LAND USE–WATER QUALITY INTERACTIONS IN THE

CENTRAL BRAZOS RIVER BASIN, TEXAS

THESIS

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DEDICATION

This work is for my mother, Dr. Gail Meredith Fraser Chanpong,

for her support and stellar example.

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CHAPTER 1 : INTRODUCTION

Land characteristics make up a significant portion of the natural and anthropogenic factors that contribute to change in surface water chemistry. Diverse influences such as density of crop or livestock cultivation, inflow of industrial effluents, diffuse pollution such as urban runoff, soil erosion, and infiltration rates all fall under this heading of "land characteristics." Land use and land cover (LULC) categorization – describing the landscape vegetation, human modifications, and physical composition in general terms such as "agriculture," "forest," or "bare rock" – effectively groups and summarizes many of these characteristics. For example, the LULC category agriculture describes both the general type and quantity of vegetation and the potential activities such as fertilization and tilling.

Landscape ecologists and watershed scientists have long studied links between LULC and water quality both as a planning tool and to focus their future research (Benke 2005, Lusch and Wolfson 1997, Allan 1995). Because of its summary nature, LULC is potentially an effective representative variable for surface water pollution risk assessment in many watersheds. The effectiveness of LULC in representing water quality conditions varies between catchments, however, as the underlying land characteristics vary. An exploratory study to evaluate the strength of LULC-water chemistry interactions is advisable before any conclusions are drawn based on LULC data for a given drainage basin. If the association between LULC and water chemistry is significant, efficiency of land-water interaction studies can be greatly improved. Spatial scale also plays an important role in the value of LULC variables in water quality studies. Measuring LULC variable connections with water chemistry parameters at multiple scales allows environmental managers and policymakers to apply land data predictors at the most appropriate scale.

Relationships between LULC and surface water chemistry have been extensively studied, in widely varied geographic conditions. Though general LULC-water chemistry connections may be similar among different areas, the representative nature of the LULC data requires that its ultimate application be calibrated to the specific area under study. Determination of how LULC should be applied to water quality protection and development planning is a highly site-specific task. Based on both the types and proportions of LULC present in the study area, impact on water chemistry may vary in both strength and affected constituents (Allan 2004, Ometo et al. 2000). The spatial scale at which LULC contributes significantly to water quality also changes from location to location, as local factors may tend to override regional factors in some but not all cases (Munn et al. 2009, Pan et al. 2004). Following this note on scale-dependent influence, published studies disagree on whether LULC distribution in riparian areas (or other local-scale area) and total catchment areas are comparable as predictors of water quality (Sliva and Williams 2001, Omernik et al. 1981). Among the goals of this study are to describe the specific relationships and identify the most effective scale for application of LULC as an indicator of water quality within the Central Brazos River Basin.

The Brazos River Basin covers an area of approximately 44,100 square miles, the River itself flowing more than 860 river miles from its headwaters in Eastern New Mexico to its Gulf of Mexico mouth near Freeport, Texas. It is the longest and has the highest discharge of all Texas rivers (Benke and Cushing 2005, Hendrickson 1981). In an era of increasing water scarcity, preserving both the quality and quantity of water resources is of paramount importance. Documenting the relationship between land use and water quality within the Brazos River Basin, one of Texas' largest and most heavily developed watersheds, is an essential step in this conservation effort. Managing land use is a critical part of an effective water pollution control and mitigation strategy.

The Central Brazos River Basin, defined for this study as the section of the Brazos River watershed downstream of the city of Waco up to and including the confluence with the Navasota River, is composed primarily of rangeland, tilled agriculture, and shrubland (NOAA 2006, EPA 2001, EPA 1992). Census data suggest that the population of this area is increasing, and city limits show that built-up areas are growing accordingly (U.S. Census Bureau 2002 and 2001). The Central Brazos River Basin's 34,800 square kilometers encompass the expanding cities of Bryan, College Station, Georgetown, Killeen, and Temple. Understanding how LULC impacts water quality within the Central Brazos River basin will enhance the effectiveness of future resource management efforts, with an especially valuable insight on the potential impact of increasing urban land use.

Much past research in this field focuses on local scale (riparian) LULC impacts on water quality and on single, relatively small watersheds. This study evaluates the land-water relationship in multiple catchments comprised by three scales:

- Local scale, the immediate riparian area
- Super-local scale of individual small, first- and second-order watersheds, designated as “microwatersheds”
- Regional scale, comprised of segments of the Brazos River itself and their major tributaries, referred to as “subwatersheds”

The subwatershed scale, as the term is used here, is a compromise between the maximum resolution of the microwatershed scale and the major river basin scale most relevant to land management policy.

Identifying the effectiveness of LULC as an element in water quality studies also requires a meaningful temporal scale. A thorough statistical evaluation of the LULC-water chemistry relationship requires repeated data points over both space and time. Using paired data from multiple years and multiple locations is essential to reliably assess interactions.

The combination of a multi-year time span and multiple spatial scales presents an analytical challenge rarely addressed in the current literature. This study uses methods so far uncommon within the field. A multi-level (or “nested”) approach is required for varying scales – single subwatersheds with their constituent microwatersheds. A longitudinal (“time-series”) analysis model is required for grouping and comparing data years. A method that addresses the cumulative, spatially overlapping nature of the watersheds and the lack of observation independence it creates is also necessary. Linear mixed effects (LME) models accommodate all of these elements within the study design.

1.1: Problem Statement

The usefulness of land use/land cover information in predicting water chemistry conditions or assessing potential risks to water quality is unknown for the Central Brazos River and its tributaries. Before researchers and policymakers can confidently consider LULC in water quality matters, its relationship with water chemistry must be described and quantified. This study will determine which, if any, LULC categories are significantly related to a panel of key water chemistry parameters, and at what spatial scale(s).

1.2: Research Questions

The core of this study is an evaluation of the linkages between land use/land cover (LULC) and surface water chemistry over time for the Central Brazos River Basin.

Specific research questions are as follows:

1. What are the nature and extent of linkages between LULC change and surface water chemistry in the Central Brazos River basin?
2. Within a nested time/space model, can the impact of urbanization within the study area be distinguished from that of other LULC types and quantified?

3. Can LULC class distribution at the riparian level be used to predict water quality at the subwatershed level?

Two data-centric tasks are necessary steps before examining the central questions of this project. These tasks, which include data collection and initial exploration, are listed below:

1. Augment the 2006 National Land Cover Dataset (NLCD), currently partially complete, to cover the entire study area
2. Compare LULC data for 1992, 2001, and 2006; describe historical changes in LULC in two sections of the Central Brazos River, eight contributing subwatersheds, and their respective riparian areas

1.3: Methods Overview

This study will take a stepwise analytical approach, using the results of each analysis as input for the following procedure. Each subwatershed, microwatershed, and riparian area has a unique LULC composition, described by LULC category percentage values. The proportional area covered by each of seven LULC categories is calculated: agriculture, built-up, brush/forest, grass, open water, wetland, and barren. These LULC categories appear often in both geographic and ecological studies. Nine water chemistry parameters act as the dependent variables: chlorophyll a, dissolved oxygen, fecal coliform bacteria, pH, orthophosphate, specific conductance, water temperature, total nitrogen (nitrate), and total phosphorus. As for the LULC categories selected, these nine water chemistry parameters are among the most commonly presented in the current literature. Values for these parameters are associated with geographic areas by sample collection location. Water chemistry data from the downstream end of a geographic area, representing the accumulated influence of the contributing landscape, are paired with the LULC category percentage values of that catchment.

General trends in LULC composition and water chemistry will be presented. The strength and nature (positive or negative) of its relationship with each LULC category will be determined for each water chemistry parameter, through Pearson correlation analysis (LeBlanc 2004, Pearson 1920). Correlation analysis will identify which LULC-WQ pairs have a significant linear relationship. Only these significantly related pairs will be included in the subsequent principal component analysis (PCA).

PCA is a tool often used in exploratory data analysis for multi-parameter studies, as it identifies the parameter or parameters that account for the most variation in response variables. PCA will yield both qualitative and quantitative information about the relationship between land use categories and water chemistry (Jolliffe 2002, Johnston et al. 1990). Optimal groupings of LULC categories and water chemistry parameters will be evident through PCA; it will show which LULC categories account for the greatest proportion of variation in each water quality parameter. These groupings will dictate which parameters will be candidate elements for the linear models used in the final analytical procedure – linear mixed effects model analysis. In order to strike what Young et al. (2006) refer to as "a workable balance between parsimony and effectiveness," a model optimization process will be applied prior to LME analysis. To ensure that only effective predictors are included in the candidate analysis models, a stepwise regression using Akaike Information Criterion (AIC) scores will be calculated (Burnham and Anderson 2002, Akaike 1973) These scores are essentially a relative ranking tool for potential linear models; they will be used to determine the optimum model for each dependent variable.

Traditional analysis of variance (ANOVA) and multiple ANOVA (MANOVA) are logical and commonly used methods for analysis of nested datasets, since they provide a quantitative description of how a panel of independent variables affects each of a panel of dependent variables. Watershed studies are a poor fit for standard M/ANOVA due to the inherent lack of independence in data collected from a cumulative, directional flow network. Instead a more appropriate alternative approach is used: a linear mixed effects (LME) model framework. LME models include both fixed and random predictors and are typically applied to data grouped by at least one factor (Zuur et al. 2009, Pinheiro and Bates 2000). Models with multiple random sources of variation (here from year and microwatershed) are referred to as “multilevel.” In this case, the data represent multiple points across space measured over time. Year, subwatershed, riparian area, and microwatershed are important as nested grouping factors. A similar hierarchical approach is used by Ahearn et al. (2005), where LME is also applied in order to correct for an unbalanced dataset and longitudinal data.

LME accommodates the grouping and nested nature of watershed and time-series data. It is an extension of generalized linear models, using iteratively reweighted least squares to include the true, original variance of a transformed dataset (Bolker 2008). This enhances model fit through more suitable variance-mean relationships (Bolker 2008). LME models also provide the ability to quantify both among-factor and within-factor variability (Zuur et al. 2009). Applied to spatially nested groups, this within-/among-factor analysis establishes whether regional and/or local differences should play an important role in future land use planning. The use of the LME model is critical to the study design, as it allows for correlation among observations within groups: in this case, correlation among LULC category results within geographic area groups. Within-group values may be correlated and groups may have unequal variances in the LME framework (Bolker 2008, Pinheiro and Bates 2000, Laird and Ware 1982). Unbalanced designs cause no complications in LME, thanks to the use of a maximum likelihood framework, in which outcomes are actually based on probability of variance from a mean (Quinn and Keough 2002, Searle et al. 1992). This ability to fully incorporate unbalanced datasets is also essential, since the number of observations (microwatersheds and riparian areas) varies per subwatershed and water quality data availability varies over both space and time.

1.4: Relevance of Study

This study describes the changes in Central Brazos LULC over a fourteen-year period (1992-2006) and assesses the strength of the LULC-water quality relationship at three scales, to aid future basin water resources management efforts. Land use and land cover are strong indicators of surface water conditions (Allan 2004, Herlihy 1998), but gathering LULC data at a resolution valuable at the watershed scale can be time-, labor-, and cost-prohibitive. LULC is most frequently used for watershed-scale water quality studies; if it were demonstrated as equally effective at the local or riparian scale, vast savings in effort would be possible. The addition of a broad time scale to the study is also noteworthy: LULC-water chemistry relationships quantified for a shorter period or even a single year, as in many other studies, are less likely to hold true over time.

Current Texas Commission on Environmental Quality (TCEQ) assessment methods for system integrity and ecological risk include some riparian characteristics as metrics. These methods, based largely on EPA Rapid Bioassessment Protocols (EPA 1999) and other similar techniques, do not currently incorporate land use data. TCEQ field methods manuals and forms include provisions for measuring percent tree canopy cover, average width of “natural” riparian buffer vegetation, and average riparian vegetation percent composition (percentages of trees, shrubs, grasses/forbs, cultivated fields, and “other”); but only riparian buffer width is included in the Habitat Quality Index “score” recorded as a summary statistic about stream habitat integrity (TCEQ 2008a, TCEQ 2004a, TCEQ 2004b, TCEQ 2004c). The apparently unused riparian land cover data have limited usefulness on their own due to their local extent, which may be between 150 meters to 1 kilometer (TCEQ 2008a), and to the sparse nature of habitat data collection. Riparian habitat data are gathered intensively in small watersheds with known water quality issues for one or two years, and so are not available at a scale or time period necessary to build an accurate LULC risk index. These riparian habitat data are not usually gathered until degradation of the area is already apparent. This study provides a robust quantitative description of LULC category relationships to key water quality parameters. Risk assessments for aquatic systems would greatly benefit from inclusion of metrics from a consistently-updated riparian LULC dataset. Texas geographic and regulatory agencies actively acquire aerial imagery on a regular basis; this imagery may be used to complete and enhance NLDC datasets across the state. Should the results indicate that riparian LULC is as effective a water quality predictor as watershed-scale LULC, the analytical data produced here create an opportunity to use the Central Brazos River basin as a pilot area for new and improved LULC-water quality assessment methods.

In addition to the LULC evaluation itself, this study is an application of the emerging linear mixed effects (LME) framework. Incorporation of multiple temporal and spatial scales in such an analysis is not common in the current literature. Since it accurately represents the covariance structure inherent in grouped data, LME may prove to be a more statistically suitable analytical context for watershed studies than M/ANOVA (Gelman and Hill 2007, Pinheiro and Bates 2000).

CHAPTER 2 : LITERATURE REVIEW

Vitousek (1994) posits that land cover change is the primary source of human impact on natural systems. Changes in topography, vegetation, and even soil composition are indeed the hallmarks of human "development" of the natural world. Addition of structures, removal and partial replacement of native flora, and modification of watercourses have extreme and often detrimental effects on the chemical and biological composition of aquatic systems. Recent years have also shown a widespread decline in availability of usable freshwater in terms of water quality and quantity due to unsustainable land use practices (Ngoye and Machiwa 2004).

Focus on the watershed as a land-water system is essential in understanding water resources issues: water quality and quantity questions cannot be answered by focusing simply on the water bodies themselves (Herricks and Suen 2006, Kraenzel 1957). Land-based activities affect water resources both directly and indirectly: land use information has powerful explanatory capacity in ecological studies of areas affected by human influence (Weng 2007, Lunt and Spooner 2005, Simpson et al. 2001, Foster et al. 1998). Urban land use can exert a heavy influence on watershed health despite being a relatively small portion of overall developed land (Wade et al. 2009, Allan 2004). Of particular concern are findings that even low-intensity or transitional built-up areas may influence water quality significantly, and that urban influence may extend farther downstream than the influence of other land use types (Wade et al. 2009, Wear et al. 1998).

Because it encompasses numerous and varied land characteristics – including geology, biology, demographics, topography, hydrology, and human activity – LULC is vastly valuable as an integrated analytical variable (Johnson et al. 1997). Generalization of multiple land characteristics creates a greatly simplified analysis framework, yet can still faithfully capture many aspects of the complex land-water interaction. Time-series and trend analysis as LULC distributions change over years or decades enhance planning for resource protection. Land cover change may well be the major avenue of anthropogenic impact on the Earth, but it is by definition under human control. With continued investment in research, LULC change can be regulated to minimize negative impacts.

Research on LULC relationships with water quality focuses largely on variables such as dissolved salts, suspended solids, and nutrients (Ahearn et al. 2005, Turner and Rabalais 2003, Sliva and Williams 2001, Smart et al. 1998, Allan et al. 1997, Johnson et al. 1997, Osborne and Wiley 1988, Hill 1981). They concluded that agricultural land use strongly influences nitrogen (Ahearn et al. 2005, Smart et al. 1998, Johnson et al. 1997), phosphorus (Hill 1981), and sediments (Ahearn et al. 2005, Allan et al. 1997, Johnson et al. 1997) in stream water. Urban land use has influenced water nutrients as well, particularly phosphorus and nitrogen (Sliva and Williams 2001, Osborne and Wiley 1988). Urban inputs have shown a significant impact on levels of fecal coliform bacteria levels, as do agricultural areas with animal feeding or dairy operations (Lewis et al. 2007, Keraita 2003). Increased nutrient inputs may result in eutrophication. Increased algal activity – photosynthesis – due both to chemical eutrophication and decreased tree cover may influence pH by altering the carbon dioxide levels in the water (Li et al. 2008, NAS 1969). Decrease in tree cover has been associated with increases in temperature due to added solar input; this in turn allows increased photosynthetic activity by algae and submerged vegetation (Allan 2004).

Rivers that flow into the Gulf of Mexico are geologically, historically, and biologically diverse; but they share the common major threat of human impact. Many of the frequently identified negative impacts to these river systems are anthropogenic: wastewater effluent, urban development, water extraction, and agricultural activities exert significant influence on many streams in the region (TCEQ 1996-2008, BRA 2007). The Brazos, Colorado, and Trinity river basins contain more than half the overall population of Texas (Benke and Cushing 2005). Many of these human threats fall neatly into LULC categories. In the case of those listed here, agriculture and built-up categories account for increased water use, wastewater input, fertilizer and animal manure runoff, vegetation removal as part of urbanization or tilled fields.

The Brazos River has many areas heavily influenced by development, most notably in the northern and far southern portions of the basin. These areas include large urban centers and large impoundments. The central portion of the Brazos River basin runs from the outflow of Lake Brazos at Waco to the confluence with the Navasota River. Recent research has shown that the Central Brazos may be the portion of the river basin least impacted by human activities, relative to the upper and lower reaches (Vogl and Lopes 2009). While it may be relatively less impacted by human activities relative to the remainder of the basin, it is still heavily agricultural and includes some growing urban areas (NLCD 1992-2006, US Census Bureau 1990 and 2000). Though initial research indicates that the Central Brazos basin remains predominantly agricultural in land use, increasing size of urban areas is of particular concern since these areas tend to have a disproportionately large impact (Ahearn et al. 2003, Karr and Chu 2000). Shifts in the dominant types of threats to water quality are more likely as the proportion of built-up land use grows.

Water quality is generally linked to LULC in the context of a watershed (Ahearn et al. 2005, Allan 2004). Some findings suggest that there may be an upper threshold for geographic area in this type of linkage study: when the LULC area under study is too large, its effectiveness as an indicator of aquatic system condition is very low (Meador and Goldstein 2003). From a purely spatial standpoint, it could be suggested that the influence of land characteristics varies with proximity to the watercourse – areas closer to lakes or rivers may exert proportionately greater influence (Allan et al. 1997). At very broad geographic scales – from the national to the regional – it appears that LULC explains a greater proportion of the variation in stream chemistry as individual land characteristics become more homogeneous (Goldstein et al. 2007).

Spatial scales represented in the literature vary, but the majority of current studies focus on smaller watersheds (Ahearn et al. 2005, Allan et al. 1997) and single watersheds (Li et al. 2008). Sub-regional scales tend to allow more accurate assessment of land use influence on stream health by reducing the confounding effect of variations in climate, geology, and topology (Goldstein et al. 2007, Allan et al. 1997, Roth et al. 1996, Omernik 1995, Omernik et al. 1981). From an observational standpoint at smaller scales – from the regional to the local – LULC distribution influence on water chemistry is location-specific (Floyd et al. 2009, Gove et al. 2001, Sliva and Williams 2001, Omernik et al. 1981). In studying land use-water quality interactions, streamside land cover is of particular interest. Riparian vegetation cover has been shown to be a strong predictor of stream health (Frimpong et al. 2005, Allan 2004, Baker et al. 2001). The most important ecological functions of vegetated riparian zones with regard to water quality is to filter runoff from adjacent areas and to reduce bank erosion/soil input to water bodies (Mander et al. 2005, Lowrance et al. 1997). Buffer zones with diverse, sequential plant communities including wooded areas seem to be more effective at removing pollutants (such as nutrients, organic material, metals, pesticides) than simple vegetation structures (Anbumozhi et al. 2005, Mander et al. 2005, Meador and Goldstein 2003, Jones et al. 2001, Lyons et al. 2000). Some studies have suggested that a riparian zone composed of less than 76% woody vegetation presents increased risk of contamination reaching the stream (Meador and Goldstein 2003). Wider simple/grassland buffers in combination with wooded/brushy strips seem to provide optimal water quality protection (Anbumozhi et al. 2005, Mander et al. 2005, Vought et al. 1994, Karr and Schlosser 1978). Reduction in riparian vegetation and livestock contact with water bodies seem to be correlated with increased bacteria and suspended solids pollution (Wilcock et al. 2007). Even when riparian grazing by livestock is permitted, grass cover adjacent to the stream reduces sediment loading (Butler et al. 2008).

Riparian studies have so far focused on reach-scale data, streamside condition along portions of watercourses perhaps 100 m to 1 km in length (Frimpong et al. 2005, Gove et al. 2001). Multi-scale comparisons generally do not offer an intermediate or sub-watershed scale, contrasting the local/reach scale directly with the whole watershed, and these comparisons do not achieve a conclusive answer on which scale is most effective for LULC-water quality studies (Frimpong et al. 2005, Wang et al. 2003, Allan et al. 1997, Allan and Johnson 1997). Several publications have noted the need for additional multi-scale research on LULC effects on water quality (Allan et al. 1997, Richards et al. 1996), and for research on riparian corridors at the system scale (Tabacchi et al. 1998). This study will determine the relative strength of LULC-water chemistry relationships at three scales for the Central Brazos basin: regional, watershed, and riparian area. Interest in the central portion of the overall Brazos River basin, combined with this evidence that analysis at a smaller scale will enhance accuracy, motivated the decision to divide the study area into subwatersheds and to add analysis at the riparian level.

This study will assess the relationship between riparian land use distributions and water quality indicators for the Central Brazos. Optimal and minimum widths of buffer zones for water quality protection have been extensively studied and found to vary greatly between scales and systems (Mayer et al. 2005, Barton et al. 1985). Research on pollutant attenuation suggests that maximum contaminant retention is achieved near 100 m for mixed grass/forest land cover but closer to 150 m for grass land cover (Mayer et al. 2005). Depending on conditions such as rainfall patterns, bank slope, and soil porosity, some wetland and stream areas require up to 200 m of buffer width for effective protection (Dosskey et al. 2008, Castelle et al. 1994). Some Texas-specific recommendations are for a minimum of 50 meters width of mature, unmanaged or unharvested forest (Rudolph and Dickson 1990, Dickson 1989), which suggests that greater widths would be desirable for thinned forests or mixed vegetation types. This study applies a buffer width of 200 m in order to capture a full description of both the immediate streamside conditions and the abutting land use activities.

The National Land Cover Dataset for 1992 includes 21 different LULC classes, grouped into 9 more general categories (EPA 1992). NLCD 2001 and 2006 include an expanded 29 LULC classes within the same 9 categories (NOAA 2006, EPA 2001). Grouping these LULC classes into slightly different general categories for the Central Brazos study allows for better separation between agricultural land, natural or minimally managed woody vegetation, and grass/herbaceous vegetation (Li et al. 2008). Simplified LULC categorization schemes like the version used for this study can offer the benefit of easier analysis and interpretation without affecting the LULC-water chemistry relationships (Jones et al. 2001, Herlihy et al. 1998).

Some expectations regarding the direction and type of relationships exhibited by the study data are reasonable, based on past research. Some general trends are consistent across scales and locations; these trends are likely to occur in the Central Brazos as well. Cultivated crop land, classified for this study as “agriculture,” has been associated with increases in nitrogen (Ahearn et al. 2005, Smart et al. 1998, Johnson et al. 1997), phosphorus (Hill 1981), and sediments contributing to greater specific conductance (Ahearn et al. 2005, Allan et al. 1997, Johnson et al. 1997), nitrogen, phosphorus, bacteria, and temperature (King et al. 2005, Jones et al. 2001, Johnson et al. 1997). Grass land cover has been shown to have varying impacts on water chemistry based both on proximity to the watercourse and activity on the land itself. Grasslands used for livestock grazing can increase bacterial input through animal waste if close to water bodies, but the grass cover itself offers some positive effects by reducing erosion and nutrient input

(Butler 2008, USDA 2000, Skovlin 1984). Grass in urban or suburban areas, cultivated for recreational use, may increase both nitrogen and phosphorus input due to fertilizer application (Law et al. 2004, Robbins et al. 2001, USDA 2000).

This group of water chemistry parameters is appropriate to a study of this nature, as it represents both key indicators of ecosystem health and a panel of constituents that appear frequently in the literature (Li et al. 2008, Ahearn et al. 2005, Meador and Goldstein 2003). All nine parameters selected for this study are part of the minimum water quality dataset collected during routine ambient monitoring by the Texas Commission on Environmental Quality (TCEQ 2008a). This selection ensures the best possible data coverage as well as plentiful background material to support analytical methods development.

Geographic Information System (GIS) tools have been widely applied to determine the extent and distribution of LULC categories (Li et al. 2008, Ahearn et al. 2005, Meador and Goldstein 2003, Tong and Chen 2002, Wang 2001, Johnson and Gage 1997). A significant majority of literature in the field incorporates correlation analysis as the initial or even primary method of quantifying the strength LULC-water chemistry relationships (Li et al. 2008, Gove et al. 2001, Allan et al. 1997). Stepwise regression for variable selection and significance testing are also often applied prior to M/ANOVA for partitioning variance among the LULC variables (Meador and Goldstein 2003, Molinero and Burke 2003, Tong and Chen 2002, Jones et al. 2001, Wang 2001). Canonical correspondence analysis (CCA) and principal components analysis (PCA), both of which are effective methods for describing variation between multivariate datasets and determining variable loadings, are recently increasing in popularity (Meador and Goldstein 2003, Wang et al. 2003).

This study incorporates correlation analysis, PCA, and stepwise regression for variable selection, techniques seen frequently in the current literature (Li et al. 2008, Ahearn et al. 2003, Meador and Goldstein 2003, Gove et al. 2001). The repeated measures component – data for the same area collected at three separate points in time – requires a nested analysis model. This nested arrangement itself might be handled with MANOVA, but MANOVA fails to address the lack of independence between data points created by the study design and the watershed itself. As network subsets of larger areas related by directional flow, watersheds are by definition hierarchical: the nested arrangement of subwatersheds and riparian areas within a watershed creates autocorrelation. Observational independence is an assumption of MANOVA and therefore would produce spurious results if applied at the watershed level.

Human-environment interactions are frequently hierarchical, so multi-level or nested modeling frameworks are a logical choice for examining these interactions (Bolker 2008, Young et al. 2006). Linear mixed-effects (LME) model designs still appear infrequently in the current literature, especially applied to land use-water quality studies (Lai and Helser 2004, Ahearn et al. 2003). LME is statistically more flexible and more appropriate to watershed studies, and so may be used in contrast to or even in place of traditional ANOVA in the future (Pinheiro and Bates 2000). Observations among subwatersheds are independent within a year, but are dependent within those subwatersheds due to repetition over time and within space. LME accommodates the lack of independence in the data and allows the multi-level nested arrangement required by the time series and hierarchical geography of the study design (Zuur et al. 2009, Gelman and Hill 2007, Pinheiro and Bates 2000). This is accomplished by incorporating both among-factor and within-factor variability, unlike classic linear regression or analysis of covariance (ANCOVA) (Zuur et al. 2009, Lai and Helser 2004). This within-/among-factor analysis establishes whether regional and/or local differences should play an important role in future land use planning.

CHAPTER 3 : METHODS

3.1: Study Area

The Central Brazos River basin was affected early on by European settlement, with colonists clustering homesteads near the confluence of the Navasota River in 1821. This site was formally named Washington-on-the-Brazos in 1835, and became a business hub for the Republic of Texas. Stephen F. Austin began exploring the Brazos for its potential as a fertile site for colonization and found the soils along the river had great potential (Benke and Cushing 2005, Hendrickson 1981). Agricultural products of the central basin remain similar to those raised in earlier times: the area generates livestock, dairy products, poultry, rice, and cotton (Benke and Cushing 2005), all of which influence water quality and quantity. The Central Brazos flows through Crosstimbers, Texas Blackland Prairie and East Central Texas Plains ecoregions before reaching the Western Gulf Coastal Plain (EPA 2007). Downstream of Waco, riparian vegetation was dominated by hardwoods (Post Oak, Pecan) prior to agricultural clearing by European immigrants; a mix of woody shrubs, hardwoods, and softwoods is now predominant (Benke and Cushing 2005).

The study area is the watershed of the Brazos River downstream of Waco down to its confluence with the Navasota River, plus all tributaries. In order to assess the LULC-water chemistry relationship at multiple scales, the Central Brazos River basin is divided into three tiers of smaller areas: subwatersheds, microwatersheds, and riparian areas. The Central Brazos River itself is divided into two zones for the study, identified as the Central Brazos River North, which extends from immediately downstream of Lake Brazos to immediately upstream of the Little River, and the Central Brazos River South, from the confluence of the Little River to the confluence of the Navasota River. Tributaries to this portion of the Brazos include Brushy Creek, Cowhouse Creek, the Lampasas River, the Leon River, the Little River, the Navasota River, the San Gabriel River, and Yegua Creek. The study area encompasses the growing metropolitan areas of Bryan, College Station, Georgetown, Killeen, and Temple. The two Central Brazos River zones and the eight tributaries constitute the ten “subwatersheds” used in this study. In order to assess linkages at the highest resolution, each of the ten subwatersheds is further subdivided into local-scale “microwatersheds.” Riparian areas were delineated at the subwatershed level.

Figure 3-1 depicts the overall study area within the Brazos River Basin and the ten subwatershed divisions. Analysis at the subwatershed level reveals details about regional scale land-water interactions. Figure 3-2 illustrates the cumulative, overlapping nature of local-scale drainage areas: a single subwatershed with its constituent microwatersheds. Figure 3-3 depicts a representative section of a riparian area, the zone directly surrounding water bodies. The riparian area is defined as a linear corridor including 100 meters on either side of stream centerlines and 100 meters inland from the average conservation pool elevation of reservoirs. Analysis at the microwatershed and riparian area levels establish connections with water chemistry at the local scale.

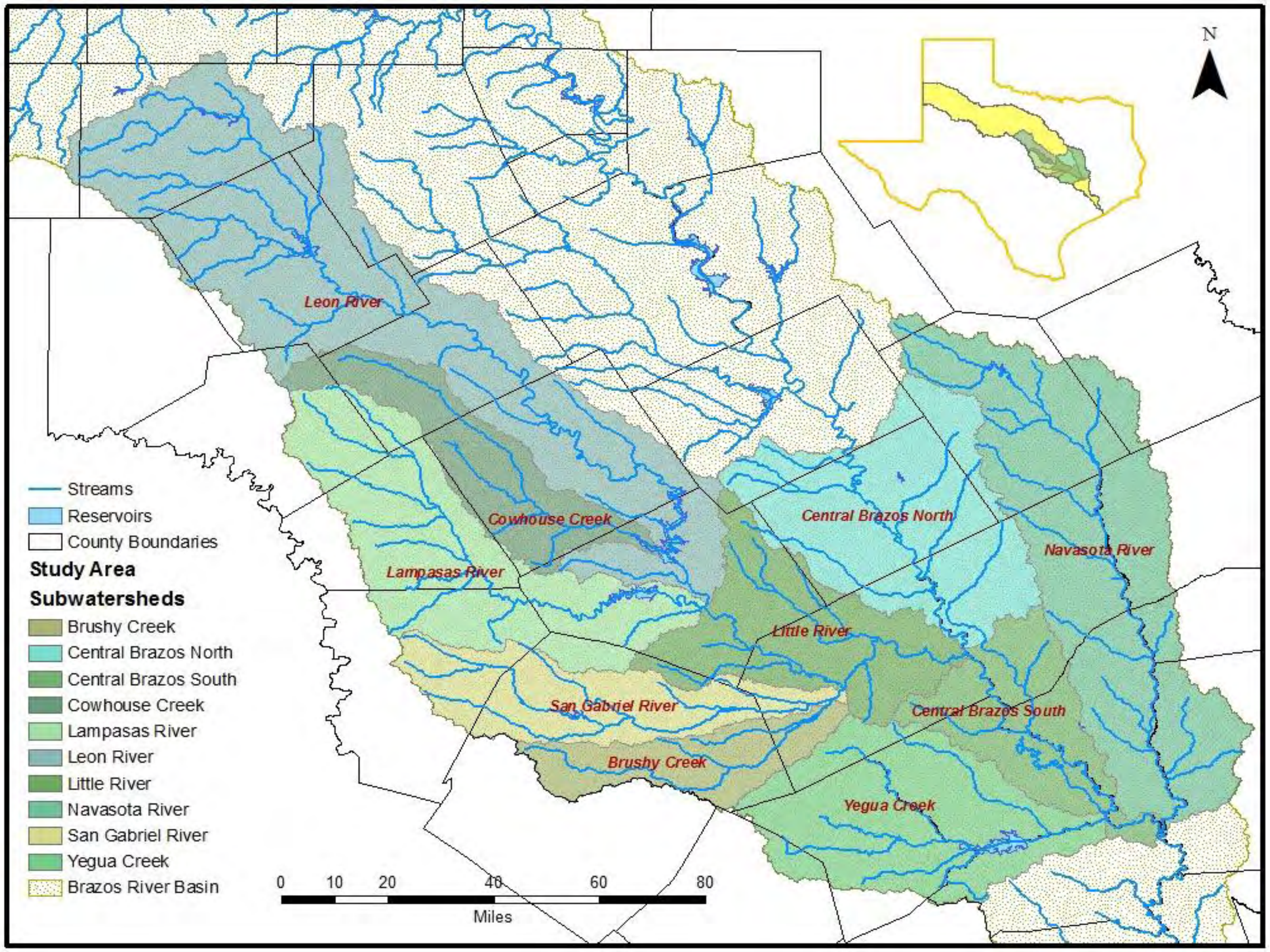


Figure 3-1: Study Area with Subwatersheds

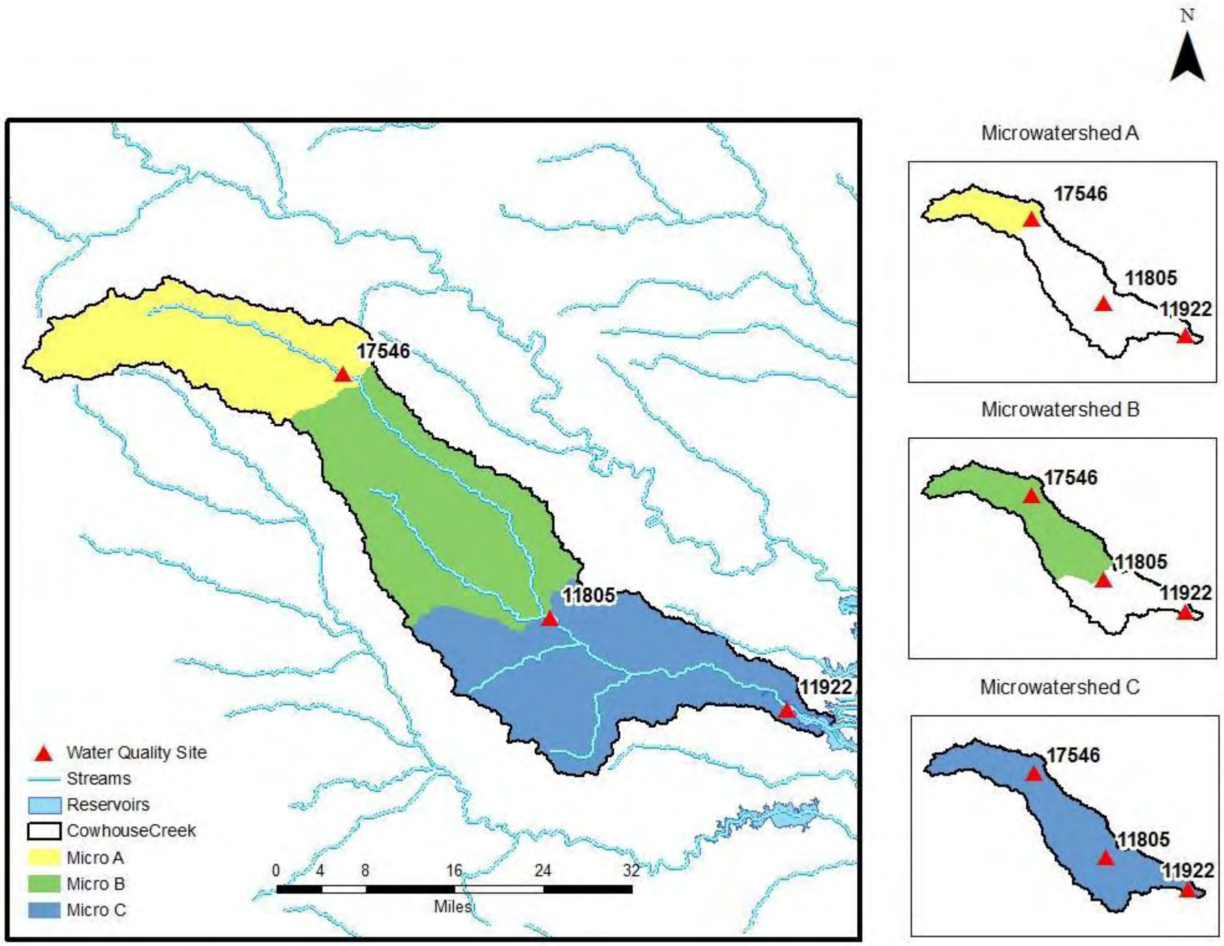


Figure 3-2: Representative Microwatersheds, Cowhouse Creek

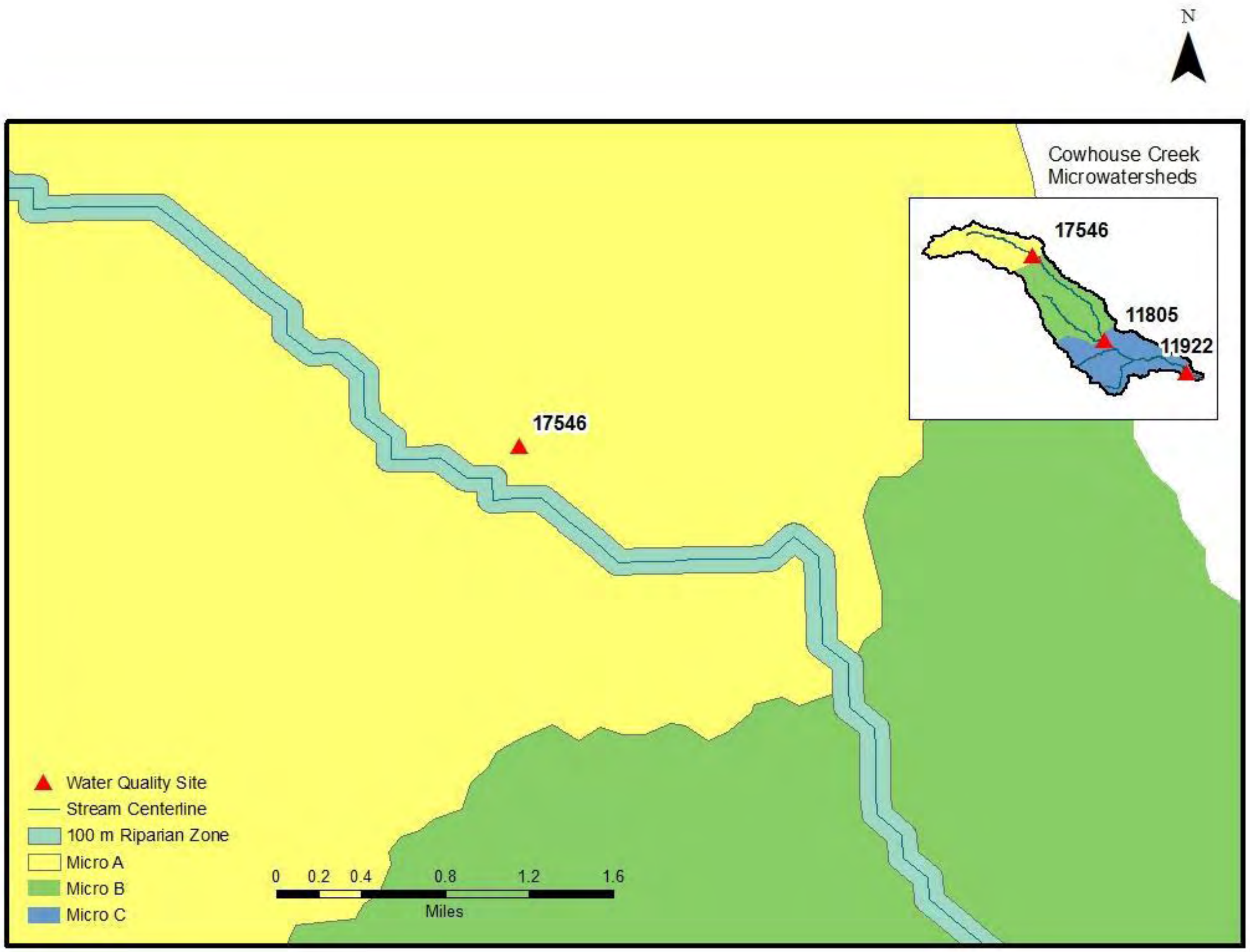


Figure 3-3: Representative Riparian Area, Cowhouse Creek

3.2: Characterizing, Selecting, and Quantifying Land Use/Land Cover and Water Chemistry Data

Complete historical LULC records are available in the form of the National Land Cover Dataset (NLCD) for 1992 and 2001; these datasets are the primary LULC source data for this study. A partially complete NLCD is available for 2006. As part of this study, the NLCD 2006 dataset will be augmented to cover the study area.

The Texas Commission on Environmental Quality (TCEQ) catalogues and stores environmental data from Federal, State, and local researchers across the state of Texas. TCEQ's data clearinghouse for surface water data, the Surface Water Quality Monitoring Information System (SWQMIS) database, is the most complete source of water chemistry data for Texas and is the sole source for this study.

Land use/land cover characteristics are often used as indicators of existing surface water conditions and predictors of future conditions. Current literature suggests that the effectiveness of LULC in this capacity varies greatly with spatial scale. The relationship between LULC and water quality is assessed most frequently at the local scale and from a watershed perspective. In this study, this relationship is examined at local, watershed, and regional scales, and from the watershed and riparian perspectives.

3.2.1: Land Use/Land Cover Data

3.2.1.1: Land Use/Land Cover Classification

Most modern studies of this nature use a simplified LULC scheme with four to seven classes (Li et al. 2008, Ahearn et al. 2005, Meador and Goldstein 2003, Molinero and Burke 2003). This is a common practice due to evidence that a simplified scheme can provide a more straightforward analysis framework without confounding effects on the LULC-water chemistry relationships (Jones et al. 2001, Herlihy et al. 1998). Agriculture, urban, forest, and grassland are among the most frequently included classes (Goldstein et al. 2007, Koroluk and de Boer 2007, Allan 2004, Pan et al. 2004, Herlihy et al. 1998, Omernik et al. 1981). In order to follow in the footsteps of former researchers and to make the most efficient use of available LULC data, this study uses a scheme only slightly different from that of the NLCD's general grouping categories. Table 3-1 shows the original and modified groupings: the modified groupings combine woody and herbaceous wetlands into a single wetland category, and combine forested upland and shrubland into a single brush/forest category for upland woody vegetation (EPA 2001 and 1992). These two grouped categories better reflect the categories seen in many similar LULC-WQ studies, yet still maintain separation between wetlands and unsaturated land and between herbaceous and woody vegetation seen in the NLCD classification scheme. Table 3-2 shows the NLCD 2006 classification scheme and how it is grouped into larger categories for this study: the grouping is similar to the native groups used for NLCD 1992 and 2001, but is completed manually since NLCD 2006 has published "Uplands" and "Wetlands" groupings (NOAA 2006). NLCD 2006 Background (code 0) and Unclassified (code 1) classes are excluded from analysis for this study, as they essentially represent null data (NOAA 2006). An alphabetical code rather than a numeric code is used here in order to facilitate interface with the selected statistical software, Program R (R Development Core Team 2009.).

Table 3-1: Cover Class Grouping and Group Modification, NLCD 1992 and 2001

NLCD Category Name	NLCD Category Code	Central Brazos Category Name	Central Brazos Category Code
Water	10	Open Water	E
Developed	20	Built-Up	B
Barren	30	Rock/Mine/Sand/Bare Earth	G
Forested Upland	40	Brush/Forest	C
Shrubland	50		
Herbaceous Upland	60	Grass	D
Planted/Cultivated	70	Agriculture	A
Woody Wetlands	80	Wetland	F
Emergent Herbaceous Wetlands	90		

Table 3-2: Land Cover Classes and Class Grouping, NLCD 2006

NLCD Category Name	NLCD Category Code	Central Brazos Category Name	Central Brazos Category Code
Developed, High Intensity	2	Built-Up	B
Developed, Medium Intensity	3	Built-Up	B
Developed, Low Intensity	4	Built-Up	B
Developed, Open Space	5	Grass	D
Cultivated Crops	6	Agriculture	A
Pasture/Hay	7	Agriculture	A
Grassland/Herbaceous	8	Grass	D
Deciduous Forest	9	Brush/Forest	C
Evergreen Forest	10	Brush/Forest	C
Mixed Forest	11	Brush/Forest	C
Scrub/Shrub	12	Brush/Forest	C
Palustrine Forested Wetland	13	Wetland	F
Palustrine Scrub/Shrub Wetland	14	Wetland	F
Palustrine Emergent Wetland (Persistent)	15	Wetland	F

Table 3-2: Continued

NLCD Category Name	NLCD Category Code	Central Brazos Category Name	Central Brazos Category Code
Estuarine Forested Wetland	16	Did Not Occur Within Study Area	
Estuarine Scrub/Shrub Wetland	17		
Estuarine Emergent Wetland	18		
Unconsolidated Shore	19	Rock/Mine/Sand/Bare Earth	G
Barren Land	20	Rock/Mine/Sand/Bare Earth	G
Open Water	21	Open Water	E
Palustrine Aquatic Bed	22	Wetland	F
Estuarine Aquatic Bed	23	Wetland	F
Tundra	24	Did Not Occur Within Study Area	
Perennial Ice/Snow	25		
Dwarf Scrub	26		
Sedge/Herbaceous	27		
Moss	28		
Lichens	29		

Reclassification is performed by structured query language (SQL) commands in Microsoft Access 2007 (Microsoft Corporation 2006). Process steps for handling and preparation of the 1992 and 2001 NLCD data are listed in Table 3-3.

Table 3-3: Method Process Steps for NLCD (1992, 2001)

Step	Process
1	Mosaic original raster data to cover study area.
2	Clip raster to study area.
3	Raster-to-polygon conversion using ArcToolbox.
4	Convert NLCD classification codes to Central Brazos classification codes in MS Access.
5	Calculate total category areas within study area from reclassified data.
6	Calculate distribution of categories within study area.

Table 3-3: Continued

7	Clip LULC coverage to subwatersheds.
8	Calculate subwatershed category areas.
9	Calculate subwatershed distribution of categories.
10	Clip LULC coverage to microwatersheds.
11	Calculate microwatershed LULC category areas.
12	Calculate microwatershed distribution of categories.
13	Clip LULC coverage to riparian areas.
14	Calculate riparian area LULC category areas.
15	Calculate riparian area distribution of categories.

3.2.1.2: Land Use/Land Cover Data Collection

As the NLCD 2006 is incomplete and does not provide coverage for the entire study area, it is necessary to generate the missing data. NLCD is raster (pixel-based) data with a cell size of 30 meters (NOAA 2006, USGS 2001 and 1992). In order to duplicate or exceed this resolution when generating new LULC data, this study uses aerial photographs with a two-meter resolution as base maps. Two-meter color-infrared digital orthophoto quarter quadrangles (DOQQs) for 2006 are available from the Texas Natural Resources Information System (TNRIS) (TWDB 2006). Color-infrared spectrum imagery is particularly suitable for identifying patterns in vegetation growth. These images, collected during the growing season, represent the peak vegetative cover achieved during 2006 (USDA 2006).

Using the 2006 DOQQs as a base map, areas of identifiable land use and/or land cover were digitally delineated using ESRI ArcMap 9.3 and ArcInfo 9.3 (ESRI 2008). Existing NLCD data, in comparison with the aerial imagery, act as an example to produce consistent new data. The NLCD classification scheme is a guideline for qualitative decisions on which category to assign to land areas: for example, shrub/forest land is defined by 80% coverage in woody vegetation. New data are collected by subwatershed and combined with the partial NLCD 2006 data to complete the study area dataset. Process steps for this data collection are listed in Table 3-4.

Table 3-4: LULC Data Collection Using TNRIS Aerial Imagery (2006)

Step	Process
1	Review digital orthophoto quarter-quadrangles by subwatershed in ArcGIS.
2	Digitize polygons representing distinct land cover categories.
3	Attribute polygons with LULC class codes.
4	Join new LULC data with existing NLCD data for 2006 to complete study area coverage.
5	Calculate total area per category within the study area.
6	Calculate distribution of categories within study area.
7	Clip LULC coverage to subwatersheds.
8	Calculate subwatershed category areas.
9	Calculate subwatershed distribution of categories.
10	Clip LULC coverage to microwatersheds.
11	Calculate microwatershed LULC category areas.
12	Calculate microwatershed distribution of categories.
13	Clip LULC coverage to riparian areas.
14	Calculate riparian area LULC category areas.
15	Calculate riparian area distribution of categories.

3.2.2: Delineating Analysis Areas

The area boundaries defined for subwatersheds, microwatersheds, and riparian areas are used to clip the LULC data, creating the unique LULC composition dataset for each analysis area.

3.2.2.1: Subwatersheds

Subwatersheds for the Central Brazos River, three tributaries, and five sub-tributaries, listed in Table 3-5 and shown in Figure 3-1, are delineated using the ArcHydro Utility Network Analyst (ESRI 2009). ArcHydro uses the USGS National Hydrography Dataset flowlines as its native stream network, and as such provides the most detailed stream line data available at the regional scale (USGS 1999). The Trace Downstream function applied to the Brazos River main channel immediately downstream of Lake Waco separates the Central Brazos from the Upper Brazos. The Trace Upstream function applied to the Central/South Brazos River segment immediately downstream of the Navasota River confluence confirms the extent of the Central Brazos basin. These subwatershed outlines were determined using NHD level 12 and level 8 Hydrologic Unit ("HUC") borders (USGS 1999). Because defining the borders of each subwatershed (and later, microwatershed) would have been performed using the same elevation data used to generate the HUC areas, it is unnecessary to repeat any catchment boundary delineation – the polygon GIS data already exist.

The Central Brazos River is divided into two subwatershed zones for analysis purposes. The zone border is selected manually and lies immediately upstream of the most upstream tributary to the Central Brazos River, the Little River. The intent of this zone division is to isolate the effects of tributary inflow on the Central Brazos main stem. The zone division is validated by applying ArcHydro Trace Upstream from immediately upstream of the confluence of the Little River: no tributary inflow is identified upstream of the Little River.

Table 3-5: Subwatersheds within the Study Area

Subwatershed Name	Subwatershed Identifier
Central Brazos River North	CBN
Central Brazos River South	CBS
Brushy Creek	BC
Cowhouse Creek	CC
Lampasas River	LAM
Little River	LIT
Leon River	LEO
Navasota River	NAV
San Gabriel River	SGR
Yegua Creek	YC

3.2.2.2: Microwatersheds

Eighty-four microwatersheds are defined within the ten subwatersheds that comprise the study area and are listed in Table 3-6. Data from 107 water quality sample collection points ("stations") are associated with these microwatersheds. Only catchments with existing water chemistry data for the study period were identified as microwatersheds for this study. Based on water chemistry data availability, not all areas or catchments within a subwatershed may be defined as microwatersheds. Where data exist, the catchment upstream of the station is selected and its extent defined by the NHD level 12 HUC boundary. Some microwatersheds overlap others within the basin, as shown in the case of Cowhouse Creek in Figure 3-2. Other microwatersheds do not overlap any others within the subwatershed.

Table 3-6: Microwatershed definitions and general data representation

Micro ID	Microwatershed Name	Subwatershed Name	Station ID	‘92	‘01	‘06
1	Brushy_12056	Brushy Creek	12056	N	Y	N
2	Brushy_17374_11735	Brushy Creek	17374	N	Y	Y
2	Brushy_17374_11735	Brushy Creek	11735	N	Y	Y
3	Brushy_12067_12068	Brushy Creek	12067	N	Y	Y
3	Brushy_12067_12068	Brushy Creek	12068	N	Y	Y
4	Brushy_12062	Brushy Creek	12062	Y	N	N
5	Brushy_12054	Brushy Creek	12054	Y	N	N
6	BrazosNorth_12034	Central Brazos North	12034	N	Y	Y
7	BrazosNorth_16407	Central Brazos North	16407	N	Y	Y
8	BrazosNorth_16400	Central Brazos North	16400	N	Y	Y
9	BrazosNorth_12032	Central Brazos North	12032	Y	Y	Y
10	BrazosNorth_16406	Central Brazos North	16406	N	Y	Y
11	BrazosNorth_16403	Central Brazos North	16403	N	Y	Y
12	BrazosNorth_16402	Central Brazos North	16402	N	Y	Y
13	BrazosSouth_16395	Central Brazos South	16395	N	N	Y
14	BrazosSouth_16394	Central Brazos South	16394	N	Y	Y
15	BrazosSouth_16401	Central Brazos South	16401	N	Y	Y
16	BrazosSouth_15767	Central Brazos South	15767	N	Y	N
17	BrazosSouth_12030	Central Brazos South	12030	N	Y	Y
18	Cowhouse_11922	Cowhouse Creek	11922	Y	Y	Y
19	Cowhouse_17546	Cowhouse Creek	17546	N	Y	Y
20	Cowhouse_11805	Cowhouse Creek	11805	Y	Y	Y
21	Lampasas_13547	Lampasas River	13547	N	Y	Y

Table 3-6: Continued

Micro ID	Microwatershed Name	Subwatershed Name	Station ID	‘92	‘01	‘06
22	Lampasas_11894_18758	Lampasas River	11894	Y	Y	Y
22	Lampasas_11894_18758	Lampasas River	18758	Y	Y	Y
23	Lampasas_12045	Lampasas River	12045	N	Y	N
24	Lampasas_12050_12051_12052	Lampasas River	12050	Y	Y	Y
24	Lampasas_12050_12051_12052	Lampasas River	12051	Y	Y	Y
24	Lampasas_12050_12051_12052	Lampasas River	12052	Y	Y	Y
25	Lampasas_12053	Lampasas River	12053	N	Y	N
26	Lampasas_18330_11724	Lampasas River	18330	N	Y	Y
26	Lampasas_18330_11724	Lampasas River	11724	N	Y	Y
27	Lampasas_18333_11725	Lampasas River	18333	N	Y	Y
27	Lampasas_18333_11725	Lampasas River	11725	N	Y	Y
28	Lampasas_18334	Lampasas River	18334	N	Y	N
29	Lampasas_11896	Lampasas River	11896	Y	Y	N
30	Lampasas_11897	Lampasas River	11897	N	Y	Y
31	Lampasas_15250_16358	Lampasas River	15250	N	Y	Y
31	Lampasas_15250_16358	Lampasas River	16358	N	Y	Y
32	Leon_11941_11939	Leon River	11941	Y	Y	Y
32	Leon_11941_11939	Leon River	11939	Y	Y	Y
33	Leon_11938	Leon River	11938	Y	Y	Y
34	Leon_15765	Leon River	15765	N	Y	Y
35	Leon_13647	Leon River	13647	Y	Y	Y
36	Leon_17538	Leon River	17538	N	Y	Y
37	Leon_17541	Leon River	17541	N	Y	Y
38	Leon_17542_11818	Leon River	17542	N	Y	Y
38	Leon_17542_11818	Leon River	11818	N	Y	Y
39	Leon_11935_14032_14033	Leon River	11935	Y	Y	Y
39	Leon_11935_14032_14033	Leon River	14032	Y	Y	Y
39	Leon_11935_14032_14033	Leon River	14033	Y	Y	Y
40	Leon_11934	Leon River	11934	Y	Y	Y
41	Leon_17379	Leon River	17379	N	Y	Y
42	Leon_17377	Leon River	17377	N	Y	Y
43	Leon_11808_17477	Leon River	11808	Y	Y	Y
43	Leon_11808_17477	Leon River	17477	Y	Y	Y
44	Leon_18781	Leon River	18781	N	Y	Y
45	Leon_17547	Leon River	17547	N	Y	Y
46	Leon_11932	Leon River	11932	Y	Y	N
47	Leon_11930	Leon River	11930	N	N	Y

Table 3-6: Continued

Micro ID	Microwatershed Name	Subwatershed Name	Station ID	‘92	‘01	‘06
48	Leon_11928_17501	Leon River	11928	N	Y	Y
48	Leon_11928_17501	Leon River	17501	N	Y	Y
49	Leon_11925	Leon River	11925	N	Y	Y
50	Leon_11923	Leon River	11923	Y	Y	Y
51	Leon_11921	Leon River	11921	Y	Y	Y
52	Leon_11915	Leon River	11915	Y	N	N
53	Leon_11907	Leon River	11907	Y	Y	Y
54	Leon_11916	Leon River	11916	Y	Y	Y
55	Little_16385	Little River	16385	N	N	Y
56	Little_13544	Little River	13544	N	Y	Y
57	Little_11887	Little River	11887	Y	N	N
58	Navasota_11756	Navasota River	11756	N	Y	Y
59	Navasota_11789	Navasota River	11789	N	Y	Y
60	Navasota_16389	Navasota River	16389	N	Y	Y
61	Navasota_20019	Navasota River	20019	N	N	Y
62	Navasota_16391	Navasota River	16391	N	Y	Y
63	Navasota_11787	Navasota River	11878	N	Y	Y
64	Navasota_11878_17586	Navasota River	11878	N	Y	Y
64	Navasota_11878_17586	Navasota River	17586	N	Y	Y
65	Navasota_12126	Navasota River	12126	Y	Y	Y
66	Navasota_13967_13968	Navasota River	13967	Y	N	N
66	Navasota_13967_13968	Navasota River	13968	Y	N	N
67	Navasota_11877	Navasota River	11877	Y	Y	Y
68	Navasota_18341	Navasota River	18341	N	Y	N
69	Navasota_11872	Navasota River	11872	Y	Y	Y
70	SanGabriel_11892	San Gabriel River	11892	Y	Y	Y
71	SanGabriel_12095	San Gabriel River	12095	Y	Y	Y
72	SanGabriel_12099	San Gabriel River	12099	N	N	Y
73	SanGabriel_11573_20305	San Gabriel River	11573	Y	Y	Y
73	SanGabriel_11573_20305	San Gabriel River	20305	Y	Y	Y
74	SanGabriel_13496	San Gabriel River	12496	N	Y	N
75	SanGabriel_12106_12107	San Gabriel River	12106	Y	Y	N
75	SanGabriel_12106_12107	San Gabriel River	12107	Y	Y	N

Table 3-6: Continued

Micro ID	Microwatershed Name	Subwatershed Name	Station ID	‘92	‘01	‘06
76	SanGabriel_12111_12113	San Gabriel River	12111	Y	Y	Y
76	SanGabriel_12111_12113	San Gabriel River	12113	Y	Y	Y
77	SanGabriel_12117	San Gabriel River	12117	N	Y	N
78	SanGabriel_12108_12114_12115 _20309	San Gabriel River	12108	Y	Y	Y
78	SanGabriel_12108_12114_12115 _20309	San Gabriel River	12114	Y	Y	Y
78	SanGabriel_12108_12114_12115 _20309	San Gabriel River	12115	Y	Y	Y
78	SanGabriel_12108_12114_12115 _20309	San Gabriel River	20309	Y	Y	Y
79	SanGabriel_11572	San Gabriel River	11572	N	Y	N
80	Yegua_11729	Yegua Creek	11729	N	Y	Y
81	Yegua_16887	Yegua Creek	16887	N	Y	Y
82	Yegua_11882	Yegua Creek	11882	Y	Y	Y
83	Yegua_11881_16879	Yegua Creek	11881	Y	Y	Y
83	Yegua_11881_16879	Yegua Creek	16879	Y	Y	Y
84	Yegua_11880	Yegua Creek	11880	Y	Y	Y

3.2.2.3: Riparian Areas

Riparian areas for streams were generated using a 100-meter buffer along the Texas Commission on Environmental Quality Classified/Unclassified Stream Segment (“TCEQ Segment”) datasets that marks stream and reservoirs within the subwatersheds. TCEQ Segment line data represents stream centerlines and average annual pool depth for lakes and reservoirs. The 100-meter buffer is applied to either side of the stream lines but only on the outside of the polygon features representing reservoirs.

TCEQ Segments rather than NHD flowlines are used for riparian area definition because the ultimate intent of this portion of the study is to validate use of riparian area LULC in pollution risk assessment. This type of risk assessment will most likely be performed by environmental regulatory agencies such as the TCEQ. Though this choice may limit the scope of this study, the analytical methodology can easily be applied to an expanded hydrologic network in future studies. A representative section of a riparian area is shown in Figure 3-3.

3.2.3: Surface Water Chemistry Data

All water chemistry data are from the TCEQ's SWQMIS database. They represent a spectrum of data collection agencies, but the majority of the data are from most active groups within the basin – the Brazos River Authority and the TCEQ itself. Water chemistry parameters, the SWQMIS identifier codes ("parameter codes") used to extract them from the database, and the number of data points within the study range is listed in Table 3-6. Only data that pass both automated SWQMIS database validation and are approved by the data collector are included for analysis. These validation checks are noted in the SWQMIS database for each data point.

Table 3-7: Water Chemistry Parameters and SWQMIS Codes

Parameter Description	Parameter Code	Data Points
Chlorophyll A, Fluorometric Method, µg/L	70953	711
Dissolved Oxygen, mg/L	00300	1,939
Fecal Coliform Bacteria, Membrane Filtered, Cultured, #/100mL sample	31616	998

Table 3-7: Continued

Parameter Description	Parameter Code	Data Points
Orthophosphate Phosphorus, Dissolved, mg/L	70507	1,048
Nitrate Nitrogen, Total, mg/L as N	00620	1,394
pH, Standard Units	00400	1,947
Phosphorus, Total, Wet Method, mg/L as P	00665	665
Specific Conductance, Field Measurement, µMhos/cm at 25° Centigrade	00094	1,884
Water Temperature, Degrees Centigrade	00010	2,016

Multiple data collection groups may collect water quality samples very close to one another, but not at the exact same point. Stations within 400 meters of one another (the TCEQ guideline for coincident stations) are grouped together (TCEQ 2008a). Because of this data grouping, some microwatersheds are associated with multiple stations. This enhances data coverage over time. The general data distribution at the microwatershed scale is shown in Table 3-6: not all three study years are available for all 84 microwatersheds, but all years are represented by one or more microwatersheds within each of the ten subwatersheds. The dataset is unbalanced with regard to the number of microwatersheds per subwatershed, but this is not a concern with the selected analytical methods. All subwatersheds contain three or more microwatersheds.

3.3: Study Design and Analysis Model

The study design includes two sets of independent variables, encompassing the three levels of geographic areas and their LULC characteristics. Each subwatershed, microwatershed, and riparian area has a unique LULC composition, described in this case by LULC category percentage values. The proportional area covered by each of seven

LULC categories is calculated: Agriculture, Built-Up, Brush/Forest, Grass, Water, Wetland, and Barren.

Nine water chemistry parameters (Table 3-7) are dependent variables, values associated with geographic areas by location. Water chemistry data from the downstream end of a geographic area, representing the accumulated influence of the contributing landscape, are paired with the LULC category percentage values of that catchment. For each of these nine water chemistry parameters, the strength (if any) of its relationship with each LULC category is quantified.

The study design incorporates independent variables as both fixed and random factors; both categories act as grouping parameters. A factor is considered fixed when the categories included in an analysis model are the only possible values of interest. A factor is random when the groups included in the study are a small sample from a larger pool of possible values. For this study, data are grouped temporally and spatially. Year is considered a random factor, since a small subset of time snapshots consisting of 1992, 2001, and 2006 was selected for inclusion in the analysis. The microwatershed can also be considered random, since it is a catchment of variable size delineated upstream from a small subset of possible sampling points within the study area. The subwatersheds, also subdivisions covering the entire study area but only a small portion of global watersheds, are similarly considered to be a random factor. These two geographic grouping factors are nested in the first-tier analysis. Area Type, denoting whether the record is for a riparian area or a subwatershed, and Subwatershed are the geographic grouping factors in the second-tier analysis; these are treated as random as well. The seven LULC category percentage variables comprise a complete, though condensed, spectrum of LULC types and act as fixed factors.

LULC category percentage is nested within microwatershed, which is nested in subwatershed, which nested in year. In the second-tier analysis, LULC is nested in subwatershed, which is nested in area type, which is nested in year. The hierarchy of predictor and grouping variables is shown in Tables 3-8 and 3-9. All ten subwatersheds have representative water quality data from all three study years, as shown in Table 3-6. The spatial hierarchy of subwatersheds and microwatersheds is shown in Figures 3-1 and 3-2; an example of a riparian area is shown in Figure 3-3. Trends on land use/land cover distributions are subtle at the subwatershed scale; data and graphics detailing these trends and trends at the microwatershed and study area scale are included in the discussion of the study results.

Table 3-8: Predictors and Grouping Variables for Detailed Subwatersheds

Year	1992		2001			2006	
Subwatershed	Ten Subwatersheds						
Microwatershed	Multiple Microwatersheds per Subwatershed						
LULC Category Percentage	Agriculture	Built Up	Brush/Forest	Grass	Water	Wetland	Barren

Table 3-9: Predictors and Grouping Variables for Riparian Areas

Year	1992		2001			2006	
Area Type	Subwatershed or Riparian Area						
Subwatershed	Ten Subwatersheds						
LULC Category Percentage	Agriculture	Built Up	Brush/Forest	Grass	Water	Wetland	Barren

3.4: Initial Data Exploration

3.4.1: Testing and Meeting Assumptions

Due to the inherent cumulative nature of directional flow networks and repeated measurements over time, the data did not meet the assumption of independence necessary for classic, parametric correlation and analysis of variance (ANOVA) techniques. Prior to beginning analysis, testing the data to ensure assumptions of normality and homoscedasticity was necessary. Each water chemistry parameter was assessed separately; LULC category percentages, as related data, were assessed with all classes in a single dataset. The Shapiro-Wilk Test was used to assess normality of the data. Visual examination of variance plots (predicted dependent variable versus standardized residuals) for patterns was used to assess homoscedasticity. None of the residual plots exhibited any discernable pattern, thus formal testing of homoscedasticity was not performed. Two datasets – dissolved oxygen and temperature – proved normal without transformation. Non-normal distributions were addressed using data transformations. Final/optimal Shapiro-Wilk scores (W) are listed for each dataset in Table 3-10. All data were ultimately suitable for analysis using parametric methods, using the transformation factors also listed in Table 3-10.

Table 3-10: Transformation applied to achieve normal distribution, listed by dataset. Shapiro-Wilk scores for normality.

Dataset	Transformation	W
Chlorophyll A (Chl A)	ln(x)	0.8565
Dissolved Oxygen (DO)	None	0.9801
Fecal Coliform Bacteria (FC)	ln(x)	0.9648
Orthophosphate (OP)	ln(x)	0.9416
pH	None	0.9137
Specific Conductance (SpC)	ln(x)	0.9720
Temperature (Temp)	None	0.9521
Total Nitrate Nitrogen (TN)	ln(x)	0.9708
Total Phosphorus (TP)	ln(x)	0.9250
LULC Category Percentages (all categories)	ln(x)	0.9385

3.4.2: Characterizing Trends

Changes over the study period are presented both graphically and as tabular percentage shifts for all water chemistry parameters and all LULC categories. Distribution of LULC categories are also presented for comparison.

3.5: Linking Land Use and Water Quality

All available data points are included in the correlation analysis, regression model selection, and linear mixed-effects (LME) model analysis. In order to accommodate the difference in sample size between water quality parameters, each parameter was examined separately. Due to square matrix limitations, principal component analysis (PCA) included only a subset of the total dataset. The data selection procedure for PCA and data handling for model selection/LME analysis are described in more detail in later sections.

In order to maximize the sample size for correlation analysis, regression model selection, and PCA, these analyses were performed on the total dataset – at the watershed level, for the entire study area. The data points included are still paired at the subwatershed or microwatershed scale, but are combined without regard for scale. LME analysis is scale-dependent, and takes advantage of the scale and year groupings.

3.5.1: Correlation Analysis

As the data transformation was fully successful, the standard parametric Pearson Correlation method was used for preliminary evaluation of the linkages between LULC and water chemistry (Cohen et al. 2003, Pearson 1920). Each LULC category was then paired with its most promising correlated parameters for further analysis – two or more of the most strongly correlated parameters, including all with correlation coefficients ≥ 10%, were included in the PCA. Significance level was defined at 0.05 per convention (Li et al. 2008).

3.5.2: Principal Component Analysis

A principal component analysis (PCA) was used to characterize relationships among predictor variables and among response variables. Individual PCA for each LULC category with its most strongly correlated parameters was performed, to isolate these most important relationships. PCA for all LULC categories against the four water chemistry parameters with the greatest data availability was also performed, to examine the relative influence of the seven LULC categories. For the all-LULC-categories PCA, composition of the analysis dataset required that only geographic areas (subwatershed or microwatershed) with a complete panel of water quality data points within a certain year to be included. For example, the LULC category values are valid for a geographic area for one of the three study years. To be included in the PCA, the software's data matrix requires that this LULC category data series be associated with all included water quality parameters: missing values are not acceptable. A representative data record from the analysis matrix is shown in Table 3-11.

Table 3-11: Example Record from PCA Data Matrix

Chl A	FC	pH	SpC	Cat. A	Cat. B	Cat. C	Cat. D	Cat. E	Cat. F	Cat. G
1.726	1.939	8.299	5.902	0.021	0.023	0.574	0.364	0.009	0.007	0.002

3.5.3: Variable Selection/Model Optimization

A stepwise regression procedure was applied to the overall linear model to identify the strongest combination of predictors for the dependent variable. Both backwards-stepping (removal of one predictor per step) and forward-stepping (addition of one predictor per step) regression comparisons were applied. Models were selected using Akaike Information Criterion (AIC) score for relative suitability ranking. AIC is a relative scoring tool that describes the difference between the true distribution of a model and each candidate model (Demidenko 2004 , Akaike 1973)

3.5.4: Linear Mixed-Effects Model Analysis

Each water chemistry parameter was paired with a panel of LULC category percentages for analysis. This pairing allowed for maximum sample size, as not all geographic area-year combinations have existing data for all dependent variables (as discussed in Section 3.5.2 on PCA). The number and combination of LULC category predictors used in each analysis was determined by the outcome of the model optimization process described in Section 3.5.3. The best model was run with several combinations of grouping factors, for comparison: grouped by year, subwatershed, microwatershed, microwatershed within subwatershed, and finally microwatershed within subwatershed within year. Significance values were set at a more flexible 0.10, as this study is considered a novel application of the technique with both longitudinal and multi-level geographical data.

CHAPTER 4 : RESULTS AND DISCUSSION

4.1: Historical Perspective

For a myriad of reasons and as in many other areas, water quality concerns in the Central Brazos River basin have grown more pressing over the 1992-2006 study period. The recent explosion in the number of TCEQ water bodies with use impairments – from three in 1992 to thirty-two in 2006 – is a strong indication that land-based activities within the basin may be exerting a negative impact on the local water resources (Table 4-1). The impact of point sources of pollution is quantified using known discharge levels and patterns, but effects not attributable to point sources are also evident (TCEQ 1992-2006). Not shown in Table 4-1 are the types of impairments to these water bodies, which include point sources and categories of non-point sources such as municipal, animal feeding operations, and rangeland grazing (TCEQ 1992-2006). These TCEQ source notations are cause for special scrutiny of agriculture (Category A) and built-up (Cat. B) LULC in the analyses presented in this chapter. The majority of these impairments are due to excessive bacteria in the water (TCEQ 1992-2006). While bacteria is indeed a problem frequently seen due to runoff from built-up areas, agricultural activities such as dairy farming (prevalent in the central Brazos) also exhibit a hallmark bacterial impact on nearby watercourses (TCEQ 1992-2006).These TCEQ source notations are cause for special scrutiny of agriculture (Category A) and built-up (Cat. B) LULC in the analyses presented in this chapter.

Table 4-1: TCEQ Segments in the Central Brazos River Basin Not Meeting Water Quality Standards

Segment ID	Segment Name / Year	1992	1994	1996	1998	1999	2000	2002	2004	2006
1209A	Country Club Lake (unclassified water body)					X	X	X	X	X
1209B	Fin Feather Lake (unclassified water body)	X				X	X	X	X	X
1253A	Springfield Lake (unclassified water body)									
1242F	Pond Creek (unclassified water body)									
1242J	Deer Creek (unclassified water body)									X
1242K	Mud Creek (unclassified water body)							X	X	X
1242B	Cottonwood Branch (unclassified water body)									X
1242	Brazos River Above Navasota River			X		X		X	X	
1242C	Still Creek (unclassified water body)									X
1242D	Thompson Creek (unclassified water body)							X	X	X
1247A	Willis Creek (unclassified water body)								X	X
1242L	Pin Oak Creek (unclassified water body)							X	X	X
1248	San Gabriel/North Fork San Gabriel River							X	X	
1242M	Spring Creek (unclassified water body)							X	X	X
1248A	Berry Creek (unclassified water body)									
1248B	Huddleston Branch (unclassified water body)									
1248C	Mankins Branch (unclassified water body)									X
1248D	Middle Fork San Gabriel River (unclassified water body)									
1242N	Tehuacana Creek (unclassified water body)							X	X	X

Table 4-1: Continued

Segment ID	Segment Name	Year	1992	1994	1996	1998	1999	2000	2002	2004
1250	South Fork San Gabriel River									
1242O	Walnut Creek (unclassified water body)									X
1253	Navasota River Below Lake Mexia					X				
1242P	Big Creek (unclassified water body)							X	X	X
1244	Brushy Creek		X				X			X
1244A	Brushy Creek Above South Brushy Creek (unclassified water body)									
1244B	Lake Creek (unclassified water body)									
1244D	South Brushy Creek (unclassified water body)									
1210	Lake Mexia			X		X	X	X	X	
1212	Somerville Lake							X	X	X
1242E	Little Brazos River (unclassified water body)									
1242I	Campbells Creek (unclassified water body)								X	X
1249	Lake Georgetown									
1252	Lake Limestone									
1202	Brazos River Below Navasota River	X	X	X	X					
1202H	Allen's Creek (unclassified water body)							X	X	X
1201	Brazos River Tidal	X		X						
1209	Navasota River Below Lake Limestone							X	X	X
1210A	Navasota River above Lake Mexia (unclassified water body)							X	X	X
1209C	Carters Creek (unclassified water body)					X	X	X	X	X
1211	Yegua Creek									
1211A	Davidson Creek (unclassified water body)								X	X
1212A	Middle Yegua Creek (unclassified water body)									
1209D	Country Club Branch (unclassified water body)					X	X			X
1202J	Big Creek (unclassified water body)							X	X	X
1209E	Wickson Creek (unclassified water body)									X
1202K	Mill Creek (unclassified water body)									
1209G	Cedar Creek (unclassified water body)							X	X	X

Table 4-1: Continued

Segment ID	Segment Name	Year	1992	1994	1996	1998	1999	2000	2002	2004
1209H	Duck Creek (unclassified water body)									X
1212B	East Yegua Creek (unclassified water body)							X	X	X
1209I	Gibbons Creek (unclassified water body)							X	X	X
1209J	Shepherd Creek (unclassified water body)							X	X	X
1209K	Steele Creek (unclassified water body)							X	X	X
1213	Little River			X		X	X			
1214	San Gabriel River					X	X			
1247	Granger Lake									
1209L	Burton Creek (unclassified water body)									X
1202I	Bessie's Creek (unclassified water body)									
	TOTAL IMPAIRED SEGMENTS	3	2	5	1	9	9	22	24	32

4.1: Land Use Change over Time: Subwatersheds and Riparian Areas

Overall variation in LULC distribution ranged widely, but some trends were revealed. Changes over time, both over the entire study period of 1992-2006 and between individual land use/land cover series, were calculated for each LULC category. Summaries of LULC change are presented in this chapter; complete results (including plots) are in Appendix A. Correlation and LME analysis, discussed later in this chapter, quantified the impact these spatial and temporal variations have had on water quality in the Central Brazos.

As discussed in Chapter 3, the types of land use/land cover grouped together to form the seven categories used for this study were selected to maximize separation of potential impacts on surface water (Section 3.2.1). Land classified as agriculture (Cat. A) included both tilled/crop land and rangeland; the lack of potential manure-based enrichment separated it from grass (Cat. D), which was either natural grassland or managed turf. Shrub/forest (Cat. C) included all types of upland woody vegetative cover, but not herbaceous vegetation (grasses in Cat. A or Cat. D) or saturated areas (wetland, Cat. F). Open water (Cat. E) was simply that – areas with less than 25% coverage by land or vegetation, precluding categorization as wetland or other land cover type (NOAA 2006). Built-up land (Cat. B) may actually have been a mosaic of land cover types, but was defined and differentiated from other groups by a minimum of 20% impervious cover (NOAA 2006). Rock/Mine/Sand/Bare Earth areas (Cat. G) were those that had none of the characteristics of the other categories: they exhibited less than 10% vegetative cover and less than 20% impervious cover, and generally consisted of mine, dune, shore, and exposed bedrock (NOAA 2006).

4.1.1: Category A - Agriculture

Agriculture (Cat. A) land use exhibited an overall increase in four of ten riparian areas (RAs): Brushy Creek RA, Central Brazos North RA, Little River RA, and Yegua Creek RA; these increases were 5% or less (Figure A-1). Percent agriculture has decreased in six of ten riparian areas: Central Brazos South RA, Cowhouse Creek RA, Lampasas River RA, Leon River RA, Navasota River RA, and San Gabriel River RA (Figure A-1). These decreases ranged from 24% to 0.5%. These decreases may be attributed to conversion to built-up and grass LULC in the rapidly growing cities of College Station, Copperas Cove, Lampasas and Killeen, Temple, College Station, and Georgetown, respectively.. Average change for riparian areas was -4% (Table A-1). Agricultural area has increased 18% for the Central Brazos North subwatershed (Figure A-2), which is likely due to conversion from grass land cover (Table A-1). The remaining nine subwatersheds showed decreased agricultural land use, changes ranging from -16% to -0.1% (Figure A-2). Average change for subwatersheds was -3% (Table A-2).

4.1.2: Category B – Built-Up

Built-up (Cat. B) areas increased in all riparian areas, where changes ranged from 0.2% to 6% (Figure A-3). Average change for riparian areas was 2% (Table A-1). All but one subwatershed showed increases in built-up area, which ranged from less than 0.1% in Yegua Creek to an extremely large 42% in Leon River (Figure A-4). The populations of the cities of Temple (9.4%) and Killeen (34.5%), both of which are adjacent to reservoirs, have risen sharply between 1990 and 2000 (U.S. Census 1990-2000). These population increases are very likely driving this dramatic increase in the Leon River RA. Large proportional changes may also be due to physically small change: the original percent cover was extremely small, and even moderate development seems proportionately large. The one subwatershed that experienced a decrease in built-up area was Central Brazos North, which showed a change of approximately -5% (Figure A-4). U.S. Census Bureau (1990, 2000) shows only small cities in the Central Brazos North subwatershed, and several of these cities (Golinda, Lott, Marlin, Calvert, Bremond, and Rosebud) have experienced population decreases between 1990 and 2000. Average change for subwatersheds was 2% (Table A-2).

4.1.3: Category C – Shrub/Forest

Shrub/forest (Cat. C) coverage change varied widely both in direction and magnitude within both spatial groups. Six riparian areas experienced decreases in shrub/forest, ranging from -39% in Brushy Creek to 8% in Lampasas River RA (Figure A-5). Riparian shrub/forest coverage increases occurred in four areas, ranging from 1% in Yegua Creek RA to 24% in Navasota River RA (Figure A-5). Average change for riparian areas was -8% (Table A-1). Shrub/forest coverage changes were also split for subwatersheds, with five decreases (from -12% in San Gabriel River to -28% in Leon River) and five increases (from 5% in Yegua Creek to 7% in Lampasas River) (Figure A-6). Average change for subwatersheds was -6% (Table A-2).

4.1.4: Category D – Grass

All riparian areas showed an increase in percent grass (Cat. D) coverage, ranging from 2% in Yegua Creek RA to 24% in Cowhouse Creek RA (Figure A-7). Average change for riparian areas was 10%, which may correspond in part to an average change of -8% in RA shrub/forest coverage (Table A-1). Grass coverage decreased in two subwatersheds, though at -2% in Lampasas River and -4% in Yegua Creek these decreases are relatively minor (Figure A-7). Increases in percent grass for subwatersheds were between 1% in Cowhouse Creek and 11% in Navasota River (Figure A-8). Average change for subwatersheds was 4% (Table A-2).

4.1.5: Category E – Open Water

All riparian areas and all subwatersheds showed decreases in open water (Cat. E) coverage (Figures A-9 and A-10). Decreases were greater within riparian areas, averaging 8% but ranging from -23% in Yegua Creek RA to -0.4% in Brushy Creek RA (Figure A-9, Table A-1). Subwatershed changes in open water averaged -0.7% and ranged from -1% in Leon River and -0.2% in Brushy Creek (Figure A-10, Table A-2).

4.1.6: Category F – Wetland

As with shrub/forest (Cat. C), changes in percent wetland (Cat. F) coverage varied widely in both riparian areas and subwatersheds. Large positive changes (up to 26% in Brushy Creek RA) and one large negative change (-22% in Navasota River RA) were seen; the overall average change for riparian areas was 9% (Figure A-11, Table A-1). Increases from 1992 to 2001 occurred in all riparian areas, followed by sharp decreases in Central Brazos South RA, Navasota River RA, and Yegua Creek RA between 2001 and 2006 (Table 4-2, Figure A-11). Percentage of wetland coverage decreased less sharply or remained near-constant for remaining riparian areas between 2001 and 2006 (Table 4-2, Figure A-11). A similar pattern of sharp increases followed by large decreases was evident for two subwatersheds (Navasota River RA and Yegua Creek RA), although the overall trend was nearly flat at 0.8% (Table 4-2, Figure A-12, Table A-2). The remaining eight subwatersheds exhibited less extreme increases followed by small decreases (Table 4-2, Figure A-12).

4.1.7: Category G – Rock/Mine/Sand/Bare Earth

No dramatic change in barren land (Cat. G) percentage was apparent among riparian areas, and the overall changes are divided between minor increases and minor decreases (Figure A-13). The overall average change for riparian areas, accordingly, was -0.2% (Table A-1). All barren land changes for subwatersheds were similarly minor, with only Navasota River exhibiting a net increase of 0.1% (Table 4-2, Figure A-14). Overall average change for subwatersheds was -0.4% (Table A-2).

Table 4-2: Changes in Proportion of Coverage by LULC Category

	Category A		Category B		Category C		Category D		Category E		Category F		Category G	
Time Period	1992-2001	2001-2006	1992-2001	2001-2006	1992-2001	2001-2006	1992-2001	2001-2006	1992-2001	2001-2006	1992-2001	2001-2006	1992-2001	2001-2006
Area Name														
BC Riparian	0.034	0.000	0.059	0.000	***-0.392***	0.000	0.040	0.000	-0.004	0.000	***0.265***	0.000	-0.002	0.000
CBN Riparian	0.044	-0.007	0.034	-0.008	***-0.128***	0.012	0.044	0.003	***-0.144***	-0.008	***0.145***	0.005	0.005	0.003
CBS Riparian	-0.029	-0.005	0.015	-0.013	***-0.159***	***0.194***	0.032	0.013	-0.067	-0.017	***0.212***	***-0.177***	-0.004	0.004
CC Riparian	-0.242	0.000	0.005	0.000	0.012	0.000	***0.245***	0.000	-0.071	0.000	0.061	0.000	-0.010	0.000
LAM Riparian	***-0.146***	0.000	0.019	0.000	-0.080	0.000	***0.214***	0.000	-0.078	0.000	0.082	0.000	-0.011	0.000
LEO Riparian	-0.063	0.000	0.014	0.000	***-0.143***	0.000	***0.175***	0.000	-0.070	0.000	0.096	0.000	-0.009	0.000
LIT Riparian	0.054	0.000	0.029	-0.004	***-0.305***	0.039	0.032	0.003	-0.039	-0.007	***0.233***	-0.033	-0.005	0.001
NR Riparian	-0.073	0.011	0.037	-0.027	-0.084	***0.327***	0.049	0.000	-0.018	-0.009	0.089	***-0.312***	-0.001	0.010
SGR Riparian	-0.037	0.031	0.032	-0.003	***-0.264***	0.019	***0.127***	0.004	-0.013	-0.002	***0.162***	-0.049	-0.007	0.000
YC Riparian	0.005	0.001	0.019	-0.019	***-0.172***	***0.272***	0.016	0.004	***-0.235***	0.001	***0.360***	***-0.262***	0.006	0.003
Brushy Creek	0.001	0.000	***0.101***	-0.003	***-0.141***	0.004	0.015	0.001	-0.002	0.000	0.030	-0.002	-0.004	0.000
Central Brazos North	***0.191***	-0.002	***-0.451***	-0.013	***-0.191***	0.008	0.080	0.007	-0.008	0.000	0.035	-0.001	-0.004	0.001
Central Brazos South	-0.064	0.000	0.004	0.000	0.053	0.000	0.025	0.000	-0.010	0.000	-0.004	0.000	-0.004	0.000
Cowhouse Creek	-0.065	0.000	0.007	0.000	0.058	0.000	0.014	0.000	-0.009	0.000	0.007	0.000	-0.013	0.000
Lampasas River	-0.058	0.000	0.015	0.000	0.073	0.000	-0.024	0.000	-0.005	0.000	0.006	0.000	-0.007	0.000
Leon River	-0.035	***-0.114***	0.020	***0.406***	-0.065	***-0.214***	0.083	-0.062	-0.009	-0.006	0.012	-0.012	-0.006	0.004
Little River	0.038	0.006	0.042	-0.009	***-0.178***	0.003	0.067	0.008	-0.005	0.000	0.038	-0.010	-0.003	0.002
Navasota River	***-0.158***	-0.003	0.048	-0.025	-0.010	0.078	0.099	0.013	-0.002	0.000	0.024	-0.065	0.000	0.001
San Gabriel River	-0.021	0.004	0.040	-0.002	***-0.120***	0.002	0.084	0.000	-0.001	0.000	0.022	-0.004	-0.004	0.000
Yegua Creek	0.000	0.003	0.046	-0.045	-0.207	***0.254***	-0.061	0.023	-0.014	0.001	0.066	-0.064	-0.005	0.003

Note: Values exceeding 10% change are shown in ***bold italics.***

4.2: Linking Land Use and Water Quality

Identifying and describing relationships between water quality indicator parameters and land use/land cover types was the first step in linking LULC change to changes in water quality. A series of analytical methods were applied in a stepwise fashion to maximize efficiency; by eliminating insignificant relationships between LULC category/water quality (WQ) parameter pairs, results are simplified.

Pearson correlation analysis was applied to measure the linear relationship between the two sets of variables. The correlation results guided the first elimination step, selecting a smaller subset of WQ parameters to include in the PCA for each LULC category. Principal component analysis identified the dominant relationships for individual LULC categories and possible redundant variable pairs. PCA results were confirmed by AIC-driven variable selection for the linear models: important variable pairings and redundancies shown by PCA were reflected in the optimized models. Linear mixed effects (LME) analysis using the optimized variable sets approached the LULC-WQ relationships from the WQ perspective, in contrast to the LULC-oriented PCA. LME analysis corroborated the relationships shown by both correlation analysis and PCA; it also allowed variance partitioning and comparison of spatial scales.

4.2.1: Correlation Analysis

Pearson correlation between each WQ parameter-LULC category pair yielded a large proportion of significant results, but no large *r* values (Table 4-3). Some small to moderate relationships do exist, however, most notably with the agriculture and wetland LULC categories.

In order to achieve a large sample size, the correlation analysis was performed on data at the microwatershed scale. Relatively low correlation coefficients may be attributed to the size of the WQ dataset compared to the LULC dataset: multiple WQ values existed for each annual LULC percentage series, so the LULC values were necessarily repeated.

Table 4-3: Pearson Correlation Coefficients, LULC Categories vs. WQ Indicators, Microwatershed Scale

LULC Category	A	B	C	D	E	F	G
WC Parameter	*r* value						
Chl A	0.252914 [a]	0.064681 [b]	-0.02904	-0.18035 [a]	0.175236 [a]	0.12193 [a]	0.030851
DO	-0.11502 [a]	-0.0444 [a]	0.030249 [b]	0.025214	-0.09435 [a]	-0.05207 [a]	-0.03113 [b]
FC	0.174525 [a]	0.0729 [a]	-0.12662 [a]	-0.038	0.071241 [a]	0.113653 [a]	-0.00124
OP	0.053714 [a]	0.055119 [a]	0.045002 [b]	0.101094 [a]	0.04211 [b]	0.015955	-0.06315 [a]
pH	-0.19117 [a]	-0.04726 [a]	0.144265 [a]	0.20103 [a]	-0.10027 [a]	-0.1846 [a]	-0.11019 [a]
SpC	-0.03218 [b]	0.003209 [b]	0.04244 [a]	0.135125 [a]	-0.07814 [a]	-0.0814 [a]	-0.15035 [a]
Temp	-0.03174 [b]	-0.03697 [a]	0.032022 [b]	-0.02531	0.00207	-0.04663 [a]	0.034243 [a]
TN	-0.04717 [a]	0.028159	-0.02363	0.113768 [a]	-0.05893	-0.05556 [a]	-0.04272 [b]
TP	0.176906 [a]	0.140062 [a]	-0.06857	0.043469 [b]	0.072135 [a]	0.18229 [a]	-0.07927 [a]

Note: [a] denotes significance at the 0.01 probability level.
[b] denotes significance at the 0.05 probability level

One purpose of conducting correlation analysis was to focus the principal component analysis (PCA) by facilitating pre-analysis reduction of variables. Each LULC category was paired with its most strongly correlated parameters for PCA. Two or more of the most strongly correlated parameters, including all with correlation coefficients ≥ 10% where the result was significant, were selected for PCA. Pairings are shown in Table 4-4.

Table 4-4: Water Quality Indicator-LULC Category Pairings for Principal Component Analysis

LULC Category		A	B	C	D	E	F	G
WQ Variable	Chlorophyll A	X	X		X	X	X	
	Dissolved Oxygen	X						
	Fecal Coliform Bacteria	X		X			X	
	Orthophosphate				X			
	pH	X		X	X	X	X	X
	Specific Conductance				X			X
	Temperature							
	Total Nitrogen (Nitrate)				X			
	Total Phosphorus	X	X				X	

4.2.2: Principal Component Analysis

Principal component analysis served to confirm the strength of WQ-LULC relationships shown by correlation analysis, as well as to highlight possible redundancies or covariance between variables. PCA based on the correlation matrix rather than a covariance matrix was performed, in order to accommodate the different measurement units of the LULC and WQ variables (Jolliffe 2002). Tables 4-5 through 4-11 summarize the PCA results through eigenanalysis, including sufficient principal components to comprise at least 80% of the dataset variation. Limits on the number of components presented were confirmed using both Kaiser's eigenvalue criterion of > 1 and qualitative examination of the "shoulder" of the eigenvalue scree plot (see Appendix C for scree plots and eigenvalues) (Quinn and Keough 2002, Cattell 1966, Kaiser 1960).

4.2.2.1: Category A – Agriculture

PCA results indicated that, of the WQ parameters included in the analysis, percent coverage of agriculture (Cat. A) impacts pH, Chl A, DO, and TP strongly (Table 4-5). This is consistent with findings in previous studies (Johnson et al. 1997, Hill 1987). Biplots of the PCA results showed that TP and FC are negatively related (Figure C-1), as are TP and DO (Figures C-2 and C-5). The combination of pH, Chl A, DO, and TP in these dominant components may suggest eutrophication; eutrophication would also likely create covariance between TP and FC and TP and DO (Allan 2004, Allan et al. 1997, Horne and Goldman 1994).

Table 4-5: Category A Component Loading Summary

Variable	PC 1	PC 2	PC 3	PC 4
Cat. A	0.731	-0.471	0.264	-0.057
Chl A	0.362	-0.819	0.140	0.198
DO	-0.379	0.206	0.776	0.453
FC	0.649	0.556	0.155	0.011
pH	-0.739	-0.341	-0.232	0.305
TP	0.521	0.202	-0.426	0.691
Cum. %	34.122	57.478	73.322	86.962

4.2.2.2: Category B – Built-Up

The proportion of built-up land (Cat. B) exerted influence on both Chl A and TP levels (Table 4-6). Biplots suggested that TP and Chl A are related, which may temper the strength of the response directly attributable to the proportion of built-up land (Figures C-9 and C-10). As seen for agriculture, these results were consistent with literature. Phosphorus has been linked to increases in urban lands, among other sources;;increased TP is a primary effect of enhanced algal activity (Sliva and Williams 2001, Horne and Goldman 1994, Osborne and Wiley 1988).

Table 4-6: Category B Component Loading Summary

Variable	PC 1	PC 2	PC 3
Cat. B	0.168	0.894	0.415
Chl A	0.706	-0.455	0.543
TP	0.791	0.216	-0.573
Cum. %	38.375	73.495	100.000

4.2.2.3: Category C – Shrub/Forest

Shrub/forest (Cat. C) coverage had a strong effect on FC levels and a less dramatic, though still significant, effect on pH (Table 4-7). Woody vegetation, particularly in riparian zones, effectively reduces bacterial input to surface waters – this may occur by sediment-in-runoff attenuation and/or physical barrier to livestock access to the watercourse (Wilcock et al. 2007, Mander et al. 2005, Anbumozhi et al. 2005, Meador and Goldstein 2003, Jones et al. 2001, Lyons et al. 2000). Figure C-13 suggested that FC and pH levels may be negatively related, as was also seen for the agriculture category.

Table 4-7: Category C Component Loading Summary

Variable	PC 1	PC 2
Cat. C	0.492	0.852
FC	-0.837	0.103
pH	0.766	-0.435
Cum. %	50.957	81.843

4.2.2.4: Category D – Grass

Total nitrogen exhibited a positive correlation with grass (Cat. D) coverage (Table 4-8, Figure C-17). This result is consistent with literature on cultivated or recreational grasses, which generally attribute increases in nitrogen to fertilizer application (Law et al. 2004, Robbins et al. 2001, USDA 2000). The grass category was largely composed of recreational grasses in the Central Brazos, since other grass areas were used as rangeland and therefore classified as agricultural (Cat. A) within the study period. Specific conductance appeared to be related to Chl A, TN, and OP, though there is no obvious documented explanation for this grouping (Figures C-17, C-18, C-19, C-21).

Table 4-8: Category D Component Loading Summary

Variable	PC 1	PC 2	PC 3	PC 4
Cat. D	0.690	0.050	0.567	-0.051
Chl A	-0.513	0.695	-0.199	0.289
OP	0.532	0.470	-0.479	0.222
pH	-0.093	0.517	0.757	0.236
SpC	0.486	0.585	-0.149	-0.533
TN	0.709	-0.232	-0.135	0.488
Cum. %	29.506	52.349	72.435	84.324

4.2.2.5: Category E – Open Water

Chlorophyll A levels were more strongly influenced by open water (Cat. E) coverage than pH, though the results may have been somewhat confounded by the relationship between these two WQ variables (Table 4-9, Figure C-25). Figure C-25 suggested that Chl A and pH may be negatively related, a conclusion also supported by current literature (Li et al. 2008, Allan 2004, NAS 1969).

Table 4-9: Category E Component Loading Summary

Variable	PC 1	PC 2
Cat E	0.641	-0.631
Chl A	0.870	0.178
pH	0.289	0.863
Cum. %	41.726	80.867

4.2.2.6: Category F – Wetland

Fecal coliform bacteria and pH levels were strongly impacted by changes in proportion of wetland (Cat. F) (Table 4-10, Figures C-27, C-28). Current literature suggests that the negative wetland-pH relationship may be attributed to decomposition of organic materials in wetlands, particularly the production of humic acids (Johnston et al. 1990). The positive wetland-FC relationship was unexpected, however, based on many studies that show wetlands are generally very effective bacterial sinks (Vacca et al. 2005, Johnston et al. 1990, Ottova et al. 1977). Wetlands research included in the literature review for this study was largely related to constructed wetlands, which are by definition low-gradient and not subject to varying flow conditions. Natural wetlands experiencing high-flow flushing into nearby surface waters may be an explanation for the unexpected FC results. As in the biplots for percent agriculture (Cat. A), TP and FC were negatively related (Figures C-27, C-28, C-29).

Table 4-10: Category F Component Loading Summary

Variable	PC 1	PC 2	PC 3	PC 4
Cat. F	0.606	-0.397	0.440	0.477
Chl A	-0.002	0.588	0.787	-0.185
FC	0.766	0.199	-0.285	-0.396
pH	-0.804	0.290	-0.132	0.275
TP	0.504	0.640	-0.303	0.465
Cum. %	37.079	57.823	77.879	92.070

4.2.2.7: Category G – Rock/Mine/Sand/Bare Earth

Percentage barren land (Cat. G) did not show a strong relative difference in its effect on the selected WQ variables, pH and SpC (Table 4-11, Figure C-31). Its negative relationship with these two variables was unexpected, as both have demonstrated positive relationships with barren land in previous literature (Conway 2007). Differences in local and regional geology, geography, and other factors may have contributed to this contradictory finding; previous studies relating barren land to pH and SpC were conducted in the Northeast region of the United States and may not be truly comparable (Conway 2007.).

Table 4-11: Category G Component Loading Summary

Variable	PC 1	PC 2	PC 3
Cat G	-0.668	0.204	0.716
pH	0.660	0.729	0.183
SpC	0.664	-0.519	0.538
Cum. %	44.061	72.139	100.000

4.2.2.8: All Categories with a Selected Panel of Water Quality Parameters

Examination of the biplot for components 1 and 2 revealed that percent coverage for agriculture (Cat. A) and wetland (Cat. F) were redundant, but also showed further evidence of the relationship between open water (Cat. E) and Chl A (Table 4-12, Figure C-35). Percent grass (Cat. D) was the best predictor of SpC. Shrub/Forest (Cat. C) was the best predictor of pH (Figure C-35). The potential redundancy between agriculture (Cat. A) and wetland (Cat. F) was also notable in Figure C-37, especially with regard to FC levels. These results are consistent with those of the single-category PCAs presented in this section.

Table 4-12: All Categories/WQ Panel Component Loading Summary

Variable	PC 1	PC 2	PC 3	PC 4
Chl A	-0.530	-0.365	-0.094	0.584
FC	0.120	0.816	-0.454	0.015
pH	0.494	-0.549	0.393	0.048
SpC	0.578	0.364	-0.318	0.091
Cat. A	-0.800	0.033	-0.449	0.271
Cat. B	-0.150	0.646	0.633	-0.077
Cat. C	0.398	-0.539	-0.290	-0.659
Cat. D	0.729	0.092	0.333	0.460
Cat. E	-0.651	-0.399	0.343	0.098
Cat. F	-0.929	-0.027	-0.175	-0.244
Cat. G	-0.617	0.400	0.547	-0.326
Cum. %	35.403	56.039	71.635	83.030

4.2.3: Variable Selection/Model Optimization

Quantitative comparison of the candidate models using Akaike Information Criterion (AIC), a relative ranking factor based on goodness of fit, determined the best possible models for the LME analysis. This formal linear model optimization was accomplished using stepwise regression. "Stepwise" describes a linear regression process in which all variables are removed and/or added one at a time, and each model with its unique combination of variables is scored. The use of a quantitative comparison method allowed elimination of superfluous or low-impact variables and reduced the risk of interference due to variable interactions. The model with the best-fit combination of LULC variables for each WQ parameter was then applied in LME analysis, results of which are presented in Section 4.2.4.

4.2.3.1: Subwatershed/Microwatershed Models

The stepwise regression procedure dictated removal of variables for DO, temperature, TN, and TP. In contrast, AIC scores confirmed the suitability of the full model for Chl A, FC, OP, pH, and SpC (Table 4-13, see also Appendix D). Top scoring of the full model for these five parameters highlights the complexity of surface water processes: in many cases, the full panel of LULC categories has significant effects on water quality. These optimized models agree with the PCA results presented in Section 4.2.2: all variables with significant impact are included and no redundancies are incorporated.

Table 4-13: Results of Model Optimization for Subwatersheds/Microwatersheds

WQ Variable	Predictor LULC Variables
Chl A	Cat. A + Cat. B + Cat. C + Cat. D + Cat. E + Cat. F + Cat. G
DO	Cat. A + Cat. C + Cat. D + Cat. E + Cat. G
FC	Cat. A + Cat. B + Cat. C + Cat. D + Cat. E + Cat. F + Cat. G
OP	Cat. A + Cat. B + Cat. C + Cat. D + Cat. E + Cat. F + Cat. G
pH	Cat. A + Cat. B + Cat. C + Cat. D + Cat. E + Cat. F + Cat. G
SpC	Cat. A + Cat. B + Cat. C + Cat. D + Cat. E + Cat. F + Cat. G
Temp	Cat. E + Cat. F + Cat. G

Table 4-13: ContinuedWQ Variable	Predictor LULC Variables
TN	Cat. A + Cat. C + Cat. E + Cat. F + Cat. G
TP	Cat. A + Cat. B + Cat. C + Cat. D + Cat. F

4.2.3.2: Subwatershed/Riparian Area Models

All best-fit models for the riparian LME analysis included six or fewer of the original seven predictor variables; none retained the full model (Table 4-14, see also Appendix D). As discussed in Chapters 1 and 2, this is likely due to local LULC composition exerting a stronger influence on the watercourse relative to outlying contributing lands (Floyd et al. 2009, Allan 2004, Gove et al. 2001).

Table 4-14: Results of Model Optimization for Subwatersheds/Riparian Areas

WQ Variable	Predictor LULC Variables
Chl A	Cat. A + Cat. B + Cat. C + Cat. D + Cat. E + Cat. F
DO	Cat. A + Cat. C + Cat. D + Cat. E
FC	Cat. B + Cat. C
OP	Cat. C + Cat. D + Cat. G
pH	Cat. A + Cat. B + Cat. C + Cat. E + Cat. F + Cat. G
SpC	Cat. B + Cat. C + Cat. D + Cat. E + Cat. F + Cat. G
Temp	Cat. A + Cat. B + Cat. D + Cat. E + Cat. F
TN	Cat. A + Cat. B + Cat. D + Cat. E + Cat. F
TP	Cat. B + Cat. G

4.2.4: Linear Mixed Effects Model Analysis

The optimized variable sets listed in Table 4-13 and 4-14 were used to perform linear mixed effects model (LME) analysis. Because it is an extension of traditional variance models that treats grouping variables as random, the lack of independence between nested watershed areas is accommodated by LME (Pinheiro and Bates 2000, Laird and Ware 1982). The application of both temporal and spatial hierarchies within an analytical model is rare in the current literature, but was particularly suited to the Central Brazos data. Results significant at the 0.10 level are marked with an asterisk (*) in Tables 4-15 through 4-32.

4.2.4.1: Microwatershed within Subwatershed within Year

Models in the subwatershed/microwatershed analysis included the random factors Microwatershed, Subwatershed, and Year, nested in that order. Fixed factors varied by WQ parameter as noted in Section 4.2.3.

As shown by the p-values in Table 4-15, no LULC category was an effective predictor of Chl A levels within this analytical structure. Results of the PCA and current literature would have corroborated an association with agriculture (Cat. A), built-up (Cat. B), open water (Cat. E), and/or wetland (Cat. F) (Johnson et al. 1997, Horne and Goldman 1994, Johnston et al. 1990,, NAS 1969).

Table 4-15: Microwatershed Chlorophyll A

	Value	Std. Error	DF	t-value	p-value
(Intercept)	-13.415	51.01686	636	-0.26295	0.7927
Cat. A	16.54123	51.07909	52	0.323836	0.7474
Cat. B	14.27286	52.00118	52	0.274472	0.7848
Cat. C	14.61439	51.05853	52	0.286228	0.7758
Cat. D	15.3311	50.86719	52	0.301395	0.7643

	Value	Std. Error	DF	t-value	p-value
Cat. E	40.33693	57.6941	52	0.699152	0.4876
Cat. F	14.26491	52.20003	52	0.273274	0.7857
Cat. G	-20.8542	17.21606	52	-1.21132	0.2312

Grass (Cat. D) percentage was a strong predictor of DO within this model, with highly significant result (Table 4-16). Grass coverage within a watershed can provide a thorough filtering/retention function, preventing input of oxygen-reducing compounds to water bodies (Butler 2008, USDA 2000, Skovlin 1984). Rangeland is effective in this capacity despite potential for increased animal waste input, but more intensively managed grass such as recreational fields have potential for the inverse effect on DO through over-fertilization (Law et al. 2004, Robbins et al. 2001, USDA 2000).

Table 4-16: Microwatershed Dissolved Oxygen

	Value	Std. Error	DF	t-value	p-value
(Intercept)	6.863161	0.739108	1774	9.285736	0
Cat. A	0.855472	0.850878	132	1.005399	0.3165
Cat. C	1.358472	0.846626	132	1.604572	0.111
Cat. D	2.241384	0.941984	132	2.379428	0.0188 *
Cat. E	-2.76215	11.92825	132	-0.23156	0.8172
Cat. G	11.20359	17.71481	132	0.632442	0.5282

The relationships between fecal coliform bacteria levels and percent agriculture (Cat A.), shrub/forest (Cat. C), and open water (Cat. E) were as expected (Table 4-17). The direction of the relationship, however, was unusual in the case of agriculture. The negative coefficient (β = -4.4043) is in opposition to the general knowledge about agricultural practices in the study area and current literature (Lewis et al. 2007, TCEQ 2006, King et al. 2005, Keraita 2003, Jones et al. 2001, Johnson et al. 1997). Some studies have suggested that the influences of grazing land and tilled agriculture on aquatic bacteria levels are significantly different (Kloot et al. 2007). It is possible that in this case the agriculture-bacteria relationship was confounded by the combination of rangeland and tilled land into Category A.

Table 4-17: Microwatershed Fecal Coliform Bacteria

	Value	Std. Error	DF	t-value	p-value
(Intercept)	9.63801	2.59256	911	3.717569	0.0002 *
Cat. A	-4.4043	2.56386	63	-1.71784	0.0907 *
Cat. B	-3.75475	3.36028	63	-1.11739	0.2681
Cat. C	-6.42464	2.65804	63	-2.41706	0.0186 *
Cat. D	-3.84936	2.66431	63	-1.44479	0.1535
Cat. E	-92.4724	23.29131	63	-3.97025	0.0002 *
Cat. F	12.13978	8.4217	63	1.441489	0.1544
Cat. G	30.18054	35.49502	63	0.850276	0.3984

As shown by the p-values in Table 4-18, no LULC category was an effective predictor of OP levels within this analytical structure. No significant relationships were evident. Results of the PCA and current literature would have corroborated an association with agriculture (Cat. A), built-up (Cat. B), grass (Cat. D), and/or wetland (Cat. F) (Allan 2004, Sliva and Williams 2001, Robbins et al. 2001, USDA 2000, Allan et al. 1997). This result was likely due to lack of independence between the LULC category predictors; the effects of correlations among predictor variables may be overwhelming when all categories are included in the model.

Table 4-18: Microwatershed Orthophosphate

	Value	Std. Error	DF	t-value	p-value
(Intercept)	-1.86603	1.560127	937	-1.19607	0.232
Cat. A	-0.64695	1.523663	81	-0.4246	0.6723
Cat. B	2.56286	2.04227	81	1.254908	0.2131
Cat. C	-1.16083	1.573618	81	-0.73768	0.4628
Cat. D	-1.13242	1.58417	81	-0.71484	0.4768
Cat. E	-14.6558	13.55885	81	-1.0809	0.2829
Cat. F	-0.90493	6.176204	81	-0.14652	0.8839
Cat. G	27.2056	23.67431	81	1.149161	0.2539

Grass (Cat. D), open water (Cat. E), and wetland (Cat. F) were reliably linked to pH levels (Table 4-19). This finding corroborates both the existence of these relationships and their direction in current literature. Grass land cover has been associated with increases in pH, and watercourses and wetland areas have been associated with reductions in pH (Farley et al. 2008, Tsegaye et al. 2006)

Table 4-19: Microwatershed pH

	Value	Std. Error	DF	t-value	p-value
(Intercept)	7.26281	0.531504	1782	13.66463	0 *
Cat. A	0.501312	0.523442	130	0.957723	0.34
Cat. B	0.218676	0.59006	130	0.3706	0.7115
Cat. C	0.454488	0.538102	130	0.844615	0.3999
Cat. D	0.998844	0.541176	130	1.845691	0.0672 *
Cat. E	7.104986	3.692056	130	1.924398	0.0565 *
Cat. F	-5.81711	1.871713	130	-3.10791	0.0023 *
Cat. G	0.72011	5.074576	130	0.141905	0.8874

Land use distributions were associated with SpC for several categories – built-up, shrub/forest, grass, and wetland (Categories B, C, D, and F respectively) (Table 4-20). Urban/built-up or other areas with increased impervious cover have been linked with increased SpC, so the negative finding here was unexpected (Conway 2007). Negative relationships between shrub/forest, grassland, wetland and other highly vegetative land cover and SpC have been documented, largely attributed to reductions in suspended solid inputs (Wilcock et al. 2007, Anbumozhi et al. 2005, Johnston et al. 1990, Binns 1986). This may also be the case here.

Table 4-20: Microwatershed Specific Conductance

	Value	Std. Error	DF	t-value	p-value
(Intercept)	7.663546	0.648363	1724	11.81984	0 *
Cat. A	-0.9785	0.640462	126	-1.52781	0.1291
Cat. B	-1.71388	0.720541	126	-2.3786	0.0189 *
Cat. C	-1.41449	0.657331	126	-2.15187	0.0333 *
Cat. D	-1.4848	0.660545	126	-2.24784	0.0263 *
Cat. E	-3.23646	4.655647	126	-0.69517	0.4882
Cat. F	-4.58229	2.194551	126	-2.08803	0.0388 *
Cat. G	-2.80619	6.108168	126	-0.45942	0.6467

The model for temperature was successful, as all three included LULC variables exhibited significant impact (Table 4-21). Associations with open water (Cat. E), wetland (Cat. F), and barren land (Cat. G) were not unusual, as sources suggest that ambient water temperature is largely controlled by surrounding heat sources/sinks (Allan 2004, Larson and Larson 1997, Allan 1995).

Table 4-21: Microwatershed Temperature

	Value	Std. Error	DF	t-value	p-value
(Intercept)	20.2627	0.51605	1844	39.26528	0 *
Cat. E	57.9726	24.42521	140	2.37347	0.019 *
Cat. F	-19.4777	9.34546	140	-2.08419	0.039 *
Cat. G	73.65863	40.09808	140	1.83696	0.0683 *

Nitrogen levels were negatively related to agriculture (Cat. A), shrub/forest (Cat. C), and wetland (Cat. E), and positively related to barren land (Cat. G) (Table 4-22). Results for shrub/forest and open water were consistent with current literature (Floyd et al. 2009). The beta value for percent agriculture was unusual, as increases in agricultural land use are generally associated with increases in nitrogen (Ahearn et al. 2005, Smart et al. 1998, Johnson et al. 1997). Local soil composition may have an impact on the agriculture-nitrogen relationship.

Table 4-22: Microwatershed Total Nitrogen

	Value	Std. Error	DF	t-value	p-value
(Intercept)	1.26495	0.426822	1257	2.963637	0.0031 *
Cat. A	-2.61513	0.680562	105	-3.8426	0.0002 *
Cat. C	-4.06896	0.675535	105	-6.02332	0 *
Cat. E	-62.1055	12.19623	105	-5.09219	0 *
Cat. F	3.53071	4.829596	105	0.731057	0.4664
Cat. G	46.10024	16.99173	105	2.713099	0.0078 *

As shown by the p-values in Table 4-23, no LULC category was an effective predictor of TP levels within this analytical structure. Positive relationships with agriculture (Cat. A), built-up (Cat. B), and grass (Cat. D) would have been supported by current literature (Robbins et al. 2001, Allan et al. 1997, Horne and Goldman 1994, Osborne and Wiley 1988).

Table 4-23: Microwatershed Total Phosphorus

	Value	Std. Error	DF	t-value	p-value
(Intercept)	-3.65024	10.61109	573	-0.344	0.731
Cat. A	2.104852	10.92815	63	0.192608	0.8479
Cat. B	5.549951	10.9269	63	0.507916	0.6133
Cat. C	0.833575	10.84403	63	0.07687	0.939
Cat. D	0.418771	10.5544	63	0.039677	0.9685
Cat. F	6.4192	12.75459	63	0.503285	0.6165

4.2.4.2: Riparian Area within Subwatershed within Year

Analysis models for riparian areas included random factors Subwatershed, Type, and Year, nested in that order. Fixed factors varied by WQ parameter as noted in Section 4.2.3. Comparisons with past research and findings from other analyses within this study were intentionally limited for this section to reduce redundancy, as relationships were similar to those described in Section 4.2.4.1. Instead, comments on the relative effectiveness of the two spatial models were included.

Only percent grass coverage (Cat. D) exhibited a reliable relationship with Chl A levels (Table 4-24), which was an improvement over the subwatershed/microwatershed analysis (Table 4-15). This may be a reflection of local levels of open canopy structure (and solar input) relative to grass proportion at the catchment scale, or possibly related to scale differences in nitrogen availability (Childress and Bathala 1998).

Table 4-24: Riparian Chlorophyll A

	Value	Std. Error	DF	t-value	p-value
(Intercept)	7.163033	3.416143	1390	2.096819	0.0362 *
Cat. A	-5.49588	3.644942	22	-1.50781	0.1458
Cat. B	-3.90658	3.813584	22	-1.02439	0.3168
Cat. C	-4.11496	3.572706	22	-1.15178	0.2618
Cat. D	-7.67059	3.29692	22	-2.32659	0.0296 *
Cat. E	-4.20952	4.126712	22	-1.02007	0.3188
Cat. F	-5.77715	3.552747	22	-1.62611	0.1182

Percent grass (Cat. D) cover showed a clear relationship with DO levels (Table 4-25). The beta values for the riparian and catchment analyses were similar, suggesting that similar mechanisms may be at work at both scales (Table 4-16, Butler 2008, USDA 2000, Skovlin 1984).

Table 4-25: Riparian Dissolved Oxygen

	Value	Std. Error	DF	t-value	p-value
(Intercept)	7.471665	0.705829	3822	10.58566	0 *
Cat. A	0.511735	0.986327	46	0.518828	0.6064
Cat. C	0.37384	0.824128	46	0.453619	0.6522
Cat. D	2.294528	1.112681	46	2.062162	0.0449 *
Cat. E	1.421613	1.555216	46	0.914094	0.3654

No LULC category was an effective predictor of FC bacteria levels within this analytical structure (Table 4-26). These results suggest that the catchment scale may be more suitable for FC studies.

Table 4-26: Riparian Fecal Coliform Bacteria

	Value	Std. Error	DF	t-value	p-value
(Intercept)	5.221198	0.536716	1108	9.728054	0 *
Cat. B	-2.64596	3.776906	28	-0.70056	0.4894
Cat. C	-1.41888	0.893028	28	-1.58884	0.1233

Shrub/forest (Cat. C)was reliably associated with OP levels, which is consistent with current research (Table 4-27, Jones et al. 2001). Past studies suggest that woody vegetation cover in riparian areas has a strong impact on phosphorus and related compounds entering waterways (Anbumozhi et al. 2005, Johnson et al. 1997, Lowrance et al. 1997).

Table 4-27: Riparian Orthophosphate

	Value	Std. Error	DF	t-value	p-value
(Intercept)	-1.15509	0.44396	398	-2.6018	0.0096 *
Cat. C	-2.39939	0.909208	37	-2.63899	0.0121 *
Cat. D	0.37324	1.03634	37	0.360152	0.7208
Cat. G	-27.5886	20.7345	37	-1.33056	0.1915

Percent agriculture, shrub/forest, wetland, and barren land (Categories A, C, F, and G respectively) were reliable predictors of pH levels at the riparian scale (Table 4-28). At the catchment scale, wetland also showed a negative relationship with pH, but not with barren land or shrub/forest (Table 4-19). The catchment scale did demonstrate a reliable relationship with grass coverage not seen at the riparian scale (Tables 4-19, 4-28). This partial overlap suggests that multi-scale studies may be a more thorough option for LULC-WQ studies of pH. The ability to compare results at multiple spatial scales could lead to interesting insights, particularly with regard to non-point source pollution.

Table 4-28: Riparian pH

	Value	Std. Error	DF	t-value	p-value
(Intercept)	8.514759	0.205248	1718	41.48521	0 *
Cat. A	-0.98023	0.249804	44	-3.92401	0.0003 *
Cat. B	-0.55209	0.403861	44	-1.36702	0.1786
Cat. C	-0.82256	0.327774	44	-2.50954	0.0158 *
Cat. E	-0.16753	0.466813	44	-0.35887	0.7214
Cat. F	-0.91447	0.356889	44	-2.56233	0.0139 *
Cat. G	-12.9631	4.193077	44	-3.09154	0.0034 *

The anticipated relationship between shrub/forest (Cat. C) and SpC proved significant at the riparian scale; the beta value was negative, as at the catchment scale (Tables 4-29, 4-20). Literature indicates that the particulate matter input that contributes to elevated SpC is effectively reduced by woody vegetation in riparian corridors (Mander et al. 2005, Meador and

Goldstein 2003). Additional relationships were described by the catchment scale analysis, suggesting that the riparian scale is less desirable for studies of SpC.

Table 4-29: Riparian Specific Conductance

	Value	Std. Error	DF	t-value	p-value
(Intercept)	6.42838	0.180632	3490	35.5883	0 *
Cat. B	-0.04416	0.591602	42	-0.07465	0.9408
Cat. C	-0.6052	0.313715	42	-1.92913	0.0605 *
Cat. D	0.309721	0.327662	42	0.94525	0.3499
Cat. E	-0.01903	0.557737	42	-0.03412	0.9729
Cat. F	-0.42908	0.462539	42	-0.92766	0.3589
Cat. G	1.90229	5.388889	42	0.353	0.7259

The riparian scale model for temperature was successful, as was the model at the catchment scale, with most category variables reported as reliable predictors (Tables 4-30, 4-21). Between the two scales, all LULC categories aside from shrub/forest (Cat. C) were accounted for. Between the two models, however, only one variable overlapped (wetland), and the direction/signs of the two beta values did not agree. Spatial variations in wetland vegetation structure, described only at finer levels of LULC classification than used for this study, may account for the difference in beta value direction seen between the two analysis structures (Allan 2004). The relative solar input for an emergent herbaceous wetland versus wetlands with mature wooded vegetation is significantly different; lack of differentiation may have confounded results here.

Table 4-30: Riparian Temperature

	Value	Std. Error	DF	t-value	p-value
(Intercept)	23.17596	1.463192	3526	15.83931	0 *
Cat. A	-3.05427	1.608257	45	-1.89912	0.064 *
Cat. B	-4.57115	2.160678	45	-2.11561	0.0399 *
Cat. D	-3.95937	2.289049	45	-1.7297	0.0905 *
Cat. E	-6.86271	3.011043	45	-2.27918	0.0275 *
Cat. F	-0.11984	2.38422	45	-0.05027	0.9601

Nitrogen levels were positively related to agriculture (Cat. A), built-up (Cat. B), and grass (Cat. D) (Table 4-31). This is consistent with current literature for agriculture and built-up, as studies describe positive associations between agriculture and urban LULC (Ahearn et al. 2005, Smart et al. 1998, Johnson et al. 1997). The positive association with percent grass, however, is likely related the type of grass cover (rangeland versus recreational grass or lawn) and may merit an additional level of detail for reliable predictive use (Butler 2008, Law et al. 2004, Robbins et al. 2001).

Table 4-31: Riparian Total Nitrogen

	Value	Std. Error	DF	t-value	p-value
(Intercept)	-6.10997	3.348845	1738	-1.8245	0.0682 *
Cat. A	5.850032	3.442874	42	1.699171	0.0967 *
Cat. B	7.620876	3.714032	42	2.051914	0.0464 *
Cat. C	4.197078	3.458657	42	1.213499	0.2317
Cat. D	7.50795	3.227466	42	2.326268	0.0249 *
Cat. E	3.922672	3.793408	42	1.034076	0.307
Cat. F	5.202325	3.476157	42	1.496574	0.142

Between the catchment and riparian scale models, only barren land (Cat. G) demonstrated any reliable impact on TP (Tables 4-23, 4-32). This relationship can be attributed to erosion or direct sediment input: Rock/Mine/Sand/Bare Earth LULC is has been shown to exert influence on TP via these types of action (Shivoga et al. 2007).

Table 4-32: Riparian Total Phosphorus

	Value	Std. Error	DF	t-value	p-value
(Intercept)	-1.87094	0.158228	504	-11.8243	0 *
Cat. B	1.44944	1.075005	40	1.34831	0.1851
Cat. G	-43.9325	20.01533	40	-2.19495	0.034 *

4.2.4.3: Variance Among and Within Spatial Divisions

For most of the LULC category-WQ parameter pairings analyzed, variance among areas (subwatershed, microwatershed, or riparian area) did not exceed the variance within the individual units (Tables 4-33, 4-34, and 4-35). Although the groupings of Year/Subwatershed, Year/Microwatershed/Subwatershed, and Year/Area Type/Subwatershed (representing Subwatershed versus Riparian Area) are naturally exhibited by the drainage network, this did not appear to be an optimal analytical structure for this dataset. Only temperature at the riparian scale showed greater among-group than within-group variance, which suggests that specifically riparian characteristic (such as streamside canopy cover) may play a greater role in determining temperature than other factors. The lack of differentiation between variance types yields no general conclusion about the relative suitability of scale for LULC-water quality studies.

Table 4-33: Random Factor Variance for Subwatersheds

	Among	Within
Chl A	50.70%	49.30%
DO	20.17%	79.83%
FC	27.29%	72.71%
OP	49.97%	50.03%
pH	44.26%	55.74%
SpC	38.44%	61.56%
Temp	9.92%	90.08%
TN	42.25%	57.75%
TP	42.74%	57.26%

Table 4-34: Random Factor Variance for Microwatersheds

	Among	Within
Chl A	46.86%	53.14%
DO	24.95%	75.05%
FC	49.04%	50.96%
OP	56.95%	43.05%
pH	48.80%	51.20%
SpC	47.35%	52.65%
Temp	0.02%	99.98%
TN	45.04%	54.96%
TP	53.13%	46.87%

Table 4-35: Random Factor Variance for Riparian Areas

	Among	Within
Chl A	40.69%	59.31%
DO	19.73%	80.27%
FC	21.28%	78.72%
OP	39.24%	60.76%
pH	25.42%	74.58%
SpC	32.44%	67.56%
Temp	**62.78%**	**37.22%**
TN	26.68%	73.32%
TP	38.55%	61.45%

4.3: The Impact of Urbanization

While literature suggest that small changes in built-up area can exert a disproportionately large impact on water quality, data for this study do not corroborate or refute this theory. Changes in built-up area (Cat. B) were indeed mostly small at both the subwatershed and riparian scales (Table 4-2). Two subwatersheds were exceptions to this general low-change trend: Central Brazos North, which showed a -40% decrease, and Little River, which exhibited a 42% increase, over the study period. These two extremes may be due in part to adjustments in LULC data generation between 1992 and 2001/2006. The later data was created using more sophisticated classification algorithms and may be better suited to identifying built structures under tree canopy (NLCD 1992-2006). Due to the inherent correlation between LULC category proportions, the effect of a single category is difficult to quantify; in combination with the complexity of the dataset itself, this may have masked the direct effect of changes in percent built-up land.

4.4: Relative Predictive Strength at Multiple Spatial Scales

The mechanisms by which land and water interact vary based on scale, and these mechanisms exert differing levels of influence over individual water quality parameters (Allan et al. 1997). Scale recommendations of other studies seem to vary by the WQ parameter of interest, and in addition to vary by region (Floyd et al. 2009, Munn et al. 2009, Goldstein et al. 2007, Pan et al. 2004, Gove et al. 2001, Allan et al. 1997). Accordingly, it was unsurprising that the results of the LME analysis suggested that optimal scales vary by the water quality parameter of interest within the Central Brazos as well (Section 4.2.4). The vast differences in riparian area LULC distribution in proportion to the relatively small corresponding changes at the subwatershed level for this study area further underscore the theory: choice of spatial scale is vastly important to full understanding of land-water interactions (Table 4-2). Gove et al. (2001) recommends incorporating multiple scales into all GIS-supported studies. Based on the contrasting mosaic of results obtained here, a multi-scale approach must be the recommendation for the Central Brazos River Basin as well.

CHAPTER 5 : CONCLUSIONS AND RECOMMENDATIONS

The intent of this study was to catalogue the land use/land cover characteristics of the Central Brazos River Basin, describe the relationship of these characteristics with surface water quality, and investigate the impact of spatial scale on land-water interactions within the study area. In truth, this study was also an evaluation of an analytical framework relatively novel within watershed research. These tasks are not frequently undertaken for watersheds of this size, nor do they usually include a broad time span. The scarcity of studies similar in scope and breadth may be due to low data availability at this time scale, the labor-intensive nature of LULC data generation, or perhaps relatively greater interest in single-scale evaluations.

5.1: Data Collection and Exploration

5.1.1: Task 1 – Generate LULC Data

In order to incorporate a more meaningful time frame into the study, the widest span of LULC “snapshot” datasets that could be accurately compared were included.

NLCD data from 1992, 2001, and 2006 were selected; but the data for 2006 were incomplete for the Central Brazos and its subwatersheds. While the 1992-2001 time frame would have yielded interesting results, inclusion of the most current data was important to provide a forward-looking perspective. With a time investment of six months and the excellent aerial imagery available from the Texas Water Development Board, a supplement to the 2006 NLCD was completed through manual classification. This hybrid dataset for 2006 was constructed with the greatest care possible, incorporating all reasonable quality assurance procedures. Even so, a consistent automated data generation method (full NLCD coverage) would provide the least probability of error and would have been preferable.

5.1.2: Task 2 – Describe Changes and Trends in LULC

Changes in land use/land cover distribution across the 1992-2006 study period were small for the Central Brazos River basin as a whole. At this regional level, the magnitude of these shifts seemed relatively insignificant to surface water quality: all category shifts were less than 6%, and half were less than 2% (Table A-2). At a smaller scale, however, percentage shifts within LULC categories widened in range: variation between subwatersheds was much greater than at the regional level (Table A-2). Decreasing scale again to the riparian area, changes did not increase in range between areas (Table A-1). Riparian areas exhibited a higher rate of change than did the subwatersheds or the study area at large (Tables A-1 and A-2). It is evident from these wide-ranging composition shifts that effects on water quality are likely to be localized:

this contributes to the general evidence that land-water interactions are more easily characterized within smaller geographic areas.

5.2: Addressing Research Questions

5.2.1: Question 1 – Quantify LULC-WQ Linkages

Correlation and PCA results demonstrated that the general nature of LULC-WQ relationships within the Central Brazos agree with those described in current literature. Increases in agriculture (Cat. A) land use were associated with increases in Chl A, FC, and TP, and decreases in DO and pH (Table 4-5). Built-up area (Cat. B) likewise influenced Chl A and TP (Table 4-6). Shrub/forest (Cat. C) land was correlated positively with pH and negatively with FC (Table 4-7). Grasslands (Cat. D) were associated with changes in TN (Table 4-8). Open water (Cat. E) coverage influenced pH, which may in turn be associated with Chl A (Table 4-9, Figure C-25). Wetland area (Cat. F) exhibited strong links with pH and FC levels (Table 4-10, Figures C-27 and C-28). Barren land (Cat. G)influenced pH and SpC (Table 4-11). These findings are consistent with all previous studies reviewed; regional land characteristics of the Central Brazos do not appear to have generated any specific deviation from previously documented results. This is positive news from a water quality protection perspective, as past successful watershed management practices are apparently also suitable for application in the Central Brazos basin.

The overall results indicate that agricultural land use has the widest-ranging impact on water quality: it exhibits a significant relationship with many more WQ parameters than any other LULC category. This validates the strong emphasis on agriculture shown by regional research institutions such as Texas A&M University. It also raises a difficult policy issue, however, suggesting that regulators at all scales should focus on managing the proportion of agricultural land in the Central Brazos.

5.2.2: Question 2 – Determine the Impact of Urbanization

The high correlation between LULC categories and the complex nested analysis model made it impossible to quantify the direct impact of changes in built-up land (Cat. B) (Section 4.3). The results did demonstrate a consistent positive relationship between proportion of built-up land and temperature, specific conductance, and total nitrogen; this relationship is consistent with existing literature. Based on this strong trend and results of studies conducted in other areas, it is evident that urbanization will continue to be a factor affecting water quality in the Central Brazos. Built-up coverage changed drastically in Central Brazos North and Leon River subwatersheds, which indicates a need for further study in those areas (Table A-2). King et al. (2005) applied an even more sophisticated model in an attempt to control for collinearity and proportional interdependence that also yielded inconclusive results. They suggest incorporating distance weighting as a possible future solution to these autocorrelation issues.

5.2.3: Question 3 – Evaluate the Predictive Power of Riparian Scale LULC

Regardless of the clear escalation of change between study scales revealed by Task 2, LME analysis did not suggest that LULC impact on water quality varies consistently with scale (Sections 4.2.4.1 and 4.2.4.2). The best choice of scale varied, depending on the water quality parameter in question: results for some parameters suggested that differing scales were more effective depending on the LULC category of interest. Based on these findings, it is not possible to make a broad recommendation on spatial scale for LULC-WQ interaction studies within the Central Brazos. The best choice of scale varies depending on the individual LULC category-WQ parameter pairing. For example, the effects of agricultural land use on bacteria levels is most effectively quantified at the catchment scale, while woody vegetation (Category C) land cover is a stronger predictor of OP levels at the riparian scale. For reduced groups of WQ parameters or LULC categories, definitive scale recommendations may be possible. Tables 5-1 and 5-2 summarize the LULC Category-WQ Parameter pairings significant at the catchment and riparian scales.

Table 5-1: Significant Relationships for Catchment Scale

LULC Category	A	B	C	D	E	F	G
WQ Parameter							
Chl A							
DO				*			
FC	*		*		*		
OP							
pH				*	*	*	
SpC		*	*	*		*	
Temp					*	*	*
TN	*		*		*		*
TP							

Table 5-2: Significant Relationships for Riparian Scale

LULC Category / WQ Parameter	A	B	C	D	E	F	G
Chl A				*			
DO				*			
FC							
OP			*				
pH	*		*			*	*
SpC			*				
Temp	*	*		*	*		
TN	*	*		*			
TP							*

5.3: Notes for Future Studies

Scale is a controlling mechanism in land-water relationships, based on many of the studies reviewed in Chapter 2. Selection of an appropriate – and hopefully optimal – scale is an important first step in any evaluation of LULC-WQ linkages. The results presented here confirm that in some cases riparian land cover data is an effective predictor of water quality. Riparian zones used for this study were only 1-5% of the overall subwatershed area. Reducing the need for large-scale LULC data collection creates a significant time and cost savings for future studies – potentially cutting the data need by 95% or more. In other cases, it appears that catchment LULC is a more successful predictor. It is not surprising that these complex land-water interactions cannot be consistently summarized by LULC impacts at a single scale; this further corroborates the many previous publications advocating inclusion of multiple spatial scales in LULC-WQ analysis.

The cumulative network structure of watersheds themselves demands further exploration and use of nested models. Repeated measurements over both time and space are necessary for precise and accurate characterization of these land-water relationships. The use of variable reduction techniques is essential when evaluating hierarchical models, to control the influence of covariation: application of stepwise variable selection and model optimization as performed here appears to be helpful. An additional assessment of LULC impacts on water quality in the Central Brazos might be valuable, using a comparison between single-scale, temporally nested LME results for the two different spatial scales may serve to confirm their relative predictive strengths.

APPENDIX A: **Land Use/Land Cover Category Trends**

A.1: Annual LULC Category Distributions

Figure A-1: Subwatersheds, 1992

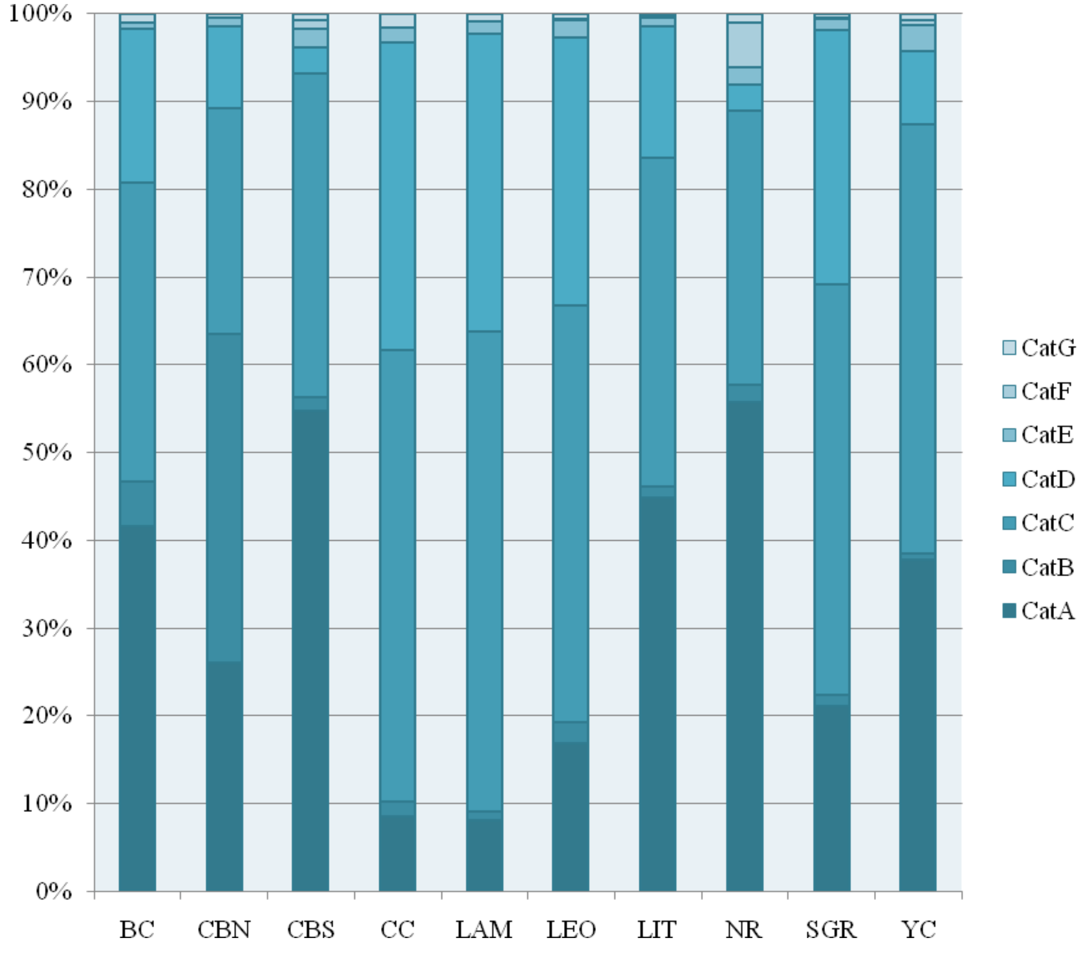


Figure A-2: Riparian Areas, 1992

Figure A-3: Subwatersheds, 2001

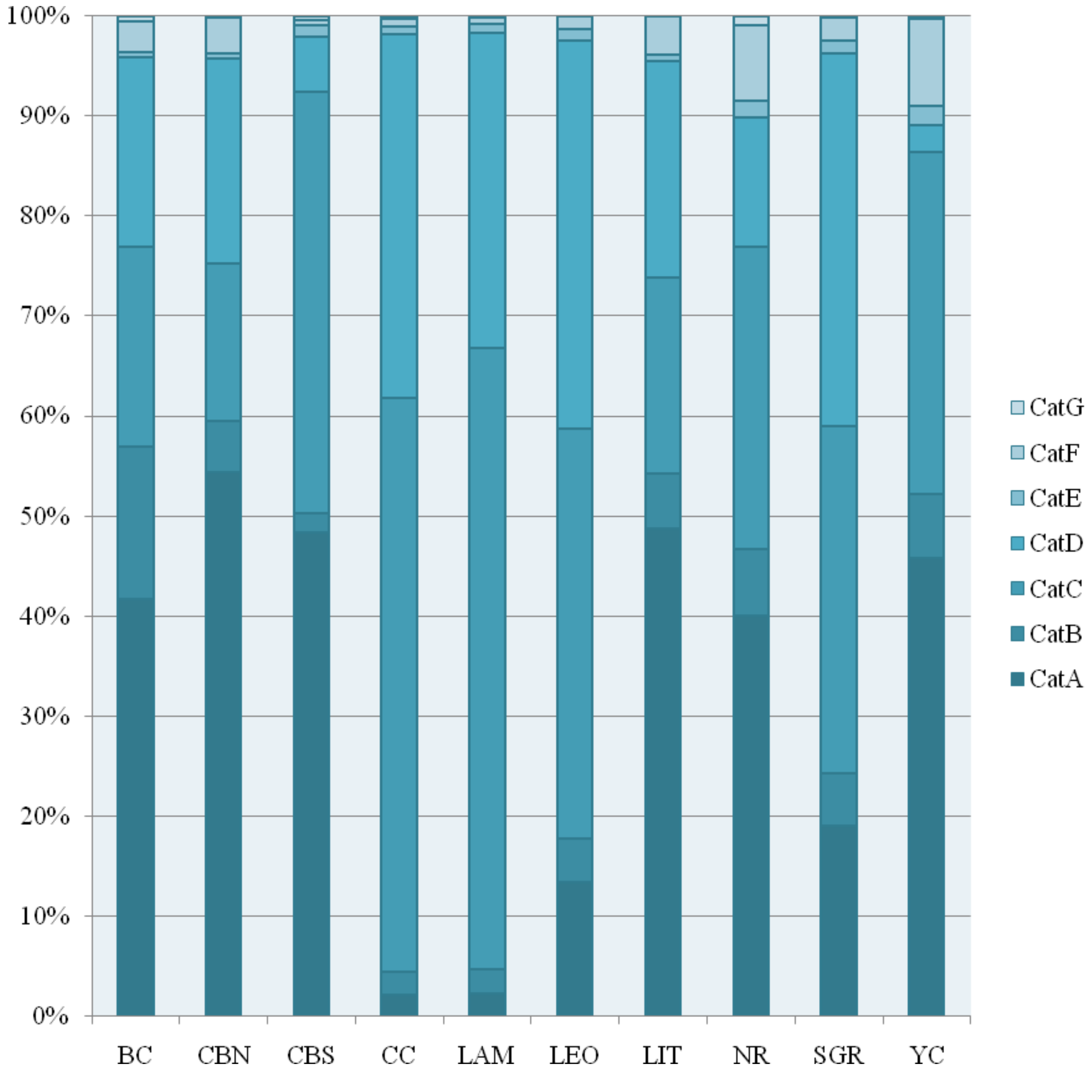


Figure A-4: Riparian Areas, 2001

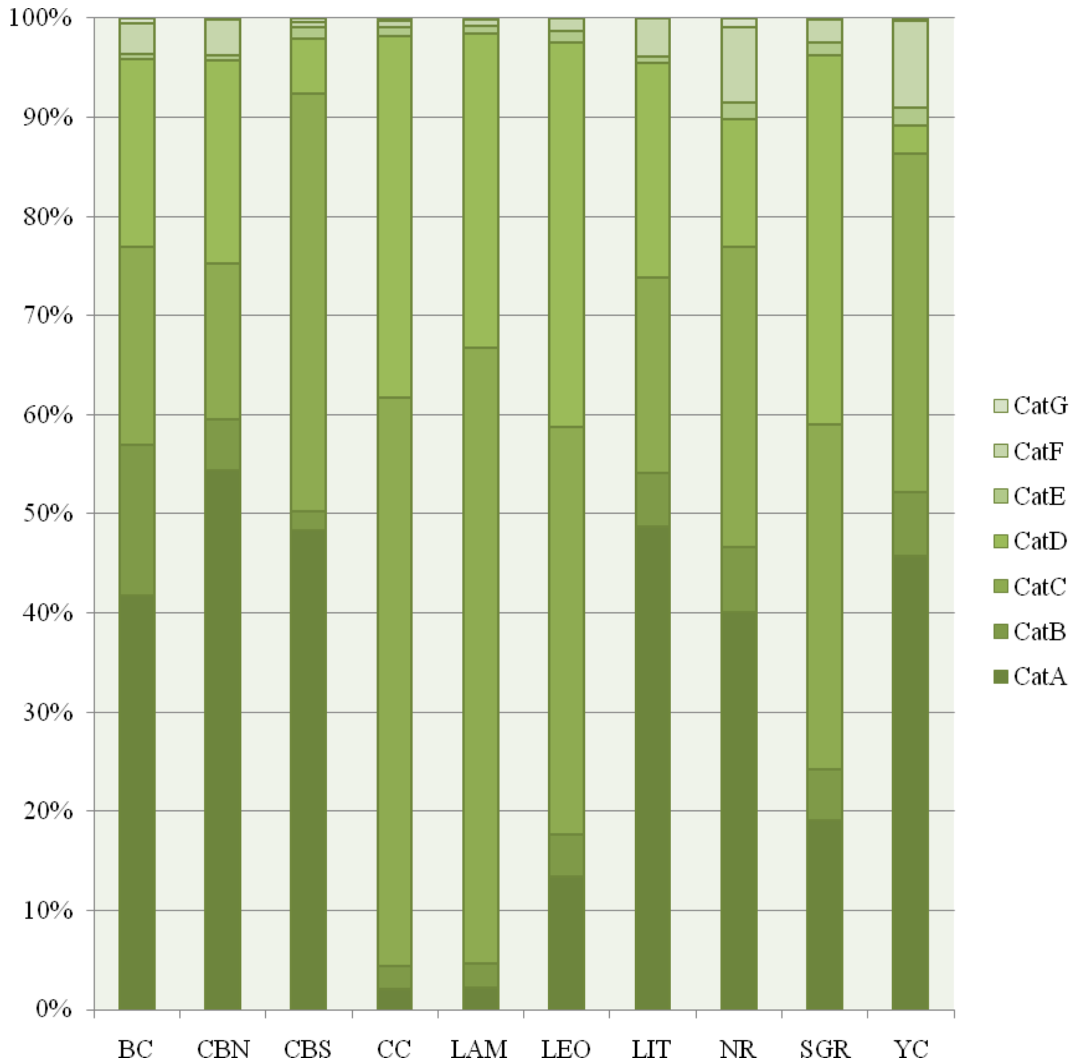


Figure A-5: Subwatersheds, 2006

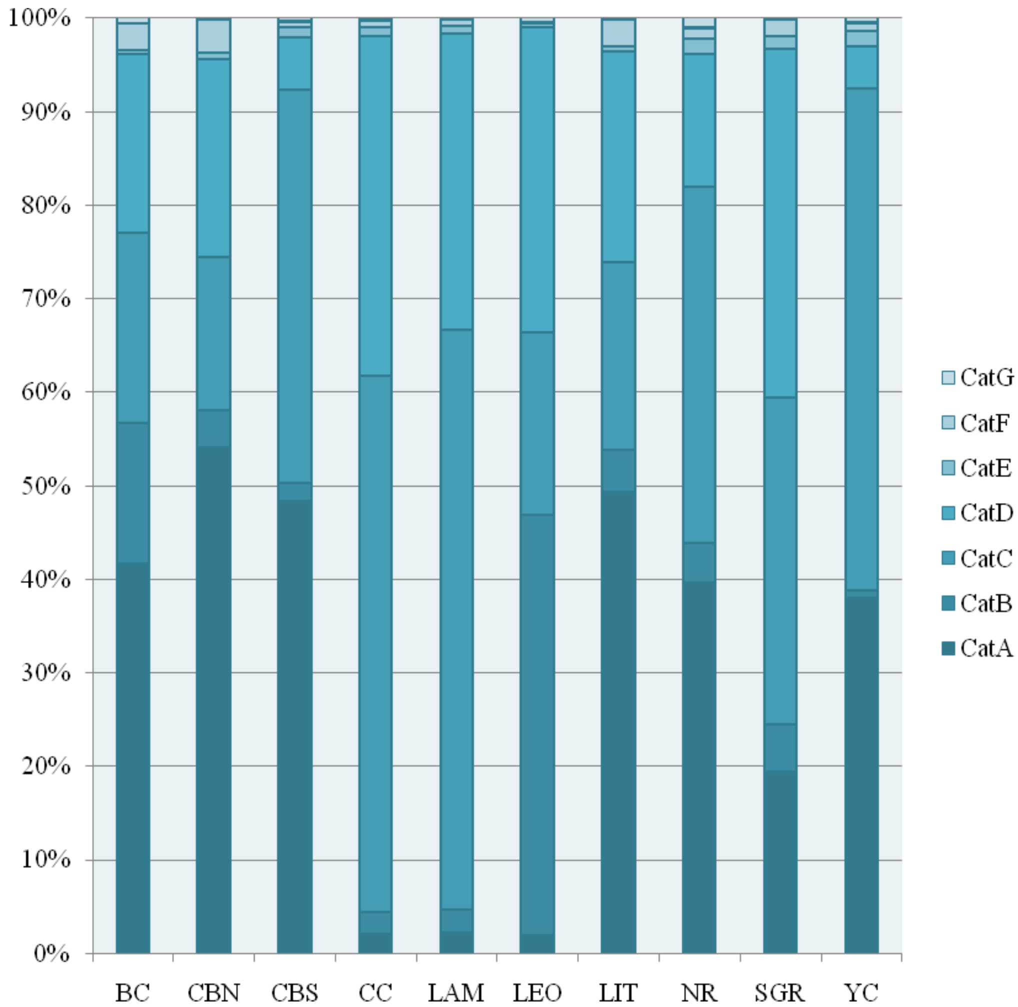
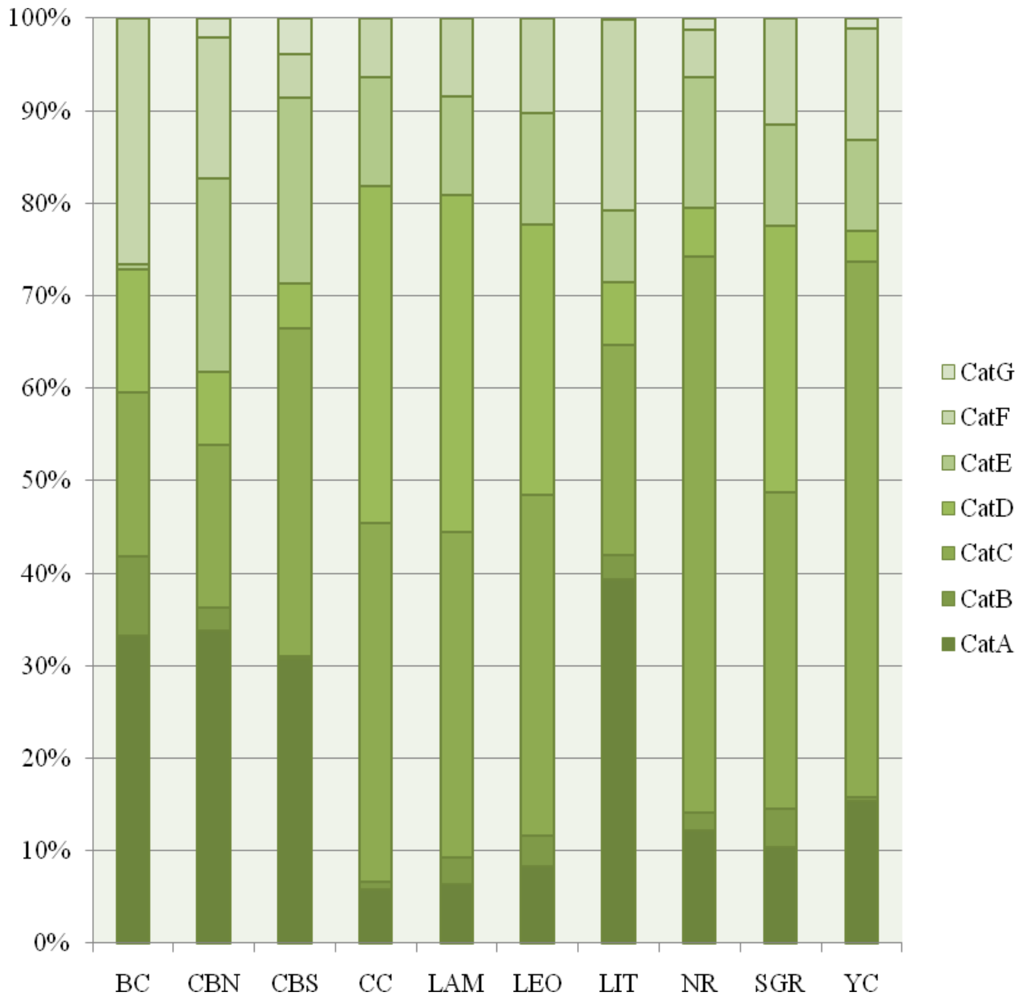


Figure A-6: Riparian Areas, 2006



A.2: Study Period LULC Category Percent Changes by Category, by Area Type

Figure A-7: Category A (Agriculture) Changes Over Time in Riparian Areas

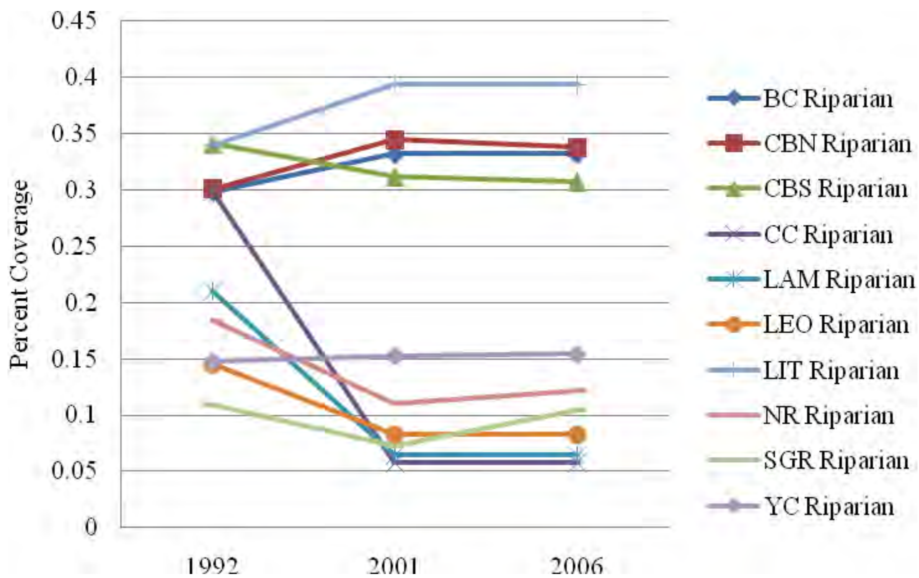


Figure A-8: Category A (Agriculture) Changes Over Time in Subwatersheds

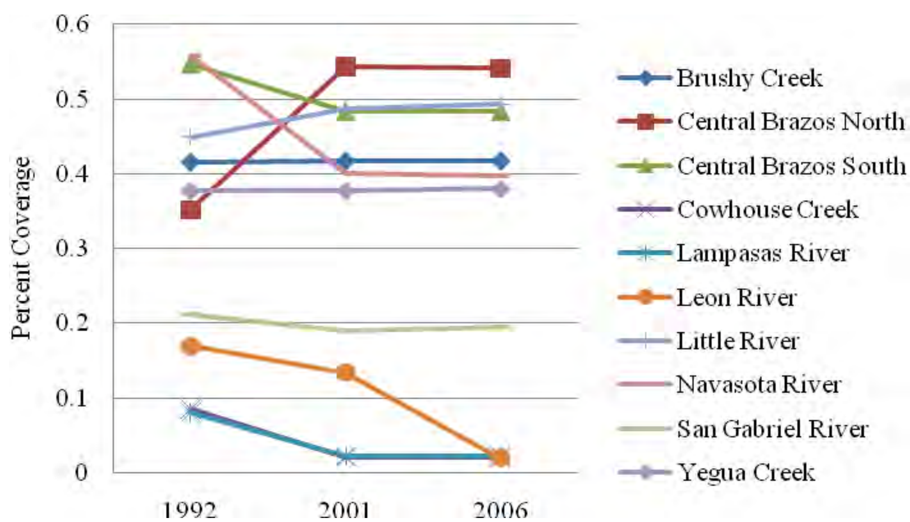


Figure A-9: Category B (Built-Up) Changes Over Time in Riparian Areas

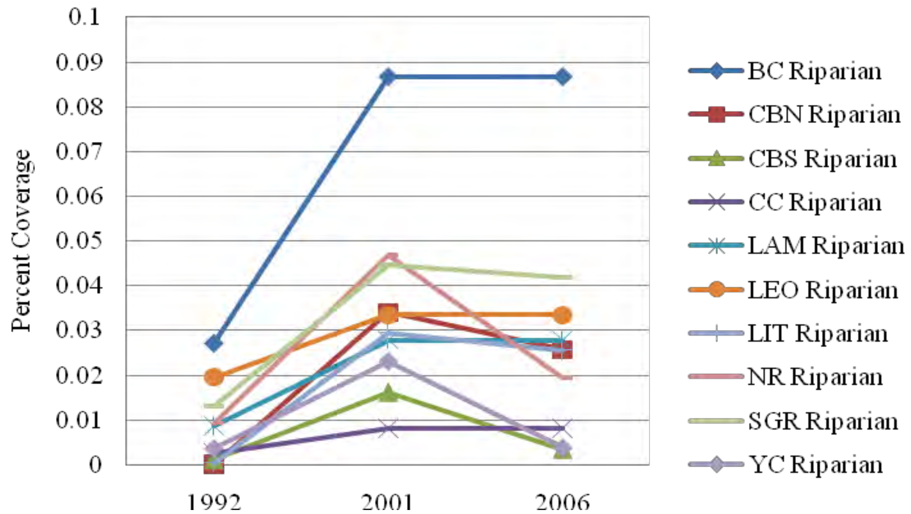


Figure A-10: Category B (Built-Up) Changes Over Time in Subwatersheds

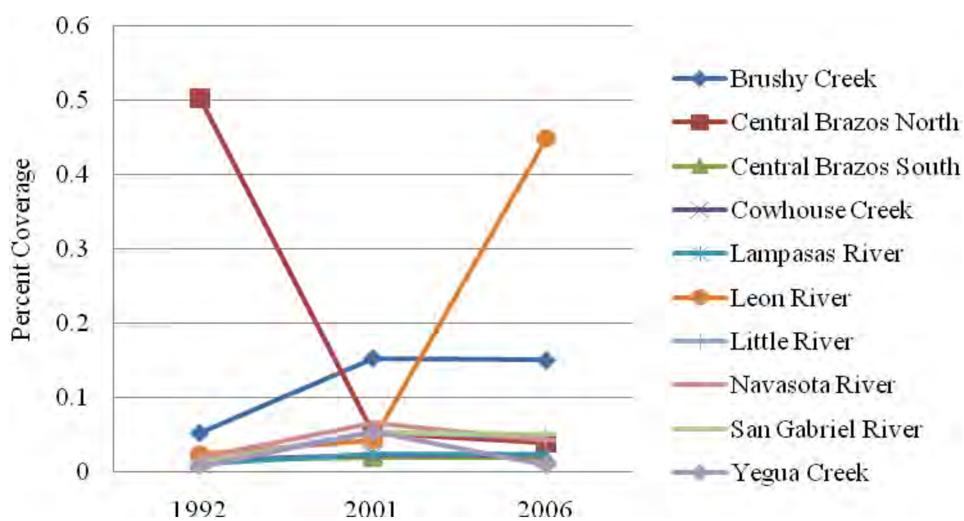


Figure A-11: Category C (Brush/Forest) Change Over Time in Riparian Areas

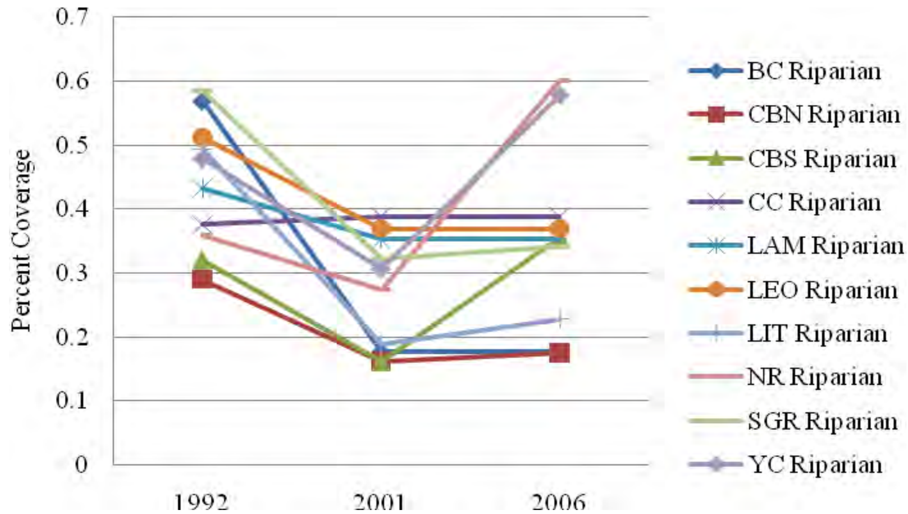


Figure A-12: Category C (Brush/Forest) Change Over Time in Subwatersheds

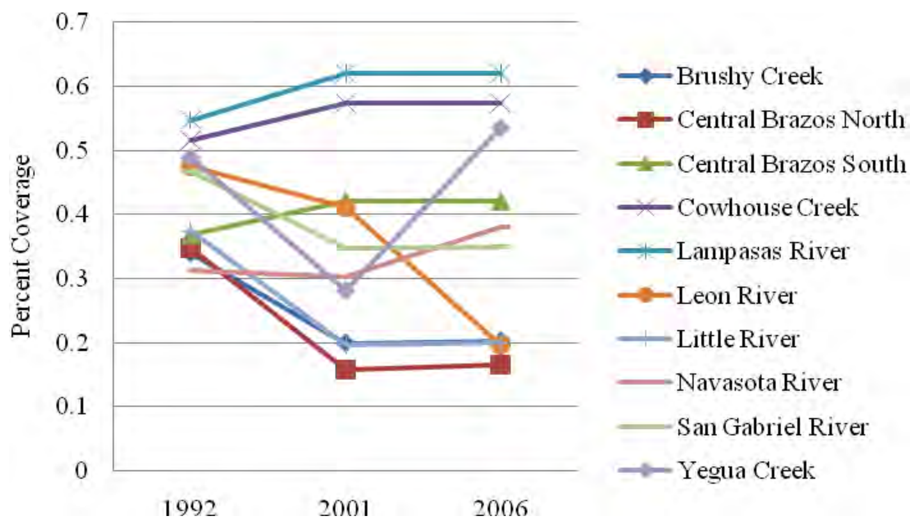


Figure A-13: Category D (Grass) Change Over Time in Riparian Areas

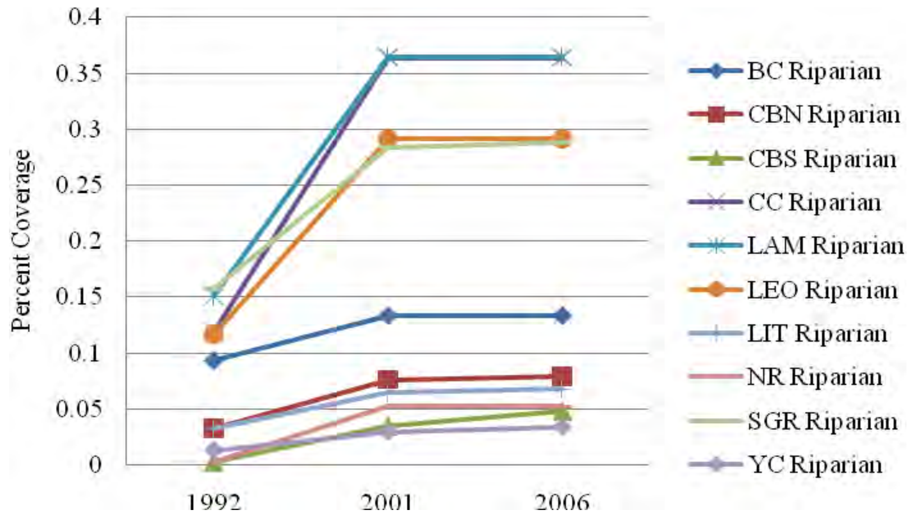


Figure A-14: Category D (Grass) Change Over Time in Subwatersheds

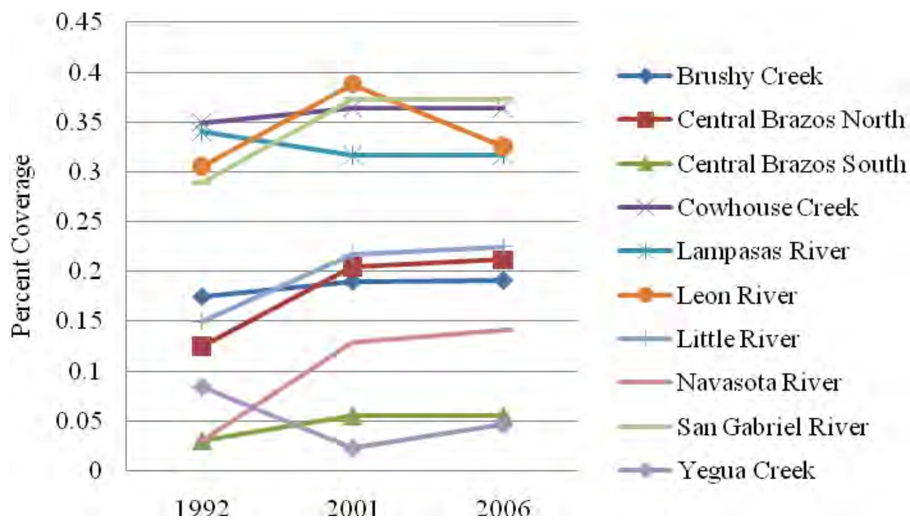


Figure A-15: Category E (Open Water) Change Over Time in Riparian Areas

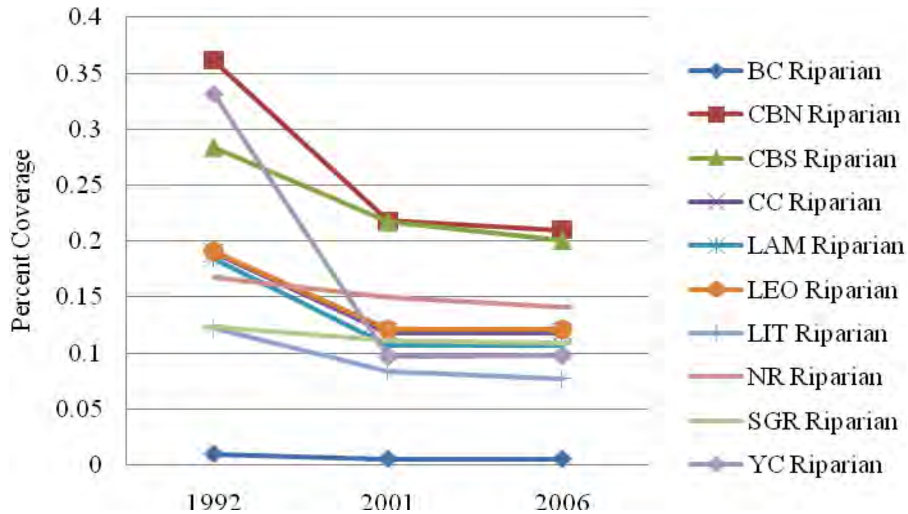


Figure A-16: Category E (Open Water) Change Over Time in Subwatersheds

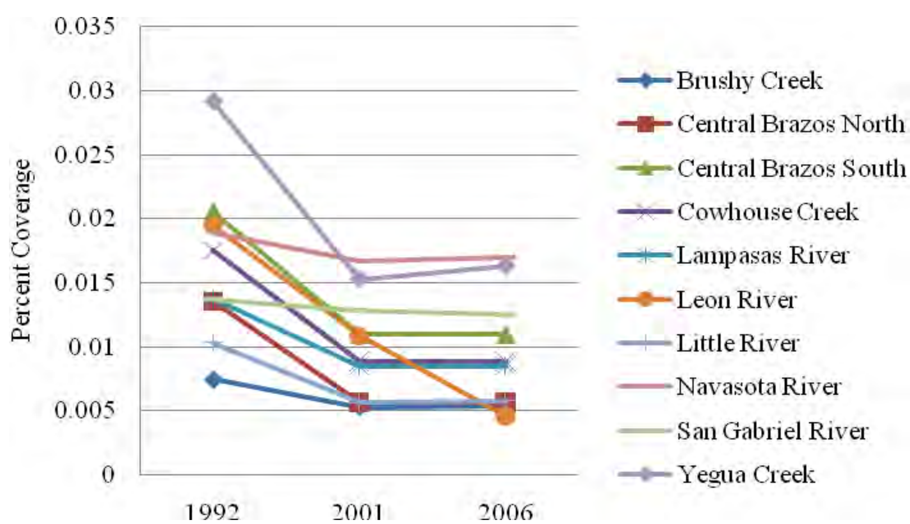


Figure A-17: Category F (Wetland) Change Over Time in Riparian Areas

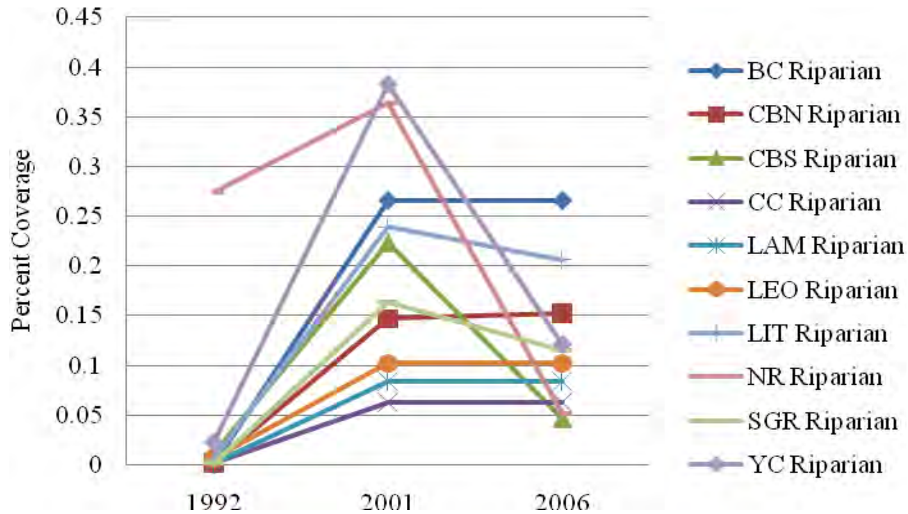


Figure A-18: Category F (Wetland) Change Over Time in Subwatersheds

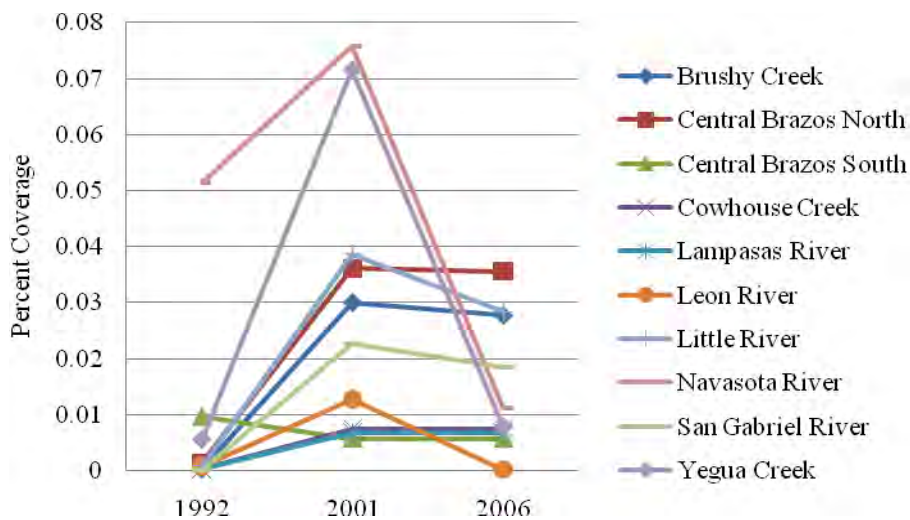


Figure A-19: Category G (Rock/Mine/Sand/Bare Earth) Change Over Time in Riparian Areas

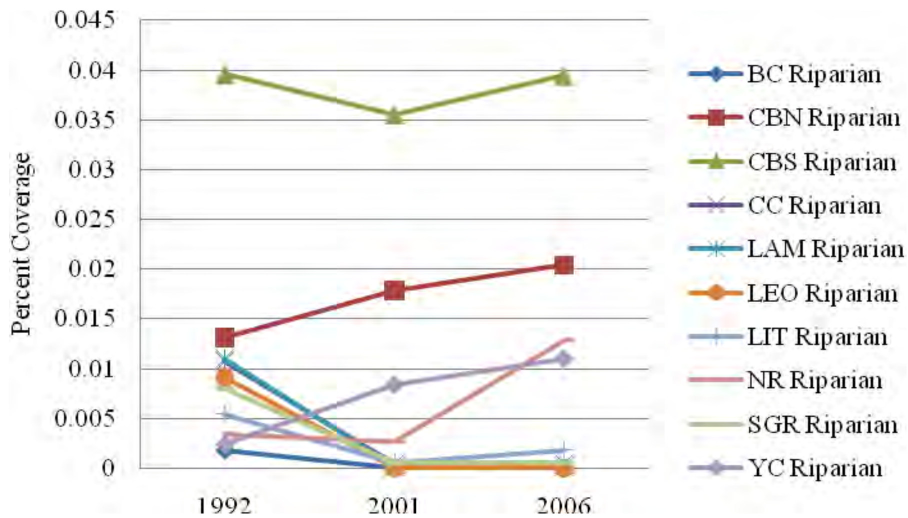


Figure A-20: Category G (Rock/Mine/Sand/Bare Earth) Change Over Time in Subwatersheds

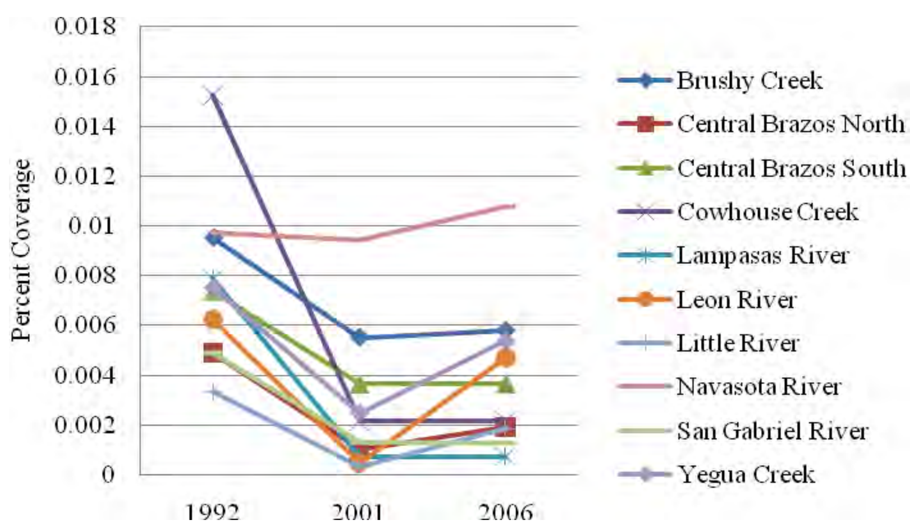


Table A-1: LULC Change in Riparian Areas, 1992-2006

Area Name	Cat A	Cat B	Cat C	Cat D	Cat E	Cat F	Cat G
BC Riparian	3.37%	5.95%	-39.22%	4.01%	-0.45%	26.51%	-0.18%
CBN Riparian	3.67%	2.56%	-11.54%	4.66%	-15.15%	15.07%	0.73%
CBS Riparian	-3.40%	0.24%	3.47%	4.54%	-8.37%	3.54%	-0.01%
CC Riparian	-24.20%	0.55%	1.25%	24.47%	-7.14%	6.10%	-1.03%
LAM Riparian	-14.60%	1.91%	-8.04%	21.38%	-7.82%	8.24%	-1.08%
LEO Riparian	-6.26%	1.39%	-14.27%	17.45%	-6.97%	9.57%	-0.91%
LIT Riparian	5.42%	2.51%	-26.58%	3.55%	-4.52%	19.98%	-0.36%
NR Riparian	-6.20%	1.02%	24.32%	4.93%	-2.72%	-22.30%	0.96%
SGR Riparian	-0.54%	2.86%	-24.45%	13.02%	-1.46%	11.32%	-0.75%
YC Riparian	0.63%	0.01%	9.94%	2.07%	-23.39%	9.87%	0.86%
Riparian Area Avg.	-4.21%	1.90%	-8.51%	10.01%	-7.80%	8.79%	-0.18%

Table A-2: LULC Change in Subwatersheds, 1992-2006

Area Name	Cat A	Cat B	Cat C	Cat D	Cat E	Cat F	Cat G
Brushy Creek	0.15%	9.80%	-13.77%	1.65%	-0.21%	2.74%	-0.37%
Central Brazos North	18.93%	-46.44%	-18.27%	8.68%	-0.79%	3.43%	-0.30%
Central Brazos South	-6.39%	0.37%	5.26%	2.49%	-0.96%	-0.39%	-0.37%
Cowhouse Creek	-6.46%	0.67%	5.84%	1.41%	-0.86%	0.72%	-1.31%
Lampasas River	-5.82%	1.46%	7.31%	-2.36%	-0.52%	0.65%	-0.71%
Leon River	-14.97%	42.53%	-27.88%	2.02%	-1.49%	-0.05%	-0.16%
Little River	4.43%	3.33%	-17.44%	7.54%	-0.46%	2.75%	-0.15%
Navasota River	-16.12%	2.31%	6.77%	11.16%	-0.19%	-4.04%	0.10%
San Gabriel River	-1.67%	3.80%	-11.87%	8.38%	-0.12%	1.83%	-0.36%
Yegua Creek	0.27%	0.08%	4.68%	-3.74%	-1.29%	0.22%	-0.21%
Regional Average	-2.76%	1.79%	-5.94%	3.72%	-0.69%	0.78%	-0.38%

APPENDIX B: Correlation Analysis Results

Table B-1: Pearson Correlation Coefficients with Significance Test Results

LULC Category		A	B	C	D	E	F	G
WC Parameter								
Chl A	n = 1491	0.252914 a	0.064681 b	-0.02904	-0.18035 a	0.175236 a	0.12193 a	0.030851
	P	< 0.0001	0.0125	0.2625	< 0.0001	< 0.0001	< 0.0001	0.2338
DO	n = 5539	-0.11502 a	-0.0444 a	0.030249 b	0.025214	-0.09435 a	-0.05207 a	-0.03113 b
	P	< 0.0001	0.0009	0.0244	0.0606	< 0.0001	< 0.0001	0.0205
FC	n = 2036	0.174525 a	0.0729 a	-0.12662 a	-0.038	0.071241 a	0.113653 a	-0.00124
	P	< 0.0001	0.001	< 0.0001	0.0865	< 0.0001	< 0.0001	0.9553
OP	n = 2881	0.053714 a	0.055119 a	0.045002 b	0.101094 a	0.04211 b	0.015955	-0.06315 a
	P	0.0039	0.0039	0.0157	< 0.0001	0.0238	0.3921	0.0007
pH	n = 5537	-0.19117 a	-0.04726 a	0.144265 a	0.20103 a	-0.10027 a	-0.1846 a	-0.11019 a
	P	< 0.0001	0.0004	0.0004	< 0.0001	< 0.0001	< 0.0001	< 0.0001
SpC	n = 5068	-0.03218 b	0.003209 b	0.04244 a	0.135125 a	-0.07814 a	-0.0814 a	-0.15035 a
	P	0.0219	0.0219	0.0025	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Temp	n = 5693	-0.03174 b	-0.03697 a	0.032022 b	-0.02531	0.00207	-0.04663 a	0.034243 a
	P	0.0166	0.0053	0.0157	0.0562	0.876	0.0004	0.0098
TN	n = 2696	-0.04717 a	0.028159	-0.02363	0.113768 a	-0.05893	-0.05556 a	-0.04272 b
	P	0.0143	0.1439	0.2199	< 0.0001	0.953	0.0039	0.0266
TP	n = 2615	0.176906 a	0.140062 a	-0.06857	0.043469 b	0.072135 a	0.18229 a	-0.07927 a
	P	< 0.0001	0.0005	0.0005	0.0262	0.0002	< 0.0001	< 0.0001

Note: [a] denotes significance at the 0.01 probability level.

[b] denotes significance at the 0.05 probability level

APPENDIX C: Principal Component Analysis Results

C.1: Category A – Agriculture

Table C-1: Category A Descriptive Statistics

Variable	Mean	Std Dev.	Std Err	N
Cat A Percentage	0.156	0.147	0.010	201
Chl A	1.986	0.923	0.065	201
DO	8.394	2.238	0.158	201
FC	3.330	1.936	0.137	201
pH	7.950	0.497	0.035	201
TP	-2.425	0.761	0.054	201

Table C-2: Category A Correlation Matrix

	Cat A	Chl A	DO	FC	pH	TP
Cat A	1.000	0.527	-0.186	0.209	-0.390	0.154
Chl A	0.527	1.000	-0.124	-0.110	0.021	0.065
DO	-0.186	-0.124	1.000	-0.048	0.138	-0.159
FC	0.209	-0.110	-0.048	1.000	-0.524	0.309
pH	-0.390	0.021	0.138	-0.524	1.000	-0.200
TP	0.154	0.065	-0.159	0.309	-0.200	1.000

Table C-3: Category A Eigenvalues

Value	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
Eigenvalue	2.047	1.401	0.951	0.818	0.448	0.334
% of Var.	34.122	23.356	15.844	13.641	7.474	5.564
Cum. %	34.122	57.478	73.322	86.962	94.436	100.000

Table C-0-4: Category A Component Loadings

Variable	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
Cat A	0.731	-0.471	0.264	-0.057	-0.113	0.398
Chl A	0.362	-0.819	0.140	0.198	0.195	-0.319
DO	-0.379	0.206	0.776	0.453	-0.085	0.000
FC	0.649	0.556	0.155	0.011	0.495	0.032
pH	-0.739	-0.341	-0.232	0.305	0.343	0.270
TP	0.521	0.202	-0.426	0.691	-0.168	0.005

Table C-0-5: Category A Eigenvectors

Variable	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
Cat A	0.511	-0.398	0.271	-0.063	-0.169	0.689
Chl A	0.253	-0.692	0.144	0.219	0.291	-0.551
DO	-0.265	0.174	0.796	0.500	-0.127	-0.001
FC	0.454	0.470	0.159	0.012	0.738	0.055
pH	-0.517	-0.288	-0.238	0.337	0.512	0.467
TP	0.364	0.171	-0.437	0.764	-0.252	0.009

Figure C-1: Category A Scree Plot

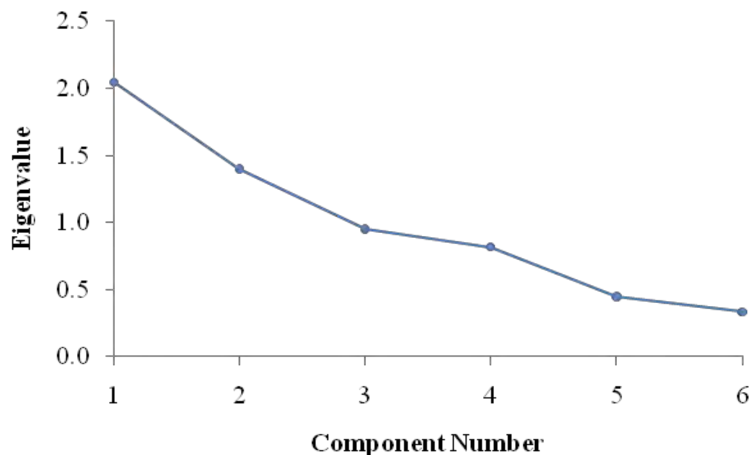


Figure C-2: Category A PC1 vs. PC2

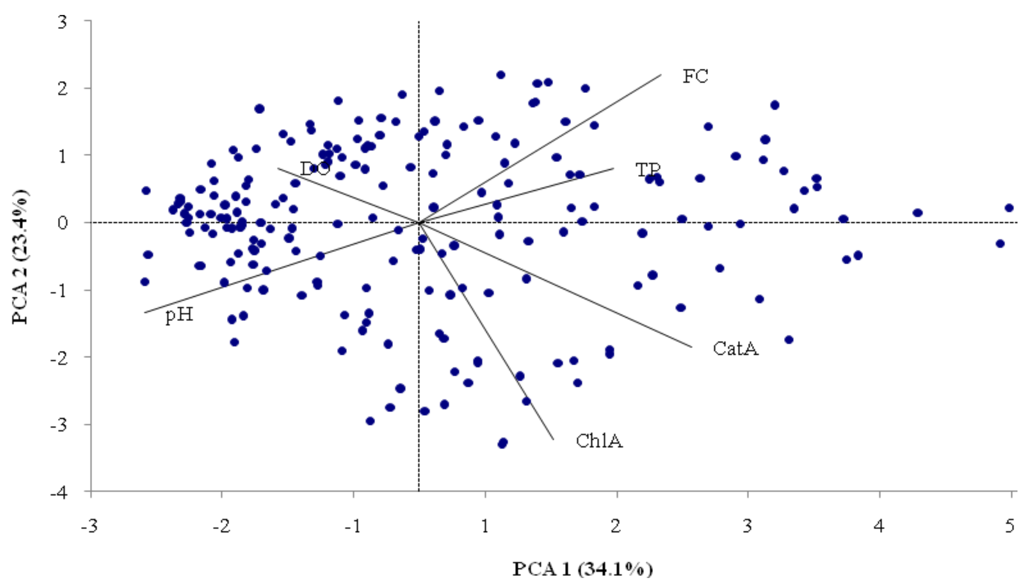


Figure C-3: Category A PC1 vs. PC3

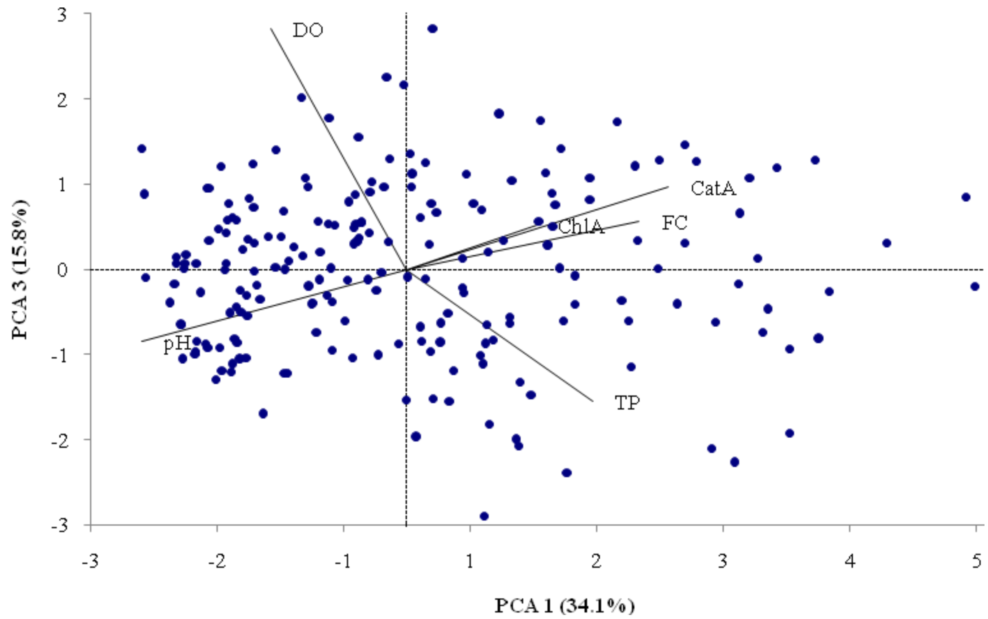


Figure C-4: Category A PC2 vs. PC3

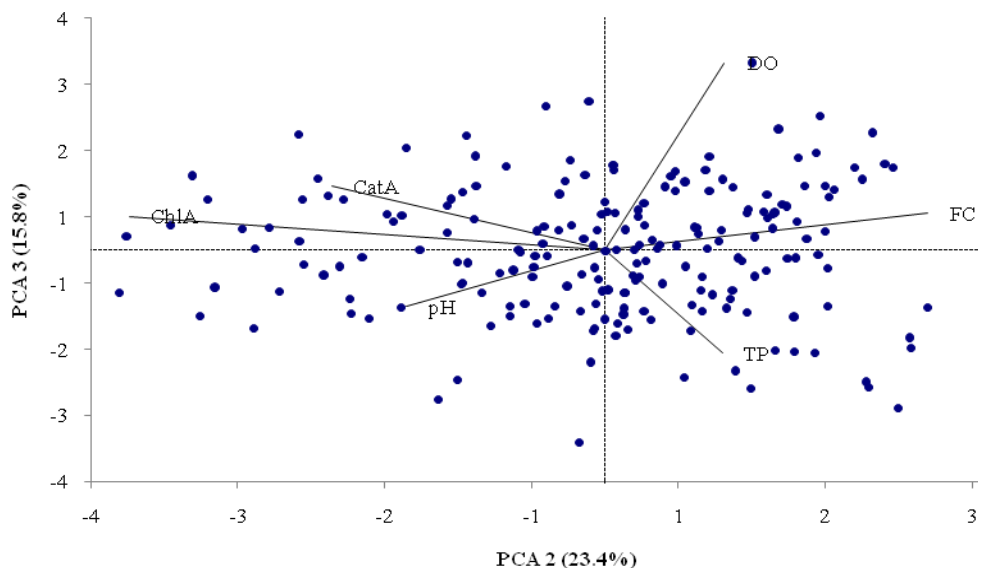


Figure C-5: Category A PC1 vs. PC4

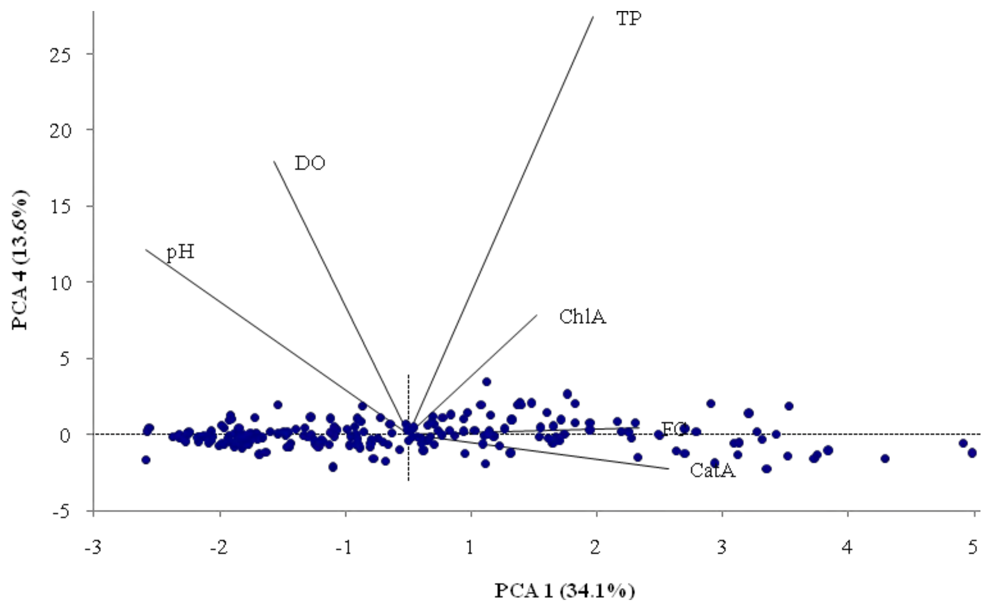


Figure C-6: Category A PC2 vs. PC4

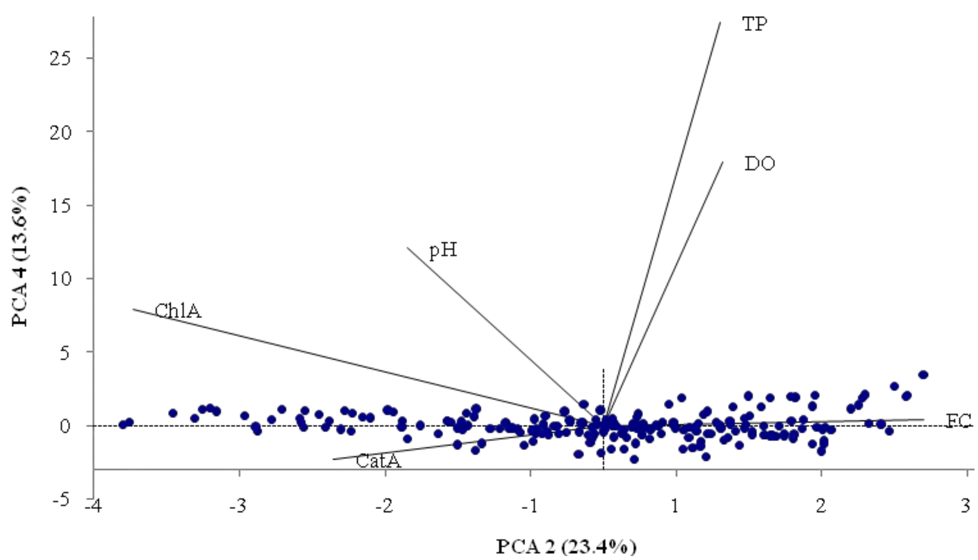
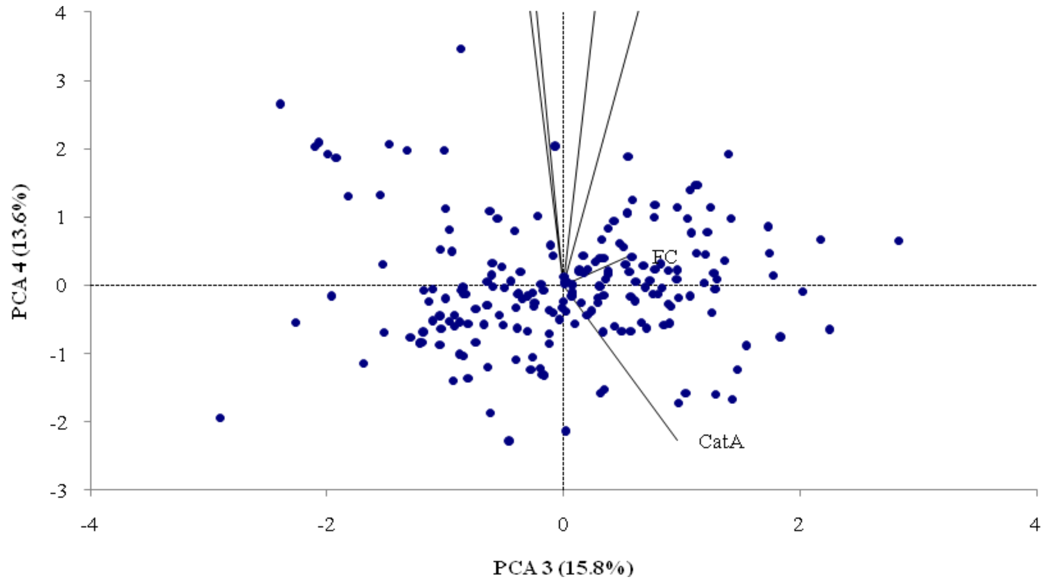


Figure C-7: Category A PC3 vs. PC4



C.2: Category B – Built-Up

Table C-6: Category B Descriptive Statistics

Variable	Mean	Std Dev.	Std Err	N
Cat. B..	1.959	1.022	0.053	369
Chl A	-2.199	0.948	0.049	369
TPTP	0.039	0.045	0.002	369

Table C-7: Category B Correlation Matrix

	Cat B	Chl A	TP
Cat B Percent	1.000	-0.063	0.089
Chl A	-0.063	1.000	0.148
TP	0.089	0.148	1.000

Table C-8: Category B Eigenvalues

Value	PC 1	PC 2	PC 3
Eigenvalue	1.151	1.054	0.795
% of Var.	38.375	35.120	26.505
Cum. %	38.375	73.495	100.000

Table C-9: Category B Component Loadings

Variable	PC 1	PC 2	PC 3
Cat B	0.168	0.894	0.415
Chl A	0.706	-0.455	0.543
TP	0.791	0.216	-0.573

Table C-10: Category B Eigenvectors

Variable	PC 1	PC 2	PC 3
Cat B	0.156	0.871	0.465
Chl A	0.658	-0.443	0.609
TP	0.737	0.211	-0.642

Figure C-8: Category B Scree Plot

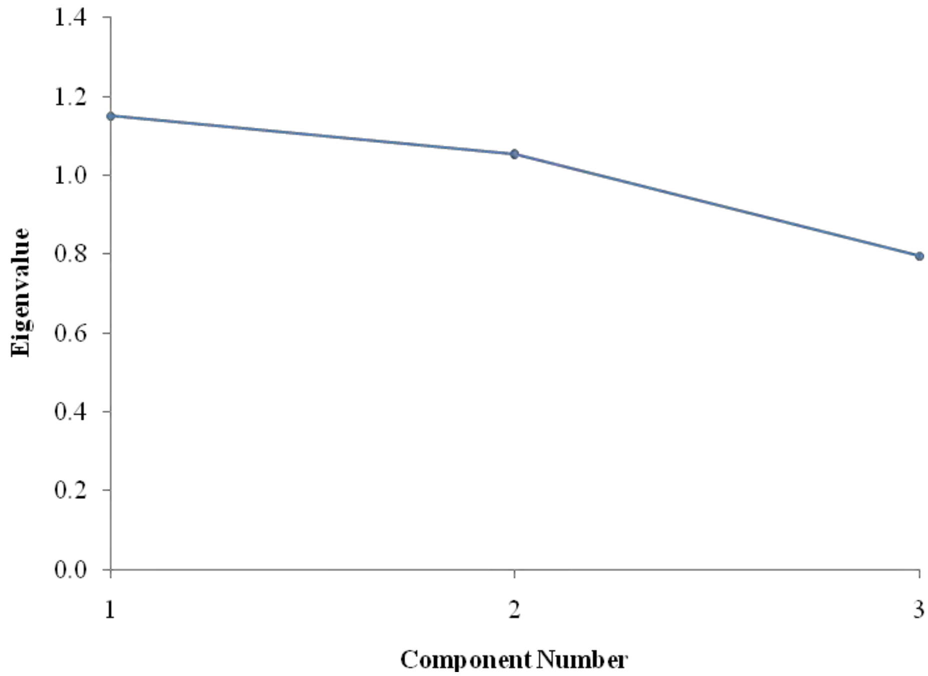


Figure C-9: Category B PC1 vs. PC2

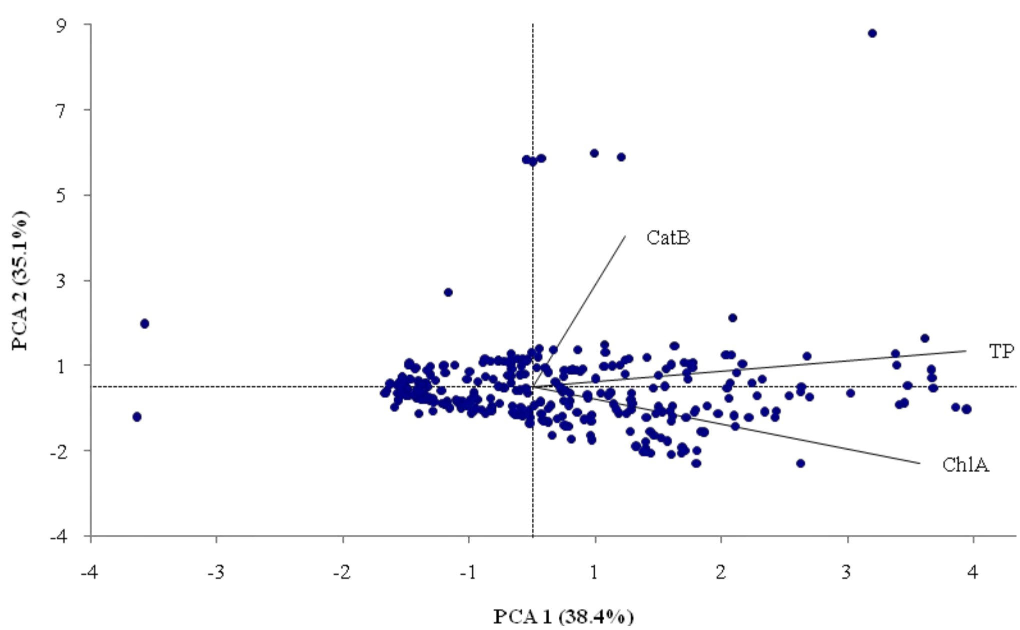


Figure C-10: Category B PC1 vs. PC3

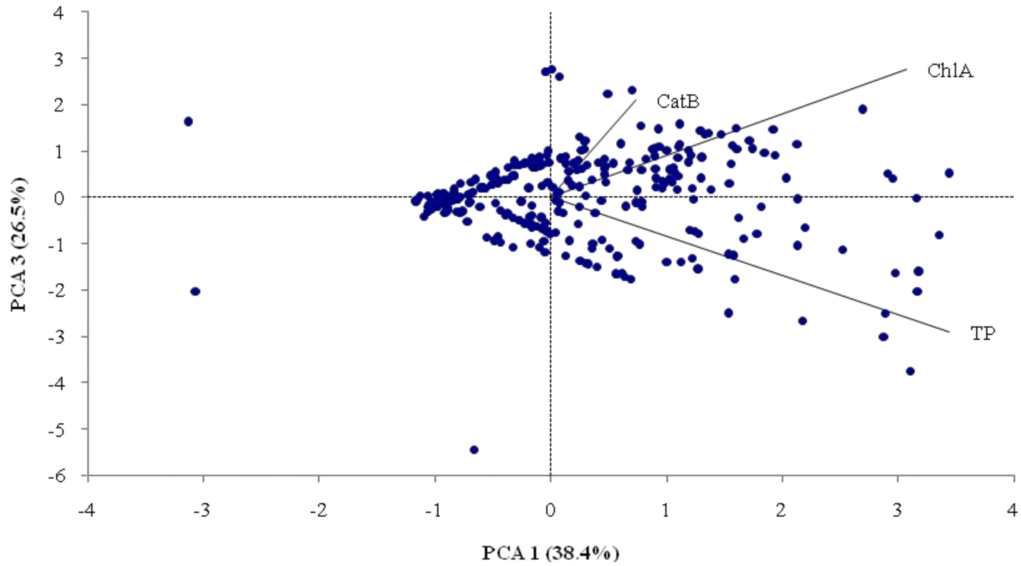
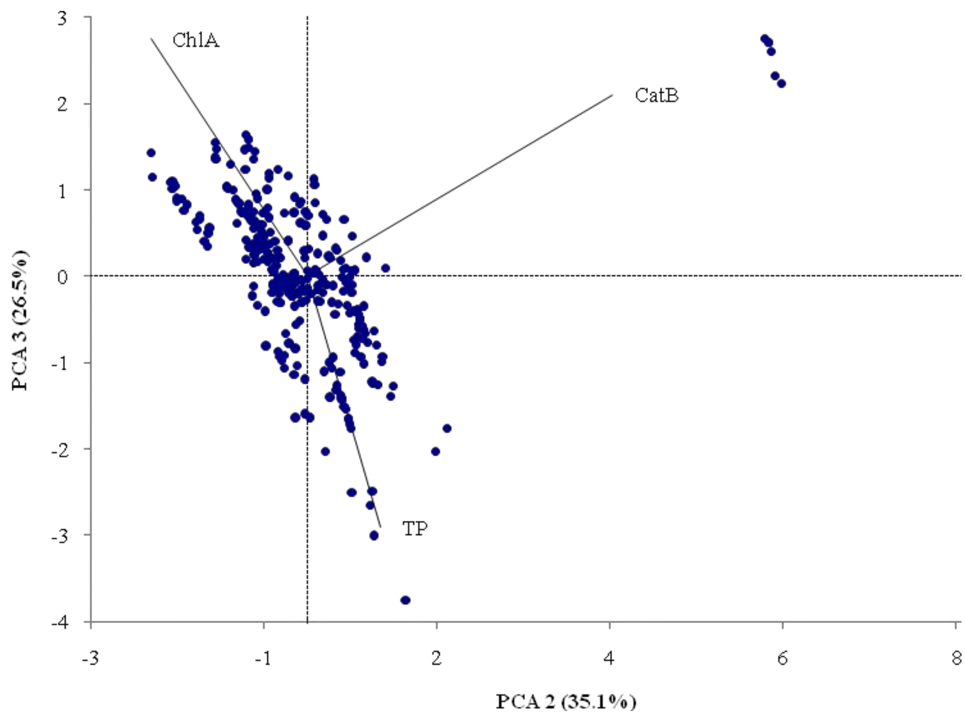


Figure C-11: Category B PC1 vs. PC2



C.3: Category C – Shrub/Forest

Table C-11: Category C Descriptive Statistics

Variable	Mean	Std Dev.	Std Err	N
Cat C	0.398	0.183	0.008	484
FC	4.217	1.905	0.087	484
pH	7.793	0.484	0.022	484

Table C-12: Category C Correlation Matrix

	Cat C	FC	pH
Cat C	1.000	-0.229	0.090
FC	-0.229	1.000	-0.431
pH	0.090	-0.431	1.000

Table C-13: Category C Eigenvalues

Value	PC 1	PC 2	PC 3
Eigenvalue	1.529	0.927	0.545
% of Var.	50.957	30.886	18.157
Cum. %	50.957	81.843	100.000

Table C-14: Category C Component Loadings

Variable	PC 1	PC 2	PC 3
Cat C	0.492	0.852	0.177
FC	-0.837	0.103	0.537
pH	0.766	-0.435	0.474

Table C-15: Category C Eigenvectors

Variable	PC 1	PC 2	PC 3
Cat C	0.398	0.886	0.240
FC	-0.677	0.107	0.728
pH	0.619	-0.452	0.642

Figure C-12: Category C Scree Plot

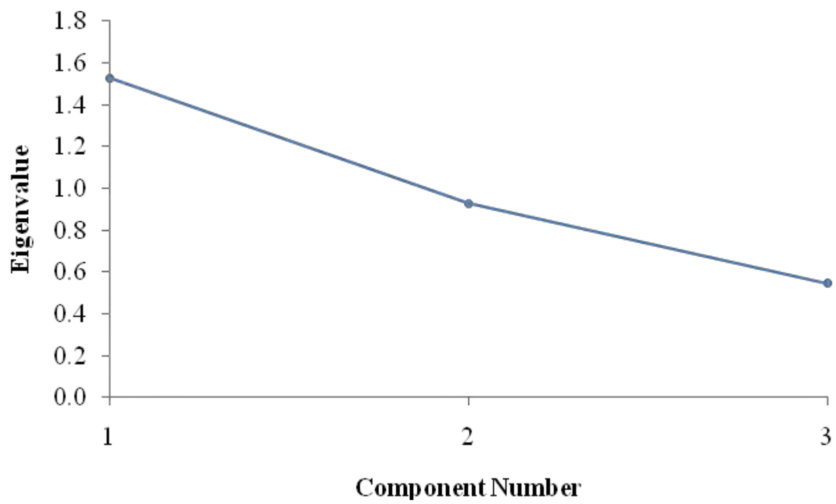


Figure C-13: Category C PC1 vs. PC2

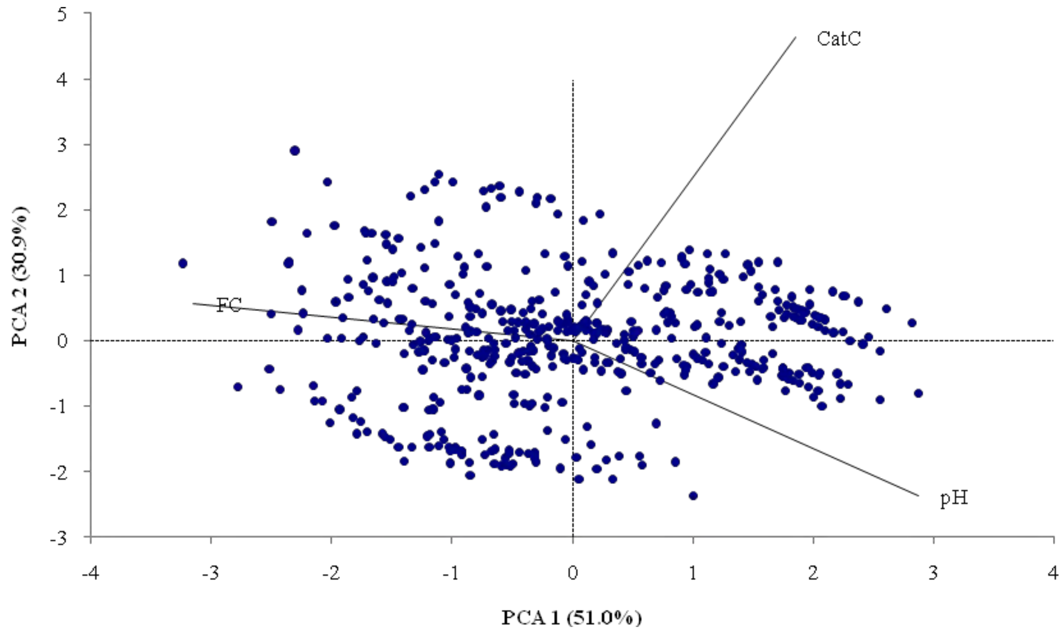


Figure C-14: Category B PC1 vs. PC3

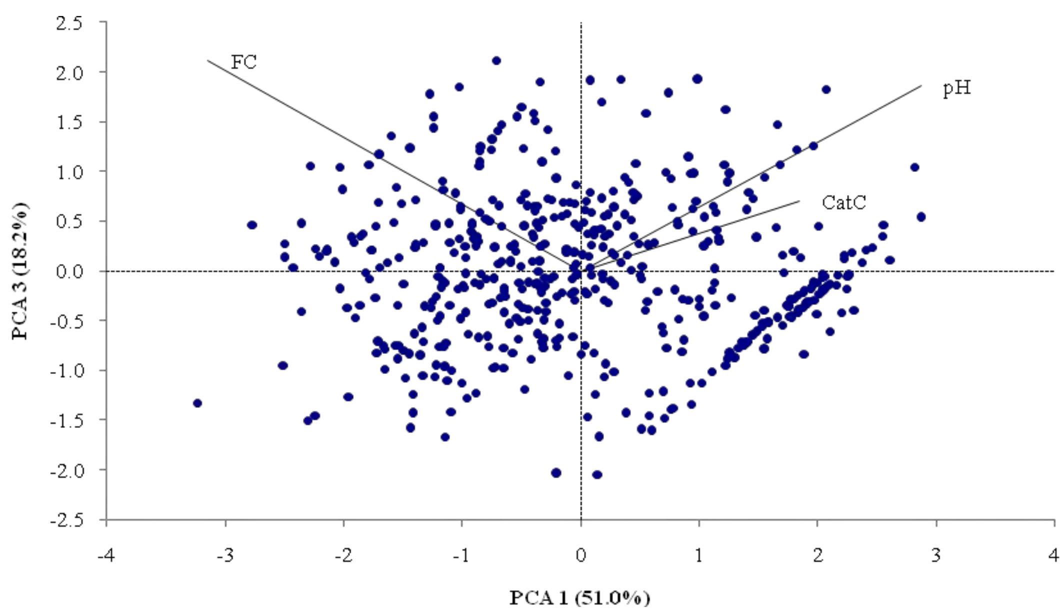
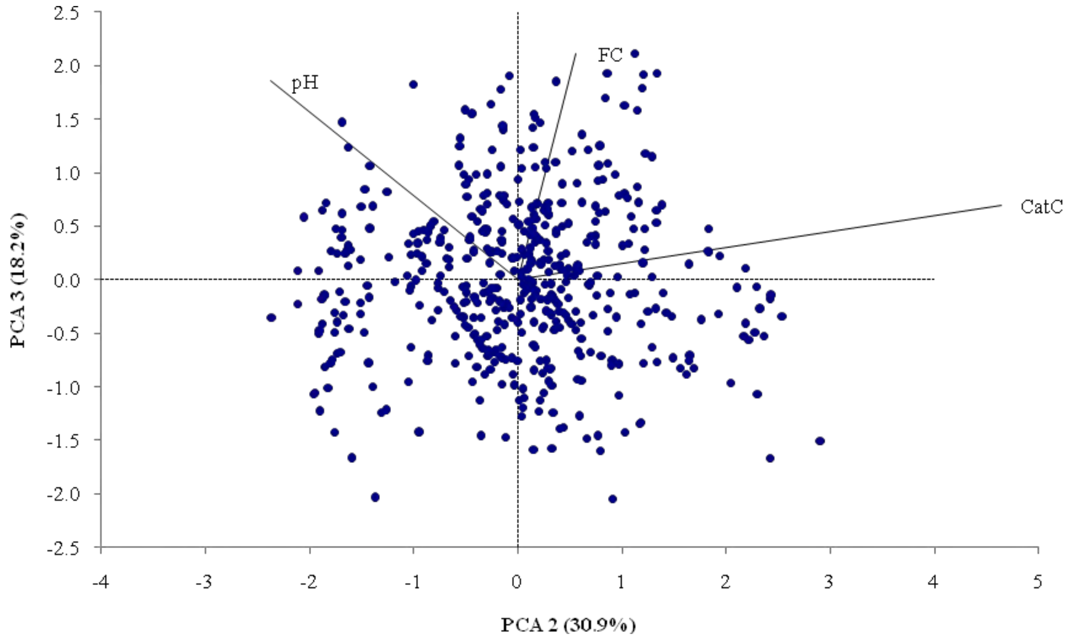


Figure C-15: Category C PC2 vs. PC3



C.4: Category D – Grass

Table C-11: Category D Descriptive Statistics

Variable	Mean	Std Dev.	Std Err	N
Cat D	0.268	0.146	0.014	103
Chl A	2.037	1.029	0.101	103
OP	-2.853	0.589	0.058	103
pH	7.977	0.531	0.052	103
SpC	6.091	0.422	0.042	103
TN	-1.897	1.554	0.153	103

Table C-12: Category D Correlation Matrix

	Cat D	Chl A	OP	pH	SpC	TN
Cat D	1.000	-0.349	0.156	0.250	0.207	0.270
Chl A	-0.349	1.000	0.109	0.233	0.056	-0.307
OP	0.156	0.109	1.000	-0.105	0.348	0.252
pH	0.250	0.233	-0.105	1.000	0.060	-0.138
SpC	0.207	0.056	0.348	0.060	1.000	0.114
TN	0.270	-0.307	0.252	-0.138	0.114	1.000

Table C-13: Category D Eigenvalues

Value	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
Eigenvalue	1.770	1.371	1.205	0.713	0.574	0.367
% of Var.	29.506	22.843	20.085	11.889	9.566	6.111
Cum. %	29.506	52.349	72.435	84.324	93.889	100.000

Table C-14: Category D Component Loadings

Variable	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
Cat D	0.690	0.050	0.567	-0.051	-0.284	0.342
Chl A	-0.513	0.695	-0.199	0.289	0.079	0.352
OP	0.532	0.470	-0.479	0.222	-0.419	-0.204
pH	-0.093	0.517	0.757	0.236	0.112	-0.287
SpC	0.486	0.585	-0.149	-0.533	0.338	-0.012
TN	0.709	-0.232	-0.135	0.488	0.430	0.046

Table C-15: Category D Eigenvectors

Variable	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6
Cat D	0.518	0.043	0.517	-0.060	-0.375	0.564
Chl A	-0.386	0.594	-0.181	0.342	0.104	0.581
OP	0.400	0.402	-0.437	0.263	-0.553	-0.337
pH	-0.070	0.442	0.690	0.280	0.147	-0.473
SpC	0.366	0.500	-0.136	-0.631	0.447	-0.020
TN	0.533	-0.198	-0.123	0.578	0.567	0.076

Figure C-1: Category D Scree Plot

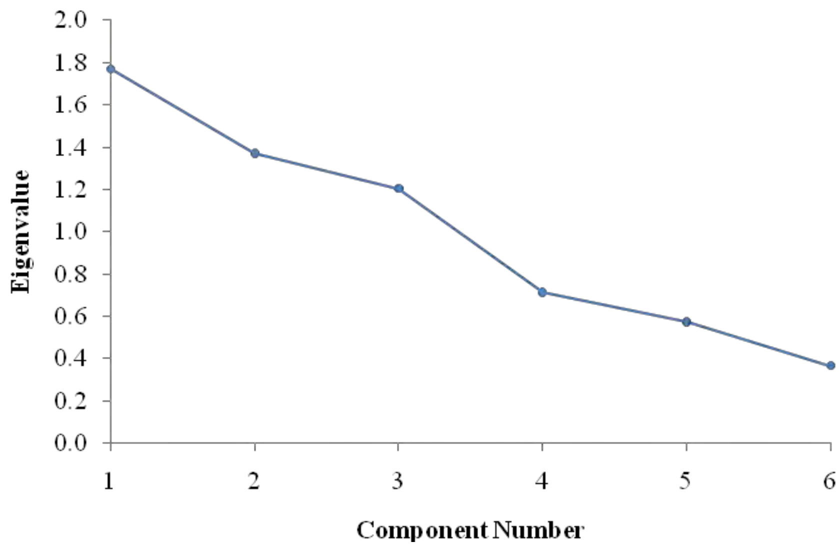


Figure C-2: Category D PC1 vs. PC2

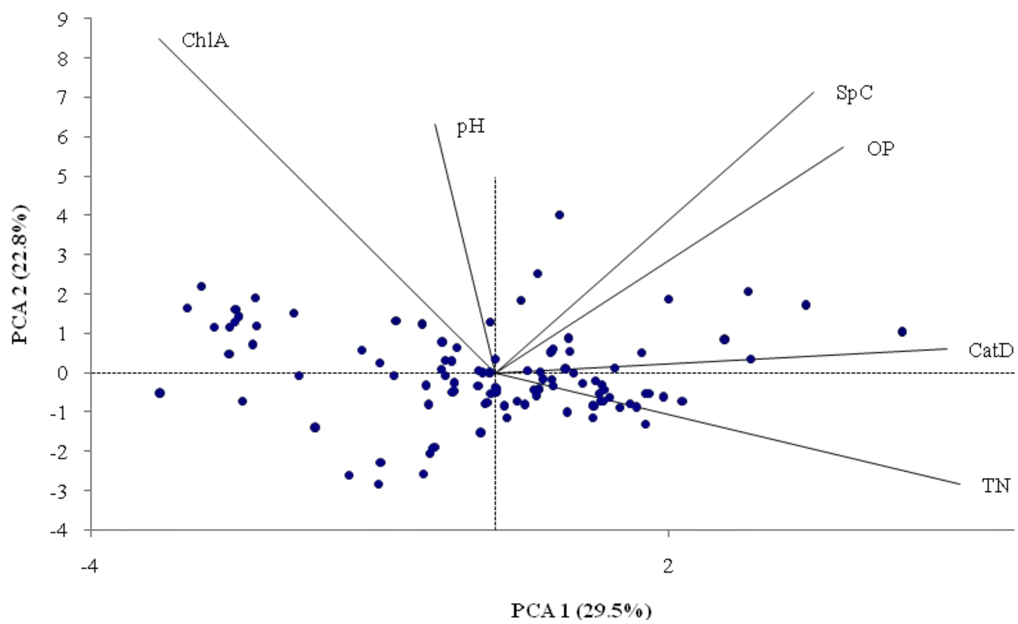


Figure C-3: Category D PC1 vs. PC3

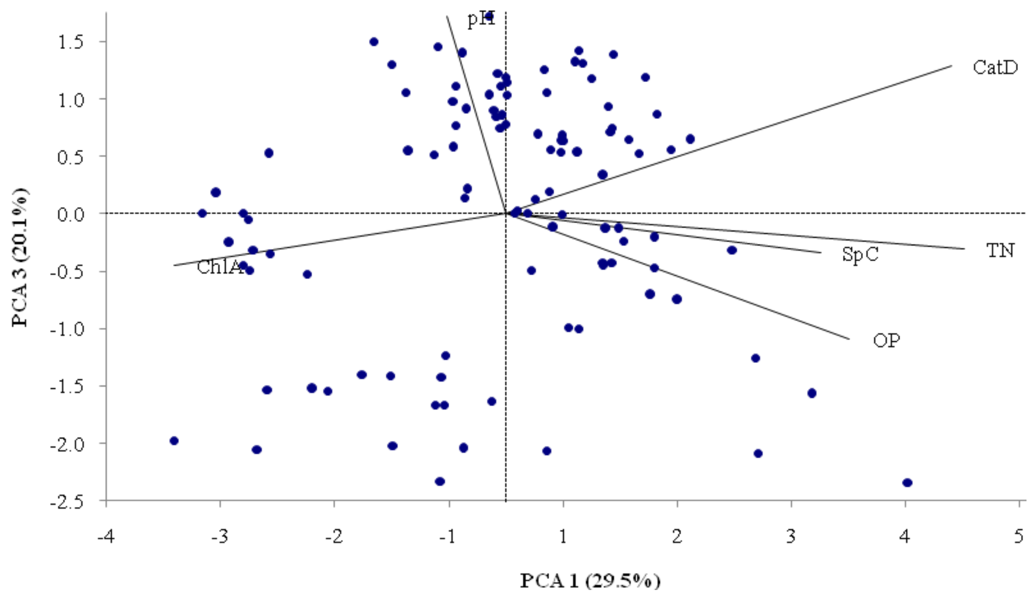


Figure C-4: Category D PC2 vs. PC3

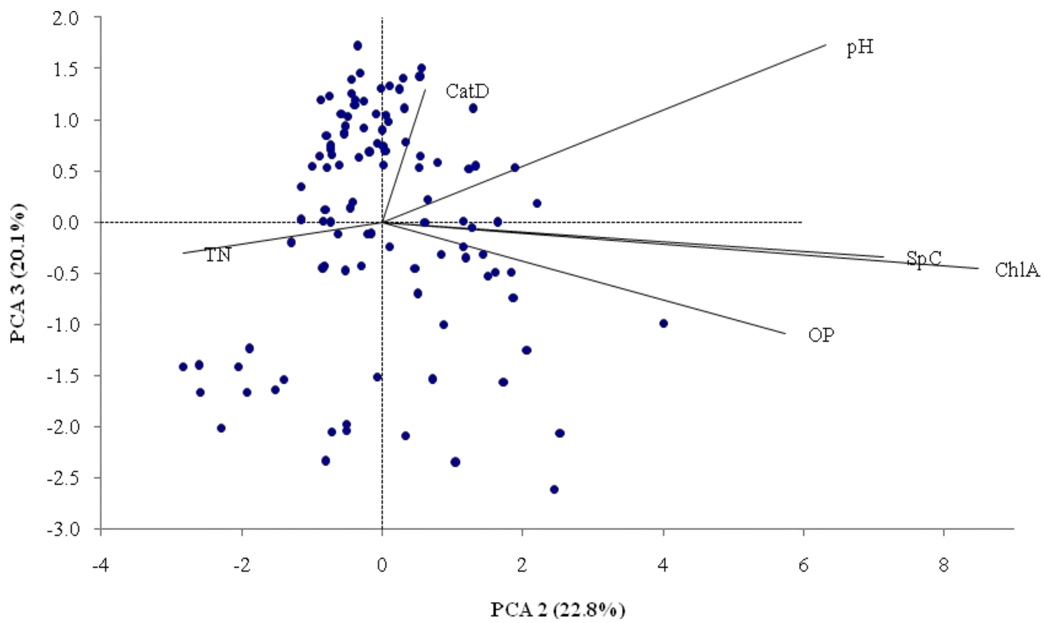


Figure C-5: Category D PC1 vs. PC4

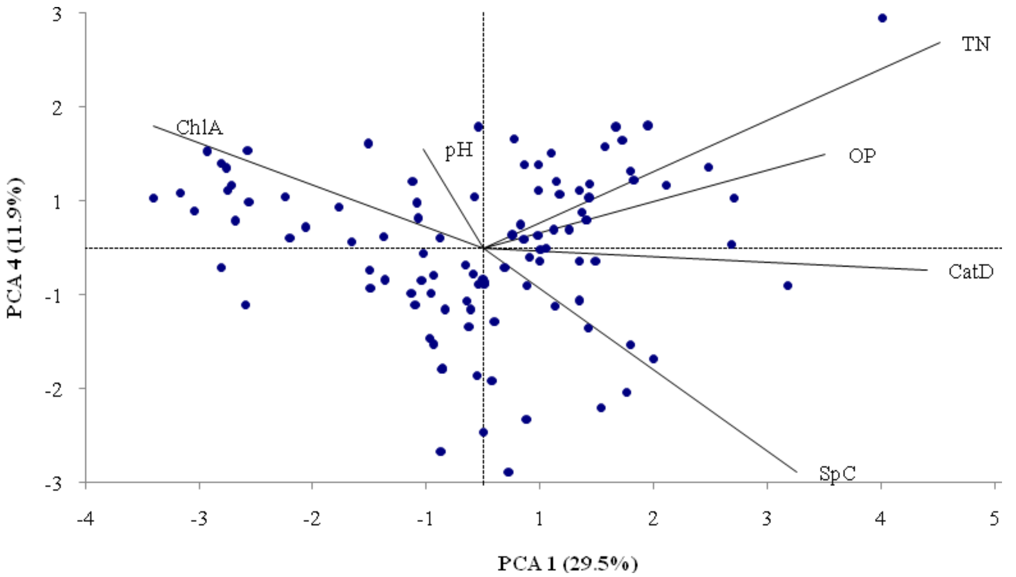
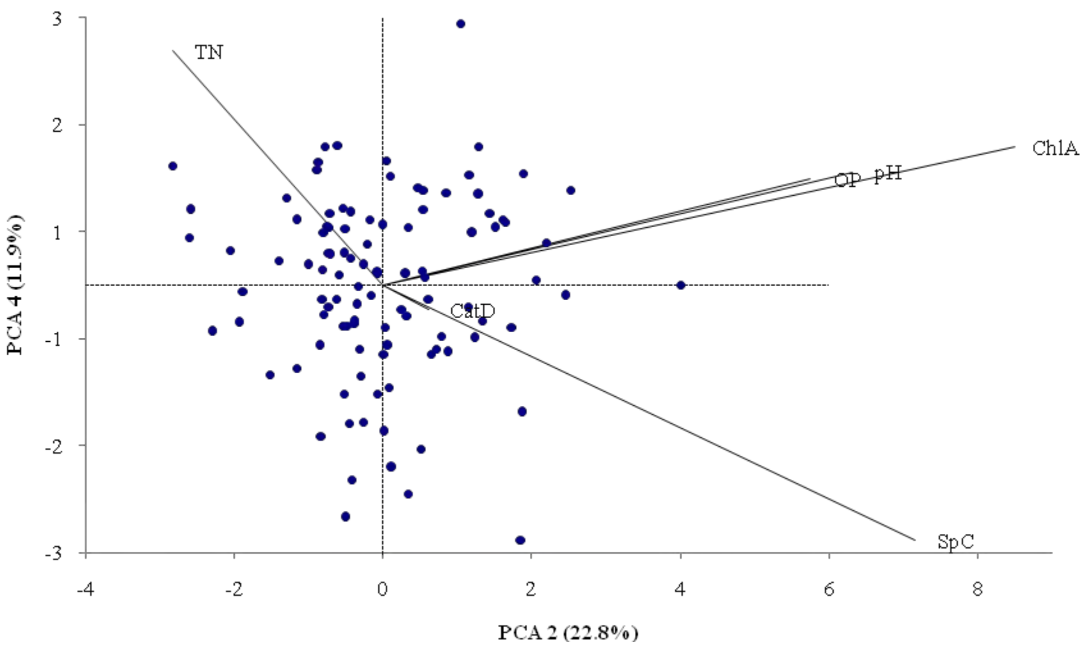


Figure C-6: Category D PC2 vs. PC4



C.5: Category E – Open Water

Table C-16: Category E Descriptive Statistics

Variable	Mean	Std Dev.	Std Err	N
Cat E	0.009	0.007	0.000	341
Chl A	2.083	0.989	0.054	341
pH	7.952	0.480	0.026	341

Table C-17: Category E Correlation Matrix

	Cat E	Chl A	pH
Cat E	1.000	0.245	-0.178
Chl A	0.245	1.000	0.215
pH	-0.178	0.215	1.000

Table C-18: Category E Eigenvalues

Value	PC 1	PC 2	PC 3
Eigenvalue	1.252	1.174	0.574
% of Var.	41.726	39.140	19.133
Cum. %	41.726	80.867	100.000

Table C-19: Category E Component Loadings

Variable	PC 1	PC 2	PC 3
Cat E	0.641	-0.631	-0.437
Chl A	0.870	0.178	0.460
pH	0.289	0.863	-0.414

Table C-20: Category E Eigenvectors

Variable	PC 1	PC 2	PC 3
Cat E	0.573	-0.582	-0.577
Chl A	0.778	0.164	0.607
pH	0.258	0.796	-0.547

Figure C-22: Category E Scree Plot

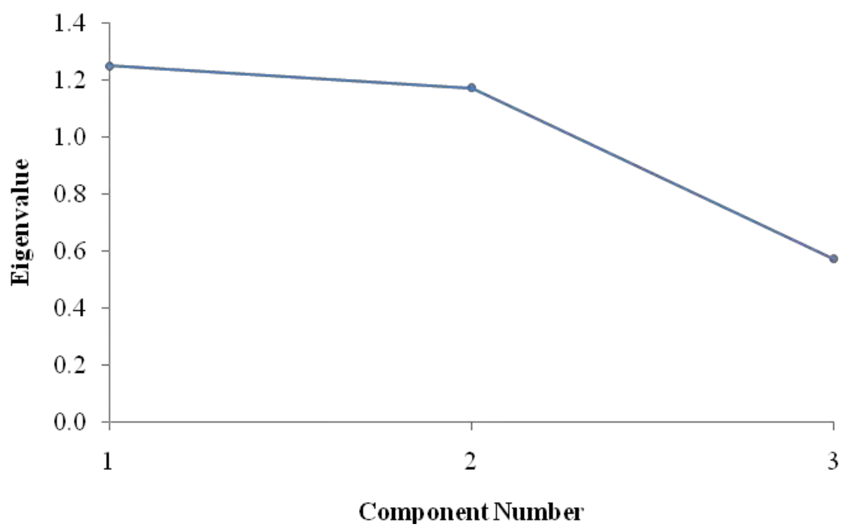


Figure C-23: Category E PC1 vs. PC2

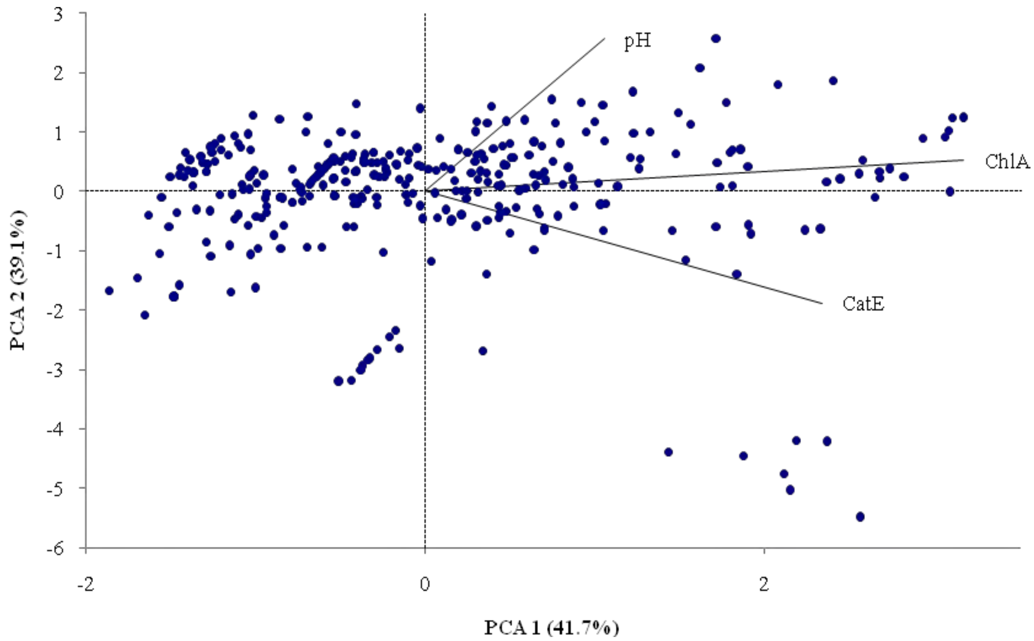


Figure C-24: Category E PC1 vs. PC3

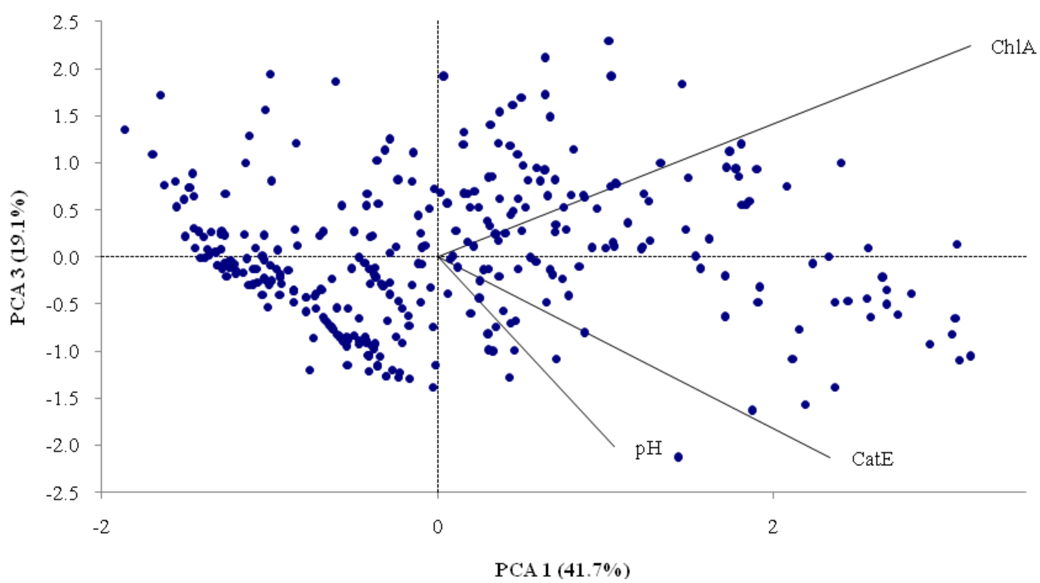
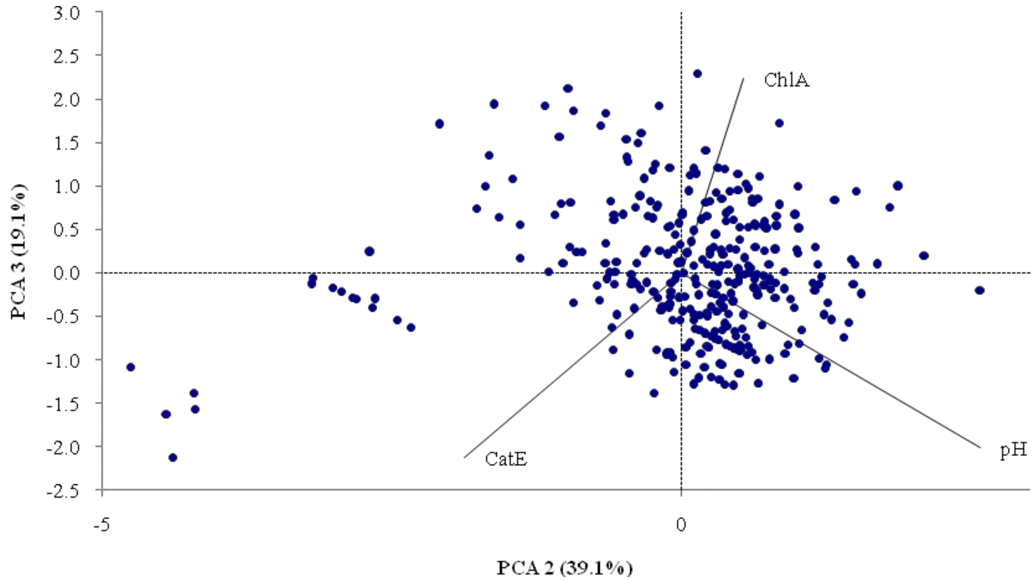


Figure C-25: Category E PC2 vs. PC3



C.6: Category F – Wetland

Table C-21: Category F Descriptive Statistics

Variable	Mean	Std Dev.	Std Err	N
Cat F	0.019	0.025	0.002	187
Chl A	2.039	1.033	0.076	187
FC	3.553	1.897	0.139	187
pH	7.916	0.501	0.037	187
TP	-2.296	0.866	0.063	187

Table C-22: Category F Correlation Matrix

	Cat F	Chl A	FC	pH	TP
Cat F	1.000	0.025	0.157	-0.431	0.100
Chl A	0.025	1.000	-0.032	0.022	0.050
FC	0.157	-0.032	1.000	-0.474	0.353
pH	-0.431	0.022	-0.474	1.000	-0.124
TP	0.100	0.050	0.353	-0.124	1.000

Table C-23: Category F Eigenvalues

Value	PC 1	PC 2	PC 3	PC 4	PC 5
Eigenvalue	1.854	1.037	1.003	0.710	0.397
% of Var.	37.079	20.744	20.056	14.191	7.930
Cum. %	37.079	57.823	77.879	92.070	100.000

Table C-24: Category F Component Loadings

Variable	PC 1	PC 2	PC 3	PC 4	PC 5
Cat F	0.606	-0.397	0.440	0.477	0.232
Chl A	-0.002	0.588	0.787	-0.185	0.009
FC	0.766	0.199	-0.285	-0.396	0.369
pH	-0.804	0.290	-0.132	0.275	0.421
TP	0.504	0.640	-0.303	0.465	-0.169

Table C-25: Category F Eigenvectors

Variable	PC 1	PC 2	PC 3	PC 4	PC 5
Cat F	0.445	-0.390	0.439	0.566	0.369
Chl A	-0.001	0.578	0.786	-0.220	0.014
FC	0.562	0.195	-0.284	-0.470	0.587
pH	-0.590	0.284	-0.131	0.326	0.669
TP	0.370	0.629	-0.302	0.552	-0.269

Figure C-26: Category F Scree Plot

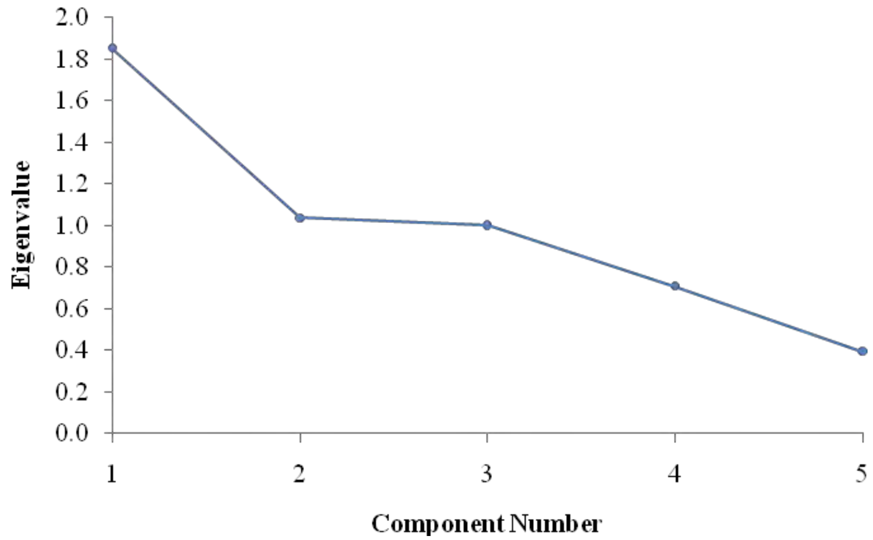


Figure C-27: Category F PC1 vs. PC2

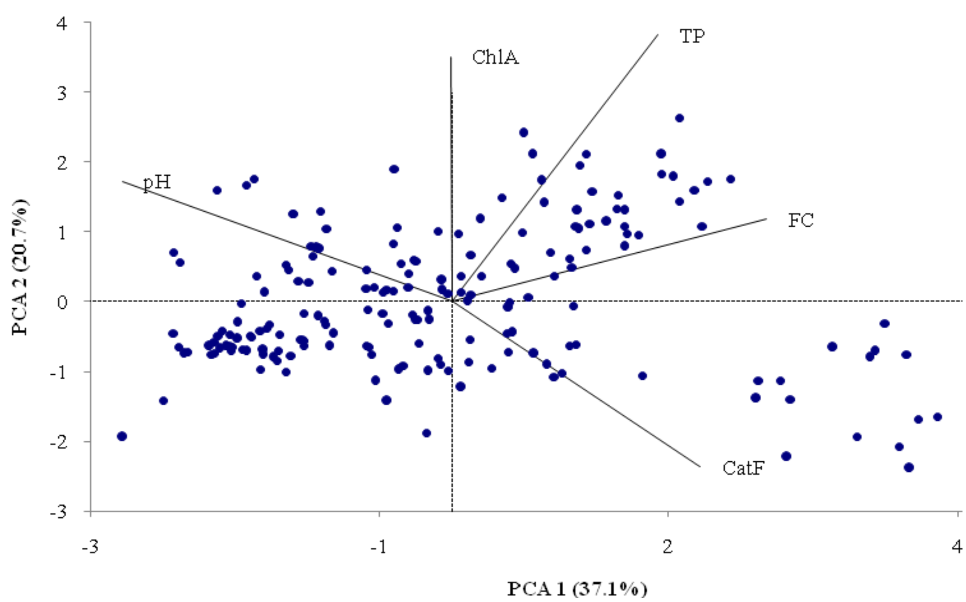


Figure C-28: Category F PC1 vs. PC3

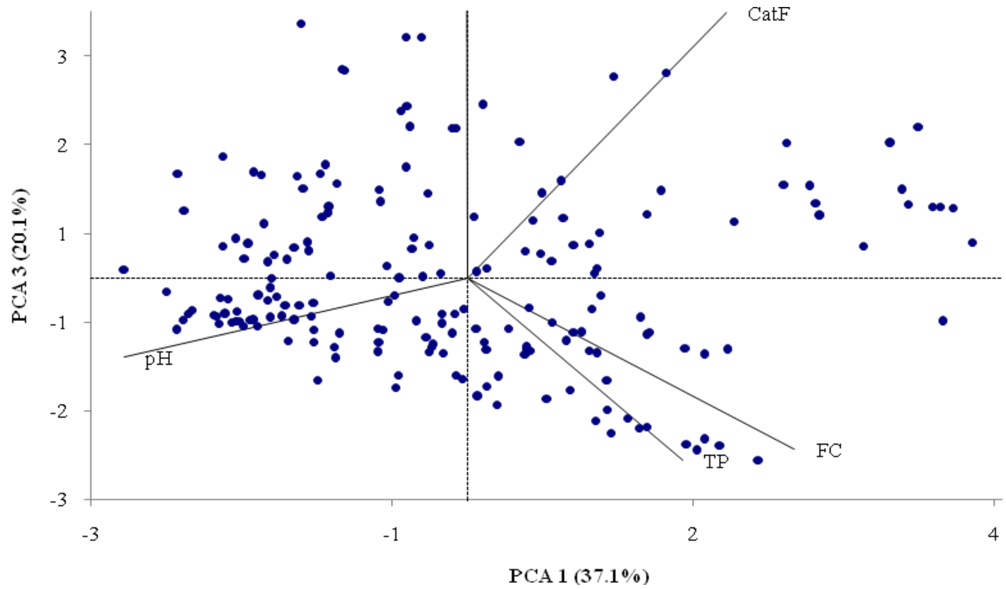
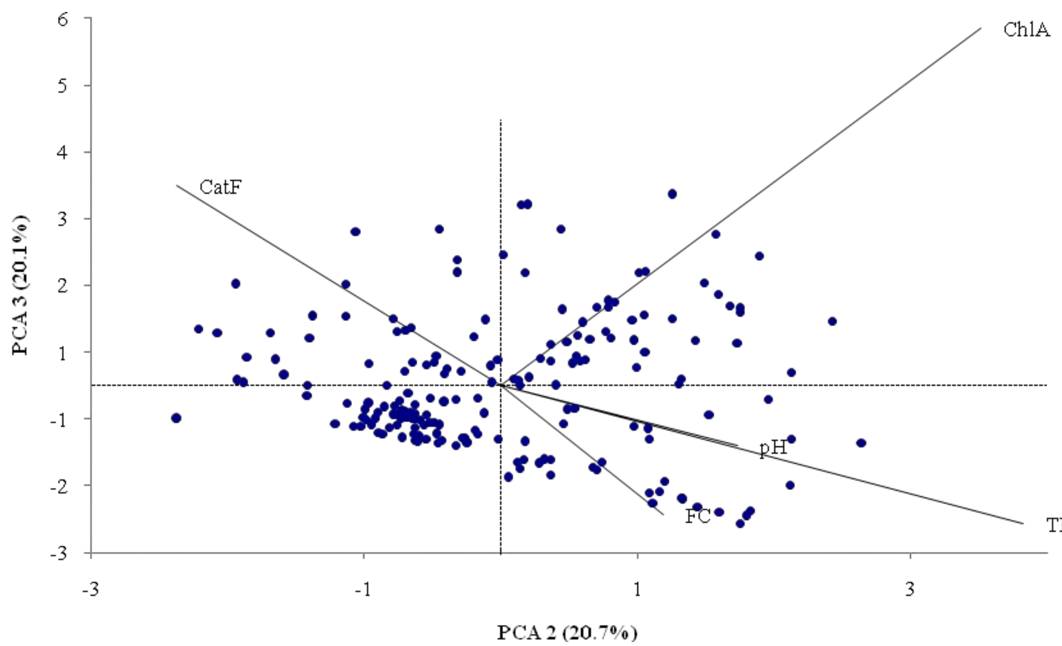


Figure C-29: Category F PC2 vs. PC3



C.7: Category G – Rock/Mine/Sand/Bare Earth

Table C-26: Category G Descriptive Statistics

Variable	Mean	Std Dev.	Std Err	N
Cat G	0.003	0.005	0.000	522
pH	7.799	0.474	0.021	522
SpC	6.244	0.540	0.024	522

Table C-27: Category G Correlation Matrix

	Cat G	pH	SpC
Cat G	1.000	-0.161	-0.164
pH	-0.161	1.000	0.158
SpC	-0.164	0.158	1.000

Table C-28: Category G Eigenvalues

Value	PC 1	PC 2	PC 3
Eigenvalue	1.322	0.842	0.836
% of Var.	44.061	28.078	27.861
Cum. %	44.061	72.139	100.000

Table C-29: Category G Component Loadings

Variable	PC 1	PC 2	PC 3
Cat G	-0.668	0.204	0.716
pH	0.660	0.729	0.183
SpC	0.664	-0.519	0.538

Table C-30: Category G Eigenvectors

Variable	PC 1	PC 2	PC 3
Cat G	-0.581	0.222	0.783
pH	0.574	0.794	0.200
SpC	0.578	-0.566	0.589

Figure C-30: Category G Scree Plot

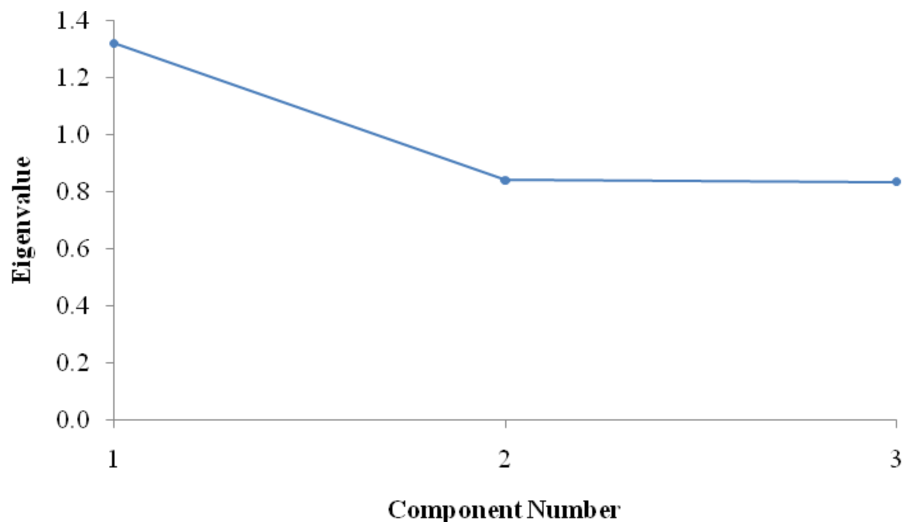


Figure C-31: Category G PC1 vs. PC2

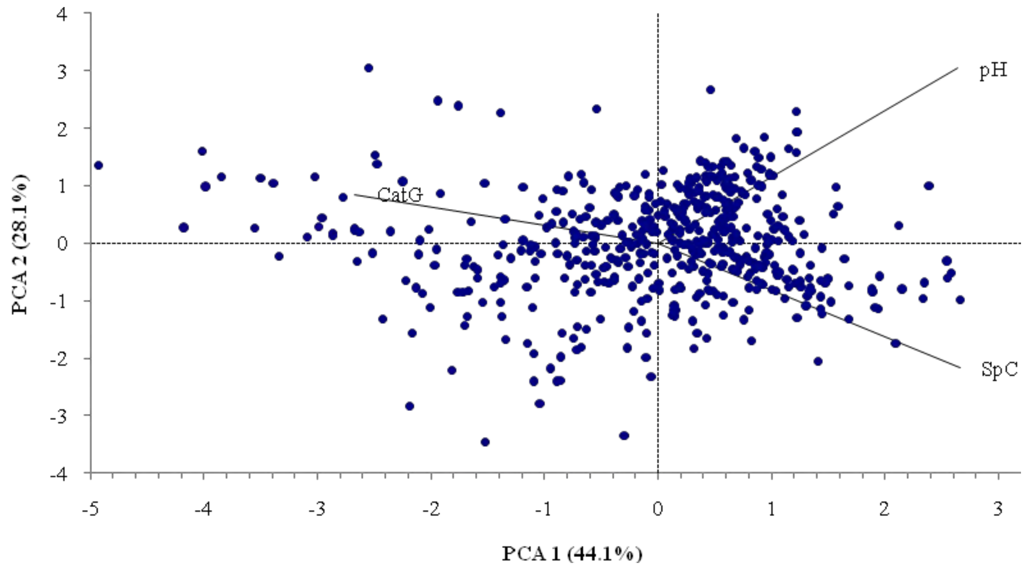


Figure C-32: Category G PC1 vs. PC3

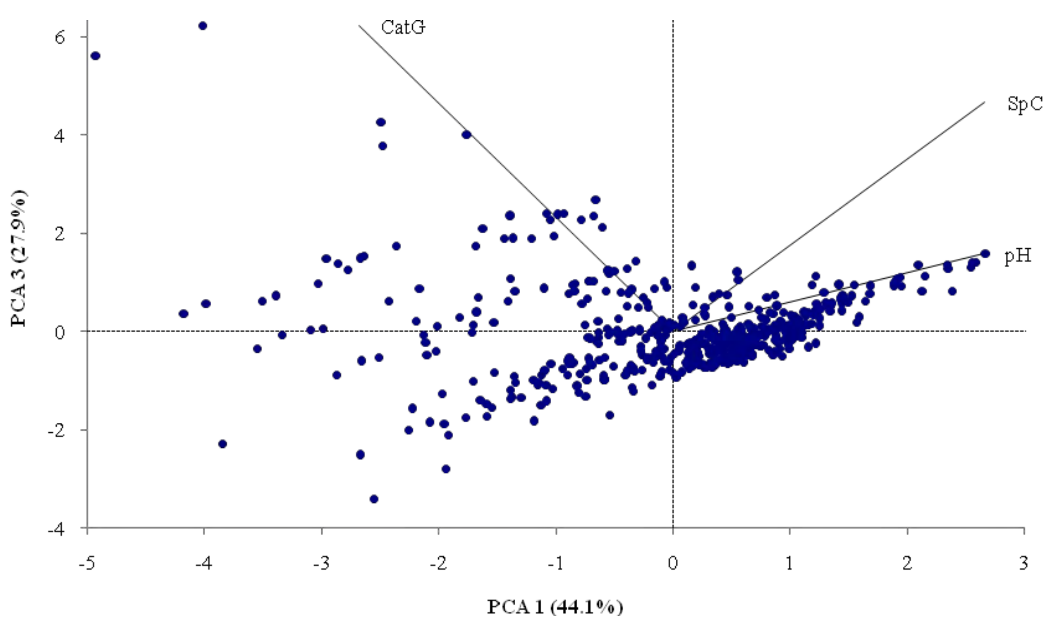
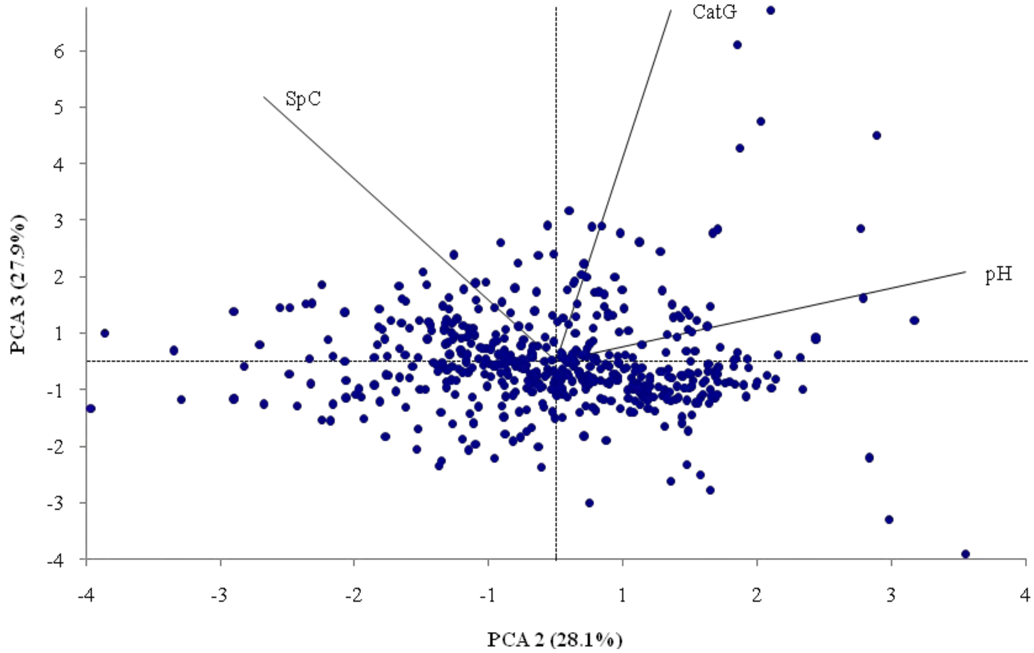


Figure C-33: Category G PC2 vs. PC3



C.7: All Categories and Most Highly Available Water Quality Parameters

Table C-31: WQ Panel Descriptive Statistics

Variable	Mean	Std Dev.	Std Err	N
Chl A	1.920	0.723	0.145	25
FC	4.149	1.565	0.313	25
pH	7.982	0.363	0.073	25
SpC	6.311	0.423	0.085	25
Cat A	0.153	0.126	0.025	25
Cat B	0.052	0.080	0.016	25
Cat C	0.478	0.122	0.024	25
Cat D	0.291	0.129	0.026	25
Cat E	0.007	0.005	0.001	25
Cat F	0.019	0.027	0.005	25
Cat G	0.001	0.003	0.001	25

Table C-32: WQ Panel Correlation Matrix

	Chl A	FC	pH	SpC	Cat A	Cat B	Cat C	Cat D	Cat E	Cat F	Cat G
Chl A	1.000	-0.362	-0.024	-0.256	0.561	-0.119	-0.301	-0.285	0.352	0.395	-0.036
FC	-0.362	1.000	-0.541	0.403	0.135	0.140	-0.278	0.077	-0.502	-0.061	0.017
pH	-0.024	-0.541	1.000	0.110	-0.464	-0.105	0.322	0.323	-0.056	-0.490	-0.282
SpC	-0.256	0.403	0.110	1.000	-0.229	0.065	0.094	0.229	-0.567	-0.499	-0.363
Cat A	0.561	0.135	-0.464	-0.229	1.000	-0.158	-0.419	-0.656	0.379	0.746	0.182
Cat B	-0.119	0.140	-0.105	0.065	-0.158	1.000	-0.511	0.000	-0.079	0.044	0.701
Cat C	-0.301	-0.278	0.322	0.094	-0.419	-0.511	1.000	-0.173	-0.223	-0.149	-0.394
Cat D	-0.285	0.077	0.323	0.229	-0.656	0.000	-0.173	1.000	-0.262	-0.853	-0.388
Cat E	0.352	-0.502	-0.056	-0.567	0.379	-0.079	-0.223	-0.262	1.000	0.498	0.406
Cat F	0.395	-0.061	-0.490	-0.499	0.746	0.044	-0.149	-0.853	0.498	1.000	0.540
Cat G	-0.036	0.017	-0.282	-0.363	0.182	0.701	-0.394	-0.388	0.406	0.540	1.000

Table C-33: WQ Panel Eigenvalues

Value	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8	PC 9	PC 10	PC 11
Eigenvalue	3.894	2.270	1.716	1.253	0.838	0.448	0.319	0.144	0.060	0.057	0.000
% of Var.	35.403	20.636	15.596	11.395	7.615	4.077	2.898	1.311	0.549	0.520	0.000
Cum. %	35.403	56.039	71.635	83.030	90.645	94.722	97.620	98.932	99.480	100.000	100.000

Table C-34: WQ Panel Component Loadings

Variable	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8	PC 9	PC 10	PC 11
Chl A	-0.530	-0.365	-0.094	0.584	-0.339	-0.246	0.162	0.182	-0.021	0.006	0.000
FC	0.120	0.816	-0.454	0.015	0.171	0.021	-0.174	0.212	-0.068	-0.060	0.000
pH	0.494	-0.549	0.393	0.048	-0.362	0.111	-0.385	0.074	0.004	-0.038	0.000
SpC	0.578	0.364	-0.318	0.091	-0.483	0.389	0.191	0.014	0.060	0.002	0.000
Cat A	-0.800	0.033	-0.449	0.271	-0.091	0.132	-0.198	-0.108	-0.030	0.076	0.000
Cat B	-0.150	0.646	0.633	-0.077	-0.338	-0.117	0.073	-0.083	-0.084	-0.078	0.000
Cat C	0.398	-0.539	-0.290	-0.659	-0.057	-0.055	0.118	0.102	-0.045	0.009	0.000
Cat D	0.729	0.092	0.333	0.460	0.352	-0.016	0.038	0.052	0.094	-0.007	0.000
Cat E	-0.651	-0.399	0.343	0.098	0.273	0.430	0.126	0.064	-0.078	-0.061	0.000
Cat F	-0.929	-0.027	-0.175	-0.244	-0.050	-0.033	-0.034	0.013	0.152	-0.133	0.000
Cat G	-0.617	0.400	0.547	-0.326	-0.051	0.066	-0.026	0.156	0.060	0.137	0.000

Table C-35: WQ Panel Eigenvectors

Variable	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8	PC 9	PC 10	PC 11
Chl A	-0.269	-0.242	-0.071	0.522	-0.370	-0.367	0.287	0.480	-0.084	0.023	0.000
FC	0.061	0.542	-0.347	0.014	0.187	0.031	-0.309	0.558	-0.277	-0.253	0.000
pH	0.250	-0.364	0.300	0.043	-0.395	0.165	-0.682	0.194	0.018	-0.160	0.000
SpC	0.293	0.241	-0.243	0.081	-0.527	0.580	0.338	0.038	0.244	0.010	0.000
Cat A	-0.406	0.022	-0.343	0.242	-0.099	0.197	-0.350	-0.285	-0.124	0.318	0.538
Cat B	-0.076	0.429	0.483	-0.068	-0.370	-0.175	0.128	-0.219	-0.343	-0.326	0.342
Cat C	0.202	-0.357	-0.221	-0.589	-0.063	-0.083	0.210	0.269	-0.185	0.038	0.523
Cat D	0.369	0.061	0.254	0.411	0.385	-0.023	0.067	0.136	0.385	-0.028	0.553
Cat E	-0.330	-0.265	0.262	0.087	0.298	0.641	0.223	0.170	-0.316	-0.255	0.022
Cat F	-0.471	-0.018	-0.134	-0.218	-0.054	-0.049	-0.059	0.035	0.618	-0.554	0.117
Cat G	-0.312	0.266	0.417	-0.291	-0.056	0.099	-0.045	0.412	0.244	0.573	0.011

Figure C-34: WQ Panel Scree Plot

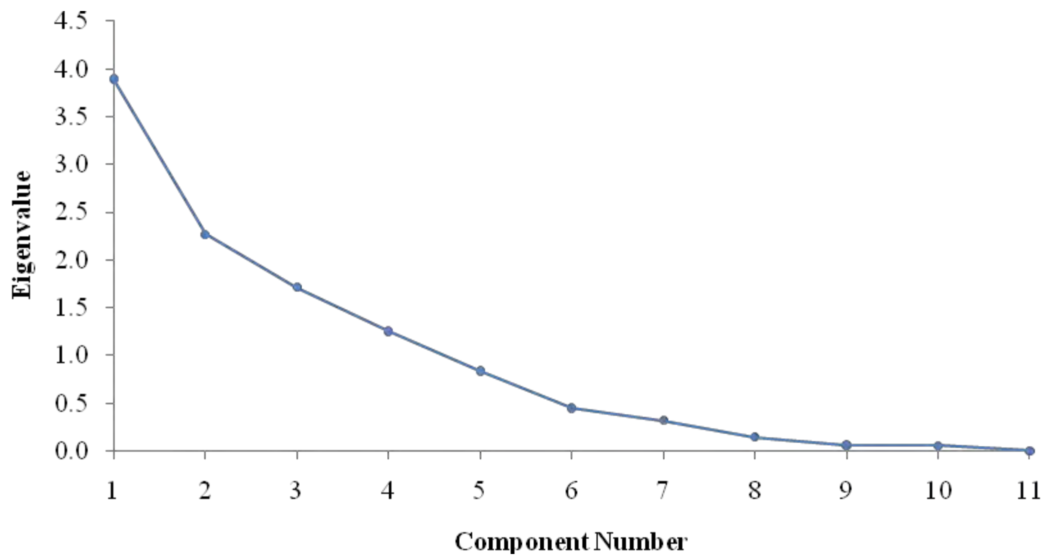


Figure C-35: WQ Panel PC1 vs. PC2

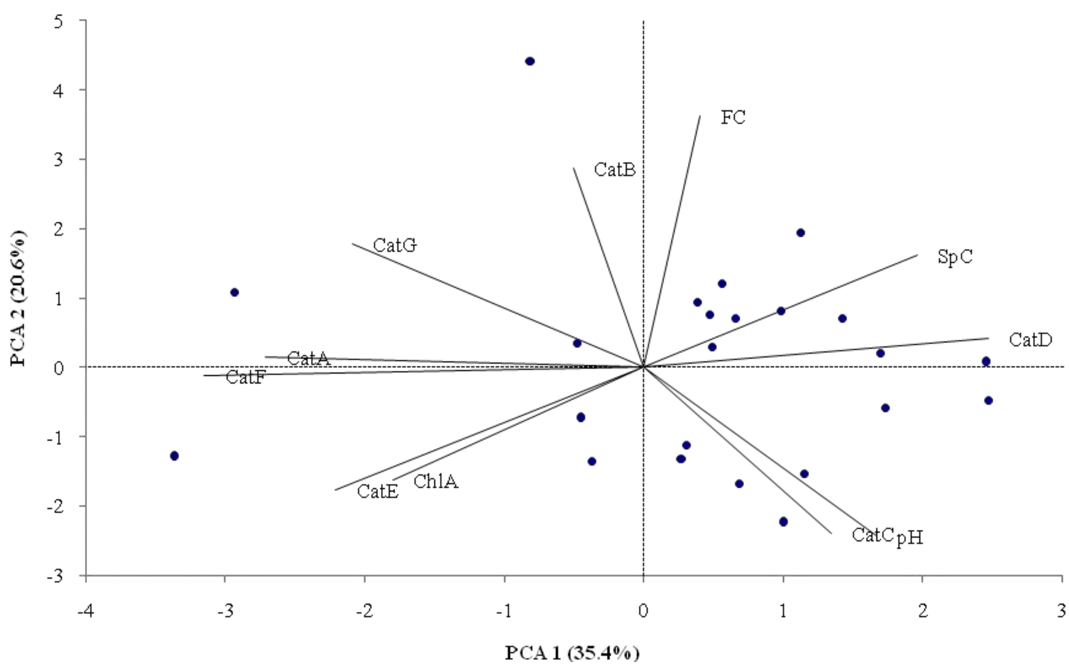


Figure C-36: WQ Panel PC1 vs. PC3

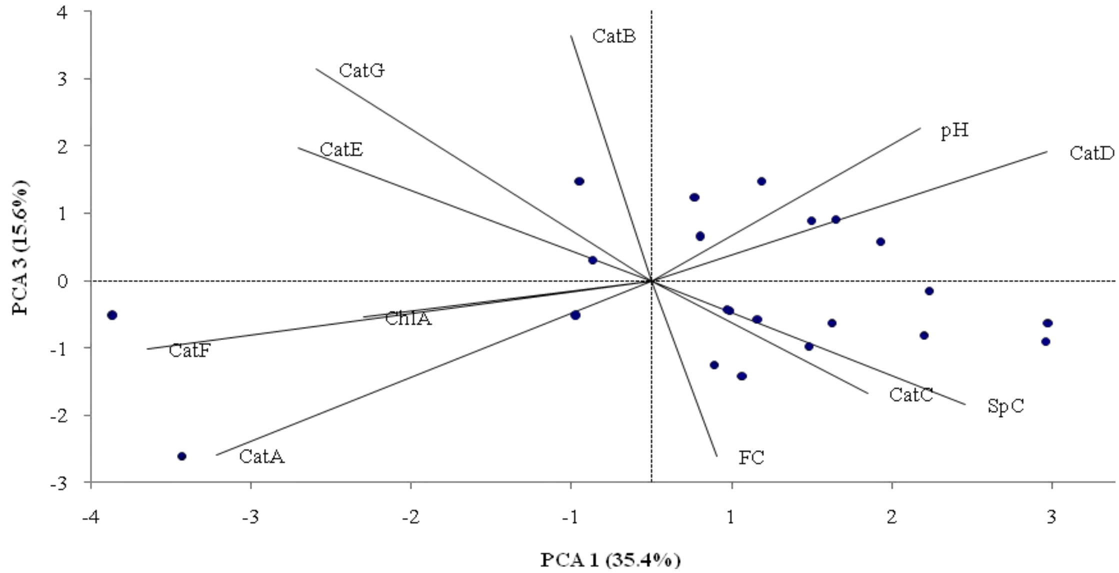


Figure C-37: WQ Panel PC2 vs. PC3

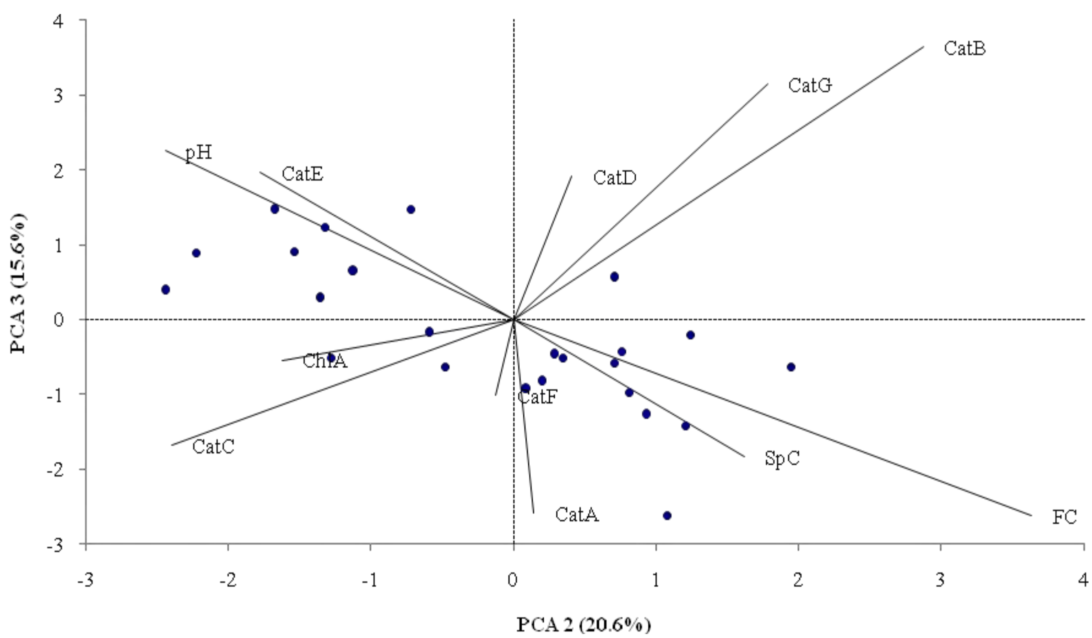


Figure C-38: WQ Panel PC1 vs. PC4

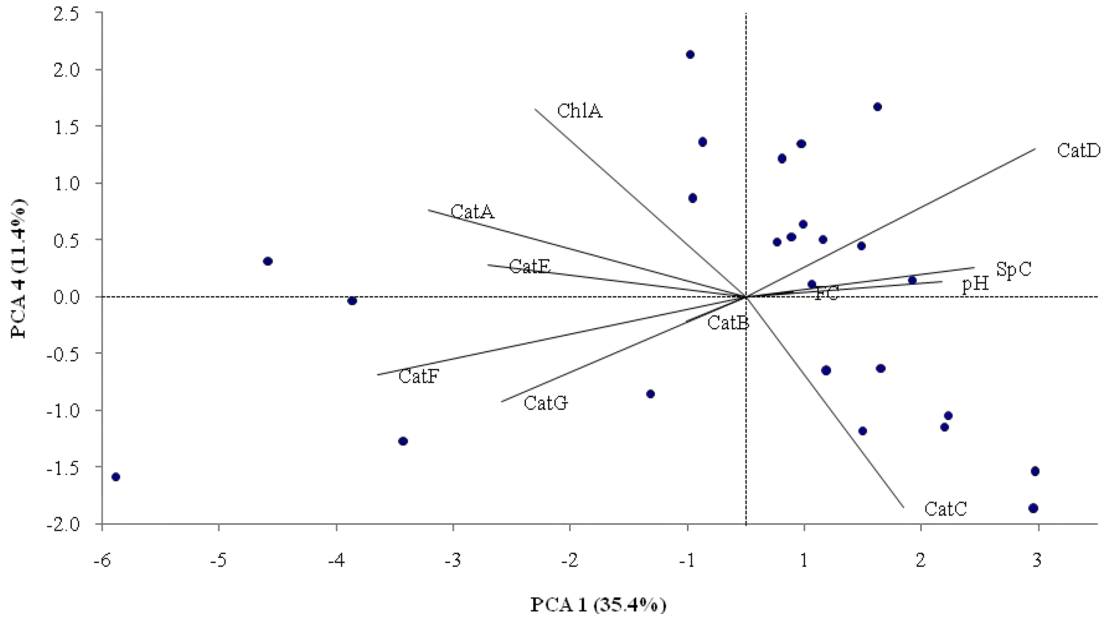


Figure C-39: WQ Panel PC2 vs. PC4

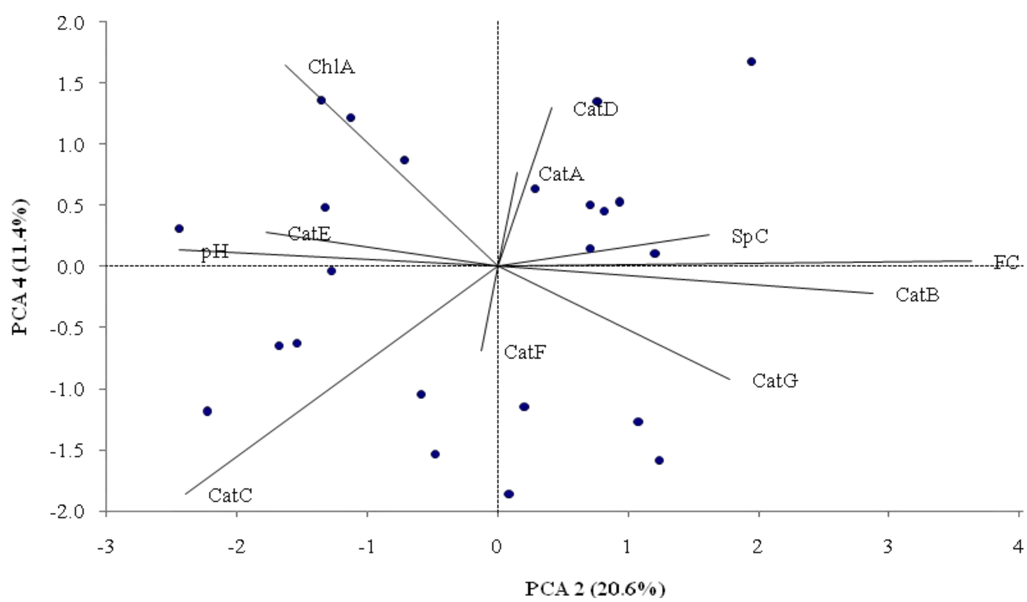
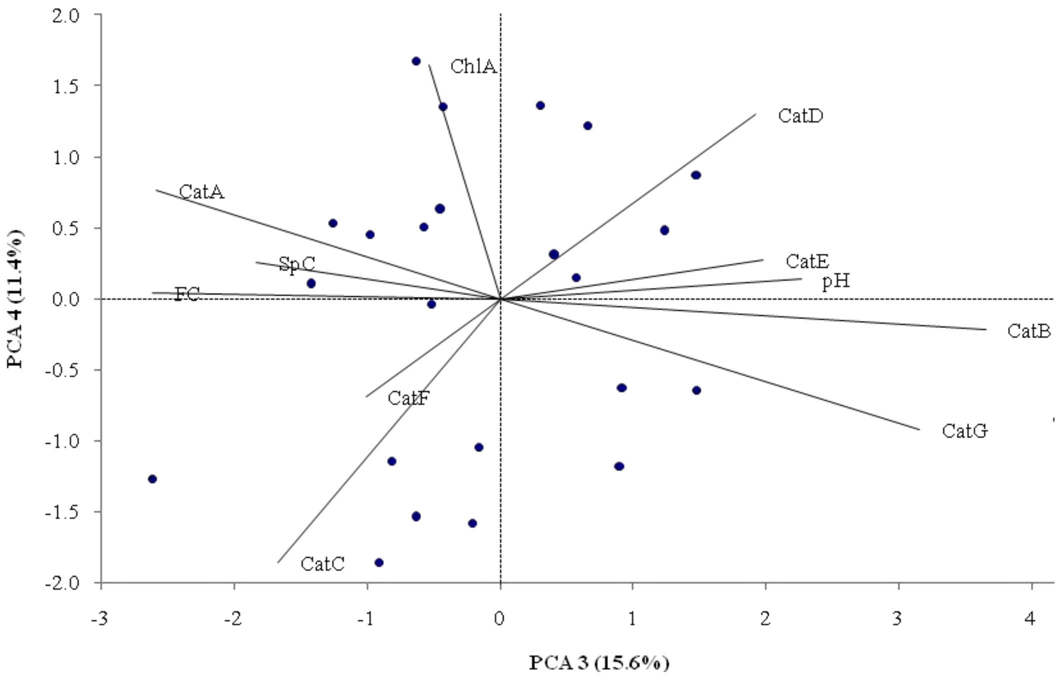


Figure C-40: WQ Panel PC3 vs. PC4



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