley, City of Woodcreek, Hays-Trinity Groundwater Conservation District, Hays County, Texas Parks and Wildlife Department, Texas Water Development Board, Texas Commission on Environmental Quality, Guadalupe-Blanco River Authority, and others.

Traditional water resources planning in this area has, to-date, relied upon a regulatory and legal structure that has treated surface water as distinct from groundwater, treated water requirements for development interests as distinct from ecological flow requirements, and considered cultural, aesthetic, and recreational uses of the creek as distinct from development activities on the landscape. Recent evidence presented here reveals that these two water sources are in fact highly interconnected and should be managed as a single resource in order to ensure the most efficient and sustainable use of land and water resources in the area.

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CHAPTER III

COMBINING PARTICIPATORY MODELING, HYDROLOGIC SIMULATION, AND MULTI-CRITERIA ANALYSIS FOR A WATER QUALITY DECISION SUPPORT SYSTEM IN AN URBANIZING WATERSHED

Abstract

Surface- and ground-water resources in semi-arid regions are threatened by intense urbanization and increasing demand for land and water resources. Like many other semi-arid environments, the central Texas Hill Country is experiencing increasing issues concerning the impacts of this development on increasing nonpoint source pollution to local streams. In recent years, much effort has gone toward the development of new methods to address development planning through a systems approach, methods that integrate quantitative research and modeling tools with qualitative and participatory approaches. Decision support systems are increasingly recognized as useful tools to help in the resolution of conflicts involving values, management approaches, and strategies. In this study, we propose a framework for developing a decision support system that embeds the DSS within a larger context of systemic development planning. In this model of systemic planning, the sum of management practices, rules, climatic drivers, and social drivers combine to create scenarios. These scenarios act upon the natural system of interest (the watershed), and the resulting impacts are evaluated based on local objectives

for management and decision criteria. The Cypress Creek Decision Support System (CCP-DSS) was developed to evaluate the impacts of urbanization on water quality in the Cypress Creek, Hays County, Texas, and is presented as a case study for development of such a system. The approach presented here incorporates participatory modeling and multi-criteria evaluation to develop decision support tools that are responsive and targeted to the needs of local decision makers. The CCP-DSS consists of two watershed runoff and erosion models coupled with a GIS interface to aid in parameterizing and generating model input files, developing land use and development scenarios, and visualizing spatial results, along with a multi-criteria analysis package to evaluate scenarios using both model outputs and user-defined criteria. In addition, the application is packaged with local data necessary to create scenarios, run simulations, evaluate and interpret results.

Introduction

Surface- and ground-water resources in semi-arid regions are threatened by intense urbanization and increasing demand for land and water resources. Like many other semi-arid environments, the central Texas Hill Country is seeing increasing concerns about the impacts of this development on nonpoint source pollution to local surface waters, compounded by potential reductions in spring flows due to declining aquifer levels. Planning in these areas would greatly benefit from decision support tools that provide stakeholders and regulatory agencies with targeted, watershed-scale tools to analyze these potential impacts. Such tools could help to determine which areas are most sensitive to development pressure, and where best management practices or other conservation measures may be targeted to greatest effect.

Traditional water resource management has focused on top-down, reductionist approaches like establishing water quality targets and regulatory action to maintain a target level of supply to meet the demands of agriculture, industry and municipalities. As a consequence of this reductionist approach, resource management has often been based upon the assumption that ecosystems exhibit stable equilibrium states that can be maintained through identifying best management practices (BMPs) or that they can be reclaimed through restoration efforts. Traditional BMP development represents a typical top-down approach to resource management, and has been criticized because of their underlying assumptions that a) BMPs are universal (thus management experiences gained elsewhere can be applied in any similar biophysical situation without regard to social or economic context); and b) local resource users are unaware of the causes of environmental problems and the consequences of their choices (thus, once informed, stakeholders are immediately expected to adopt new management practices; Johnson et al 2001). In addition, it has been argued that policies based primarily on public perceptions (as opposed to expert assessments) may fail to adequately protect fundamental human rights to health and liberty (Perhac, 1996), implying that expert evaluation is necessary for the most efficient and effective results.

A common criticism of traditional resource planning approaches is that in many cases unforeseen or seemingly insignificant interactions (based solely on scientific assessments) may also result in undesirable side effects such as pollution and environmental degradation (Sharifi, 2002; Walker *et al.*, 2002). In addition, environmental conflicts following policy implementation are often based on values and contrasting beliefs about the distribution of costs and benefits between individuals and groups. Often these conflicts are shunted to the judicial system, which is concerned with legal arguments rather than establishing consensus or scientific accuracy (van den Belt, 2004).

An alternative view to that of traditional reductionism, one that is based in complex adaptive systems theory, is that social-ecological systems are dynamic, impacts of management decisions will be highly dependent on context, and that humans are an integral part of the system and so cannot be ignored when developing management and decision support tools. From an institutional point of view, there is increasing recognition that resource management should be accountable and responsive to the public whenever feasible. Recent legislation in various countries (including the United States) now require public input for certain decisions, particularly those regarding risk management, such as the siting of radioactive waste facilities or prioritizing environmental clean-up and mitigation projects (Rowe and Frewer, 2000).

Participatory Decision Making

Participatory approaches aim to address the problem of perception and value conflicts between disparate groups, and are popular because many of their features match well with resources that are optimally managed on a community level, i.e. those that can be characterized as common pool resources (Dietz *et al.*, 2003): a) they are useful for capturing behavioral patterns and changes among stakeholders; b) they can incorporate perceptions and interpretations as well as facts; and c) they are less intimidating to stakeholders than more traditional models of "stakeholder input" (Johnson *et al.*, 2001; Mendoza and Prabhu, 2005). Participatory approaches can range across a spectrum from less to more public involvement and dialogue. On one end of the spectrum lie the more "one-way" models of stakeholder involvement, from traditional public information sessions where information passes from agency to public, to public input forums where information passes from public to agency, often filtered through agency questionnaires or surveys. Recently there has been a focus on developing more "two-way" participatory approaches to resource management, that allow for multi-directional information flow between regulatory agencies, experts, and stakeholders. This last category of interactive participatory approaches often involves adaptive learning, dialogue, and participatory model-building. These approaches seek to give stakeholders a more active role in decision-making than do the one-directional approaches. It is these approaches will be referred to collectively in the remainder of this paper as participatory decision making.

At the most basic procedural level, arguments for stakeholder-based, participatory approaches recognize a basic human right to be involved in decisions that potentially impact one's health or livelihood. This type of argument often cites concerns over democracy and procedural justice as well (Rowe and Frewer, 2000). In addition, it is increasingly recognized in democratic societies that unpopular policies may result in widespread protest and potentially reduced trust in governing bodies (Kasperson *et al.*, 1992).

The recognition that resource management is in practice the management of complex linked social-ecological systems means that no single perspective, whether proceeding from the basis of scientific inquiry and data gathering or from the personal experiences of local residents, can adequately picture the whole of the system and its component interactions. Therefore these types of systems are best understood using a multiplicity of perspectives (Berkes *et al.*, 2003). The multiple perspectives that are solicited as part of a participatory decision-making process contribute to a broader and potentially more accurate shared understanding of system dynamics, relevant processes, and feasible management alternatives. There is also increasing recognition that a multiplicity of perspectives exists even among traditional "experts" for a given problem domain, that persistent biases affect how problems and potential solutions are defined and addressed, and therefore that reliance on experts does not necessarily result in an objective evaluation. Participatory processes, on the other hand, explicitly recognize the subjective nature of all information that is brought to the decision-making table and incorporates methodologies (such as multi-criteria analysis and uncertainty evaluations) that allow for explicit examination of these biases.

It is often argued that participatory decision-making will result in "better" resource management policies as a result of stakeholder input. Stakeholders can add a significant amount of information and knowledge to aid in problem structuring and model building, such as their understanding of the processes behind resource degradation, the adequacy of current management practices, and criteria for potential new technologies or policy instruments (Costanza and Ruth, 1998; Johnson *et al.*, 2001; Mendoza and Prabhu, 2005; van den Belt, 2004; Walker *et al.*, 2002). Inclusion of community values at all stages of research design and decision-making assures a focus on what is important to the community, as opposed to adopting scientific research priorities or basing priorities simply on available data (Stroup, 2008).

A second category of arguments often cited for participatory decision-making primarily involves stakeholder perceptions of problems and alternative solutions, and issues of legitimacy. Proponents of the participatory approach argue that this methodology will increase the likelihood that stakeholders will accept policy decisions, because the integrity and credibility of the process underlying their formation and their underlying assumptions are enhanced by stakeholders' direct interactions. Because of the interactive nature of the participatory process, it will ultimately result in an increased level of shared understanding of the nature of problems and possible solutions to management challenges, and can help to build trust between different individuals, groups, and regulatory agencies, helping to ensure collectively and socially desirable outcomes (van den Belt, 2004). This shared level of understanding improves the chances that mutually acceptable solutions may be found that incorporate multiple priorities and trade-offs, and can help to build consensus about which management options would be most effective and appropriate given the social, political, and logistical realities (Costanza and Ruth, 1998; Johnson *et al.*, 2001; Mendoza and Prabhu, 2005; van den Belt, 2004; Walker *et al.*, 2002). Finally, the level of consensus brought about through the participatory process means that implementation costs will be reduced, presumably from reduced litigation and enforcement costs. In addition, a participatory process can shift focus from the search for a single "solution" and its successful implementation to an adaptive management model (Holling, 1978; van den Belt, 2004; Walker *et al.*, 2002).

On the other hand, participatory decision-making for natural resource management has been heavily criticized by some for its procedural, methodological, and legitimacy shortcomings. Rowe and Frewer (2000) develop evaluation criteria for participatory processes based on two categories: methodological limitations that make the process unacceptable to the public, and process limitations that make the outcomes ineffective. Increased stakeholder acceptance of the decision process is one of the fundamental arguments for public participation. However basing an assessment on participation and consensus is effectively built on the idea of finding a shared interpretation of reality that may not exist, and often a lack of emphasis is placed upon the processes required for building shared understanding and shared decision making among diverse stakeholders (Gregory *et al.*, 2006). In addition there are inherent difficulties in bringing scientists, managers, and stakeholders to a common understanding of the issues of scientific uncertainty, confidence and credibility (Walters, 1997). Furthermore, participation is often not entirely representative, and when deciding which stakeholders should be included, it is impossible to ignore existing structures of political power, local power, populism and representation, and to keep these structures from alienating or disenfranchising certain individuals or groups (Robbins, 2004; Ruggeri Laderchi, 2001). Methodological limitations can cause even the most publicly acceptable participatory process to fail in its outcomes, because it has failed to efficiently address the management problems at hand. This argument stems from the recognition that bounded human rationality can create persistent biases and systematic errors of judgment when faced with highly complex decisions (Kahnemann and Tversky, 1974; Simon, 1979).

Apart from ignorance, other factors like beliefs, values, and motivations may influence decision outcomes in a way that undermines the effectiveness of resulting resource management policies (McCallum and Santos, 1997).

Despite the above arguments, participatory methods show promise for the development of context-specific management policies, based upon a local understanding of a system's unique drivers of key ecosystem processes and the socio-economic processes with which they are linked. The challenge for researchers is to ensure a that the process is accessible, transparent, and employs systematic methodologies for stakeholder input so that the researcher's own biases will not have a significant impact on what types of and how information is translated from stakeholder perceptions to project outcomes (Ruggeri Laderchi, 2001).

Complex Adaptive Systems Approach to Decision Support

The great complexity of social-ecological systems makes it difficult to forecast future behavior in a way that is meaningful to management decisions. Key drivers to such systems are unpredictable and change nonlinearly, such as climate and technological advances. Human responses to forecasted information often changes the system in such a way that forecasts subsequently prove to be inaccurate, and during times of transition a system may change faster than the forecasting models can be recalibrated, causing unreliability in predictions when they are most needed (Walker *et al.*, 2002). This means that complex problems arising from intricate linkages in social and biophysical networks often cannot be solved for optimality, because the optimal solution will always be a moving target.

Recognition that the complex nature of water resources planning makes it an exercise in social-ecological management has led to increasing understanding of the need for systemic and participatory approaches. A systems approach addresses resource management from a holistic and transdisciplinary perspective, examining the effects of variable interactions over time. Such an approach does not seek to optimize a single variable or output to define a long-term management strategy, but rather takes into account the various biophysical, economic, legal, environmental, and other factors that impact the availability and use of the resource (Pierce, 2006). This approach would aim to identify and implement proactive strategies for adaptive management with a focus on building resilience in all levels of linked-social ecological systems (Lal *et al.*, 2001).

In recent years, much effort has gone toward the development of new methods to address development planning through a complex adaptive systems approach, methods that integrate quantitative research and modeling tools with qualitative approaches. The qualitative approach is useful because it can make the planning process more participatory and incorporate considerations that may be difficult to quantify, while the quantitative and structured approach enables a more systematic method for generating management alternatives and making decisions (Mendoza and Prabhu, 2005). Planning decision support systems are an example of such a tool that seeks to incorporate both quantitative modeling and qualitative data to aid decision-makers in the integrated evaluation of management and policy impacts on both social and ecological aspects of a system.

In any participatory watershed planning process, conflicts of interest, values, and approaches is inevitable. Decision support systems are increasingly recognized as useful tools to help in the resolution of conflicts involving values, management approaches, and strategies. Decision support system (DSS) is a general term for a computer-based information system that supports decision making by providing information to assist in solving complex problems. In this study, a water quality decision support system is developed that takes the form of an interactive watershed simulation model and multi-criteria analysis. The DSS described here incorporates relevant data and aids in the selection of appropriate management strategies. A DSS is particularly useful in complex, semi-structured or unstructured problems by allowing an interactive dialogue between the user and the dynamic system (Pierce, 2006). The primary goal is to generate and evaluate alternative solutions in order to increase understanding of the problem structure and inherent tradeoffs.

A DSS is commonly composed of data, models, and visualization tools, which are primarily developed to support different phases of the planning and decision making processes (Lal *et al.*, 2001; Sharifi, 2002). Due to the complex nature of water resources planning, decision support systems developed for this purpose are still in their relative infancy. Those that have been developed to address management questions stress the need for inclusion of both hydrologic and socio-economic considerations (Andreu *et al.*, 1996; Pierce, 2006; Reitsma, 1996). They make use of a wide variety of data, often applying analytical and statistical modeling capabilities and multi-criteria analysis to assess alternative development strategies and to suggest methods to mitigate runoff and nonpoint source pollutant increases from land conversion (Costanza and Ruth, 1998;

Voinov *et al.*, 1999; Westphal *et al.*, 2003). Many existing decision support systems, however, still focus primarily on pollution generation, contaminant transport, and BMP assessment (Camara *et al.*, 1990; Lovejoy *et al.*, 1997; Xiang, 1993). Even fewer are those that specifically incorporate both ground- and surface-water processes, related management issues, local and regional stakeholder input into the decision support structure, as is proposed in this study (Facchi *et al.*, 2004; Pierce, 2006).

The primary focus of DSS design should be oriented toward decision makers, making stakeholder input critical throughout its development. The end goal of a DSS is to provide a user-friendly interface, typically relying on graphical displays, that presents decision-makers with targeted information given particular scenarios of land development or other issues of concern to the stakeholder community. Following initial development, the DSS will also serve as a tool to disseminate insights gained by participants to a larger audience (van den Belt, 2004). An ideal DSS will be transparent, easy to use, flexible enough to incorporate different styles of problem solving, and adaptable to new capabilities as required. This often involves trade-offs between the ease of understanding and precision of results, and between efficiency/ease of use and flexibility (Costanza and Ruth, 1998).

In this study we propose a framework for developing a decision support system that embeds the DSS within a larger context of systemic development planning (Figure 3.1). In this model of systemic planning, the sum of current (or proposed) management practices, rules, climatic drivers, and social drivers combine to create scenarios. These scenarios act upon the natural system of interest (the watershed), and the resulting impacts are evaluated based on local objectives for management and decision criteria.

Once the results are evaluated, management decisions may be reformulated to better achieve the specified objectives and criteria. The proposed DSS framework replaces the natural system with a series of analytical models, and includes tools for developing and evaluating scenarios. In this study a participatory modeling approach is employed to develop such a planning decision support system to assist in managing water quality in an urbanizing watershed in the central Texas Hill Country.

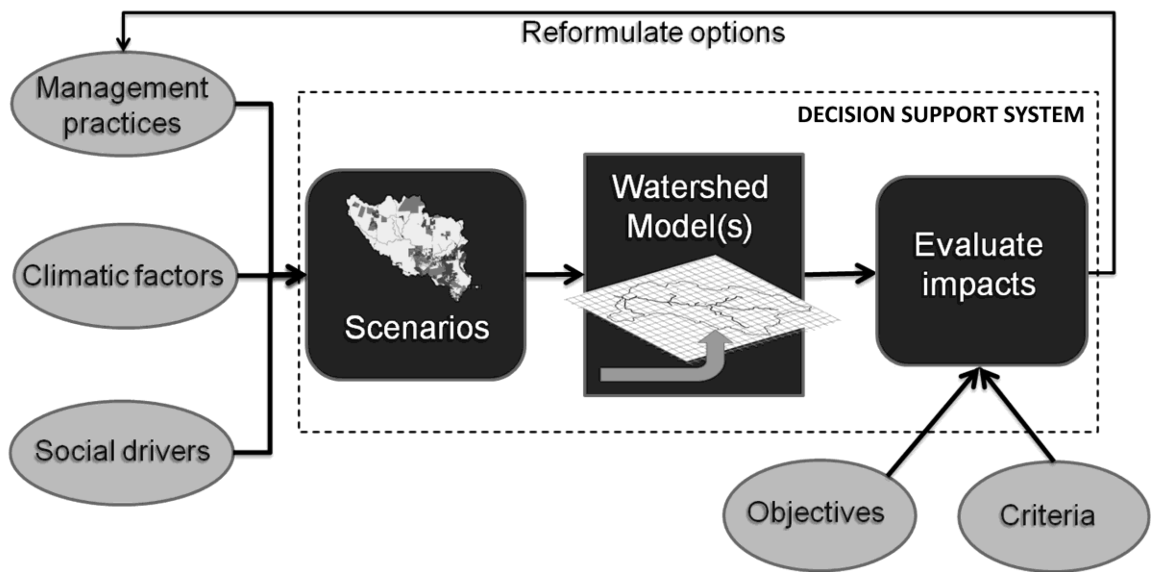

Figure 3.1. Conceptual model of decision support system within the context of systemic development planning.

Participatory Modeling

The recent focus on developing more interactive participatory approaches to resource management and decision support means that a methodology is needed to incorporate adaptive learning, dialogue, and participatory model-building. A form of participatory planning that incorporates quantitative data in the form of dynamic simulation modeling is called mediated, or participatory, modeling. The goal of mediated modeling is a "collaborative team learning experience to raise the shared level of understanding in a group, as well as fostering a broad and deep consensus" (van den Belt, 2004). This approach is in contrast to a more science-driven approach to modeling, where stakeholder input might be ignored or incorporated only in a limited fashion.

Recent trends in participatory modeling have been to facilitate problem structuring and group decision support (Checkland, 1989; Phillips, 1990), stemming from the recognition that bounded human rationality can create persistent biases and systematic errors of judgment when faced with highly complex decisions (Kahnemann and Tversky, 1974; Kahnemann *et al.*, 1982; Simon, 1979). In order to counter these persistent biases, it is very useful to have a situation where one can reduce the lag time between cause and effect. Dynamic simulation modeling is a tool that helps us "close the spatial and temporal gaps between decisions, actions, and results" (Costanza and Ruth, 1998). In order for the model to be integrative and counter the biases of individual researchers or disciplines, the modeling process should be participatory and involve decision makers, resource users, and other stakeholder groups affected by management policies.

Costanza and Ruth (1998) propose a three step modeling process: The first stage is to develop a high-generality, low-resolution scoping and consensus building model. The purpose of this stage is to build consensus among project participants on influential factors and the linkages between them, re-iterate the interrelated nature of "problems" and possible "solutions", and add to researchers' knowledge of important factors that should be considered in DSS development (specific political, economic, or social concerns not included in the initial physiological assessment). Second-stage research models are more detailed and realistic attempts to replicate the dynamics of the particular system of interest. This stage generally involves collecting large amounts of historical data and analyses of areas of uncertainty in both conceptual models and available data inputs. The third stage of modeling focuses on producing scenarios and management options in the context of adaptive feedback and monitoring and is based on the earlier scoping and research models. The results reported here represent the first two stages of the above process as employed in this study. The third stage will occur as the DSS developed herein is used for formulating a watershed management plan and implementing ongoing monitoring and adaptive management.

Participatory modeling is expected to create more realistic and reliable models as a result of vital information provided by stakeholders, understanding of problems and possible solutions will be increased and trust in the model enhanced, and conflicts between competing groups and costs of implementation and enforcement will be reduced (van den Belt, 2004; Walker *et al.*, 2002). In addition, a mediated modeling process helps to shift the focus from the search for a single “solution” and its successful implementation to an adaptive management approach (Holling, 1978; van den Belt, 2004). The participatory DSS development process described here represents a novel approach to developing decision support tools for systemic development planning that incorporates stakeholder knowledge and preferences throughout its design and implementation.

Multi-criteria Analysis

In order to objectively incorporate stakeholder inputs into an analytical decision support model, it is necessary to translate stakeholder preferences into criteria that may be used to evaluate simulated scenarios. Multi-criteria analysis (MCA) is a method of decision analysis that seeks to incorporate multiple conflicting criteria into the management planning process (Hermans and Erickson, 2007; Malczewski, 1999). MCA in general refers to any structured approach used to rank alternatives, where the goal is to accomplish multiple objectives. Desirable objectives are specified and corresponding attributes or indicators are specified (Roy and Vincke, 1981). MCA is useful in a participatory resource management context because a) it is capable of incorporating multiple criteria in the analysis; b) it can accommodate mixed data (both qualitative and quantitative), adding some rigor to what might otherwise be a highly subjective and qualitative decision-making process; c) it allows for direct involvement of multiple experts and interest groups; and d) the analysis is relatively transparent and intuitive for participants (Mendoza and Prabhu, 2005).

In normative (simple A vs B) decision analysis, the optimal choice is often to be found between two or more alternatives, which can be defined as $x_1, x_2, x_3, \ldots, x_n$. Simple optimization would attempt to maximize an objective function and produce a single, optimal value of x (Malczewski, 1999; Roy and Vincke, 1981). An example of this approach would be to set the optimal price of water x, such that the annual net return Z for a water supply company is maximized. All other considerations are second to the primary goals of maximizing Z through manipulating the value of x. Formally, the decision-making problem becomes:

optimize $Z = f(x_1, x_2, ..., x_n)$

where $f(x_1, x_2, ..., x_n)$ is the objective function

Multi-criteria analysis is simply an extension of this simplified illustration, but it incorporates multiple objective functions, or criteria (Hermans and Erickson, 2007; Roy and Vincke, 1981). Thus the problem becomes:

optimize $Z_1 = f_1(x_1, x_2, x_3, ..., x_n)$

optimize $Z_2 = f_2(x_1, x_2, x_3, ..., x_n)$

optimize $Z_k = f_k(x_1, x_2, x_3, ..., x_n)$

where, $Z_1, Z_2, ..., Z_k$ are the different criteria.

The criteria, $Z_1, Z_2, ..., Z_k$, may be ranked to reflect the fact that they may have different levels of importance to the stakeholder community (Hermans and Erickson, 2007; Mendoza and Prabhu, 2005). The incorporation of a multi-criteria analysis package into the DSS framework described here provides a means for resource managers to make sense of the massive amounts of data produced by watershed simulation models, by structuring these results in a way that is meaningful in terms of real-world management objectives and decision criteria.

Methods

Study Area

The Cypress Creek watershed was chosen as a case study to implement the proposed DSS development framework. Because of its natural beauty and proximity to a major transportation corridor (I-35) and rapidly urbanizing population centers such as

Austin (Travis County) and San Antonio (Bexar County), land and water resources in the watershed are under increasing pressure as urban areas expand and land use is converted from low-density ranching to medium- and high-density residential. The Cypress Creek watershed has a total area of 98 km^2, a mean elevation of 350 m, and a mean annual precipitation between 846 mm (Fischer's Store to the west) and 944 mm (Wimberley to the east). This watershed is located in west central Hays County, and is in the Edwards Plateau region of the Texas Hill Country (Figure 3.2). Elevations in the study area range from 247 to 479 m above mean sea level. The topography of the Hill Country varies from hills of predominantly karstic limestone overlain with thin, rocky soils, to plateaus that serve as major recharge zones to the underlying Edwards, Edwards-Trinity, and Trinity Aquifers (Longley, 1986). The hills are characterized by unstable inter-bedded limestone, shale and clays (Riskind and Diamond, 1986). The limestone plateaus are karstic, with the dissolved bedrock providing many conduits for recharge from rainfall events, and resulting in a high degree of interconnectivity between surface- and ground-water to the point where they could be considered one resource (HTGCD, 2010).

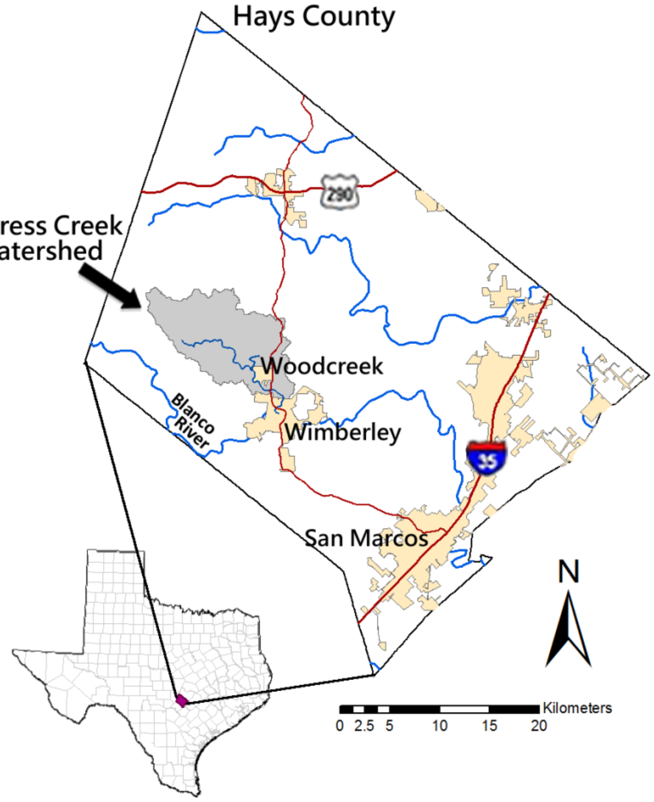

Figure 3.2. Location of study area and nearby urban areas.

Spring fed waterways such as Cypress Creek dissect the hills and normally dry channels provide recharge to the underlying aquifers during storm events. The upper two thirds of the creek are intermittent and flow only during and immediately following rainfall events. Jacob's Well is a natural flowing artesian spring located in the bed of Cypress Creek roughly 16 km upstream of the creek's confluence with the Blanco River, just upstream of Woodcreek. On average, Jacob's Well provides 92% of the flow to the perennial portion of the creek, which runs through downtown Woodcreek and Wimberley and is a major source of inflows to the Blanco River.

Climate in the study area is semi-arid, with relatively mild winters and hot, dry summers. Annual mean precipitation is highly variable from year to year and follows the general pattern of the Hill Country with peak rainfall in the summer and fall.

Temperature is highest from May to October, resulting in fairly predictable summer weather patterns. The period of July through September is often both hot and dry, with average daily temperatures above 26.7 ^{o}C and little rainfall. Evapotranspiration accounts for as much as 90% of the water budget (Ockerman, 2005).

Soils in the watershed are predominantly shallow clay loams and shallow clays such as the Brackett-Rock outcrop-Comfort complex (41.5%) and the Brackett-Rock outcrop-Real complex (15.3%) on the uplands; and shallow stony clays such as the Comfort-Rock outcrop complex (17.9%) and the Real-Comfort-Doss complex (5.6%) on hill slopes. The remaining 20% of the watershed is a mix of deep clay and clay loam uplands and hydric loamy bottomland soils along creek beds in the lower portion of the watershed (NRCS, 2008).

The hydrology and hydrogeology of the Cypress Creek watershed are shaped by the karstic limestone character of its underlying geology. Other than a few small domestic rainwater collection systems, the area is entirely dependent on groundwater for its potable water supply. Baseflow to Jacob's Well is primarily from groundwater under artesian conditions in the Cow Creek formation. However the flow from the spring also varies significantly with major precipitation patterns. According to USGS spring flow data beginning in 2005, artesian flow maintains an average discharge of 0.08 to 0.20 $m^3 s^{-1}$, but during major precipitation events peak discharge has been measured at over 1.7 $m^3 s^{-1}$. This indicates either a local pressure surge in the Cow Creek, or direct recharge from open karst features seen locally in the Lower Glen Rose.

Aquifers underlying the study area include the Middle and Lower Trinity. The Middle Trinity consists of the Lower Glen Rose, Hensel, and Cow Creek formations. Where the Lower Glen Rose layer is exposed, it is often faulted and fractured and contains surficial karst features that allow for rapid recharge from precipitation events. The Cow Creek formation acts as a confined aquifer which recharges to the north and west of the watershed, while the Lower Glen Rose responds rapidly to precipitation events within the watershed and acts as an unconfined aquifer. The Lower Trinity consists of the Sligo and Hosston formations, which is recharged through diffuse percolation through the confining layers above, and does not crop out within the study area. Also important to the hydrogeology of the study area are the multiple faults trending northeast-southwest throughout the region. Jacob's Well spring occurs along one of these faults (Tom Creek Fault Zone), which restricts subsurface flow in the Cow Creek formation and redirects it to discharge at the surface.

Vegetation on the hilltops is often sparse because of thin layers of topsoil. In the northern portion of the study area, shallow or disturbed soils support evergreen shrubs and grasses. Woodlands of juniper, oak and mesquite are interspersed along the landscape with native grasses where slopes are lower. The plateau-like uplands throughout this area support woody species such as Ashe Juniper (*Juniperus ashei*), Texas Oak (*Quercus buckleyi*), and Lacey Oak (*Quercus laceyi*) along with grasses. In the lower portion of the watershed along the floodplain and stream course of Cypress Creek, deciduous stands of Bald Cypress (*Taxodium distichum)*, Sycamore (*Platanus occidentalis*), and Black Willow (*Salix nigra*) exist (Riskind and Diamond, 1986). Commonly found grasses include Little bluestem (*Schizachyrium scoparium*), Curly mesquite (*Hilaria belangeri*), Texas wintergrass (*Stipa leucotricha*), White tridens (*Tridens muticus*), Texas cupgrass (*Eriochloa sericea*), Tall dropseed (*Sporobolus asper*), Seep muhly (*Muhlenbergia reverchonii*), Hairy grama (*Bouteloua hirsuta*), and Side oats grama (*Bouteloua curtipendula*) (Riskind and Diamond, 1986).

Land use in the Cypress Creek watershed is predominantly Rangeland (73.9 km^2; 75%), followed by Residential (10.8 km^2; 11%), Open/Undeveloped (9.1 km^2; 9%), and Transportation (3.2 km^2; 3%). Commercial land uses are concentrated in and around downtown Wimberley and Woodcreek, and comprise only 1.1% of the total watershed area (1.0 km^2). Population increases in the past two decades, have resulted in a shift from predominantly ranching to residential land uses, as formerly large acreage holdings are subdivided for both high-density residential (<2 ha) and large lot “ranchettes” (>2 ha). Although the combined residential, commercial, and transportation uses account for only 16% of total area, much of this percentage is impervious surface cover, and is concentrated at the southern and eastern portions of the watershed. Higher-density development is coincident with the perennial creek, making this area both the most valuable in terms of ecosystem services as well as the most vulnerable to anthropogenic impacts.

Stakeholders have become increasingly concerned as the impacts of development are beginning to be seen in the creek and the aquifer. Karst springs such as Jacob’s Well provide excellent indicators of the health of local groundwater resources. Well pump tests have proven that nearby public water supply wells, which pump water from karst conduits in the Cow Creek formation, directly influence discharge from Jacob’s Well (HTGCD, 2008). Flows from Jacob’s Well were significantly reduced during the droughts of 2005–2006 and 2008. The Cypress Creek was placed on the 303(d) list for impaired water bodies in 2000 due to low dissolved oxygen concentrations. This impairment coincided with the first time in recorded history that flow at Jacob's Well Spring was reduced to zero. Under drought conditions, spring flow again dropped to zero in 2008.

Ambient water quality data show that the Cypress Creek, as a whole, remains in adequate condition when assessments are based on state water quality standards. However stakeholders and experts have agreed that meeting state water quality standards would be insufficient to maintain the desired health and historical nature of the creek as a spring-run stream. Impervious cover in the watershed was estimated at 6% in 1996. By 2005, total impervious cover increased to 9%. A recent study showed that healthy watershed functions are impacted at impervious cover rates as low as 10% (Cuffney *et al.*, 2010). A recent economic assessment conducted by business and landowner stakeholders showed that decreased water quality and quantity will not only negatively impact the creek but also land and business values, thus creating a concern among local residents and stakeholders that historic water quantity and quality be maintained (RSI, 2010).

Decision Support System Development

The hydrogeologic setting in the study area results in a very strong connection between surface and groundwater, to the point where they could be considered a single resource (HTGCD, 2010). Surface streams rely on baseflow from springs and seeps, yet normally dry stream channels often provide recharge to underlying aquifers during precipitation events. Addressing this interconnectedness is of primary importance in developing a decision support system for development planning. Because water quality impacts from development in the watershed will be mediated by flow in the creek, it is important to address the Cypress Creek watershed from multiple scales. Regionally, aquifer levels in the Middle Trinity are impacted by climate and development patterns that influence recharge and pumping rates in areas surrounding the watershed. Since Hays County as a whole relies on groundwater for 63% of public supplies (USGS, 2006), management for water availability must be addressed on this regional scale. Within the watershed, development and land use patterns coupled with local topography impact where and what types of pollutants are generated and how they are transported into the creek. Therefore management for stormflow pollution and water quality impacts of development must occur at the watershed scale. Finally, variability at the sub-watershed level means that some areas may be more vulnerable to impacts on water quality or recharge rates, and therefore management efforts may be more effective in some areas over others.

A spatially-explicit hydrologic model within a GIS framework addresses the need to assess and visualize these multiple scales of concern. In addition, employing a participatory process for decision support system development insures that the resulting product will directly address issues of concern and provide results pertinent to local decision-makers, and will incorporate realistic assumptions and options into scenarios of future development. The approach taken in this study is to develop, through a participatory process, a decision support system that enables stakeholders and decision-makers to evaluate the impacts of management policies in and around the Cypress Creek watershed. The Cypress Creek Project Decision Support System (CCP-DSS) consists of two watershed runoff and erosion models coupled with a GIS interface to aid in parameterizing and generating model input files, developing land use and development scenarios, and visualizing spatial results. The CCP-DSS also includes a multi-criteria analysis package to evaluate scenario outcomes using model outputs and user-defined criteria. The participatory process employed in development of the CCP-DSS implies that the resulting application will be useful to stakeholders and decision makers, that it will be understood and accepted, and that it will be superior to models developed with a disciplinary focus (Costanza and Ruth, 1998; Johnson *et al.*, 2001; Mendoza and Prabhu, 2005; van den Belt, 2004; Walker *et al.*, 2002).

Participatory Modeling Process

Participatory modeling for development of the CCP-DSS took place within the broader context of a community initiative for watershed planning, the Cypress Creek Project (CCP). The Cypress Creek Project is an initiative of the Texas State University River Systems Institute and a coalition of local stakeholders, and is coordinated with technical and research assistance through grants from the Texas Commission on Environmental Quality (TCEQ) and the US Environmental Protection Agency (EPA). The main goal for this project is to ensure that the long-term integrity and sustainability of the Cypress Creek watershed is preserved and that water quality standards are maintained for present and future inhabitants (both human and wildlife). The project aims to keep Cypress Creek clean, clear, and flowing. Objectives of the CCP include watershed characterization, delineation, developing a stakeholder input process, partnership development, and education/outreach. The overriding purpose of the CCP is the creation of a Watershed Protection Plan (WPP) as well as the production of science-based information and tools to empower stakeholders to develop such a plan.

As part of this project, the Cypress Creek Watershed Committee was formed in 2009 consisting of local regulatory, municipal, conservation, landowner, scientific, and development interests. Several subcommittees were formed to address various aspects of watershed planning (water quality, economics, land stewardship, etc.) and one such subcommittee was recruited specifically to participate in DSS development. Members for the subcommittee were recruited in the initial Watershed Committee meetings, with additional members recruited to fill gaps in representation and expertise as identified by the subcommittee. The DSS subcommittee consisted of eleven members representing:

- Hays-Trinity Groundwater Conservation District (groundwater management authority)
- Wimberley Valley Watershed Association (conservation and resource advocates)
- Guadalupe-Blanco River Authority (surface water management authority)
- Texas Parks and Wildlife Department (biological and habitat conservation for public use)
- Texas Stream Team, Texas State University-San Marcos River Systems Institute (citizen science and water quality monitoring)
- Texas State Soil and Water Conservation Board (agricultural extension, rangeland management)
- Texas Commission on Environmental Quality (water permitting and water quality management authority)

- City of Woodcreek (municipal city council)
- Developers
- Local landowners

The participatory modeling process used in this study was adapted from the first two stages of mediated modeling suggested by Costanza and Ruth (1998). The process consisted of a series of workshops over the course of one year to guide stakeholders through conceptualizing the watershed system, identifying priority issues, inputs and outputs, developing land use scenarios, and generating evaluation criteria by which to compare outcomes. The first stage involved developing a high-generality, low-resolution scoping and consensus building model. The purpose of this exercise was to build consensus among project participants on influential factors and the linkages between them, re-iterate the interrelated nature of “problems” and possible “solutions”, and add to researchers’ knowledge of important factors that should be considered in DSS development (specific political, economic, or social concerns not included in the initial physiological assessment). The scoping phase included activities to address conceptual models of watershed functioning to ensure that DSS assumptions, inputs and outputs are relevant to local issues, developing goals for how the DSS would be used, and to help researchers select an appropriate watershed modeling approach to address these issues. The stakeholder group was also asked to define its own scope and goals for its participation in the DSS development process.

Phase two of the participatory modeling process involved more detailed and realistic attempts to replicate the dynamics of the study area using watershed simulation models. This stage involved collecting large amounts of historical data and articulating areas of uncertainty in both conceptual models and available data inputs. Stakeholder participation in phase two involved reviewing the proposed watershed modeling and DSS framework, providing input on the utility of various analytical capabilities and structuring output to be most useful and pertinent for development planning. In addition, stakeholders were led through a scenario development exercise that identified best- and worst-case scenarios for the watershed's future to provide a jumping-off point for the scenario evaluation process.

The third stage of participatory modeling suggested by Costanza and Ruth (1998) focuses on producing scenarios and management options in the context of adaptive feedback and monitoring and is based on earlier scoping and research models. This phase will occur as the CCP-DSS is adopted and used in ongoing watershed planning.

A series of meetings were held with project participants from September 2009 through June 2010. The goal of these meetings was to guide the stakeholder group through the above participatory modeling process with the following goals: 1) input on DSS content, objectives, inputs and outputs; 2) input on DSS analytical capabilities, parameters of concern and criteria; 3) scenario development; 4) input on DSS user interface for results visualization; 5) training to use the DSS to evaluate scenarios.

Decision Support System Framework

A primary goal for the CCP-DSS is to evaluate impacts of different types of development scenarios on water quantity (flow, storm peaks) and nonpoint source pollutant loadings to the creek. A key issue with producing a model for evaluating these types of impacts in the Cypress Creek watershed is to determine how these variables can be adequately simulated given the interdependence of (regional) groundwater processes and (local) surface runoff and pollution processes. In addition, the DSS must be easily updateable as new information becomes available and as land use continues to change.

Building such a watershed simulation model from scratch was determined to be outside the scope and technical capacity of the project and the stakeholder group involved. Such an undertaking would be time- and cost-prohibitive for many (if not most) community-based watershed management initiatives. The overall goal in model selection and development was to incorporate an intermediate level of complexity, to allow for an adequate level of predictive ability without sacrificing too much accuracy lost through compounding errors (Costanza and Maxwell, 1993). Therefore the decision support system framework utilized here was structured to take advantage of existing and well-vetted models and decision support applications that meet specific needs, with a focus on linking inputs, outputs and functionality between them to create a seamless flow-through from scenario definition, model parameterization, hydrologic simulation, and evaluation of results. This allowed for inclusion of a higher level of technical functionality while still preserving the spirit of participatory development as the various DSS components were chosen and customized to meet specific needs, as identified in stakeholder workshops. An open-source data model was incorporated to allow for continuing improvements to both data and functionality as new needs are identified.

As mentioned above, a major modeling consideration is how best to incorporate both surface hydrologic processes with the impacts of changing aquifer levels and spring flow. As nonpoint source pollution and watershed-scale impacts of development were identified as the primary goals for DSS use, watershed models that simulate surface flow but allow for point source inputs of spring flow were considered for inclusion in the CCP-DSS. A spatially-distributed modeling structure was also required to meet the goal of evaluating both the magnitude and distribution of impacts from development at different intensities and locations.

Of central concern to water quantity and quality in the Cypress Creek are the processes of runoff generation, percolation, subsurface flow, evapotranspiration, nutrient and contaminant entrainment and transport, sediment entrainment and transport, channel flow, and spring flow. Spring flow and recharge in the watershed are the primary direct linkages between the ground- and surface-water systems. Of particular interest to managers and stakeholders in the area are changes associated with increasing development and groundwater pumping on peak flows during large storm events, pollutant and sediment concentrations during low flows, and overall changes in flow levels as a result of a potentially permanent drop in Jacob's Well flow volumes.

The issues facing the Cypress Creek watershed are similar to those facing many rapidly urbanizing areas. Development planning and assessment involving land and water resources management are evolving from simple, local-scale problems to complex, regional ones with a need for spatially-explicit evaluation of drivers and impacts. Such problems can be addressed with distributed models that can compute runoff, erosion, and nonpoint source pollution generation at different spatial and temporal scales. The extensive data requirements for such models and the high degree of technical expertise required to create input and parameter files present serious obstacles to the timely and cost-effective use of such complex models by decision makers. The U.S. EPA Office of Research Development and the US Department of Agriculture-Agriculture Research

Service (USDA-ARS) Southwest Watershed Research Center developed the Automated Geospatial Watershed Assessment (AGWA2) tool to facilitate this process (Miller *et al.*, 2007). AGWA2 uses publicly available standardized spatial datasets to develop input parameter files and display results from two watershed runoff and erosion models within a geographic information system (GIS) framework. AGWA2 includes both an event-based hydrologic model (KINEROS2) and a continuous simulation model (SWAT2000).

AGWA2 was developed under the following guidelines:

- Provide simple, direct, and repeatable method for hydrologic model parameterization
- Use only basic, obtainable GIS data
- Be compatible with other geospatial watershed-based environmental analysis software
- Be useful for scenario and alternative futures simulation work at multiple scales

The decision support system for the Cypress Creek watershed (CCP-DSS) is based on the AGWA2 software package and the hydrologic simulation models included there. The CCP-DSS consists of a database management system to integrate available data, a set of integrated hydrologic and water quality simulation models, and a user interface that allows for the analysis of potential management scenarios. Although the AGWA2 package is capable of parameterizing and building input files for several watershed models, the SWAT2000 and KINEROS2 models were chosen to for the CCP-DSS based on their robustness and data requirements for the desired applications. SWAT (version 2000) is a physically-based model developed by the USDA-ARS to simulate continuous-time landscape processes and streamflow with a high level of spatial detail

(Neitsch *et al.*, 2002). SWAT has been used to evaluate the impacts of land use change on watershed hydrology and nonpoint source pollution loadings in watersheds throughout the world, including several examples in Texas (Afinowicz *et al.*, 2005; Green *et al.*, 2007; Santhi *et al.*, 2006). KINEROS2 is another physically-based model, but simulates watershed response on an event basis. This model simulates the processes of interception, infiltration, surface runoff and erosion from small agricultural and urban watersheds (Semmens *et al.*, 2008; Woolhiser *et al.*, 1990). These two models allow for examination of hydrologic and NPS impacts of changing land use at both storm-event and long-term scales.

In addition to relevant hydrologic simulation models, development of the CCP-DSS also involved selection of appropriate data to include that will assist users in developing scenarios and running hydrologic models. Publicly available GIS data was utilized wherever possible, but in some cases these data were updated to reflect local conditions to the greatest extent possible. Data were selected for inclusion in the DSS database based on a) GIS data required for model parameterization (topography, soils, land cover); b) required inputs for hydrologic simulation modeling (climate, springflow); c) data to evaluate model outputs relative to actual conditions (observed stream flow and water quality data); and, d) data relevant to generating and interpreting scenarios (road networks, land uses, infrastructure, planning data, etc.).

The final component of the CCP-DSS is a multi-criteria analysis module that incorporates stakeholder-identified criteria and priorities to produce ranking scores for different management options that represent shared visions of possible futures for watershed development. The MCA component of the CCP-DSS utilized the open-source

Facilitator program developed by the USDA-ARS Southwest Watershed Research Center (Heilman *et al.*, 2002). Multi-criteria analysis for environmental management has matured to a point where multiple software implementations exist to address different types of structured problems. The Facilitator is a generic, multi-objective decision making tool that can utilize information from a variety of sources to build an effects matrix that quantifies the impacts of user-specified options on each decision criterion (Heilman *et al.*, 2002). It incorporates the hierarchy tree approach to evaluating decision criteria developed by Yakowitz and Weltz (1998). This approach eliminates the need for users to specify rankings, a common problem with earlier MCA applications. Instead, users rank criteria in order of their subjective importance and the embedded algorithms assign all possible weighting combinations to produce a ranking of alternatives (Heilman *et al.*, 2002). In the CCP-DSS, results from watershed simulations can be imported into the MCA evaluation module where users can choose criteria to include, add additional criteria if desired, rank their chosen criteria, and run analyses to evaluate the outcomes.

Results

Participatory Modeling

Input from the stakeholder committee included information on the following:

1) conceptual models of critical factors and interactions;
2) political, economic, and social concerns of importance (development rules and practices, assumptions);
3) objectives for how the DSS will be utilized;
4) target user groups;

5) additional model inputs and outputs desired for decision support;
6) analytical capabilities and user interface design;
7) areas of particular vulnerability in the watershed based on local knowledge and experience;
8) appropriate policies and/or best management practices (for scenario development);
9) goals for watershed management and criteria to evaluate scenarios relative to goals; and,
10) how outputs should be structured so as to be most useful to decision makers.

The stakeholder committee was asked to assist in defining the committee's scope and focus relative to the DSS development. Goals articulated by members of the committee included:

- Determine issues/problems that model will address
- Determine what happens to the DSS at the end of the process
- Legitimize the data used in the model
- Validate the DSS development process and the model(s) used
- Incorporate economic impacts
- Determine parameters and criteria to use for evaluation
- Provide technical input to the general Watershed Committee

These stakeholder-defined goals address many of the issues relevant to stakeholder participation described above, such as the ability to include community values at all stages of research design and decision-making, legitimizing the DSS and thus increasing buy-in to the credibility and integrity of the results presented.

Goals for how the CCP-DSS would be utilized and target user groups were also discussed, to ensure that the tools provided would perform the functions desired by the ultimate end-users. Goals for DSS use included: determining what actions are needed to maintain the Cypress Creek within water quality standards; evaluating the impacts of potential new rules or recommendations from the WPP development process; evaluating the cost versus benefit of BMPs (cost per load reduction attained); and prioritizing different types and locations of BMPs. In addition, state regulatory interests expressed a desire that the CCP-DSS focus on providing a scientific basis for WPP recommendations, specifically those relating to elements A, B, and C: identification of the causes of nonpoint source pollution, management measures to reduce nonpoint source pollution loading, and estimation of load reductions expected to result from these measures.

Potential end-users initially identified included city governments, county governments, developer interests, businesses, landowners, and the groundwater conservation district. Through subsequent discussions, it became apparent that there would ultimately be a distinction drawn between end-users of the DSS program itself and end-users of the information generated from it. In addition it was necessary to identify a location and organization to house the DSS and the source code, both to ensure version control and to ensure that users are aware of the technical expertise and training required to use the DSS appropriately and reliably. The River Systems Institute (RSI), an institution providing the primary financial and technical support to the project, was designated as the keeper of the CCP-DSS. Stakeholders expressed a desire that the organization housing the tool have diverse representation, indicating a commitment to continuing broad participation in its refinement and use. The Cypress Creek Watershed Committee was recommended to perform this role in cooperation with RSI.

Criteria for scenario evaluation were discussed relative to the management goal for the watershed area (keep the Cypress Creek "clean, clear and flowing"), and in many cases criteria directly corresponded to model outputs (flow regime, erosion and sediment transport, nutrient loading). Maintaining the excellent historical water quality of the stream provides a target for management and the CCP-DSS was designed to automate the incorporation of these criteria into the MCA module based on input received from the stakeholder committee. Implementation cost and economic impacts are also of great interest but are not directly estimated by the simulation models, requiring an alternative approach for integrating these into the evaluation framework.

Once the modeling approach based on AGWA2 was chosen, the basic capabilities of that system and the watershed simulation models (SWAT and KINEROS2) were demonstrated to the stakeholder committee. The assumptions of the models, input types and resolution were presented, along with the concept of hydrologic response units, which are areas defined by topography and flow and that are assumed by the model to have similar properties (lumped parameters). This ensures that stakeholders understand conceptually how the watershed models work, the type of information that they are based on, and the quality of data available.

Following the initial series of meetings, an email survey was taken to gather input on likely future scenarios. The survey was structured as a series of open-ended questions regarding the best and worst possible futures for the watershed 10 and 25 years in the future. These responses were used to bound the set of alternative futures envisioned.

Following the initial survey, a series of maps and three alternative futures were developed based on input from the DSS committee, best available data on land uses, subdivision and parcel boundaries, transportation networks and planning, and considering the types of changes that can be analyzed using the CCP-DSS tools. Stakeholders were again asked to comment on the proposed scenarios relative to their representativeness of probable futures based on current conditions and priorities. These alternative futures took the form of a) unrestricted development, where the watershed is fully built out using existing regulations and high-intensity commercial and industrial development exists along major roadways; b) middle ground, where restrictions to growth and structural BMPs are placed in key areas and commercial development is reduced; and c) conservation development, where restrictions on impervious surface cover are imposed, BMPs are utilized and some existing open spaces are maintained. These patterns of development were determined irrespective of how water would be supplied to the new homes & businesses (surface- or ground-water, domestic or centralized supplies). The purpose of the scenario exercise is to show the potential impacts that development patterns could have on flow peaks during storm events, and the annual pollutant loading to the creek that could result if appropriate mitigation measures are not taken. In addition to surface pollution loading, stakeholders also wished to examine the impact that various levels of groundwater input to the creek will have on water quality under the various scenarios. These alternative futures and the results from the simulation models are used to demonstrate the functionality of the CCP-DSS to the Watershed Committee who will determine the next steps to be taken using the tool to develop the WPP. In addition, the Education and Outreach committee are developing strategies to use the results from these scenarios to educate the broader community about the consequences of development planning decisions.

Training workshops were held with the DSS committee in July 2010 to review modeling assumptions, data necessary to develop scenarios and run hydrologic models, and the CCP-DSS interface. The final activity was training stakeholders on visualizing and evaluating results from scenarios generated during the training. It was decided to follow a "train the trainers" model, so that the first round of training is intended to cement the knowledge of how to use the CCP-DSS with a few key people who can carry the knowledge forward and help to train others (RSI staff, Watershed Committee members).

Cypress Creek Decision Support System

The resulting CCP-DSS includes the existing software applications described above: AGWA2, which provides the hydrologic simulation, parameterization and visualization tools; SWAT, a continuous-simulation hydrology and water quality model; KINEROS2, an event-based runoff and erosion model; and Facilitator, a scenario evaluation module. In addition the application is packaged with data necessary to create scenarios, run simulations, evaluate and interpret results. Primary customization of components within the CCP-DSS involved putting together a package and associated database that will install and run as a single application extension to ESRI's ArcGIS 9.3.1. The DSS components utilize several different programming languages and structures (Fortran, Visual Basic, and Java). The CCP-DSS application was created by modifying the AGWA2 code in Microsoft Visual Basic to pass information between and call the various components as needed. The resulting structure and relationship between components are given in Figure 3.3. The CCP-DSS acts as a point-of-entry for users to store data and manage the component applications. The interface utilizes ArcGIS functions to calculate model inputs and prepare simulation input files. It interfaces directly with the SWAT and KINEROS models to run simulations, retrieve results and display model outputs spatially. Simulation outputs are exported to the Scenario Evaluator module for multi-criteria analysis.

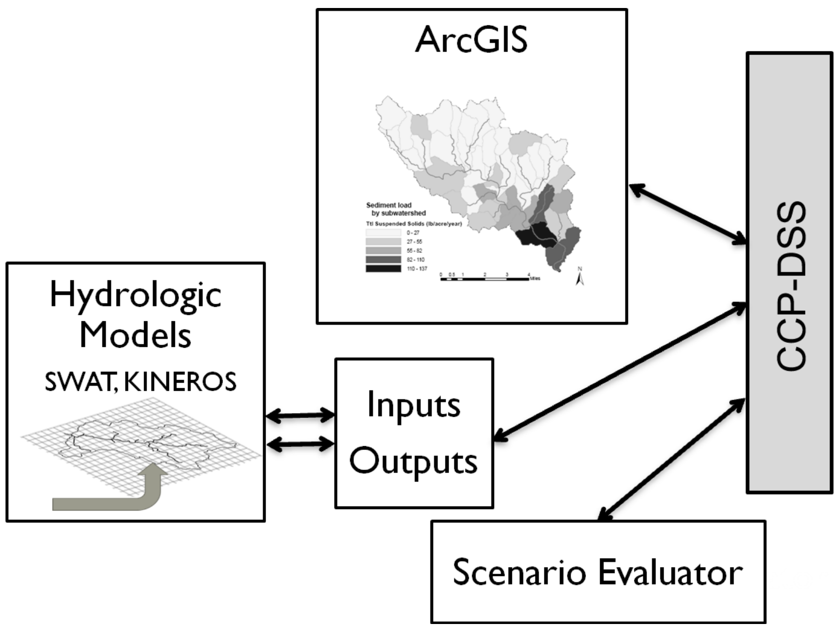

Figure 3.3. Schematic of CCP-DSS components and interactions. The CCP-DSS provides an interface that utilizes GIS functions to calculate model inputs, write input files, and display model outputs. Model outputs are passed to the Scenario Evaluator module for multi-criteria analysis.

The AGWA2 system provides the basic functionality for watershed delineation, model parameterization, writing model input files, running models, and visualizing the results spatially (Table 3.1). Additional functions were added based on input from the participatory modeling process. One such addition is the ability for users to view the time series of model results for user-selected elements, expanding the results visualization beyond spatial patterns to temporal ones as well. Viewing these time series relative to a target or an optimal range of values assists decision makers in visualizing model outputs relative to water quality standards or other criteria.

Table 3.1. AGWA2 system base functionality.

Type	Function	Inputs needed	Outputs
Watershed	- Delineate - Break into sub-watersheds (response units) - Create channel network	- Topography - Rating curves (if ponds are used)	- Response units - Channel network
Parameterization & Calibration	- Parameterize response units - Parameterize channels - Parameter multipliers - Climate multipliers	- Response units - Channel network - Soils - Land cover - Observed stream flow - Observed sediment, N, P	- Parameter input files - Climate input files
Simulation	- Run simulations	- Parameter files - Precipitation - Temperature - Groundwater inputs	- Infiltration (S,K)* - Stream flow S – daily, monthly, annually K – minute - Peak flow (K) - Sediment yield (S,K) - Evapotranspiration (S) - Nitrogen (S) - Phosphorous (S)
Scenario generation	- Land cover modification tool (manual, random, or fractal clustering) - Parameterize response units and channels - Climate multipliers		- Modified land cover - Modified parameter Files - Modified climate inputs
Visualization	- View simulation results - Differences between simulations	- Simulation outputs	- Watershed map showing outputs, difference, or % difference for each response unit/segment

* S = SWAT model; K = KINEROS2 model

A key issue derived from the participatory modeling process was the need to address the impacts of groundwater (base flow) scenarios on water quality. To address this need, the CCP-DSS was designed to easily allow users to alter the time series spring flow inputs at Jacob’s Well (the primary source of base flow to the creek). Also added was the ability for users to access tabular summary results from watershed simulations from within the DSS environment. Simulation model outputs can be exported to the MCA module as criteria for scenario evaluation. Once there, users can create custom matrices of multiple scenario results, add additional criteria or outcomes for each scenario (such as implementation cost, economic impacts, estimated bacterial loading, etc.), and evaluate the outcomes. Users can therefore examine additional criteria identified as important in the participatory modeling process, but that may not be feasible to simulate with the available watershed models. This also allows for inclusion of both quantitative and qualitative data in the decision matrix, as well as more subjective criteria (such as quality of life indices) for different scenarios.

The database packaged with the CCP-DSS system includes all the topographic, soils, land cover, and climate data necessary to run the SWAT2000 and KINEROS2 watershed models and evaluate results (Table 3.2). The nature of the interface allows for continuous updates of data. Users can use data from any source provided that it conforms to the format and specifications used in the watershed models. Also included are some additional data to assist users in visualizing the watershed, creating scenarios, and interpreting results. The selection of model-required data was based on the best available sources, whereas the selection of additional interpretive data was driven primarily by input from the participatory modeling process.

Table 3.2. Data included in CCP-DSS database.

	Data type	Description (source)
Data required to run hydrologic simulation models (SWAT2000 and KINEROS2)	Topography	10m resolution DEM from USGS. Sinks were filled using the DSS tools (USGS, 2009)
	Flow direction and flow accumulation grids	Created from 10m DEM using DSS tools
	Soils	SSURGO soils data for Hays County (NRCS, 2008)
	Climate	NCDC and LCRA rain gauge locations and daily data CCP rain gauge locations and storm event data Weather generator file with statistics for Cypress Creek area
	Land cover	2001 land cover (MRLC, 2001) 2009 land cover (RSI, 2010)
	Spring flow inputs	Daily mean spring flow at Jacob's Well
	Stream flow	Estimated daily mean stream flow at watershed outlet Observed stream flow for storm events
	Water quality	Observed water quality data (sediment and nutrient concentrations) for storm events (CCP) Observed ambient water quality monitoring data (nitrate-nitrogen, total phosphorous, TSS, *E. coli*, temperature; TCEQ, 2010)
Data to assist users in visualizing, creating scenarios and interpreting results	Aerial photos 2004, 2008	
	City boundaries and extra-territorial jurisdictions	
	Road networks (Hays County)	
	Subdivision boundaries	
	Parcels geodatabase (information on parcel boundaries, land use designations and tax appraisal values)	
	Water quality monitoring site locations	
	Land cover layers for example scenarios: stream buffers, mixed intermediate development, full development of selected subdivisions, etc.	
	Spring flow inputs at average, reduced, and increased levels	
	Example pond and reservoir files	

Discussion

The CCP-DSS consists of a database management system to integrate available data, a set of integrated hydrologic and water quality simulation models, and a user interface that allows for the analysis of potential management scenarios. The CCP-DSS is based on the AGWA2 software package developed by USDA-ARS and US EPA. In addition, it incorporates a scenario evaluation tool, Facilitator, also developed by USDA-ARS Southwest Watershed Research Center, and is populated with all the relevant GIS, climate, and hydrologic data in an associated database. The CCP-DSS package and associated database installs and runs as a single application extension to ESRI's ArcGIS 9.3.1.

The CCP-DSS was developed to assist decision makers and stakeholders to understand the processes that support a healthy creek and watershed, to evaluate the impacts of development on water quantity and quality in the creek, to encourage consensus regarding sensitive areas and appropriate ordinances, BMPs, or other management strategies, and to assist in development of a Watershed Protection Plan. A commonly articulated goal for the CCP-DSS was to provide a system that is user-friendly, and distills many variables down to an easily understood outcome. After a point, there was a conflict between the expectation that a model could be both scientifically defensible, reasonably accurate, and yet simple enough that anyone could use. The attainment of all three of these criteria is not a reasonable goal, given the great emphasis placed on accuracy of the underlying models for producing flow and pollutant loading estimates.

Because of these limitations, the level of engagement of any given stakeholder with the CCP-DSS will vary depending on the person's level of knowledge and interest. At the most general level, the CCP-DSS allows for the production of spatially-explicit maps that demonstrate future land use scenarios and the magnitude and distribution of resulting impacts across the watershed area. These provide decision support tools for display at public meetings, educational forums, and to help build consensus about future watershed management. At a regulatory or watershed planning level, managers will be interested in more specific outputs of model runs as the CCP-DSS is used to analyze different scenarios. Production of high-quality model inputs and continuing model calibration for specific areas will require more specialized expertise such as engineers, planners, and hydrologists.

Decisions about watershed management are very complex and must take into account many different variables, assumptions, and priorities. The purpose of decision support is to distill this complexity down into a form that provides targeted and useful information to help in this process. However one single decision support tool cannot address every consideration identified as important by stakeholders. Throughout the participatory process there were ongoing discussions about the trade-offs necessary to provide a useful tool that is both reasonably accurate and targeted to specific questions, yet is also broad enough for general application and use. In the end, some issues of concern to stakeholders were not addressed directly by the hydrologic simulation models. The CCP-DSS is capable of evaluating potential flow and water quality impacts of:

- Development intensity (i.e. % impervious cover) and location within the watershed

- Prioritizing areas to set aside for conservation and/or education efforts
- Detention ponds, location and size
- Rainwater harvesting impacts on peak flows and pollutant loading to creek for a given storm event
- Riparian/stream buffers
- Reduction in spring flow at Jacob's Well

However the CCP-DSS is not capable of evaluating the impacts of:

- Well spacing rules and the resulting impacts on groundwater levels and spring flow at Jacob's Well
- Septic system (OSSF) failures, or other underground pollution sources such as petroleum storage tanks
- Site-specific development practices
- Site-specific ranching practices, stocking densities, etc.

In general, issues regarding the location and density of development can be addressed with CCP DSS. This includes combinations of conservation areas, open space protection, and impacts of different development intensities. It can also be used to identify areas that are most sensitive to development impacts and that may require additional protections.

The participatory modeling approach to DSS development presented here ensures that there will be a high degree of buy-in from the stakeholder community, and increases the likelihood that the tool will be adopted and the results given weight in future decision-making. However most participants agreed that while bringing science-based tools to the process helps everyone have a common knowledge base to work from, the actual outcomes of management decisions are regularly subject to compromise and political maneuvering that may override the benefits of knowledge gained from the DSS. Still, most agree that science-based evaluation of potential development impacts and the translation of these results into easily-understood pictures is a preferable approach to purely anecdotal or opinion-based decisions and also to scientific information that is inaccessible to most audiences.

Every effort was made during the participatory modeling process to solicit input from a wide range of interests and expertise. The stakeholders who chose to become involved in the DSS development process tended to be highly educated, knowledgeable about technical and political issues critical to decision support, and highly engaged with the process. However this group was self-selected, and ultimately represented primarily regulatory, conservation, and local development interests. The perspectives of individual small land owners or the less-educated general public may not have been well-represented. The framework of the CCP-DSS and the process by which it was developed ensures that as additional viewpoints and information is obtained and local needs evolve, the application may be updated and altered to incorporate additional functionality and evaluation criteria.

The need for systemic approaches to water resources planning in central Texas is clear, given the complex nature of the problem. To date, little work has been done attempting to link the multiple scales and processes that impact water resources. This study provides a test case for participatory model development and implementation of a decision support framework to inform watershed management in karstic spring-fed streams, where impacts on both surface and groundwater must be considered.

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CHAPTER IV

HYDROLOGIC AND WATER QUALITY IMPACTS OF URBANIZATION IN A SMALL KARSTIC WATERSHED, CENTRAL TEXAS

Abstract

Understanding the potential impacts of human-induced land use and land cover changes is critical for planning and management of sustainable watersheds and water resources. The ability to manage groundwater supplies while taking into account impacts on stream ecosystems is critically important in karst areas due to tight linkages between surface- and ground-water. In central Texas, declining aquifer levels will likely lead to reduced spring flow volumes in the near future. The objective of this paper is to evaluate the potential for hydrologic and water quality impacts of several scenarios of development in a typical spring-fed Hill Country watershed, and to examine how these local changes may interact with changed imposed at a larger scale that reduce spring flow input. This study combines scenario analysis with watershed modeling to: 1) develop conceptual scenarios for future urban development; 2) model land cover change associated with each scenario to serve as input for hydrologic simulation modeling; 3) evaluate impacts on water quality for scenarios relative to current (2009) conditions using the SWAT hydrologic model; and 4) evaluate impacts of reduced spring flow inputs. In general, the results of the scenario analysis indicate that land cover changes associated

with potential future urbanization will alter the hydrology of the watershed, even at low intensities. A scenario of full development had the greatest impacts overall, but the results are spatially variable and all scenarios resulted in negative impacts in some areas. For most water quality parameters, negative impacts due to urbanization are overshadowed by negative impacts from spring flow reduction. This study demonstrates that the current management framework that seeks local solutions to regulating water quality in spring-fed streams is inadequate where water quality is highly dependent on maintaining adequate spring flows, which are regulated by processes at the regional scale.

Introduction

Understanding the potential impacts of human-induced land use and land cover changes is critical for planning and management of sustainable watersheds and water resources. The hydrologic response and flow regime of a watershed are integrated indicators of watershed condition that can be used to evaluate such impacts (Hernandez *et al.*, 2000; Miller *et al.*, 2002a). Spatially variable watershed properties and their links to watershed processes govern the response to land cover changes. Three primary watershed characteristics that govern rainfall-runoff response are land cover, soils, and topography. Changes in land use associated with urbanization can alter these, the primary impact being felt in alterations in land cover and an increase in impervious surfaces. As urban development occurs, watershed-level hydrologic response is primarily impacted by changes in land cover, as impacts on soils and topography tend to occur on a more local scale (Miller *et al.*, 2002a).

Water quality impacts due to urbanization are also well-documented, particularly related to erosion, sedimentation, and nutrient loading (Brabec *et al.*, 2002; Miller *et al.*, 2002a; Novotny and Olem, 1994). Impacts on the health of stream ecosystems can be seen at levels of impervious surface cover as low as 10% (Cuffney *et al.*, 2010). This highlights the need for planning even for low-intensity development relatively far from urban centers. The ability to assess the trends and magnitudes of hydrologic changes due to changes in land use is essential, especially if planning includes sustainability goals.

Urbanization in areas with karst topography presents a unique set of issues related to predicting and mitigating human-driven impacts. Although rainfall intensity may be high and infiltration may be low in many areas, the existence of karst sinkholes and conduits means that the watershed often does not demonstrate the typical rainfall-runoff response. Rapid recharge to aquifers in karst areas means that water often infiltrates into the subsurface rapidly, but then may also re-appear rapidly as throughflow in karst fractures and conduits. In addition, many stream ecosystems are historically perennial spring-run creeks, which are highly dependent on baseflow to maintain both flow and water quality. This implies a potentially large impact of change at the regional scale (for example groundwater pumping on aquifer levels) on local water quantity and quality.

In the central Texas Hill Country, rapid urbanization is occurring around major city centers interspersed with distributed, low-intensity development along major transportation corridors. The ability to manage water supply while taking into account impacts on stream ecosystems is critically important to central Texas because of the tight linkages between surface- and ground-water, and the heavy reliance on local groundwater sources for municipal and domestic supplies. Many of the area aquifers are fully or possibly over-allocated, with a legal structure that currently allows for a great deal more growth that is exempt from pumping regulation. Although state legislation supposedly encourages conjunctive use of surface- and ground-water resources, there is a fracturing of jurisdictions that divides the responsibility for allocating and managing different water sources. This division makes such cooperation difficult in practice.

Hydrologic and water quality impacts of development in karst areas such as the central Texas Hill Country will likely be mediated by spring flow inputs from regional aquifer systems. Future reductions in spring flow volumes are very likely due to the combined forces of 1) rapid development of urban areas dependent on groundwater supplies; 2) continued drilling of personal supply wells that are exempt from pumping regulation; 3) the lack of a single planning authority for surface- and ground-water quantity and quality; and 4) the lack of adequate legal jurisdiction for managing development in rural and semi-rural areas. Many small watersheds in rural and semi-rural areas are experiencing problems with regional aquifer impacts affecting local stream ecosystems, but local jurisdictions (municipalities) who are most affected by these impacts are not able to influence the patterns of growth outside of their borders effectively.

The objective of this study was to evaluate the potential for hydrologic and water quality impacts of several scenarios of development in a typical spring-fed Hill Country watershed, and to examine how these changes are mediated by reductions in spring flow input such as are likely to occur in the near future. Analysis of alternative futures combined with spatially explicit watershed modeling was used to scope problems associated with conjunctive use of water resources and increase understanding of how current policies, regulations, and practices could play out in the future and impact both watershed-level hydrologic response and water quality.

Alternative futures describe various visions for the future and represent different pathways to get there – different management or regulatory schemes that result in different outcomes (Kepner *et al.*, 2008; Shearer, 2005). Scenario studies are based on information from the past and assumptions of possible future trajectories, and can be used to assist in setting goals, defining management options, and communicating potential future results from current management decisions. Alternative futures are typically defined over long time periods (20-50 years) and can incorporate a wide range of stakeholder perspectives into a single coherent vision, the results of which can then be analyzed in detail for their associated consequences and/or benefits (Kepner *et al.*, 2008). Shearer (2005) defines alternative futures as snapshots of future conditions at a single point in time, while scenarios are the decision pathways that result in those futures. In this study, alternative futures were envisioned with the help of local stakeholders, and are represented as a series of land cover maps showing different potential distributions and intensities of development. The terms alternative futures and scenarios are used interchangeably here to refer to these end-points.

Watershed processes and impacts are highly variable in time and space and so spatially explicit hydrologic modeling lends itself well as an approach to quantify potential impacts. The Cypress Creek watershed is used as a case study to demonstrate the potential impacts of development. By incorporating scenarios of groundwater declines, this study adds to the scientific evidence that management for water supply in karst areas should also take into account potential impacts on water quality due to surface-groundwater linkages.

Methods

Study Area

Because of its natural beauty and proximity to a major transportation corridor (I-35) and rapidly urbanizing population centers such as Austin (Travis County) and San Antonio (Bexar County), land and water resources in the Cypress Creek watershed are under increasing pressure as urban areas expand and land use is converted from low-density ranching to medium- and high-density residential. The Cypress Creek watershed has a total area of 98 km^2, a mean elevation of 350 m, and a mean annual precipitation between 846 mm to the west (Fischer's Store; 413156) and 944 mm to the east (Wimberley; 419815). This watershed is located in west central Hays County, and is in the Edwards Plateau region of the Texas Hill Country (Figure 4.1). Elevations in the study area range from 247 to 479 m above mean sea level. The topography of the Hill Country varies from hills of predominantly karstic limestone overlain with thin, rocky soils, to plateaus that serve as major recharge zones to the underlying Edwards, Edwards-Trinity, and Trinity Aquifers (Longley, 1986). The hills are characterized by unstable inter-bedded limestone, shale and clays (Riskind and Diamond, 1986). The limestone plateaus are karstic, with the dissolved bedrock providing many conduits for recharge from rainfall events, and resulting in a high degree of interconnectivity between surface-and ground- water to the point where they could be considered a single water source (HTGCD, 2010).

Spring-fed waterways such as Cypress Creek dissect the hills and normally dry channels provide recharge to the underlying aquifers during storm events. The upper two thirds of the creek are intermittent and flow only during and immediately following rainfall events. Jacob's Well is a natural flowing artesian spring located in the bed of Cypress Creek roughly 16 km upstream of the creek's confluence with the Blanco River. On average, Jacob's Well provides 92% of the flow to the perennial portion of the creek, which is located just upstream from the City of Woodcreek. The stream then runs through more densely developed areas of the two small incorporated cities, Woodcreek and Wimberley, and provides a major source of inflows to the Blanco River (Figure 4.1).

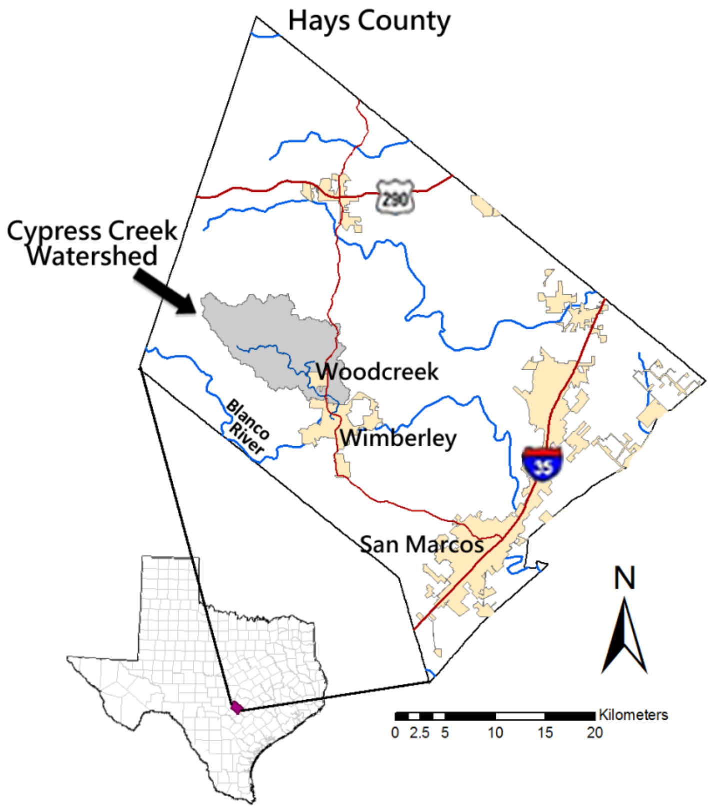

Figure 4.1. Study area location map. The Cypress Creek watershed is located in close proximity to major urbanizing areas along the I-35 corridor.

Climate in the study area is semi-arid, with relatively mild winters and hot, dry summers. Annual mean precipitation is highly variable from year to year and follows the general pattern of the Hill Country with peak rainfall in the summer and fall. Temperature is highest from May to October. The period of July through September is often both hot and dry, with average daily temperatures above 26.7 ^{o}C and little rainfall. In this region, evapotranspiration can account for as much as 90% of the water budget (Ockerman, 2005).

Soils in the watershed are predominantly shallow clay loams and shallow clays such as the Brackett-Rock outcrop-Comfort complex (41.5%) and the Brackett-Rock outcrop-Real complex (15.3%) on the uplands; and shallow stony clays such as the Comfort-Rock outcrop complex (17.9%) and the Real-Comfort-Doss complex (5.6%) on hill slopes. The remaining 20% of the watershed is a mix of deep clay and clay loam uplands and hydric loamy bottomland soils along creek beds in the lower portion of the watershed (NRCS, 2008).

The hydrology and hydrogeology of the Cypress Creek watershed are shaped by the karstic limestone character of its underlying geology. Other than a few small domestic rainwater collection systems, the area is entirely dependent on groundwater for its potable water supply. Baseflow to Jacob's Well is primarily from groundwater under artesian conditions in the Cow Creek formation. However the flow from the spring also varies significantly with major precipitation patterns. Artesian flow maintains an average discharge of 0.08 to 0.20 $m^3 s^{-1}$, but during major precipitation events peak discharge has been measured at over 1.7 $m^3 s^{-1}$. This indicates either a local pressure surge in the Cow Creek, or direct recharge from open karst features seen locally in the Lower Glen Rose.

Aquifers underlying the study area include the Middle and Lower Trinity. The Middle Trinity consists of the Lower Glen Rose, Hensel, and Cow Creek formations. Where the Lower Glen Rose layer is exposed, it is often faulted and fractured and contains surficial karst features that allow for rapid recharge from precipitation events. The Cow Creek formation acts as a confined aquifer which recharges to the north and west of the watershed, while the Lower Glen Rose responds rapidly to precipitation events within the watershed and acts as an unconfined aquifer. The Lower Trinity consists of the Sligo and Hosston formations, which is recharged through diffuse percolation through the confining layers above, and does not crop out within the study area (HTGCD, 2008). Also important to the hydrogeology of the study area are the multiple faults trending northeast-southwest throughout the region. Jacob's Well spring occurs along one of these faults (Tom Creek Fault Zone), which restricts subsurface flow in the Cow Creek formation and redirects it to discharge at the surface.

Vegetation on the hilltops is often sparse because of thin layers of topsoil. In the northern portion of the study area, shallow or disturbed soils support evergreen shrubs and grasses. Woodlands of juniper, oak and mesquite are interspersed along the landscape with native grasses where slopes are lower. The plateau-like uplands throughout this area support woody species such as Ashe Juniper (*Juniperus ashei*), Texas Oak (*Quercus buckleyi*), and Lacey Oak (*Quercus laceyi*) along with grasses. In the lower portion of the watershed along the floodplain and stream course of Cypress Creek, deciduous stands of Bald Cypress (*Taxodium distichum),* Sycamore (*Platanus occidentalis*), and Black Willow (*Salix nigra*) exist (Riskind and Diamond, 1986). Commonly found grasses include Little bluestem (*Schizachyrium scoparium*), Curly mesquite (*Hilaria belangeri*), Texas wintergrass (*Stipa leucotricha*), White tridens (*Tridens muticus*), Texas cupgrass (*Eriochloa sericea*), Tall dropseed (*Sporobolus asper*), Seep muhly (*Muhlenbergia reverchonii*), Hairy grama (*Bouteloua hirsuta*), and Side oats grama (*Bouteloua curtipendula*) (Riskind and Diamond, 1986).

Land use in the Cypress Creek watershed is predominantly Rangeland (73.9 km^2; 75%), followed by Residential (10.8 km^2; 11%), Open/ Undeveloped (9.1 km^2; 9%), and Transportation (3.2 km^2; 3%). Commercial land uses are concentrated in and around downtown Wimberley and Woodcreek, and comprise only 1.1% of the total watershed area (1.0 km^2). Population increases in the past two decades have resulted in a shift from predominantly ranching to residential land uses, as formerly large acreage holdings are subdivided for both high-density residential (<2 ha) and large lot “ranchettes” (>2 ha). Although the combined residential, commercial, and transportation uses account for only 16% of total area, much of this percentage is impervious surface cover, and is concentrated at the southern and eastern portions of the watershed. Higher-density development is coincident with the perennial creek, making this area both the most valuable in terms of ecosystem services as well as the most vulnerable to anthropogenic impacts.

Watershed Modeling and Calibration

Watershed modeling of the Cypress Creek contributing area was performed using the Cypress Creek Project Decision Support System (CCP-DSS; described in the previous chapter), a modeling and results visualization package based on the Automated Geospatial Watershed Assessment (AGWA2) tool. AGWA2 is an interface for ESRI’s

ArcGIS jointly developed by the U.S. Environmental Protection Agency, U.S. Department of Agriculture (USDA) Agricultural Research Service, and the University of Arizona to automate the parameterization and execution of two commonly-used hydrologic models, SWAT and KINEROS (Miller *et al.*, 2007). The CCP-DSS is based on the AGWA2 system and in addition has been populated with all the relevant local data on topography, soils, land cover, etc., to perform scenario analyses on the Cypress Creek watershed. It consists of a database management system to integrate available data, a set of integrated hydrologic and water quality simulation models, and a user interface that allows for the analysis of potential management scenarios. The development of the CCP-DSS and the scenario analysis reported in this study took place within the broader context of a community initiative for watershed planning, the Cypress Creek Project (CCP).

SWAT (version 2000) is a public domain, physically-based watershed model developed by the USDA-ARS to simulate in continuous-time surface flow, infiltration and sub-surface flow, and route these flows, sediment, and nutrients through stream channels. The model uses input with a high level of spatial detail, including information on soils, topography, land cover, rainfall, and temperature (Neitsch *et al.*, 2002). SWAT includes eight major sub-models for the representation of hydrology, weather, erosion and sedimentation, soil temperature, plant growth, nutrients, pesticides and land management (Arnold *et al.*, 1998; Miller *et al.*, 2007). SWAT was developed specifically to predict the long-term impacts of land management practices and related nonpoint source pollutant loadings on water, sediment, nutrients, and agricultural chemical yields in complex watersheds with varying soils and land uses. SWAT has been used to evaluate the impacts of land use change on watershed hydrology and nonpoint source pollution loadings in watersheds throughout the world, including several examples in Texas (Afinowicz *et al.*, 2005; Green *et al.*, 2007; Santhi *et al.*, 2006).

Parameterization

The CCP-DSS watershed delineation and discretization tools were used to define the watershed boundary and to divide the area into 46 sub-basins and 31 channel segments. Required input parameters are estimated as a function of topographic, soil, and land cover characteristics for each watershed response unit/sub-basin. Default parameters were taken from look-up tables provided with AGWA2 which are based on soil type, land cover, vegetative cover, etc. (Hernandez *et al.*, 2000). The SWAT model was parameterized using the SSURGO soils geodatabase from NRCS, a 10-m resolution digital elevation model from USGS, and a baseline land cover layer based on the NLCD 2001 land cover raster which was updated using recorded land uses as of 2009 (RSI, 2010). Parameterization tools in the CCP-DSS were used to determine initial parameter values for the model based on the above datasets. A comprehensive survey of existing BMPs within the watershed does not exist and was not within the scope of this project to obtain. Therefore existing BMPs such as detention structures were not input into the model.

Calibration

Observed daily rainfall data for 2000 to 2009 from two NCDC and one LCRA station (Wimberley, Fischer's Store, and Dripping Springs 5 SSW) and daily temperature data from Dripping Springs were used to drive the model (Figure 4.2). The period 2000-

2009 was used for calibration. Daily mean flows at Jacob's Well spring are available for April 2005 to 2009 only. Therefore daily mean flows for the spring from 2000 to April 2005 were estimated through regression analysis using the available flow records for Jacob's Well spring (USGS), the Blanco River at Wimberley (USGS), and estimated Cypress Creek flow (see Chapter 2 for flow estimation methods). As mentioned above, spring flow consists of both artesian components and a stormflow component that responds very quickly to rainfall events. Therefore total spring flows were separated into baseflow and stormflow components using the automated baseflow filter program recommended for use with SWAT (Arnold and Allen, 1999; Arnold *et al.*, 1995). Filtered baseflow results were then injected into the modeled stream at Jacob's Well spring to represent flow from the deep aquifer that is not influenced by local subsurface flow.

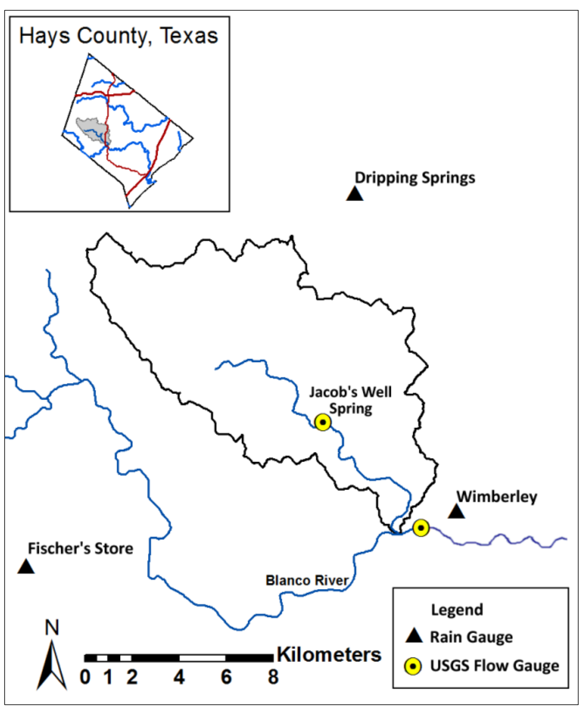

Figure 4.2. Data stations used for watershed modeling.

A major limitation to rainfall-runoff modeling in ungauged basins is the lack of long-term coupled rainfall and runoff observations that would allow for adequate model calibration and verification. The AGWA2 tools and the SWAT model used in this study have both undergone sensitivity analysis, hydrologic model calibration and verification on well-instrumented basins (Goodrich, 1990; Hernandez *et al.*, 2000; Miller *et al.*, 2002a; Syed, 1999). Vetting of the models and parameterization methods in these previous studies implies that the predicted trends and directions in hydrologic response to changes in land surface characteristics can be adequately simulated with this approach, even with limited calibration. In addition, when applying scenario evaluation to assess the potential impacts of alternative futures, the focus should be on examining trends and directions rather than absolute predictions, due to the high degree of uncertainty in predicting other drivers of hydrologic response (such as climate). If the direction and magnitude of changes is the primary focus of study, then careful calibration of the model becomes less important as the focus shifts to examining the relative magnitude of changes projected by different scenarios (Kepner *et al.*, 2008; Miller *et al.*, 2007)

A lack of observed flow data for Cypress Creek means that model calibration for this watershed is possible only in a limited fashion. The Cypress Creek is ungauged, so no record of observed daily mean flows exists such as would typically be used for model calibration. For this study, the focus of model parameterization was achieving a reasonable approximation of the overall flow regime under current (2009) land cover conditions. An estimate of daily mean flows at the watershed outlet was used to compare with model outputs and to determine if this criterion was adequately met (see Chapter 2 for description of flow estimation methods). Calibration to annual flow volumes was not attempted due to the uncertainty in estimating historical total annual volumes given the lack of data on peak flow rates.

Calibration of daily flow volumes included changing the most sensitive model parameters relating to rainfall-runoff partitioning, infiltration and groundwater return flows, based on information provided in the SWAT documentation (Neitsch *et al.*, 2002; Table 4.1). The most sensitive parameter in SWAT is the curve number, which is estimated as a function of hydrologic group, hydrologic condition, cover type, and antecedent moisture condition, based on look-up tables provided with the AGWA2 package. Curve number multipliers were applied by land cover category rather than by sub-basin, to calibrate these parameters and to preserve the model's sensitivity to changes in land cover for scenario evaluation. There was an assumption that the integrated hydrologic response of an area, as represented by the curve number, would show more variability between watersheds for undeveloped land cover types (forest, shrub, grassland, etc.) than for developed ones. As development density and impervious cover increase, the influence of local soil and vegetation conditions become less important and runoff from these areas is consistently much higher than for undeveloped areas with high vegetative covers (Brabec *et al.*, 2002; Corbett *et al.*, 1997; Whitford *et al.*, 2001). For this reason, multipliers applied to curve numbers during calibration were of larger magnitude for undeveloped land classes than for developed ones.

Flow duration curves of estimated and calibrated modeled daily flows are relatively similar, although the model tends to underestimate flow at medium to low flows (Figure 4.3). This may be due to limitations of the SWAT model in reproducing groundwater flows in complex karst topography and/or the influence of additional small springs and seeps contributing groundwater from deep aquifers into the creek. There is a wealth of anecdotal evidence that such springs and seeps exist, although their locations and specific contributions to flow have not been documented. Discrepancies at the highest flows are due to the fact that those flows are missing from the estimated time series used as the “observed” flow duration curve. Actual peak flows at the outlet may be higher or lower than simulated flows. Reliable measurements of peak flows would be necessary to further calibrate modeled peak flows.

Load duration curves for sediment, nitrate-nitrogen, mineral and organic phosphorus were constructed using model outputs for the final stream reach at the watershed outlet (Figure 4.4). Three water quality monitoring sites are located along this reach. Data on total suspended solids, nitrate-nitrogen, and total phosphorus observed at these sites were plotted and compared with the simulated load duration curves for sediment, nitrate-nitrogen, and total phosphorus (organic plus mineral P). Three soil-related parameters were adjusted to increase the sediment and nutrient loading from the initial parameter set (Table 4.1). Calibrated results for sediment, nitrate-nitrogen, and total phosphorus are simulated within a reasonable range when compared with observed values. However the model tends to underestimate these parameters as flow levels decrease. Therefore model results for sediment and nutrient yields should be taken as conservative estimates.

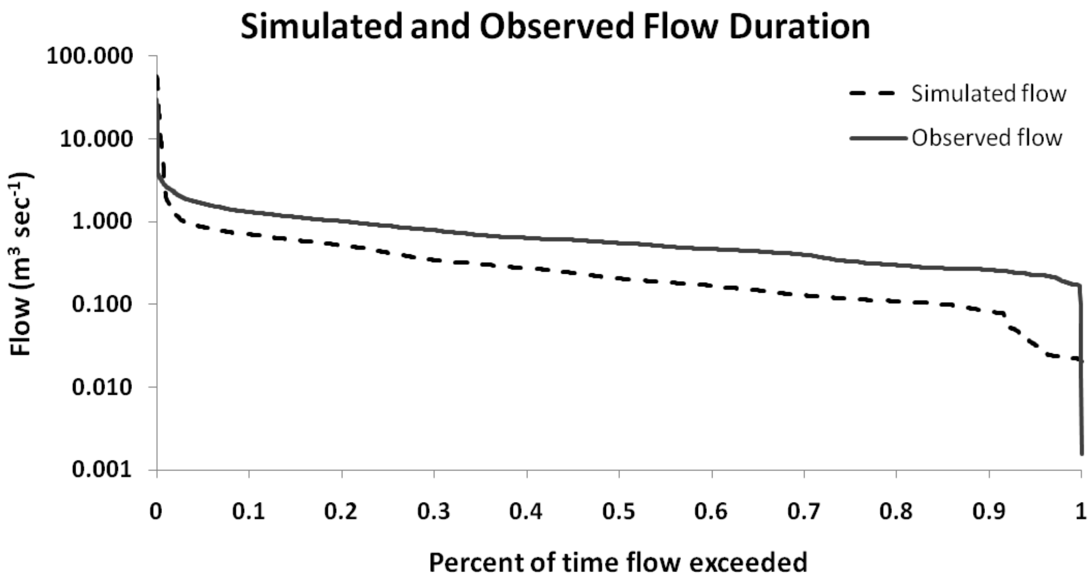

Figure 4.3. Flow duration curves at the watershed outlet for observed (estimated) and modeled flows using calibrated parameters.

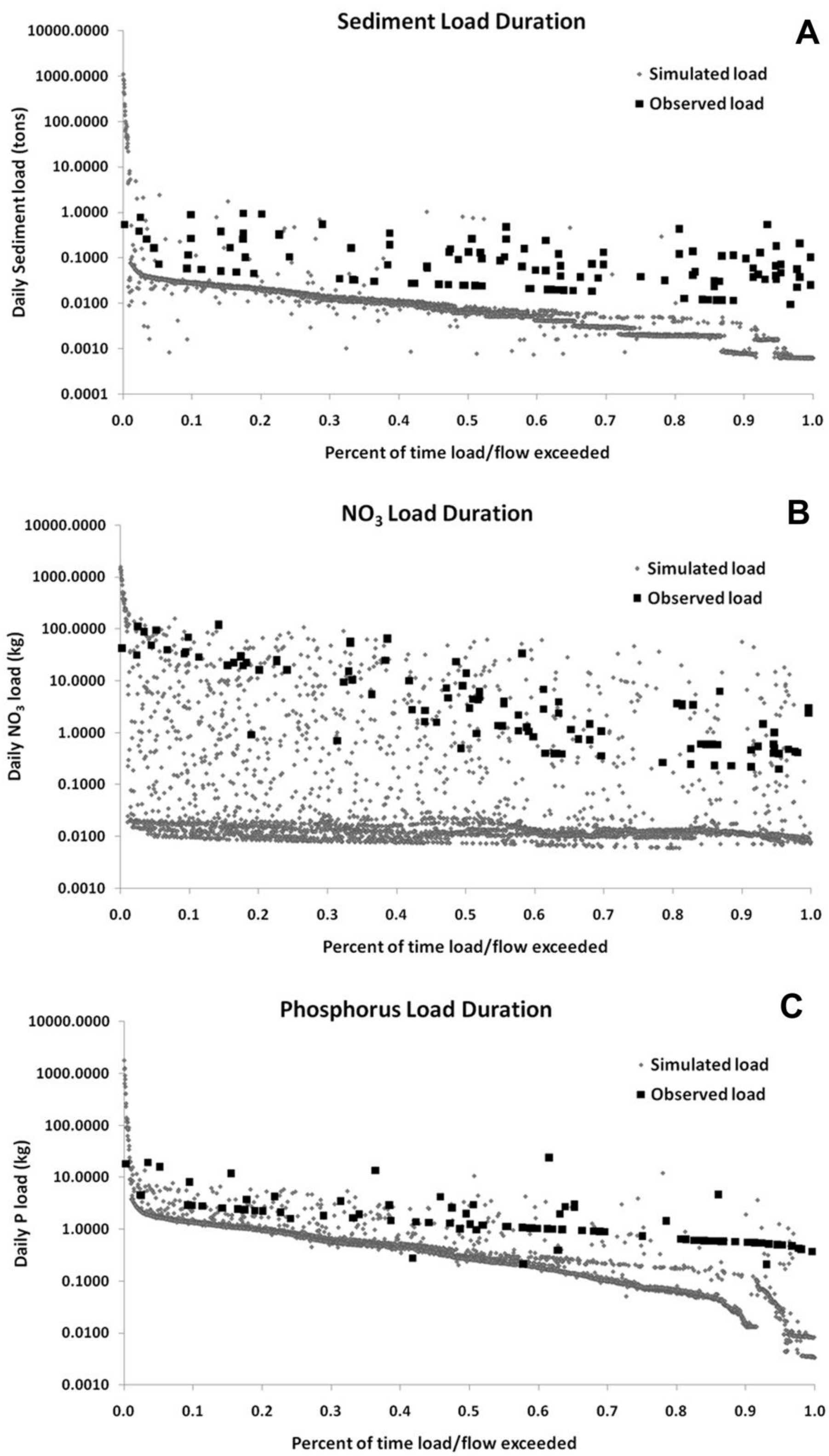

Figure 4.4. Load duration curves for A) sediment, B) nitrate-nitrogen, and C) total phosphorus measured at three water quality sites and simulated by the calibrated SWAT model.

Table 4.1. Default and calibrated model parameters.

Parameter	Description	Default Value	Calibrated Value
	Hydrologic Parameters:		
GW_DELAY	Groundwater delay time (days)	1	100
ALPHA_BF	Baseflow alpha factor (days)	0.0086	0.0009
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O)	1000	500
GW_REVAP	Groundwater "revap" coefficient	0.2	0.1
REVAPMN	Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur (mm H_2O)	1500	3000
RCHRG_DP	Deep aquifer percolation fraction	0.1	0.1
CH_N(2)	Manning's "n" value for the main channel	0.03	0.08
CH_K(2)	Effective hydraulic conductivity in main channel alluvium (mm hr^{-1})	0.0	Losing segment: 150.0 Gaining segment: 0.0
CH_N(1)	Manning's "n" value for the tributary channels	0.05	0.05
CH_K(1)	Effective hydraulic conductivity in tributary channel alluvium (mm hr^{-1})	50.0	200.0
CN multiplier	Multiplier applied to default CN values. Default CNs vary by subwatershed based on relative area in each land cover class.	1.0	Developed, open: 0.6 Developed: 0.9 Undeveloped: 0.4
	Soil parameters:		
APM	Peak rate adjustment factor for sediment routing in the *subbasin (tributary channels)*	1.0	1.5
LAT_SED	Sediment concentration in lateral and groundwater flow (mg L^{-1})	0.0	0.2
USLE_K multiplier	Multiplier applied to USLE equation soil erodibility (K) factor (units: 0.013 (metric ton m^2 hr) (m^3-metric ton cm)$^{-1}$)	1.00	1.25

Water Quality Targets

Based on observed water quality data from five monitoring sites along the creek and considering input from local stakeholders, target concentrations for sediment, nitrogen, and phosphorus were set and provide an additional method for evaluating scenario impacts (RSI, 2010). Target water quality parameters for the Cypress Creek were determined as follows:

Suspended Sediment: Sediment levels and impacts on aquatic habitats are highly site-specific and so standards are difficult to quantify. Median observed TSS ranges from 0.5 mg L^{-1} at Jacob's Well spring, 1.3 mg L^{-1} at RR12 north, 3.3 mg L^{-1} at Blue Hole, 1.8 mg L^{-1} at RR12 downtown, to 1.25 mg L^{-1} at the watershed outlet. A load duration curve of observed suspended solids reveals a cluster of values across all flow levels ranging from 0.5 to 5.0 mg L^{-1}. Therefore 5.0 mg L^{-1} is used as a target maximum concentration for sediment.

Nitrogen: Texas has no nitrogen standard for aquatic life use, and the sensitivity of aquatic organisms to nitrogen enrichment varies by species. NO_3 measured in the Cypress Creek has historically been relatively low, with median values at the four downstream sites averaging 0.11 mg L^{-1} and 0.47 at Jacob's Well spring. Therefore a target of 0.5 mg L^{-1} is used as a level that is likely to support a healthy aquatic ecosystem within historical conditions.

Phosphorus: Total phosphorus levels are routinely below detection limits in the creek (<0.05 mg L^{-1}), although very high values have been recorded, particularly at downstream sites. Because the Cypress Creek is historically a phosphorus-limited system, a target of 0.1 mg L^{-1} is used as an adequate indicator of excessive phosphorus loading.

In addition, dissolved oxygen is a water quality issue of great concern for aquatic ecosystem health in karst spring-fed streams such as Cypress Creek. Colder water can hold more dissolved oxygen, so spring-fed streams with a lower mean water temperature tend to have very high levels. Water quality impairments in Cypress Creek related to dissolved oxygen (i.e. concentrations below 6.0 mg L^{-1}, the 24-hour mean standard for high aquatic life use) are highly correlated with depressed flow levels. At flow levels above 0.14 m^3 s^{-1} (5 cfs), dissolved oxygen exceeds 6.0 mg L^{-1} in 75% of samples taken, so this level was used as the target for flow.

Scenario Development and Evaluation

The method utilized in this study incorporated scenario analysis along with watershed modeling. The method involved 1) developing conceptual scenarios to examine change relative to specific issues or endpoints (in this case, urban development); 2) modeling land cover change associated with each scenario in a form that is easily used as input for hydrologic simulation modeling; 3) evaluating watershed simulation results for scenarios relative to baseline simulation results; and 4) evaluating watershed simulation results for all scenarios using reduced spring flow levels. That the first step in this process involve participation from local stakeholders is critical for scientific and collective decision-making, as it helps to create shared visions for desirable and likely alternative futures (Kepner *et al.*, 2008). Development of conceptual scenarios for the Cypress Creek watershed involved a series of workshops with local stakeholders over the course of one year to conceptualize the watershed system, identify priority issues, and to define the regulatory and economic context within which development will occur in the near future.

Following the initial series of meetings, an email survey was taken to gather input on likely future scenarios. The survey was structured as a series of open-ended questions regarding the best and worst possible futures for the watershed 25 years in the future. These responses were used to bound the set of alternative futures envisioned. Following the initial survey, a series of maps showing major growth areas and three alternative futures were developed to represent the watershed in 25 years. Stakeholders were again asked to comment on the proposed scenarios relative to their representativeness of probable futures based on current conditions, trends, and priorities.

We used the model to examine the following watershed states 25 years into the future (Table 4.2; Appendix A):

1) Limited development (LIM): restrictions on impervious surface cover were imposed, riparian buffers are utilized in critical areas and some existing open spaces are maintained
2) Moderate development (MOD): where restrictions to growth are employed in key areas and commercial development is reduced
3) Unrestricted development (UNRST): the watershed was fully built out using existing regulations and high-intensity commercial and industrial development exists along major roadways

In addition, a fourth scenario was added representing what many stakeholders envisioned as the “worst-case” scenario 40 years into the future:

4) Full development (FULL): continuing unrestricted development at capacity, i.e. extending into the uplands.

These patterns of development were determined irrespective of how water would be supplied to the new homes and businesses (surface- or ground-water, domestic or centralized supplies). The purpose of the scenario exercise is to show the potential impacts that development patterns could have on flow peaks during storm events, and the annual pollutant loading to the creek that could result if appropriate mitigation measures are not taken.

Table 4.2. Conceptual development scenarios for the Cypress Creek watershed. These scenarios were based on input from local stakeholders obtained through a series of workshops and questionnaires.

Scenario	Description
25 year scenarios:	
Limited development (LIM)	Half of currently vacant lots are built out in residential development, ordinances limit impervious cover and riparian buffers are maintained in critical areas. Major commercial and retail development is limited to the RR2325 corridor. Some existing open spaces are maintained, and upland land uses are limited to large-lot residential and ranching.
Moderate development (MOD)	Two-thirds of currently vacant lots are built out in residential development, with some infill in downtown areas. Major transportation corridors are kept under 80% ISC with lower-impact commercial/retail developments. Higher intensity of development in upland areas than Limited scenario.
Unrestricted development (UNRST)	All currently vacant lots in major development areas are built out in residential and commercial land use with no riparian buffers or stormwater management. Downtown areas have more residential and commercial development. High-intensity development along all major transportation corridors, with low-intensity residential in upland areas.
40 year scenario:	
Full development (FULL)	Trends reflected in Unrestricted scenario continue, and much of upland areas are built out in low-intensity residential. Transportation networks are extended and widened, and local infill results in higher ISC in already-developed areas.

Next, the conceptual scenarios were translated into land cover rasters which were created using the 2009 baseline land cover (RSI, 2010) and altered using the Land Cover Modification Tool (LCMT) packaged with the AGWA2 system (Miller *et al.*, 2002b). The alterations were based on input from the stakeholder committee, best available data on land uses, subdivision and parcel boundaries, topography, FEMA flood zone boundaries, transportation networks and planning, and the conceptual scenarios outlined above. For each projected change in land use (i.e. a series of parcels converted from undeveloped to residential), the LCMT was used to alter the base raster from the existing land cover to the new land cover (i.e. from a mixture of forest and shrub to low intensity development). In the upland areas of the watershed, outside of major growth areas, land cover was converted to a mixture of low-intensity development, deciduous forest, evergreen forest, and shrub using the LCMT's patchy fractal distribution tool. Changes were applied incrementally from lowest intensity land uses to the highest, until the resulting land cover layer adequately represented the associated conceptual scenario.

The resulting land cover layers (Appendix A) were then used to parameterize the SWAT model using calibrated parameter look-up tables and the CCP-DSS parameterization tools. Because future climate is unknown, the same time series of precipitation and temperature from 2000 to 2009 that was used for model calibration was used to drive the baseline and scenario simulations. This ensures that results reported here represent impacts from changes in land cover only. Results from the ten-year baseline and scenario simulations were summarized by sub-basin and channel segment, and reported as percent change from baseline conditions.

Next, baseline hydrologic conditions and the four development scenarios were evaluated with differing levels of groundwater input. Regional aquifer impacts due to development outside the watershed area were outside the scope of this study to determine. Instead, the method used here was to alter spring flow inputs to the creek from 10 to 100 percent of historical levels as a proxy for different scenarios of regional aquifer declines. Because Jacob's Well spring has historically been the single largest source of baseflow to the creek, spring flow input at that location was altered to reflect potential draw-down of aquifer levels in the future. Daily mean flows at Jacob's Well spring from 2000 to 2009 were adjusted by a multiplier ranging from 0.1 to 1.0. This allows for examination of trends in watershed response along a continuum of potential future aquifer levels, rather than focusing on specific projected aquifer declines and associated spring flow impacts (the magnitudes of which are largely unknown and currently the focus of much debate).

Results and Discussion

The results of the scenario analysis show that impacts on watershed hydrologic response can be significant, particularly for scenarios with the greatest relative increases in developed land classes. A pattern of increasing surface runoff and decreasing percolation and potential for aquifer recharge is seen as levels of impervious cover rise. Increases in basin average surface runoff (mm) ranged from 1.8% for the limited scenario to 8.2% for the full development scenario (Table 4.3), while total water yields (surface runoff plus lateral and groundwater flow minus transmission losses) decreased from -1.9% for the limited scenario to -7.3% for the full development scenario. Maximum daily mean flows also increase as impervious surface expands, evidenced by an increase from 57.7 m^3s^{-1} under baseline conditions to 66.6 m^3s^{-1} under full development, an increase of over 15% (Figure 4.5). The time series modeled includes only ten years of recorded climate, so the potential also exists for large increases in maximum daily flow for the 100- or 500-year return period floods.

Total modeled aquifer recharge decreased 12.9% for the limited development scenario, and in karst areas even this relatively small change could have a significant impact on long-term aquifer recharge. Compare this to the 28.8% and 51.3% decreases in aquifer recharge for the unrestricted (25 year) and full development (40 year) scenarios, respectively, and it is clear that continuing urbanization has the potential to greatly reduce long-term aquifer recharge.

Table 4.3. Average annual basin results for baseline conditions and four scenarios. LIM = Limited Development; MOD = Moderate development; UNRST = Unrestricted development (25 years); and FULL = Full development (40 yrs). See Table 4.2 for details on scenarios.

		Scenario							
Average Annual Basin Values	BASE	LIM	(% chg)	MOD	(% chg)	UNRST	(% chg)	FULL	(% chg)
Surface runoff (mm)	241.99	246.28	(1.8)	250.02	(3.3)	252.79	(4.5)	261.76	(8.2)
Lateral soil flow (mm)	0.36	0.36	(0.0)	0.35	(-2.8)	0.35	(-2.8)	0.34	(-5.6)
Groundwater (shallow aquifer) flow (mm)	19.51	16.91	(-13.3)	15.07	(-22.8)	13.74	(-29.6)	9.28	(-52.4)
Total aquifer recharge (mm)	21.52	18.75	(-12.9)	16.75	(-22.2)	15.32	(-28.8)	10.49	(-51.3)
Total water yield (mm)	80.82	79.26	(-1.9)	78.37	(-3.0)	77.66	(-3.9)	74.90	(-7.3)
Percolation out of soil (mm)	21.81	19.00	(-12.9)	16.98	(-22.1)	15.53	(-28.8)	10.64	(-51.2)
Total sediment yield (t ha^{-1})	0.089	0.090	(1.1)	0.091	(2.2)	0.092	(3.4)	0.094	(5.6)
Organic N yield (kg ha^{-1})	0.621	0.631	(1.6)	0.642	(3.4)	0.651	(4.8)	0.670	(7.9)
Organic P yield (kg ha^{-1})	0.084	0.086	(2.4)	0.087	(3.6)	0.088	(4.8)	0.091	(8.3)
NO3 yield (kg ha^{-1})	0.552	0.563	(2.0)	0.572	(3.6)	0.579	(4.9)	0.6	(8.7)
% of days target load exceeded:									
Sediment (5.0 mg L^{-1})	1.42	1.39	(-1.9)	1.42	(0.0)	1.45	(1.9)	1.56	(9.6)
NO_3 (0.5 mg L^{-1})	4.98	5.20	(4.4)	5.47	(9.9)	5.47	(9.9)	5.67	(13.7)
Total P (0.1 mg L^{-1})	2.30	2. 38	(3.6)	2.63	(14.3)	2.82	(22.6)	2.87	(25.0)
% of days flow below target (<0.14 m^3 s^{-1})	33.32	35.40	(6.2)	36.52	(9.6)	37.37	(12.2)	40.30	(21.0)

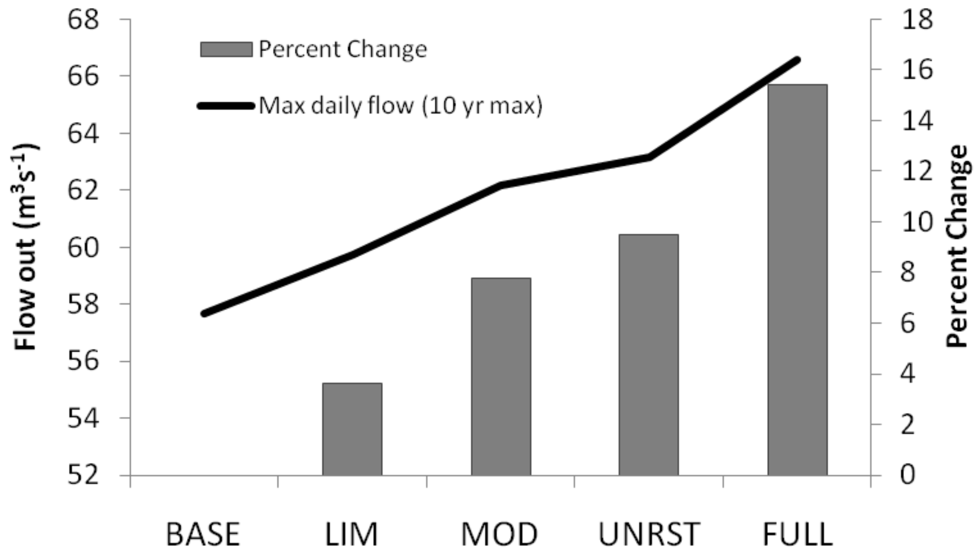

Figure 4.5. Change in maximum daily flow at watershed outlet for baseline conditions and four development scenarios. LIM = Limited Development; MOD = Moderate development; UNRST = Unrestricted development (25 years); and FULL = Full development (40 yrs). See Table 4.2 for details on scenarios.

Changes in hydrologic response under the four scenarios also vary by sub-basin, with the greatest impacts concentrated in the central and eastern areas where the highest-impact development is projected to occur (Figures 4.6 to 4.8). Average annual surface runoff increased 17.5% in some areas in the limited development scenario, and under full development some areas saw increases as high as 49.7%.

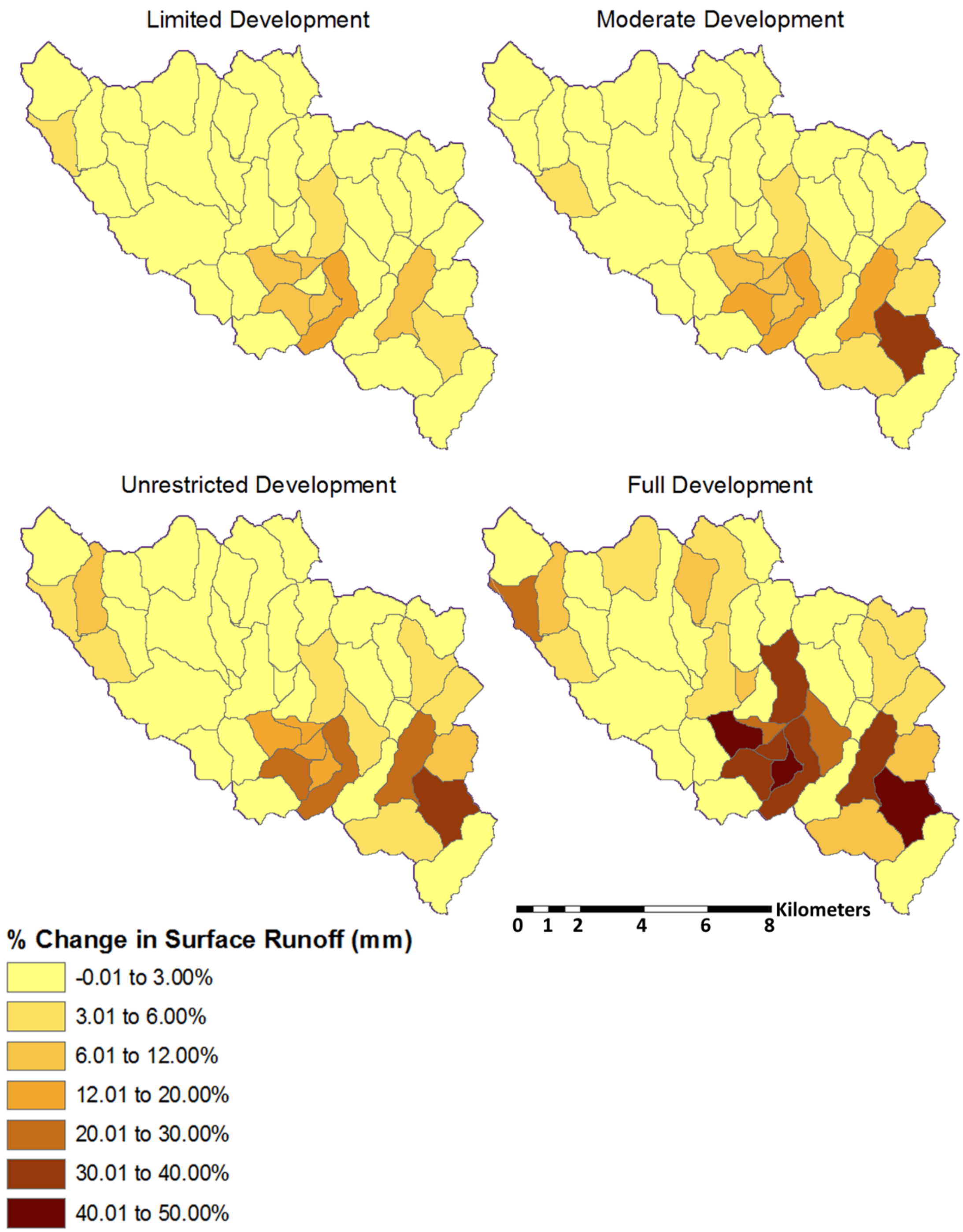

Figure 4.6. Percent change in surface runoff simulated for baseline conditions and four development scenarios. Changes in surface runoff range from -0.01% to 50.00%, and the highest increases are seen in central and southern areas where high-intensity development is concentrated.

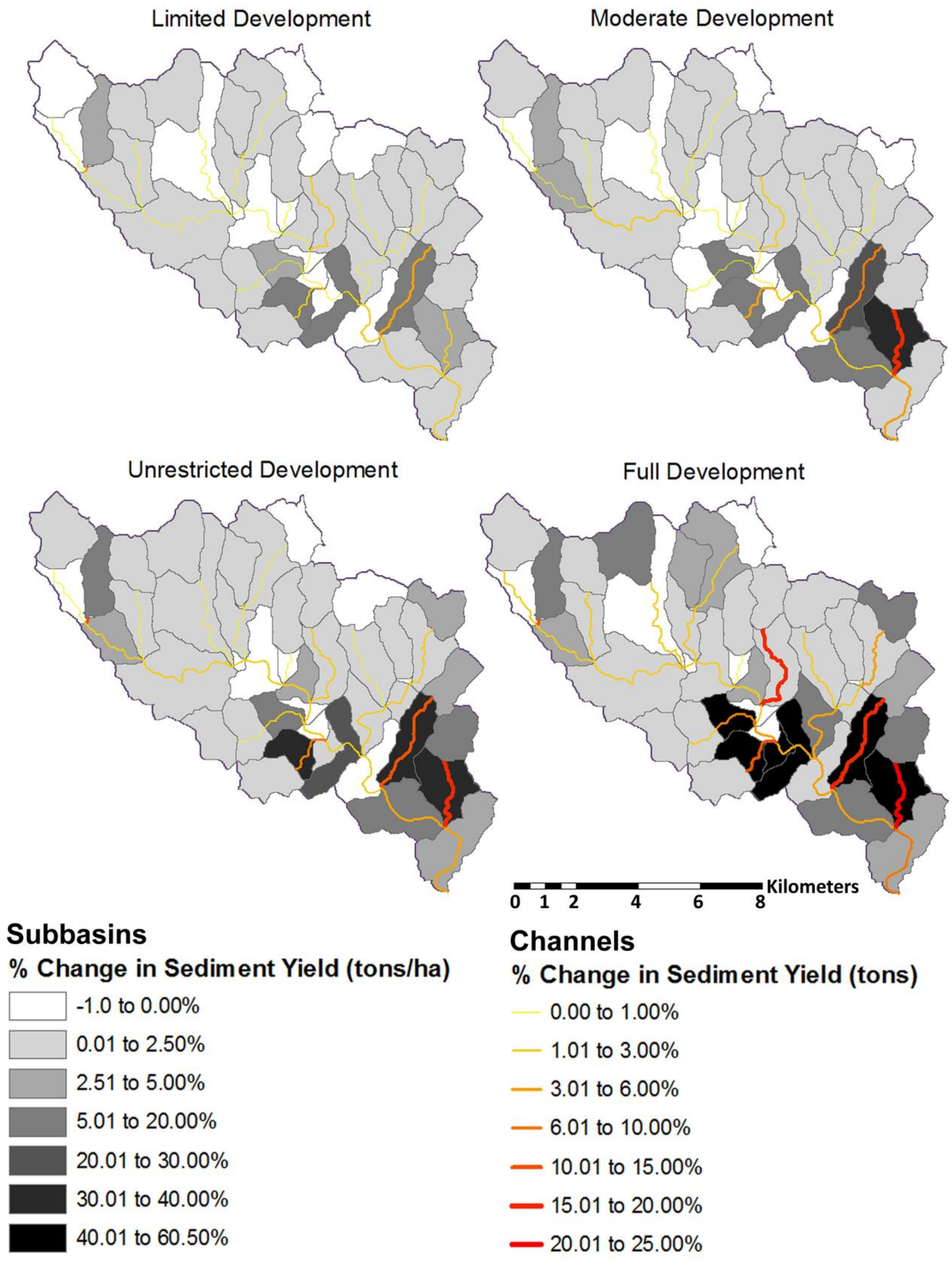

Figure 4.7. Percent change in sediment yields simulated for baseline conditions and four development scenarios. Changes in sediment yields from sub-basins range from -1% to over 60%, and from 0% to 25% for stream channels.

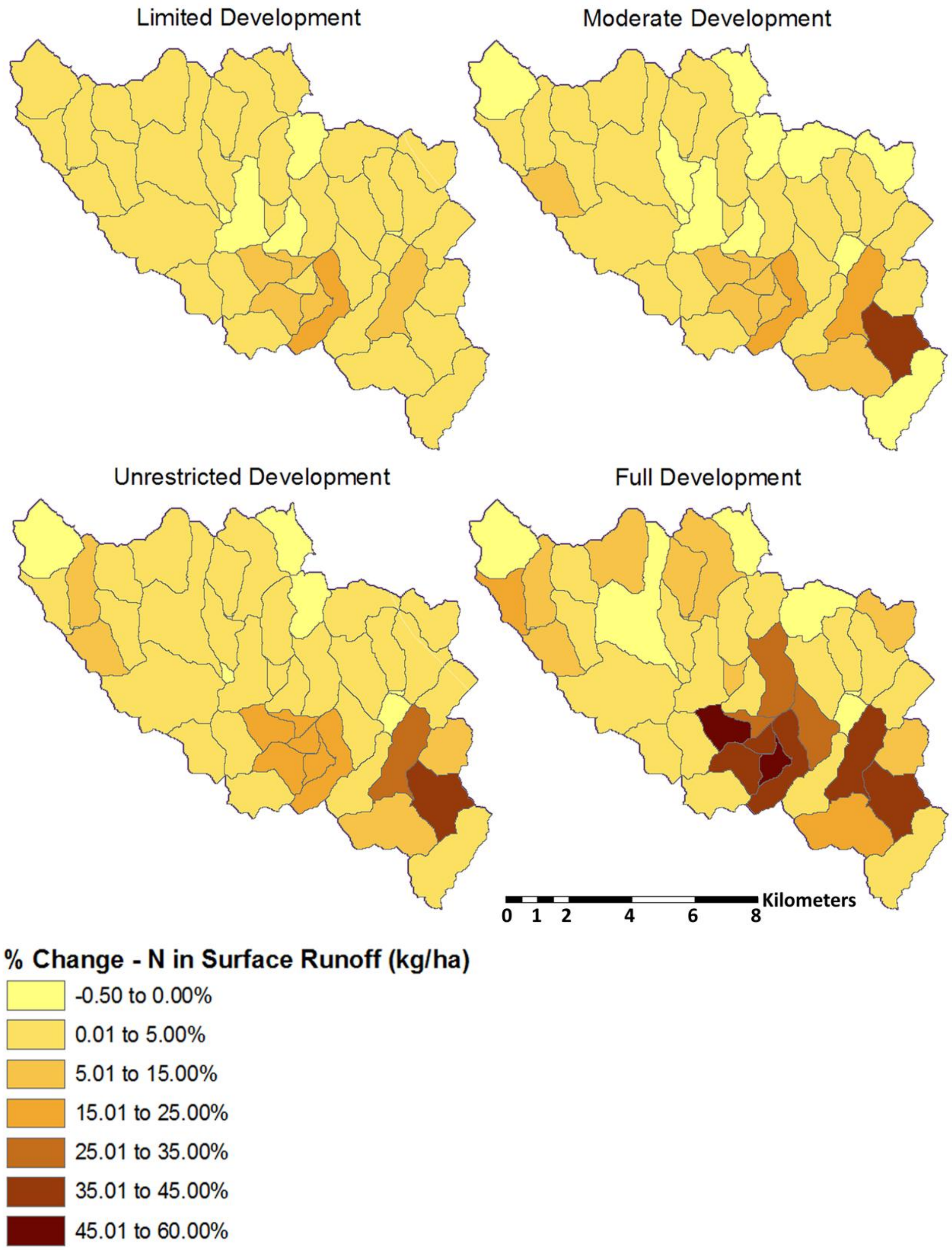

Figure 4.8. Percent change in nitrogen carried in surface runoff simulated for baseline conditions and four development scenarios. Changes in nitrogen loads range from -0.5% to 60.0%, and the highest increases are seen in central and southern areas where high-intensity development is concentrated.

In addition to impacts on water quantity and aquifer recharge, results also demonstrate impacts on water quality resulting from the different levels of development modeled. Under baseline conditions, target daily sediment, NO_3, and P loads are exceeded 1.4%, 5.0%, and 2.3% of the time, which is consistent with the overall high water quality observed in the creek historically. As development increases from the limited to the full development scenario, impacts on water quality are seen primarily as increases in nutrient exceedances with smaller increases in sediment. Sediment load exceedances actually decrease under the limited and show no change under the moderate scenario; however results show an increase of 9.6% in sediment load exceedances under full development. Increases in daily exceedances of NO_3 range from 4.4 to 13.7% and from 3.6 to 25.0% for P (Table 4.3).

Under baseline conditions, simulated stream flow exceeds the target level (0.14 $m^3 s^{-1}$) approximately 67% of the time, but under full development the flow target is met only 60% of the time. When impacts of decreasing spring flow levels are included in the analysis, it is clear that lower spring flow results in a greater impact on the maintenance of target flow than changes in land cover (Figure 4.9). As the level of spring flow input drops closer to 10% of historical levels, the importance of watershed management for development impacts is overwhelmed by the importance of maintaining adequate flow. As spring flow decreases to 70% of historical levels, the minimum flow target is met only half the time under a full development scenario.

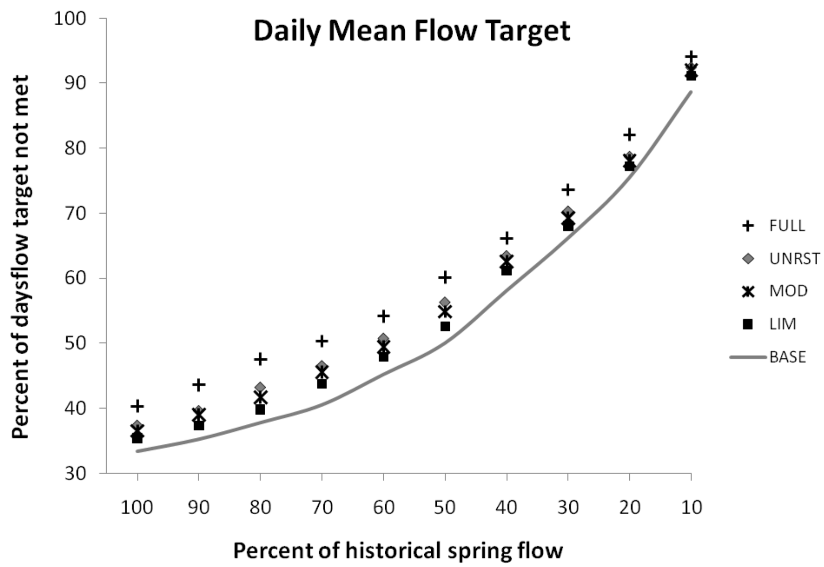

Figure 4.9. Percent of days that flow target (0.14 $m^3 s^{-1}$) not achieved under different levels of groundwater input. As spring flow input decreases, impacts of development scenarios become less pronounced relative to the influence of base spring flows.

Results show a similar pattern for nitrogen and phosphorus loading (Figure 4.10a,b), while sediment loads appear less sensitive to spring flow inputs (Figure 4.10c). However, unlike nitrogen, impacts on phosphorus loading from increasing development are most pronounced at the lowest spring flow levels.

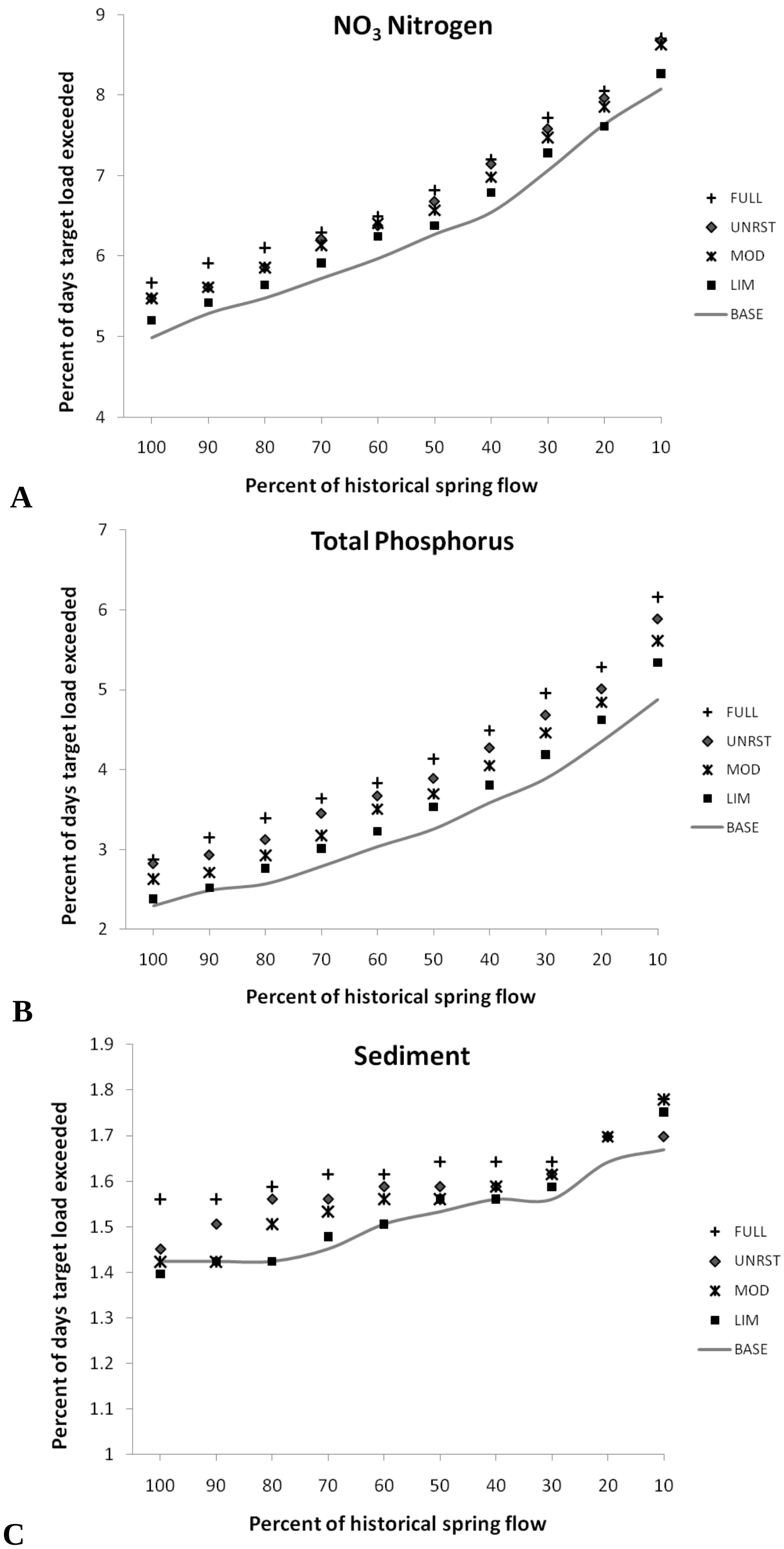

Figure 4.10. Percent of time that target maximum sediment (A), nitrogen (B), and phosphorus (C) loads are exceeded under different development scenarios and spring flow inputs.

Conclusions

In general, the results of this scenario analysis indicate that land cover changes associated with potential future urbanization will alter the hydrology of the watershed, even at relatively low development intensities. Although the worst case (40 year) scenario had the greatest negative impacts overall, the results are spatially variable and all scenarios resulted in negative impacts in some areas. The most significant impacts of urbanization relative to changing watershed hydrologic response are an increase in surface runoff and maximum flows, a decrease in baseflow between storm events, and decreasing percolation and aquifer recharge. This hydrologic response is consistent with studies of urbanization in other areas: an increase in surface runoff and peak flow rates which act to transport water quickly out of the watershed, with corresponding decreases in infiltration and percolation that reduce lateral and groundwater flows between storm events.

In karst areas like the Cypress Creek watershed, the potential for impacts of urbanization on percolation through the soil profile and aquifer recharge can be significant, even at relatively low intensity development. Therefore it is important to ensure that urbanization occurs in conjunction with management measures and/or structural approaches to help mitigate the potential impacts on long-term groundwater recharge. However it is important to note that BMPs to mitigate recharge losses due to increased impervious cover are not well developed and their effectiveness in karst areas has not been well established at this time.

Water quality impacts are also seen at relatively low development intensities, and are demonstrated through an increase in nutrient loading and, to a lesser degree, sediment. Under baseline conditions, simulated stream flow exceeds the target minimum flow level approximately 67% of the time, but under full development the flow target is met only 60% of the time. Decreases in flow are highly correlated with times of depressed dissolved oxygen in the creek, which historically has been excellent and supported a diverse aquatic community.

In addition to hydrologic and water quality impacts due to development, it is likely that future spring flow input will be reduced as groundwater supplies are fully allocated and population and pumping in the surrounding areas increases. For flow, sediment, and nitrogen, as spring flow decreases the impacts of development become overwhelmed by the magnitude of impacts predicted from declining spring flows. Under the limited development scenario, reducing spring flow inputs to 50% of historical levels results in flow targets being met less than half the time, and under full development this occurs at 70% of historical levels. Although storm-based loading of sediment, nutrients, and other nonpoint source pollutants may be mitigated by proper planning and management on a watershed level, as spring flows are reduced the hydrologic character of the stream will change to an ephemeral regime with flow only during and immediately following rainfall events. The effects of a substantial decrease in spring flow would greatly outweigh the effects of local development, so mitigation on a local level, while important, cannot compensate for the loss of regional aquifer levels.

The current legal framework for managing ground- and surface-water in Texas does not provide any protection from water quality degradation due to decreased aquifer levels and spring flows. Unlike the neighboring Edwards Aquifer, where the existence of endangered species dictates that springs and associated habitat must be maintained, the allocation of groundwater supplies in the Trinity Aquifer has no such legal responsibility to ensure adequate spring flows. State law requires that surface water quality standards are met, but the only mechanisms available for managing water quality are through the issuing of permits for point-source discharges and watershed-level management for nonpoint source pollutants. However, this study shows that in spring-fed systems like those found throughout the Texas Hill Country, this management framework is inadequate to ensure good water quality when such quality is so highly dependent on maintaining adequate spring flows.

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CHAPTER V

CLIMATE VARIABILITY AND THE FUTURE OF A RAPIDLY URBANIZING WATERSHED IN THE CENTRAL TEXAS HILL COUNTRY

Abstract

Based on the results from various global climate models, central Texas is expected to see increasing temperatures and either increasing or decreasing precipitation on an annual basis over the next 30 to 100 years, accompanied by an increase in extreme weather events such as multi-year droughts and major floods. In the central Texas Hill Country, rapid urbanization is occurring around major city centers interspersed with distributed, low-intensity development along major transportation corridors. Impacts of urbanization will vary depending on future climatic conditions and so will appropriate mitigation measures. Understanding potential impacts of climate change on a regional level is important, but for the purposes of local decision-making regarding the location and density of development, hydrologic impacts must be understood within the changing context of both climate and urbanization. The objective of this study is to evaluate hydrologic and water quality impacts of potential climate and development futures for central Texas, using scenarios of both decreasing and increasing precipitation. The Cypress Creek watershed, in western Hays County, is used as a case study to demonstrate

these potential interactions. Results show that climate change will impact the hydrology and nonpoint source pollution potential from the Cypress Creek watershed, but that the direction and magnitude of changes vary greatly depending upon the level of development in the area. Impacts are seen in both water quantity (surface runoff, total runoff volume, aquifer recharge) and quality (sediment and nutrient loading). This study presents the results of scenarios modeling as a sensitivity analysis of the system to a likely range of conditions. The results could be used to develop policy alternatives that are robust under a variety of likely future conditions.

Introduction

Texas is located in a climate region of high rainfall variability, and this variability appears to have been increasing over the past decades. For example, Texas experienced significantly more high intensity rainfall events in the last half of the 20^{th} century than the first half (USGCRP-NAT, 2000). Additionally, the snow season is ending earlier in the spring, evidence that temperatures are increasing (USGCRP-NAT, 2000). Based on the results from various global climate models (GCMs), central Texas is expected to see increasing temperatures and either increasing or decreasing precipitation on an annual basis over the next 30 to 100 years, accompanied by an increase in extreme weather events such as multi-year droughts and major floods (Mace and Wade, 2008). Seasonally, these warming trends will not occur evenly, but rather the highest levels of warming will occur in winter and spring (USGCRP-NAT, 2000). These changes in climate present serious challenges to long-term water resources management, challenges that are exacerbated by ongoing urban development in the region (HTGCD, 2010; Loáiciga *et al.*, 2000; RSI, 2010).

In central Texas, much human development is dependent on highly prolific regional aquifers, such as the Edwards and Trinity Aquifers along the Balcones Fault Zone, with limited alternatives for large-scale water supplies to meet municipal, agricultural, industrial, and recreational water demands. The central Texas region is particularly sensitive to climate change impacts, for the following reasons: 1) there is a strong and immediate relationship between precipitation and regional hydrology, where the conversion of rainfall to runoff and runoff to aquifer recharge through stream losses is critical to maintaining water supply levels; 2) the region is already subject to a high degree of variability in precipitation, with occasional multi-year droughts that can temporarily reduce or eliminate natural aquifer recharge; 3) economic and population growth over the last 65 years have resulted in increasing ground water extraction, a pattern that is projected to continue through 2050 (TWDB, 2006). Regional aquifers support unique aquatic habitats with a variety of endangered species, and many of these species face extinction if current trends of ground water extraction continue. The institutional framework for addressing water management issues at the local, state, and federal levels is characterized by a complex web of technical, scientific, and legal uncertainties (Loáiciga *et al.*, 2000). Taken together, these factors point to a structural vulnerability to climate change that will require careful analysis of potential changes and impacts on water resources, coupled with appropriate development planning, in order to avert undesirable and non-sustainable outcomes.

The objective of this study is to evaluate hydrologic and water quality impacts of potential climate and development futures for central Texas, using scenarios of both decreasing and increasing precipitation. A climate scenarios approach provides a way to address the challenges presented by inevitable uncertainties of climate prediction. As applied to planning, this approach includes the analysis of historic trends and potential variations in the future, to determine thresholds for key indicators in relation to plausible future climates (Felzer and Heard, 1999).

Most GCMs predict increasing evaporation potential across central Texas (Felzer and Heard, 1999). Increased evaporation can cause soil moisture as well as the potential for recharge to regional aquifers to decline. Higher evaporation can lead to an increase in overall water demand and therefore groundwater withdrawals (the primary source of water supply for the region). Increases in municipal water demand are projected between 1.54% and 1.91% in 2030, and between 2.52% and 3.47% in 2090 (Chen *et al.*, 2001). Due to increased temperatures, heat events (i.e. three days in a row above 32°C) are expected to increase across the region (USGCRP-NAT, 2000). These events are a major cause of heat stress for humans, livestock, and potentially for native species as well.

The other major climate variable is precipitation, but global climate models are not always in agreement about emissions-induced changes in rainfall in central Texas. The Canadian Climate Center (CCC) model predicts decreases in precipitation, from

14.36% in 2030 to 4.56% in 2090 (Chen *et al.*, 2001). Another model developed by the Geophysical Fluid Dynamics Laboratory (GFDL) of the National Aeronautics and Space Administration (NASA), the GFDL R30 GCM, was used to predict 2 x CO_2 scenario impacts in central Texas for the year 2030 (Loáiciga *et al.*, 2000). These results indicate seasonally varying impacts on rainfall, ranging from a 45% decrease in May to a 446% increase in August on average. Most models agree in their prediction of increasing precipitation extremes in Texas (USGCRP-NAT, 2000).

Based on these projections, the impacts on water resources and associated aquatic habitats could be significant, especially when coupled with continuing urban development. Water quality impacts due to urbanization are well-documented, particularly related to erosion, sedimentation, and nutrient loading (Brabec *et al.*, 2002; Miller *et al.*, 2002; Novotny and Olem, 1994). Impacts on the health of stream ecosystems can be seen at levels of impervious surface cover as low as 10% (Cuffney *et al.*, 2010), making proactive planning for even low-intensity development important in rapidly urbanizing areas. Understanding potential impacts of climate change on a regional level is important, but for the purposes of local decision-making regarding the location and density of development, regional hydrologic impacts must be understood in the context of local development. This is essential for meaningful watershed planning, however climate-aware local planning is seldom done, because managers are often not able to make effective use of regional and global-scale predictions.

Here, I report a case study performed in a small watershed in the central Texas Hill Country, where rapid urbanization is occurring around major city centers interspersed with distributed, low-intensity development along major transportation corridors. Because the region is situated in karst, surface- and ground-water are tightly linked, and the heavy reliance on local groundwater sources for municipal and domestic supplies makes the climate-aware management of water resources critically important. Hydrologic and water quality impacts of development in karst areas will be mediated by spring flow inputs from regional aquifer systems, which in turn are likely to be impacted by changing climatic conditions. I use a previously developed watershed assessment tool to examine the impacts of a range of future climate scenarios and spring flow inputs on the water quantity and quality of the watershed's central stream, the Cypress Creek. Because of the high degree of uncertainty inherent in predictions of future climate regimes, this study presents the results of scenarios modeling as a sensitivity analysis of the system to a likely range of conditions. The results of this analysis are presented at a scale that is most useful to planning and management and most effective for informing policy decisions. The results could assist managers in planning for development and management of groundwater to minimize the potential for impacts on water quality and quantity in face of an uncertain future.

Methods

Study Area

Because of its natural beauty and proximity to a major transportation corridor (I-35) and rapidly urbanizing population centers such as Austin (Travis County) and San Antonio (Bexar County), land and water resources in the Cypress Creek watershed are under increasing pressure as urban areas expand and land use is converted from low-density ranching to medium- and high-density residential. The Cypress Creek watershed has a total area of 98 km^2, a mean elevation of 350 m, and a mean annual precipitation between 846 mm (Fischer's Store to the west) and 944 mm (Wimberley to the east). This watershed is located in west central Hays County, and is in the Edwards Plateau region of the Texas Hill Country (Figure 5.1). Elevations in the study area range from 247 to 479 m above mean sea level. The topography of the Hill Country varies from hills of predominantly karstic limestone overlain with thin, rocky soils, to plateaus that serve as major recharge zones to the underlying Edwards, Edwards-Trinity, and Trinity Aquifers (Longley, 1986). The hills are characterized by unstable inter-bedded limestone, shale and clays (Riskind and Diamond, 1986). The limestone plateaus are karstic, with the dissolved bedrock providing many conduits for recharge from rainfall events, and resulting in a high degree of interconnectivity between surface- and ground- water to the point where they could be considered a single water source (HTGCD, 2010).

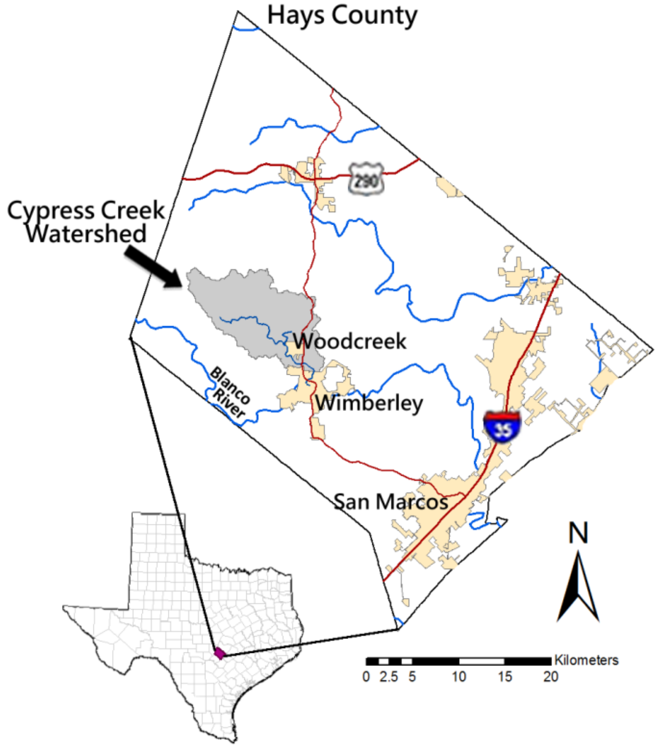

Figure 5.1. The Cypress Creek watershed, located in western Hays County, central Texas.

Spring fed waterways such as Cypress Creek dissect the hills and normally dry channels provide recharge to the underlying aquifers during storm events. The upper two thirds of the creek are intermittent and flow only during and immediately following rainfall events. Jacob's Well is a natural flowing artesian spring located in the bed of Cypress Creek roughly 16 km upstream of the creek's confluence with the Blanco River. On average, Jacob's Well provides 92% of the flow to the perennial portion of the creek, which runs through more densely developed areas of two small incorporated cities, Woodcreek and Wimberley, and provides a major source of inflows to the Blanco River.

Climate in the study area is semi-arid, with relatively mild winters and hot, dry summers. Annual mean precipitation is highly variable from year to year and follows the general pattern of the Hill Country with peak rainfall in the summer and fall. Temperature is highest from May to October, resulting in fairly predictable summer weather patterns. The period of July through September is often both hot and dry, with average daily temperatures above 26.7°C and little rainfall. In this region of Texas, evapotranspiration can account for as much as 90% of the water budget (Ockerman, 2005).

Soils in the watershed are predominantly shallow clay loams and shallow clays such as the Brackett-Rock outcrop-Comfort complex (41.5%) and the Brackett-Rock outcrop-Real complex (15.3%) on the uplands; and shallow stony clays such as the Comfort-Rock outcrop complex (17.9%) and the Real-Comfort-Doss complex (5.6%) on hill slopes. The remaining 20% of the watershed is a mix of deep clay and clay loam uplands and hydric loamy bottomland soils along creek beds in the lower portion of the watershed (NRCS, 2008). Vegetation on the hilltops is often sparse because of thin layers of topsoil. In the northern portion of the study area, shallow or disturbed soils support evergreen shrubs and grasses. Woodlands of juniper, oak and mesquite are interspersed across the landscape with native grasses where slopes are gentle.

Aquifers underlying the study area include the Middle and Lower Trinity. The Middle Trinity consists of the Lower Glen Rose, Hensel, and Cow Creek formations. The Lower Trinity consists of the Sligo and Hosston formations which do not crop out within the study area. Also important to the hydrogeology of the study area are the multiple faults trending northeast-southwest throughout the region. Jacob's Well spring occurs along one of these faults (Tom Creek Fault Zone), which restricts subsurface flow in the Cow Creek formation and redirects it to discharge at the surface.

The hydrology and hydrogeology of the Cypress Creek watershed are shaped by the karstic limestone character of its underlying geology. Other than a few small domestic rainwater collection systems, the area is entirely dependent on groundwater for its potable water supply. Baseflow to Jacob's Well is primarily from groundwater under artesian conditions in the Cow Creek formation. However the flow from the spring also varies significantly with major precipitation patterns. Artesian flow maintains a base discharge of 0.08 to 0.20 $m^3 s^{-1}$, but during major precipitation events peak discharge has been measured at over 1.7 $m^3 s^{-1}$. This indicates either a local pressure surge in the Cow Creek, or direct recharge from open karst features seen locally in the Lower Glen Rose.

Land use in the Cypress Creek watershed is predominantly Rangeland (73.9 km^2; 75%), followed by Residential (10.8 km^2; 11%), Open/ Undeveloped (9.1 km^2; 9%), and Transportation (3.2 km^2; 3%). Commercial land uses are concentrated in and around downtown Wimberley and Woodcreek, and comprise only 1.1% of the total watershed area (1.0 km^2). Population increases in the past two decades have resulted in a shift from predominantly ranching to residential land uses, as formerly large acreage holdings are subdivided for both high-density residential (<2 ha) and large lot "ranchettes" (>2 ha). Although the combined residential, commercial, and transportation uses account for only 16% of total area, much of this percentage is impervious surface cover, and is concentrated at the southern and eastern portions of the watershed. Higher-density development is coincident with the perennial creek, making this area both the most valuable in terms of ecosystem services as well as the most vulnerable to anthropogenic impacts.

Ambient water quality data show that the Cypress Creek, as a whole, remains in adequate condition when assessments are based on State water quality standards. However stakeholders and experts have agreed that meeting State water quality standards would be insufficient to maintain the desired health and historical nature of the creek as a spring-run stream. Impervious cover in the watershed was estimated at 6% in 1996. By 2005, total impervious cover increased to 9%. A recent economic assessment conducted by business and landowner stakeholders showed that decreased water quality and quantity will not only negatively impact the creek but also land and business values (RSI, 2010).

Watershed Modeling

Watershed modeling and model parameterization for the Cypress Creek contributing area was performed using the Cypress Creek Project Decision Support System (CCP-DSS), a modeling and results visualization package based on the Automated Geospatial Watershed Assessment (AGWA2) tool. AGWA2 is an interface for ESRI's ArcGIS jointly developed by the U.S. Environmental Protection Agency, U.S. Department of Agriculture (USDA) Agricultural Research Service, and the University of Arizona to automate the parameterization and execution of two commonly-used hydrologic models, SWAT and KINEROS (Miller *et al.*, 2007). The SWAT model (version 2000) was used in this study to model the impacts of development, varied groundwater inputs, and two different climate conditions on water, sediment, and nutrient yields in the Cypress Creek watershed. This model uses information on soils, topography, land cover, rainfall, and temperature to simulate hydrologic processes on the land surface that create surface flow, infiltration and subsurface flow, and routes these flows, sediment and nutrients through stream channels (Neitsch *et al.*, 2002). It is a continuous-simulation model, so impacts can be evaluated over long periods of time. SWAT includes eight major components: hydrology, weather, erosion and sedimentation, soil temperature, plant growth, nutrients, pesticides and land management (Arnold *et al.*, 1998; Miller *et al.*, 2007). In addition, SWAT includes a statistical weather generator, which was utilized to create climate scenarios for this analysis. Details of model parameterization are given in Chapter 4.

Scenarios

The parameterized SWAT model was used to run watershed simulations under current (2009) land use conditions as well as four alternative futures: 1) limited development, where restrictions on impervious surface cover are imposed, riparian buffers are utilized in critical areas and some existing open spaces are maintained; 2) moderate development, where restrictions to growth are employed in key areas and commercial development is reduced; 3) unrestricted development, where the watershed is fully built out using existing regulations and high-intensity commercial and industrial development exists along major roadways; and 4) full development 40 years in the future, envisioned by many local stakeholders as a "worst-case" long-term scenario for water resources (see Appendix A for alternative futures maps). These scenarios were developed with input from stakeholders as part of the participatory modeling process through which the CCP-DSS was originally developed. Development of conceptual scenarios involved a series of workshops with local stakeholders over the course of one year to conceptualize the watershed system, identify priority issues, and to define the regulatory and economic context within which development will occur in the near future.

Climate scenarios simulated were taken from two leading global climate models and include current and two future climate conditions that have higher average temperatures and either increasing or decreasing total rainfall. Current conditions were based upon over 100 years of climate records at San Marcos (approx. 22 km southeast of the study area) and 86 years recorded at Blanco (approx. 20 km west-northwest; Figure 5.2). Statistics used by the SWAT weather generator include monthly averages for minimum and maximum temperature, monthly total precipitation, number of wet days, and maximum half-hour precipitation depth. Baseline values for these parameters were obtained by averaging the statistics for the San Marcos and Blanco weather stations which are approximately equidistant to the northwest and southeast.

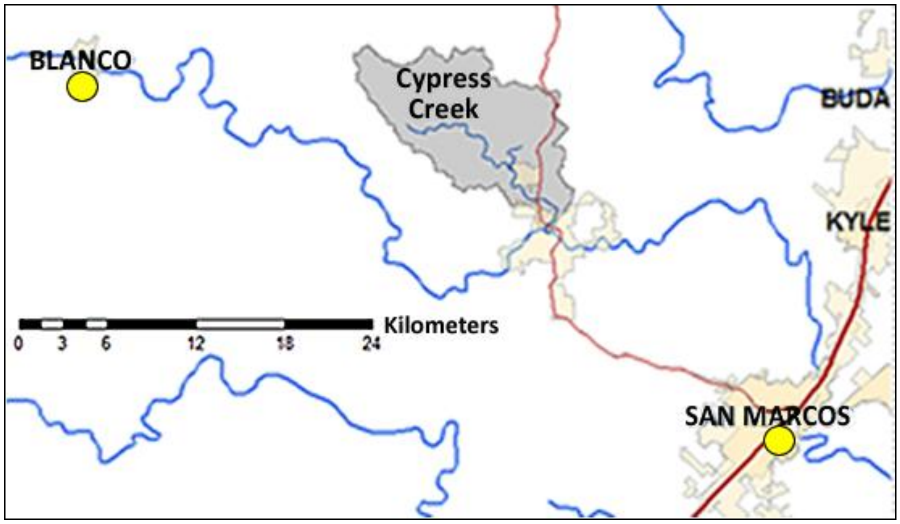

Figure 5.2. Weather data sites used to represent historical climate conditions.

Various models have been created to investigate the impacts of increasing CO_2 and other greenhouse gas emissions on global climate patterns. The Canadian Climate Center Model (CCC) utilizes the IPCCs "business as usual" scenario to estimate future emissions levels and the impacts on global climate, specifically a 1 percent per year equivalent CO_2 compound increase plus a doubling of sulfur emissions by 2100 (Felzer and Heard, 1999). The CCC model results were chosen to represent decreasing rainfall conditions, as they predict an average decrease in rainfall over the study area by 10%. Loáiciga et al. (2000) utilized results from the GFDL R30 model, developed by the Geophysical Fluid Dynamics Laboratory (GFDL) of the National Aeronautics and Space Administration, to predict 2 x CO_2 scenario impacts on groundwater resources of central Texas for the year 2030. The GDFL R30 model predicts an overall increase in precipitation in the study area, although some months show decreases as well.

Adequate regionalization of global climate results to a local area is critical because of the spatially variable nature of these impacts, but even the best of these techniques still retain some degree of error. The Vegetation/Ecosystem Modeling and Analysis Program (VEMAP) database is based on historical precipitation measured at 8500 stations and temperature at 5500 stations in the coterminous United States (Kittel *et al.*, 2004; Kittel *et al.*, 1995). VEMAP researchers employed techniques relying on geostatistical and physical relationships to create a temporally and spatially complete dataset on a 0.5° by 0.5° latitude/longitude grid (Kittel *et al.*, 2004). Monthly scaling factors based on multi-year simulation results from the CCC and GFDL R30 models were obtained for the grid cell covering the Cypress Creek watershed. Table 5.1 shows the monthly average scaling factors for temperature, precipitation and streamflow that were used in this analysis, based on results obtained from the CCC and GFDL R30 models. Both models predict an increase in temperature, though to different degrees. The GFDL R30 model predicts an overall increase in precipitation, while the CCC model predicts an overall decrease for this area.

Global climate models generally agree that Texas will experience an increase in extreme weather events, regardless of the direction of change in total rainfall (Bernstein *et al.*, 2007; Mace and Wade, 2008; USGCRP-NAT, 2000). Therefore the maximum half-hour rainfall total was increased 15% for both climate scenarios, and the number of wet days per month was decreased by 15%. This has the effect of increasing the intensity of storm events while simulating those events on fewer days of the month, increasing the average dry period length. The monthly scaling factors shown in Table 5.1 were applied to the baseline weather statistics described above. Baseline and modified weather generator files were then used to simulate daily climate parameters and to drive the watershed model for baseline conditions and two potential climate futures. Simulations were run for 10 years.

Hydrologic and water quality impacts of development in karst areas such as the central Texas Hill Country are likely to be mediated by spring flow inputs from regional aquifer systems. Future reductions in spring flow volumes are very likely due to the combined forces of 1) rapid development of urban areas dependent on groundwater supplies; 2) continued drilling of personal supply wells that are exempt from pumping regulation; 3) the lack of a single planning authority for surface- and ground-water quantity and quality; and 4) the lack of adequate legal jurisdiction for managing development in rural and semi-rural areas. Therefore baseline watershed conditions and the development and climate scenarios were also evaluated with differing levels of groundwater input. Because Jacob's Well spring has historically been the single largest source of baseflow to the creek, spring flow input at that location was altered to reflect potential draw-down of aquifer levels in the future. For this study, the long-term average flow at Jacob's Well spring (0.229 $m^3 s^{-1}$) was used to represent baseline conditions, based on a filled record of daily flows from 2000 to 2009 (see Chapter 4). The GFDL R30 scenario predicts increasing precipitation, which conceptually could result in increasing aquifer levels and thus increasing flows from regional springs. However the exact relationship between precipitation, recharge, and spring flow depends on multiple factors and there is a high degree of uncertainty in making such predictions. Because of the reasons listed above and the continuing rapid population growth in the area, it is unlikely that spring flows will increase substantially even under a scenario of increased precipitation. Therefore it was assumed that even under a “best case” scenario, spring flows are highly unlikely to increase more than 30%. Historical spring flow inputs were adjusted by a multiplier ranging from 0.1 to 1.3 to evaluate potential water quality interactions that may occur under the above-listed development and climate scenarios.

Table 5.1. Average monthly scaling factors (maximum and minimum temperature, total precipitation, precipitation days in month, and maximum half-hour rainfall) derived from two global climate models.

Model	Parameter	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
GFDL R30	Maximum Temp.	1.25	1.25	1.22	1.20	1.13	1.12	1.06	1.06	1.08	1.11	1.19	1.28
	Minimum Temp.	2.63	2.12	1.64	1.44	1.23	1.20	1.10	1.09	1.14	1.23	1.57	2.48
	Precipitation	1.15	0.93	0.82	0.92	0.67	3.41	3.03	4.10	0.71	1.83	0.83	1.61
	Precipitation days	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	Max half-hour rainfall	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
CCC	Maximum Temp.	1.17	1.14	1.13	1.11	1.10	1.08	1.08	1.08	1.09	1.10	1.13	1.16
	Minimum Temp.	2.07	1.65	1.37	1.23	1.17	1.14	1.13	1.13	1.16	1.22	1.39	1.83
	Precipitation	0.78	0.71	0.90	0.90	0.88	0.73	0.83	0.82	1.42	1.01	0.97	0.85
	Precipitation days	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	Max half-hour rainfall	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15

Results

Results show that local effects of global climate change will impact the hydrology and nonpoint source pollution potential from the Cypress Creek watershed, but that the direction and magnitude of changes vary greatly depending upon the level of development in the area. Impacts are seen in both water quantity (surface runoff, total runoff volume, aquifer recharge) and quality (sediment and nutrient loading). Average rates of spring flow input do not greatly impact the response of the watershed to rainfall events, but do have an influence on water quality in the perennial portion of the creek. Selected results from the 10-year scenario runs are given in Table 5.2.

Table 5.2. Selected effects of climate scenarios on watershed hydrology and nonpoint source pollution loading. BASE = 2009 land cover, MOD = moderate development scenario, FULL = full development scenario.

	Annual average, percentage change from current conditions*							
			CLIMATE SCENARIO:					
Result	Current		CCC			GFDL R30		
	MOD	FULL	BASE	MOD	FULL	BASE	MOD	FULL
Precipitation	0.00	0.00	-8.67	-8.67	-8.67	66.94	66.94	66.94
Evapotranspiration	-0.76	-2.08	4.15	2.97	0.78	32.69	31.19	28.21
Flow volume	-0.35	-0.52	-26.81	-25.34	-22.54	105.71	106.80	110.20
Surface Runoff	4.16	10.65	-57.04	-51.91	-42.61	200.54	207.69	220.99
Aquifer Recharge	-29.39	-63.01	-76.18	-82.09	-92.74	5.74	-27.70	-68.07
Maximum daily flow	0.98	2.69	58.12	61.47	66.56	320.40	321.21	323.62
Sediment Loading	2.44	6.10	-47.56	-41.46	-32.93	254.88	273.17	303.66
Organic N Loading	3.58	8.23	-43.65	-37.75	-29.16	256.71	278.18	306.08
Total P Loading	3.96	9.90	-43.56	-36.63	-25.74	239.60	259.41	288.12

* Current conditions = 2009 land cover, historical climate and spring flow

Simulated evapotranspiration increases in both climate scenarios due to warmer temperatures. Under historical climate conditions, evapotranspiration decreases as development increases due to removal of vegetation cover. Total annual flow volume exiting the watershed increases as expected under the GFDL R30 and decreases under the CCC climate scenarios, but the differences are much more pronounced in wet years than in dry years (Figure 5.3). In the dryer scenario, flow volume is reduced but is also much less variable, while the wetter scenario results in a wider fluctuation of conditions from wet to dry years. This could present other challenges for management even though water scarcity may be lessened.

Under historical climate conditions, average flow volume decreased overall in response to increased levels of development in the watershed. Although peak flows and flow volumes increase substantially in wet periods, these increases are offset in dry years when flow is reduced. Flow volume for all development levels is decreased under the CCC climate scenario, but the decreases are smallest where impervious cover is highest that acts to augment flow volumes by decreasing infiltration. Under the GDFL R30 scenario, average annual flow volume increased from 105.71% for base land cover to 110.20% for full development. Even under a scenario of limited development, flow volume increases more than 106% under the GFDL R30 climate. Peak daily flow rates likewise increase with more development, and do so under all climate scenarios. However the rate of change is actually highest under historical climate conditions.

Surface runoff, which is of primary importance for managing nonpoint source (NPS) pollution contribution to streams, decreases under the CCC scenario but increases dramatically under the GFDL scenario. Potential impacts on surface runoff under full development conditions range from a decrease of 42.61% (dryer climate) to an increase of 220.99% (wetter climate).

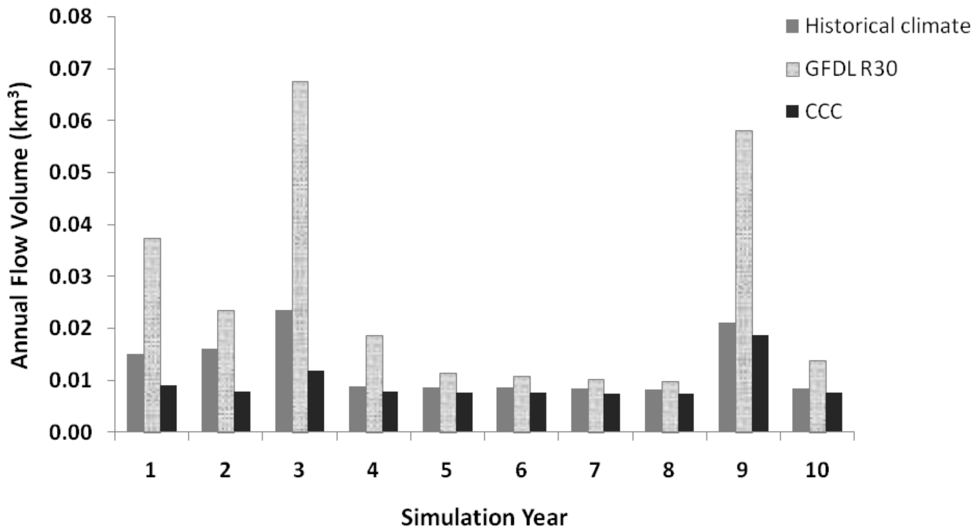

Figure 5.3. Annual runoff volume for historical climate and climate scenarios under current (2009) development conditions.

Aquifer recharge is an issue of primary importance in the region due to the strong dependence on local groundwater supplies. Results show that even under a climate regime with increasing precipitation, aquifer recharge may decrease substantially if impervious cover and increasing rainfall intensities impede the ability of rainfall to percolate through the soil profile. The benefit of increasing recharge is seen only modestly and at baseline land cover conditions (5.74% increase), whereas under all other development scenarios simulated recharge decreases, from 16.39% under limited development, to 68.07% under full development (Figure 5.4). With full development and a drier climate, recharge could decrease substantially in the study area (92.74%).

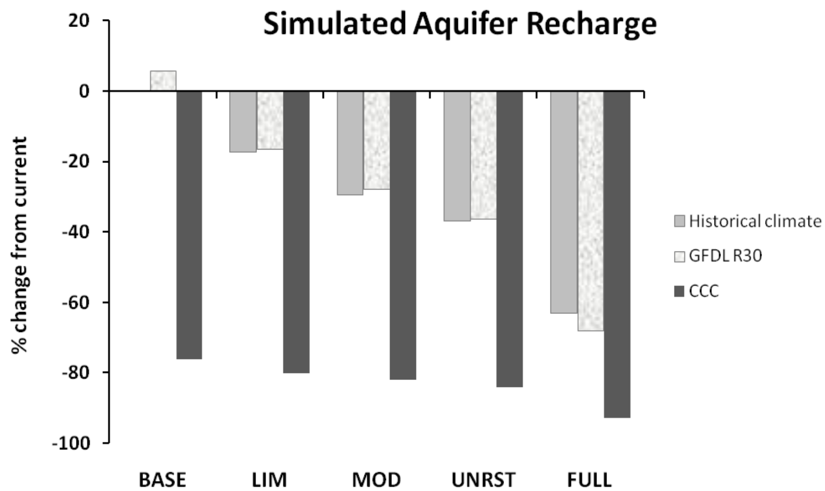

Figure 5.4. Simulated change in aquifer recharge from baseline conditions for four development scenarios and three climate scenarios.

Water quality impacts due to increasing urban development are evident even under historical climate conditions, as detailed in Chapter 4 of this work. Results from this analysis show that climate conditions can also greatly influence the potential for NPS loading to the stream, and that impacts are different depending on the precipitation scenario examined. Sediment yields decrease under the CCC scenario, but higher levels of development act to increase sediment from baseline conditions under all climate scenarios. The largest rate of increase is seen under the GFDL R30 scenario, where differences from baseline to full development are 3.6 times larger than those seen under the CCC scenario. The larger volumes of water and faster flow rates of surface runoff act to increase sediment loading particularly when conditions are wetter. Phosphorus also shows a greater rate of increase as development increases under wetter conditions than drier, whereas for nitrogen the rate of change is more comparable.

Simulation results show that changing climate coupled with declines in spring flow inputs and continuing development can impair the ability of the creek to maintain good water quality even under a wetter climate regime. Historically, decreases in flow are highly correlated with times of depressed dissolved oxygen in the creek. At flow levels above 0.14 $m^3 s^{-1}$ (5 cfs), dissolved oxygen exceeds 6.0 mg L^{-1} in 75% of samples taken (RSI, 2010). Therefore 0.14 $m^3 s^{-1}$ was set as a target flow to maintain a healthy aquatic community under historical conditions. For the wetter GFDL R30 climate scenario and with limited development, baseflow is insufficient to maintain this target once spring input drops below 35 to 40% of the historical average (0.08 to 0.09 $m^3 s^{-1}$). Under higher levels of development this threshold increases to 40 to 45% of historical spring flow (0.09 to 0.10 $m^3 s^{-1}$). For the dryer CCC scenario, this threshold is about 60% of historical spring flow, close to the target average of 0.14 $m^3 s^{-1}$. For all three climate scenarios, the threshold amount of spring flow needed to maintain water quality standards increases as development intensity increases.

Conclusions

The results of this study highlight the need for proactive development planning to manage both aquifer levels and urbanization in the central Texas Hill Country. Planning studies and models currently assume historical recharge conditions and use those results to plan for water resources needs through 2050. Our results show that this assumption may not be valid, especially in the face of potential climate change. Under scenarios of increasing urbanization, simulated hydrologic impacts include a decrease in percolation and recharge to underlying aquifers. Even under a scenario of increased precipitation, the benefits of higher recharge are seen only under baseline land use conditions. With increasing development and associated impervious cover, recharge continues to decrease and the additional precipitation is simply sent downstream as runoff. As the total flow volume occurs in fewer, more intense, storm events there will be less opportunity for streambed recharge to underlying aquifers. This might increase recharge to the downstream Edwards Aquifer, but will likely have deleterious effects on water storage in the Trinity Aquifer.

Increased maximum flow rates and flow volumes due to a combination of more intense rainfall events and urbanization can cause flooding downstream, and many existing developments along the banks of the perennial creek are not adequately protected against the magnitude of flow increases predicted under a wetter climate scenario. Wetter conditions also greatly increase the potential for sediment and phosphorus loading to the creek, particularly under full development. However the wetter GFDL R30 scenario is more likely to maintain spring flow levels needed to ensure good water quality in the creek. Under the dryer CCC scenario, the combined impacts of aquifer mining, decreased recharge, and increased NPS loading from urbanization may make it impossible to maintain the historically high water quality and perennial character of the creek.

For all three climate scenarios, the threshold amount of spring flow needed to maintain water quality standards increases as development intensity increases. Given that declines in spring flow levels are likely regardless of whether central Texas becomes wetter or dryer, these results highlight the importance of careful management for mitigating nonpoint source loads from urbanized areas. It may not be possible to manage water quality entirely through ensuring an adequate supply of spring flow, but with a combination of aquifer management and local watershed best practices in critical areas, the impacts could be reduced. This study demonstrates that proactive development planning is critical, both to ensure adequate base flow to surface water bodies to maintain water quality standards, and to maintain and mitigate potential decreases in recharge that can accompany urban development.

It is important to note that a portion of recharge in karst areas can occur through preferential pathways such as sinks and fractures, but there is a great deal of uncertainty and local heterogeneity in the distribution of these features across the landscape.

Recharge values simulated by the SWAT model reflect the volume of water that is able to percolate past the soil profile into the shallow and deep aquifers. SWAT is not a dynamic groundwater model, and therefore recharge estimates should not be taken literally, but rather from a water balance perspective as the amount of water that has a high potential for diffuse recharge. Simulated recharge values should therefore be taken as indicators of the relative magnitude of potential change, not as absolute prediction.

The primary challenge to incorporating climate change into long-term planning is the high degree of uncertainty in model predictions. This is clear by the various conflicting predictions made by different global climate models. However the fact that uncertainty is inherent in predicting impacts of climate change and its potential interactions with human behavior, economic drivers, urban development, and other anthropogenic changes does not stop people from making decisions every day about the location and intensity of new developments. A climate scenarios approach provides a way to address the challenges presented by persistent uncertainty. This study presents the results of scenarios modeling as a sensitivity analysis of the system to a likely range of conditions. The results could be used to develop policy alternatives that are robust under a variety of likely future conditions.

Even though climate change is best understood at a global scale, it is important to describe potential impacts over a more localized area because this is the scale at which many management decisions are made that can mitigate or exacerbate such impacts.

Decisions about site planning, zoning, and best management practices are often made at the local municipal or county level. These decisions are most likely to result in the most effective outcomes when they are based on an understanding of the potential range of impacts that could result from probable future scenarios. At the same time it is important for larger regional water planning entities to understand the potential impacts of declining aquifer levels, not just on domestic supply wells and overall water production, but on the ability of local surface waters to maintain good quality for both healthy ecosystems and recreational use.

The results presented here are only for one small watershed, but these patterns of development are not unique to the Cypress Creek area. If regional development trends continue, hydrologic impacts like these could be seen many times over in watersheds across the Hill Country, and cumulative impacts could be substantial. When these impacts are combined with increasing water withdrawals due to population growth plus increases in water demand due to direct climate change effects, water availability for environmental flows and aquatic species could be severely limited. This study underscores the need for proactive and comprehensive planning to ensure the sustainable use of both land and water resources in the Hill Country in the face of an unknown climate future.

The potential for climate change impacts on water resources in central Texas is high. Even under current water use levels, increases in temperature and potential decreases in water supply would make it difficult to manage for environmental flows given the institutional and legal framework for water resource management. It is clear that climate change must be considered when planning for the future of human communities in this region. Given the preponderance of evidence, it is unreasonable to use current climate and land use conditions as the only reference for water resources planning in the future, as they will only be applicable for a fairly narrow range of conditions that are not likely to continue. Not incorporating potential climate change impacts could make seemingly effective long-term plans for resource sustainability entirely ineffective and greatly increase the potential for catastrophe in the future.

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CHAPTER VI

ASSESSING THE IMPACTS OF STAKEHOLDER PARTICIPATION ON THE PERCEIVED LEGITIMACY OF SCIENCE-BASED DECISION SUPPORT MODELS

Abstract

Although much literature exists on the supposed benefits of stakeholder participation in the development of science-based planning tools, there has been very little critical evaluation of the level of effectiveness of participatory modeling processes for actually increasing stakeholder buy-in and consensus. To assess the validity of these arguments, a combination of questionnaires and structured interviews were conducted with local stakeholders involved in development of a decision support system for the Cypress Creek watershed, in central Texas. The Cypress Creek Project Decision Support System (CCP-DSS) takes the form of an interactive watershed simulation model and multi-criteria analysis package, incorporating relevant data to aid in the selection of appropriate management strategies. The goal of the survey and interviews was to evaluate the degree of impact that participation had on stakeholder's trust, buy-in to the process, and degree of consensus regarding priority issues for watershed management, effective and appropriate management instruments, and barriers to effective long-term management. Results demonstrate that involvement in development of the CCP-DSS did

in fact increase participants' perceptions of its legitimacy and utility for decision-making in the local area. However while the stakeholder process had positive impacts on stakeholder understanding and consensus in some areas, in other areas consensus actually decreased.

Introduction

The complexity of social-ecological systems makes it difficult to forecast future behavior in a way that is meaningful to management decisions. Key drivers to such systems are unpredictable and change nonlinearly, such as climate and technological advances. Human responses to forecasted information often changes the system in such a way that forecasts subsequently prove to be inaccurate, and during times of transition a system may change faster than the forecasting models can be recalibrated, causing unreliability in predictions when they are most needed (Walker *et al.*, 2002). This means that complex problems arising from intricate linkages in social and biophysical networks often cannot be solved for optimality, because the optimal solution will always be a moving target.

Recognition of these complexities in water resources planning has led to increased understanding of the need for systemic and participatory approaches. A systems approach addresses resource management from a holistic and transdisciplinary perspective, examining the effects of variable interactions over time. This approach does not seek to optimize a single variable or output to define a long-term management strategy, but rather takes into account the various biophysical, economic, legal, environmental, and other factors that impact the availability and use of the resource

(Pierce, 2006). The approach aims to identify and implement proactive strategies for adaptive management with a focus on building resilience in all levels of linked-social ecological systems (Lal *et al.*, 2001).

No single perspective, whether proceeding from the basis of scientific inquiry and data gathering or from the personal experiences of local residents, can adequately picture the whole of the system and its component interactions. Therefore these types of systems are best understood using a multiplicity of perspectives (Berkes *et al.*, 2003). The multiple perspectives that are solicited as part of a participatory decision-making process contribute to a broader and potentially more accurate shared understanding of system dynamics, relevant processes, and feasible management alternatives. There is also increasing recognition that a multiplicity of perspectives exists even among traditional "experts" for a given problem domain, that persistent biases affect how problems and potential solutions are defined and addressed, and therefore that reliance on experts does not necessarily result in an objective evaluation. Participatory processes, on the other hand, explicitly recognize the subjective nature of all information that is brought to the decision-making table and incorporates methodologies (such as multi-criteria analysis and uncertainty evaluations) that allow for explicit examination of these biases.

It is often argued that participatory decision-making will result in "better" resource management policies as a result of stakeholder input. Stakeholders can add a significant amount of information and knowledge to aid in problem structuring and model building, such as their understanding of the processes behind resource degradation, the adequacy of current management practices, and criteria for potential new technologies or policy instruments (Costanza and Ruth, 1998; Johnson *et al.*, 2001; Mendoza and Prabhu, 2005; van den Belt, 2004; Walker *et al.*, 2002). Inclusion of community values at all stages of research design and decision-making assures a focus on what is important to the community, as opposed to adopting scientific research priorities or basing priorities simply on available data (Stroup, 2008).

A second category of arguments often cited for participatory decision-making primarily involves stakeholder perceptions of problems and alternative solutions, and issues of legitimacy. Proponents of the participatory approach argue that this methodology will increase the likelihood that stakeholders will accept policy decisions, because the integrity and credibility of the process underlying their formation and their underlying assumptions are enhanced by stakeholders' direct interactions. Because of the interactive nature of the participatory process, it will ultimately result in an increased level of shared understanding of the nature of problems and possible solutions to management challenges, and can help to build trust between different individuals, groups, and regulatory agencies, helping to ensure collectively and socially desirable outcomes (van den Belt, 2004). This shared level of understanding improves the chances that mutually acceptable solutions may be found that incorporate multiple priorities and trade-offs, and can help to build consensus about which management options would be most effective and appropriate given the social, political, and logistical realities (Costanza and Ruth, 1998; Johnson *et al.*, 2001; Mendoza and Prabhu, 2005; van den Belt, 2004; Walker *et al.*, 2002). Finally, the level of consensus brought about through the participatory process means that implementation costs will be reduced, presumably from reduced litigation and enforcement costs. In addition, a participatory process can shift focus from the search for a single "solution" and its successful implementation to an adaptive management model (Holling, 1978; van den Belt, 2004; Walker *et al.*, 2002).

Increased stakeholder acceptance of the decision process is one of the fundamental arguments for public participation. However basing an assessment on participation and consensus is effectively built on the idea of finding a shared interpretation of reality that may not exist, and often a lack of emphasis is placed upon the processes required for building shared understanding and shared decision making among diverse stakeholders (Gregory *et al.*, 2006). In addition there are inherent difficulties in bringing scientists, managers, and stakeholders to a common understanding of the issues of scientific uncertainty, confidence and credibility (Walters, 1997). Furthermore, participation is often not entirely representative, and when deciding which stakeholders should be included it is impossible to ignore existing structures of political power, local power, populism and representation, and to keep these structures from alienating or disenfranchising certain individuals or groups (Ruggeri Laderchi, 2001). An increased polarization of stakeholder groups may result from the participatory process, and would be evidenced by a decrease in the level of trust in the motives of other participants.

In recent years, much effort has gone toward the development of new methods to address development planning through a systems approach, methods that integrate quantitative research and modeling tools with qualitative approaches and stakeholder participation. Planning decision support systems are an example of such a tool that seeks to incorporate both quantitative modeling and qualitative analysis to aid decision-makers in the integrated evaluation of management and policy impacts on both social and ecological aspects of a system. Decision support systems are increasingly recognized as useful tools to help in the resolution of conflicts involving values, management approaches, and strategies. Decision support system (DSS) is a general term for a computer-based information system that supports decision making by providing information to assist in solving complex problems. A DSS is particularly useful in complex, semi-structured or unstructured problems by allowing an interactive dialogue between the user and the dynamic system (Pierce, 2006). The primary goal is to generate and evaluate alternative solutions in order to increase understanding of the problem structure and inherent tradeoffs.

Proponents of the participatory modeling approach argue that this methodology will increase the likelihood that stakeholders will accept the model results, because the integrity and credibility of the model structures and underlying assumptions are enhanced by stakeholders' direct interaction during its development. In addition, it is argued that stakeholders will be better able to perceive interconnections between system components and that they will better understand the implications of the many management, policy, and resource use decisions that are made regularly, including the ability to see these implications play out over long time scales. Because of the interactive nature of the participatory process, it will ultimately result in an increased level of shared understanding of the nature of problems and possible solutions to management challenges. This shared level of understanding improves the chances that mutually acceptable solutions may be found that incorporate multiple priorities and trade-offs, and can help to build consensus about which management options would be most effective and appropriate given the local social, political, and logistical constraints (Costanza and Ruth, 1998; Johnson *et al.*, 2001; Mendoza and Prabhu, 2005; van den Belt, 2004; Walker *et al.*, 2002).

In this study, a decision support system was developed using a participatory (mediated) modeling process with local stakeholders in the Cypress Creek watershed, in central Texas. The Cypress Creek Project Decision Support System (CCP-DSS) takes the form of an interactive watershed simulation model and multi-criteria analysis package. The CCP-DSS incorporates relevant data and aids in the selection of appropriate management strategies.

Of all the case studies of mediated modeling for environmental consensus-building, there is very little critical evaluation of the level of effectiveness of this process for delivering on its promises. Research is often focused on those aspects of society, institutions and social mechanisms that are generally present in stories of successful community resource management (Armitage, 2005; Berkes and Folke, 1998). The stated goal of many of these studies is to identify properties that characterize "effective" community management institutions, rather than explicitly evaluating a given method for promoting more effective management. To assess the validity of these arguments, a combination of questionnaires and structured interviews were conducted with project participants before and after the CCP-DSS stakeholder process. The goal of the survey and interviews was to evaluate the degree of impact that participation had on stakeholder's trust, buy-in to the process, and degree of consensus regarding priority issues for watershed management, effective and appropriate management instruments, and barriers to effective long-term management.

Methods

Study Area

The Cypress Creek, located in western Hays County, Texas is a prime example of a spring-run stream characteristic of the Hill Country, one that is faced with the relatively common problems of urban encroachment and associated impacts on local ecosystems. Springs provide a continuous supply of cold, clear water from the underlying Upper and Middle Trinity Aquifers which make up the majority of flow to the creek year-round. Because of its natural beauty and proximity to a major transportation corridor (I-35), and rapidly urbanizing population centers such as Austin (Travis County) and San Antonio (Bexar County), land and water resources in the area are under increasing pressure as urban areas expand and land use is converted from low-density ranching to residential and "ranchette" home sites (usually between 5 and 25 acres). Land use in the watershed area is primarily low-intensity ranching except for dense residential and commercial development in the cities of Wimberley and Woodcreek, in the south. Rapid population growth and accelerated urban development are increasing the potential for impacts to wildlife habitat, groundwater and surface water resources, and aquatic habitats.

The Cypress Creek trends roughly northwest to southeast, and is a major tributary contributing flow to the Blanco River (Figure 6.1). The confluence with the Blanco River is located south of Wimberley, TX, just upstream of the Blanco River/RR 12 junction. The watershed area contributing surface flow to Cypress Creek encompasses approximately 98 km^2. A major spring, Jacob's Well, is the largest single contributor to baseflow in the creek, providing on average about 92% of the flow to the perennial portion of the creek. Except under heavy rainfall conditions, the 10.4 km segment upstream of Jacob's Well is usually dry, while the lower 8.8 km stream that generally flows year-round is commonly referred to as Cypress Creek. The watershed is located in west central Hays County, in the Edwards Plateau region of the Texas Hill Country. The topography of the Hill Country varies from hills of karstic limestone to plateaus that serve as major recharge zones to the underlying Edwards, Edwards-Trinity, and Trinity Aquifers (Longley, 1986). Climate in the study area is semi-arid, with relatively mild winters and hot, dry summers.

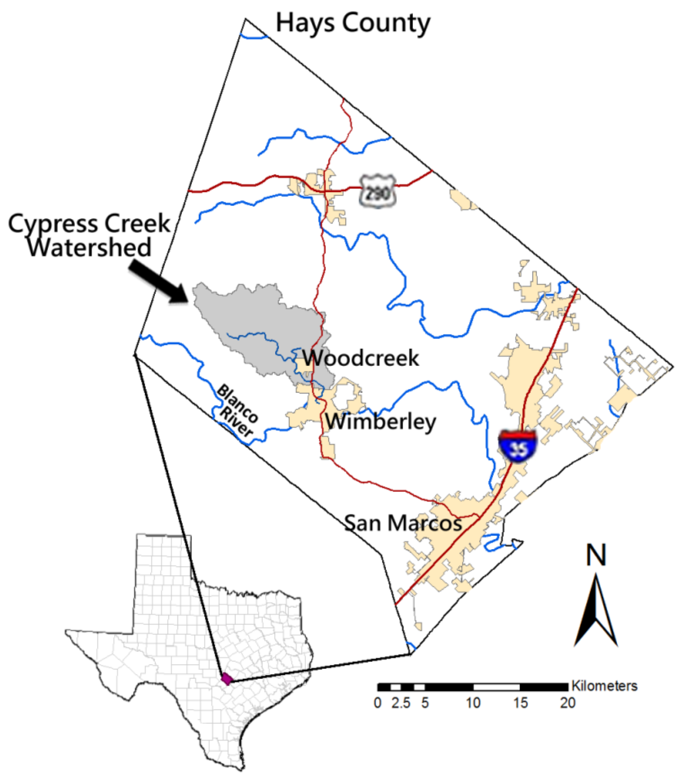

Figure 6.1. The Cypress Creek watershed, located in western Hays County, central Texas.

The hydrogeologic setting in the study area results in a very strong connection between surface and groundwater, to the point where they could be considered a single resource (HTGCD, 2010). Surface streams rely on baseflow from springs and seeps, yet normally dry stream channels often provide recharge to underlying aquifers during precipitation events. Karstic conduits in Cow Creek carbonates are also an important source of discharge to springs such as Jacob's Well that provide baseflow to the Cypress Creek and the Blanco River. Therefore watershed-based management may be appropriate for protecting from flooding and water quality impacts of storm runoff in Cypress Creek. However management for aquifer levels and thus spring flow volumes must be addressed on a regional scale coincident with the boundaries of the Trinity aquifer that are contributing and recharge zones for flows at Jacob's Well and other minor springs that perennially feed the creek.

Because water pollution and water quality management issues cross multiple scales and agency jurisdictions, they are best controlled through cooperative efforts that are coordinated through comprehensive water resource management strategies. However comprehensive management in and around the Cypress Creek watershed is complicated since there is not one governing entity overseeing its development. Agencies with water resource regulation and protection roles include: City of Wimberley, City of Woodcreek, Hays-Trinity Groundwater Conservation District, Hays County, Texas Parks and Wildlife Department, Guadalupe-Blanco River Authority, Texas Commission on Environmental Quality, among others.

Stakeholder Participation

Stakeholder participation in modeling and development of the decision support system (CCP-DSS) took place within the broader context of a community initiative for watershed planning, the Cypress Creek Project (CCP). The Cypress Creek Project is an initiative of the Texas State University River Systems Institute and a coalition of local stakeholders, and is coordinated with technical and research assistance through grants from the Texas Commission on Environmental Quality (TCEQ) and the US Environmental Protection Agency (EPA). The main goal for this project is to ensure that the long-term integrity and sustainability of the Cypress Creek watershed is preserved and that water quality standards are maintained for present and future inhabitants (both human and wildlife). The project aims to keep Cypress Creek clean, clear, and flowing. Objectives of the CCP include watershed characterization, delineation, developing a stakeholder input process, partnership development, and education/outreach. The overriding purpose of the CCP is the creation of a watershed protection plan, as well as the production of science-based information and tools to empower stakeholders to develop such a plan.

As part of this project, the Cypress Creek Watershed Committee was formed in 2009 consisting of local regulatory, municipal, conservation, landowner, scientific, and development interests. Several subcommittees were also formed to address various aspects of watershed planning (water quality, economics, land stewardship, etc.) and one such subcommittee was recruited specifically to participate in DSS development (see Chapter 3 for details on DSS development process). Members for the subcommittee were recruited in the initial Watershed Committee meetings, with additional members recruited to fill gaps in representation and expertise as identified by the subcommittee. Several members of the DSS subcommittee also served on the Watershed Committee. The DSS subcommittee consisted of eleven members representing:

- Hays-Trinity Groundwater Conservation District (groundwater management authority)

- Wimberley Valley Watershed Association (conservation and resource advocates)
- Guadalupe-Blanco River Authority (surface water management authority)
- Texas Parks and Wildlife Department (biological and habitat conservation for public use)
- Texas Stream Team, Texas State University-San Marcos River Systems Institute (citizen science and water quality monitoring)
- Texas State Soil and Water Conservation Board (agricultural extension, rangeland management)
- Texas Commission on Environmental Quality (water quality management authority)
- City of Woodcreek (municipal city council)
- Developers
- Local landowners

The participatory process used with the DSS subcommittee was adapted from the first two stages of mediated modeling suggested by Costanza and Ruth (1998). The process consisted of a series of workshops from September 2009 to August 2010. The scoping phase included activities to address conceptual models of watershed functioning to ensure that DSS assumptions, inputs and outputs are relevant to local issues, developing goals for how the DSS would be used, and to help researchers select an appropriate watershed modeling approach to address these issues. Phase two of the process involved more detailed and realistic attempts to replicate the dynamics of the study area using watershed simulation models. Stakeholder participation in phase two involved reviewing the proposed watershed modeling and DSS framework, providing input on analytical capabilities and structuring output to be most useful and pertinent for development planning. Input from stakeholders to the CCP-DSS included information on: conceptual models of critical factors and interactions; political, economic, and social concerns of importance (development rules and practices, assumptions); objectives for how the DSS will be utilized; target user groups; additional model inputs and outputs desired for decision support; analytical capabilities and user interface design; areas of particular vulnerability in the watershed based on local knowledge and experience, appropriate policies and/or best management practices (for scenario development); goals for watershed management and criteria to evaluate scenarios relative to goals; and how outputs should be structured so as to be most useful. In addition, stakeholders were led through a scenario development exercise that identified best- and worst-case scenarios for the watershed's future to provide a jumping-off point for the scenario evaluation process.

Surveys were conducted with participants in the general Cypress Creek Watershed Committee both before and after the series of meetings. The surveys included a combination of ranking and open-ended questions relating to legitimacy of watershed models, trust in the stakeholder process and other participants, and effective/appropriate watershed management strategies. In multiple-choice questions, respondents were asked to indicate their preference using a 5-category Likert scale, i.e. strongly disagree, somewhat disagree, neutral, somewhat agree, strongly agree. Responses to quantitative questions were scored 1 to 5 such that 1 = strongly disagree, 2 = somewhat disagree, 3 = neutral, 4 = somewhat agree, and 5 = strongly agree. In addition, structured interviews covering the same topics were held with DSS subcommittee members before and after the DSS development process.

Both the surveys and structured interviews were designed to elicit participants' opinions relating to

1) Level of trust in the underlying structure and assumptions of simulation models and their utility as tools for planning;
2) Degree of perceived ownership of simulation models for the local area;
3) Level of trust in the motives of other participants in the watershed planning process;
4) Perceived role of science-based tools for achieving consensus regarding complex problems facing the watershed;
5) Level of satisfaction with current methods of decision-making for water management;
6) Degree of consensus regarding priority issues for watershed management, effective and appropriate management instruments, and barriers to effective long-term management.

Interviews were tape-recorded and transcribed for analysis using grounded theory (Esterberg, 2002; Strauss and Corbin, 1990). This qualitative methodology involves reviewing transcribed data for common themes, and later developing a model of overarching categories within which respondents' themes can be grouped. Grounded theory is not an exact quantitative methodology (though it *is* systematic), rather it is a guideline for exploring qualitative data to reveal potential meanings (Esterberg, 2002). Surveys, which employed a combination of closed- and open-ended questions, were analyzed using both grounded theory and statistical methodologies.

Consensus is important in participatory resource management if the process is to achieve the goals of reducing conflict and future transaction costs. However the classical definition of consensus, the full and unanimous agreement of all parties regarding possible alternatives, is not always achievable and so has given way to the notion of "soft" consensus (Herrera-Viedma *et al.*, 2002). Accordingly, a variety of techniques have been developed to characterize and to measure the strength or degree of consensus (Herrera-Viedma *et al.*, 2002; Tastle and Wierman, 2005). In this study the degree of consensus was determined in two ways, depending on the nature of the question as qualitative or quantitative. For qualitative analysis using grounded theory, the recurrence of similar themes between different respondents was taken as evidence of their agreement on the primacy of those issues; the degree of consensus regarding a particular theme or issue was assumed to be related to the number of respondents that mentioned that theme as important. For quantitative questions that utilized the categorical Likert scale, the degree of consensus was calculated using the consensus measure (Cns) proposed by Tastle and Wierman (2005):

$$Cns(X) = 1 + \sum_{i=1}^{n} p_i \log_2 \left(1 - \frac{|X_i - \mu_x|}{d_x}\right)$$

Where X is any finite discrete random variable with a probability distribution $p(x)$ (i.e. the Likert scale scored 1 to 5), p_i is the probability of the frequency associated with each X, d_x is the width of X, X_i is the particular Likert attribute, and $\mu_x = \sum_{i=1}^{n} p_i X_i$ is the mean of X. This consensus measure ranges from 0 (indicating no consensus) to 1 (indicating complete consensus), and is relatively insensitive to sample size.

Surveys were solicited from all members of the watershed committee and subcommittees before and after the stakeholder process, while interviews were conducted only with members of the DSS subcommittee. The percentage of survey responses received both pre- and post-process was roughly 45% of the total stakeholders involved at the time (pre: n=11; post: n=22). The composition of the committees was somewhat fluid and so the total number of stakeholders involved in the process at any given time changed, but in general total participants increased between the two surveys. The DSS subcommittee composition also changed slightly during the stakeholder process, but the majority of interviewees were the same between the pre- and post- process interviews. There were a total of 9 participants in the DSS subcommittee that were active throughout the process; the number of pre-process and post-process interviews conducted was 8 and 7, respectively.

Responses from the initial and final surveys and interviews were compared to assess the degree of change in stakeholder perceptions regarding the above-listed issues, both for the DSS subcommittee and the general Watershed Committee (whose involvement with CCP-DSS development was often more indirect). The surveys, interviews, and analysis performed in this study were designed to address the question of whether the participatory process will have positive impacts on perceptions of model applicability and legitimacy and will result in a greater consensus regarding priority issues, vulnerable areas, effective and appropriate management policies, and the belief that a positive and mutually acceptable consensus solution may be found. If consensus methods can in fact polarize conflicting groups, then we would expect the opposite effect.

Results

Results for each area of inquiry are summarized below.

1) Level of trust in the underlying structure and assumptions of simulation models and their utility as tools for planning.

In general, survey respondents agreed that computer-based water resource models are based on good science and a sound understanding of the natural system, and that they can provide useful information on which to base planning decisions (Table 6.1). The level of trust in models in general increased, evidence by a mean response of 3.6 pre-process versus 4.1 post-process. Consensus (*Cns*) on this issue increased from 0.66 to 0.78. However, agreement on the utility of models as planning tools was not as strong among this group; mean response decreased slightly from 4.4 to 4.3, and *Cns* decreased by 0.14.

Interview results with the members of the DSS subcommittee (those most closely involved in DSS development) show a somewhat different trend. Among this group, those that stated that models can be powerful and useful tools to assist with local planning decisions increased from 75% of respondents pre-process to 100% post-process. The most common themes among this group prior to the participatory modeling process were 1) an overall belief in the utility of models, 2) that models are generally based on the best current scientific understanding, 3) there is often a lack of adequate high-resolution data to allow their application to the local area, and 4) the dangers of applying a model without sufficient attention to the quality of input data. In addition the theme of trust in both science and the engineers that develop models was mentioned by 75% of respondents. In post-process interviews, the themes shifted away from the limitations of high-quality local input, to the need for clear communication of model inputs and results to the general public in order to see the greatest adoption and overall utility. There was a clear indication from the majority of respondents that even models developed for the local area will not be accepted for use in planning if they are not clearly understood by decision makers and the public, in terms of the type of information needed to produce results (inputs), the basic assumptions and capabilities of the model, and the type of information produced (outputs). In addition the idea that models are all somewhat inaccurate was much more prominent post-process, reflecting a greater degree of understanding of the capabilities and limitations of models beyond a blind faith in the rationality of science. The themes of trust in science and model engineers shifted to the need for trust in a neutral messenger that can explain the inputs and outputs clearly to decision-makers and the public in order to obtain general buy-in.

Table 6.1. Selected results from the grounded theory qualitative analysis. Responses are grouped into common themes and the most common themes are compared for pre- and post-process interviews.

Rank	PRE	POST
Level of trust in the underlying structure and assumptions of dynamic simulation models, usefulness for planning		
1	Models can be important, powerful, useful tools	Models can be important, powerful, useful tools
2	Models are limited by data resolution and current scientific understanding	Important to convey inputs, assumptions and outputs clearly to public to get buy-in
3	Junk in, junk out. Importance of verifying inputs and assumptions to get good outputs	All models are inaccurate, problem of averaging
4	Models are based on good science	Models are limited by data resolution and current scientific understanding
5	Models are constantly improving, always in need of improvement	Models are based on good science
6	Models are neutral, rational	Junk in, junk out. Importance of verifying inputs and assumptions to get good outputs
7	Important to convey inputs, assumptions and outputs clearly to public to get buy-in	Models are constantly improving, always in need of improvement
8	Trust in science and the rational approach	Models can increase understanding of large, complex problems
9	Trust in model developers	CCP-DSS uses good inputs and assumptions and is accurate for local conditions
10	Importance of calibration to local conditions	Importance of calibration to local conditions
Barriers to long-term effective water management		
1	Prior economic investment, expectation of future profits	Socio-cultural attitudes, habits
2	Legal constraints, potential for litigation	Prior economic investment, expectation of future profits
3	Lack of general awareness and understanding	Legal constraints, potential for litigation
4	Lack of regulatory authority on various levels	Lack of understanding cumulative impacts of individual decisions
5	Private property rights	Lack of regulatory authority on various levels
6	Lack of funding mechanisms, cost of implementation and enforcement	Lack of general awareness and understanding
7	Diversity of interests and perspectives	Private property rights
8	Socio-cultural attitudes, habits	Lack of funding mechanisms, cost of implementation and enforcement
9	Fracturing of jurisdictions with inconsistent regulations	Aversion to regulation in any form
10	Inertia, fear of change	Lack of political leadership and will

2) Degree of perceived ownership of simulation models for the local area.

For both groups of respondents, the participatory process appears to have had the greatest impact on perceptions regarding the perceived ownership and utility of models for the Cypress Creek watershed and for aiding local planning decisions. Among those surveyed, agreement that models for the local area are developed with real-world management needs in mind increased significantly, from an average response of 2.9 pre-process (somewhat disagree to neutral) to 4.1 post-process (somewhat agree). Consensus (*Cns*) increased 0.20, the largest increase for any single topic (Table 6.2).

Among interviewees, the majority recognized pre-process that models are often developed by government agencies for management and decision-making on a regional scale, but that the applicability of these models for local decision-making was limited by the model's resolution and the available local data. Some, particularly those from the business and development communities who had little personal experience with using models, felt no ownership of "their" models even though they exhibited a certain degree of trust that the science behind them was rational and substantiated. After the participatory modeling process, there was increased consensus that the CCP-DSS that they helped to develop was methodical, included high quality local data inputs, and would be useful for assisting with planning decisions for the local area. All respondents agreed that the CCP-DSS was improved by the stakeholder input that went into it, and would therefore be of more utility for local decision-making than previously available models. However roughly half of the respondents expressed some question as to whether the CCP-DSS would be utilized by local decision-makers, indicating that there are often considerations beyond science that influence decisions. Many expressed a strong need for continuing efforts to market the CCP-DSS and its capabilities to local regulatory authorities, many of whom were not represented on the DSS subcommittee.

Table 6.2. Results from quantitative survey analysis. Results are based on a 5-category Likert scale scored 1 to 5 (1 indicates strong disagreement, 3 indicates neutral, and 5 indicates strong agreement).

	Mean Response (scale of 1 to 5)			Consensus measure (*Cns*, scale of 0 to 1)		
Area of inquiry	PRE	POST	Change	PRE	POST	Change
Level of trust in models	3.6	4.1	0.5	0.66	0.78	0.12
Models provide useful information for planning	4.4	4.3	-0.1	0.82	0.68	-0.14
Perceived ownership of models	2.9	4.1	-1.2	0.59	0.79	0.20
Level of trust in the motives of other participants	4.2	4.4	0.2	0.73	0.79	0.06
Level of satisfaction with current methods of decision-making	2.8	2.7	-0.1	0.64	0.63	-0.01
Effectiveness of proposed management measures:						
Establishing pumping limits	4.1	4.1	0.0	0.70	0.55	-0.15
Development restrictions	4.2	4.1	-0.1	0.81	0.73	-0.08
Well permits	3.4	3.9	0.5	0.62	0.65	0.03
Regulation thru POAs[1]	3.6	3.4	-0.2	0.76	0.67	-0.09
Restrictions on lawn watering	3.9	4.1	0.2	0.78	0.72	-0.06
Vegetated riparian buffers	3.8	4.0	0.2	0.64	0.77	0.13
Voluntary water conservation	2.8	3.2	0.4	0.72	0.66	-0.06
Voluntary reduction in fertilizer use	3.0	2.9	-0.1	0.63	0.51	-0.12
Construction of wastewater treatment facilities	3.7	4.0	0.3	0.68	0.78	0.10
OSSF[2] regulation	3.6	4.1	0.5	0.72	0.73	0.01
Installing low flow toilets	2.8	3.5	0.7	0.62	0.63	0.01
Xeriscaping	3.6	4.1	0.6	0.70	0.66	-0.04
Acceptability of proposed management measures:						
Establishing pumping limits	3.2	3.2	0.0	0.61	0.65	0.04
Development restrictions	3.6	3.6	0.0	0.65	0.69	0.04
Well permits	3.3	3.0	-0.3	0.55	0.63	0.09
Regulation thru POAs[1]	3.5	3.2	-0.3	0.59	0.65	0.06
Restrictions on lawn watering	3.5	3.7	0.2	0.69	0.69	0.00
Vegetated riparian buffers	3.4	3.6	0.2	0.75	0.65	-0.10
Voluntary water conservation	3.9	3.8	-0.1	0.73	0.55	-0.18
Voluntary reduction in fertilizer use	4.0	3.6	-0.4	0.79	0.53	-0.26
Construction of wastewater treatment facilities	3.3	3.9	0.6	0.65	0.62	-0.03
OSSF[2] regulation	3.8	3.7	-0.1	0.77	0.60	-0.17
Installing low flow toilets	3.8	3.8	0.0	0.73	0.67	-0.06
Xeriscaping	3.5	4.0	0.5	0.81	0.72	-0.09

[1] POAs = Property Owners' Associations
[2] OSSF = On-site sewage facilities

3) Level of trust in the motives of other participants in the watershed planning process.

Across the board, community members both came to the stakeholder process and left it with a strong belief in the good intentions of the people involved. Among the group surveyed, the average response increased from 4.2 to 4.4, indicating a shift toward even stronger agreement that other stakeholders were committed to positive solutions for the community as a whole. There was a great deal of consensus on this issue, too, evidenced by *Cns* measures of 0.73 and 0.79 for pre- and post-process, respectively. The same pattern is clear among members of the DSS group that were interviewed. Early opinions were unanimous that the majority of people involved had the larger interest of the community in mind, although some indicated that there are many different perspectives on what that means and different opinions on how to get there. This perception did not change significantly by the end of the process. However in post-process interviews there were some hints that people who participated in the process early on but with a purely selfish agenda may have quickly left, or did not feel the need to be particularly vocal about their agenda because they did not yet feel like their interests were sufficiently threatened. Overall the participants in the stakeholder process expressed a very strong degree of trust in the motives of other stakeholders at the table. Several participants who had previous experiences with stakeholder processes indicated that they were very impressed with the commitment and positive motives of the vast majority of committee members.

4) Perceived role of science-based tools for achieving consensus regarding complex problems facing the Cypress Creek watershed.

The perceived role of science-based tools for fostering consensus was not directly addressed in surveys but was addressed in the structured interviews. Among interviewees, there was a substantial increase in agreement that science-based tools can be used to build a bridge between different viewpoints by creating a common vision (from 38% pre- to 71% post-process). In general, participants had much more concise ideas on how the CCP-DSS could be used to inform local planning decisions at the end of the participatory modeling process than at the beginning. At the end, the majority felt that the real benefit to using watershed models for development planning lies in their ability to demonstrate cause and effect; to educate decision-makers, business interests and the public on the collective and long-term potential impacts of individual decisions. Many (71%) also felt that the utility of science-based tools is predicated on the clear communication of inputs and outputs in a way that most people can understand, i.e. take the model out of the black box by clearly defining the type of information needed to produce results (inputs), the basic assumptions and capabilities of the model, and the type of information produced (outputs). This feeling was present at both pre- and post-process about equally. However at the end of the process there was an increase among those who mentioned that having a scientific "answer" is not everything, that there will always be additional political, economic, and social considerations involved in decision-making, and that people sometimes either distrust science in general or else distrust the messenger who communicates it. Overall this indicates a more sophisticated understanding after their participation of the complexities involved in watershed management in this area.

5) Level of satisfaction with current methods of decision-making for water management.

When survey respondents were asked about whether current approaches for finding, implementing, and enforcing water management solutions are effective, the average response was 2.8 pre- and 2.7 post-process, indicating an overall dissatisfaction with current management that was not impacted by their involvement in the stakeholder process. Consensus (*Cns*) for this issue before and after the stakeholder process was not particularly strong and decreased slightly, from 0.64 to 0.63 (Table 6.1). The watershed committee process does not appear to have had a substantial impact on people's level of satisfaction or consensus regarding current methods of managing water quantity and quality.

The same pattern is clear among the DSS group interviewed. The level of satisfaction with decision-making on a regional or state level was not impacted at all. Pre-process there was a general consensus that current legal and regulatory approaches to water management are not really effective, specifically to address issues of over-allocation of water supplies (88%). There was general agreement (63%) that rules for managing surface water quality are more effective than those for managing water supply in a way that would ensure adequate water for environmental and recreational uses. After the participatory modeling process, respondents were unanimously positive about the potential of the CCP-DSS to aid in more effective local development planning and management of water quality impacts. The majority continued to cite larger legal issues and the need for comprehensive regional planning to effectively address issues beyond local nonpoint source pollution impacts.

6) Degree of consensus regarding priority issues for watershed management, effective and appropriate management instruments, barriers to long-term effective management.

Results show an overall small decrease in consensus regarding the effectiveness of various management measures presented, although there was increasing agreement about some measures while agreement decreased on others. The largest increases in consensus were for maintaining vegetative buffers in riparian areas (average response pre-process=3.8, *Cns* = 0.64 versus post-process average = 4.0, *Cns* = 0.77) and construction of new wastewater treatment facilities (average response pre-process = 3.7, *Cns* = 0.68 versus post-process average = 4.0, *Cns* = 0.78). The largest decreases in consensus were seen for establishing pumping limits and voluntary reduction in fertilizer use, followed by regulation through Property Owners' Associations (POAs). Average response for the effectiveness of establishing pumping limits was 4.1 both pre- and post-process, but *Cns* decreased from 0.70 to 0.55. Average response for the effectiveness of voluntary fertilizer reduction was 3.0 pre- and 2.9 post-process, but *Cns* decreased from 0.63 to 0.51 (Table 6.1).

Respondents were also asked to indicate the acceptability of these various management measures to stakeholders in the local area. Again there was an overall decrease in consensus regarding this issue, though for some measures *Cns* increased and for others it decreased. Agreement on the acceptability of issuing well permits to landowners decreased from an average score of 3.3 to 3.0, and *Cns* increased from 0.55 to 0.63. The largest decreases in consensus occurred with regards to the practices of voluntary water conservation (pre-process *Cns* = 0.73; post-process *Cns* = 0.55), voluntary reduction in fertilizer use (pre-process *Cns* = 0.79; post-process *Cns* = 0.53), and regulation of on-site sewage facilities (pre-process *Cns* = 0.77; post-process *Cns* = 0.60). In all these cases the average response decreased somewhat, indicating that respondents felt less confident that these measures would be acceptable to the general public. The decrease in consensus level among respondents indicates that these practices are also somewhat controversial.

Both survey and interview respondents were asked open-ended questions regarding the top priorities for watershed. Results show an overall shift in focus among participants from general to more specific goals, with a small corresponding decrease in consensus. Among those surveyed pre-process, people overwhelmingly cited as top priorities the need for better management of groundwater supplies (60%) and for proactive measures to manage population growth and development (70%). In the post-process survey, groundwater management and proactive growth planning are still prominent (37% and 53%, respectively), but public education/outreach and acquiring additional water supplies (surface water or distributed rainwater collection) also came to the top, and there were more topics mentioned only by one or two people. The changing focus is evidenced by a shift from more general statements, like "maintain good ecosystems," to more specific recommendations, like "develop taxing authority for the city." This suggests a positive impact on stakeholders' knowledge regarding the complexity of resource management issues and the multiple ways that could exist to achieve the desired goals. Among interviewees, answers were relatively consistent pre- to post-process. The need to regulate and mitigate the impacts of growth and development was at the top of everyone's priority list. In general there was more clustering of similar responses post- versus pre-process. There were a greater variety of different priorities mentioned at the beginning, while at the end they tended to converge on a fewer number of basic issues: sustainable management of groundwater, increasing access of local and regional authorities to technology and tools like the CCP-DSS, creating funding mechanisms for implementation and enforcement and incentives for compliance, and the importance of rainwater collection as a supplemental water supply. Education dropped from number three to twelve pre- versus post-process, the opposite effect of what was seen among the watershed committee group surveyed.

When respondents were asked about the primary barriers to implementing effective long-term resource management in the Cypress Creek watershed, the level of consensus was generally higher than on specific priorities. In general people seem to be better able to agree on what the problem is than on how to fix it. Among those surveyed there was high agreement both pre- and post-process that legal, jurisdictional issues and the lack of effective funding mechanisms were primary barriers. Education and awareness for the general public and the need for clearer, simpler public relations messaging went from number three to a strong number one from pre- to post-process surveys. The greatest impact therefore was seen on participants' agreement on the need for better education and outreach.

Answers regarding barriers were also very similar among pre- and post-process interviews, although the focus was somewhat different. The top barriers mentioned were the prior economic investment in land and the expectation of future profits from it; legal constraints, taking claims, etc. related to the above; lack of regulatory authority on various levels (state, local, county, groundwater districts, etc.); and strong private property rights attitudes resulting in aversion to regulation. Prior to the participatory process 50% of respondents indicated lack of general awareness as a barrier and 25% attributed it to socio-cultural attitudes and inertia, but post-process only 29% cited lack of general awareness while 57% cited socio-cultural attitudes and inertia. This implies a shift in perception from the problem being primarily due to lack of education, to something more deeply ingrained in the culture of the area.

Discussion

Results from this study show that a participatory (mediated) modeling approach to DSS development helps to create a high degree of buy-in from the stakeholder community, and increases the likelihood that the tool will be adopted and the results given weight in future decision-making. Overall, the impacts on stakeholder perceptions were greater in some areas than in others, and also depended on whether the individual participated in the DSS subcommittee (which was highly involved in CCP-DSS development), or in the general Watershed Committee (whose involvement with DSS development was more indirect). A high degree of trust in the motives of other participants was clear both pre- and post-process, which is likely to have influenced the way that participants perceived the process as a whole.

In general, the level of trust in watershed models and the consensus on this issue increased due to involvement in the stakeholder process. A belief in the utility of watershed models to inform planning was unanimous among the DSS group and consensus was increased by the process, but among the Watershed Committee the feeling was less strong and consensus actually decreased from pre- to post-process surveys. In post-process interviews, respondents' concerns shifted away from the limitations of high-quality local input, to the need for clear communication of model inputs and results to the general public in order to see the greatest adoption and overall utility.

For both groups of respondents, the participatory process appears to have had the greatest impact on perceptions regarding the perceived ownership and utility of models for the Cypress Creek watershed and for aiding local planning decisions. Consensus on this issue increased greatly, and there was a unanimous feeling among the DSS subcommittee that the CCP-DSS was improved by the stakeholder input that went into it. Respondents believed strongly that the CCP-DSS would be of greater utility for local decision-making than previously available models. However there was still some uncertainty among participants as to what degree the CCP-DSS would be utilized by local decision-makers, indicating that there are often considerations beyond science that influence decisions.

Among interviewees, there was a substantial increase in consensus that science-based tools can be used to build a bridge between different viewpoints by creating a common vision. In general, participants had much more concise ideas on how the CCP-DSS could be used to inform local planning decisions at the end of the participatory modeling process than at the beginning, indicating a positive impact on their understanding of the capabilities and limitations of watershed modeling due to their involvement in DSS development.

On the other hand, the stakeholder process does not appear to have had a substantial impact on people's level of satisfaction or consensus regarding current methods of managing water quantity and quality. There was a general level of dissatisfaction with current decision-making processes that was not affected by involvement with the stakeholder committees. In some cases the level of dissatisfaction increased and consensus decreased from pre- to post-process surveys. Although there seems to be a high degree of buy-in to the stakeholder process as a whole, participants evidently feel that decision-making among that group has not yet progressed to a point where it significantly impacts the ability of local and regional authorities to effect positive changes in the way that resources are managed. This could be due, once again, to the fact that the stakeholder process in Cypress Creek has not yet evolved past the scoping phase. It is also possible that increasing dissatisfaction may be due to participants' increased understanding of the difficulties and nuances in resource management through their involvement with the process and exposure to multiple viewpoints. Although the level of satisfaction with current management was not impacted, there was a positive impact on stakeholders' hope for the future, in that respondents were unanimously positive in post-process interviews about the potential of the CCP-DSS to aid in more effective local development planning and management of water quality impacts.

In regards to effective and appropriate management instruments, the overall impact of involvement in the stakeholder process appears to be a slight decrease in consensus, although there was increasing agreement about some measures while agreement decreased on others. This information could be useful going into the next phase of watershed planning and implementation, by allowing the group to focus on those measures that have the highest agreement as to their utility and acceptability in the local area. Voluntary measures, although listed as high priority for some respondents, scored relatively low in their effectiveness and consensus was not very strong about their acceptability.

There was also an apparent decrease in consensus from pre- to post-process regarding the top priorities for watershed management. This decrease in consensus is accompanied, however, by an overall shift in focus from more general goals, like "maintain good ecosystems," to more specific recommendations, like "develop taxing authority for the city." This suggests a positive impact on stakeholders' knowledge regarding the complexity of resource management issues and the multiple ways that could exist to achieve the desired goals. Among members of the general Watershed Committee, there was a significant increase in consensus regarding the need for more education and outreach to the general public, local decision-makers, and business interests. However among the DSS subcommittee, education dropped from priority number three to number twelve, and instead consensus seemed to emerge on a fewer number of basic issues: sustainable management of groundwater, increasing access of local and regional authorities to technology and tools like the CCP-DSS, creating funding mechanisms for implementation and enforcement and incentives for compliance, and the importance of rainwater collection as a supplemental water supply.

Consensus regarding barriers to long-term effective water resource management was more positively impacted than consensus on priorities. The greatest impact in this area was seen in a large increase in consensus among survey respondents that a general lack of awareness and education was the primary barrier to effective management in the area. However among the group interviewed, a more complex picture emerged. In pre-process interviews there was a belief that lack of education was a primary barrier and basic socio-cultural attitudes played a lesser role. Following the participatory process, this perception shifted and socio-cultural attitudes and inertia were cited more often as the primary barriers. This implies a shift in perception from the problem being primarily due to lack of education, to something more deeply ingrained in the culture of the area. Lack of awareness may be addressed by education and outreach, but socio-cultural attitudes are more intractable. This is opposite of the expected result, which was that participants would feel more optimistic about the tractability of resource management problems as a result of their participation. Instead it seems as though, among the DSS group at least, the problems appear to be less tractable to those stakeholders.

Among all respondents there was a strong belief in the good intentions of the people involved both pre- and post-process. Consensus on this issue was likewise strong and increased in the final surveys, indicating that the stakeholder process did positively influence participants' perceptions in this regard. However some participants reflected that the current stakeholder process encompassed only the initial stage of watershed planning, i.e. the scoping and data-gathering phase, and that subsequent phases involving plan development and implementation may be more controversial, meaning that more personal biases and self-interests may begin to emerge.

There was perfect consensus at the beginning among survey respondents that the Cypress Creek watershed is vulnerable to negative impacts from actions taken in the watershed, that the distribution of these impacts is not uniform, and that some areas are more sensitive than others. There was also a strong sense that a consensus-based approach is needed due to the lack of regulatory authority on various levels that can effectively address environmental problems. These ideas and the high degree of trust among participants are likely to have influenced the success of the stakeholder process, making it more effective and more acceptable to those involved.

However most participants agreed that while bringing science-based tools to the process assists in the development of a common knowledge base to work from, the actual outcomes of management decisions are regularly subject to compromise and political maneuvering that may override the benefits of knowledge gained from a more scientific approach such as the one provided by the CCP-DSS. Still, most agree that science-based evaluation of potential development impacts and the translation of these results into easily-understood pictures is a preferable approach to purely anecdotal or opinion-based decisions, and also to scientific information that is inaccessible to most audiences.

Every effort was made during the participatory modeling process to solicit input from a wide range of interests and expertise. The stakeholders who chose to become involved in the DSS development process tended to be highly educated, knowledgeable about technical and political issues critical to decision support, and highly engaged with the process. However this group was self-selected, and ultimately represented primarily regulatory, conservation, and local development interests. The perspectives of individual small land owners or the less-educated general public may not have been well-represented. In addition, the purpose of the surveys and interviews was to gauge the impact that participation in the stakeholder process had on the opinions of those actively involved; therefore no assumption is made of the transferability of these results to the public at large who did not actively participate in the stakeholder process.

In summary, results of this study demonstrate that stakeholder involvement in development of a decision support system for local planning increases participants' perceptions of its legitimacy and utility for local decision-making. However while the stakeholder process might have positive impacts on stakeholder understanding and consensus development in some areas, in other areas consensus may actually decrease. This study demonstrates that the impacts of stakeholder participation are not always consistent and are influenced by many other factors beyond the process itself. In addition, the impacts on stakeholders may change depending upon where in the process the group is. During the early scoping phases, participation may decrease consensus as people move from a more general understanding that there are critical problems to be addressed, to a more nuanced understanding of the scientific, legal, and political complexities of natural resource management.

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CHAPTER VII

CONCLUSIONS AND LESSONS LEARNED

The previous chapters present a case study for the application of a complex adaptive systems approach to development planning on a watershed scale. The need for systemic approaches to water resources planning is clear, given the complex and interrelated nature of the problems and solutions. In this study, a participatory process was conducted with stakeholders of the Cypress Creek watershed, in central Texas, that incorporated mediated modeling, development of a decision support system (DSS), alternative futures and a hydrologic modeling analysis of potential impacts on local water quantity and quality. By scoping the study at a small watershed scale, the analysis and results are presented at a level that is most useful to local decision-makers, those who are directly responsible for managing the intensity and location of new developments.

Ambient water quality data show that the Cypress Creek, as a whole, remains in adequate condition when assessments are based on state water quality standards (see Chapter 2). However stakeholders and experts have agreed that meeting state water quality standards would be insufficient to maintain the desired health and historical nature of the creek as a spring-run stream. Furthermore, no state standards exist for concentrations of sediment and nitrogen for contact recreation, and both anecdotal and measurable evidence show a decline in the quality of these parameters over the last 10 years. Furthermore, water quality in karst spring-fed streams like the Cypress Creek is highly dependent on maintaining aquifer levels that provide adequate spring flows. Future reductions in spring flow volumes are very likely due to the combined forces of 1) rapid development of urban areas dependent on groundwater supplies; 2) continued drilling of personal supply wells that are exempt from pumping regulation; 3) the lack of a single planning authority for surface- and ground-water quantity and quality; and 4) the lack of adequate legal jurisdiction for managing development in rural and semi-rural areas. Many small watersheds in rural and semi-rural areas are experiencing problems with regional aquifer impacts affecting local stream ecosystems, but local jurisdictions (municipalities) who are most affected by these impacts are not able to influence the patterns of growth outside of their borders effectively.

Analysis of alternative development and climate futures for the Cypress Creek watershed (Chapters 4 and 5) show that even at relatively low intensity development, the impacts of increased impervious cover and nonpoint source pollution on flooding, instream flows, and water quality may be significant, particularly when coupled with potential climate changes that result in decreased precipitation and more intense storm events. The potential for impervious cover to decrease soil infiltration and potential groundwater recharge is one of the more significant findings of this study. Simulated potential recharge declined in all alternative future scenarios (up to 92%) with the exception of the limited development scenario coupled with a wetter climate (increased total precipitation plus low-intensity development only). Aquifer recharge is an issue of primary importance in central Texas due to the strong dependence on local groundwater supplies.

A major challenge to incorporating climate change into long-term planning is the high degree of uncertainty in model predictions. This is clear by the various conflicting predictions made by different global climate models. However the fact that uncertainty is inherent in predicting impacts of climate change and its potential interactions with human behavior, economic drivers, urban development, and other anthropogenic changes, does not stop people from making decisions every day about the location and intensity of new developments. A climate scenarios approach, such as presented in Chapter 5, provides a way to address the challenges presented by persistent uncertainty. This method could be applied to other watersheds, provided that the necessary data are available for development of a hydrologic model.

The patterns of development described in this study are not unique to the Cypress Creek area. If regional development trends continue, hydrologic impacts like these could be seen many times over in watersheds across the Hill Country, and cumulative impacts could be substantial. When these impacts are combined with increasing water withdrawals due to population growth plus increases in water demand due to direct climate change effects, water availability for environmental flows and aquatic species could be severely limited. Results from alternative futures analyses can be used to develop policy alternatives that are robust under a variety of likely future conditions.

The participatory process used in this study resulted in both a decision support system product (Chapter 3) and provided new results regarding the utility of participation for increasing stakeholder's trust, buy-in to the process, and degree of consensus around key issues (Chapter 6). Results of the impact study show that stakeholder involvement in development of a DSS for development planning increases participants' perceptions of its legitimacy and utility for local decision-making, and increases consensus for several key issues. In addition, the study revealed that during the early scoping phases of a stakeholder process, participation may actually decrease consensus as people move from a more general understanding that there are critical problems to be addressed, to a more nuanced understanding of the scientific, legal, and political complexities of natural resource management.

Using a mediated modeling approach, as with the Cypress Creek Decision Support System (Chapter 3), provides researchers with a wealth of local knowledge and insight to scope problems and target outputs to local needs. The participatory approach presented here ensures that there will be a high degree of buy-in from the stakeholder community to the resulting DSS, and increases the likelihood that the tool will be adopted and the results given weight in future decision-making. Most participants agreed that while bringing science-based tools to the process helps everyone have a common knowledge base to work from, the actual outcomes of management decisions are regularly subject to compromise and political maneuvering that may override the benefits of knowledge gained from the DSS. Still, most agree that science-based evaluation of potential development impacts and the translation of these results into easily-understood pictures is a preferable approach to purely anecdotal or opinion-based decisions, and also to scientific information that is inaccessible to most audiences.

To apply this method in other areas, there were some key lessons learned that are valuable to note: 1) The importance of strong local leadership; 2) the importance of careful preparation for each and every meeting; 3) patience and a willingness to listen carefully to many different perspectives on an issue; and 4) the importance of clear and concise communication of the science. Strong leadership is critical to provide a community project with the impetus to begin, to bring diverse interests together as a coherent group, and to ensure that efforts continue once the initial participants have left the process. The Wimberley community was fortunate to have several strong local leaders that helped to bring people to the process and to maintain momentum. Researchers coming in from an academic or regulatory agency who wish to perform this type of work must first identify and form strong partnerships with these individuals. Careful preparation for every interaction with stakeholder participants was also found to be very important. In order to maintain the researcher's legitimacy and the trust of stakeholders, it is imperative that one come prepared to every meeting and/or discussion with relevant materials, a well-constructed and efficient agenda, and a demonstrable knowledge of relevant issues. It is also important for researchers to be open to listening to ideas from a variety of perspectives, as well as on issues that may initially seem outside the scope of or tangential to the problem at hand. These tangential issues may turn out to be quite relevant and valuable once they are allowed to be fully fleshed out in discussion. Finally, it is vital that presentations of scientific and technical information be carefully planned in advance, distilled down to the most relevant and digestible information, and targeted to the audience of the day. Figures, charts, and other materials must be carefully constructed to be efficient and clear, without highly technical jargon. As scientists, it is often easy to assume that the most detailed information is the best and most convincing, however when presenting to non-scientists, it was found that this type of information often alienates an audience. Instead, a simple figure and face-to-face explanation is often much more effective.

To date, little work has been done attempting to link the multiple scales and processes that impact water resources in small karstic watersheds like the Cypress Creek. The study presented here is a test case for participatory model development and implementation of a decision support framework to inform watershed management in karstic spring-fed streams, where impacts of continuing urbanization on both surface and groundwater must be considered. Alternative futures analysis provides a means for stakeholders to both see the outcomes of their participation in model development (through interacting with the final DSS product), and to understand how current policies, regulations, and practices could play out in the future and impact both watershed-level hydrologic response and water quality.

APPENDIX A

LAND COVER SCENARIOS

Cypress Creek Watershed – Land Cover Scenarios

The first three land cover scenarios are for the extent and density of development in 25 years. The final scenario, Full Development, represents unrestricted development at 40 years from present. These land cover maps were created using the Land Cover Modification Tool in the AGWA2 software package (Miller et al. 2007). See Chapter 4 for more details on scenario development.

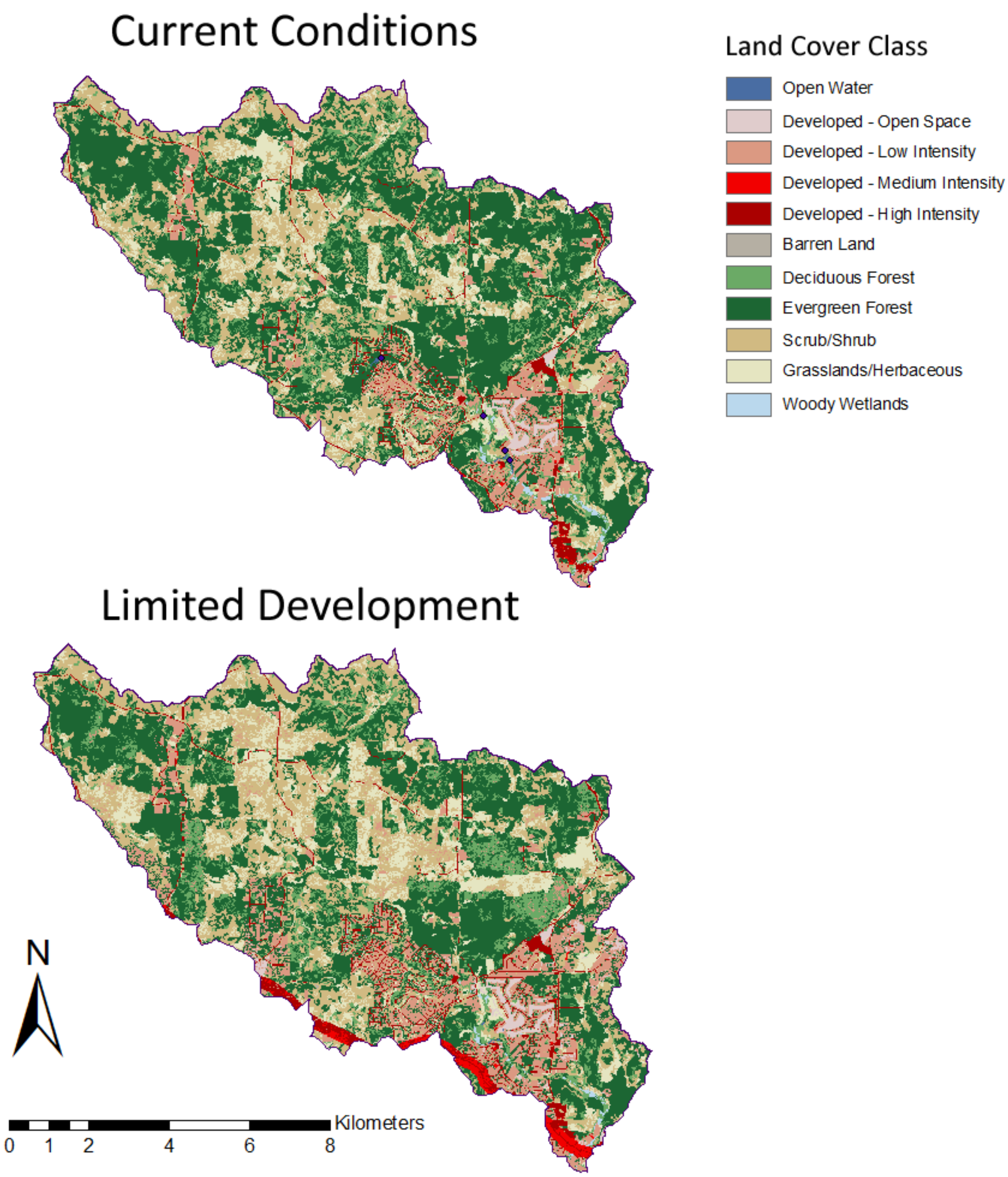


Figure A.1. Current conditions and cover scenarios for Limited, Moderate, and Unrestricted development in 25 years, and Full development in 40 years.

Figure A.1 (continued)

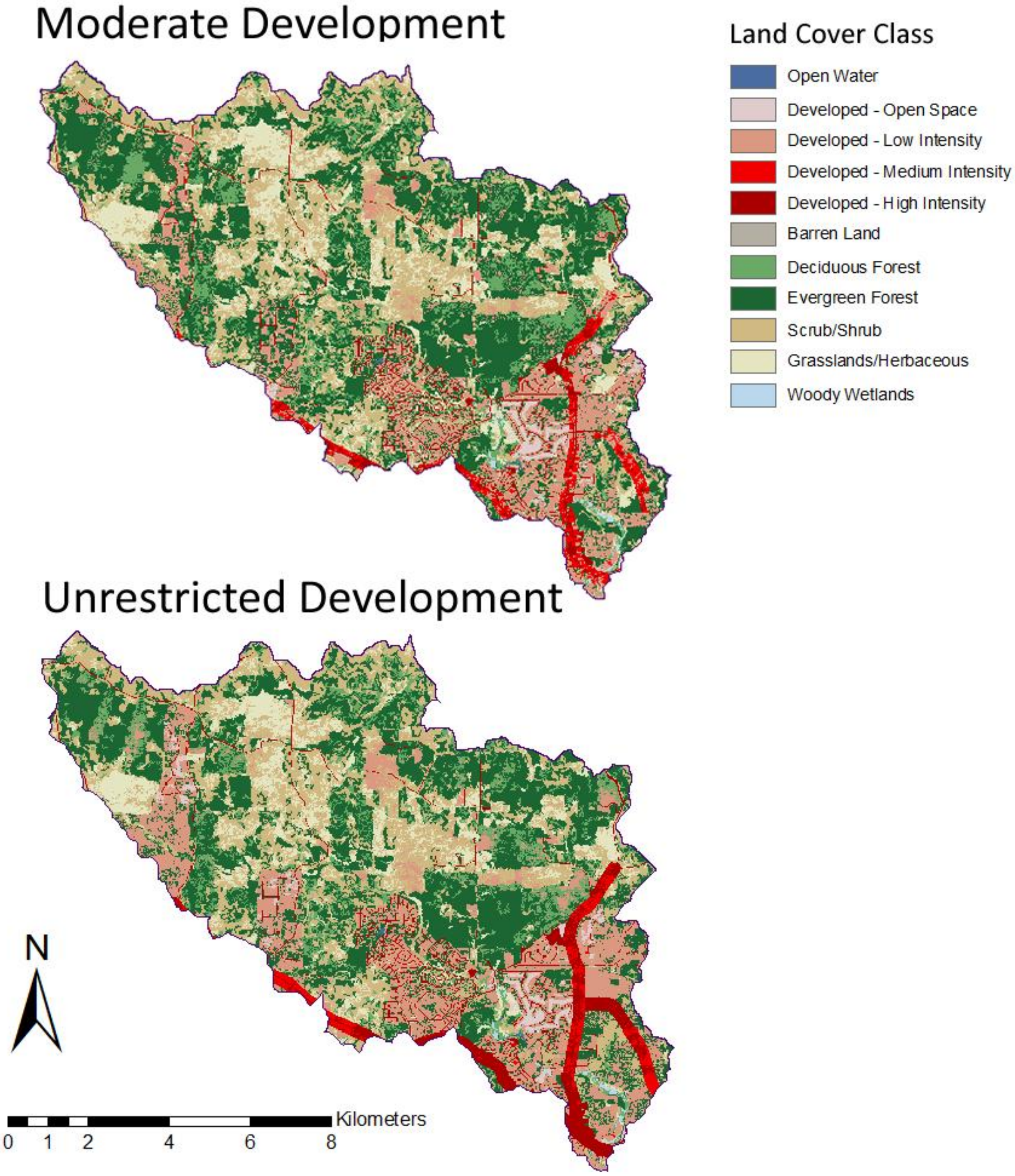
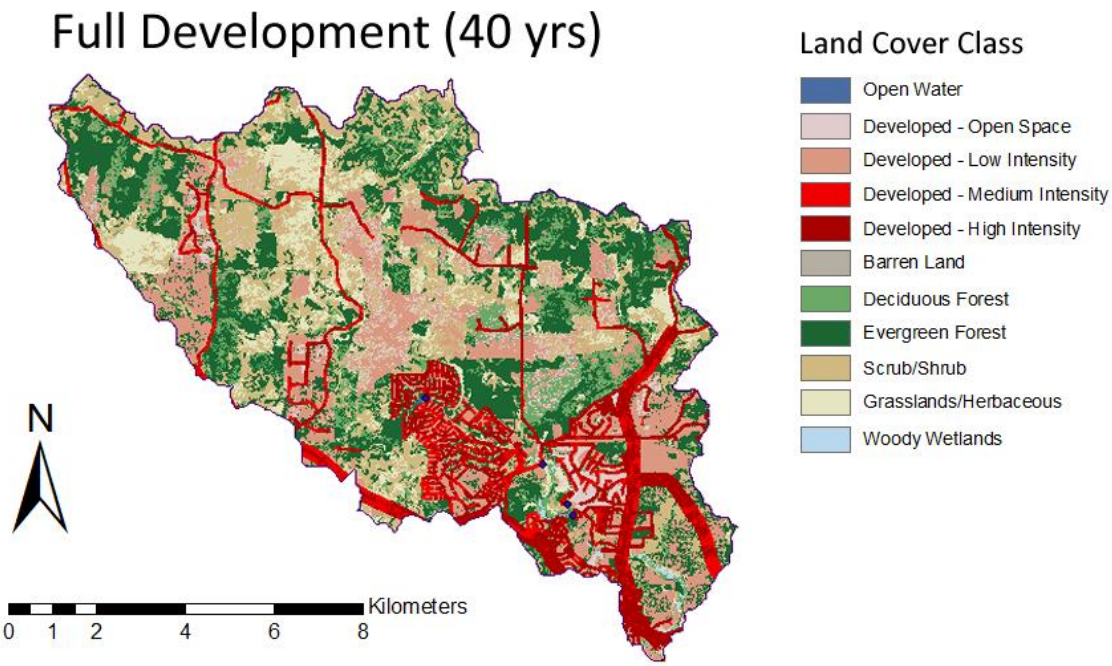


Figure A.1 (continued)



Requests for scenario input from DSS Subcommittee

Letter 1 (email)
Friday 01/08/2010

In our meetings, there has been a lot of talk about different scenarios that could be evaluated using the Cypress Creek DSS. Based on the information I've collected at our meetings, we are developing alternative future land use maps for the Cypress Creek watershed that we will use to model hydrologic and water quality impacts. Our goal is to create a concise set of alternative futures that we can use to demonstrate the functionality of the DSS, both to train you all to use the program and to show the Steering Committee how the final product works.

Before I finalize the alternative future land maps for this next step, I would like to get your input. Think about the best and worst possible future states for the Cypress Creek watershed, both short- and long-term. Please reply by email with your answers to the following questions:

How would you describe the worst possible state for the Cypress Creek watershed in 5 years? The best?

How would you describe the worst possible state for the watershed in 25 years? The best?

Please make your answers as complete, as explicit, and as precise as possible. Be sure to address how you envision future development, BMPs, and/or land management practices in the watershed, as well as in the creek. Please send me your response by Wednesday, January 13.

Thank you for your continuing involvement in this process. I look forward to hearing your input.

Sincerely,
Adrian

Letter 2 (email)
Monday 03/15/2010

Hello,

Attached is a map of potential growth areas and a document that explains several alternative futures for development in the Cypress Creek watershed. Before analyzing these scenarios using the DSS, I'd like to get your input to make sure that we are on the right track. Please respond by Tuesday, March 23 with your comments.

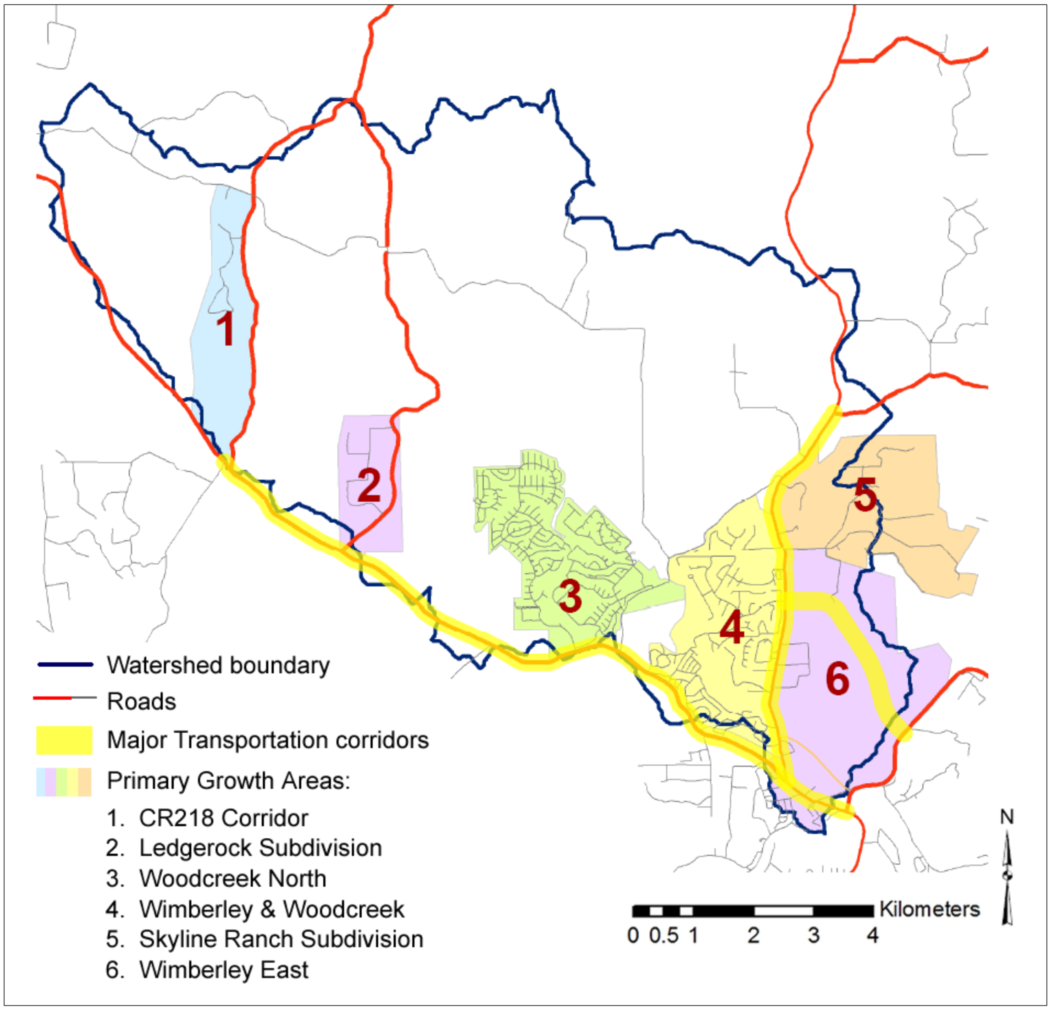
These growth areas and scenarios were created after reviewing input from the DSS/Technical subcommittee, best available data on land uses, subdivision and parcel boundaries, and considering the types of changes that can be analyzed using the DSS tools. These patterns of development were determined irrespective of how water would be supplied to the new homes & businesses (surface- or ground-water, domestic or centralized supplies). The intent of this scenario exercise is to show the potential impacts that development patterns like these could have on the flow peaks during storm events, and the amount of annual pollutant loading to the creek that could result if appropriate mitigation measures are not taken. In addition to surface pollution loading, we will also examine the impact that various levels of groundwater input to the creek may have on water quality. Using these alternative futures, we will demonstrate the functionality of the DSS to the stakeholder committees who will help to determine the next steps to be taken using the tool. The scenario results can also be used as a jumping off point to dive into more specific questions about where and how development should occur in the watershed, as well as where and what types of BMPs are most needed.

Please look over the attached map of potential growth areas. Development areas were delineated based on road networks, Hays County's 2025 Transportation Plan, city limits and extra-territorial jurisdiction areas (ETJs), water and wastewater service areas, and existing parcel boundaries. The attached document summarizes three scenarios that combine different levels of development intensity in the six growth areas. I would greatly appreciate any feedback that you may have on the delineation of these growth areas or the scenarios that I have outlined here. Please send your comments/suggestions by Tuesday, March 23.

Thank you,
Adrian

Letter 2 Attachments: Development scenarios map, Development scenarios summary

Development Scenarios Map



Major growth areas for land cover scenarios. Projected residential and commercial development is concentrated in the colored growth areas and along major transportation corridors. These areas are based on existing road networks, Hays County's 2025 Transportation Plan, city limits and extra-territorial jurisdiction areas (ETJs), water and wastewater service areas, and existing parcel boundaries. Major transportation corridors were defined as 150 m buffers (approximately 500 ft) along both sides of roadways. Outside of these areas land uses are limited to low- and medium- intensity residential.

Development Scenarios Summary[1]

Major development areas in the Cypress Creek watershed (see map):

1. CR218 corridor
2. Ledgerock subdivision
3. Woodcreek North
4. Wimberley & Woodcreek
5. Skyline Ranch subdivision
6. Wimberley East

Transportation corridors: RR12, RR2325, and Winters Mill Pkwy ("Bypass")

These scenarios are for the extent and density of development in the watershed 25 years from now.

"Worst case" scenario:

All major development areas in the Cypress Creek area are built out in residential and commercial land use with no BMPs or stormwater management. Area 1 in residential development with <20% impervious surface cover (ISC). Areas 2, 3, 4, 5, 6 in residential development at 20-40% ISC. RR12, RR2325, and Bypass transportation corridors in high intensity commercial and retail development, 80-100% ISC. Other areas in the watershed remain in large-lot agricultural use.

Middle ground scenario:

70% of lots in Woodcreek North (area 3) are in residential development (20-40% ISC) with some detention ponds. Some low-intensity residential infill in the downtown Wimberley and Woodcreek city limits (areas 4 and 6) but a portion of current open space is maintained. Areas 1, 2, and 5 have half of currently vacant lots built out at 20-40% ISC. RR12, RR2325, and Bypass corridors are kept under 80% ISC with lower-impact commercial and retail developments.

"Best case" scenario:

In areas 2, 3, and 5 only half of currently vacant lots are built out in residential development, but ordinances limit ISC to <20% and detention ponds are required. Major commercial and retail development is limited to the RR2325 corridor. Open/undeveloped spaces in downtown

Wimberley and Woodcreek (areas 4 and 6) are maintained. Portions of these two areas have several large lot holdings set into conservation easements. The western portion of the watershed is left in large-lot agricultural use with appropriate BMPs and well spacing.

Stage II

Groundwater scenarios:

“Worst:” Input to the creek from Jacob’s Well spring decreases, groundwater table drops due to climate change and/or over-pumping of aquifer in contributing area. The spring dries up regularly during the summer months, so the 7Q2* flow essentially drops to zero. Even during wet periods the distribution of 10, 25, 50, 75, and 90 percentile flows is shifted down (i.e. 15-30%)

“Middle:” Input to the creek from Jacob’s Well spring remains at historical levels, with wet years and dry years following recorded distribution (USGS data and other published sources). Historical 7Q2 for flow during dry periods; same distribution of 10, 25, 50, 72, and 90 percentile flows through time.

“Best:” Input to the creek from Jacob’s Well spring increases due to climate change and/or recharge enhancement, conservation, and management practices in the contributing area. Distribution of flows slightly increased (i.e. 15-30%) and 7Q2 increases by 50%.

Each of the above scenarios will also be assessed with various precipitation inputs (very wet year, very dry year, “average” year).

* 7Q2 denotes the lowest average discharge for 7 consecutive days with a 2-year recurrence interval.

References

Miller, S., Semmens, D., Goodrich, D., Hernandez, M., Miller, R., Kepner, W., and Guertin, D. P. 2007. The automated geospatial watershed assessment tool. Environmental Modeling & Software 22: 365-377.

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[1] This scenario summary was provided to stakeholder participants to solicit feedback on the approach taken. The final conceptual scenarios for land use, groundwater, and climate were slightly altered from what was proposed here based on input received from stakeholders and other experts. See Chapters 4 and 5 for more details on the final conceptual scenarios employed in the analysis.

APPENDIX B

INSTITUTIONAL REVIEW BOARD (IRB) DOCUMENTATION

TEXAS STATE UNIVERSITY
SAN MARCOS
The rising STAR *of Texas*

Institutional Review Board

Request For Exemption

Certificate of Approval

Applicant: Adrian Vogl

Request Number : EXP2009N6501

Date of Approval: 05/27/09

Assistant Vice President for Research and Federal Relations	Chair, Institutional Review Board

APPENDIX C

STAKEHOLDER INTERVIEWS AND SURVEYS

CCP-DSS Input Subcommittee
Interview questions (pre-process)

In general, how do you feel about the use of computer models (such as water availability models or water quality models) to inform planning and resource management decisions? Should they be used, or do the costs outweigh the benefits?

Do you believe that existing computer models of the surface and/or groundwater systems in central Texas are based on good science and a sound understanding of the natural system? Why or why not?

Are the methods for finding, implementing, and enforcing policy solutions that have been used currently or in the near past effective to address problems of water management in the Cypress Creek area? Why or why not?

Do you think that science-based tools, like computer models, can help people from diverse backgrounds and interests to arrive at mutually acceptable solutions to complex resource management problems like those facing the Cypress Creek watershed?

Do you think that the majority of people involved in the current stakeholder process for Cypress Creek planning are committed to achieving positive solutions to benefit the community as a whole, or are they driven mainly by self-interest?

In your opinion, what should be the top three priorities addressed in the Cypress Creek watershed management plan?

What do you think are the primary barriers to implementing long-term effective water management strategies in the Cypress Creek area?

How has your participation so far in the stakeholder process for Cypress Creek affected your thinking about community-based resource management?

CCP-DSS Input Subcommittee
Interview questions (post-process)

How would you characterize your level of involvement with the Cypress Creek DSS over the last year (i.e. high, medium, low)? Were you satisfied with this level of involvement?

In general, how do you feel about the use of computer models (such as water availability models or water quality models) to inform planning and resource management decisions? Should they be used, or do the costs outweigh the benefits?

Do you believe that existing computer models of the surface and/or groundwater systems in central Texas are based on good science and a sound understanding of the natural system? Why or why not?

In your opinion, how will the CCP-DSS impact the ability of local and regional authorities to find and implement effective solutions to water management/water quality issues in the watershed?

Do you think that science-based tools, like the CCP-DSS, can help people from diverse backgrounds and interests to arrive at mutually acceptable solutions to complex resource management problems like those facing the Cypress Creek watershed?

What do you think are the primary barriers to implementing long-term effective water management strategies in the Cypress Creek area?

Do you think that the majority of people involved in the stakeholder process for Cypress Creek over the last two years have been committed to achieving positive solutions to benefit the community as a whole, or are they driven mainly by self-interest?

Do you feel that the applicability and/or effectiveness of the CCP-DSS was enhanced by stakeholder participation in its development? Why or why not?

How has your participation in the stakeholder process for Cypress Creek affected your thinking about community-based resource management? About watershed models?

How could we improve this process in the future?

Planning Process Participant Survey

The Cypress Creek Project requests your help by filling out the following survey, and returning it to us at the meeting on June 3rd. The purpose of this survey is to gather participants' opinions on the Cypress Creek and issues of concern, management goals and strategies, and stakeholder planning processes. All responses will be kept anonymous.

These results will help to improve the planning process and decision support tools that will be developed over the coming year. Thank you for your participation in the Cypress Creek Project and this survey.

Please indicate the level to which you agree with each of the following statements:	Strongly Disagree	Some-what Disagree	Neither Agree nor Disagree	Some-what Agree	Strongly Agree
Computer models (such as water availability models) can provide useful information on which to base watershed management decisions.	1	2	3	4	5
Computer models of the surface and/or groundwater systems in Cypress Creek are based on good science and a sound understanding of the natural system.	1	2	3	4	5
Computer models of the surface and/or groundwater systems in Central Texas are developed with the needs of real-world managers and landowners in mind.	1	2	3	4	5
The majority of people involved in the Cypress Creek water planning process are committed to achieving positive solutions to water management challenges.	1	2	3	4	5
The majority of people involved in the Cypress Creek water planning process are driven only by special interests, not the good of the community as a whole.	1	2	3	4	5
It is possible for people from diverse backgrounds and interests to arrive at mutually acceptable solutions to complex problems of water management.	1	2	3	4	5
Current approaches for *finding* policy solutions are effective to address problems of water management in the Cypress Creek area.	1	2	3	4	5
Current approaches for *implementing* policy solutions are effective to address problems of water management in the Cypress Creek area.	1	2	3	4	5
Current approaches for *enforcing* policy solutions are effective to address problems of water management in the Cypress Creek area.	1	2	3	4	5

In your opinion, what are the short-term priorities for managing the Cypress Creek (i.e. 5 years)?

In your opinion, what are the long-term priorities for managing the Cypress Creek (i.e. 15+ years)?

Please rank how *effective* each of the following management practices is for achieving water quantity and quality goals in the Cypress Creek and surrounding areas:
(1 = not at all effective, 5 = most effective)

	Not at all effective	Poor	Fair	Good	Most effective
Establishing pumping limits	1	2	3	4	5
Development restrictions (e.g. minimum lot sizes, impervious cover limits)	1	2	3	4	5
Well permits	1	2	3	4	5
Regulation through Property Owners' or Homeowners' Associations (POAs/HOAs)	1	2	3	4	5
Restrictions on lawn watering	1	2	3	4	5
Maintaining a vegetated buffer along creek channels	1	2	3	4	5
Voluntary water conservation	1	2	3	4	5
Voluntary reduction in fertilizer use	1	2	3	4	5
Construction of wastewater treatment facilities	1	2	3	4	5
On-site sewage facility (i.e. septic system) regulation	1	2	3	4	5
Installing low flow toilets	1	2	3	4	5
Xeriscaping	1	2	3	4	5
Other (please specify):	1	2	3	4	5

Please rank how *acceptable* each of the following management practices is to stakeholders in the Cypress Creek and surrounding areas:
(1 = not at all acceptable, 5 = most acceptable)

	Not at all accept-able	Poor	Fair	Good	Most accept-able
Establishing pumping limits	1	2	3	4	5
Development restrictions (e.g. minimum lot sizes, impervious cover limits)	1	2	3	4	5
Well permits	1	2	3	4	5
Regulation through Property Owners' or Homeowners' Associations (POAs/HOAs)	1	2	3	4	5
Restrictions on lawn watering	1	2	3	4	5
Maintaining a vegetated buffer along creek channels	1	2	3	4	5
Voluntary water conservation	1	2	3	4	5
Voluntary reduction in fertilizer use	1	2	3	4	5
Construction of wastewater treatment facilities	1	2	3	4	5
On-site sewage facility (i.e. septic system) regulation	1	2	3	4	5
Installing low flow toilets	1	2	3	4	5
Xeriscaping	1	2	3	4	5
Other (please specify):	1	2	3	4	5

In your opinion, what are the barriers to implementing long-term effective water management strategies in the Cypress Creek area?

Are there particular geographic areas of the Cypress Creek watershed that are more vulnerable to negative water quality impacts than other areas? YES / NO (circle one)

If so, please describe where these places are and why they are more vulnerable.

In your opinion, what criteria should be considered to determine whether a creek is impaired?

In your opinion, is the Cypress Creek watershed vulnerable to negative impacts on water resources? YES / NO (circle one)

If so, why?

Have you been involved with a stakeholder process in the past? YES / NO (circle one)

If so, was your experience: POSITIVE or NEGATIVE (circle one)

Why?

What did you hope to achieve through your participation?

How would you improve on the process?

Would you be likely to seek out involvement in another such process? YES / NO (circle one)

Why or why not?

Post-Process Participant Survey (online)

How would you describe your level of involvement with the Cypress Creek stakeholder process over the last year? (Low/Med/High)

Did you participate in the DSS/Technical subcommittee? Yes/No

Please indicate the level to which you agree with each of the following statements:	Strongly Disagree	Some-what Disagree	Neither Agree nor Disagree	Some-what Agree	Strongly Agree
Computer models (such as water availability models) can provide useful information on which to base watershed management decisions.	1	2	3	4	5
Computer models of the surface and/or groundwater systems in Cypress Creek are based on good science and a sound understanding of the natural system.	1	2	3	4	5
Computer models of the surface and/or groundwater systems in Central Texas are developed with the needs of real-world managers and landowners in mind.	1	2	3	4	5
The majority of people involved in the Cypress Creek water planning process are committed to achieving positive solutions to water management challenges.	1	2	3	4	5
The majority of people involved in the Cypress Creek water planning process are driven only by special interests, not the good of the community as a whole.	1	2	3	4	5
It is possible for people from diverse backgrounds and interests to arrive at mutually acceptable solutions to complex problems of water management.	1	2	3	4	5
Current approaches for *finding* policy solutions are effective to address problems of water management in the Cypress Creek area.	1	2	3	4	5
Current approaches for *implementing* policy solutions are effective to address problems of water management in the Cypress Creek area.	1	2	3	4	5
Current approaches for *enforcing* policy solutions are effective to address problems of water management in the Cypress Creek area.	1	2	3	4	5

In your opinion, what are the short-term priorities for managing the Cypress Creek (i.e. 5 years)?

In your opinion, what are the long-term priorities for managing the Cypress Creek (i.e. 15+ years)?

Please rank how *effective* each of the following management practices is for achieving water quantity and quality goals in the Cypress Creek and surrounding areas:
(1 = not at all effective, 5 = most effective)

	Not at all effective	Poor	Fair	Good	Most effective
Establishing pumping limits	1	2	3	4	5
Development restrictions (e.g. minimum lot sizes, impervious cover limits)	1	2	3	4	5
Well permits	1	2	3	4	5
Regulation through Property Owners' or Homeowners' Associations (POAs/HOAs)	1	2	3	4	5
Restrictions on lawn watering	1	2	3	4	5
Maintaining a vegetated buffer along creek channels	1	2	3	4	5
Voluntary water conservation	1	2	3	4	5
Voluntary reduction in fertilizer use	1	2	3	4	5
Construction of wastewater treatment facilities	1	2	3	4	5
On-site sewage facility (i.e. septic system) regulation	1	2	3	4	5
Installing low flow toilets	1	2	3	4	5
Xeriscaping	1	2	3	4	5
Other (please specify):	1	2	3	4	5

Please rank how *acceptable* each of the following management practices is to stakeholders in the Cypress Creek and surrounding areas:
(1 = not at all acceptable, 5 = most acceptable)

	Not at all accept-able	Poor	Fair	Good	Most accept-able
Establishing pumping limits	1	2	3	4	5
Development restrictions (e.g. minimum lot sizes, impervious cover limits)	1	2	3	4	5
Well permits	1	2	3	4	5
Regulation through Property Owners' or Homeowners' Associations (POAs/HOAs)	1	2	3	4	5
Restrictions on lawn watering	1	2	3	4	5
Maintaining a vegetated buffer along creek channels	1	2	3	4	5
Voluntary water conservation	1	2	3	4	5
Voluntary reduction in fertilizer use	1	2	3	4	5
Construction of wastewater treatment facilities	1	2	3	4	5
On-site sewage facility (i.e. septic system) regulation	1	2	3	4	5
Installing low flow toilets	1	2	3	4	5
Xeriscaping	1	2	3	4	5
Other (please specify):	1	2	3	4	5

In your opinion, what are the barriers to implementing long-term effective water management strategies in the Cypress Creek area?

VITA

Adrian L. Vogl was born in Fort Worth, Texas, to a family of artists. In 2004 Adrian received a B.A. in Cultural Anthropology from the University of Arizona, with a focus on human-environment interactions. Adrian was admitted to the Aquatic Resources Ph.D. Program in September 2005. She has received numerous scholarships and recognitions including the Durrenberger Scholarship for Women in Science and the Texas State University-San Marcos Associated Student Government Scholarship. While in the Ph.D. program, she has worked as a Research Assistant with the River Systems Institute involved in community-driven watershed protection planning. Adrian's research integrates quantitative and qualitative methods to explore the dynamics of social and ecological change on landscapes where human activity and natural functions are inextricably linked by the flows of water.

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This dissertation was typed by Adrian L. Vogl.