Cypress Creek Project

Draft Watershed Characterization & Report on Initial Findings

Adrian L. Vogl, Vince Lopes, Lori Carter

June 2008

TABLE OF CONTENTS

METHODS

RESULTS

DISCUSSION

APPENDIX 1. DATA INVENTORY

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The Cypress Creek watershed, which flows through Wimberley (Hays County, Texas) is under increasing demands from a variety of sources. The watershed is located between the two major metropolitan areas of Austin and San Antonio and is easily accessed by major roadways (Figure 1). This region is undergoing rapid urbanization. Hays County is listed as the 31st fastest growing county in the United State, and population in Hays county is expected to grow from 97,589 in 2000 to between 130,323 and 573,916 by the year 2040 (TSDC 2004). The two communities of Wimberley and Woodcreek are located within the watershed and their populations have expanded rapidly. Between 1990 and 2000, Wimberley's population grew by 58.01% while Woodcreek's grew by 43.31.

[FIGURE 1]

Such rapid growth over the region's aquifers is already straining groundwater resources. The Trinity Aquifer extends through central Texas from the Red River to the eastern edge of Bandera and Medina counties, and is the primary water source for much of the Hill Country, including development within the Cypress Creek watershed (Figure 2). Therefore development in this area could potentially have a large impact on aquifer water quality, beyond the boundaries of the watershed itself.

[FIGURE 2]

This watershed is a part of the Edwards Plateau region of the Texas Hill Country. The topography of the Hill Country varies from hills of predominantly karstic limestone terrain 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 rain events. Spring fed waterways such as Cypress Creek dissect the hills and also provide recharge to the underlying aquifers. 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).

Peak rainfall amounts in this area occur during May and September (Bomar 1983). Intense downpours are common in the area due to the collision between fronts of warm air from the Gulf of Mexico and cooler eastward-moving air masses. This zone of convective uplift combines with the orographic effects of increased elevations within the region to produce extreme rain events that often lead to flooding (Slade 1986). The steep and sparsely vegetated limestone cliffs respond with low infiltration and high runoff rates. Urban development in the region also contributes to the low infiltration and high runoff rates through increased imperviousness.

Both the climate and the topography contribute to the plant associations in the area. Woody species that occur commonly throughout the Balcones Canyonlands include Ashe Juniper (*Juniperus ashei*), Live Oak (*Quercus fusiformus*), Mexican Persimmon (*Diospyros texana*), Honey Mesquite (*Prosopis glandulosa*), and Texas Oak (*Quercus buckleyi*) (Riskind and Diamond 1986). Grasses commonly found here 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).

The Cypress Creek watershed has a total area of 98 km^2 (38 mi^2) a mean elevation of 350 m (1,148 ft), and a mean annual precipitation of 965 mm (38 in). The watershed has recharge zones throughout. The upper two thirds of the watershed are intermittent and flow only with rainfall. 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. During low flow conditions, Jacob's Well forms the headwaters for Cypress Creek. Water from Jacob's Well flows into the perennial portion of the creek, runs through downtown Wimberley and Woodcreek, and eventually provides inflows to the Blanco River.

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 hillslopes. The remaining ~30 % 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 3). Table 1 gives the types and relative area of soils present in the watershed. Soil classes are based on the Natural Resources Conservation Service (NRCS) SSURGO soils database available online at http://soils.usda.gov/survey/geography/ssurgo/.

[FIGURE 3]

[TABLE 1]

Slopes are higher 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 4). Urban development has thus far been concentrated in the lower third of the watershed around Woodcreek and the Village of Wimberley. Therefore the highest risk for excess sediment flow in the creek due to high slope comes from agriculture (primarily grazing) activities in the upper and northern portions of the watershed, and in bottomland areas the primary threat for excess sediment flow results from development activities and land clearing.

[FIGURE 4]

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 hillsides and, towards the bottom of the slopes, more native grasses can be found. The plateau-like uplands in the western portion of the watershed support woody species such as Ashe Juniper, Texas Oak, and Lacey Oak along with grasses. In the lower portion of the watershed along the floodplain and stream course of Cypress Creek, deciduous stands of Bald Cypress, Sycamore, and Black Willow exist (Riskind and Diamond 1986).

[FIGURE 5]

During dry conditions of July 2000, Jacob's Well ceased to flow for the first time in recorded history, degrading fish, wildlife, and water quality in the creek. Cypress Creek made the 303(d) list for low dissolved oxygen levels for the first time that year. 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 must have exacerbated dry conditions and led to the lack of flow in 2000. 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.

In addition, the underlying aquifers in the region are particularly susceptible to numerous nonpoint source pollutants from development, septic, spray and below ground effluent discharge, fertilizers, and leaking petroleum storage tanks (TCEQ 2008). Future development will only increase the risk of water quality degradation through sedimentation, pathogens, nitrogen cycle impairment, depressed dissolved oxygen, biological impairments and mutations, and habitat alteration and isolation. Development patterns of the area show that septic systems and small package treatment plants will serve as the main means to treat home and business wastewater. Historically, these systems can cause nutrient loading, increase aquifer seepage, change indicator bacteria populations, and lead to eutrophic conditions and depressed oxygen levels. Development will also require increased attention to storm flow and flood management.

OBJECTIVES

The objectives of this watershed characterization study are to 1) summarize available data regarding current biophysical condition of the watershed; 2) develop rainfall-runoff relationships to predict stream flow and pollutant loadings; 3) assess land cover and land uses; and 5) estimate annual NPS pollutant loadings across the watershed.

METHODS

Data collection

Resolving conflicts between ongoing human development and the health of the Cypress Creek requires a collaborative and comprehensive understanding of the dynamic linkages between social, ecological, and historical drivers that affect water quantity and quality in the creek. This requires performing an integrated watershed assessment to build understanding of how the local community and regional institutional framework respond to and affect changes in ecological systems, and how these experiences have led to behaviors that either promote resilience or degrade it. Pahl-Wostl (2005) discuss integrated assessment as a means by which various types of knowledge about a specific problem domain are integrated and made available for decision-making processes. Thus integrated assessment is focused on producing an outcome that will be directly useful to decision-makers in a given context. The key difference between a traditional watershed assessment (i.e. biophysical inventory) and an integrated assessment is the latter's inclusion of social, economic and demographic factors and an examination of linkages between different elements in the social-ecological landscape (Simonsson 2001).

McCammon et al (1998) outline a five step process for characterizing a watershed, identifying important factors, and quantifying changes through time. The first step in the process involves gathering existing data to characterize what is known about the watershed in terms of meteorological, surface- and ground-water, physical and biological factors, and biophysical processes. This step is important in order to set the stage for identifying the most relevant factors that directly influence the quantity, quality, or timing of water. The factors used in this initial characterization are then assigned relative weights based on their potential to influence the quantity, quality, or timing of water flows. The rationale for each weighting is documented. Those factors that emerge as being of highest importance are considered the key or controlling factors. McCammon et al (1998) recommend selecting factors based on the following criteria:

- Directly link to and greatly influence flow, quality, and timing
- Are influenced by management
- Are obtainable (quantifiable and/or qualifiable)
- Reflect the dominant biophysical processes
- Have a definable reference or range of variation over time.

The fourth step in the process is developing a monitoring plan and collecting data that allows for the assessment of baseline and current conditions. The final step is to evaluate any changes between the two, the likely causes for such, and the potential for recovery through management intervention.

This study represents preliminary work towards developing such a comprehensive historical assessment for the Cypress Creek. Therefore the focus of data collection has been to collect and generate information that will inform this assessment of historical and current conditions in the watershed, with a focus on variables that directly link to and influence the timing, quantity, and quality of water resources in the watershed area. Information from existing data sets was compiled to characterize it in terms of

- the underlying geology of the area, dominant soil types and erosion processes
- groundwater/ surface water connections (recharge features, caves, springs)
- the dominant hydrologic characteristics of the watershed

- chemical and physical water quality
- current condition and diversity of aquatic habitats and species
- the types and distribution of vegetation cover and its relationship to soils and topography
- the abundance and distribution of different land uses and its relationship to topography, erosion and flow patterns in the watershed.

In addition, another goal of the assessment is to develop a database for later incorporation into a watershed simulation model and decision support system, therefore a search was made for all available data that are commonly used in landscape simulation or water balance modeling, such as precipitation, streamflow, temperature, soil types, topography, etc. Information on groundwater was included to the extent that it impacts surface flows, such as recharge rates and spring flows. Data on watershed physiography, geology, soils, and human infrastructure is widely available in both GIS and tabular form, though resolutions and coverages vary.

An extensive internet search was done on federal, state, and county level government databases to identify and collect sources of data related to the Cypress Creek watershed physiography, hydrography, surface and groundwater quantity, quality and climate. This includes the US Geological Survey (USGS), US Environmental Protection Agency (EPA), National Oceanic and Atmospheric Administration (NOAA) climate data, Texas Natural Resource Information System (TNRIS), Texas Water Development Board (TWDB), Texas Commission on Environmental Quality (TCEQ), Texas General Land Office, and Hays County. All available GIS coverages and historical data were acquired. All GIS data layers were converted to a common projection, North American Datum 1983 – UTM Zone 14N, using the Project function in ESRI's ArcGIS 9.1. Population and demographic data for Hays County and the Wimberley and Woodcreek areas were collected from the US Census bureau and the Texas State Data Center. Historical and projected water use and demand data was acquired from USGS and TWDB.

Water flow and quality data were acquired for all sites relating to the Cypress Creek and the Blanco River, and a local Microsoft Access database developed for all relevant climatologic, hydrologic, water quality, water use, and demographic data. Data sources for water quality and quantity include the Texas Clean Rivers Program monitoring, the US Geological Survey (USGS) gages at Jacob's Well and on the Blanco River at Wimberley, long-term TCEQ monitoring of the

Creek at Ranch Road 12, and local volunteer bacteria monitoring. A complete inventory of data and sources is given in Appendix 1. A map of site locations and types is shown in Figure 6. [FIGURE 6]

Watershed delineation

Watershed delineation was performed using BASINS, a multipurpose environmental analysis system developed by the EPA's Office of Water. BASINS includes an *Automatic Watershed Delineation* tool that segments a region into several hydrologically connected sub-watersheds for use in characterization and modeling. The tool is based on ESRI's ArcView and Spatial Analyst extension functions and requires a Digital Elevation Model (DEM) raster and, optionally, a pre-digitized stream network. The National Elevation Dataset (NED) 1/3 arc second raster is a seamless mosaic of best-available elevation data from 7.5-minute USGS quadrangles. The area covering the watershed was obtained from the USGS's National Map Seamless Server (http://seamless.usgs.gov). This data set has a resolution of approximately 10 meters, and is processed to filter artifacts and fill missing data at quadrangle seams.

Automatic Delineation was performed using the NED raster and the National Hydrography Dataset's (NHD) high-resolution stream network file. BASINS' automatic delineation uses a threshold method of flow accumulation to delineate hydrologically distinct areas. The threshold parameter may be increased to decrease the number of output basins, or decreased to increase the number of output basins. The threshold value was varied from 33,402 (1.1644/mi^2) to 99,999 (3.4860/mi^2), and the resulting delineation compared to soils and infrastructure in order to choose the best balance between the number and resolution of basins and potential watershed management units. The resulting watershed, sub-watersheds, and stream network files were used to calculate statistics for land use, soils, impervious cover, etc.

Climate & hydrology

Development of precipitation record

The NCDC maintains a large database with over 19,000 sites across the US that report daily surface data (NCDC 2006). An initial selection of precipitation stations was made by plotting latitude/ longitude coordinates of Texas stations in ArcMap and selecting those within

25km from the watershed boundary. Daily precipitation data was collected from NCDC for stations within 25 km of the watershed.

A common method for determining areal precipitation across a basin is through the use of Thiessen polygons, which enables delineation of the contributing area for each weather station relative to other stations, and calculates average areal precipitation across the basin as a weighted average of records from the contributing stations. Thiessen polygons were created in ArcMap using the Create Thiessen Polygons 3.0 script developed by Lomas (2003). Figure 6 shows the contributing area from each station, and details of the three stations whose contributing areas cover the watershed are given in Table 2. Application of the Thiessen polygon method requires a complete record from all stations, which can be achieved by filling records based on a derived empirical relationship between neighboring stations. This is done by developing a linear regression using the basic model:

$$P_{\mathrm{x}} = \alpha_1 P_1 + \alpha_2 P_2 + \cdots + \beta \qquad [1]$$

Where P_{x} is the station with missing record(s), P_1, P_2, etc. are neighboring station(s) with existing records, α and β are the slope and intercept coefficients, respectively. The Fischer's Store station (413156) has the longest and most complete record of daily precipitation, from 01-1896 to 12-2007; the Henly station (414088) has records only from 03-1948 to 11-1965; the Wimberley station (419815) has records from 03-1984 to 12-2007. Daily precipitation from Wimberley and Henly were plotted against Fischer's store to establish a relationship using equation [1]. Only data points where both stations had records and at least one station recorded positive precipitation for that day were included to develop the regression. (Figure 7).

[TABLE 2]

[FIGURE 7]

The weakness of fit between neighboring stations, evidenced by an R^2 value of 0.16 for Wimberley and 0.08 for Henly, means that records estimated using this technique would lead to unreliable results. Because the majority of the watershed falls within the influence of the Wimberley station, this station was used instead as an index gage to represent rainfall over the basin. Wimberley records were used for comparison with recent hydrological data and development of rainfall-runoff relationships. Fischer's Store data were used when a longer record was required, to assess long-term trends in the data.

Hydrograph Separation

Total flow (Q_t) in the Cypress Creek involves two components, surface water (primarily as runoff from storm events, Q_s) and base flow (spring flows from underlying groundwater sources, Q_b):

$$Q_t = Q_s + Q_b \qquad [2]$$

Management of the creek requires knowledge of the relative contribution of these two sources to the total stream flow, particularly because these sources likely have very different contributing areas. Traditional watershed-based management may be appropriate for protecting from flooding and water quality impacts of storm runoff, while management for spring flow volumes and water quality 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. To estimate the relative contribution of base flow and storm runoff in Cypress Creek, daily mean flows at Jacob's Well (USGS gage 08170990) from 04-23-2005 to 04-30-2008 were used. The stream is dry above that point except during storm events, and so this point most directly represents groundwater flow from the aquifer during times of no precipitation plus storm flow from the contributing watershed upstream. The period of record includes much of an exceptionally dry year (2005) and an exceptionally wet year (2007).

The issue of base flow separation has been widely studied in hydrology and there are several methods available for hydrograph analysis. Digital filter methods are used in signal analysis and processing to separate high frequency signals from low frequency signals. These methods were later adapted to hydrographic analysis, because storm runoff often manifests as high frequency waves against a background of low frequency base flow fluctuations (Eckhardt 2005). The model adapted from signal processing (Lyne and Hollick 1979) is as follows:

$$q_t = \alpha \times q_{t-1} + \frac{(1+\alpha)}{2} \times (Q_t - Q_{t-1}) \qquad [3]$$

Where, q_t = filtered direct runoff at time step *t*,

q_{t-1} = filtered direct runoff at *t-1*,

α = filter parameter,

Q_t = total stream flow at time step *t*,

Q_{t-1} = total stream flow at *t-1*.

A problem with the above method is that is assumes a constant stream flow and base flow when direct runoff has ceased (Kyoung et al. 2005). Eckhardt (2005) later proposed a form of the digital filter that takes into account both base flow recession rates and a $\mathrm{BFI}_{\mathrm{max}}$ parameter, which represents the maximum value of the long-term ratio of base flow to total stream flow:

$$b_t = \frac{(1-BFI_{max}) \times \alpha \times b_{t-1} + (1-\alpha)\times BFI_{max} \times Q_t}{1-\alpha \times BFI_{max}} \qquad [4]$$

Where, b_t = filtered base flow at time step *t*,

b_{t-1} = filtered base flow at *t-1*,

BFI_{max} = maximum value of long-term ratio of base flow to total stream flow,

α = filter parameter (base flow recession rate),

Q_t = total stream flow at time step *t*.

Recently, automated programs such as ABSCAN (Parker 2006) have been developed that utilize these analytical methods to estimate daily runoff and base flow given daily total stream flow. The Eckhardt method was chosen for base flow separation within ABSCAN. The base flow recession parameter α is analogous to $q_t = \alpha(q_{t-1})$, i.e. the coefficient of the base flow recession rate. Therefore to estimate α a random selection of storm events were chosen. For the receding limb of the hydrograph only, flow at time t was plotted against flow at t-1, and a linear regression with β (intercept) = 0 was fit. The resulting values of α ranged from 0.967 to 0.984 and averaged 0.98; therefore a value of 0.98 was chosen for α.

Eckhardt (2005) proposed default values of BFI_{max} of 0.25 for perennial streams with hard rock aquifers, 0.50 for ephemeral streams with porous aquifers, and 0.80 for perennial streams with porous aquifers, based on application and calibration on watersheds in Pennsylvania, Maryland, Illinois, and Germany. However there is evidence that the long-term contribution of Jacob's Well flow to the Cypress Creek is even higher. Estimation of BFI_{max} was done by varying the parameter between 0.80 and 0.98, running ABSCAN base flow separator for each value, and comparing the results. ABSCAN produces a daily sequence of mean base flow and storm runoff, which was averaged by month to yield monthly mean flows. For each resulting set of monthly base flows and storm flows, $Q_b$and $Q_s$were plotted against Q_t and a linear regression performed (Figure 8). An inverse relationship is evident between the coefficient of determination (R^2) of $Q_b = f(Q_t)$ and that of $Q_s = f(Q_t)$. On days with no precipitation in the watershed, one may assume that all flow in the creek is base flow. Therefore the flow record was separated into days without precipitation recorded at Wimberley, and those with. The mean flow at Jacob's Well on days with no precipitation is 7.48 cfs; mean flow for all days is 8.14 cfs; therefore the overall ratio of base flow to total flow is 0.92. Base flow separation using α = 0.98 and BFI_{max} of 0.92 was therefore used to develop rainfall-runoff relationships.

[FIGURE 8]

Rainfall-runoff relationships

Predicting runoff volumes as a result of rainfall over an area is important for understanding the behavior of a watershed during storm events, to estimate erosion and NPS pollution generated in the watershed and carried into the stream, and for calibration of runoff and pollution modeling. Once base flow separation is complete, it should be possible to represent total flows by a revision of equation [2] as follows, where both base flow and surface flow are a function of precipitation:

$$Q_t = s(P - P_{0s}) + Q_b$$

$$\text{where } Q_b = \overline{\mathrm{Q_0}} \text{ if } P = 0$$

$$\mathrm{Q_b} = \mathrm{b}(P - P_{0b}) \text{ if } P > 0 \qquad [5]$$

Q_t = daily total flow (in)

Q_{b} = daily base flow (in)

$\overline{\mathrm{Q_0}}$ = median flow on days where P = 0

s = coefficient of the rainfall-runoff relationship

P = daily total precipitation (in)

P_{0s} = precipitation threshold below which runoff = 0 (in)

b = coefficient of the rainfall-base flow relationship

P_{0b} = precipitation threshold below which base flow = 0 (in)

Equation [5] states that base flow has a relatively constant value when there is no rainfall, which may be estimated by the median flow recorded on those days. The median is used in hydrologic analysis because mean values are strongly influenced by outliers and hydrological data is often highly variable and positively skewed, therefore the median is often a more accurate representation of "average" conditions. Equation [5] states that both surface flow and base flow respond linearly to precipitation above a threshold value, one that may be different for each type of flow. Figure 9 shows this model in graphical form for a hypothetical plot of surface runoff versus precipitation.

[FIGURE 9]

For rainfall-runoff analysis in the study area, daily flow data from Jacob's Well were converted to inches (using the basin area delineated above Jacob's Well only) and compared to daily total precipitation at Wimberley. Median flow on days where $P = 0$ was calculated. To estimate the s, P_{0s}, b, and P_{0b}coefficients, base flow separation was performed using data only from days where $P > 0$, and setting $\alpha = 0.98$ and $BFI_{max} = 0.92$. Separated daily base flow and surface runoff values at Jacob's Well were converted to inches and each was plotted against daily total rainfall in inches, and regression analysis performed. The threshold values P_{0s} and P_{0b} are estimated by examining the rainfall-runoff plots, and the slope of the resulting linear regressions provides estimates for s and b. Due to the poor fit of data to this model, an alternative method was used to assess rainfall-runoff relationships using the Curve Number, and the results from these methods compared.

The Soil Conservation Service (SCS) Curve Number method (SCS 1993) is another common method for assessing rainfall-runoff relationships. This method is based on an initial equation developed by SCS using observed trends in hydrologic data from various basins:

$$Q = \frac{(P-I_a)^2}{(P-I_a)+S} \qquad [6]$$

Where Q = runoff (in)

P = rainfall (in)

S = potential maximum retention after runoff begins

I_a = initial abstraction

The initial abstraction (I_a) is generally defined as $0.2S$. Therefore, equation [6] may be re-written as

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \qquad [7]$$

The Curve Number parameter (CN) is a transformation of S that varies from 0 to 100, and it is used to make interpolating, averaging, and weighting operations more linear:

$$S = \frac{1000}{CN} - 10 \qquad [8]$$

The Curve Number is an empirical parameter that may be thought of as representing the combined effects of soils, land use, and antecedent conditions. A higher CN means that a higher proportion of rainfall becomes runoff, and vice versa. Impervious surfaces such as parking lots have a CN of 100, while highly pervious surfaces will have values below 50. Where runoff data is unavailable, CN is often assigned using information on soils, land use, and a lookup table provided by SCS with CN documentation (SCS 1993). However soils-defined CN obtained from the given handbook tables are relatively accurate only for traditional agricultural watersheds, whereas estimations for semiarid rangelands are not as accurate, and those derived for forested watersheds are often least accurate (Hawkins 1985; Hossein et al. 1989). An alternative method for estimating CN has been developed where rainfall and runoff data is available (Hawkins 1993). For this method, daily rainfall and runoff data are ranked from highest to lowest value, which results in data pairs that are "frequency matched," i.e. a rainfall event with a return period of 50 years is matched to the 50 year return period runoff and so on, even though these data may not result from the same storm event. Equation [7] may be solved using the quadratic formula and re-written to express S as a function of P and Q thus (Hawkins 1993):

$$S = 5[P + 2Q - (4Q^2 + 5PQ)^{1/2}] \qquad [9]$$

Separated surface runoff values for days with positive precipitation were frequency matched with daily precipitation from the same data set, and S and CN were calculated using equations [8] and [9]. Calculated CN values were then plotted against rainfall. The resulting curve represents the behavior of a watershed in response to precipitation, and these behaviors may be classified into three categories: complacent, standard, and violent (Hawkins 1993). In most watersheds, CNs calculated using this method approach or maintain a near-constant value with increasing rainfall. This is a standard watershed response, and the resulting asymptotic CN may be used in estimating direct runoff from storms (Figure 10a). Another variation of curve number response is complacent behavior, in which the calculated CN values decline steadily with increasing precipitation depth, and show no tendency toward an asymptotic value (Figure 10b). This behavior has been found to indicate that there is only a partial source area in the watershed that contributes to runoff, and that fraction may be quite small, i.e. 0.1 to 5.0% (Hawkins 1979; Pankey and Hawkins 1981). The third variation is violent response, where calculated CNs increase rapidly and asymptotically approach a near-constant value, which may represent threshold behavior at some critical precipitation value (Figure 10c). The CN curve for

Jacob's Well data was used to estimate a mean CN value for the watershed above that point, and to determine general watershed behavior.

[FIGURE 10]

As part of the Water Availability Modeling system for Texas, TCEQ maintains a database of curve number values for watersheds in Texas. The Guadalupe-San Antonio watershed raster was obtained from TCEQ and georeferenced to the watershed boundaries using the Texas River Basins geodatabase obtained from the Texas Water Development Board (TWDB). Zonal statistics were computed in ArcGIS 9.1 for the Jacob's Well gage watershed to determine the mean curve number. These results were compared to CN estimates developed above, for validation of the asymptotic method. In addition, mean CN was computed for each of the sub-watersheds based on the TCEQ dataset to allow for estimation of runoff from different areas of the watershed.

Land use and land cover assessment

Analysis of land cover change

Urban sprawl can have a profound effect on natural systems. Around growing cities, human culture and natural systems collide. Assessment of changes associated with urban development in areas located within hydrologically and ecologically sensitive watersheds is important to understand the state of the watershed's resources and to plan for future development (Nataluk and Dooley 2003; France 2006). Characteristics of urban sprawl include increased infrastructure such as roads, fire services, utilities, buildings, storm drainage systems, and sewer services. With these comes the conversion of formerly rural or pastoral lands into those with increased impervious surface cover, ISC.

Many studies have been performed on the various effects of imperviousness, the "sum of roads, parking lots, sidewalks, rooftops, and other impermeable surfaces on the urban landscape" (Schueler 1994), on natural systems (Paul and Meyer 2001; Ourso and Franzel 2003; Snyder et al. 2003; Wissmar and Timm 2004; Sadler et al. 2006). In ecologically and hydrologically sensitive areas such as urbanizing watersheds located in karst topography, these effects can be profound. 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 (Veni 1999, Nataluk and Dooley 2003). Therefore, the changes in ISC should be measured and used in projections for future growth and vulnerability. In addition to the hydrologic effects, urbanization has been proven to fragment the landscape, creating loss in biodiversity.

Habitat fragmentation involves the "division of large, contiguous areas of habitat into smaller patches isolated from one another" (Johnson 2001). Habitat fragmentation is a focus for conservation biologists because it can help in creating vulnerable wildlife biodiversity protection strategies (Wilcox and Murphy 1985, McGarigal and Marks 1995, France 2006). Human associated fragmentation causes biodiversity decline because it destroys species (Ehrlich and Ehrlich 1981), changes community interactions (Wilcox and Murphy 1985), and harms evolutionary processes (Levin 1999). The resulting loss is a reduction in biological diversity (Olff and Ritchie 2002) through land transformation (Wackernagel et al 2002). Habitat loss lowers populations through interbreeding (Akçakaya and Sjőgren-Gulve 2001) and isolates communities, which lowers the chance that they will re-colonize (Hanski and Ovaskainen 2000). Research has shown that habitat fragmentation reduces populations by eliminating linkages between habitat patches (Beier and Noss 1998).

In particular, urbanization and accompanying increases in impervious surface cover have been found to be one of the most biologically homogenizing of all human activities (McKinney 2006). Studies have been performed on a range of organisms that have undergone homogenization due to urban development fragmenting the landscape (Dickman and Doncaster 1987, Marzluff 2001, Baker et al 2003). Development, subdivision of larger land tracts, utility easements, boundary fencing, and agricultural activity all contribute to habitat fragmentation and loss (McGarigal and Marks 1995).

Landscape composition, "the relative amount of each habitat type contained within the landscape" (Dunning et al. 1992), includes metrics that "measure the presence, absence, or relative proportions of landscape components" (Turner 1989, Dunning et al. 1992) such as number of patches, average patch size and percent occupation of land cover class types. Wilson and Willis showed that smaller patches were less diverse and created more fragmented landscapes (Wilson and Willis 1975). For this study, land cover in the watershed was characterized and the degree of change from 1996 to 2005 determined, through the use of digitally orthorectified aerial photos and ArcGIS 9.1. The objective was to estimate the degree of fragmentation change in the watershed as a result urban development and land use change.

An interpretation of digitized aerial photographs to assess land cover change over the study area required a composite of several images taken at both the 1996 and the 2005 observation periods. This study utilized remote sensing technology to map land cover in the Cypress Creek watershed through assembled digital orthorectified quarter quadrangles (DOQQs). DOQQs are digital images of aerial photographs that have been corrected (rectified) for distortion that could have been caused by changes in camera angles and varying slopes in terrain. They have both the image characteristics of infrared color photography and geometric qualities of maps (OSU 2002). They represent areas that comprise one quarter of a USGS topographic quadrangle. The DOQQs are projected in the Universal Transverse Mercator grid coordinate system, North American Datum of 1983 (NAD83).

The DOQQs of Wimberley Northwest, Driftwood Northwest and Driftwood Southwest, Rough Hollow Northeast, Southeast, Southwest and Northwest were obtained through TNRIS. They are located in the UTM Zone 14N. The target spatial resolution for the 1996 DOQQ classification was one meter and the target spatial resolution for the 2005 DOQQ classification was two meters. In order to obtain images representative of the whole study area for both observation periods, two mosaics were created using ERDAS Imagine 8.2. Image tone adjustment was performed to reduce the visible tone differences between the input DOQQs. This adjustment drove all input images toward a common value. For this study, the reference pixel values, or reference tone, were taken from the images visually determined to have the best contrast and resolution. In the 1996 set of photos, the Driftwood Southeast DOQQ was selected to be the best image. In the 2005 set of photos, the Rough Hollow Northeast DOQQ was selected.

Seams were created in ERDAS Imagine by determining pairwise "where, within the overedge area, to place the seam line" (ERDAS 2002). Because the 1996 and 2005 mosaics were compiled from seven images each, the best layout was visually determined to be that which had the most alignment between all of the input images. Seam feathering was also performed in the mosaic process using ERDAS Imagine. This was a "tone adjustment performed along a gradation a specified distance out from the seam line" (Biediger 2004). In this study, the appropriate feathering distance was determined to be 500 meters by using ArcMap. All images for the respective observation periods were input and the overlap between the images was measured using the measuring tool. The goal of the seam feathering was to insure that features on the ground that were dissected by more than one DOQQ were represented as a single contiguous field and to "minimize the visible effects of geometric misalignments between digital orthophoto quadrangles, such as an offset in linear field boundaries" (Zhou and Robson 2000). Histogram matching modified the histograms of the six non-reference DOQQs to fit that of the reference image as closely as possible. This created "new histograms for all images and moves the distribution of brightness values" (Richards 1993) so that all images appeared to have the same brightness and a true classification across the mosaic could be performed.

In this study, patch classes were defined as broad land cover classes whose physical traits could be distinguished from one another. After the mosaics were created, unsupervised classification was performed in ERDAS Imagine 8.2 in order to sort pixels into a finite number of individual classes, or categories, based on their data file values. In unsupervised classification, individual pixels were compared to each discrete cluster that had been limited by the user to see which one they were closest to (Short 2007). From this comparison, ERDAS Imagine created a map of all of the pixels in the image classified by the likelihood that the pixels belong to particular clusters. The grayscale maps for 1996 and 2005 were then imported into ArcMap and interpreted.

The newly classified single image was then imported back into ArcMap and overlaid onto the original images. By using the effects tool, each class that was created with ERDAS was checked with the land cover in the images. It was determined that the classes could be reduced to six basic cover classes. In order to insure the accuracy of the new classifications, a simple random sampling was performed of 300 pixel points on each of the new classes. In the 1996 data set, there was an eighty two percent accuracy rate and, in the 2005 data set, there was an eighty six percent accuracy rate. The six cover classes are:

1) Dense Canopy
    - Ashe Juniper, Live Oak, Texas Oak, Bald Cypress
    - Density reflected by highest amount of tree coverage within polygon class
2) Woodland
    - Ashe Juniper, Honey Mesquite, Live Oak, Texas Oak, Mexican Persimmon
    - Less dense than previous class, still defined by woody species

3) Park/Riparian
    - Bald Cypress, sedges, woody species
    - Distribution of woody species more interspersed than previous two classes
    - Savannah-like topography with intermix of grasses and trees
4) Dense grasses
    - Little bluestem, King Ranch bluestem, Purple three-awn, Curly mesquite, Ashe Juniper saplings
    - Open swaths of grasslands, deep color in aerial image analysis
5) Sparse grass and bare soil
    - Open exposed portions of soil, rocky outcrops, escarpments
    - Sparse grasses interspersed throughout
6) Impervious surface cover and developed land
    - Roads, rooftops, parking lots, storm flow systems

Once these categories were checked for accuracy, GIS Spatial Analyst extension and the Spatial Statistics tools were used to quantify the structure of land cover at the watershed level for each of the two time periods (1996 and 2005). The raster data were vectorized with Spatial Analyst, and the Spatial Statistics Utilities tool was then used to calculate the area coverage for each of the six classes. After that, summary statistics were performed in ArcCatalog to find the total number of "patch" polygons, and average area for the polygon "patches".

It is important to note that water was not classified. Parts of the creek that are intermittent were dry in both observation periods. The perennial portion of the creek has overhanging canopies and was not easily discernible in the aerial image analysis. Because both images did not have a classification for water, change in land cover would be reflected along the same trajectory. The results from the two years were compared to each other in order to show the change over time.

For visual representation of the land cover classes and their spatial relationship, several other layers were imported into ArcMap. These layers included political information on city limits and county boundaries and street centerlines from the Capital Area Council of Governments (CAPCOG 2008a,b); hydrological data for the 12 digit HUC layer from the National Hydrology Dataset (NHD); elevation information for the National Elevation Dataset from the USGS Seamless server; and soil mapping units and special feature coverage types from the National Resource Conservation Service of the USDA Soil Data Mart server.

Development of land use data layer

Developing estimates of NPS pollution generated in the watershed requires knowledge not only of hydrologic processes, but also detailed knowledge of land uses and other pollution-generating activities. A study was done in 1996 on the NPS pollution generation in the Corpus Christi Bay area, and land use was used as the primary predictor for estimates of Event Mean Concentrations of pollutants in the watersheds (Baird et al. 1996). In order to obtain estimates of NPS pollution in the Cypress Creek watershed, a land use data layer was developed using the Hays County parcels GIS dataset obtained from the Capital Area Council of Governments (http://www.capcog.org/Information_Clearinghouse/Geospatial_main.asp), produced in 2005.

County-level parcel data includes tax assessment information such as land value, improvement value, and a State Property Tax Board (SPTB) code that identifies land uses. Tax appraisal data has been used by the City of Austin to develop 2003 and later Land Use GIS Inventories, as they have proven to be significantly more efficient and accurate then using aerial photography. The City of Austin's study area included a good portion of Hays County (but not the Cypress Creek watershed), and their quality control process found that Hays County's expanded SPTB code proved overall to be an accurate record of land uses (City of Austin 2005). In addition, appraisal land use codes correspond more readily to land uses in available estimates of NPS pollution generation than do land cover classes such as those used in the National Land Cover Dataset.

Parcels with missing land use data were first assigned codes by referencing mosaicked 2004 DOQQs obtained from the USGS seamless server (http://seamless.usgs.gov/) and the USDA common land unit spatial dataset obtained from the USDA-NRCS Geospatial Data Gateway server (http://datagateway.nrcs.usda.gov/). The common land unit (CLU) dataset consists of digitized farm tract and field boundaries identified through aerial photography analysis. The USDA Farm Service Agency defines farm fields as agricultural land that is delineated by natural and man-made boundaries such as road ways, tree lines, waterways, fence lines, etc. This data layer is useful because it often includes multiple tax parcels in a single polygon which have been identified as having a common land use, which assists in filling missing records for one or more of the component parcels.

All parcels were then assigned a general land use code based on the specified SPTB code and filled records. Hays County SPTB codes present in the watershed include:

- Single-Family Residential
- Multifamily Residential
- Vacant Lots and Tracts
- Qualified Agricultural Land
- Non-qualified land
- Farm and Ranch Improvements
- Commercial
- Utilities

General land use codes were taken from Baird et al. 1996, and include Residential, Open/Undeveloped, Cropland, Rangeland, Commercial, Industrial, and Transportation. Hays County SPTB codes Single- and Multi-family Residential were coded as Residential; Vacant Lots and Non-qualified land were coded Open/Undeveloped; Commercial and Utilities were coded as Commercial; no Industrial/Manufacturing parcels were present in the study area. It is often difficult to distinguish between Cropland and Rangeland using aerial photos. Given that much of the watershed is covered by thin, rocky soils and hilly topography, there is a relatively small area under cultivation and the primary land use in open areas is grazing. Therefore all Qualified Agricultural land and Farm and Ranch Improvements were coded as Rangeland. In the cases where a parcel was assigned two codes, such as Qualified Agriculture/Farm Improvements, the primary land use code was used. The exception to this was for parcels coded primarily as Non-qualified land (which would be classified as Undeveloped) and secondarily as Residential or Farm Improvements. In this case a general land use code was assigned by referencing the 2004 DOQQs and adjacent parcels. Finally, parcels which primarily covered roads were coded Transportation based on comparison with DOQQs and a Hays County roads layer.

A union of the finalized land use data layer and the sub-watershed layer was created, and relative area calculated for each land use category and sub-watershed using the Union and Calculate Areas functions in ArGIS 9.1.

Water quality assessment

Urban NPS pollution is generated by deposition, accumulation, and washoff by surface runoff. Runoff from urban areas generally includes suspended and dissolved solids, bacteria, metals, oxygen demanding substances, nutrients, oil and grease, and pesticides. NPS pollution sources include vehicles, construction activities, fertilizer and pesticide application, erosion, animal wastes, and atmospheric deposition. NPS pollutants associated with agricultural areas include nutrients, pesticides, organic matter, and animal wastes, and are transported in solution, suspended in surface runoff, or adsorbed onto eroded soil particles (Baird et al. 1996).

Browne (1989) provides an overview of NPS pollution that stresses the following:

- Nonpoint sources are diffuse, cover substantial areas, and act either in response to human activity or as “background pollution” from natural lands.
- NPS pollution is related to land management, geologic, and hydrologic variables which may vary over time. Only the land management factors may be controlled by society.
- NPS pollutants are generated and transported as part of the hydrologic cycle. Surface runoff transports eroded soil particles from pervious areas, and picks up and transports pollutants deposited on impervious areas. Groundwater transports pollutants from septic tanks and landfills.
- Urban runoff includes suspended solids, bacteria, metals, oxygen-demanding substances, nutrients, and oil and grease. Sources of these pollutants include vehicles, fertilizer and pesticide application, animal wastes, construction activities, and road salting.
- Non-urban pollutants are often related to agricultural activities. Agricultural pollutants include pesticides, sediments, nutrients, and organic materials. NPS loading from agricultural areas tends to be seasonal with higher loading associated with planting and harvesting activities.

Descriptions of Selected NPS Constituents and Water Quality Parameters

Suspended Solids is the concentration of suspended material in water. Suspended solids interfere with the transmission of light, affecting aquatic vegetation and the overall health of the ecosystem. Suspended solids also provide transport for other pollutants including organics and metals. Suspended solids are often related to the amount of erosion occurring in a watershed.

Dissolved Solids consist mainly of silica, calcium, magnesium, sodium, potassium, carbonate, bicarbonate, chloride, and sulfate, and trace quantities of other organic and inorganic constituents. Dissolved solids concentrations are often used as an indicator of water quality, since high values of dissolved solids affect taste in drinking water and may limit the use of water for irrigation or certain industrial applications.

Nitrogen (N) containing compounds that are most important, from a water quality standpoint, are: organic N, ammonia, nitrate, nitrite, urea ($CO(NH_2)_2$), and nitrogen gas (N_2).

Nitrate (NO_3) is indicative of fertilizer use.

Nitrite (NO_2) and organic species are indicators of pollution by sewage or organic waste.

Ammonia (NH_3) is generally a product of compounds containing organic nitrogen including sewage. Unionized ammonia is toxic to fish and other aquatic animals and consumes oxygen as it is converted to nitrate. At pH below about 9.2, ammonia nitrogen is largely of the form NH_4+.

Total Phosphorus (TP) includes dissolved and suspended phosphorus in both organic and inorganic forms. Orthophosphates (inorganic) are associated with fertilizers. Organic phosphates are formed primarily by biological processes. In instances where phosphate is a growth-limiting nutrient, the discharge of phosphates into a water body may stimulate excess growth of algae or other organisms in nuisance quantities.

Copper (Cu) is potentially toxic to many species of fish. Sources of copper include pesticides and water pipes and plumbing fixtures.

Zinc (Zn) is widely used in metallurgical processes. Zinc is an undesirable contaminant for some aquatic species even at low concentrations.

Lead (Pb) based paints and older water pipes and solder are sources of lead contamination. Although the use of leaded gasoline has declined, large quantities of lead, accumulated in soils, are a potential source of pollution to ground and surface waters.

Cadmium (Cd) is used for electroplating, for pigments, as a stabilizer for PVC plastic and electrical batteries. Many of these uses will tend to make the element available to water that comes in contact with buried wastes.

Chromium (Cr) groundwater contamination has occurred in many localities where chromium is used in industrial applications.

Nickel (Ni) is an important industrial metal, used extensively in stainless steel.

Biochemical Oxygen Demand (BOD) is a measure of the amount of oxygen required by aquatic organisms to decompose biodegradable organics during a five day test period. BOD pollutants deplete oxygen from the aquatic environment and affect the ability of the water body to support its desired usage (aquatic life, recreation, etc.).

Fecal Coliform bacteria are present in the feces of warm blooded animals and are indicators of bacteriological water quality. Coliform concentrations are measured in number of bacteria colonies per 100 ml of sample (Baird et al. 1996).

Specific Conductance (SC) is a measure of how well water can conduct an electrical current. SC is an indirect measure of the presence of dissolved solids such as chloride, nitrate, sulfate, phosphate, sodium, magnesium, calcium, and iron.

Dissolved oxygen (DO) is necessary for good water quality. Natural stream purification processes require adequate oxygen levels in order to provide for aerobic life forms. If DO levels in water drop below 5.0 mg/L, aquatic life experiences stress.

Water quality monitoring in the Cypress Creek is performed at 5 sites along the creek, from Jacob's Well to the confluence with the Blanco. No systematic water quality monitoring or flow data have been collected 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. Data from 12-03-1973 to 01-09-2008 were analyzed in this study, and provides the best long-term dataset for surface water quality in the creek. The Jacob's Well site (12677) has been sampled monthly from 08-08-2002 to present, and continuously (USGS#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 12-27-05; and at the confluence with the Blanco (12673) sampled from 08-08-2002.

Texas Stream Team sites are sampled monthly or bi-monthly, and data through June 2007 were used in this study. Where discrepancies exist between data provided by Texas Stream Team and the TCEQ database, data from TCEQ was used for analysis. Values below detection limits were replaced with 50% detection limits. All TCEQ and Texas Stream Team sites include instantaneous flow data and the following water quality parameters: temperature (^{o}C), dissolved oxygen (mg/L), specific conductance (umhos/cm), pH (SU), total nitrogen (mg/L), total phosphorous (mg/L), total suspended solids (mg/L), ammonia (mg/L), E. coli (colonies/100mL). Ortho phosphorous (mg/L), total dissolved solids (mg/L), and fecal coliform were sampled infrequently at various sites. A more extensive dataset of fecal coliform is provided by a volunteer bacteria monitoring program that has sampled five sites along the creek (Jacob's Well, Woodcreek, RR12, Blue Hole, and downtown Wimberley) semi-monthly from 10-13-1971 to 04-07-2008. No time-averaged flow data are available at the creek's outlet. This represents a serious limitation to establishing runoff volumes from the lower watershed, to assessing changes in flow as a result of ongoing urbanization, developing estimations of NPS pollution and determining assimilative capacity of the creek.

For this study, data from site 12674 at downtown Wimberley were analyzed for long-term trends in water quality, while data from Texas Stream Team sites were analyzed for spatial trends.

Estimate NPS pollutant loadings

Estimates of event mean concentrations (EMC) of various agricultural and urban NPS pollution constituents are given in Baird et al. 1996. These values have been used in several studies in Texas when localized EMCs are not available. Although the Cypress Creek watershed has a good record of pollutant data for the watershed, these values have not been separated into the contributions from component land uses. In addition some parameters, such as metals and BOD, are not included in the current data set. For that reason, EMCs given in the Baird et al. NRCS study were used to estimate pollutant loadings in the study area (see Table 3). The goal of this study is to develop an initial screening model to provide loading estimates for geographic comparisons, rather than absolute NPS loadings.

[TABLE 3]

Mean annual runoff depth is calculated using the mean CN for each sub-watershed and the mean annual rainfall at Wimberley (38.029 in). Mean CN for each sub-watershed are given in Table 4. Runoff depth is then converted to runoff volume $(\frac{m^3}{yr})$ by converting to meters and multiplying by the total area of the sub-watershed. EMC values for constituents given in µg/L were converted to mg/L, and bacterial EMCs converted to colonies/L. EMCs for land use-constituent combinations for which no estimates are provided are not included in loading estimates. Also, EMC values below detection limits (i.e. <0.01) also were not included. NPS loadings for each constituent are calculated as the sum of EMCs for each land use multiplied by runoff volume and scaled by the relative area in each land use:

$$l_x = \sum(0.001EMC_{x1} * Q * a_1) + (0.001EMC_{x2} * Q * a_2) + \cdots + (0.001EMC_{ax} * Q * a_{n*}) \qquad [10]$$

Where l_x = annual loading of constituent *x* $(\frac{kg}{yr})$

EMC_{x1} = event mean concentration of constituent *x* from land use 1 $(\frac{mg}{L})$

Q = runoff volume $(\frac{m^3}{yr})$

a_1 = percent of watershed area in land use 1

For loading estimates on bacteria, the following variation of equation [10] was used:

$$bl_x = \sum(1000EMC_{x1} * Q * a_1) + (1000EMC_{x2} * Q * a_2) + \cdots + (1000EMC_{ax} * Q * a_{n*}) \qquad [11]$$

Where bl_x = annual loading of bacteria type *x* $(\frac{colonies}{yr})$

EMC_{1a} = event mean concentration of bacteria type *x* from land use 1 $(\frac{colonies}{L})$

Q = runoff volume $(\frac{m^3}{yr})$

a_1 = percent of watershed area in land use 1

The results are then converted to unit loads (per unit area) given the formula:

$$L_x = \frac{10\,000 * l_x}{A} \qquad [12]$$

Where L_x = annual unit loading of constituent *x* (kg/ha/yr); or bacteria *x* (colonies/ha/yr)

A = total area of sub-watershed (m^2)

RESULTS

Watershed and sub-watershed delineation

Automatic delineation in BASINS using default settings and an outlet point at the creek's confluence with the Blanco River resulted in 21 sub-basins. The threshold parameter was increased and outputs compared against soils and human infrastructure to find a good fit between basin boundaries and potential management units, and a final value of 48,126 (1.6777/mi^2) chosen, resulting in 17 sub-basins (Figure 11a). Sub-basins were assigned a watershed ID (WS_ID) by which they are referenced in subsequent analyses. Additionally, an outlet was drawn at Jacob's Well, and the watershed delineated above that point. This information is necessary for comparison with hydrologic data from the USGS gage at the Well, because this point represents outflow from only 64% of the total watershed area that drains to the Blanco (Figure 11b).

[FIGURE 11]

[TABLE 4]

Climate & Hydrology

The mean annual precipitation at Wimberley is 965 mm (38.0 in); and at Fischer's Store it is 851 mm (33.5 in). The difference in long-term means at these two stations is probably due to two factors: 1) the period of record at Fisher's Store includes the drought of record in the 1950s and Wimberley does not; and 2) a west-east gradient of increasing precipitation exists throughout Texas, and the Fisher's Store station lies approximately 16 km west of Wimberley. Annual mean P is highly variable from year to year (Figure 12), making responsible management for water resources in this area critical. Climate in the study area follows the general pattern of the Hill Country, in that peak rainfall amounts occur in the summer and fall. At the Wimberley gage, 24% of annual rainfall occurs between May and June, while 21% occurs between October and November (Figure 13). A linear regression fitted to monthly and annual mean rainfall data at Fisher's store shows a slight upward slope (0.15), indicating a potential trend toward higher precipitation values in recent years. However these trends are highly influenced by lower than average rainfall in the early part of the record (i.e. 1950s) and higher than average rainfall in the latter part of the record (i.e. 2004 and 2007). Because of the high degree of variability in rainfall between years and the low coefficient of determination for the regression ($R^2 = 0.07$), it is unlikely that this apparent trend is accurate. However there is evidence that the climatic regime has been more variable in recent years. A 2-sample test for equality of variances (Systat 11.0) shows a significant difference ($p < 0.001$) in the variance of monthly precipitation in inches at Fischer's Store between the period 1941-1979 (mean = 2.725 in; variance = 4.855; n = 455) and 1980-2007 (mean = 3.026 in; variance = 7.578; n = 332).

[FIGURE 12]

[FIGURE 13]

Base flow separation and rainfall-runoff

For all data points, total flow plotted against precipitation shows no apparent linear relationship between these two variables ($R^2 = 0.06$). Flow at Jacob's Well ranges from 0.0007 to 0.0981 inches when there is zero rainfall, and from 0.0034 to 0.1001 inches at 2 inches precipitation. 99.5 percent of data points fall between 0 and 2.1 in of rainfall. Median flow at Jacob's Well for days where $P = 0$ is 0.0054 in (3.50 cfs).

The time series of separated base flow and runoff for days with precipitation only is shown in Figure 14.

[FIGURE 14]

Separated base flow and surface flow for days where $P > 0$ were then plotted against precipitation. One high outlier of $P = 7.3$ in was removed; all other values of P were less than 3 in. Linear regression analysis resulted in the following relationships:

$$Q_b = 0.0052P + 0.0128 \text{, when } P > 0 \; (R^2 = 0.03) \qquad [13]$$

$$Q_s = 0.005P + 0.0015 \; (R^2 = 0.10) \qquad [14]$$

No discernible threshold value was observed, and the fit of the regressions was very poor (Figure 15).

[FIGURE 15]

Because of the poor fit of data to the regression model described above, the SCS Curve Number method was also used to estimate surface runoff as a result of precipitation. Using frequency-matched data from Jacob's Well, CN was calculated for all days where $P > 0$, and the results plotted against rainfall (Figure 16). If one were to fit an asymptotic curve to the calculated CN values, the value would fall at approximately 33 (between 25 and 42). TCEQ data for the Guadalupe-San Antonio basin show a mean CN of 33.3 for the watershed above Jacob's Well, a value that falls in the middle of our estimate range. Therefore a curve number value of 33.3 was used to estimate daily runoff as a result of rainfall. For the regression method, the sum of Q_b and Q_s, using equations [10] and [11], were used to estimate Q_t when $P > 0$; the median flow value of 0.0054 was used when $P = 0$. Both the regression and the Curve Number methods resulted in estimated values of Q_t that were overstated during low flow conditions (Figure 17). While the CN method greatly overestimates peak flows, the regression method underestimates them. Runoff values generated using CN may be thought of as *potential* runoff from the watershed, but because of rapid infiltration and the presence of sinks and recharge features much of this flow never reaches the watershed outlet as surface runoff. However some of this water may travel as subsurface flow and be included in base flow at Jacob's Well or farther downstream in the Blanco River.

[FIGURE 16]

[FIGURE 17]

Land cover change

[TABLE 5]

Dense Canopy and Woodlands

Dense canopy patch count increased slightly, whereas patch area was reduced by 5% and average patch size was reduced slightly. This cover type experienced the most drastic reduction in coverage area among all cover types. That could be attributed to several factors. As land use needs are changing in this urbanizing watershed, trees are being cleared or relocated. This can be seen in the increase in number of woodland patches and decrease in total woodland coverage. For this study, woodland patches had trees that were spread out slightly more than the dense canopy class and, if some of the trees from the dense canopy class have been removed, it would be reclassified as woodlands. However, the percent coverage that woodlands occupy in the landscape was also reduced by 3.4%. This could mean that both cover types were replaced over the nine year period.

Open Park and Riparian

The number of patches for this cover type was reduced by 22%, whereas average patch size and percent of watershed coverage increased significantly. Watershed coverage for open parks and riparian vegetation appears to have increased the most of all coverage types with a change of 5.8%. This could be correct or, it could be an inaccurate reflection of true land cover change over the watershed. If it is correct, open parks and riparian coverage replaced other coverage types such as woodlands, dense canopy and dense grasses. Agricultural portions of the watershed, such as crop fields, are included in this category and farm owners could have acquired adjacent parcels of land or consolidated production into larger units. However, this number may reveal a shortcoming of aerial image analysis, variations in vegetative moisture content. It could have been wetter during the 1996 observation period, which would have recorded as darker vegetation, or “dense grasses”. It also reveals a flaw in the classification system which used different standards of classification for “open park and riparian” and “dense grasses.”

Dense grasses

The numbers of patches, average patch size, and percent of watershed coverage all decreased. If this is an accurate reflection of true land cover change, dense grasses such as King Ranch bluestem and silver bluestem were reduced in both count and areal extent. This could be due to land management practices, such as a controlled burn. If it was removed by fire, either natural or prescribed, it could reflect as “open parks” with early successional, lighter forbs and wildflowers. It could also have been converted from dense, natural grasslands used for grazing to bare soil, sparse grasses or developed lands. The techniques in this study do not reveal the precise reason for the 4.9% reduction in watershed coverage for this land cover class.

Sparse grasses and bare soil

These coverage types experienced a 4.5% increase in total coverage area and a slight increase in average patch size, whereas there was a slight decrease in number of patches. There could be several causes for the increase in percent coverage area. An increase in erosion could increase the amount of sparse grasses and bare soil. The steep terrain of the upper portion of the watershed lends itself to erosive factors which would create new areas of low vegetation and act as “unifying” agents for formerly fragmented sparse and bare soil coverages. Possible overgrazing of ranchlands could have depleted the supply of natural grass cover and left swaths of bare land. Brush management through removal and controlled burns could also increase the coverage area by reducing the number of trees and shrubs. Brush removal for development could also open up these areas. The increase in area covered by sparse grasses and bare soil over the watershed indicates that there was a conversion from one coverage type (likely woodlands or dense canopy) into land that is more susceptible to erosive factors such as overland flow, rainsplash, and compaction.

Impervious surface cover and developed land

An increase in impervious surface cover can cause increased fragmentation of landscapes that were formerly contiguous patches of vegetation. As subdivisions, roads, and utilities spread into formerly rural areas, they act as agents of fragmentation. ISC and developed land patch size was reduced by 3.45%, but total number of patches and percent occupation increased by 2.03% and 3%, respectively. One reason why ISC patch size could have appeared to shrink and number of patches seemed to grow during the time between observation periods is an increase in tree canopy size. When parking lots, roads, and new homes are first constructed, saplings are often used in the landscaping. As the canopies grow, they could appear to replace the impervious surface cover. One limitation of using aerial photography to classify land cover is this dilemma. Because of this, broad generalizations can be made by looking at the *percent* change in land cover metrics over time. The three percent increase in area covered by ISC and developed land indicates that there was, in fact, an increase in development.

Land Use

Land use in the Cypress Creek watershed is predominantly Rangeland (69.528 km^2; 70.6%), followed by Open/Undeveloped (15.657 km^2; 15.9%), Residential (9.213 km^2; 9.4%), and Transportation (2.501 km^2; 2.5%). Commercial land uses are concentrated in and around downtown Wimberley and Woodcreek, and comprise only 1.6% of the total watershed area (1.588 km^2) (Figure 18). Table 6 gives types and relative areas of land uses found in each of the 17 sub-watersheds delineated above.

[FIGURE 18]

[TABLE 6]

The focus in this study was on filling missing data and producing a complete record of land uses in the watershed. However some discrepancies exist between the 2005 appraisal data layer and aerial photos. Some areas coded as Vacant Lots with no improvement value had buildings clearly visible on DOQQs. Others coded as Qualified Agriculture were small (i.e. < 1 acre) lots that were adjacent to or surrounded by other parcels coded as Residential. Further quality control measures will need to be taken to ensure that coded land uses represent actual conditions with the greatest possible accuracy. Transportation includes most major roadways and new developments; however there is some degree of error there as well, because in some cases roads cut across larger parcels and so are included in other land use categories. This is especially true in the more rural northern and western parts of the study area. In addition, in some cases where roadways were designated as separate parcels, the parcel often included a right-of-way or easement, which resulted in the Transportation land use areas being overstated in those cases. To improve the representation of Transportation land uses, the polygon layer will need to be edited to separate roads from adjacent polygons, and to exclude easements from existing polygons. The land use data developed here will need to be further ground-truthed and these discrepancies addressed before the data is to be used in calibration of watershed models.

Water quality assessment

Overall water quality in the Cypress Creek is relatively high, though data reveal both spatial and temporal trends that may be due to climate variability or changes in land use and/or management in the watershed. Median temperatures are lowest at Jacob's Well (20.6 ^{o}C) and at Blue Hole (20.3 ^{o}C), where spring flows provide fresh inflows of groundwater to the creek (Figure 19a). There is increasing variability in temperatures as you move downstream from the headwaters, and the highest median temperature is at the Blanco site (21.25 ^{o}C). The highest temperature recorded was 28.0 ^{o}C in July 1978, at RR12 in downtown Wimberley. This falls just below the TCEQ standard of 30 degrees maximum temperature for the segment. pH generally increases as you move downstream from Jacob's Well (Figure 19b), and specific conductance generally decreases (Figure 19c). Dissolved oxygen varies considerably from site to site (Figure 19d), and remains above the 6.0 mg/L standard for exceptional aquatic life use in 98% of samples taken in downtown Wimberley (n=124). There is some spatial variation in DO from site to site, with only 92% of samples at the Blanco confluence exceeding 6.0 mg/L (n=48), and only 38% taken at Blue Hole (n=13). Low DO values (below 4.0 mg/L) were recorded at both RR12 (12676) and at Blue Hole (12675) during the summer of 2006, when flow dropped to below 0.5 cfs at those sites. Dissolved oxygen is particularly sensitive to flow volumes, especially when temperatures are high, and therefore it is critical to maintain flow in the creek in order to maintain a healthy aquatic system.

[FIGURE 19]

Total suspended solids (TSS) are lowest at Jacob's Well, and peak at Blue Hole (Figure 20a). The two sites along RR12 have the highest recorded values of TSS. TSS is often an indicator of erosion in the watershed, and Ranch Road 12 is a major corridor for both transportation and urban development in the area. Blue Hole, an area with frequent recreational use, also exhibits high median value for TSS. At site 12674 in downtown Wimberley, long term trends in TSS appear to show a slight decrease over the period of record, however the slope is essentially zero (Figure 21). In an undeveloped watershed, one would expect that TSS would have a direct relationship with flow, as higher flow volumes have greater force to carry sediment than lower flows. However Figure 21 demonstrates that TSS also peaks at times when flow volumes are lower, indicating excessive erosion occurring at those times. This supports anecdotal evidence of highly turbid waters being observed as a result of recent construction activities or dredging in the channel.

[FIGURE 20]

[FIGURE 21]

Nutrient constituents like nitrogen and phosphorous, which are of concern in residential and urbanizing areas, remain below screening levels. Median nitrogen concentrations are highest at Jacob's Well (0.34 mg/L) and lowest at Blue Hole (0.04 mg/L), though relatively high concentrations have been measured at all sites (Figure 20b). Over the long term, nitrite plus nitrate nitrogen shows a slight increase at site 12674 through the period of record, though the slope of the line is slight (0.00002). More significantly, there is an increasing variability in values measured (Figure 22). Although the median value decreased, there is an increase in the 75th and 95th percentiles and a greater scatter of data in the period 1999-2007 than in the previous period. This means that data exhibits higher high and lower low values during the last eight years than in the previous record. This increasing variability is not seen in the flow record from the same site, indicating that land management factors play a role in the observed change. Phosphorous appears to exhibit the same trend, though because over half of all samples taken are at or below screening levels, statistical analysis of variability should be approached with caution.

[FIGURE 22]

Bacteria levels, both E. coli and fecal coliform, are of concern because they affect contact recreation in the creek, and may be indicative of contamination from septic systems or animal wastes in the watershed. Although median values remain below the screening level of 394 colonies/100mL, higher values than this have been measured for both types of bacteria (Figure 20d and e). High values (>2400) of E. coli have been recorded at Ranch Road 12 upstream, Blue Hole and at the Blanco confluence, and high values of fecal coliform (>2400) at the downtown square in Wimberley. Even at Jacob's Well, bacteria levels above 1000 colonies/100mL have been recorded. Therefore bacterial pollution poses a potential problem along the length of the perennial Cypress Creek. Additional screening above Jacob's Well would be useful to determine if bacteria presents a water quality problem in storm flows in the ephemeral creek as well. Unlike low DO, however, the highest E. coli counts have been recorded in spring and fall, coincident with times of higher precipitation and storm flows.

Estimate Pollutant Loadings

[TABLE 7]

Results of loading analysis on sub-watersheds indicate that pollutant loads associated with urban and transportation infrastructure are generally concentrated in the lower part of the watershed. This includes most heavy metals, like nickel, copper, and zinc. Nitrogen loading and biochemical oxygen demand (BOD) are highest in urban and sub-urban areas as well. Total suspended solids are highest in areas with a large proportion of land in impervious surface cover and transportation, particularly in the southwestern portions of the watershed.

Estimates of pollutant loads are based on runoff volume estimation using the Curve Number method. As noted above, runoff based on these estimates may not reach the creek because of losses throughout the watershed area, evidenced by the poor fit between rainfall-runoff models and observed conditions. Therefore pollutant loads calculated using this method represent potential loadings generated in the watershed, and are intended as a screening model to allow for geographic comparisons and prioritization of watershed areas in terms of NPS pollution constituents. In addition, pollutants generated in the watershed will have a direct impact on groundwater quality because of rapid recharge through the karst topography.

[FIGURE 23]

DISCUSSION

Pollutant Sources

Assessment of water quality data indicates that bacteria loading and excessive erosion are currently the primary issues of NPS pollution concern in the watershed. Although excessively high levels of nutrient pollutants, like nitrogen and phosphorous, have not been recorded, the increasing variability and occurrence of higher than normal values during periods of low flow indicate that the creek may be experiencing increasing loading of these constituents as urban areas expand. Further data collection and monitoring will help to determine if these trends continue.

Likely sources of NPS pollution in the watershed include on-site septic treatment, residential landscaping, fertilizer and pesticide application, land clearing for new construction, pet and livestock wastes, runoff from roads and parking lots, grazing activities, and recreational use of the creek. NPS pollution sources associated with urbanizing areas include on-site septic treatment, which remains the primary method of wastewater treatment in many areas of the watershed. It is not known how future developments will treat wastewater, but an increase in septic systems is likely, particularly in unincorporated areas. NPS pollution associated with residential land use includes the application of fertilizers and pesticides for landscaping. In addition, the removal of native vegetation and land clearing for new construction can increase erosion and runoff and decrease available habitat for native fauna. Urban areas and associated transportation networks increase runoff and are associated with higher levels of suspended and dissolved solids and metals. According to estimates from Baird et al. 1996, residential land use is the highest source of nutrient-based pollutants like nitrogen, phosphorous, and thus biochemical oxygen demand. Commercial land uses are associated with higher levels of heavy metals. Recreational use of the creek by humans and pets may contribute to sediment flow, bacteria, and nitrogen levels in the creek, particularly in areas where there is heavy recreational use such as Blue Hole.

Assuming similar pollutant concentrations, larger volumes of runoff per unit area associated with impervious surface cover result in larger mass loads of pollutants for urban areas versus rural areas. In addition to an increase in impervious surface cover in urbanizing areas, the installation of drainage systems and concrete channels can result in pollutant loadings being delivered to the creek faster and in greater concentrations than in areas with natural drainage systems (Novotny and Olem 1994).

Rangeland generates higher levels of suspended and dissolved solids. In addition, potential loading results from animal wastes and increased erosion from soil compaction and vegetation removal. Therefore the upper areas of the watershed require different management activities to control excess sediment production than do urban areas where excess nutrients and metals represent a greater problem.

Climate & Hydrology

Examination of the calculated CN curve (Figure 16) indicates that the watershed above Jacob's Well exhibits complacent behavior as described by Hawkins (1993) and seen in Figure 10b, which indicates a partial source area condition. This means that there are significant areas of the watershed above the Well that are not contributing to measured flow at the outlet. Because of the relatively small size of the catchment (63 km^2), it is likely that much of this direct runoff is lost through rapid infiltration to the karst topography. This is supported by the weak relationship between P and flow measured at the watershed outlet. If the watershed exhibited a more standard response (i.e. Figure 10a), one would expect a tighter fit between rainfall and runoff. Although direct runoff generated in the watershed may not reach Cypress Creek through overland flow, it may travel as subsurface flow and re-appear as base flow in the creek or in the Blanco River. Therefore pollutant loads generated in the upper portions of the study are may still have a very direct impact on subsurface flows, recharge, and groundwater quality.

Increasing variability in precipitation measured at Wimberley is not mirrored in instantaneous flow data from 1973 to present. However comparison between these flow values and total precipitation is problematic because measurements represent only instantaneous flow, rather than time-averaged flows (i.e. daily means). Although flow recorded at site 12674 shows a relatively consistent relationship with flow in the Blanco River downstream of Cypress Creek (approximately 9%, R^2=0.49, n=115), this comparison is somewhat suspect because we are comparing instantaneous flows in the creek to averaged daily flows in the Blanco. A flow gage at the Cypress outlet that records daily mean flows would greatly enhance the ability to create a verifiable relationship between Blanco and Cypress flows, and therefore to estimate historical flows in the creek as well. This information will greatly enhance our understanding of rainfall-runoff relationships in the watershed and make runoff volume predictions more accurate.

Land use & land cover

Land use in the watershed is predominantly rangeland, with the combined residential, commercial, and transportation uses accounting for 13.5% of total area. However much of this 13.5% is impervious surface cover (estimated at 9% through DOQQ analysis, and is concentrated at the southern and eastern portions of the watershed. Increased impervious surface cover has been proven to alter hydrologic and ecologic functioning. In this study, impervious surface cover increased by three percent over the watershed and increased by fifty percent of its former coverage in nine years. This is likely to have altered watershed functioning from the previous less developed states. Additional analysis will need to be done to determine the spatial patterns of this change across the watershed, though it is clear that most urban development has occurred in the lower portions of the watershed around Wimberley, Woodcreek and Woodcreek North, and much of the projected development is expected to occur in these areas along major transportation routes such as RR 12.

Changes in land cover between 1996 and 2005 are consistent with an urbanizing watershed. Overall, an increase in impervious cover 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. There is also some indication that clearing of previously forested areas may have occurred, though conclusions are not entirely reliable given limitations of the remote sensing approach used for analysis.

One of the biggest problems with digitized aerial imagery analysis is the lack of ground-truthing. When assessing land cover change and habitat fragmentation, detailed and coordinated information from the ground is ideal. Performing vegetation and habitat inventories and cross referencing them with aerial imagery would provide more answers to questions that were left unanswered in this study. However, time and financial resources were limited. Therefore, a rudimentary analysis of general cover change was sufficient in answering the big question of: Was there change?

Habitat fragmentation involves a number of spatial matrices that were not performed in GIS and ERDAS Imagine. The spatial arrangement of the patches and the movement or trends of fragmentation could reveal more about the functioning of fragmentation in this area. Average patch size is not the most reliable index of habitat fragmentation. As patch numbers decrease, average patch size based upon the coverage area could reflect inaccurate trends in connectivity. If the coverage area stays the same or is reduced to slightly less than the previous proportion, it will appear that average patch areas have increased. This could be misconstrued as an opening up of habitat. Instead, a more geometric analysis, such as Jaeger’s Effective Mesh Size method (Jaeger 2000), could be performed. This would statistically reveal more about the likelihood that species could meet one another on a landscape scale.

Landscape fragmentation caused by anthropogenic activity can have profound effects on biotic communities, ecological processes, and hydrologic functioning. The measures utilized in this study provide a launching point for further investigation into the habitat fragmentation of the Cypress Creek watershed. The shift between endangerment and extinction is tenuous, especially in karst regions such as the Texas Hill Country. Many species have evolved to their highly specialized niches of cave systems, steep slopes, and shallow soils. The threat to these systems is high from the increased pressure of urbanization. Protection of biota in interdependent ecosystems such as the Balcones Canyonlands is key to the proliferation of functional ecosystems.

Water quality and pollution monitoring

Although water quality remains relatively high in Cypress Creek, there are indications that pollutant loads may be increasing due to changes in land use and land cover, and perhaps to an increase in large storm events and associated runoff. Bacteria currently present the greatest threat to water quality based on available data. Monitoring for heavy metals and other urban pollutants is not being done continuously, however studies indicate that these constituents are not currently a threat to water quality. Seasonal or yearly monitoring for these pollutants in highly urbanized areas of the watershed (i.e. sites 12676, 12675, 12674, 12673) would help to determine if and when these do become a problem.

The apparent partial source area condition for runoff measured at Jacob's Well means that CN estimates, and therefore estimates of surface runoff and pollutant loadings, may be unreliable because the watershed does not respond to rainfall in a standard fashion. However preliminary results from gain/loss studies indicate that there is little gain or loss in the creek from the headwaters to the outlet. Therefore much of the runoff that is lost to rapid recharge in the watershed may reappear quickly downstream as springflow and subsurface flow. The Cypress Creek is highly unusual in that flow is currently monitored at the headwaters of the creek but not at the outlet. Typical hydrologic techniques are primarily designed for analysis of data at a watershed outlet, making it difficult to generate an accurate picture of the hydrology of the study area. Installation of a gage at the watershed outlet is critical to better understand the behavior of the watershed as a whole, to establish runoff volumes from the lower watershed, to assess changes in flow as a result of ongoing urbanization, to develop accurate estimations of NPS pollution, and to determine the assimilative capacity of the creek.

In addition, storm flow monitoring of runoff rates and pollutant concentrations above Jacob's Well would be greatly beneficial for determining the actual runoff amounts generated in the upper watershed from different size storms. Storm hydrographs and pollutographs for both the watershed above Jacob's Well and at the confluence with the Blanco will be important to characterize the watershed for flood studies and to calibrate pollution loading models.

A rain gage at the upper area of the watershed would be highly beneficial, to have a more complete record of rainfall over the watershed and contributing area. These values could be compared to and averaged with data from the Wimberley station to have a more accurate picture of areal rainfall, to improve predictions of runoff volumes, an essential factor in computation of pollutant loadings to the creek.

It is envisioned that Year 2 and 3 of this study will involve watershed simulation modeling to generate a comprehensive geographic analysis of the contribution of NPS pollutants to the Cypress Creek. Additional data on rainfall, flow, and pollutant concentrations during storm events will greatly add to the existing data on ambient conditions and allow for calibration and verification of simulation models. Initial estimates for pollutant loadings provided in this document will be compared to later modeling results, and should for now be considered a preliminary screening method to identify geographic areas of greatest concern for management of various NPS pollution constituents.

LITERATURE CITED

Akçakaya, H. and P. Sjőgren-Gulve. 2001. Population variability analyses in conservation planning: An overview. Ecological Bulletins 48: 9-21.

Baird, C., M. Jennings, D. Ockerman, and T. Dybala. 1996. Characterization of nonpoint sources and loadings to the Corpus Christi Bay National Estuary Program study area. Texas Natural Resource Conservation Commission CCBNEP-05. Austin, TX.

Baker, P., R. Ansell, P. Dodds, C. Webber, and S. Harris. 2003. Factors affecting the distribution of small mammals in urban areas. Mammal Review 33: 95-100.

Beier, P. and R. Noss. 1998. Do habitat corridors provide connectivity? Conservation Biology 12: 1241-1255.

Biediger, J. 2004. Instructions for reprojecting MDOQ tiles and MrSID compressed county mosaics. USDA: Aerial Photography Field Office.

Bomar, G.W. 1983. Texas weather. University of Texas Press, Austin, Texas, USA.

Browne, F. X., 1989, Stormwater Management. In Corbit, R. A., 1990, Standard Handbook of Environmental Engineering, McGraw-Hill, New York, NY. Pp. 7.1-7.121.

Capitol Area Council of Governments (CAPCOG). 2008a. City Limits. Information Clearinghouse. CAPCOG, Austin, TX, USA. Accessed online February, 2008 at: http://capcog.org.

Capitol Area Council of Governments (CAPCOG). 2008b. Street Centerlines: Regional. Information Clearinghouse. CAPCOG, Austin, TX, USA. Accessed online February, 2008 at: http://capcog.org.

City of Austin, 2005. 2003 Land Use Inventory Overview and Methodology. Accessed 04-26-2008. url: http://www.ci.austin.tx.us/landuse/survey2003.htm.

Dickman, C. and C. Doncaster. 1987. The ecology of small mammals in urban habitats. I. Populations in a patchy environment. Journal of Mammal Ecology 56: 629-640.

Dunning, J.B., B.J. Danielson, and H.R. Pulliam. 1992. Ecological processes that affect populations in complex landscapes. Oikos 65(1): 169-175.

Eckhardt, K. 2005. How to construct recursive digital filters for baseflow separation. Hydrological Processes 19(2): 507-515.

Ehrlich, P. and A. Ehrlich. 1981. Extinction. Oxford University Press. Oxford, England.

ERDAS Imagine. 2002. ERDAS Field Guide. Sixth Edition. Leica Geosystems, Atlanta, GA.

France, R.L. 2006. Introduction to Watershed Development: Understanding and Managing the Impacts of Sprawl. Rowman and Littlefield Publishers, Inc. Lanham, MD.

Hanski, I. and O. Ovaskainen. 2000. The metapopulation capacity of a fragmented landscape. Nature 404: 755-758.

Hawkins, R.H. 1979. Runoff curve numbers from partial area watersheds. Journal of Irrigation and Drainage Engineering (ASCE) 105(4): 375-389.

Hawkins, R.H., A.T. Hjelmfelt, Jr., and A.T. Zevenbergen. 1985. Runoff probability, relative storm depth, and runoff curve numbers. Journal of Irrigation and Drainage Engineering (ASCE) 111(4): 330-340.

Hawkins, R.H. 1993. Asymptotic determination of runoff curve numbers from data. Journal of Irrigation and Drainage Engineering (ASCE) 119(2): 334-345.

Hossein, A.A., D.H. Pilgrim, G.W. Titmarsh, and I. Cordery. 1989. Assessment of U.S. Conservation Service method for estimating design floods. New directions for surface water modeling; Proceedings, Baltimore Symp., IASH publication 181, Int. Assoc. of Hydro. Sci., Washington, D.C., 283-291.

Johnson, D.H. 2001. Habitat fragmentation effects on birds in grasslands and wetlands: a critique of our knowledge. Great Plains Research 11(2):211-213.

Kyoung J.L., B.A. Engel, Z. Tang, J. Choi, K.-S. Kim, S. Muthukrishnan, D. Tripathy. 2005. Automated web GIS based hydrograph analysis tool, WHAT. Journal of the American Water Resources Association 41(6):1407–1416.

Levin, S. 1999. Fragile Dominion. Perseus Books, Reading, MA.

Lomas, T. 2003. Create Thiessen Polygons 3.0. ArcGIS script. http://arcscripts.esri.com/details.asp?dbid=11958. Updated 03/16/03. Accessed 10/22/06.

Longley, G. 1986. Biota of the Edwards Aquifer and the implications for paleozoogeography. In: The Balcones Escarpment, Central Texas. Abbott, P. and C.M. Woodruff, eds. Geological Society of America, pp. 51-54.

Lyne, V. D. and M. Hollick, 1979. Stochastic time-variable rainfall-runoff modeling. Hydrology And Water Resources Symposium. Institution of Engineers, Australia, Perth. Pp. 89-92.

Marzluff, J., R. Bowman, and R. Donnelly. 2001. Avian ecology and conservation in an urbanizing world. Kluwer Press, Netherlands.

McCammon, B., J. Rector, and K. Gebhardt, 1998. A framework for analyzing the hydrologic condition of watersheds. USDA Forest Service, U.S. Department of the Interior, Bureau of Land Management: 47 pp.

McGarigal, K., and B.J. Marks. 1995. FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. Gen. Tech. Report PNW-GTR-351, USDA Forest Service, Pacific Northwest Research Station. Portland, OR.

McKinney, M. 2006. Urbanization as a major cause of biotic homogenization. Biological Conservation 127(3): 247-260.

Nataluk, D.M. and R. Dooley. 2003. The Practice of Low Impact Development. US Department of Housing and Urban Development. NAHB Research Center, Inc. Marlboro, MD.

National Climatic Data Center (NCDC). 2006. Climate and weather – Global surface data. NOAA Satellite and Information Service, NESDIS. http://cdo.ncdc.noaa.gov/CDO/cdo.

Novotny, V. and H. Olem, 1994. Water Quality: Prevention, identification and management of diffuse pollution. Van Nostrand Reinhold. New York, NY.

Ohio State University Extension (OSU). 2002. Digital Orthophoto Quadrangles (DOQs). Ohio State University. Accessed online April, 2008 at: http://geospatial.osu.edu/resources/DOQ.pdf.

Olff, H and M. Ritchie. 2002. Fragmented nature: consequences for biodiversity. Landscape and Urban Planning 58(2002): 83-92.

Ourso, R.T. and S.A. Franzel. 2003. Identification of linear and threshold responses in streams along a gradient of urbanization in Anchorage, Alaska. Hydrobiologia 501: 117-131.

Pahl-Wostl, C. 2005. Actor based analysis and modeling approaches. The Integrated Assessment Journal 5(1): 97-118.

Pankey, J.M. and R.H. Hawkins. 1981. Stormflow as a function of watershed impervious area. Proceedings, Arizona Section of American Water Resources Association, Hydrology Section. Arizona-Nevada Academy of Science, Univ. of Arizona, Tucson, AZ.

Parker, G. 2006. Automated Baseflow Separation for Canadian Datasets (ABSCAN): User's manual. Thinknew Analytics. Ottawa, Canada. http://www.thinknew.ca/.

Paul, M.J. and J.L. Meyer. 2001. Streams in the urban landscape. Annual Review of Ecology and Systematics 32(2001): 333-365.

Richards, J.A. 1993. Remote Sensing Digital Image Analysis: An Introduction. Springer-Verlag, Berlin, Germany.

Riskind, D.H. and D.D. Diamond. 1986. Plant communities of the Edwards Plateau, Texas. In: The Balcones Escarpment, Central Texas. Abbott, P. and C.M. Woodruff, eds. Geological Society of America, pp. 21-32.

Sadler, J.P., E.C. Small, H. Fispan, M.G. Telfer, and J. Niemels. 2006. Investigating environmental variation and landscape characteristics of an urban-rural gradient using woodland carabid assemblages. Journal of Biogeography 33(6): 1126-1138.

Schueler, T.R. 1994. The Importance of imperviousness. In: The Practice of Watershed Protection. T.R. Schueler and H.K. Holland, eds. Center for Watershed Protection, Ellicott City, MD. http://www.stormwatercenter.net/Library/Practice/1.pdf.

Short, Nicholas M. 2007. "Image Processing and Interpretation". In: Remote Sensing Tutorial. Morro Bay, California, USA. Accessed online April, 2008 at: http://rst.gsfc.nasa.gov/Homepage/Homepage.html.

Simonsson, L. 2001. Applied landscape assessment in a holistic perspective: A case study from Babati District, north-central Tanzania. Applied Environmental Impact Assessment. Department of Earth Sciences, Uppsala University. Uppsala, Sweden. 84 pp.

Slade, R.J. 1986. Large rainstorms along the Balcones Escarpment in central Texas. In: The Balcones Escarpment, Central Texas. Abbott, P. and C.M. Woodruff, eds. Geological Society of America, p. 15-20.

Snyder, C.D., J.A. Young, R. Villella, and D.P. Lemarie. 2003. Influences of upland and riparian land use patterns on stream biotic integrity. Landscape Ecology 18(7): 647-664.

Soil Conservation Service, U.S. Department of Agriculture (SCS). 1993. National Engineering Handbook, Section 4, Hydrology (NEH-4).

Texas Commission on Environmental Quality (TCEQ). 2008. Atlas of Texas surface waters. TCEQ, Austin, TX, USA. Accessed online February, 2008 at: http://tceq.state.tx.us.

Texas Parks and Wildlife Department (TPWD). 2008. Endangered species in the Texas hill country. Texas Parks and Wildlife Department. Accessed online February, 2008 at: http://www.tpwd.state.tx.us.

Texas State Data Center and Office of the State Demographer (TSDC). 2008. Texas population estimates program. Texas State Data Center and Office of the State Demographer, Institute for Demographic and Socioeconomic Research, The University of Texas at San Antonio, TX, USA. Accessed online February, 2008 at: http://txsdc.utsa.edu/tpepp/txpopest.php.

Turner, M.G. 1989. Landscape ecology: The effect of pattern on process. Annual Review of Ecology and Systematics 20: 171-197.

Veni, G. 1999. A geomorphological strategy for conducting environmental impact assessments in karst areas. Geomorphology 31: 151–180.

Wackernagel, M., N.B. Schulz, D. Deumling, A.C. Linares, M. Jenkis, V. Kapos, C. Monfreda, J. Loh, N. Myers, R. Norgaard, and J. Randers. 2002. Tracing the ecological overshoot of the human economy. Proceedings of the National Academy of Sciences of the United States of America 99(9): 9266-9271.

Wilcox, B. and D. Murphy. 1985. Conservation strategy: The effects of fragmentation on extinction. American Naturalist 125: 879-887.

Wilson, E. and E. Willis. 1975. Applied Biogeography. In: Cody, M. and J. Diamond, Eds. Ecology and Evolution of Communities. Harvard University Press, Cambridge, MA.

Wissmar, R.C. and R.K. Timm. 2004. Effects of changing forest and impervious land covers on discharge characteristics of watersheds. Environmental Management 34(1): 91-98.