ABSTRACT

Title of Document: LAND USE/LAND COVER CHANGE AND ITS IMPACTS ON STREAMS AND ESTUARINE WATER QUALITY IN THE GALVESTON BAY WATERSHED, TEXAS.

Angira Baruah, Ph.D, and 2012

Directed By: Prof. Michael Kearney, Geographical Sciences

The nature of society's relationship with coastal environments is illustrated well by the Galveston Bay watershed in Texas, which is an important economic, recreational, and environmental asset. However, the watershed has been altered by growth in the port of Houston and by human populations and industry. High rates of inter-basin transfer of water was observed from the USGS stream gauging station data for those stations lying within the highly urbanized area with increasing trends in river discharge. Land use and land cover classification for the lower Galveston Bay watershed from 1989-2009 showed an increase in urban growth followed by a decrease in agriculture and forest cover. Land cover data for four selected catchments: Brays Bayou, Greens Bayou, East Fork San Jacinto and West Fork San Jacinto within the Galveston Bay watershed were combined for "space for time-substitution" analysis to increase the number of observations and check for correlations between percent land cover and stream hydrology and stream chemistry

with significant results. Variations in percent urban, forest, pasture and wetlands explained most of the variability in water yield followed by rainfall which had a small but significant effect. Results of the analysis clearly demonstrated increasing water yields and nutrient inputs with increasing urban land use. Population changes explained the increasing trends in water yield for the highly urbanized catchments of Brays Bayou and Greens Bayou. Similarly, highly significant positive relationships were observed between river nutrients and total population for Brays Bayou, Greens Bayou, and the West Fork San Jacinto catchments. Results from this research show that anthropogenic changes in the watershed have a significant impact on the river flow and stream water quality. Continued development and future population growth in the highly urbanized areas near Houston will cause increasing water demand from adjacent watersheds resulting in higher downstream flows in the estuary. Increasing freshwater flow in the estuaries results in higher nutrient loading and Bay stratification. Higher rates of stratification caused by rising temperatures as a result of global warming and larger freshwater flow along with increased nutrient inputs will increase the vulnerability of the Galveston Bay to severe eutrophication during the warm summer months.

LAND USE/LAND COVER CHANGE AND ITS IMPACTS ON STREAMS AND ESTUARINE WATER QUALITY IN THE GALVESTON BAY WATERSHED, TEXAS

By

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Dissertation submitted to the Faculty of the Graduate School of the
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Dedication

To my parents,
Sannu Devi and Ganesh Chandra Baruah

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Table of Contents

List of Tables

List of Figures

CHAPTER 1: INTRODUCTION

ABSTRACT

Coastlines in the United States have developed the highest densities of population, agriculture and industrial growth. The nature of society's relationship with coastal environments is illustrated well by the Galveston Bay watershed in Texas, which is an important economic, recreational, and environmental asset. However, the watershed has been altered by growth in the port of Houston and by human populations and industry. The growing number of users, uses, and the unintended impacts on Galveston Bay strain its ability to maintain the services and opportunities that it has historically provided. An extensive literature review of studies shows significant inter-annual changes in river water quantity and quality over time, which appears to have resulted in large inter-annual changes in estuarine water quality in the Bay. The Galveston Bay receives the second-highest freshwater inflow of any Texas estuary with an annual average of 450 m^3/s. The principal sources of freshwater inflow are the San Jacinto River, Buffalo Bayou and the Trinity River. Most of the freshwater volume to the estuary is contributed by the Trinity River that drains a major portion of the watershed and has the maximum influence on the seasonal distribution for total freshwater inflows to the estuary. On these rivers, several flow gauges have measured increasing base flow to the Galveston Bay from urbanized sub-watersheds primarily due to return flow from treated wastewater. Approximately nine percent of the total inflow volume in the estuary is contributed by the bayou watersheds in the Houston metropolitan area, and this volume is

disproportionate relative to the land area involved. Besides the Trinity and San Jacinto Rivers which mainly contribute nutrients to the Bay, treated and untreated domestic sewage is also released into the water from surrounding areas along with atmospheric inputs contributing to the eutrophic state of Galveston Bay. Another internal source is nutrient release from sediments particularly during parts of the year when sediment-water interactions are most intense in shallow-aquatic systems. Reports suggest that nutrient concentrations in Galveston Bay have decreased since the 1970s along with corresponding decreases in phytoplankton biomass which could be due to a combination of improved waste treatment, altered land use, and impoundments on the principal rivers along with the entrapment of fine-grain sediments. There has been little change over the past three decades in the total amount of Total Suspended Sediments (TSS) in the Bay. There has been significant urban development along the western edge of the Bay and effects of non-point source loadings as a result of increased surface runoff caused by impervious surfaces such as roads and parking lots. This has been a problem that is generating more concern in recent years. It is the goal of this thesis to explore these issues, to investigate their drivers, and to understand the consequences for Galveston Bay.

BACKGROUND

More than three-quarters of the world's human population live in coastal watersheds (Paerl et al., 2003). As a result, human activities have altered the landscape, and coastal eutrophication has become a major global environmental problem (Rabalais et al., 2002). Human population growth and land cover change are two major forces that are reshaping freshwater flows to estuaries worldwide. Besides alterations in freshwater quantity, population growth and anthropogenic activities cause nutrient enrichment in the estuaries through large increases in pollutant discharge from agricultural and urban development of the coastal watersheds (Paerl et al., 2006). As a result of anthropogenic nutrient influxes from adjacent lands, coastal eutrophication is widespread and increasing in the United States (Scavia and Bricker, 2006).

The nature of society's relationship with coastal environments is illustrated well by the Galveston Bay watershed (Fig. 1.1) in Texas. The estuary is an important economic, recreational, and environmental asset; however, the watershed has been altered by growth in the port of Houston and by human populations and industry. The growing number of users, uses, and the unintended impacts on Galveston Bay strain its ability to maintain the services and opportunities that it has historically provided. The Bay is known to be the most productive of all Texas' estuaries with an oyster production that is unsurpassed in the country (about 1,800 metric tons with a value of $8 million), a commercial fishery industry that is one third of the state's commercial fishing income (contributing $99 million from 1994 to 1998) and a recreational

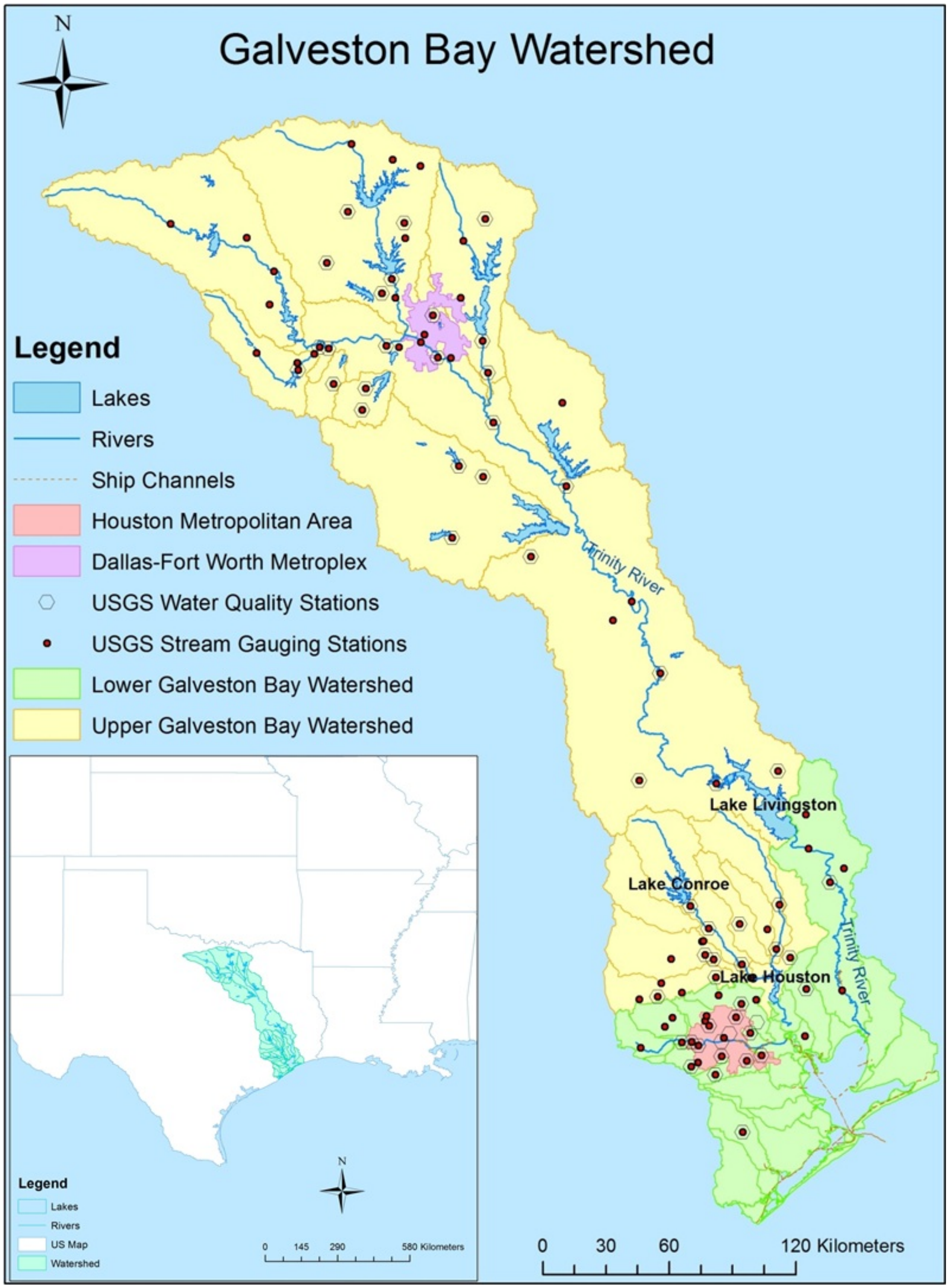


Fig. 1.1 Galveston Bay Watershed with the major rivers, lakes and USGS monitoring stations

fishery that made a gross direct contribution to the local economy of $171.5 million in 1986 (Thronson and Quigg, 2008).

The Houston Metropolitan area is located near the estuary which has been heavily impacted by industrial and municipal development, discharge of pollutants and wastewater effluent, channelization and dredging projects, subsidence, and alterations in bay-water circulation dynamics (Pulich, 2006). The estuary is heavily polluted with wastewater from large cities (Dallas-Ft. Worth and Houston), heavy industrialization along the shore, shallow water and restricted exchange with the Gulf of Mexico, and extensive recreational activities (fishing and boating) by the large adjacent population (Jiann and Presley, 1997). The drainage basin for the Galveston Bay estuary includes 60% of major industrial facilities in Texas (Ornolfsdottir et al., 2004a). The region has exhibited continuous immigration and economic expansion over the past 50 years as a result of the construction of the Houston Ship Channel (Fig. 1.2) and the discovery of oil in the early 20th century (Lester and Gonzalez, 2002). The Bay's population has grown from 3.2 million in 1980 to 4.8 million in 2000 (Pulich, 2006). The current estimate according to Thronson and Quigg (2008) is that about 47% of the total state population (almost ten million people) live within the watershed. More than four million people live in the five counties bordering the Bay using an estimated 5.3 x 10^6 m^3 of freshwater every day (Thronson and Quigg, 2008). The area around the Bay is one of the most densely populated in the United States (Pulich, 2006).

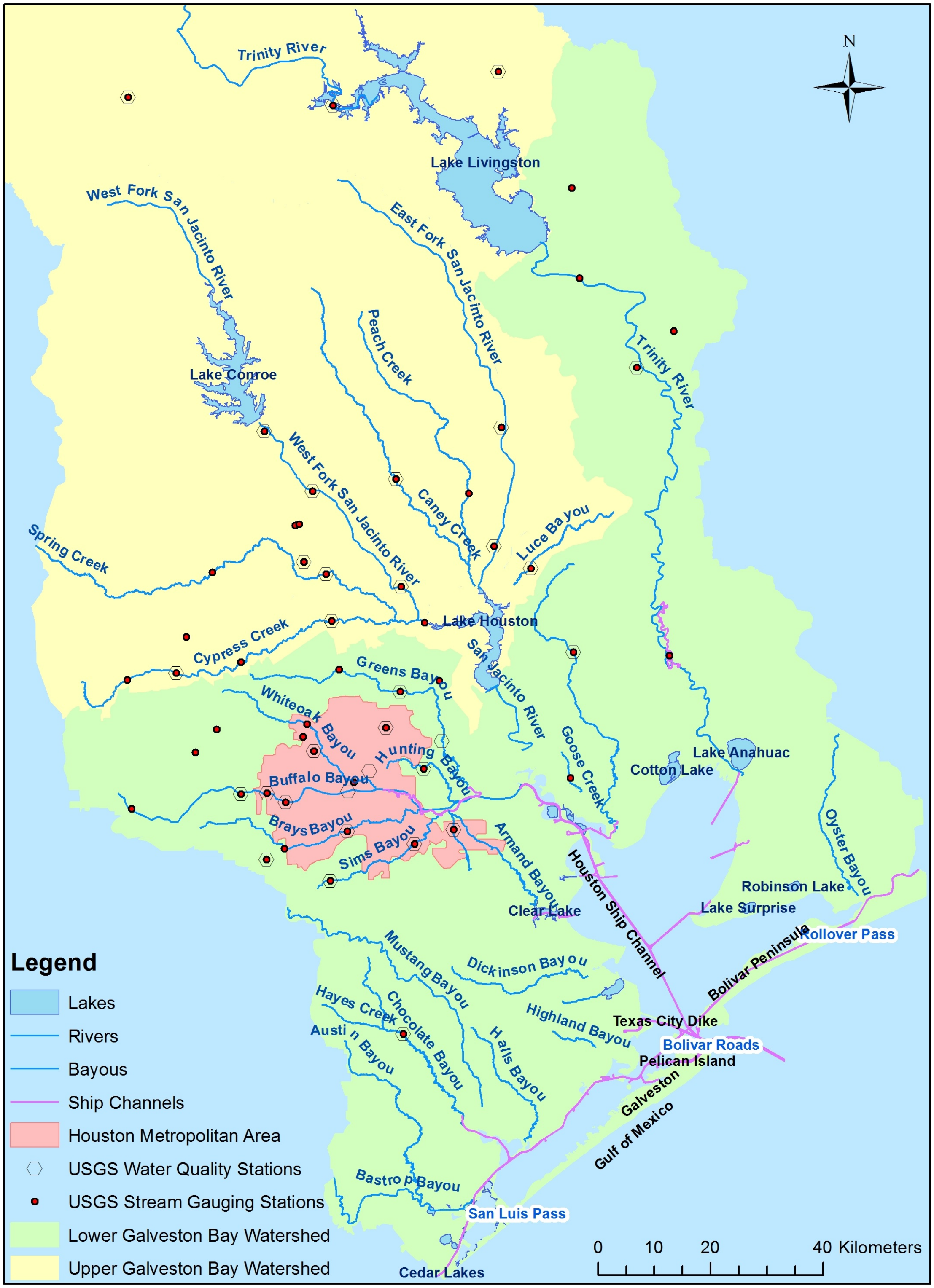


Fig. 1.2 Lower Galveston Bay Watershed with the lakes, rivers and bayous

1.1 Changes in Streamflow

An estuary is defined as a semi–enclosed transitional zone where salt water from the sea mixes with fresh water flowing from rivers and streams. There is nothing more fundamental to the functioning of an estuary than the quantity and timing of freshwater delivery to the mixing zone (Montagna et al., 2002). According to a study by Sklar and Browder (1998), there are basically two types of freshwater alterations that affect nutrient distributions in estuaries: (1) direct watershed runoff leading to eutrophication, and (2) river diversion or channelization that can lead to either eutrophication or nutrient deprivation. Sklar and Browder (1998) also state that primary production is most often directly related to freshwater inputs of nutrients, and although nutrients carried by a river are not always the limiting factor, nutrients generally control total ecosystem metabolism and community structure.

The health of the Galveston Bay is largely determined by the volume, timing and quality of freshwater inflows into the estuary from the surrounding watersheds (Solis and Longley, 1993). The nutrient budget of the Bay is dominated by the nutrients derived from freshwater inflows that account for over 80% of the nutrients reaching the estuary (Armstrong, 1982). The Galveston Bay receives the second-highest freshwater inflow of any Texas estuary with an annual average of 450 m^3/s (Buzan et al., 2009). The principal sources of freshwater inflow are the San Jacinto River and Buffalo Bayou (Fig. 1.2) to the west and northwest and the Trinity River to the northeast (Powell et al., 2003). Most of the freshwater volume to the estuary is contributed by the Trinity River (Powell et al., 2003) that drains a major portion of the watershed. Its water exits the Bay primarily by flowing down the eastern shore of

Trinity Bay and then South around Smith Point (Fig. 1.3) and across Redfish Bar while the waters of the San Jacinto River and Buffalo Bayou flow down the western shore of the Galveston Bay between the shoreline and the Houston Ship Channel (Powell et al., 2003).

The seasonal inflow distribution for the Bay is typified by peak springtime inflows in May followed by minimum inflows in August (Solis and Longley, 1993). Seasonal inflow distributions for the Trinity River basin, the San Jacinto River basin and the surrounding coastal watersheds are distinct from each other, and the seasonal distributions for the San Jacinto River basin and for the coastal basins exhibit significantly less seasonal variability than the Trinity River (Solis and Longley, 1993). The Trinity River has the maximum influence on the seasonal distribution for total freshwater inflows to the estuary (Solis and Longley, 1993). The normal pattern of the Trinity River flow is composed of an annual "flood", the spring freshet, and an annual "drought", the summer low flow season (Ward and Armstrong, 1992). There is considerable inter annual variability in the river flow with some years exhibiting a pronounced and extended freshet, while in others the spring freshet may be totally absent (Ward and Armstrong, 1992).

There have been reports (Solis and Longley, 1993) that have stated that several USGS gauges in the Galveston Bay drainage basin have shown increasing stream flow trends from 1968 to 1987. According to the Galveston Bay National Estuary Program (GBNEP, 1994) report, several flow gauges have measured increasing base flow to the Galveston Bay from urbanized sub-watersheds primarily

Fig. 1.3 Galveston Bay System with the bay segments and the Houston Ship Channel

due to return flow from treated wastewater. The analysis in the report (GBNEP, 1994) demonstrated at Main Street showing a base flow component of over 0.23 m^3s^{-1} compared to no permanent base flow prior to 1955. This was basically due to a wastewater return flow produced by a population of around 25,000 people primarily from the City of Houston Southwest Plant (GBNEP, 1994). The report also states that similar trends have been observed in several other urbanized bayous in the Houston area, most of which drain into the Houston Ship Channel. Approximately nine percent of the total inflow volume in the estuary is contributed by the bayou watersheds in the Houston metropolitan area (Fig. 1.2), and this volume is disproportionate relative to the land area involved (Lester and Gonzalez, 2002). According to the Galveston Bay Estuary Program GBEP-T7 (Lester and Gonzalez, 2002) report, river discharge from these watersheds during extremely wet years may increase by 60 percent compared to average years. The effects of municipal and industrial return flows can serve as an important component of the typical four-month summer drought flow (Lester and Gonzalez, 2002). Another study (Pacheco et al., 1990) reports that industrial process wastewater alone was equivalent to approximately 20 percent of the average annual summer drought flow and roughly 100% of the lowest summer drought flows on record. Most of this return flow originates as water supply from Lake Livingston (Fig. 1.1) and Lake Houston (GBNEP, 1994). Some fraction of this supply is groundwater acquired for drinking water and discharged as treated wastewater which represents an external source of freshwater to Galveston Bay (GBNEP, 1994). The bulk of this wastewater returns to the Bay via the upper Houston Ship Channel (Fig. 1.3), making the Ship Channel a larger source of freshwater inflow to the Bay during extreme low-flow conditions than historically occurred (GBNEP, 1994).

There have also been conflicting reports regarding the changes in freshwater inflows to the Bay. A study by Solis and Longley (1993) analyzed Trinity River inflow along with total freshwater inflow from 1941 to 1987 and found that both total inflow and inflow from the Trinity River remained unchanged over this 46-year period. The average for the total inflow volume during this period was 393 m^3s^{-1} (Lester and Gonzalez, 2002). Another study (Criner and Johnican, 2001) analyzed the total surface water inflow from the Trinity River from January 1977 through May 1999 and found that there was no clear evidence of long term or short-term trends in the flow, although periodicity was evident. It was also not clear as to what effect, if any, the cyclical nature of the flows have on Bay productivity (Criner and Johnican, 2001). This study states that looking at the Trinity Bay map, it is clear that the Trinity River freshwater flow has the potential to significantly impact the brackish water areas but the effect of these freshwater flows on the Bay productivity has yet to be demonstrated. Solis and Longley (1993) concluded that no inflow trends, increasing or decreasing were found for the time series representing total freshwater inflows to Galveston Bay, or for the Trinity River time series. They attributed the increasing trends from 1968 to 1987 for the USGS stations to a variety of reasons, including reduced consumptive use due to conservation practices, increases in groundwater return flows, increases in surface runoff due to greater impervious cover, and inter-basin transfers (Solis and Longley, 1993).

1.2 Changes in Water Quality

The majority of the US population lives within 50 miles of the coastline, contributing large anthropogenic inputs of nutrients and trace contaminants to estuaries (Santschi, 1995). Excessive nutrient enrichment of estuaries enhances phytoplankton growth and biomass and increases the rate of organic matter loading, ultimately resulting in eutrophication (Ornolfsdottir et al., 2004b). The potential for nutrient limitation in aquatic ecosystems (both marine and freshwater) is usually governed by the concentrations of nitrogen and phosphorus (combined dissolved organic and inorganic forms) and the relative ratio of these two major nutrients (Ornolfsdottir et al., 2004b).

The Galveston Bay is one of the largest industrialized coastal embayments along the US coastline receiving substantial inputs of urban and industrialized waste waters from the Houston and Dallas-Fort Worth metropolitan area (Santschi, 1995, Fig. 1.1). High concentrations of phosphorus and nitrate in these waste waters help to support a productive fisheries industry on one hand and cause eutrophication in the Bay on the other, leading to hypoxic events along with toxic and nuisance algal blooms (Santschi, 1995). The two major rivers—the Trinity and San Jacinto mainly contribute nutrients to the Bay (Santschi, 1995). Besides these sources, treated and untreated domestic sewage is also released into the water from surrounding areas along with atmospheric inputs contributing to the eutrophic state of Galveston Bay (Santschi, 1995). Another internal source is nutrient release from sediments particularly during parts of the year when sediment-water interactions are most intense in shallow-aquatic systems (Santschi, 1995). According to Santschi, (1995), the Galveston Bay receives annual amounts of anthropogenic nutrients ranging from 3.7 to 12.5 x 10^6 kg of phosphorus and 23-50.5 x 10^6 kg of kjeldahl nitrogen, depending on the source of data. The primary sources of nutrient inputs by rivers are listed in Table 1.1. Nutrient inputs in the Galveston Bay are large overall compared to other estuaries (Santschi, 1995). The Bay is turbid with Total Suspended Sediments (TSS) ranging from 10 to 500 mg/l, and large variations in concentrations of different nitrogen species are observed in the Galveston Bay, although little is known about the causes of these variations (Santschi, 1995). The factors that control dissolved nitrogen species include nitrification/denitrification reactions, nitrate and ammonia regeneration from dissolved and particulate organic forms of nitrogen, processes occurring in freshwater reservoirs in the watersheds, and overflows of storm sewers after heavy rainfalls (Santschi, 1995).

Santschi's (1995) study on the seasonality of nutrients in the Galveston Bay found that nitrate concentrations in the water appear to be mostly regulated by freshwater inputs while phosphorus concentrations in the Bay vary seasonally and are higher than in many other estuaries. Phosphorus maxima in the estuary occur regularly in September during low river flow at the mid-bay station (Smith Point/Eagle Point), and the Trinity Bay and Upper Bay/Buffalo Bayou station, suggesting the internal sources of P from sediments (Santschi, 1995). Nutrient concentrations in the East and West Bay (Fig. 1.3) are considerably lower and do not significantly correlate with temperature and salinity as those in the mid and upper regions of the Bay (Santschi, 1995).

	Sources of Nutrient Inputs by Rivers	Nitrogen (%)	Phosphorus (%)
1	Waste Water Treatment Plants	50	35
2	Industrial Facilities	30	40
3	Agriculture	10	10
4	Other Upstream Sources	10	10

Table 1.1 Primary Sources of Nutrient Inputs by the *Trinity* and *San Jacinto* rivers to the Galveston Bay (Santschi, 1995).The *Trinity River* drains an area of 4.44 x 10^4 km^2 and is responsible for the majority of the average total inflow into Galveston Bay. The *San Jacinto* watershed has an area of about 1.02 x 10^4 km^2 and contributes to the remaining flow along with runoff from coastal urban watersheds.

There have been reports (Jensen et al., 1991; Ward and Armstrong, 1992) stating that nutrient concentrations in Galveston Bay have decreased since the 1970s along with corresponding decrease in phytoplankton biomass. The following is a summary of four main water quality indicators and their historical trends:

1.2.1 Nitrogen (N)

Nitrogen is a critical macronutrient directly contributing to coastal eutrophication (Fisher et al, 2006). Increases in human populations in the Galveston Bay watershed has led to increases in the amount of nitrogen introduced in point source discharges (Jensen et al., 1991). Increased urbanization and more intensive agricultural activity are the other two main causes that lead to an increase in total nitrogen in the Bay, while on the other hand reservoir development results in the removal of nitrogen that would otherwise have entered the Bay (Jensen et al., 1991). Reservoir development and water supply systems in the watershed have resulted in shifts in the points at which freshwater and nitrogen are introduced into the Bay, and some nitrogen introduced to the Bay is also removed in the course of routine maintenance dredging (Jensen et al., 1991).

Jensen et al., (1991) undertook a study that involved the analysis of the variation in the major nitrogen loads to the Bay system during 1971-1990 working with a range of data sources. All of the information in this paragraph is drawn from that paper. The data included the City of Houston's (CoH) wastewater treatment system data, studies of the historical and projected freshwater needs of the Houston metropolitan area, and available routine monitoring data from the major tributaries to the system. Also included in the analysis were estimates of nitrogen loads in earlier periods. The authors observed that over the period 1978 to 1990, the distribution of the TN load changed substantially with highly soluble nitrate-N representing three percent of the TN at the beginning of the period and growing to over 86% towards the end. For industries along the Houston Ship Channel (HSC), the average, flow-weighted TN concentration was 8.8 mg/l, which was considerably lower than that for secondary treated domestic wastewater. The study found that industries along the HSC represented roughly 70% of the total Bay industrial flow, while the TN load during the 1980's was approximately 6810 kg/day. A third step in the study involved estimating loads at decade intervals back to 1980, using the population of the City as a scaling factor for domestic and industrial loads prior to 1970. Results of this analysis showed a fairly dramatic increase in the average annual TN load corresponding to the population growth in the area, with the highest growth occurring during the period 1940-1970. There was substantial growth during the 1970's but improvements in wastewater treatment offset this growth. Increases in inter-basin transfer and points where water enters the Bay was another change that occurred over time.

According to the study, about 0.284 x 10^6 m^3/d of Brazos River water added to the western portion of the Bay along with roughly 0.379 x 10^6 m^3/d of groundwater. At the same time, on the order of 1.14 x 10^6 m^3/d of Trinity River water was diverted to the western side of the Galveston Bay, and these inter-basin transfers enter as domestic and industrial return flows. Navigational channel dredging contributes to TN removal—around 500,000 kg/yr of TN are removed by dredging the HSC above Morgan's point (Fig. 1.3). Lake Livingston began filling in 1972, causing the biggest change in the Galveston Bay system and growth in the Dallas/Ft. Worth metropolitan area was producing a substantial increase in the TN concentration of the Trinity River prior to 1972. Average TN concentration for the Trinity River at Crockett (the last gauge before Lake Livingston) during the period 1972-1988 was 4.14 mg/l, which is more than four times as high as undeveloped background conditions. The average TN concentration for the station at Romayor (immediately below Lake Livingston) was 1.07 mg/l for the same period, which is a roughly 75% reduction as a result of the Lake effect (Jensen et al., 1991). There was also a similar occurrence with Lake Houston, although the reductions appeared to be only on the order of 50%, reflecting a much smaller lake. As a result of these removals by reservoirs, the TN load to the Bay probably peaked in 1971.

Another report (Ward and Armstrong, 1992) has documented a decline in nitrogen loads since around 1970. In the early 1970's reductions in industrial nitrogen loads began to be implemented sooner than those for municipal discharges, and the reductions were probably much greater than those of domestic discharges. The industrial nitrogen load was estimated to be about one-third of the domestic load during that time, and there has been a decline in N loading from the rivers due to a combination of improved waste treatment, altered land use, and impoundments on the principal rivers along with the entrapment of fine-grain sediments. As a result, total inorganic nitrogen concentrations range up to about 0.2 mg/l in the lower Bay, 0.2-0.5 in the upper Bay and as much as an order of magnitude greater in the upper Houston Ship Channel. Ward and Armstrong (1992) document the decline in nutrient concentrations throughout the Bay since the 70's with total ammonia N on the order of 0.1 mg/l per year and total nitrate on the order of 0.01 mg/l per year. These reductions were a consequence of decreased waste loads, due to advanced waste treatment and decreased loadings in the inflows, perhaps due to reservoir entrapment or altered land uses. Guillen (1999) observed ammonia levels to have declined throughout the Bay system; however there has been an increase in total inorganic nitrogen (TIN = nitrate + nitrite + ammonia) along with increasing levels of dissolved oxygen in many tributaries.

According to the GBEP-T7 (Lester and Gonzalez, 2002) report, very high values for ammonia greater than 10 mg/l were recorded in the Houston Ship Channel, Buffalo Bayou, Cedar Bayou and Vince Bayou (Fig. 1.3). Ammonia concentrations in the Galveston Bay ranged from less than 0.1 mg/l to 39 mg/l, with high concentrations in the Houston Ship Channel and Buffalo Bayou occurring between 1972 and 1983 while extreme values were recorded from Cedar Bayou in July 1987 and from Vince Bayou in 1986 and 1998. The analysis showed a pattern of increasing concentrations in the early 1970's, followed by a high and fluctuating period that ended around 1983 after which it dropped significantly, continuing to remain low. According to the GBEP-T7 (Lester and Gonzalez, 2002) report, the declines in ammonia were related to changes in the secondary and tertiary phases in wastewater treatment facilities. As for the nitrate concentrations in the Bay, the general trend from 1969 to 1994 was an increase throughout most of the Bay, with the exception of West Bay (Lester and Gonzalez, 2002). There are no accounts of nitrate trends in East Bay, but the Houston Ship Channel exhibited increasing nitrate concentrations, which may be due to the move by most point sources to nitrify the ammonia they previously discharged (Lester and Gonzalez, 2002). Nitrate concentrations began to decline after peaking in 1989-1990, with a typical pattern of high spring concentrations.

1.2.2 Phosphorus (P)

Phosphorus serves as an important nutrient since it is required for the synthesis of genetic material and energy compounds (Parsons et al., 1984). Occurring in natural waters in the form of orthophosphate and organic phosphorus, it is mainly associated with fertilizer runoff and treatment plant effluent (Newell et al., 1992). According to the GBEP-T7 (Lester and Gonzalez, 2002) report, the total phosphorus concentrations recorded for Galveston Bay range from less than 0.1 mg/l to greater than 12.9 mg/l. Bay locations that had the highest values exceeding 6 mg/l were the Trinity Bay, the Houston Ship Channel, Buffalo Bayou, Armand Bayou and Moses Bayou (Lester and Gonzalez, 2002, Fig. 1.3). These values are very high and attempts to verify them were unsuccessful. The high values ranged from 1972 to 1990, and they were obtained in all seasons, and monthly averages of total phosphorus from Bay samples and its tributaries show a declining trend (Lester and Gonzalez, 2002). The GBEP-T7 (Lester and Gonzalez, 2002) report documents a sharp increase in the early 1970's followed by a 15-year period of high but variable concentrations followed by a sharp drop in 1990.

Ward and Armstrong, (1992) indicated that total phosphorus increased from average values on the order of 0.1 mg/l at the inlets of Galveston Bay to 1.0 or greater in regions of waste discharges, especially the upper Houston Ship Channel. A predominant declining trend was observed in total phosphorus in the open Bay and the Houston Ship Channel (Ward and Armstrong, 1992).

Guillen (1999) on trends in nutrient levels in the Galveston Bay states that overall trends in nutrient and chlorophyll *a* levels suggest that phosphorus levels have been declining over time; however, differences exist between open Bay and larger tributaries. The study observed that phosphorus levels continued to decline in urbanized and major tributaries and rates of decline in open Bay areas are lower and/or have leveled off.

1.2.3 Chlorophyll *a* (Chl *a*)

Chlorophyll *a* (Chl *a*) is the green pigment used by plants during photosynthesis (Parsons et al., 1984) and is sampled from the water column to monitor phytoplankton biomass in the Bay. Drifting with the motion of the currents, phytoplankton serve as food for higher trophic levels such as oysters, shrimp, fish and birds. Hence, a shortage of phytoplankton production in the estuaries could deplete the food supply for these primary consumers in the Galveston Bay. On the other hand, excessive phytoplankton blooms caused by an increasing supply of nutrients from rivers, particularly during wet time periods, could lead to hypoxia as a result of high oxygen demand through respiration and decomposition. Hence, chlorophyll *a* serves as an important indicator of Bay water quality in productive estuaries like the Galveston Bay. According to the GBEP-T7 (Lester and Gonzalez, 2002) report, there are some possible areas of high chlorophyll *a* abundance: Clear Lake, Black Duck Bay and Trinity Bay (Fig. 1.3) near the Cedar Bayou Generating Station outfall. In low salinity regimes, blue-green and green algae dominate, whereas higher salinity sites are dominated by diatoms.

Based on prior investigations, the GBEP-T7 (Lester and Gonzalez, 2002) report provides evidence of an increase in chlorophyll *a* from the late 1950s to the 1970s. Since the 1970's there has been a declining trend in the measured concentration of chlorophyll *a* from routine monitoring data for the Bay (Ward and Armstrong, 1992), and mean chlorophyll *a* concentration fell by more than 75 percent throughout much of the Galveston Bay from 1972 to 1998. Average monthly chlorophyll *a* concentration for the Bay including the tidal tributaries in 1972 was 28.5 $\mu g\ L^{-1}$ while the calculation for 1998 yielded an average concentration of 3.6 $\mu g\ L^{-1}$ indicating that phytoplankton biomass levels are lower than levels typical of Galveston Bay in the 1950s (Lester and Gonzalez, 2002).

The GBEP-T7 (Lester and Gonzalez, 2002) report states three potential hypotheses to explain the observed decline in chlorophyll *a* concentration in the Galveston Bay waters: First, the reduction in phytoplankton populations could be due to improvements in effluent discharges after 1970 that permitted a resurgence in zooplankton populations. There are not enough data available to confirm such a temporal change in zooplankton populations, but populations of planktivorous fishes have an increasing trend. Second, the decline of primary production and phytoplankton concentration could be due to the declining concentration of a limiting nutrient (e.g., P) as a result of curtailed point source loadings from permitted discharges, trapping of Trinity River nutrients by the dam on Lake Livingston, and reduced fertilizer use in the upper watershed due to changes in land use. Third, an increased population of filter-feeders such as oysters, clams or menhaden in the Bay could result in the decline in phytoplankton population. The GBEP-T7 (Lester and

Gonzalez, 2002) report, states that in selected areas of San Francisco Bay, the unintentional introduction of the Asian marine clam (*Potamocorbula amurensis*) resulted in a ten-fold reduction in phytoplankton levels in two years. This clam is not found in Galveston Bay, but a study by Powell et al. (1994) identified substantially higher oyster reef area in 1992 than was documented for the late 1960's and early 1970's.

One investigation (Guillen, 1999) suggests that declining phosphorus levels may have contributed to decreased phytoplankton biomass. There was a positive correlation between declining phosphorus and chlorophyll *a* in the Bay, and most portions of the Galveston Bay system do not appear to be nitrogen-limited, whereas phytoplankton populations are more regulated by fluctuations in phosphorus levels. However, Ornolfsdottir et al., (2004a), observed that the phytoplankton community in the Bay was not usually phosphate-limited. According to Ornolfsdottir et al., (2004a), all major phytoplankton groups increased in biomass following nitrate additions, but diatoms increased in biomass at a faster rate than other groups, shifting the community composition toward higher relative abundance of diatoms.

1.2.4 Total Suspended Sediments (TSS)

Total Suspended Sediments (TSS) in the Bay refers to the concentration of suspended solids in water consisting of both organic and inorganic particles. Rivers draining the watershed acquire sediments through erosion and resuspension, and the rivers transport the sediments to the Bay, leading to deposition and forming of deltas such as the Trinity River Delta (Lester and Gonzalez, 2002). The Bay receives most of the riverine sediments under flood conditions, whereas another source of sediment reaching the Bay through various tributaries is the clearing of land prior to urbanization (Lester and Gonzalez, 2002). Shoreline erosion, particularly where the shoreline protrudes into the Bay, also releases sediment into the Bay, and wind and waves cause bottom resuspension making the estuary turbid, particularly during severe storm events (Lester and Gonzalez, 2002). Another factor in resuspension of bottom sediments is intensive trawling and dredging activity in the Galveston Bay (Lester and Gonzalez, 2002; T. M. Dellapenna, pers comm.). Dellapenna et al., (2006), estimated that for Trinity Bay, on average an area equivalent to at least 100 % of the Bay bottom is trawled annually for shrimping and that the suspended sediment load created by shrimp trawling was equivalent to 200-267% of the suspended sediment being derived from the Trinity River.

According to the GBEP-T7 (Lester and Gonzalez, 2002) report, another source of sediment entering the Bay through the tidal passes is the sediment plume from the Mississippi River that is carried westward by longshore currents. Suspended sediments are known to transport pollutants, and upon deposition become sinks for many pollutants (Lester and Gonzalez, 2002). On the other hand, large quantities of TSS can have a deleterious effect on biological communities as they block sunlight which is essential for photosynthetic activity. In their study, Ward and Armstrong (1992) observed that TSS concentrations generally increase towards point of inflow. There are turbidity maxima also in Bolivar Roads and in East Bay near Rollover Pass (Fig. 1.3). There is also a vertical gradient in TSS which decreases upward (Ward and Armstrong, 1992), probably as a result of bottom resuspension. This study (Ward and Armstrong, 1992) observed a declining trend throughout the Galveston Bay and its tributaries with virtually all open bay segments showing either probable or possible negative trends over time (1960-1990).

The GBEP-T7 (Lester and Gonzalez, 2002) report summarized the results of the TSS analysis from 1969 to 1999. This indicates that on the whole, TSS has remained stable throughout the period of record apart from a slightly elevated period that was observed from 1972-1975. Several of the highest readings recorded during this period represented sample points receiving runoff from the Houston Metropolitan area and hence may reflect high sedimentation rates commonly associated with urbanization. The report, concludes that there has been little change over the past three decades in the total amount of TSS in the Bay.

1.3 Land Use/Land Cover Change

Land use/land cover is one of the most significant determinants of water quality (Griffith et al., 2002) as well as stream hydrology. The effects of environmental change are experienced most in estuaries not only because the rate of change in human activities on the land surrounding estuaries is highest in the coastal areas, but also because rivers deliver to estuaries the products of environmental change occurring 100’s to 1000’s of kilometers distant (Hopkinson, et al., 1995). Land cover change from forest to agricultural and urban areas, due to increasing human population have resulted in greater freshwater flows and increased fluxes of particulates, nitrogen (N), and phosphorus (P) from watersheds to estuaries and coastal areas (Fisher et al., 2006). GBEP-T7 (Lester and Gonzalez, 2002) report, suggested that significant urban development in the Galveston Bay watershed is responsible for enhanced terrestrial inputs to Galveston Bay, and the following is a brief account of the changes in human activity and land use in the watershed.

Dating back to the late 1800's agricultural production was the dominant land use of the coastal prairies. The arrival of a group of Japanese to farm rice in Harris, Galveston and Brazoria counties after 1900 introduced cultivation methods that revolutionized farming practices. The Japanese cultivation methods were also employed to establish large citrus farms in many parts of the western side of the Bay. After 1900, increasing quantities of shell, soil and sand resources were used for the construction of roads and buildings. River sand from the San Jacinto and Trinity rivers was made available by the hydraulic dredge. The mining of bank sand from ancient river tributaries gave rise to "sand pits" creating new pond habitats and wetlands on the coastal prairies. Following World War II, upon their return men left the farms and went to work for industries around Galveston Bay.

Oil production came to Galveston in the early 1900's and the growth of the petroleum industry led to changes of land use in and around Galveston Bay. With the demand for petroleum during World War I, lumber barons were investing their fortunes in drilling for oil, and cattlemen who owned large acreage of rangeland began leasing to oil companies. The construction of the first oil refinery along the Houston Ship Channel on Buffalo Bayou began in 1918, and by 1927 eight oil refineries were in operation on the channels in Galveston Bay. New oil refineries were built after 1930 on the upper reaches of the Houston Ship Channel and on the southwestern shore of the Bay at Texas City. The growth of the petroleum industry in the early 20th century was the beginning of a trend that led to the highest concentration of refineries and petrochemical plants in the world and a very high concentration of oil and gas wells in and around the Bay. Increased industrial and residential growth resulted in increased use of groundwater that caused land subsidence and taxed the limits of aquifers (Lester and Gonzalez, 2002).

There is not much literature available documenting historical trends in land cover change in the Galveston Bay watershed. The major land use categories in the watershed are developed upland, which includes industrial and municipal land use, cultivated upland, and undeveloped lands which include uplands, wetlands and transitional lands (Lester and Gonzalez, 2002).

Based on the information derived from the GBEP-T7 (Lester and Gonzalez, 2002) report, there is extensive residential and commercial use of coastal land in the Galveston Bay watershed. Many industries and shipping concerns located on the Houston Ship Channel are concentrated in the channel area. There has been significant urban development along the western edge of the Bay while the lands east of Trinity and north of West Bay are primarily rural. Suburban and industrial development is interspersed with grazing and agricultural operations in the western shore of the Bay. The report also states that the effects of non-point source loadings as a result of increased surface runoff caused by impervious surfaces such as roads and parking lots has been a problem that is generating concern in recent years.

There are five Texas counties surrounding the Bay—Brazoria, Chambers, Galveston, Harris and Liberty and the following information is summarized from Lester and Gonzalez, 2002. Refining and petrochemical industries are most prominent in the eastern portion of Harris County around the Houston Ship Channel. Galveston

County is highly urbanized where land available for development is limited due to development and natural barriers. Land use in Chambers County is primarily agricultural, with rice and soybean as the main agricultural crops, but it also has some petrochemical plants near the border with Harris County. Large areas of Chambers County have been reserved for conservation and recreational parks, and most parts of Brazoria County are rural with a few medium sized communities—large areas are under conservation and recreation. Among the five counties, Liberty County is the fastest growing county with land use primarily in ranching and agriculture. With the increase in Houston's population, development has moved beyond Harris County, and Liberty is now experiencing suburban development. Each of the five counties has agricultural land use, though it is more prominent in Liberty and Brazoria counties with livestock grazing and crop production being the primary activities.

1.4 <u>Changes in Population Growth</u>

The Galveston Bay is adjacent to one of the most urbanized and industrialized areas in the U.S (Lester and Gonzalez, 2002). Approximately four million people reside in the five counties surrounding Galveston Bay (Brazonia, Chambers, Galveston, Harris and Liberty Counties), among which Harris County remains the most populous in the state with 3.4 million people (Fig. 1.4). The land around the Bay has become increasingly urbanized over the years, and population growth is expected to continue in the region. As per the GBEP-T7 (Lester and Gonzalez, 2002) report, report, the average population density in the five-county area is 211 persons per km^2 with Harris County (760 people per km^2) being the most densely populated and Chambers County (17 people per km^2) the most sparsely populated county. Out of the

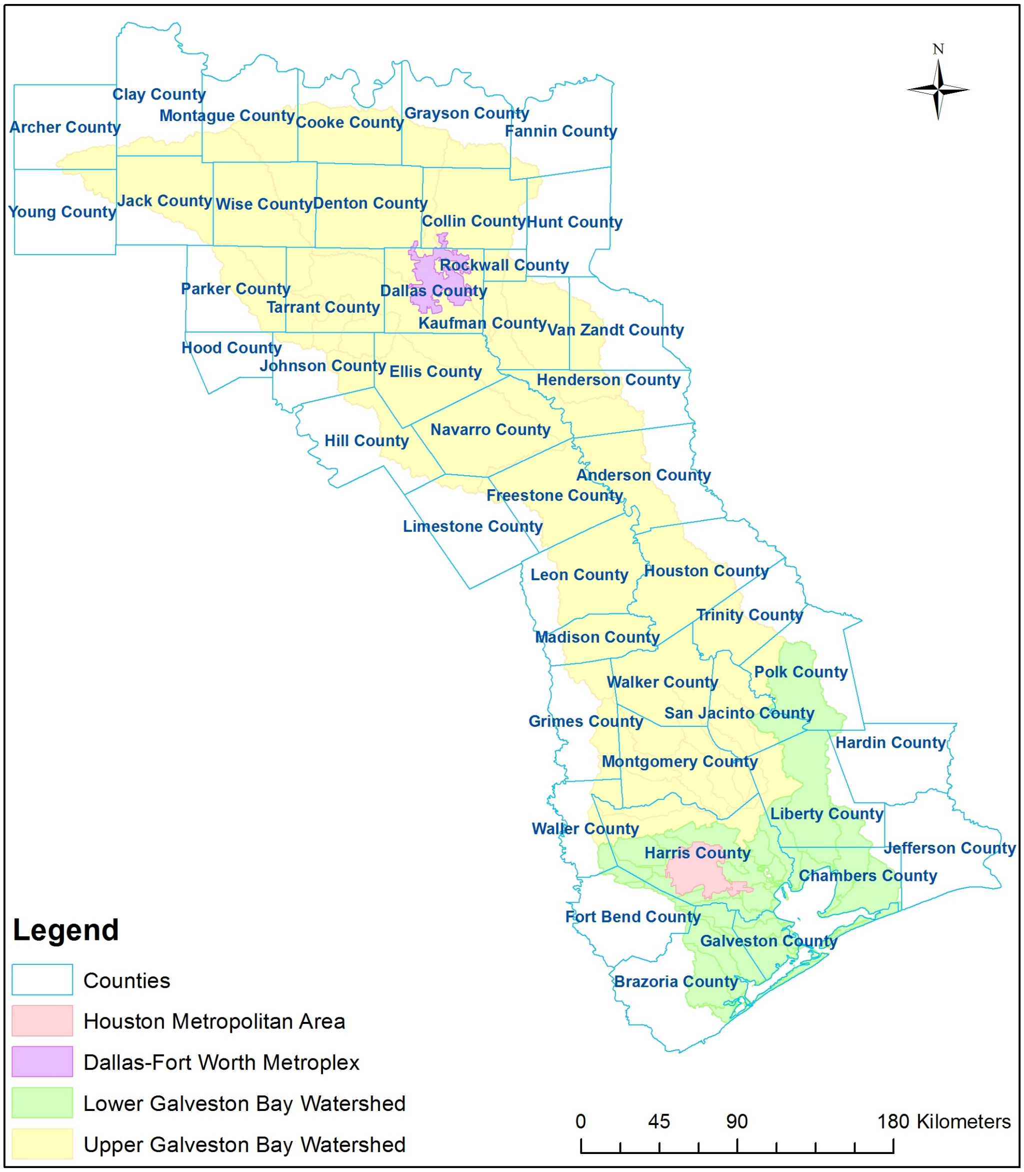


Fig. 1.4 Counties lying within the Galveston Bay Watershed

4 million people in the five-county area, around 20 percent of the population lives within a two-mile buffer zone around the Bay and its tidally influenced tributaries, and over the last 50 years the region has exhibited continuous immigration and economic expansion. Much of the growth in this area has been attributed to the construction of the Houston Ship Channel and the discovery of oil in the early part of

the twentieth century, and growth of the Houston metropolitan area as a major population and industrial center after World War II, with huge population increases during the 1970s and 1980s. A large part of Houston's population growth is due to immigration from within and outside the US, and the strength of the region's economy and its ability to provide jobs has continually attracted new residents from national and international sources.

1.5 Proposed Research

Indications of changes in stream flow, stream chemistry, bay water quality, and land cover change along with increases in population growth make the Galveston Bay watershed an interesting case study. Hence, this watershed has been selected as a study area for the proposed research to understand the interrelationships between the physical environment and human activity. The only current land cover information for the entire Galveston Bay watershed is available from the 2006 National Land Cover Dataset (NLCD). The NLCD 1992-2001 Land Cover Change Retrofit product can only be used for quantifying land cover change from 1992-2001. Other sources of land cover data for this region include the NOAA CCAP (Coastal Change Analysis Program) land cover data and the land use data from HGAC (Houston-Galveston Area Council), but these datasets only pertain to the lower Galveston watershed. This study will use remote sensing to analyze land cover change from 1989-2009 along with forest cover change on a high temporal scale for the lower Galveston Bay watershed.

The overall goal of this research is to relate the changes in water quantity and quality to changes in land cover and population growth. To achieve this goal, the following objectives needed to be accomplished:

- Quantify land use/land cover change (LULCC) in the watershed
- Quantify change in population growth in the watershed
- Relate LULCC and population dynamics to stream hydrology and stream water quality

CHAPTER 2: STUDY AREA, HYDROLOGY AND WATER QUALITY CHARACTERISTICS

ABSTRACT

The analysis of time series data for stream hydrology, stream water quality and bay water quality confirm most of the evidence documented in the literature review (Chapter 1). High rates of inter-basin transfer of water can be observed from the USGS stream gauging station data for those stations lying within the highly urbanized area with increasing trends in river discharge. In order to meet the demands of the growing population, more water has been pumped from the Trinity River, as can be observed from the trends in discharge for the USGS Station 08067070 on the Coastal Water Authority (CWA) Canal in the lower Trinity basin. Some of the stream gauging stations did not show any significant trends in water quality while a few of them did have decreasing trends in concentrations, particularly for TP, probably as a result of improved waste water treatment and the natural ban in phosphorus on laundry detergents. As for the bay water quality, the trends in Chl *a* and TSS were more or less similar for most of the sections of the Bay in general, with the exception of TSS trends in the western part where a continuous declining trend was observed. The declining Chl *a* and TSS are probably due to the combined effects of reductions in industrial nitrogen loads, improved waste water treatment, altered land use, and impoundments on the principal rivers (San Jacinto and Trinity).

2.1 Watershed and Basin Description

The state of Texas has about 600 km of coastline along the Gulf of Mexico. The coastline includes seven major estuarine systems and three minor estuaries along the shoreline (Armstrong, 1982). The Galveston Bay estuary is the largest (1,456 km^2) and most urbanized, supporting a population of more than four million inhabitants in five counties bordering the Bay (Thronson and Quigg, 2008).

The watershed draining into Galveston Bay (Fig. 1.1) consists of 8.5×10^4 km^2 of land and water (Lester and Gonzalez, 2002). The basin extends inland from the Gulf of Mexico approximately 643.7 km to eventually encompass the Dallas-Ft Worth metroplex (Keith et al., 2002). The San Jacinto and Trinity (Fig. 1.2) are the two main rivers that provide most of the freshwater to the Bay. Besides these, the watershed comprises a multitude of bayous, streams and rivers that carry surface flow to the Bay. A bayou is a water body typically found in flat, low-lying areas and can refer to an extremely slow-moving stream or river or to a marshy lake or wetland (http://dictionary.reference.com/browse/bayou?s=t). The bayous are the most common form of tributary to the Galveston Bay and operate primarily as extensions of the bay system changing their nature from source to mouth (Lester and Gonzalez, 2002).

Based on the basin hydrology and their impact on the Bay, the Galveston Bay watershed can be divided into two parts: the lower and upper watersheds. Each of these has distinctive characteristics and is described below.

2.1.1 The Lower Watershed

The lower watershed (Fig. 1.2) comprises the area draining to the Bay downstream of two major impoundments: (a) *Lake Houston* on the *San Jacinto River* and (b) *Lake Livingston* on the *Trinity River* (Fig. 1.1). The lower watershed has an area of 1.1 x 10^4 km^2 (~ $1/8^{th}$ of the basin) and according to Steven Johnston at GBEP/TCEQ (pers.com.), lakes do a lot of modification to the nutrient loading from the upper watershed. As a result, the lower Galveston Bay watershed begins at *Lake Houston* and *Lake Livingston* (Todd Running, pers comm.). The major urban drainage within this watershed includes the Houston Ship Channel-Buffalo Bayou system and its associated tributaries: White Oak Bayou, Brays Bayou, Sims Bayou, Hunting Bayou and Greens Bayou (Fig. 1.2) in the Houston area (GBNEP, 1994). The rural watersheds basically include the lower Trinity River, Chocolate Bayou, and Austin/Bastrop Bayous (GBNEP, 1994). The lower watershed more directly contributes runoff and runoff-borne detritus and pollutants to the Bay than the upper watershed (Lester and Gonzalez, 2002). Even across the lower watershed runoff varies significantly and is usually controlled by land use and land cover (GBNEP, 1994). The western part of the lower watershed is highly urbanized with the metropolis of Houston (Fig. 1.2) and its suburban communities which are very significant to the Bay through their contributions of waste water and storm water runoff produced by impervious cover e.g. from parking lots, streets, highways, roofs and yards. In contrast, the eastern side of the Bay is primarily rural, with agriculture and pasture being the dominant land use types contributing non-point sources of nutrients, fecal coliforms, herbicides and pesticides (Lester and Gonzalez, 2002).

2.1.2 The Upper Watershed

There are two large "upper watersheds". These include the drainages upstream of two main reservoirs (Fig. 1.1)—*Lake Houston* on the *San Jacinto River* and *Lake Livingston* on the *Trinity River* (Lester and Gonzalez, 2002).

2.1.2.1 Lake Houston Watershed

The total drainage area of the Lake Houston Watershed is 0.7×10^4 km^2 with the West Fork of the San Jacinto River contributing over half of this area (GBNEP, 1994). Lake Conroe (Fig. 1.2), a major reservoir draining an area of 0.1×10^4 km^2 is situated above Lake Houston (GBNEP, 1994). The creation of Lake Houston in 1954 was by construction of an earth-filled dam on the San Jacinto River, producing an initial storage capacity of about 1.8×10^8 m^3 and a surface area of 51.7 km^2 (GBNEP, 1994). The typical annual discharge from Lake Houston was estimated to be 54.8 m^3/s while the annual sediment load to Lake Houston was estimated to be 160 million kilograms per year in 1980, with over 70 percent settling out in the lake during an average year. The trapping of nitrogen and phosphorus by Lake Houston varies but is lower than for sediment (GBNEP, 1994). Residence times during high flow periods are short, leading to a washout effect moving sediment, nutrients and algae towards the Bay (GBNEP, 1994). Land use in the San Jacinto River basin is mostly forested upstream of Lake Houston with some urbanization in its lower drainage area. The river is heavily industrialized along the inland part of the Houston Ship Channel (Fig. 1.3) bringing industrial wastewater into the Galveston Bay from Houston and adjacent area (Jiann and Presley, 1997).

2.1.2.2 Lake Livingston Watershed

The Trinity River runs through Central Texas extending past the Dallas-Fort Worth metroplex (Fig. 1.1) with numerous man-made reservoirs on tributaries in addition to Lake Livingston on the main stem (Lester and Gonzalez, 2002). The Trinity River (Fig. 1.1) provides approximately 90% of the freshwater flow to the Galveston Bay (Dellapenna et al., 2006). Comprising an area of 6.7×10^4 km^2, the Trinity River Watershed varies dramatically from Lake Livingston to the headwaters of the Trinity near Throckmorton County, Texas (GBNEP, 1994). The River drops 370.3 m from its source near Oklahoma to its mouth in the Trinity Bay (GBNEP, 1994) which is a part of the Galveston Bay system (Fig. 1.3). The amount of rainfall received varies in different parts of the watershed—some of the upper parts receive less than 0.76 m of rain per year, while the Lake Livingston area gets close to 1.27 m y^{-1} (GBNEP, 1994). The average rainfall for the entire watershed amounts to about 0.91 m per year, and the average annual water yield ranges from greater than 0.4 m y^{-1} in the southern part of the basin to less than 0.1 m y^{-1} in the far northwestern portion of the watershed (GBNEP, 1994). This is illustrated in Fig. 2.1 for rain gauging stations located in the upper, middle and lower parts of the Galveston Bay watershed (Fig. 2.2). Rainfall in the Dallas/Fort Worth metroplex creates significant amounts of urban runoff and wastewater discharges to the River (GBNEP, 1994). Land use types within the watershed include forest and wetland along the river floodplain; urban areas and rangeland occur in the far north west, and agriculture occurs throughout the

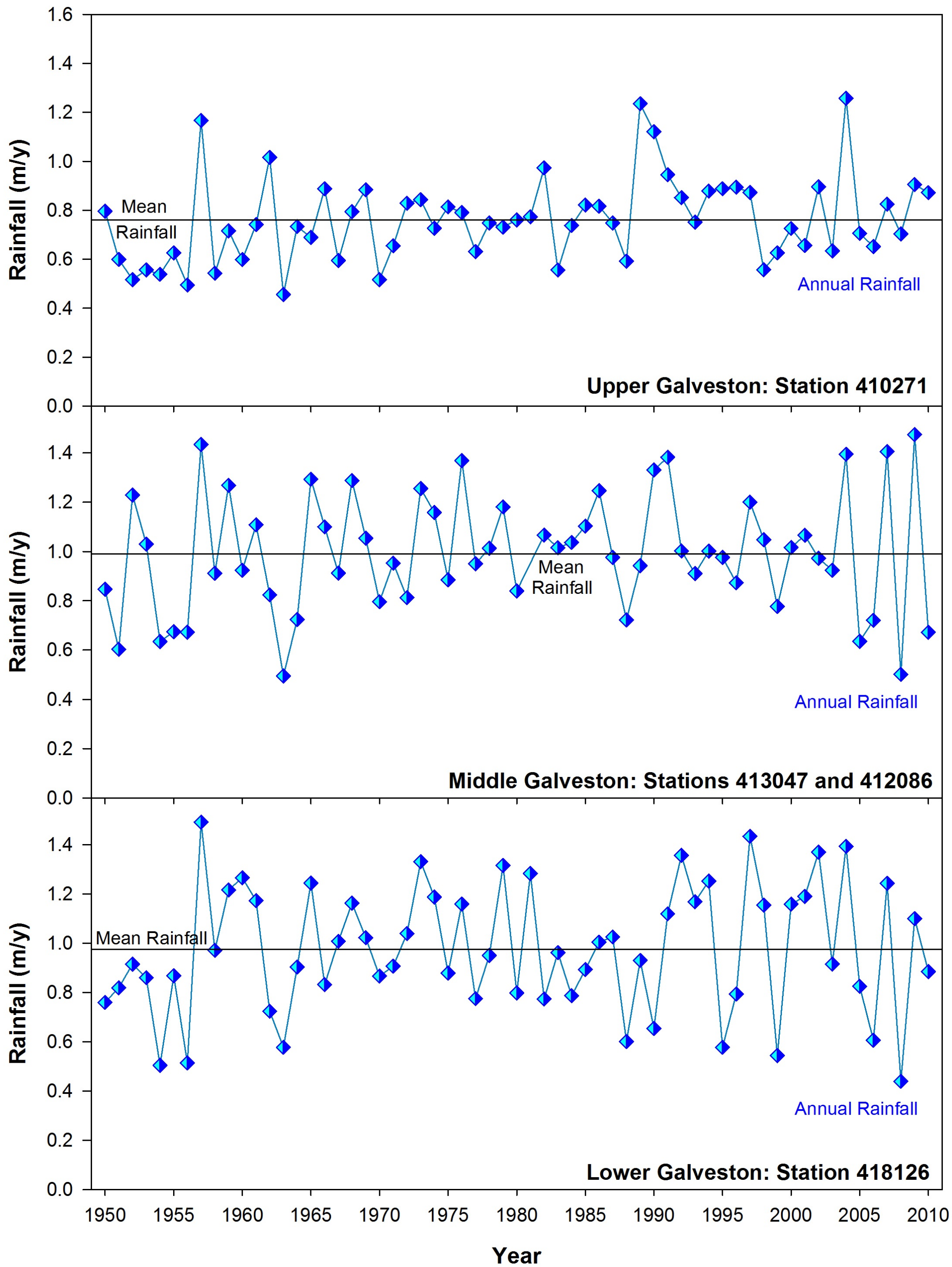


Fig. 2.1 Annual Rainfall in the Upper, Middle and Lower Galveston Bay Watershed

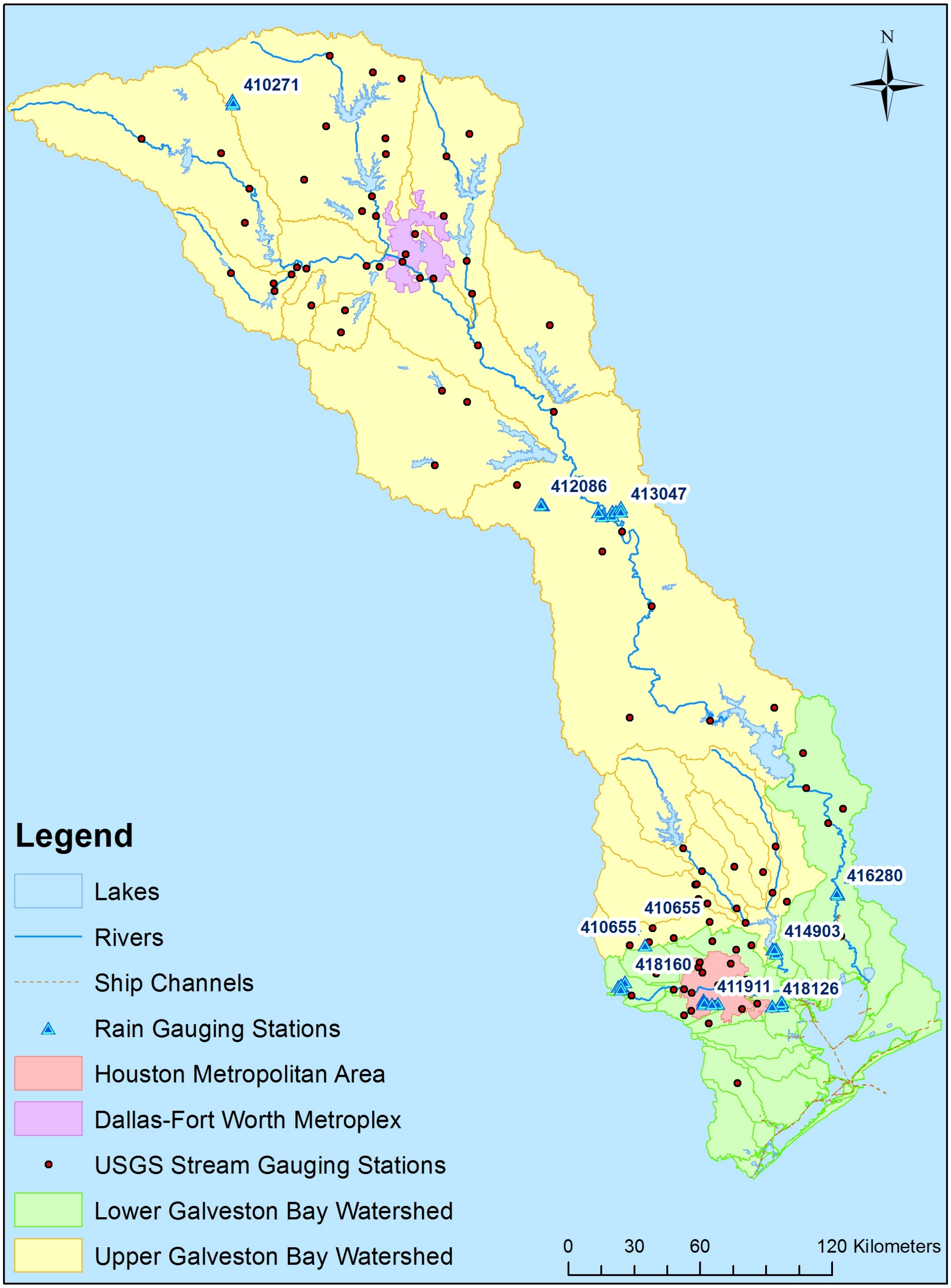


Fig. 2.2 Galveston Bay Watershed with the Rain Gauging Stations and USGS Stations

watershed (Lester and Gonzalez, 2002). Numerous reservoirs have been constructed in the *upper watershed* for the purpose of flood control, water supply and recreation. The reservoirs (Fig. 2.3) include Lake Worth, Lewisville Lake, Lake Ray Hubbard, Cedar Creek Reservoir, Richland-Chambers Reservoir, Benbrook Lake and Lake Livingston (GBNEP, 1994). Twenty-nine major reservoirs have a cumulative storage capacity of about 9.9×10^9 m^3, with Lake Livingston being the largest at 2.2×10^9 m^3 (GBNEP, 1994). All reservoirs were constructed between 1910 and 1987, with over 80 percent of the storage capacity being added in the 1950s and 1960s (GBNEP, 1994). The impounding of water by Lake Livingston began in October of 1968, which had a significant beneficial effect on water quality in the Trinity River because most of the suspended solids carried by the river are trapped in the lake, as well as two-thirds of the phosphorus and one-third of the river nitrogen (GBNEP, 1994).

2.1.3 The Galveston Bay

The Galveston Bay (Fig. 1.3) is a large, shallow bar-built estuary formed in a drowned river delta (Lester and Gonzalez, 2002). The average depth of the Bay is 2-3 m, with the exception of the *Houston Ship Channel* (Fig. 1.3), which is currently dredged to 12.2 m deep for major ship traffic (Powell et al., 2003). Galveston Bay is composed of four major sub-bays: Galveston Bay, Trinity Bay, East Bay and West Bay (Fig. 1.3). Each is described below.

(i) *Galveston Bay*: Galveston Bay receives the outflow of the San Jacinto River and most of the local drainage from the City of Houston via Buffalo Bayou and the

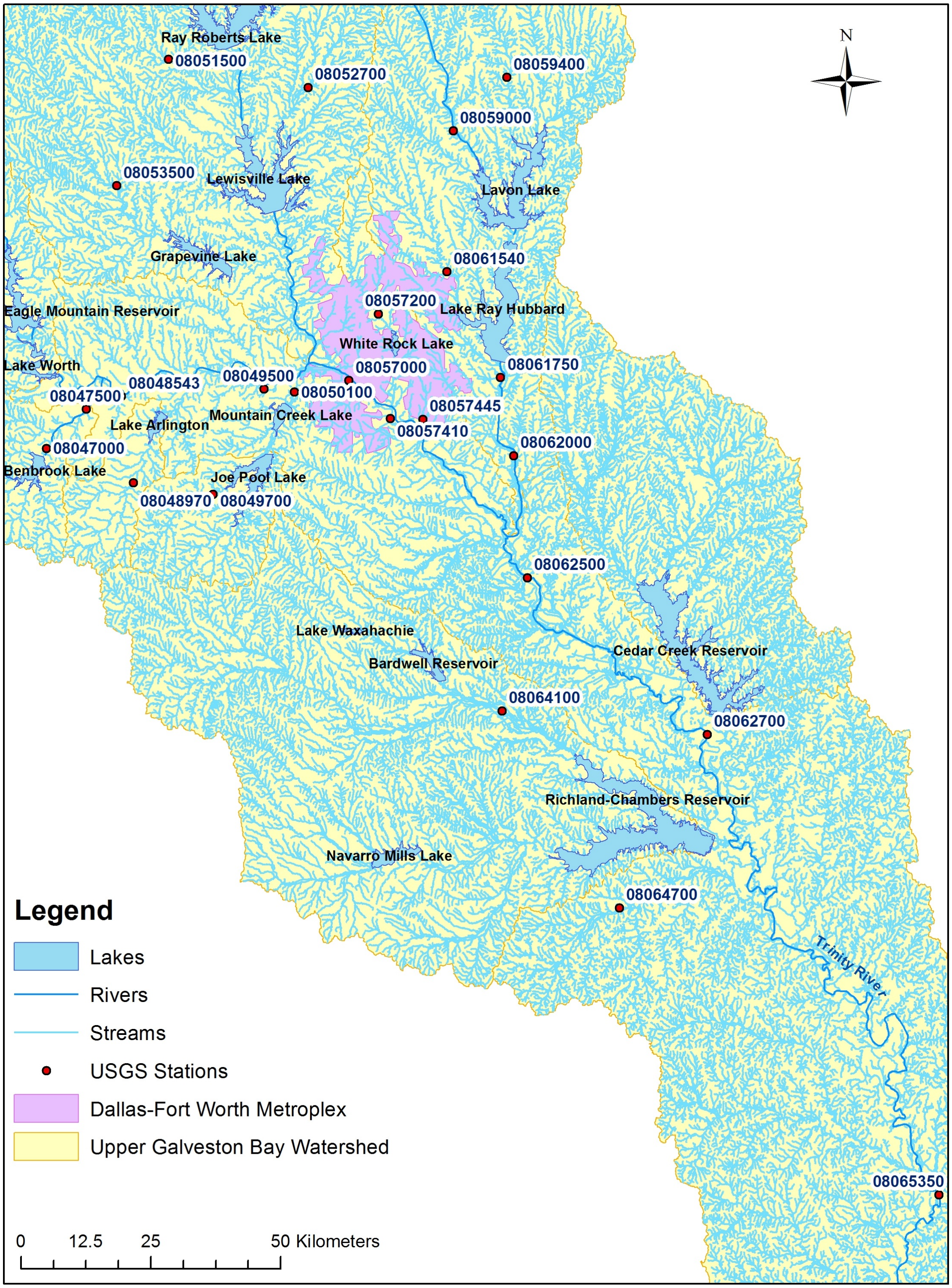


Fig. 2.3 Reservoirs and USGS Monitoring Stations for the Upper Galveston Bay Watershed

Houston Ship Channel (GBNEP, 1994). The Bay is divided into *upper* and *lower* bays at Smith Point.

(ii) *Trinity Bay*: The Trinity Bay receives the outflow from the Trinity River which drains a large watershed extending north to encompass the Dallas-Fort Worth (Fig. 1.1) region, contributing 90 percent of the freshwater input to the Galveston Bay (Dellapenna et al., 2006). Salt moves up-bay into the central deeper portion of Trinity Bay via the Houston Ship Channel (Powell et al., 2003).

(iii) *East Bay*: East Bay is located landward of the Bolivar Peninsula receiving inflow from Oyster Bayou and other runoff from Chambers County.

(iv) *West Bay*: West Bay lies landward of Galveston Island, and receives runoff from Chocolate Bayou, Mustang Bayou and other local bayous.

Upper Galveston and *Trinity* are the two upper bays that comprise most of the Bay area. The combined area of the four sub-bays accounts for about 1×10^3 km^2 making Galveston Bay the largest estuary along the Texas Gulf Coast (Lester and Gonzalez, 2002).

In addition to the four major bays, *Christmas Bay* and *Bastrop Bay* are two secondary bays in the far southwestern part of the estuary. These are relatively undisturbed and somewhat isolated from the rest of the estuary (Lester and Gonzalez, 2002).

There are three tidal inlets (Fig. 1.3) to the Bay. Of these three only two inlets are of major importance with regard to exchange with the Gulf of Mexico (Lester and Gonzalez, 2002). *Bolivar Roads*, an inlet situated between Galveston Island and

Bolivar Peninsula, accounts for the majority of the tidal exchange between the Bay and the Gulf of Mexico. *San Luis Pass* is a natural inlet between the western end of Galveston Island and Follets Island providing a lesser amount of the Bay's tidal exchange. However, this inlet provides important access for commercial and recreational fishermen (GBNEP, 1994). *Rollover Pass* is a man-made pass that cuts through Bolivar Peninsula providing minor tidal exchange between the Gulf of Mexico and *East Bay*. According to Dr. Jan Culbertson (pers comm.) at the Texas Parks and Wildlife Department (TPWD), this pass came into being as a result of hurricane activity on the coast and was later modified. There is a lot of fishing activity on this *Pass*. The Texas Parks and Wildlife Department (TPWD) was planning to shut it down in July 2011 in an effort to conserve freshwater habitats in *East Bay*. The Texas General Land office applied for a permit to close it and they are still waiting for a final decision from the United States Army Corps of Engineers (USACE). They hope to shut down the *Pass* in the summer of 2012 (Dr. Jan Culbertson, pers comm.).

The *East* and *West Bay* are less hydrodynamically active than other areas (Powell et al., 2003). The Texas City Dike (Fig. 1.3) minimizes flow into *West Bay* while the flow into *East Bay* is minimized by the bypassing of Trinity River water as it flows south of Smith Point to *Bolivar Roads*, the primary inlet to the Gulf of Mexico (Powell et al., 2003). The Houston Ship Channel along the main north-south axis of the Bay connects the port of Houston with the Gulf of Mexico (Powell et al., 2003). The channel, completed in 1914, permits ocean-going vessels to traverse the shallow Galveston Bay all the way to Houston. This resulted in a tremendous upsurge in new industrial growth in Houston (GBNEP, 1994). The dredging of this channel has produced the greatest impact on circulation by providing a conduit for saltwater intrusion into the central deeper portion of *Trinity Bay* (Powell et al., 2003). It acts as a barrier to flow separating the much smaller San Jacinto/Buffalo Bayou-impacted western shore from the much larger eastern area that receives the bulk of the Trinity River flow (Powell et al., 2003). Thus, sections of the Bay operate quasi-independently with respect to the hydrodynamic and salinity regime.

2.2 Approach

Land use and land cover changes such as those described in Chapter 1 should strongly influence water yields (Mustard and Fisher, 2004) and stream water quality (Jones et al., 2001). Forests generally have higher rates of evapotranspiration than agricultural or urban land uses, leaving less water for groundwater flows to streams (Mustard and Fisher, 2004). Agricultural and urban land uses have higher nutrient (Nitrogen and Phosphorus) yields than forests due to lower plant biomass, fertilizer applications and disturbance (Lee et al., 2001); urban lands also generate large volumes of nutrient-rich wastewater delivered by public sewer systems quickly and directly to aquatic systems (e.g., Fisher et al., 2006). Therefore, the conversion of forest land cover to anthropogenic land uses results in increased water yields (Mustard and Fisher, 2004) as well as increased concentrations of nitrogen and phosphorus (Lee et al., 2001). Therefore analysis of stream flow and stream water quality is an important factor in understanding the effects of land use and land cover change downstream. Local data from the watershed and estuary of Galveston Bay were obtained from USGS and the Texas Commission on Environmental Quality

(TCEQ). The methodology for this research begins with understanding the dynamics of stream hydrology, stream water quality and bay water quality for the study area. Subsequent chapters will link these results to remote sensing data. Analysis for Chapter 2 includes river hydrology and water quality as well as water quality in Galveston Bay.

2.3 Datasets

2.3.1 Precipitation

Data on daily rainfall were acquired from the National Climatic Data Center for 4 stations located in the upper, middle and lower Galveston Bay watershed and 5 stations located in and around 3 catchments—Brays Bayou, Greens Bayou and the Trinity River watershed. Appendix I describes the station locations and their period of record. The mean annual rainfall (m/year) for the respective basin area was computed from the daily precipitation data.

2.3.2 Streamflow

The stream discharge data were obtained from the USGS stream gauging stations at the mouths of the watersheds (Appendix II). The average annual stream discharge (cubic feet per second) as reported by USGS was converted to water yield ($m\ y^{-1} = m^3$ water m^{-2} land area y^{-1}) for all stations using the watershed area (m^2). The stream gauging stations with their period of record and trends in water yield are listed in Appendix III.

2.3.3 Stream Water Quality

The water quality data include annual averages of the USGS TN (mg/l) and TP (mg/l) data from the stream gauging stations in the Galveston Bay watershed. Appendix IV lists the USGS stations, their period of record and observed trends for TN and TP data.

2.3.4 Bay Water Quality

Chlorophyll *a* (Chl *a*), Total Suspended Sediments (TSS) and Salinity (ppt) data were sampled by the Texas Commission on Environmental Quality (TCEQ, 2009). These data were obtained from stations lying outside a 500 m buffer from the shoreline (Fig. 2.4). For the most part, samples were collected at a depth of 0.3 m for both Chl *a* and TSS. Data for Chl *a* were obtained during 1972-2009, while the period of record for TSS is 1969-2009 (See Appendices V, VI and VII). Salinity was measured at different depths during 1980-2009 (Appendix VI).

2.3.5 GIS Data

The GIS data included the watershed boundaries of the upper and lower Galveston Bay watersheds, the TCEQ (Texas Commission on Environmental Quality) Bay segments, Bay water quality monitoring stations, stream network, lakes and reservoirs, USGS stream monitoring stations, rain gauging stations, urban areas, cities and ship channels. This dataset have been obtained from several sources: Trinity River Authority (TRA), Houston-Galveston Area Council (H-GAC), Texas

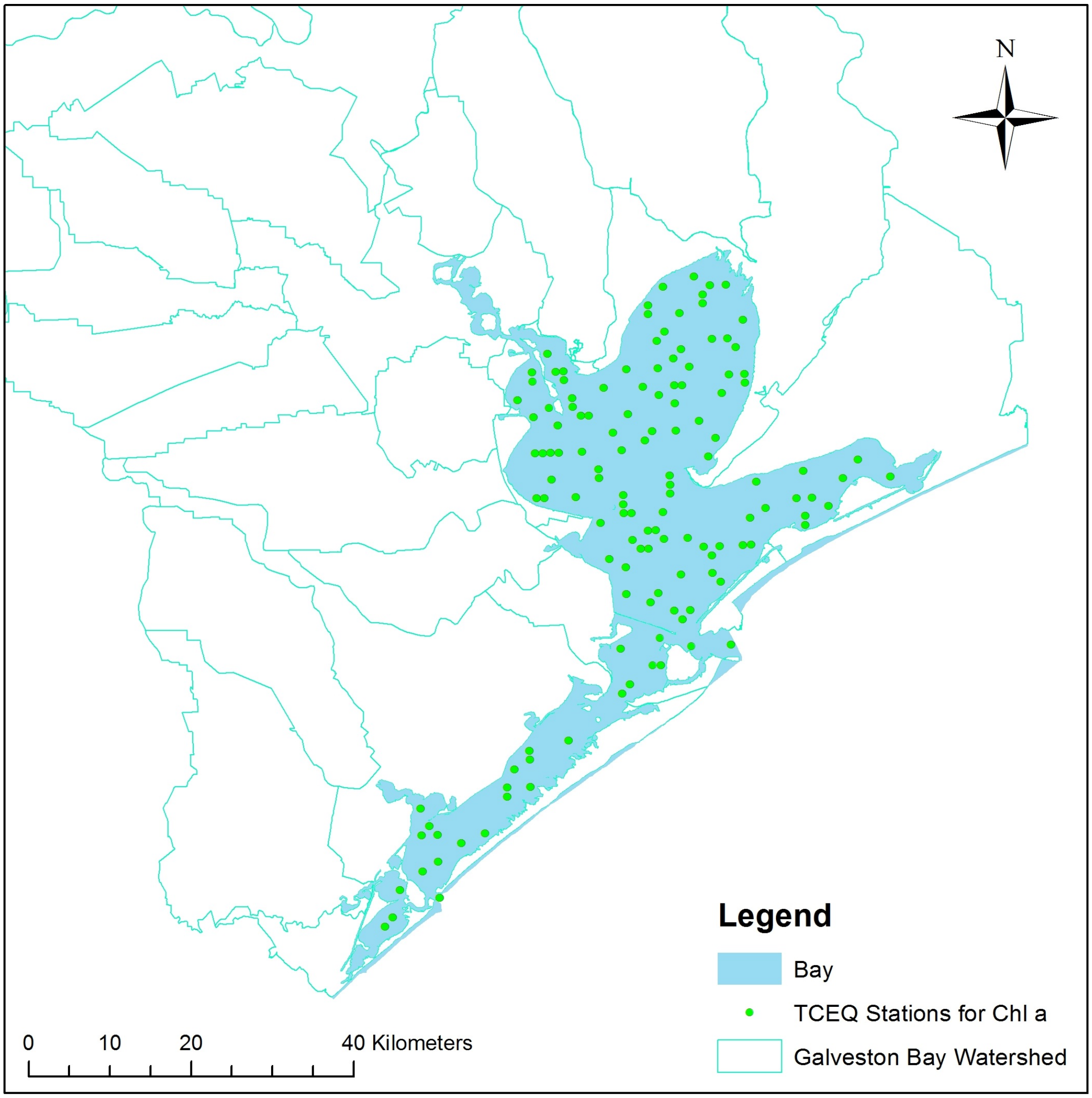


Fig. 2.4 Galveston Bay with the TCEQ monitoring stations for Chl *a*

Commission on Environmental Quality (TCEQ), United States Geological Survey (USGS) and the National Climatic Data Center (NCDC). Appendix VIII describes the list of GIS data and their respective sources. The catchment boundaries for all watersheds within the Galveston Bay watershed have been delineated using the USGS EDNA viewer (http://edna.usgs.gov/EDNA_Viewer/viewer.php).

2.4 Stream Analysis

Anthropogenic changes for Galveston Bay have greatly influenced rivers within the watershed. Based on the availability of long term data, a total of 99 USGS stations were analyzed to study the historical trends in stream flow and stream water quality (Appendix II). Stations with less than 5 year records were not included in the analysis. Stream flow data were available for a total of 96 stations for the entire watershed while there were 56 stations with water quality data (TN and TP) for 5 years or longer. Using these stations as the watershed outlet, catchments were delineated for each individual station upstream of the gauge using the USGS EDNA viewer (http://edna.usgs.gov/EDNA_Viewer/viewer.php). This was followed by analysis of stream hydrology and stream water quality with respect to watershed properties.

2.4.1 Hydrology

The average annual stream discharge (cubic feet per second) as reported by USGS was converted to water yield ($m\ y^{-1} = m^3\ m^{-2}\ y^{-1}$) for all stations using the watershed area (m^2). Water yield has the same units as rainfall, which facilitates comparisons with rainfall and between watersheds with differing areas. Regression analysis of year vs water yield was conducted to look for trends in stream flow over time. Below in Figs. 2.5-2.7 are some examples of stations with increasing water yields over time. Out of the 96 stations analyzed, 27 had significantly increasing trends (Appendix III). Most of these stations are located in and around the two major

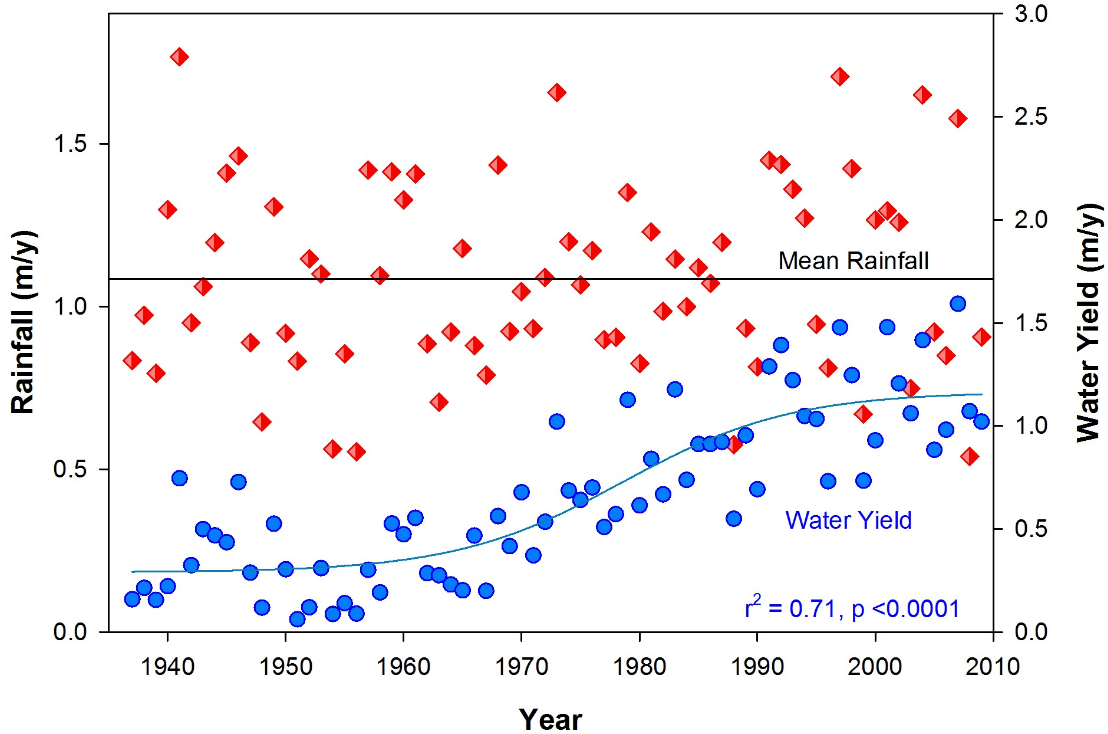


Fig. 2.5 Water Yield for USGS Station 08075000 (Fig. 2.8) on the Brays Bayou River (Fig. 1.2) and mean rainfall for the Brays Bayou watershed. A sigmoidal plot has been fitted to the water yield data using the equation: **Water Yield = 0.290 + 0.876/(1+exp((1979-year)/7.15))**. Bray's Bayou shows an increasing trend in water yields from 1960 to 2000, and water yields after 1990 are equivalent to 100% of rainfall, indicating tapping of other freshwater resources.

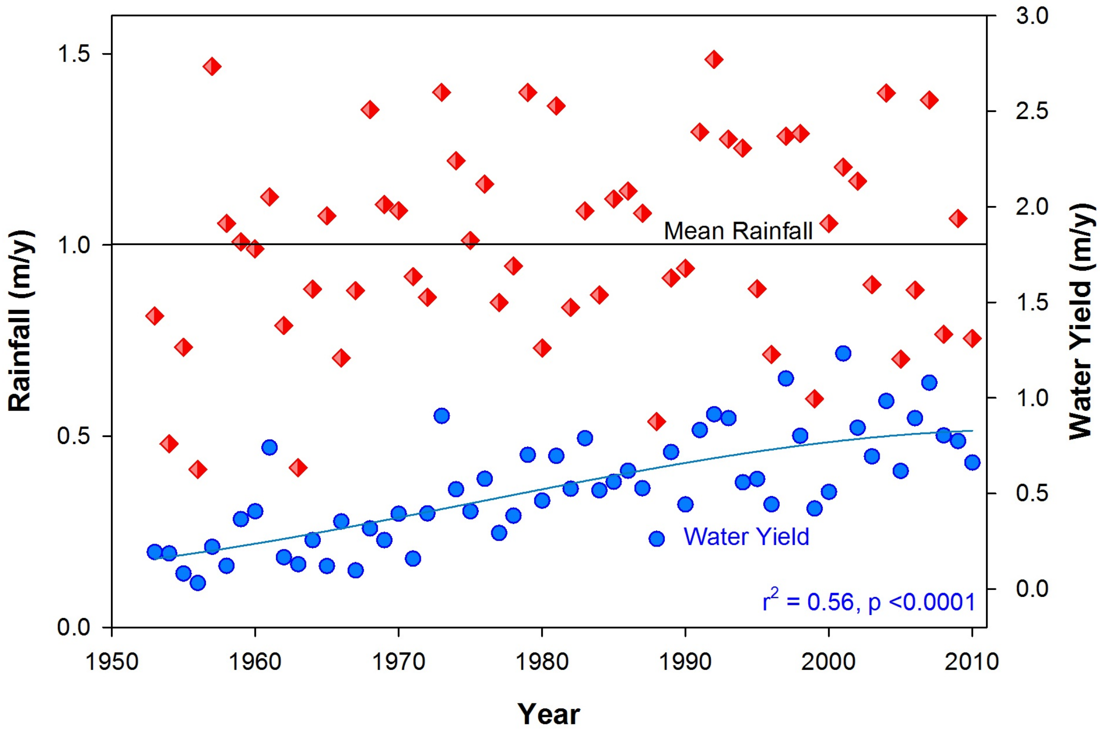


Fig. 2.6 Water Yield for USGS Station 08076000 (Fig. 2.8) on the Greens Bayou River and mean rainfall for the Greens Bayou Watershed. A cubic polynomial plot has been fitted to the water yield data using the equation: **Water Yield = 25754.15 + (-39.1431)*year+0.0198*year^{2} + (-3.3453E-006)*year^{3}**. Greens Bayou (Fig. 1.2) shows an increasing trend in water yield from 1953-2010, approaching annual rainfall values. This trend indicates the results of deforestation and urbanization, inter-basin transfers, and/or deep groundwater pumping.

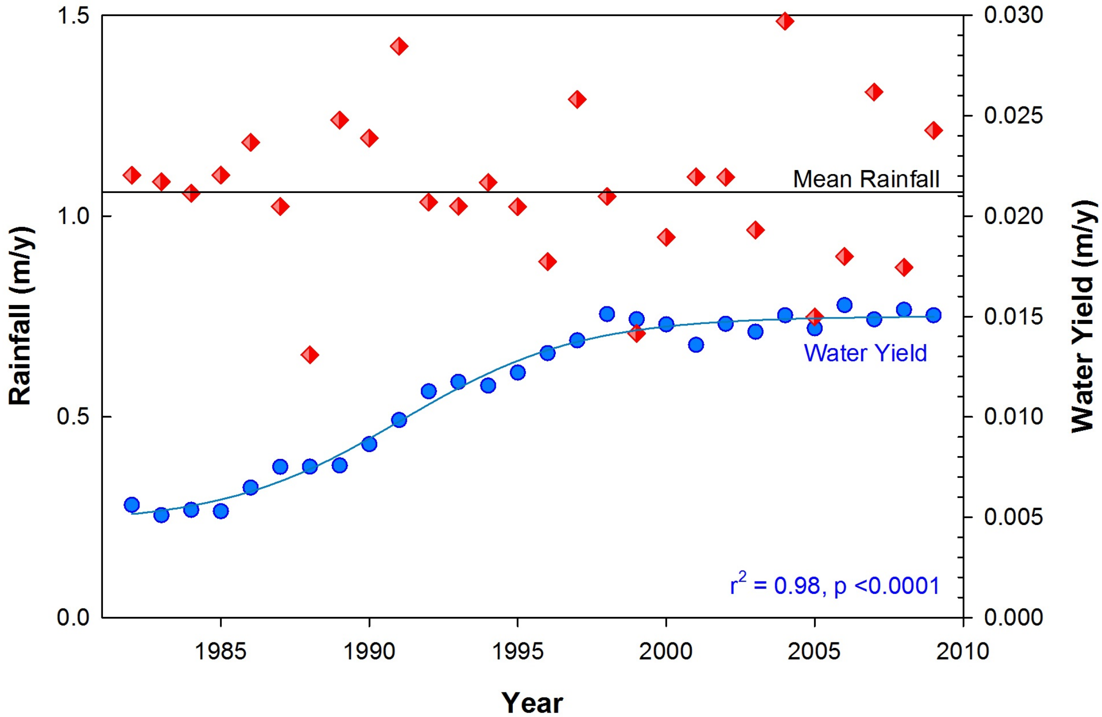


Fig. 2.7 Water Yield for USGS Station 08067070 (Fig. 2.8) on the CWA Canal in the lower Trinity River basin and mean rainfall for the Trinity River watershed. A sigmoidal plot has been fitted to the water yield data using the equation: **Water Yield = 0.0047+0.0103/(1+exp((1991-year)/3.01))**. This station also shows a steady increase in interannual water yield from 1985-2000, indicating higher water yields over a 26 year period. However, water yields are very low compared to rainfall.

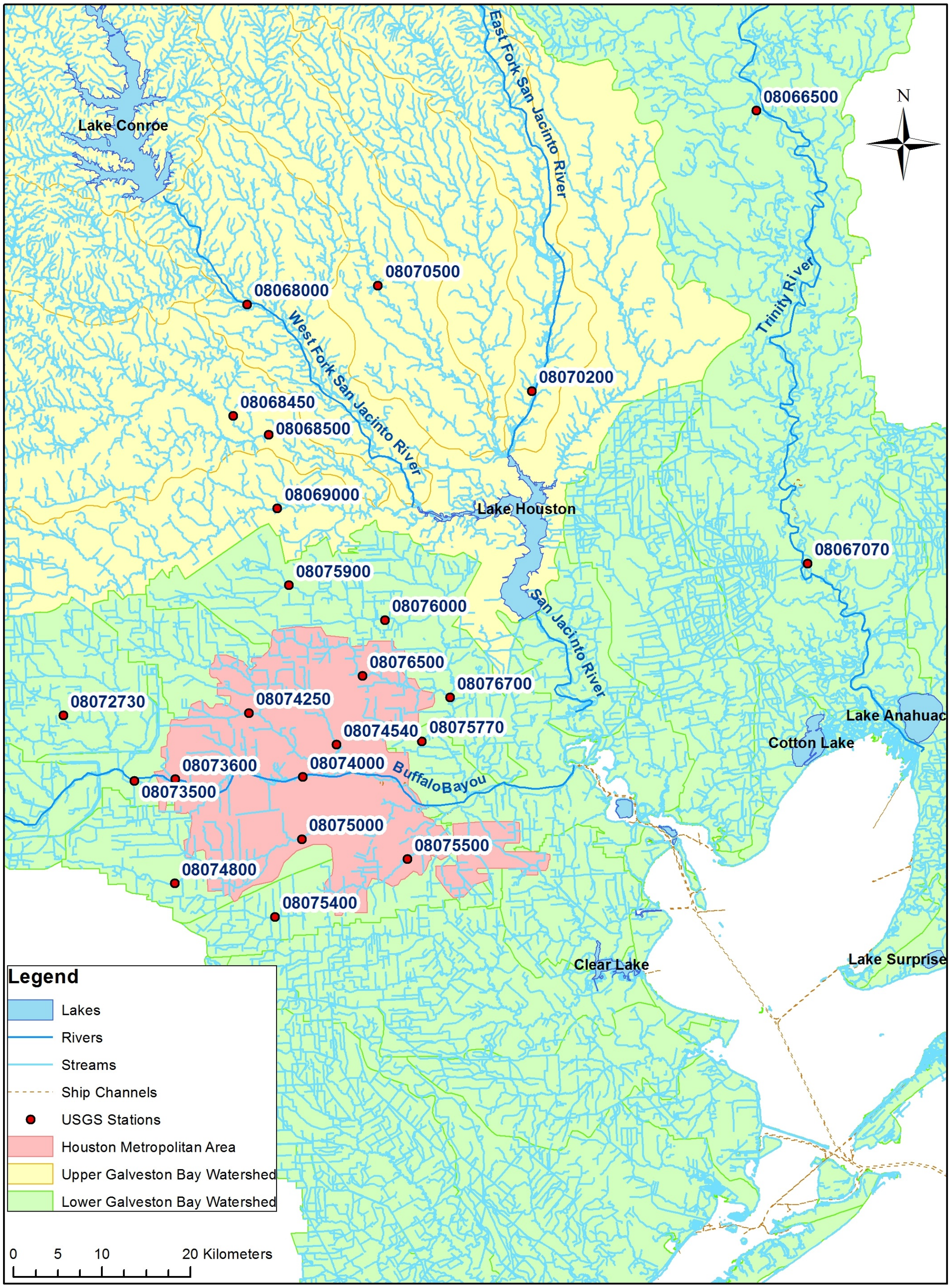


Fig. 2.8 USGS Monitoring Stations for the Lower Galveston Bay Watershed

urban clusters—Houston Metropolitan area (Fig. 2.8) on the western side of the lower watershed and the Dallas-Fort Worth metroplex (Fig. 2.3) towards the northern part of the upper watershed. The majority of the stations did not have any trend but there was large interannual variability as a result of dry and wet years.

It is clear from Figs. 2.5-2.7 that water is transferred from the lower Trinity River (Fig. 2.7) to other areas within the Galveston Bay Watershed, including Brays Bayou (Fig. 2.5) and Greens Bayou (Fig. 2.6). Water yields at these latter two stations are equivalent to rainfall (1-1.5 m/y), indicating that water must be supplied from elsewhere. Since some percentage of rainfall is lost to the atmosphere through evapotranspiration, water yield under normal circumstances should be below average rainfall in the watershed. In contrast, water yields of the Trinity River are only 1.5% of rainfall, suggesting that the Trinity River is the major or only source of water used in other areas.

According to USGS (water.usgs.gov), water is pumped from the Trinity River for industrial and municipal use. This is the only known diversion upstream of the gauge (08067070) and is an example of inter-basin transfer as a result of population increase and urban growth. As for the Trinity River gage at Romayor (08066500, Fig. 2.8) with the longest data record for the Galveston Bay area, there was no significant trend in inter annual discharge (Appendix III), although there were large inter annual and seasonal variations associated with variations in precipitation and evapotranspiration. A detailed description of the analysis and results for all the stations is listed in Appendix III.

2.4.2 Water Quality

The water quality analysis basically involved examining inter annual trends in nutrient concentration (TN and TP) for all the rivers with more than 5 years of data. The annual mean concentration was calculated for the TN and TP data for each year. The time period of data availability varied among different stations, but analysis of water quality data for most of the stations showed high nutrient concentration in the early 1970's followed by a drop in the 1990's. For some stations there is a slow increasing trend in the late 1990's, while for others the nutrient concentrations continued to decline beyond 2000. A general trend that was observed for most of the stations was a decline in phosphorus levels. Results of the analysis and the period of record for each station are described in Appendix IV. A few examples of water quality trends for various rivers are described below.

Water quality has declined at eleven stations. For instance, there has been a steady increase in N and P concentrations (Fig. 2.9) in the West Fork San Jacinto River near Conroe. These are likely to be the result of variations in agricultural development, population growth and waste water discharges from urban areas. Low concentration for N and P can be observed in the 1970's, but the concentration increased linearly over time through the mid 90's. Another station showing increasing concentration of N and P was 08051500 (Appendix IV, Fig. 2.3).

Water quality improved at eighteen stations. For instance, station 08052700 on the Little Elm Creek near Aubrey (Fig. 2.3) showed a declining trend in TN and TP concentrations from the early 1980's till the late 1990's (Appendix IV). The reasons for these declining trends are unknown, but may be related to improving wastewater technology or diversions of wastewater.

Decreasing trends in TN and TP over time from the early 1980's till 2010 can also be observed for station 08070200 (Fig. 2.10) on the East Fork San Jacinto River.

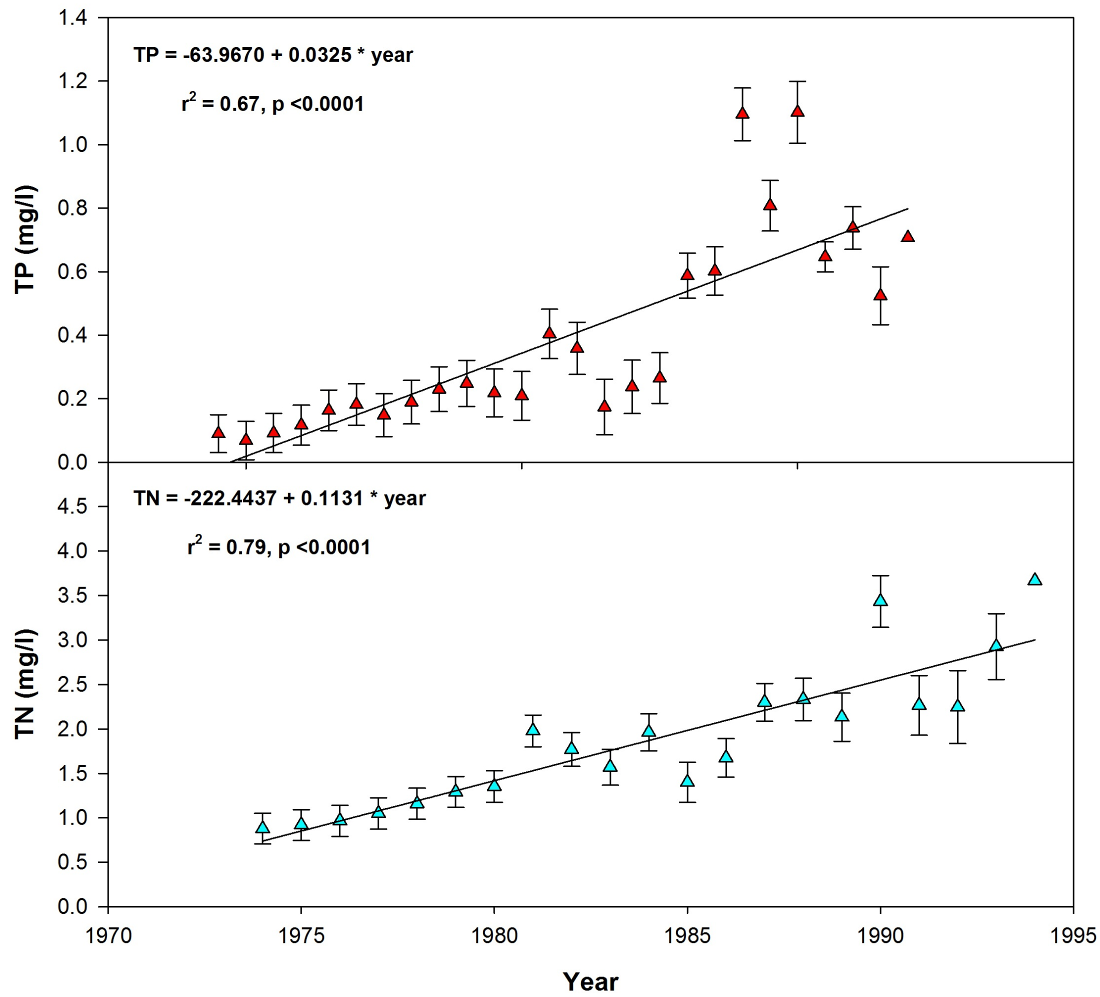


Fig. 2.9 Mean annual TN and TP concentrations for USGS Station 08068000 (Fig. 2.8) on the West Fork San Jacinto River

This is in sharp contrast to trends in nutrient concentrations for the station 08068000 located on the West Fork of the same river (Fig. 2.9). Other stations showing decreasing concentration of N and P were 08062000, 08062700, 08066500 and 08074000. The causes of these differences in the water quality trends will be investigated in the following chapters.

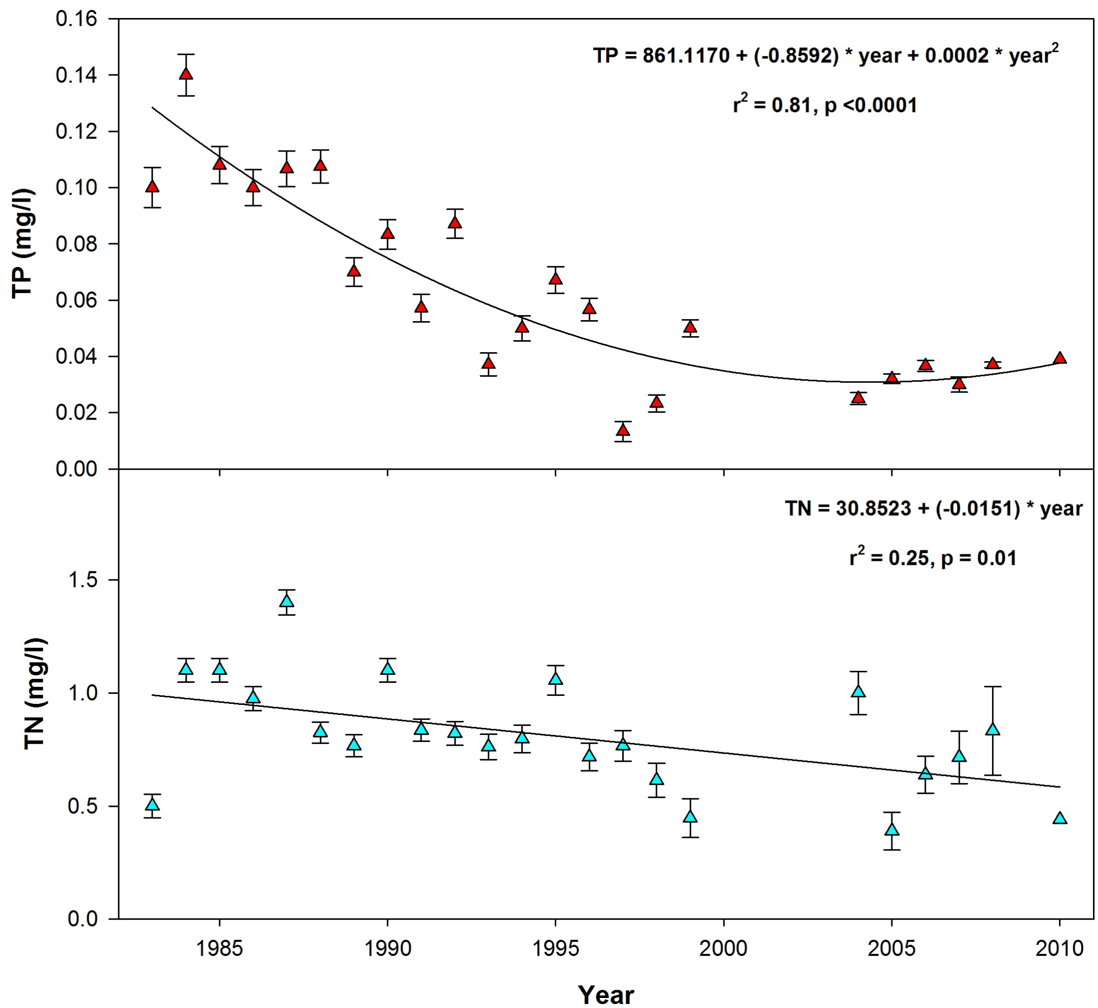


Fig. 2.10 Mean annual TN and TP concentrations for USGS Station 08070200 (Fig. 2.8) on the East Fork San Jacinto

Another example of improving water quality was observed for station 08057410 on the Trinity River below Dallas (Fig. 2.3). TN concentrations appear to be high in the mid-70s followed by a drop in the mid-1990s after which they start rising again through 2010 (Appendix IV). Concentrations of TP on the other hand show a steady declining trend from the early 1970s through 2010 (Appendix IV). These observed interannual trends in water quality parameters and variations in water yield will be useful as potential indicators of land use change (Appendices III & IV).

In order to check for relationships between river flow and nutrient concentrations, a correlation analysis between river discharge and nutrient concentration was done for four selected stations: 08075000, 08076000, 08070200 and 08068000 on the Brays Bayou, Greens Bayou, East Fork San Jacinto and West Fork San Jacinto rivers (Fig. 2.8). Results of this analysis showed significant inverse relationships between river flow and nutrient concentrations for these stations. These plots clearly show river flow diluting sewage inflows. When river flow is low, the concentrations are high because the river discharge is mostly sewage. All the rivers (Figs. 2.11, 2.12 and 2.14) except for the East Fork San Jacinto River (Fig. 2.13) showed decreasing nutrient concentrations with increasing river discharge. I volume-weighted the concentrations whenever there was a statistically significant relationship between nutrient concentration and river flow. Table 2.1 describes the means of nutrients and the volume-weighted means for all stations. The volume-weighted means are slightly lower than the means for river nutrients because at high flows the concentration is lower. In many rivers without sewage inputs, the opposite occurs: nutrients increase with discharge, especially TP. Then the volume-weighted mean is higher than the mean of the concentrations.

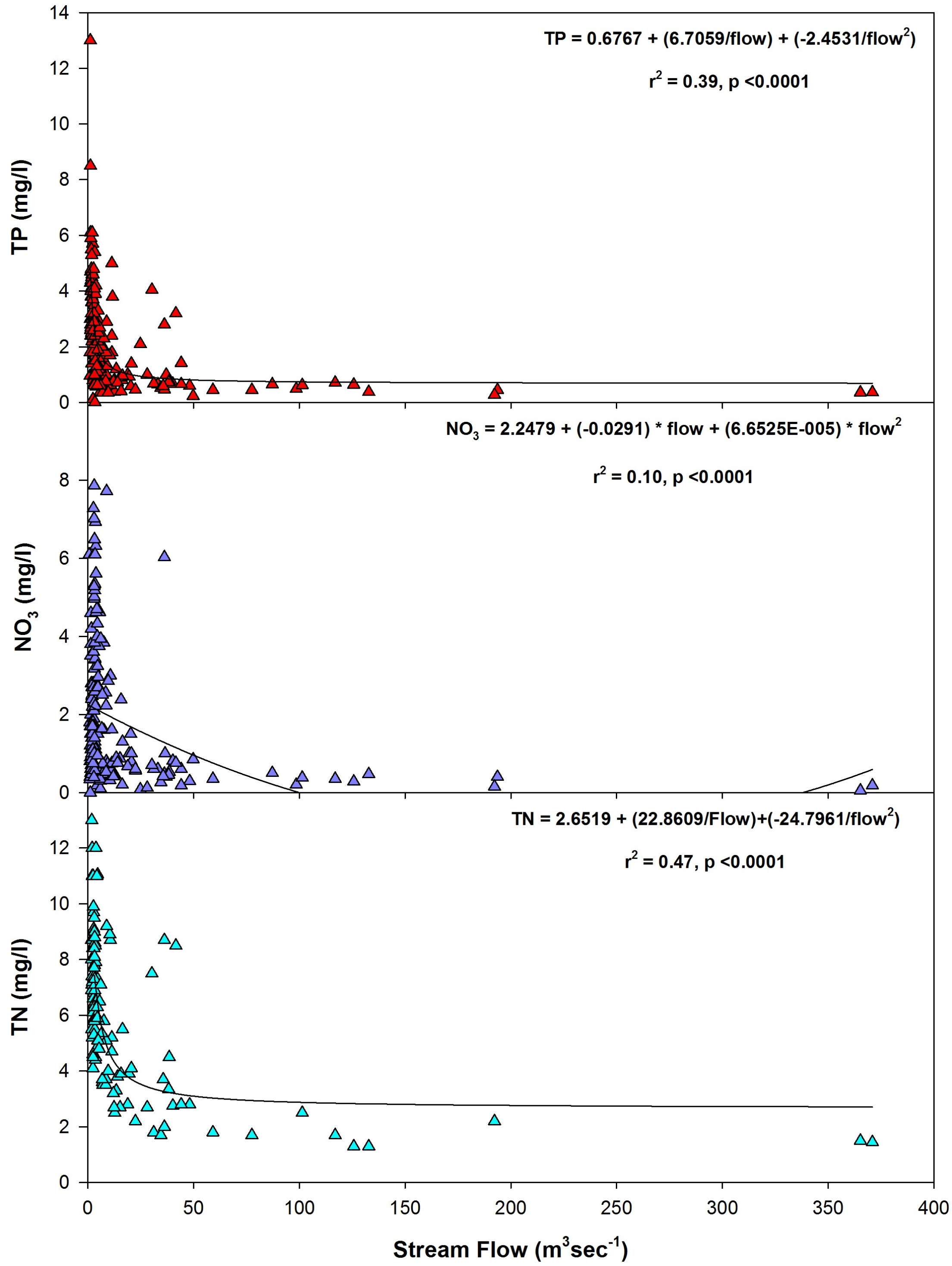


Fig. 2.11 Relationship between stream flow and TN, NO_3 and TP in the Brays Bayou River

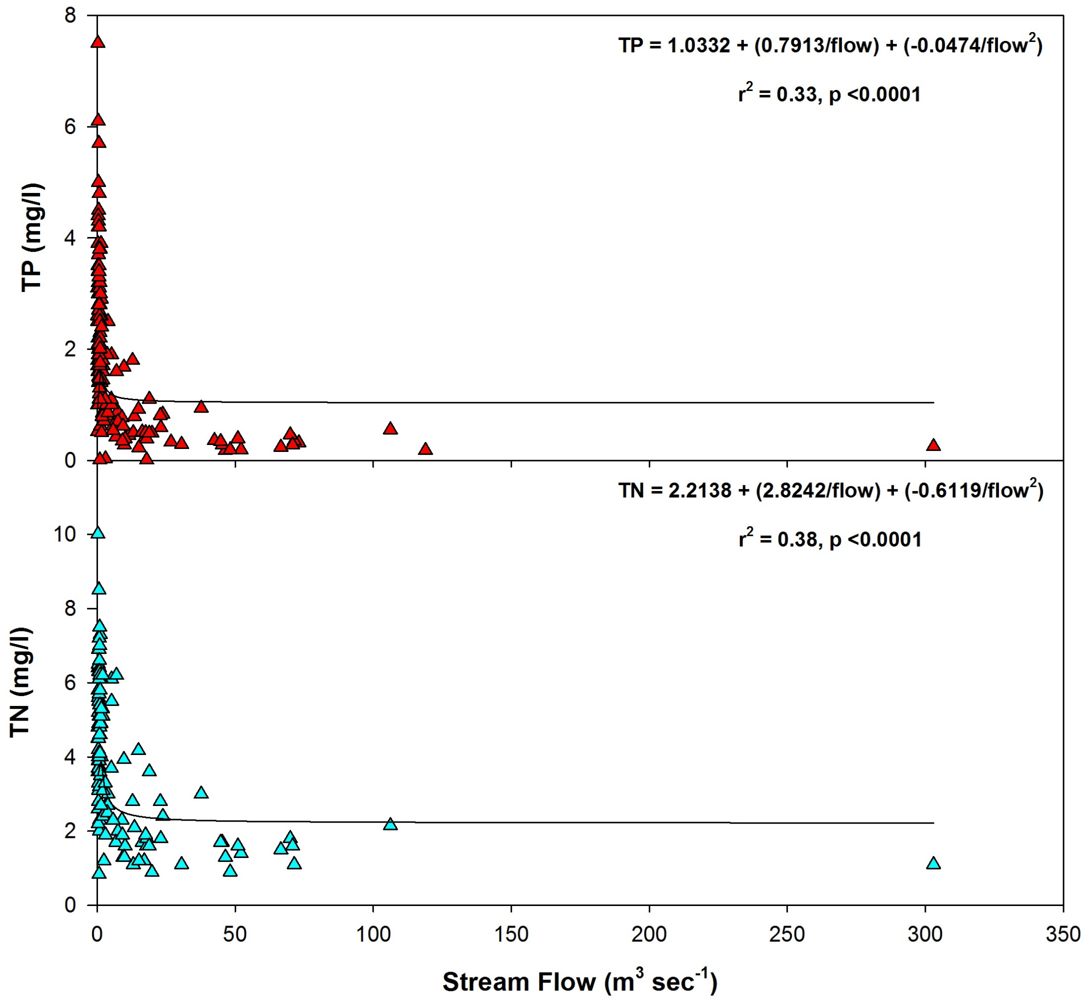


Fig. 2.12 Relationship between stream flow and TN, and TP in the Greens Bayou River

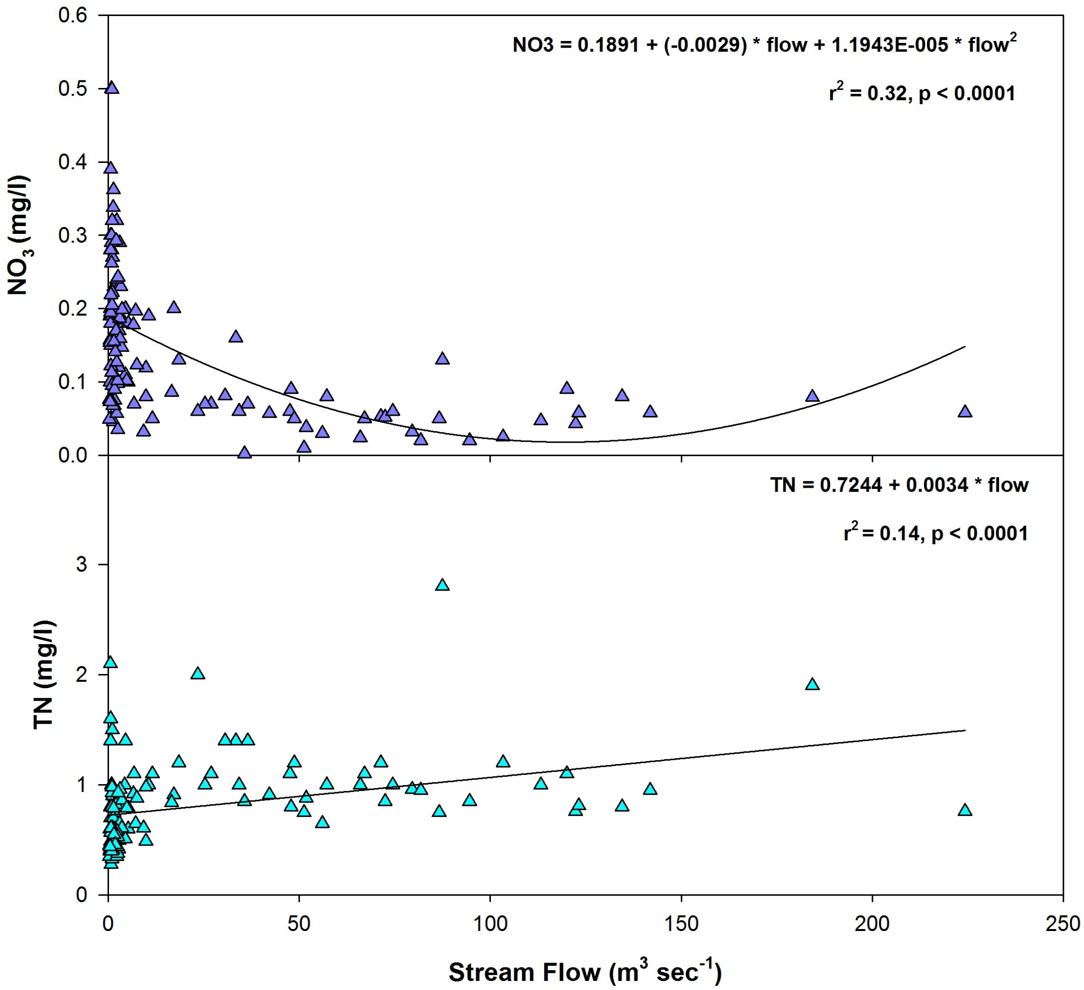


Fig. 2.13 Relationship between stream flow and TN, and NO_3 in the East Fork San Jacinto River

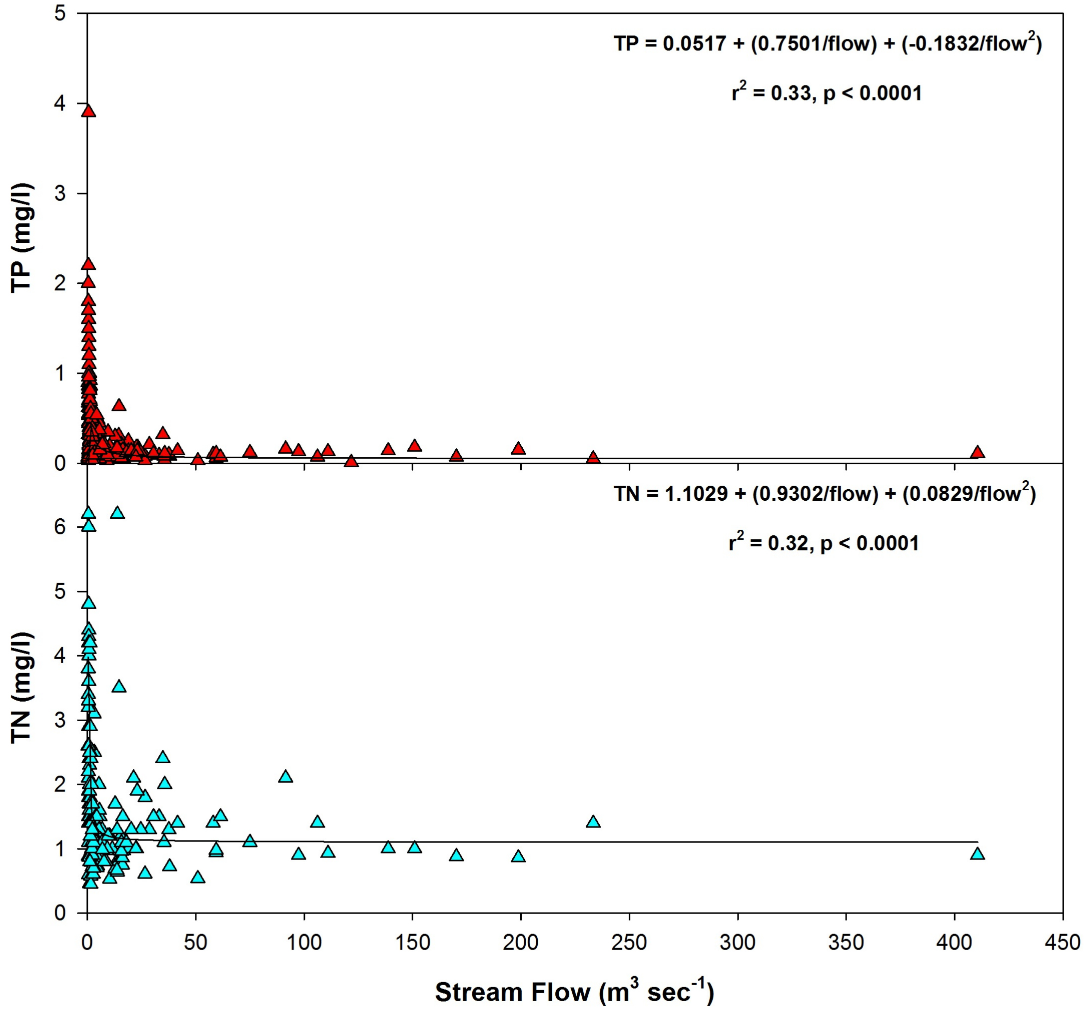


Fig. 2.14 Relationship between stream flow and TN and TP in the West Fork San Jacinto

USGS Station	Watershed	Mean			Volume Weight Mean		
		TN (mg/l)	TP (mg/l)	NO_3 (mg/l)	TN	TP	NO_3
08075000	Brays Bayou	5.94	2.23	1.89	2.91	0.89	0.72
08076000	Greens Bayou	3.87	1.86		1.88	0.5	
08070200	East Fork San Jacinto	0.80		0.15	1.05		0.07
08068000	West Fork San Jacinto	1.67	0.36		1.19	0.13	

Table 2.1 Volume-weighting of river nutrients

2.5 Bay Water Quality Analysis

The Bay water quality analysis examined interannual trends for Salinity, Chlorophyll *a* (Chl *a*) and Total Suspended Sediments (TSS) from Bay *in situ* data (TCEQ, 2009). The methodology involved selecting stations lying outside a 500 m buffer from the shoreline (Fig. 2.4). Appendix V describes the list of stations and their locations in the Bay. For the most part, samples were collected at a depth of 0.3 m for both Chl *a* and TSS. Data for Chl *a* were obtained during 1972-2009, while the period of record for TSS is 1969-2009 (Appendices VI and VII). Salinity was measured at different depths during 1980-2009 (Appendices VI and VII). The analysis involved inter annual trends for the water quality indicators (Salinity, Chl *a* and TSS) for the entire Bay, and then the TCEQ segmentation of the Bay was adopted to study the spatial variation and trends in water quality of the different geographical regions of the Galveston Bay estuary (Appendix VII).

2.5.1 Salinity

High salinity in the Bay was observed in the early 1980's, followed by a drop in the mid 1990's after which it began to rise again (Fig. 2.15C). The increase in Bay salinity in the late 1990's is a result of drought conditions from 1997 through 1999 that reversed a declining trend in the 1980's (Lester and Gonzalez, 2002). Time series of rainfall for the entire watershed and Bay salinity (Fig. 2.16) suggest an inverse relationship between Bay salinity and basin rainfall, which is confirmed in Fig. 2.17. Rainfall in the watershed is therefore one of the important drivers of variation in the salinity of Galveston Bay.

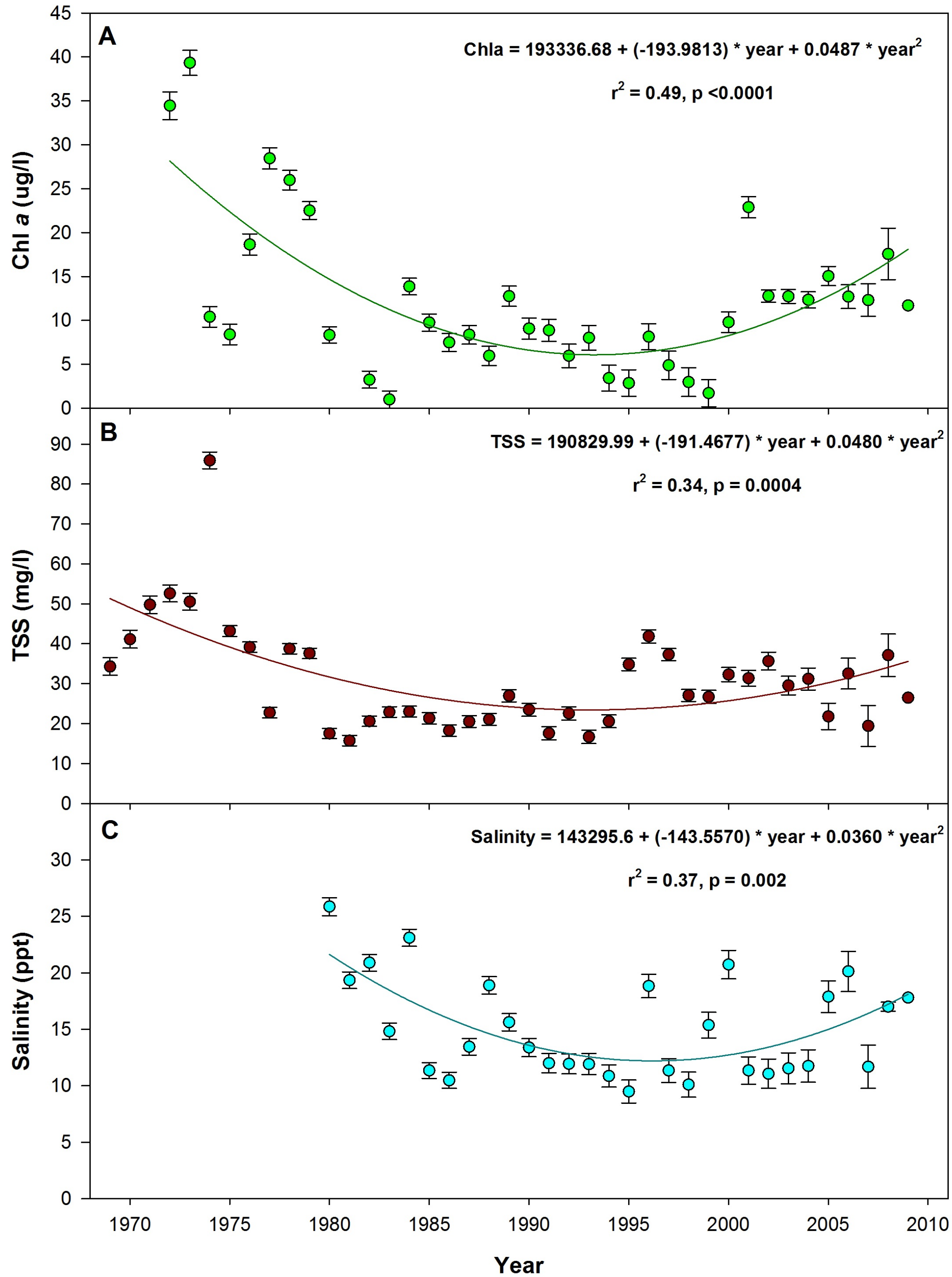


Fig. 2.15 Estuarine Station Average for Chlorophyll *a* (A), TSS (B) and Salinity (C) in the Galveston Bay

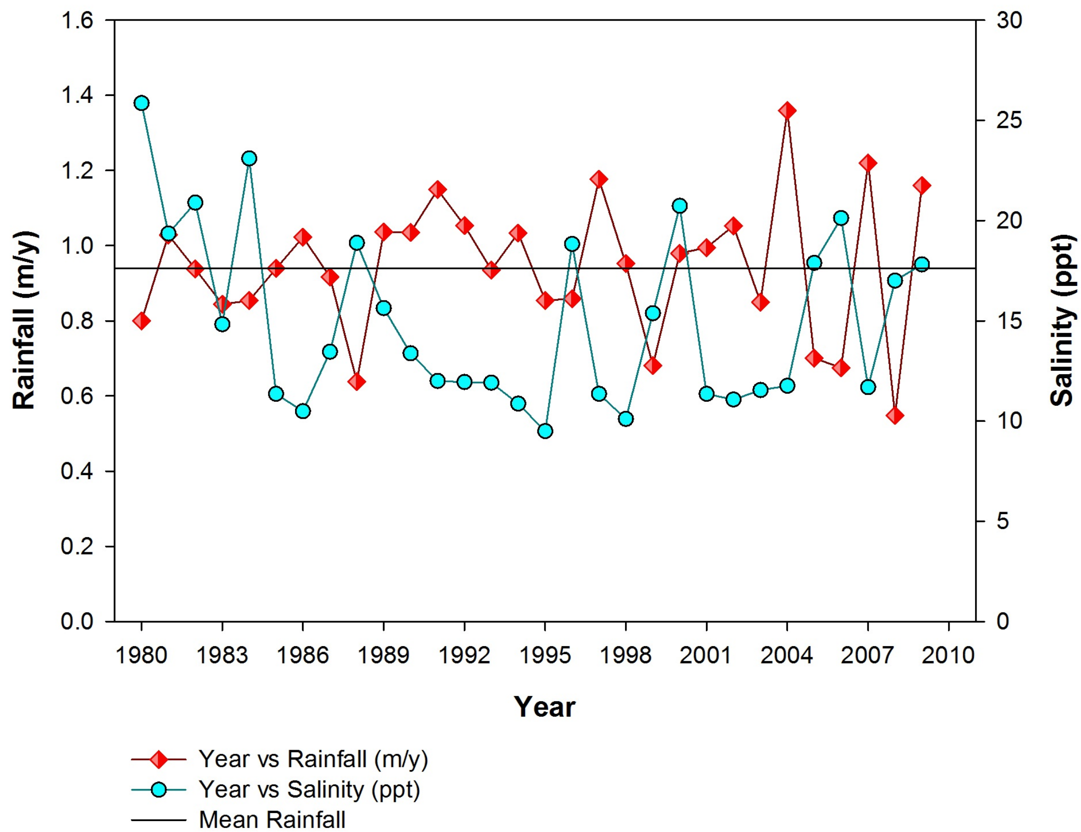


Fig. 2.16 Estuarine Station Average for Salinity in the Galveston Bay and Rainfall in the watershed from 1980-2009. Rainfall for the entire watershed was calculated from stations 41027, 413047, 412086 and 418126 combined for the upper, middle and lower watershed (Fig. 2.2) from 1980-2009.

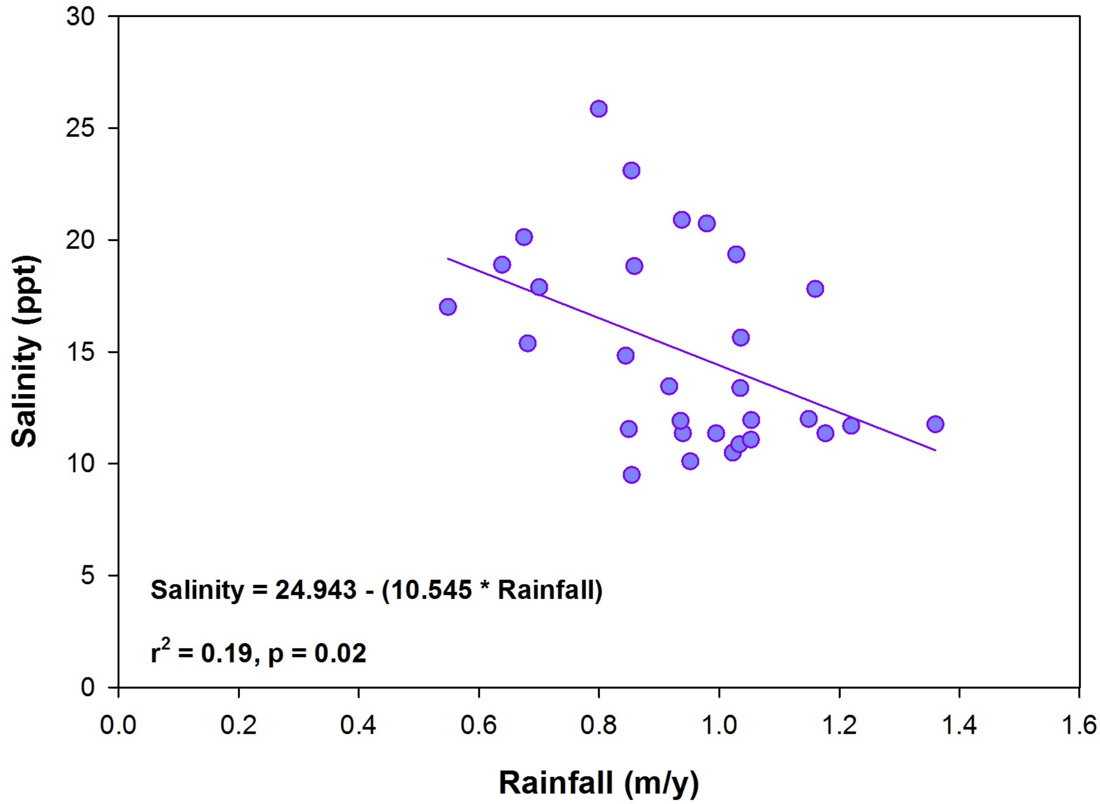


Fig. 2.17 Relationship between Bay salinity and rainfall in the Galveston Bay watershed

2.5.2 Chlorophyll *a* (Chl *a*)

Analysis of *in situ* data for Chl *a* also exhibited minima in the 1990’s (Fig. 2.15A). There were high levels of Chl *a* in the early 1970's (20-40 µg L^{-1}), followed by a drop in the 1990's (2-10 µg L^{-1}), and then Chl *a* began to rise again from 2000 onwards (10-25 µg L^{-1}). According to the literature on Bay Chl *a* (Lester and Gonzalez, 2002), mean Chl *a* concentration fell by more than 75 percent throughout much of the Galveston Bay watershed from 1972 to 1998, probably as a result of decreasing TN and TP in rivers flowing to the Bay (Fig. 2.10).

2.5.3 Total Suspended Sediments (TSS)

TSS followed a temporal pattern similar to that of Chl *a* (Fig. 2.15B). There was comparatively higher values in the 1970's (30-60 mg L^{-1}), followed by a period in 1980-1994 with lower values (10-30 mg L^{-1}) and then a rise after 1995 (20-40 mg L^{-1}). The GBEP-T7 (Lester and Gonzalez, 2002) report indicates that the sparse sampling of suspended sediment concentration temporally and spatially makes accurate assessment of conditions difficult.

The Texas Water Commission system of segmentation forms the basis for water management in the state (Ward and Armstrong, 1992). The Galveston Bay system has been divided into 37 segments, 19 in the open bays plus 18 in the tributaries for analytical purposes; i.e., for data aggregation by area of the Bay, to support statistical and trend analysis (Ward and Armstrong, 1992). In order to understand the spatial variability of the Bay water quality, data for Salinity, Chl *a* and TSS were analyzed for eight different sections of the Bay—*East Bay*, *West Bay*, *Upper Galveston Bay*, *Lower Galveston Bay*, *Trinity Bay*, *Chocolate Bay*, *Bastrop Bay* and *Christmas Bay* (Fig. 2.18). Analysis of the monitoring stations had to be limited to these 8 geographical regions as a result of the 500 m shoreline buffer that was used as criteria for selecting the monitoring stations. Appendices V, VI and VII describe the list of stations, their respective segment locations and their period of record in the Bay. Results of the analysis for Salinity, Chl *a* and TSS for the TCEQ

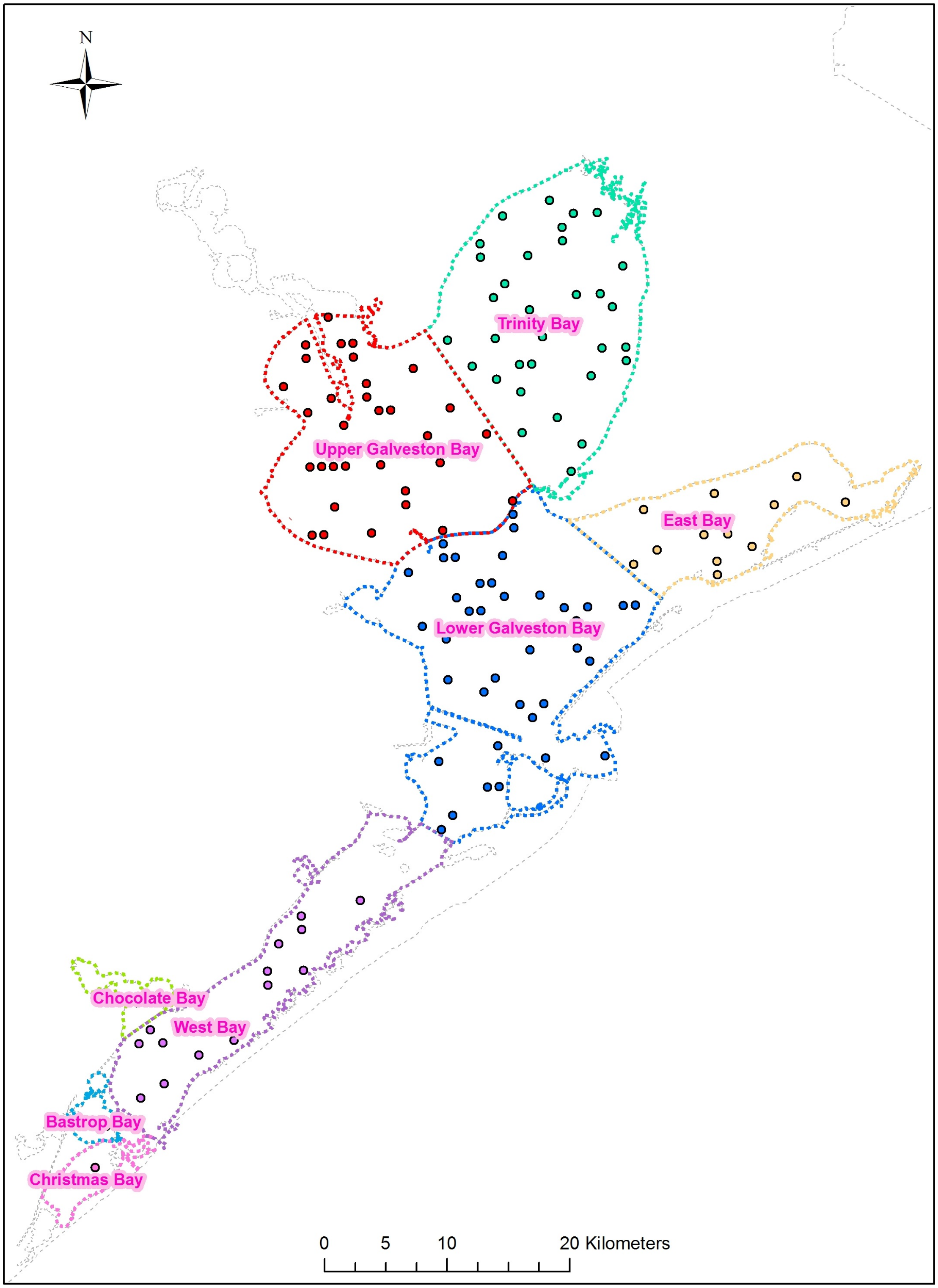


Fig. 2.18 TCEQ Bay Segments and their monitoring station locations

Bay segments have been listed in Appendix IX. A description of the results and interpretation of the time series analyses (Salinity, Chl *a* and TSS) for the 8 different Bay segments (Fig. 2.18) are as follows:

East Bay: The salinity data for the East Bay are available from 1985 to 2009 showing an increasing trend (Appendix IX). According to the GBEP-T7 (Lester and Gonzalez, 2002) report, salinity is higher in both the East and West Bays than the other parts of the Bay due to the high salinity gulf water that enters the bays through the tidal passes.

There were some gaps in the Chl *a* data for the East Bay (Appendix IX). There are no records for Chl *a* from 1980-1984. High Chl *a* concentrations can be seen in the early 1970's followed by a drop in the 1990's after which phytoplankton are on the rise again from 2000 onwards. In contrast to Chl *a*, no significant trends for TSS was observed in the East Bay (Appendix IX).

West Bay: Salinity in the West Bay appears to be high in the 1980’s followed by a drop in the mid-1990’s after which it begins to rise again (Fig. 2.19). According to the GBEP-T7 (Lester and Gonzalez, 2002) report, West Bay experiences the highest average Baywide salinity (15 ppt) due to the influence of more saline gulf waters and the presence of the Texas City Dike (Fig. 1.3). The disposal of dredged material in elongate sites parallel to the Houston Ship Channel act as barriers to flow across the Bay and hence dredged material islands have increased the salinity of the western part of the Bay (Lester and Gonzalez, 2002).

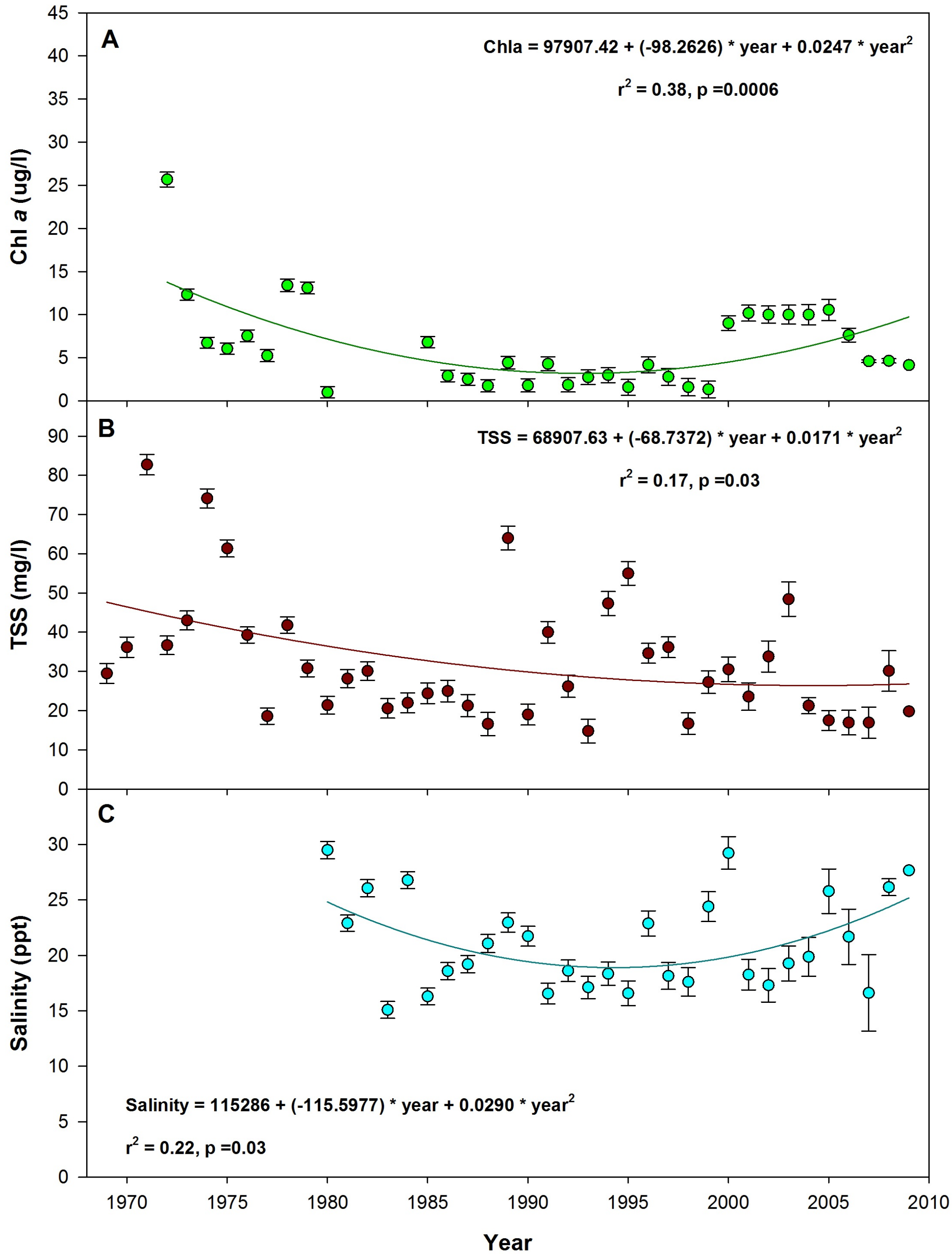


Fig. 2.19 Estuarine Station Average for Chlorophyll *a* (A), TSS (B) and Salinity (C) and in the West Bay

West Bay appears to experience a declining trend in the bay chlorophyll levels from the 1970's (5-25 µg L^{-1}) till the mid 1990's (2-8 µg L^{-1}, Fig. 2.19). However, Chl *a* does appear to increase slightly after 2000 (5-12 µg L^{-1}) and there are no data for chlorophyll *a* from 1981 through 1984 (Appendix IX).

A declining trend in TSS can be observed with very high values in the 1970's (30-80 mg L^{-1}). After 1980 TSS decreased through 2000 (15-40 mg L^{-1}, Fig. 2.19). One of the factors causing the decreased TSS could be declining agricultural activities and higher rates of urban growth, resulting in lower sediment levels from shoreline erosion or river delivery.

Upper Galveston Bay: No significant trend for salinity was observed in the Upper Galveston Bay (Appendix IX). Salinity is low overall (8-20 ppt) due to the urban watershed runoff as well as the San Jacinto River inflow. The Upper Houston Ship Channel is another major contributor of freshwater coming from industrial processing (Lester and Gonzalez, 2002).

Chl *a* values were very high in the early 1970’s (20-60 µg L^{-1}). Chl *a* then declined through the mid 1990’s (2-7 µg L^{-1}) after which it began to rise again (10-30 µg L^{-1}), (Appendix IX). This part of the Bay is adjacent to a highly urbanized and industrial area, and the effects of improvements in effluent discharges after 1970 as documented in the literature review are evident. There are no data for chlorophyll *a* for the years 1981 and 1983 for the Upper Galveston Bay (Appendix IX).

TSS followed a temporal pattern similar to Chl *a* (Appendix IX). There were high concentrations in the 1970’s (24-63 mg L^{-1}) that declined through the mid

1990's (18-30 mg L^{-1}) and then rose again in the last decade ((22-42 mg L^{-1}), Appendix IX).

Lower Galveston Bay: No significant trend in salinity was observed for the Lower Galveston Bay (Appendix IX). Chl *a* concentrations were high in the early 1970's (5-80 µg L^{-1}) and declined through the mid 1990's (3-13 µg L^{-1}), after which Chl *a* started to rise slightly. A similar trend can be observed from the TSS data with high values in the early 1970's (10-60 mg L^{-1}) with a declining trend till the mid 1990's (17-30 mg L^{-1}) after which TSS began to rise slowly towards late 2000s (30-45 mg L^{-1}).

Trinity Bay: There is no indication of any significant trend in salinity in the Trinity Bay (Appendix IX). The Bay is particularly sensitive to the effects of freshwater inflow from the Trinity River (Lester and Gonzalez, 2002); during high river flows (>424.752705 cms), the Trinity Bay is virtually fresh providing conditions for freshwater fish species to thrive (Lester and Gonzalez, 2002). Chl *a* was high in the early 1970's (6-47 µg L^{-1}) and declined through the 1990's (2-8 µg L^{-1}), after which Chl *a* began to rise again (10-33 µg L^{-1}). TSS appears to follow a declining trend from the early 1970's (33-171 mg L^{-1}) through the late 1990's (15-20 mg L^{-1}).

Chocolate Bay: No significant trend in salinity was observed in the Chocolate Bay (Appendix IX). Part of the reason could be due to inconsistent data—this dataset ranged from 1987-2009 with missing data from 1998-2003. Again, for Chl *a*, no significant trend was found. A declining trend in TSS was observed from mid-1970 (31-96 mg L^{-1}) till late 1990's ((17-45 mg L^{-1}), Appendix IX).

Bastrop Bay: No significant trends were observed for Salinity, Chl *a* and TSS probably due to the limited number of observations and data inconsistencies in the Bastrop Bay (Appendix IX).

Christmas Bay: No significant trends were observed for Salinity, Chl *a* and TSS in the Christmas Bay due to data inconsistencies (Appendix IX).

SUMMARY

This chapter is a description of the Galveston Bay Watershed and the estuary in general as well as a review of the stream flow, stream water quality and bay water quality in the study area. Time series analysis for stream hydrology shows increasing trends in river discharge for those USGS stations lying within the highly urbanized area which is an indication of high rates of inter-basin transfer. In order to meet the demands of the growing population, more water has been pumped from the Trinity River, as can be observed from the trends in discharge for the station 08067070 on the CWA Canal in the lower Trinity basin. Some of the stream gauging stations did not show any significant trends in water quality while a few of them did have decreasing trends, particularly in TP. This could be a result of improved waste water treatment and the ban on phosphorus on laundry detergents (Todd Running, H-GAC, pers comm.). Time series analysis of the bay water quality showed more or less similar trends in Chl *a* and TSS for most of the sections of the Bay in general. A continuous declining trend in TSS was observed in the western part of the Bay. The declining Chl *a* and TSS are probably due to the combined effects of reductions in industrial nitrogen loads, improved waste water treatment, altered land use, and impoundments on the principal rivers (San Jacinto and Trinity). In the following chapters, results of these analyses will be related to census and remote sensing data—population and land cover information derived from Landsat TM data.

CHAPTER 3: FOREST COVER CHANGE AND RELATIONS TO HYDROLOGY AND WATER CHEMISTRY IN THE GALVESTON BAY WATERSHED

ABSTRACT

Forested landscapes are most retentive of water as well as sediments and river nutrients. Forests have higher rates of evapotranspiration than other land uses leaving less water for infiltration or overland flow. The effects of natural and anthropogenic disturbances i.e. deforestation in forest cover can be seen in higher water yields producing faster flowing streams along with increased nutrient input to the bays and estuaries where they drain thus affecting the health of the estuarine ecosystem. Time series maps (1985-2010) of the Galveston Bay watershed show a decreasing trend in forest cover for four selected catchments: Brays Bayou, Greens Bayou, East Fork San Jacinto and West Fork San Jacinto watersheds. Out of these, two of the highly urbanized watersheds: Brays Bayou and Greens Bayou show increasing trends in water yield. Results of regression analysis for each individual watershed showed that variations in forest cover did not influence stream hydrology or stream chemistry. Rainfall was the primary driver of water yield for all four catchments. In the case of Brays Bayou and Greens Bayou, forest cover was the secondary cause with a small but significant land use effect on water yield. Linear regression analysis between forest cover and water yield did not yield any significant results. No significant land cover effect was observed for TN and NO_3 for both these catchments. Same was the case with the East Fork San Jacinto and West Fork San Jacinto watersheds where

forest cover and forest disturbance did not have any significant effect on river nutrients (TN, NO_3 and TP). The limited number of observations affected the regression analyses reducing the chance of a significant correlation. Therefore, the data for all four catchments—Brays Bayou, Greens Bayou, East Fork San Jacinto and West Fork San Jacinto watersheds were combined for "space for time-substitution" to increase the number of observations and check for correlations between forest cover and stream hydrology and stream chemistry. Results of the analysis showed that forest cover had a highly significant negative relationship with water yield indicating increasing water yields with decreasing forest cover. Forest cover was the primary driver of water yield followed by rainfall. This was in sharp contrast to what was observed for the regression analysis for all four catchments on an individual basis where rainfall was the primary driver and only significant variable explaining water yield. Highly significant negative correlations were observed between forested watersheds and river nutrients (TN, NO_3 and TP) indicating decreasing levels in nutrient concentrations with increasing forest cover. Results from this research show that anthropogenic changes in the watershed have a significant impact on the river flow and stream water quality. Removal of forest cover for development leads to higher water yields resulting in faster flowing streams and flooding during storm events. Increasing water yields and anthropogenic land uses also increase nutrient inputs to streams. Higher freshwater flows along with nutrient inputs make the Bay more susceptible to eutrophication. With rising temperatures as a result of global warming, eutrophication in the Bay could become more severe and lead to increased hypoxia ultimately resulting in fish kills during the warm summer months.

3.1 Introduction

Forest is a critical component of the Earth's surface (Huang et al., 2008). Thirty-three percent of earth's land area is forested. Forests process nearly two-thirds of the fresh water supply and provide water to about 180 million people in the United States (Jones et al., 2009). Besides water, forests provide refuge for wildlife, timber and recreation.

Strong connections exist among forest, water and people. Forests cycle water from precipitation through soil, return some to the atmosphere via evapotranspiration, and ultimately deliver a fraction as stream flow (NAS Report, 2008) that is used to supply the local population in the watershed. The quantity and quality of downstream water resources are largely influenced by changes in forested head water areas which include the tributary streams that feed into the rivers (NAS Report, 2008). Hence forests and water are closely intertwined. Removal of forest cover results in a decrease in evapotranspiration and an increase in the proportion of precipitation that becomes stream flow (Jones et al., 2009), and hence in certain areas cutting trees causes an increase in the volume of water flowing downstream (NAS Report, 2008). Forests generally have higher rates of evapotranspiration than agricultural or urban land uses, leaving less water available for groundwater or overland flows to streams (Mustard and Fisher, 2004). Besides retaining precipitation, land cover under forests is the most retentive of water as well as particulates and dissolved materials. Thus, conversion of forest to anthropogenic land uses increases the total flow as well as the volume and erosive power of storm flows while decreasing base flows (Mustard and Fisher, 2004). From a water quality perspective, water draining from forested watersheds is generally of the highest quality, and this has been one of the driving factors for establishment of forest reserves and for development of forest management practices designed to protect this high quality (Schoenholtz, 2004).

Forests are subjected to disturbances arising from various management activities as well as natural events (Huang et al., 2009a). Drought, outbreaks of insects and pathogens, wildfire, storms and ecological succession alter the ability of forests to provide abundant clean water in the headwaters of the water supply systems (Jones et al., 2009; Eshleman et al., 2008). Forest management activities in some cases such as road construction, harvesting, site preparation for regeneration of forest tree species, and fertilization of existing forests have been shown to alter water quality by causing changes in sediment loads, stream temperature, dissolved oxygen and dissolved nutrients, particularly nitrogen (Schoenholtz, 2004). Therefore, continuous monitoring of forest changes is necessary to determine such disturbances and the post-disturbance recovery processes in order to assess the conditions of the forests, address critical water issues and monitor the effectiveness of management approaches for developing sound management strategies (Huang et al., 2009a).

3.1.1 Hypotheses

This chapter analyzes the annual variations in forest cover and forest disturbance and their influence on stream hydrology and stream chemistry in selected catchments in the Galveston Bay watershed (Fig. 1.1). This watershed drains into the Galveston Bay which is the largest (1,456 km^2) and most urbanized of all estuaries in Texas and supports a population of more than four million inhabitants in five counties bordering the Bay (Thronson and Quigg, 2008). The Galveston Bay watershed consists of 8.5 x 10^4 km^2 of land and water (Lester and Gonzalez, 2002) extending inland from the Gulf of Mexico approximately 643.7 km to eventually encompass the Dallas-Ft Worth metroplex (Keith et al., 2002). The San Jacinto and Trinity (Fig. 1.2) are the two main rivers that provide most of the freshwater to the Bay. Besides these, the watershed comprises a multitude of bayous, streams and rivers that carry surface flow to the Bay. A bayou is a water body typically found in flat, low-lying areas and can refer to an extremely slow-moving stream or river or to a marshy lake or wetland (http://dictionary.reference.com/browse/bayou?s=t). The bayous are the most common form of tributary to the Galveston Bay and operate primarily as extensions of the tidal bay system changing their nature from source to mouth (Lester and Gonzalez, 2002). Based on the basin hydrology and their impact on the Bay, the Galveston Bay watershed can be divided into two parts: the lower watersheds comprising the area draining to the Bay downstream of two major impoundments: (a) *Lake Houston* on the *San Jacinto River* and (b) *Lake Livingston* on the *Trinity River* (Fig. 1.2) and upper watersheds which include the drainages upstream of these two main reservoirs.

The hypotheses for this research are as follows:

H1: There is an inverse relationship between annual water yield and annual forest cover

H2: Forest cover and river nutrients (TN, NO_3 and TP) are inversely related

3.2 <u>Watershed Description</u>

The impact of forest cover change and disturbance rates on stream hydrology and chemistry was analyzed for four selected catchments within the Galveston Bay watershed: the *Brays Bayou* and the *Greens Bayou* watersheds near Houston, the *East Fork San Jacinto River watershed near New Caney* and the *West Fork San Jacinto River watershed near Lake Conroe* (Fig. 3.1). Details of the four watersheds with their drainage area, percent land use and total population in 2010 is provided in Table 3.1.

3.2.1 Brays Bayou Watershed

The Brays Bayou watershed (Fig. 3.2) is a fully urbanized watershed encompassing 253.6 km^2 of land draining to USGS station 08075000 southwest of the city of Houston, Texas. The watershed lies within two counties—approximately 87 percent of the watershed area lies within Harris County and the remaining 13 percent in Fort Bend County (Technical Support Document, 2009). The Bayou flows eastward from Fort Bend County to its confluence with the Houston Ship Channel (Harris County Flood Control District—Brays Bayou Watershed, Figs. 1.2 and 3.1) draining parts of the cities of Houston, Missouri City, Stafford, Bellaire, West University, Southside Place and Meadows. There are 194.7 km of open streams within the watershed including three primary streams: *Brays Bayou*, *Keegans Bayou* and *Willow Waterhole Bayou* (Fig. 3.2).

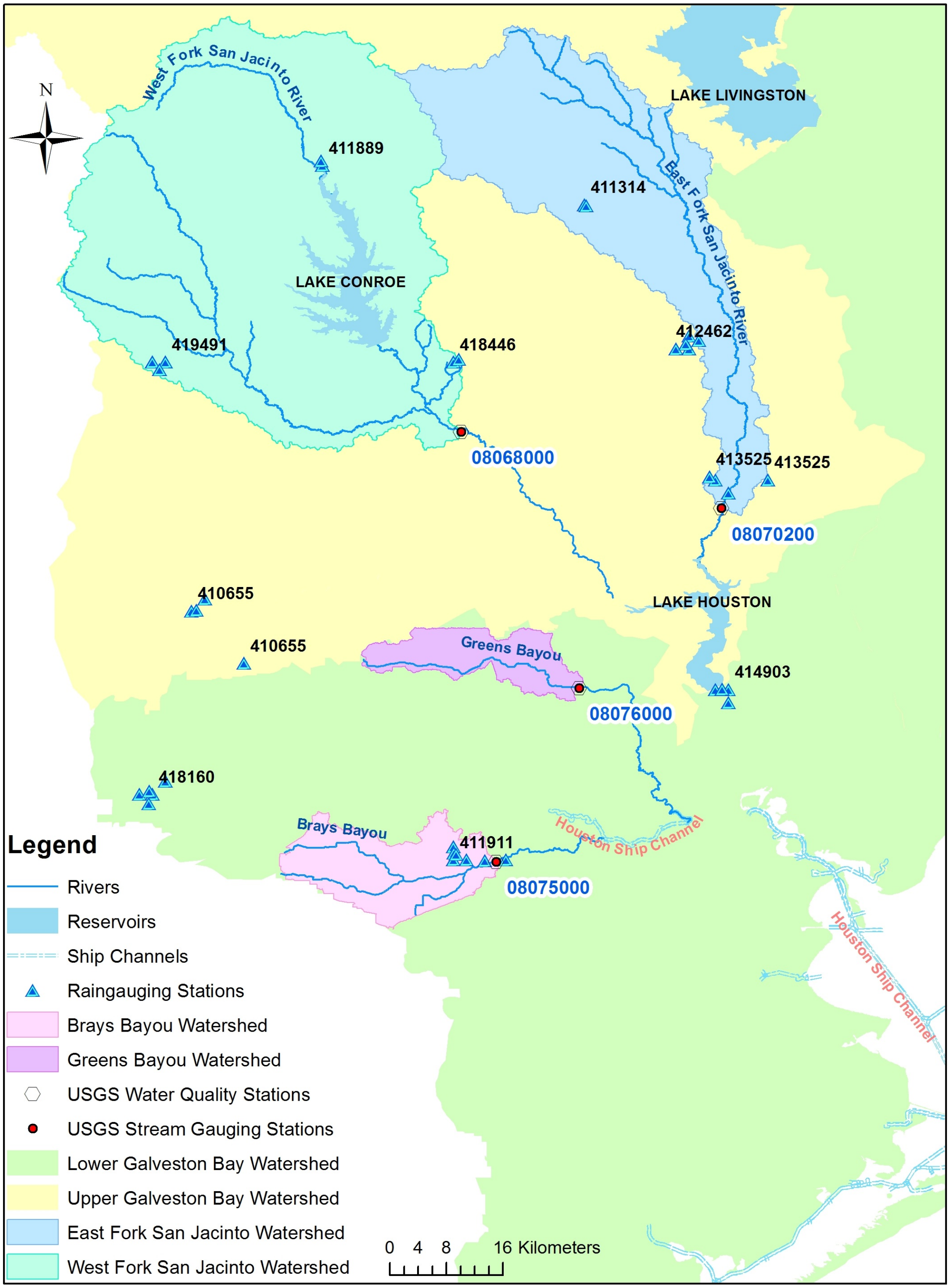


Fig. 3.1 Catchments with the USGS Stream Monitoring Stations and Rain Gauging stations in the Galveston Bay Watershed

Watershed	Drainage Area (km^2)	% Landuse (2009)							Total Population (2010, Block Level)
		Urban	Agriculture	Pasture	Barren	Forest	Water	Wetlands	
Brays Bayou	253.6	89.3	0.9	4.2	0.6	4.7	0.01	0.2	653231
Greens Bayou	153.3	58.5	3.9	13.5	2.8	17.9	0.03	3.3	184300
East Fork San Jacinto	984.9	6.1	4.9	17.1	0.9	51.8	0.2	18.9	20903
West Fork San Jacinto	2147.6	4.9	7.8	27.5	0.9	40.9	3.9	13.9	115232

Table 3.1 Watersheds with their drainage area, percent land use (derived from LULCC classification in Chapter 4) and total population in 2010

Fig. 3.2 Brays Bayou Watershed at Houston. Inset graph shows the location of the Brays Bayou watershed within the lower Galveston Bay Watershed. The high irregular stream pattern in the watershed is a result of channelization.

The region experiences subtropical humid climate with very hot and humid summers and mild winters. The average daytime summer temperature is

34^0C, while averaging between 4 and 16 ^0C during the winter season. Rainfall is basically dominated by subtropical convection in the summer, frontal storms during the winter, and a combination of these two during the fall and spring seasons (Technical Support Document, 2009). Fig. 3.3 shows the monthly mean seasonality in the air temperature, rainfall, river discharge and river chemistry in the Brays Bayou Watershed. Land use is predominantly urban with several large parks and regions of open space within the watershed (Technical Support Document, 2009). The total population of the Brays Bayou watershed in 2010 lying within the Harris County was around 653,231 (U. S. Census Bureau).

3.2.2 Greens Bayou Watershed

The Greens Bayou is a tributary of the Buffalo Bayou (Fig. 3.4) in Houston, Texas (Greens Bayou Reevaluation Report, 2005) and drains an area of 153.3 km^2 at USGS station 08076000. The upper reach of the Greens Bayou flows eastward while the lower reach flows south into the Houston Ship Channel (Figs. 1.2 and 3.1). The watershed is located in north central Harris County, approximately 10 miles north of the central business district of the city of Houston and is highly developed urban land studded with wastewater outfalls (Technical Support Document, 2009).

The topography of the drainage basin is typical of the Texas Gulf Coastal Plains. The area is flat, grassy and mostly treeless, with elevations ranging from about 6 m above sea level near the mouth of the bayou to about 41 m near its headwaters (Greens Bayou Reevaluation Report, 2005).

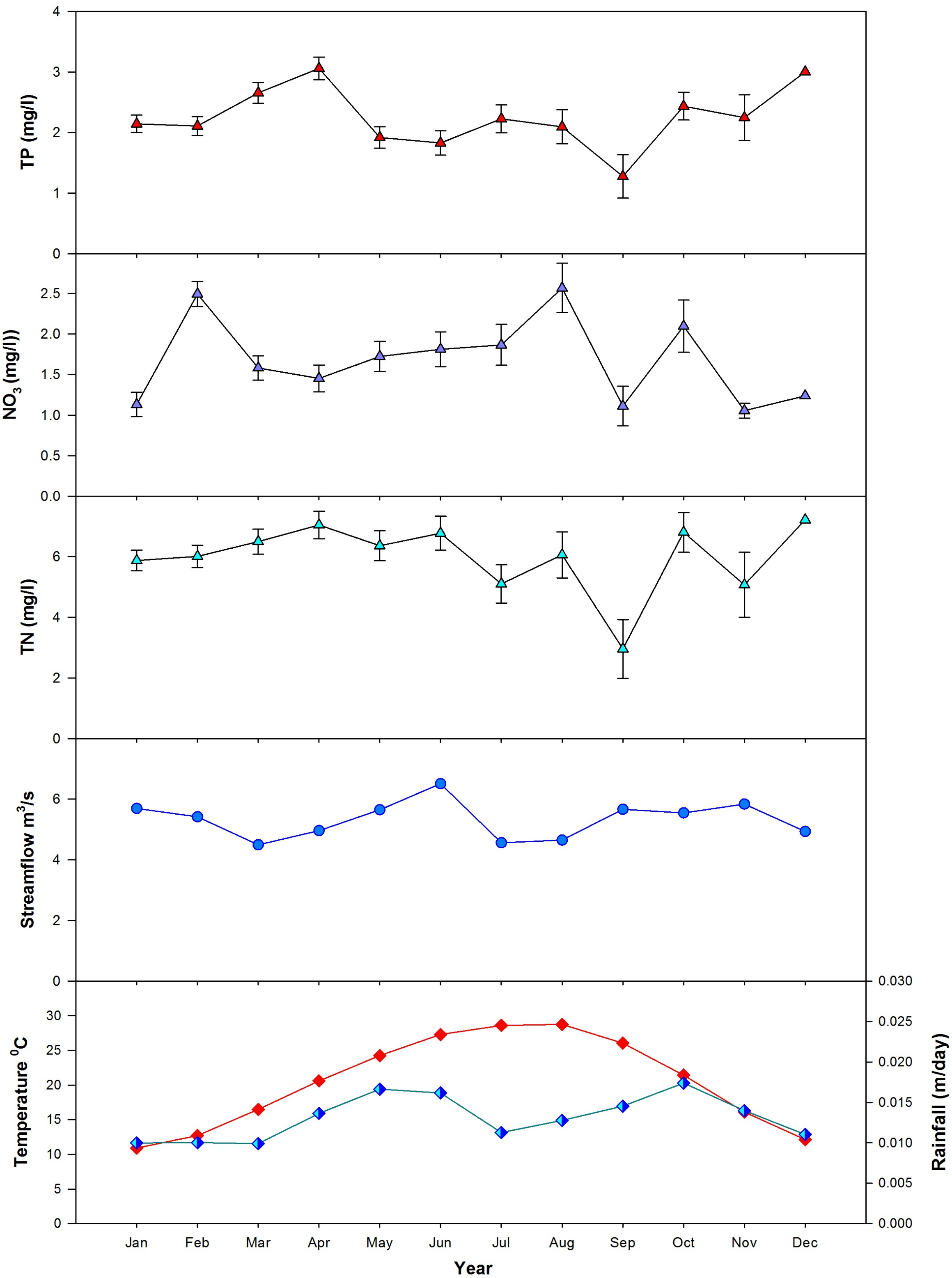


Fig. 3.3 Mean monthly seasonality of air temperature, rainfall, river discharge and river chemistry in the Brays Bayou Watershed

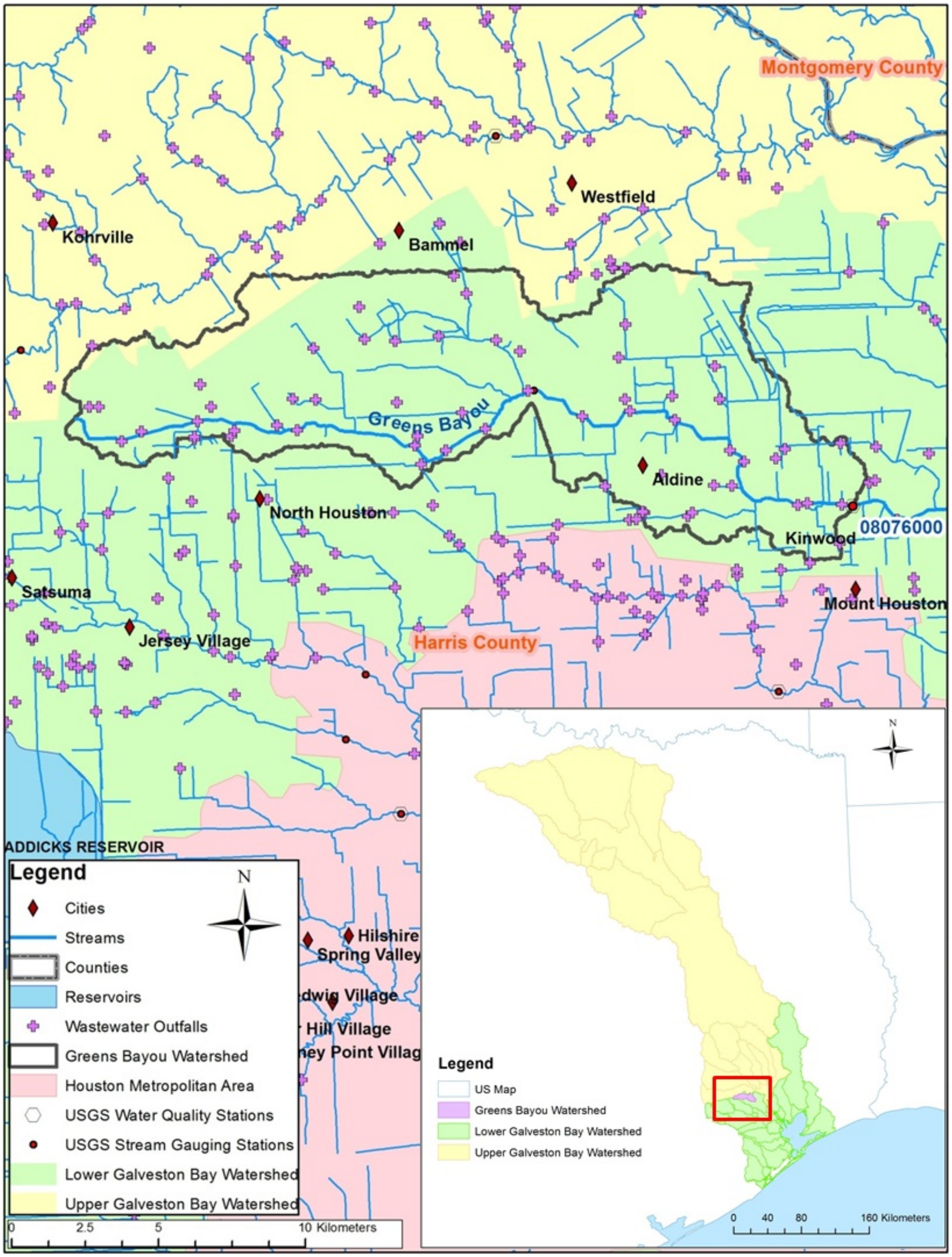


Fig. 3.4 Greens Bayou Watershed near Houston

Soils are mostly clay contributing to higher runoff than percolation, and the rapid development and high average annual rainfall (1 m/y) combine to make the area prone to damaging floods (Greens Bayou Reevaluation Report, 2005). The climate is very similar to that of the Brays Bayou watershed—hot and humid summers and mild winters.

3.2.3 East Fork San Jacinto Watershed near New Caney

Originating in San Jacinto County, the East Fork San Jacinto River (Fig. 3.5) flows 74 km into Harris County where it joins the West Fork and creates Lake Houston (Figs. 1.2 and 3.1). The river is extremely narrow and shallow and retains most of its natural characteristics as it flows through Sam Houston National Forest (Texas Parks & Wildlife Department). Its tributaries include Mill, McCombs, Johnson, Negro, Sand and Miller Creeks (Handbook of Texas Online).

The East Fork San Jacinto River drains an area of 984.9 km^2 at USGS station 08070200 and is the least densely populated of the seven sub-watersheds that drain to Lake Houston (Oden et al., 2010). As per 2000 census statistics, the watershed had a population density of about 30.9 people per km^2 (Oden et al., 2010). Urban and agricultural land together constitutes 18 percent of the land use in the watershed, with the remainder in forest (Oden et al., 2010). The climate is humid and subtropical, characterized by cool temperate winters and long hot summers with high humidity (Oden et al., 2010).

Fig. 3.5 East Fork San Jacinto Watershed near New Caney

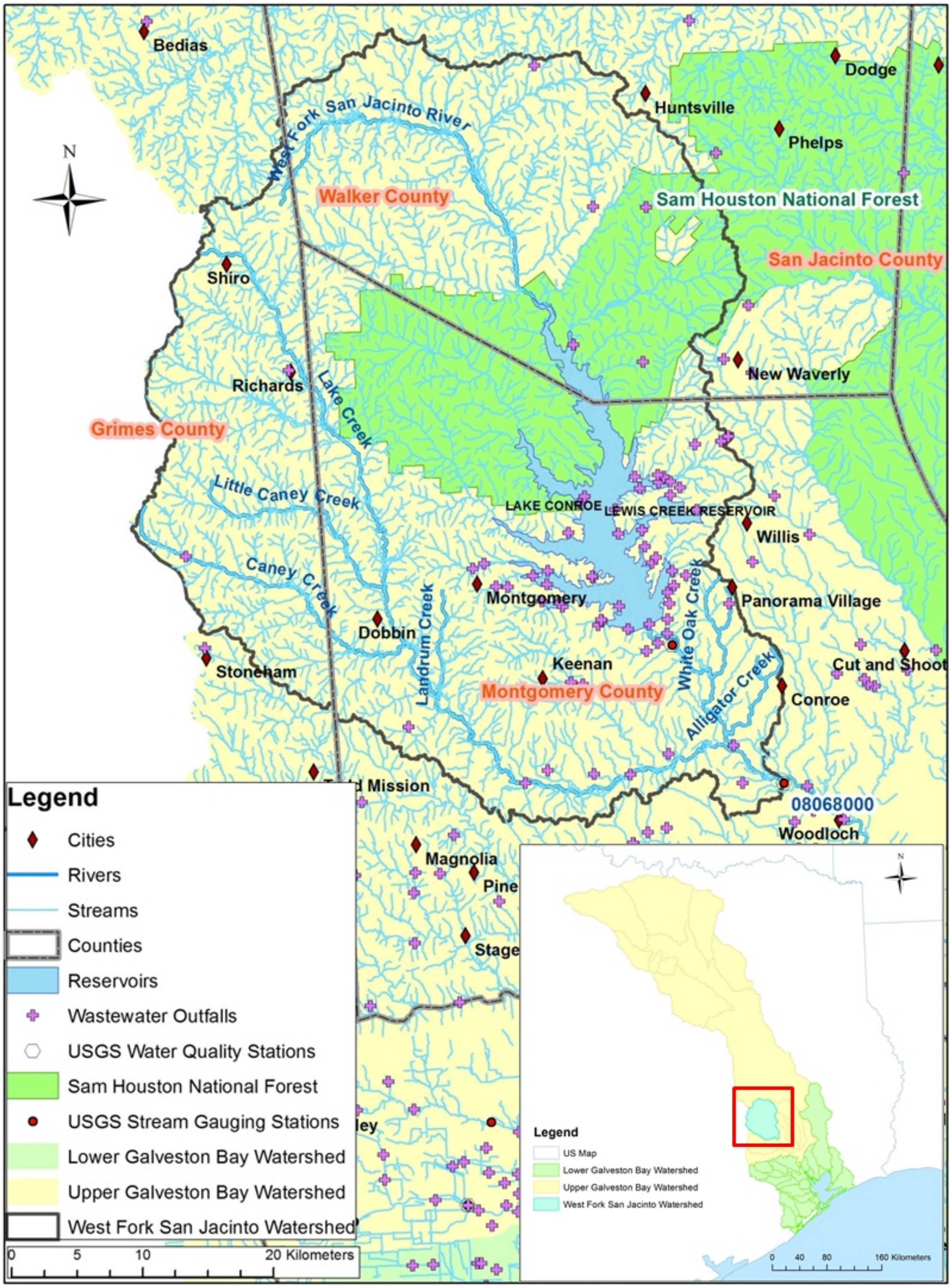


Fig. 3.6 West Fork San Jacinto Watershed near Conroe

3.2.4 West Fork San Jacinto Watershed near Lake Conroe

The headwaters of the West Fork San Jacinto River (Fig. 3.6) originate in Walker County, draining an area of 2147.6 km^2 at USGS station 08068000 (Bodkin & Oden, 2010). Its tributaries include Lake Creek, White Oak, and the West Fork San Jacinto River. In order to help meet the municipal water-supply needs of Houston, the river was dammed in 1973 to form the 24 km-long Lake Conroe (Handbook of Texas Online) that receives much of the inflow from the West Fork San Jacinto River. Lake Conroe has a storage volume of 531 x 10^6 m^3 (Bodkin & Oden, 2010). Downstream from Lake Conroe, the river flows through Montgomery County and a small portion of Harris County before merging with Lake Houston—a municipal water supply reservoir that was impounded in 1954 (Bodkin & Oden, 2010). Timber dominates the northern part of the West Fork San Jacinto watershed which has a gently rolling topography while the southern part is mostly prairie. Land cover primarily includes municipal, commercial, agricultural, forested, and residential area while downstream from Lake Conroe is predominantly a woody wetland with some hay pastures and mixed forest (Bodkin & Oden, 2010). A mix of land covers from open space to high-intensity developments are found in Conroe and other towns and cities in the watershed. Climate is humid subtropical characterized by high relative humidity, long hot summers and short temperate winters. Population density in the West Fork San Jacinto basin ranges from 17 to 212 people per km^2 (Bodkin & Oden, 2010).

3.3 Datasets

3.3.1 Landsat TM

Landsat TM imagery was used to generate forest cover maps and evaluate forest disturbance history in the Galveston Bay watershed. To be able to analyze forest disturbance for the entire Landsat Record (1972-present) would have been ideal; however the time frame had to be restricted from 1985 onwards owing to poor quality TM data prior to 1984 as well as differences in sensors (TM and MSS) and their spectral and geometric characteristics. The data were downloaded from GLOVIS for the period 1985 to 2010 May-October, when the forest cover was at its peak (pers comm, C. Huang). This was necessary to maintain a consistent seasonal landscape condition from one year to next. High quality Landsat acquisitions are needed to constitute a Landsat Time Series Stack (LTSS) which refers to a sequence of Landsat images acquired at a nominal temporal interval for a particular Worldwide Reference System (WRS) path/row tile (Huang et al., 2009b). The Galveston Bay watershed constitutes a total of 8 path/row tiles. Although the goal was to select one image every year for an annual LTSS, multiple scenes had to be acquired to substitute pixels for those images that had cloud cover.

3.3.2 Precipitation

Data on daily rainfall were acquired from the National Climatic Data Center for 10 stations located in and around the 4 catchments—Brays Bayou, Greens Bayou, East Fork San Jacinto near New Caney and West Fork San Jacinto near Conroe. Appendix I describes the station locations and their period of record. The mean annual rainfall (m/year) averaged from the daily precipitation data were used as an independent variable for the multiple linear regression models describing water yield and water chemistry.

3.3.3 Streamflow

The stream discharge data were obtained for the USGS stream gauging stations at the mouths of the watersheds. The stream gauging stations for the 4 catchments with their period of record are listed in Table 3.2. The average annual stream discharge (cubic feet per second) as reported by USGS was converted to water yield ($m\ y^{-1} = m^3$ water m^{-2} land area y^{-1}) for all stations using the watershed area (m^2). This was followed by linear and non-linear regression analysis of year versus water yield to test for trends in stream flow using SigmaPlot VII.0 software.

3.3.4 Stream Water Quality

The water quality data include annual averages of the USGS TN (mg/l), nitrate (mg/l) and TP(mg/l) data (calculated by averaging the daily data over a period of one year) from the stream gauging stations for Brays Bayou, Greens Bayou, East Fork San Jacinto and West Fork San Jacinto watersheds. Table 3.2 lists the USGS stations, their respective basins and their period of record for TN, nitrate and TP data. SigmaPlot VII software was used to test for linear and non-linear trends in annual TN, NO_3 and TP.

USGS Station	Location		Period of Record	Basin	Drainage Area (km^2)	Period of Record		
	Latitude	Longitude				TN	NO_3	TP
08075000	29°41'49"	95°24'43"	1937-2009	Brays Bayou at Houston, TX	253.6	1974-1985 1987-1998	1969-1985 1987-1998	1969-1985 1987-1998
08076000	29°55'05"	95°18'24"	1953-2010	Greens Bayou near Houston, TX	153.3	1974-1985 1987-1998	1968-1985 1987-1998	1969-1985 1987-1998
08070200	30°08'43"	95°07'27"	1985-2010	East Fork San Jacinto River near New Caney, TX	984.9	1983-1999 2004-2008 2010	1983-1999 2004-2008 2010	1983-1999 2004-2008 2010
08068000	30°14'40"	95°27'25"	1973-2010	West Fork San Jacinto River near Conroe, TX	2147.6	1974-1994	1961-1979 1983-1994	1969-1994

Table 3.2 USGS Stream Gauging Stations with their locations and period of record for stream flow, TN, nitrate and TP

3.3.5 GIS Data

The GIS data included the watershed boundaries of the upper and lower Galveston Bay watersheds, stream network, lakes and reservoirs, USGS stream monitoring stations, rain gauging stations, county boundaries, urban areas, cities, ship channels and wastewater outfalls. This data have been obtained from several sources: Trinity River Authority (TRA), Houston-Galveston Area Council (H-GAC), U. S. Census Bureau, United States Geological Survey (USGS) and the National Climatic Data Center (NCDC). Appendix VIII describes the list of GIS data and their respective sources. The catchment boundaries for Brays Bayou, Greens Bayou, East Fork San Jacinto and West Fork San Jacinto watersheds have been delineated using the USGS EDNA viewer (http://edna.usgs.gov/EDNA_Viewer/viewer.php). Using the monitoring stations as the watershed outlet, the four catchments were delineated for each individual station upstream of the gauge.

3.4 Approach

This research is based on studying the association between forest cover on stream hydrology and stream chemistry in the Galveston Bay Watershed. The percent forest cover and forest disturbance were used as independent variables along with precipitation data, in multiple linear regression models to describe and predict annual water yield and nutrient data (TN, NO_3 & TP) for four individual catchments that were delineated for the USGS stream gauging stations within the Galveston Bay watershed. The methodology that was adopted to produce the forest cover and disturbance maps for the multiple linear regression analysis is described in Fig. 3.7.

3.4.1 Remote Sensing Analysis

3.4.1.1 Forest Cover Mapping

In one study, Huang et al., (2009b) observed that owing to vigorous forest regrowth in many areas, the signal of a forest disturbance may be lost quickly and become spectrally undetectable in just a few years. Hence some changes may not be captured when analyzed over long temporal intervals (Huang et al., 2009b). For research on rapid changes in land cover, maps are typically generated over a temporal interval of 5 to 10 years; however, this interval is inadequate to capture forest disturbance. In order to quantify forest cover disturbance, maps for each individual year for the Galveston Bay Watershed were created from Landsat TM data. The data were downloaded from GLOVIS for the period 1985 to 2010 for May-October, when the forest cover was at its peak (pers comm. C. Huang). The annual forest cover and disturbance area for the multiple linear regression model were derived from the forest cover change maps with the help of the *Vegetation Change Tracker (VCT)* algorithm (Huang et al., 2010a).

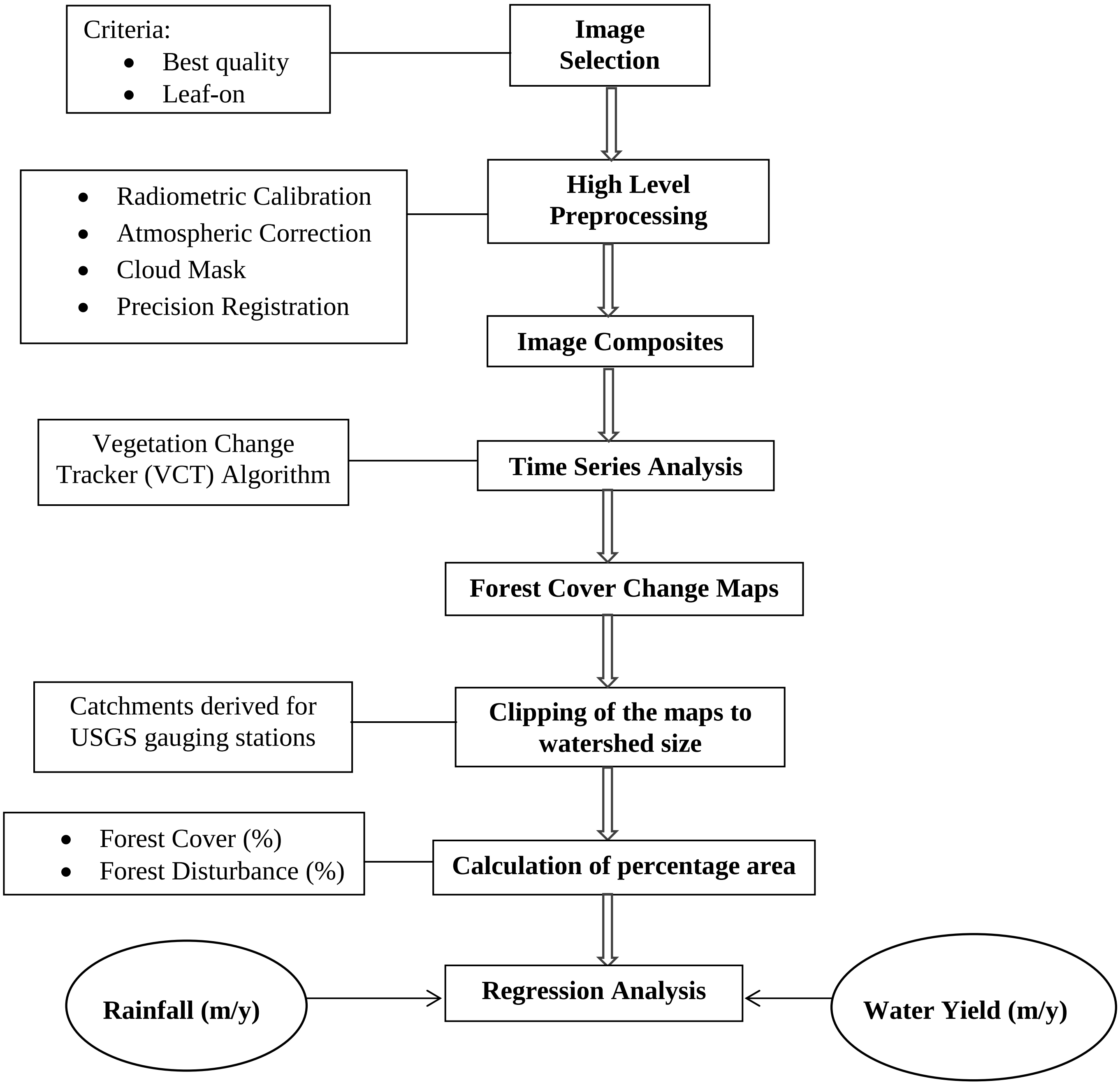


Fig. 3.7 Flowchart showing the steps involved in deriving the Forest Cover Change maps using the Vegetation Change Tracker (VCT) algorithm and the regression analysis for the catchments within the Galveston Bay Watershed.

3.4.1.2 Vegetation Change Tracker Algorithm

The *Vegetation Change Tracker (VCT)* algorithm developed by Huang et al., (2010a) is a highly automated change detection algorithm which can be used to analyze all images of a time series stack of Landsat (LTSS) at the same time. Huang et al., (2009a) used this algorithm to evaluate the dynamics of seven National Forests in the eastern U.S. for the period between 1985 and 2006. This study was done with a nominal interval of one image every 2 years for each of the National Forests to map forest disturbance. The derived disturbance maps had overall accuracy values of about 80% with most of the disturbance classes having user's accuracies ranging from 70% to 95 % (Huang et al., 2009a).

The VCT algorithm comprises two major steps (Thomas et al., 2011): (1) individual image analysis and (2) time series analysis. The annual maps of forest disturbance produced from VCT identify three static classes—persistent forest, persistent non forest, and water. In addition, it flags the year of disturbance for all pixels where forest change was detected. The following is a description of the mapped classes:

- Persistent Forest – This class is comprised of pixels that remained forested throughout the time series.
- Persistent Nonforest – This class consists of pixels that were never forested during the entire observing period of the time series
- Persistent Water – This class consists of pixels that were water pixels throughout the observing period.

- Forest Disturbance – This constitutes forested pixels that are not classified as one of the persisting land cover classes. It contains the time step in which the disturbance event occurred.
- Pre-series Disturbance – This class comprises pixels that are classified as nonforest during time 1 of the series but change to forest at some point during the observation period. This category includes both forest regrowth and afforestation processes. It is categorized as *previously disturbed but looked like forest by a given year* in the map legend.
- Post Disturbance Nonforest – This class includes pixels that indicate forest disturbance long ago and have been converted into another land cover class

The annual map product of forest disturbance summarizes forest cover changes in the study area that have occurred during the observation period of 1985-2010 (Thomas et al., 2011).

3.5 Results

3.5.1 Forest Cover Trends

Once the maps were derived from VCT (Fig. 3.8), the percentage area was calculated for the forest cover and disturbance classes. The *persistent forest* and *previously disturbed but looked like forest by this year* classes were combined to derive the total forest cover for each year. Time series plots (Fig. 3.9) of *Forest Cover* and *Forest Disturbance* for the entire Galveston Bay Watershed were constructed to analyze the trends in forest cover change and disturbance from 1985 to 2010. Forest cover in the Galveston Bay watershed ranged over 24-29 % with the percent disturbance ranging over 0.4-2.2% during 1985-2010. There was minimum disturbance in 1990 which was followed by the maximum forest growth in 1991 with 29.6 % area under forest cover. Year 2000 had the minimum forest cover with 24.3% area due to the high forest disturbance that occurred in the preceding years—1998 and 1999 which was 2.14 and 2.16% respectively. Similar changes also occurred in 2005.

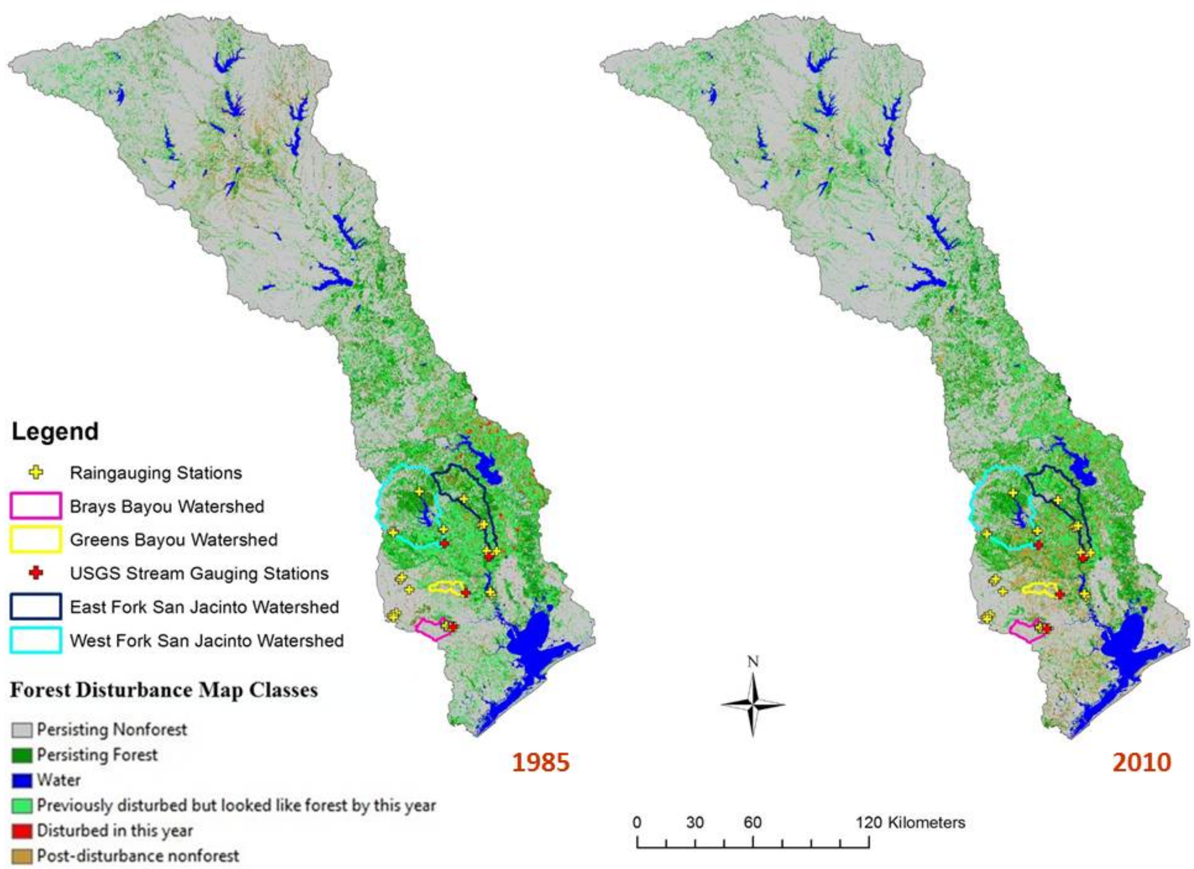


Fig. 3.8 Forest Disturbance Maps for the Galveston Bay Watershed for 1985 and 2010

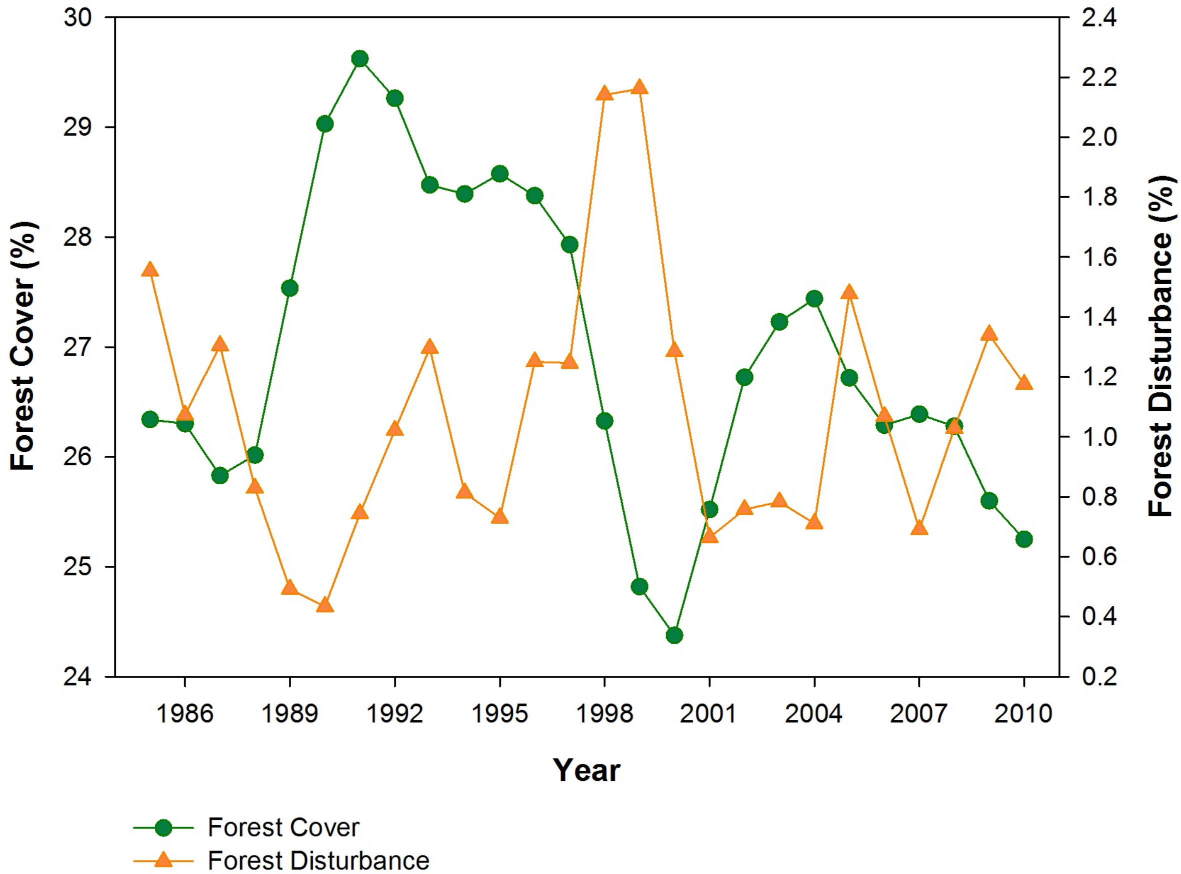


Fig. 3.9 Time Series plots showing the trends in Forest Cover Change and Forest Disturbance for the Galveston Bay Watershed from 1985 through 2010

For hypothesis testing, the annual variations in forest cover were analyzed for the 4 selected catchments in the Galveston Bay Watershed (Figs. 3.10, 3.12, 3.14, 3.16). The percentage area for forest cover and disturbance classes were calculated for each year for *Brays Bayou*, *Greens Bayou*, *East Fork San Jacinto River watershed near New Caney* and the *West Fork San Jacinto River watershed near Lake Conroe* (Figs. 3.11, 3.13, 3.15, 3.17). These data were then used to examine their association with stream hydrology and stream chemistry.

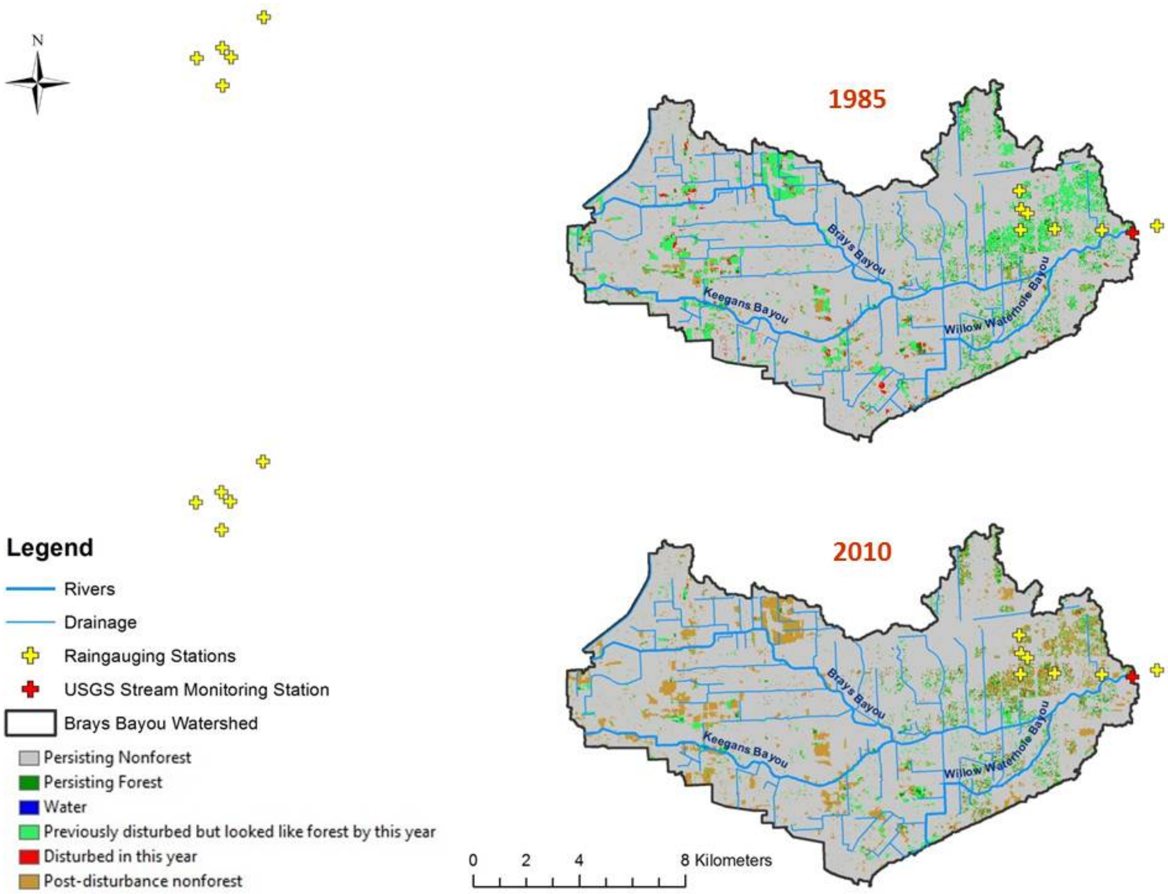


Fig. 3.10 Forest cover change in the Brays Bayou catchment from 1985 through 2010

3.5.1.1 Forest Cover Change in the Brays Bayou Catchment

There were significant changes in percent forest cover in the Brays Bayou catchment. Based on the time series plots (Fig. 3.11) derived from the VCT maps (Fig. 3.10), the Brays Bayou watershed experienced low but steady levels in forest cover (10-11%) during 1985-1996, followed by a steady decline in forest cover

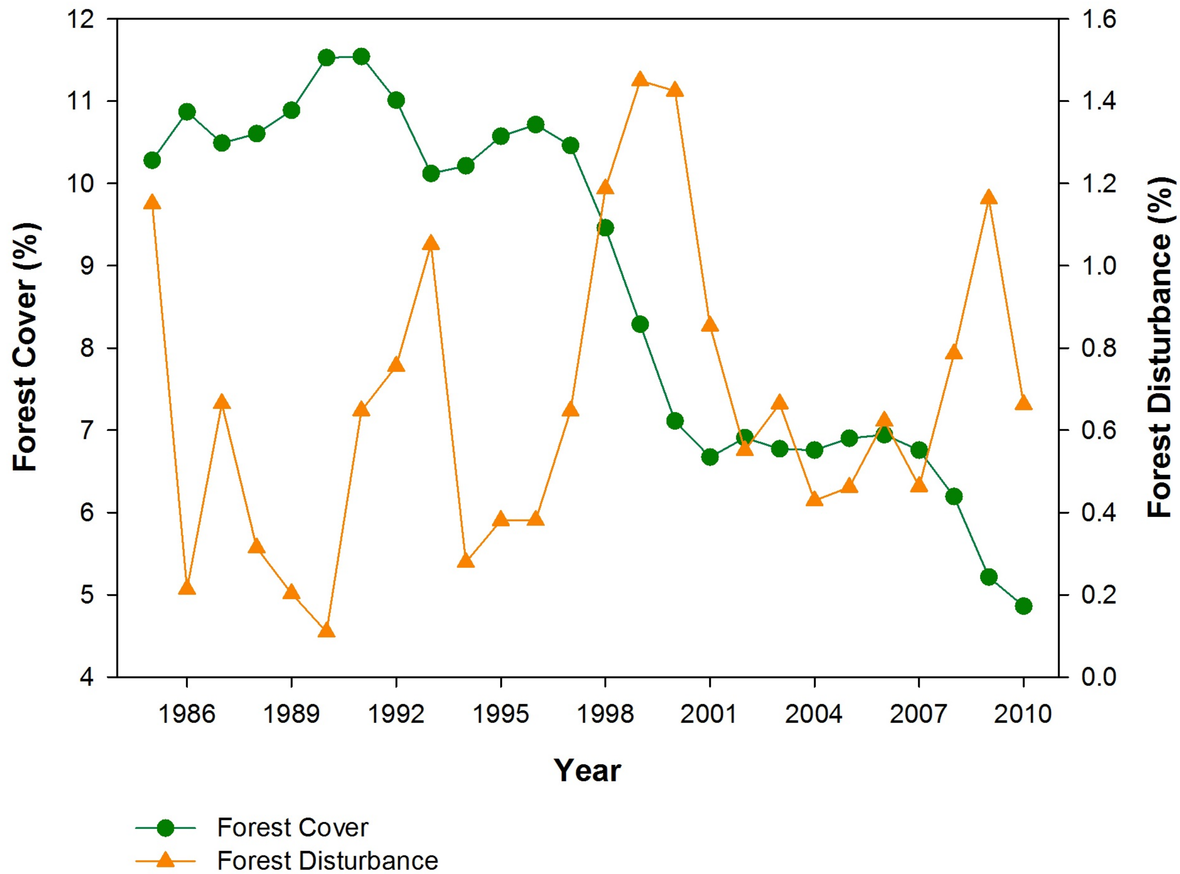


Fig. 3.11 Time Series plots showing the trends in Forest Cover Change and Forest Disturbance for the Brays Bayou Watershed from 1985 through 2010

from 11 % in 1996 to 4.9 % in 2010. Forest cover for this period appears to be at its peak in 1991 with 11.5% of the catchment under forests because it was preceded by a minimum disturbed area of 0.1% in 1991. The maximum disturbance occurred in 1999 (1.45 %), while 2010 marked the year with the minimum area under forest cover in the Brays Bayou watershed.

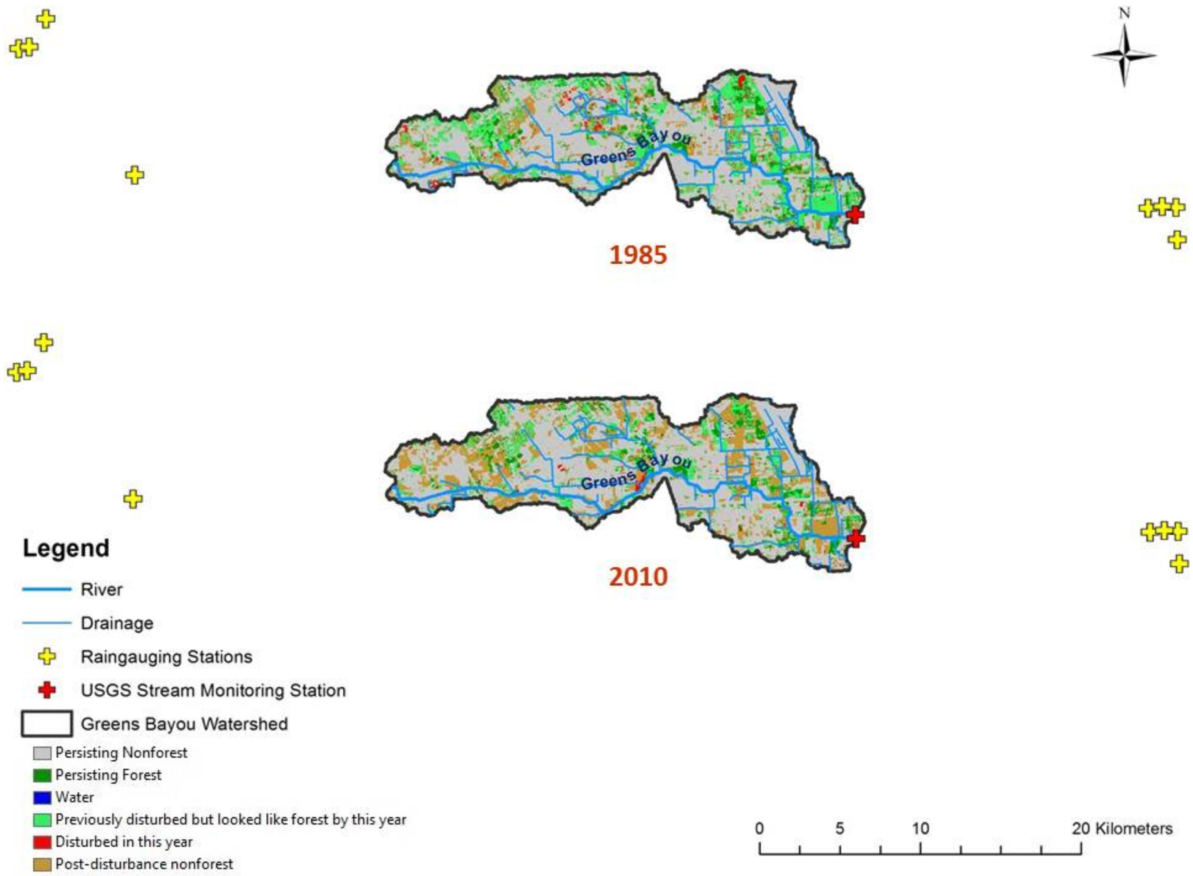


Fig. 3.12 Forest cover change in the Greens Bayou catchment from 1985 through 2010

3.5.1.2 Forest Cover Change in the Greens Bayou Catchment

Greens Bayou catchment also exhibited significant changes in forest cover (Fig. 3.12). An increasing trend in percentage area under forests was observed from 25.5% in 1985 to 34.3 % in 1991 (Fig. 3.13) when forest cover was at its peak following the year of minimum disturbance of 0.14 % in 1990. After 1991, forests in the Greens Bayou catchment (Fig. 3.13) declined with their values reaching a minimum of 15.9% in 2010, which is less than 50% of the total forest area in 1991. This decline in forest cover was largely due to urbanization (See Chapter 4).

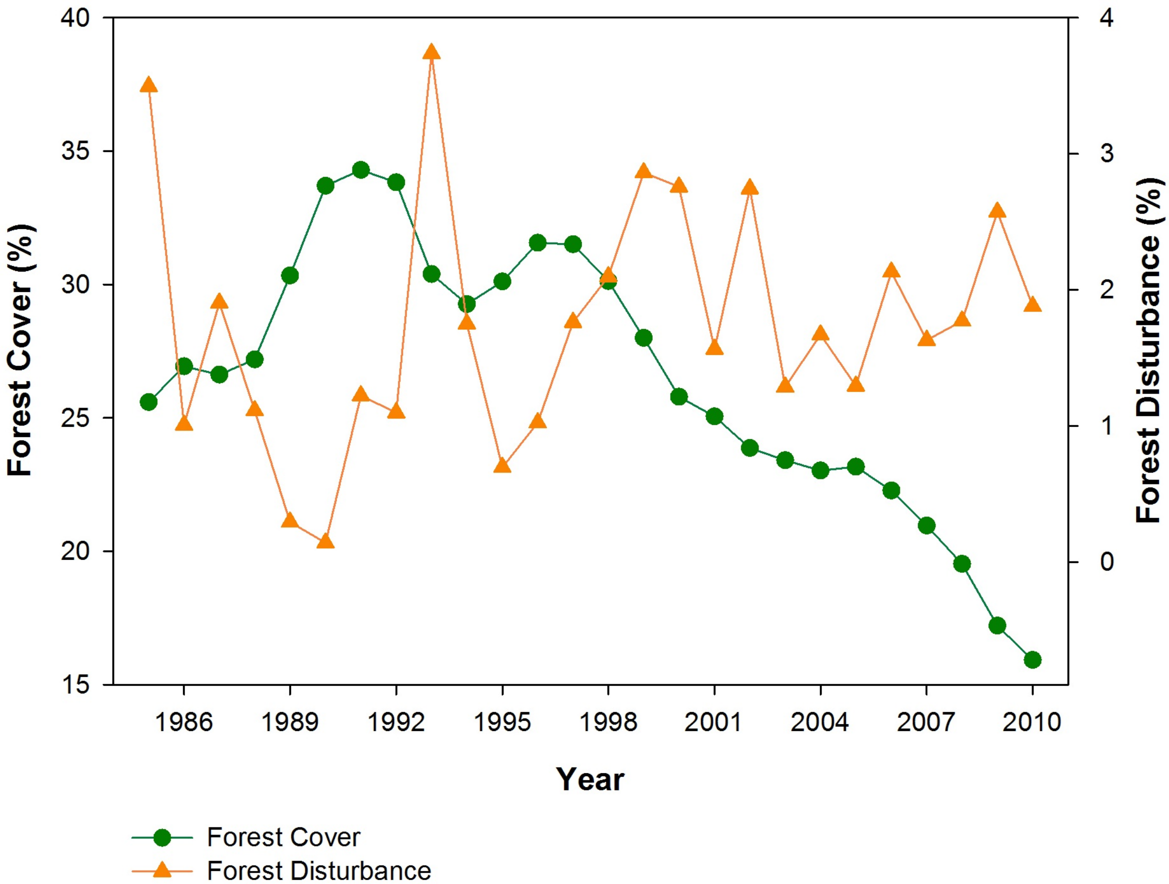


Fig. 3.13 Time Series plots showing the trends in Forest Cover Change and Forest Disturbance for the Greens Bayou Watershed from 1985 through 2010

3.5.1.3 Forest Cover Change in the East Fork San Jacinto Catchment

Unlike the previous two watersheds, the East Fork San Jacinto catchment is largely forested. Encompassing a large part of the Sam Houston National Forest (Texas Parks & Wildlife Department), the majority of the catchment area of the East Fork San Jacinto watershed was under forest cover (Fig. 3.14). The trend analysis

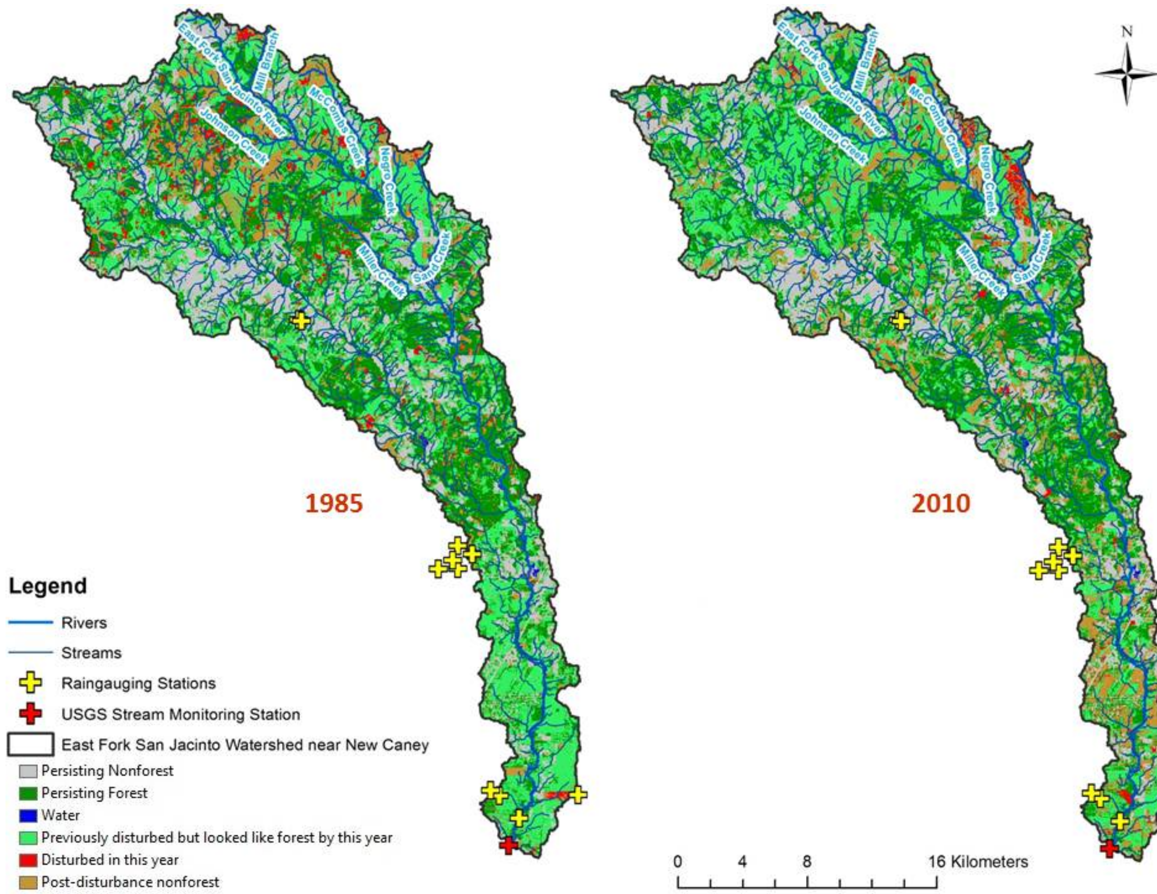


Fig. 3.14 Forest cover change in the East Fork San Jacinto Watershed near New Caney from 1985 through 2010

(Fig. 3.15) shows fluctuations in the percentage forest cover with a 3 % decrease from 1985 (66.9%) to 1987 (63.9%), followed by a steady increase to 72.9% in 1991 when the forest cover was at its peak. 1990 was the year of minimum disturbance (0.7%), and 1985 was the maximum (5%). From 1991 onwards there was a constant decline in forested area through 2000, when forests accounted for 63% of the watershed area, approximately a 10% reduction from 1991. Forest cover then rose again and remained fairly constant, with minor fluctuations between 2002-2007 (66.7-66.9%), after which

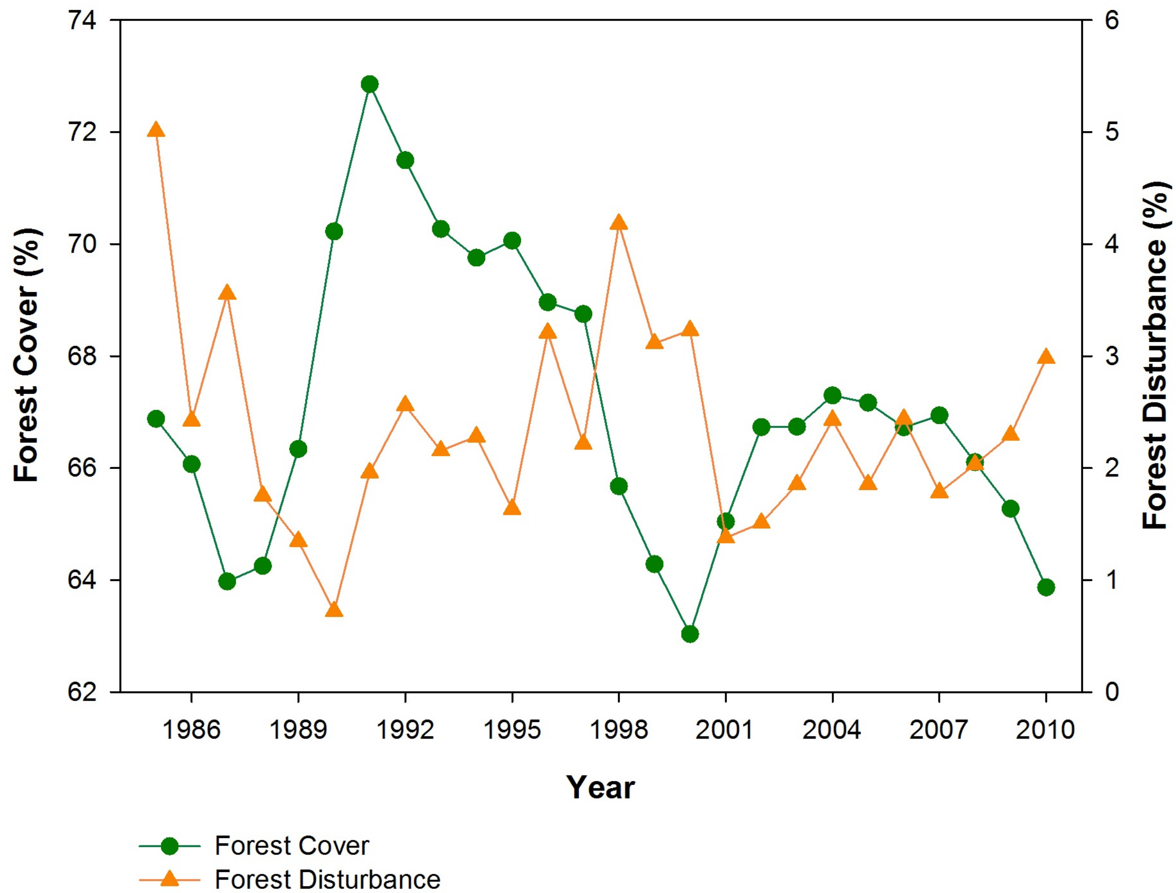


Fig. 3.15 Time Series plots showing the trends in Forest Cover Change and Forest Disturbance for the East Fork San Jacinto Watershed from 1985 through 2010

occurred a steady decline through 2010 resulting in a percentage area of 63.8%, approximately a 3% forest loss from 2002.

3.5.1.4 <u>Forest Cover Change in the West Fork San Jacinto Catchment</u>

The West Fork San Jacinto watershed is similar to the East Fork San Jacinto. The West Fork is also largely a forested watershed, being a part of the Sam Houston National Forest with approximately 51% of the catchment area under forest cover as

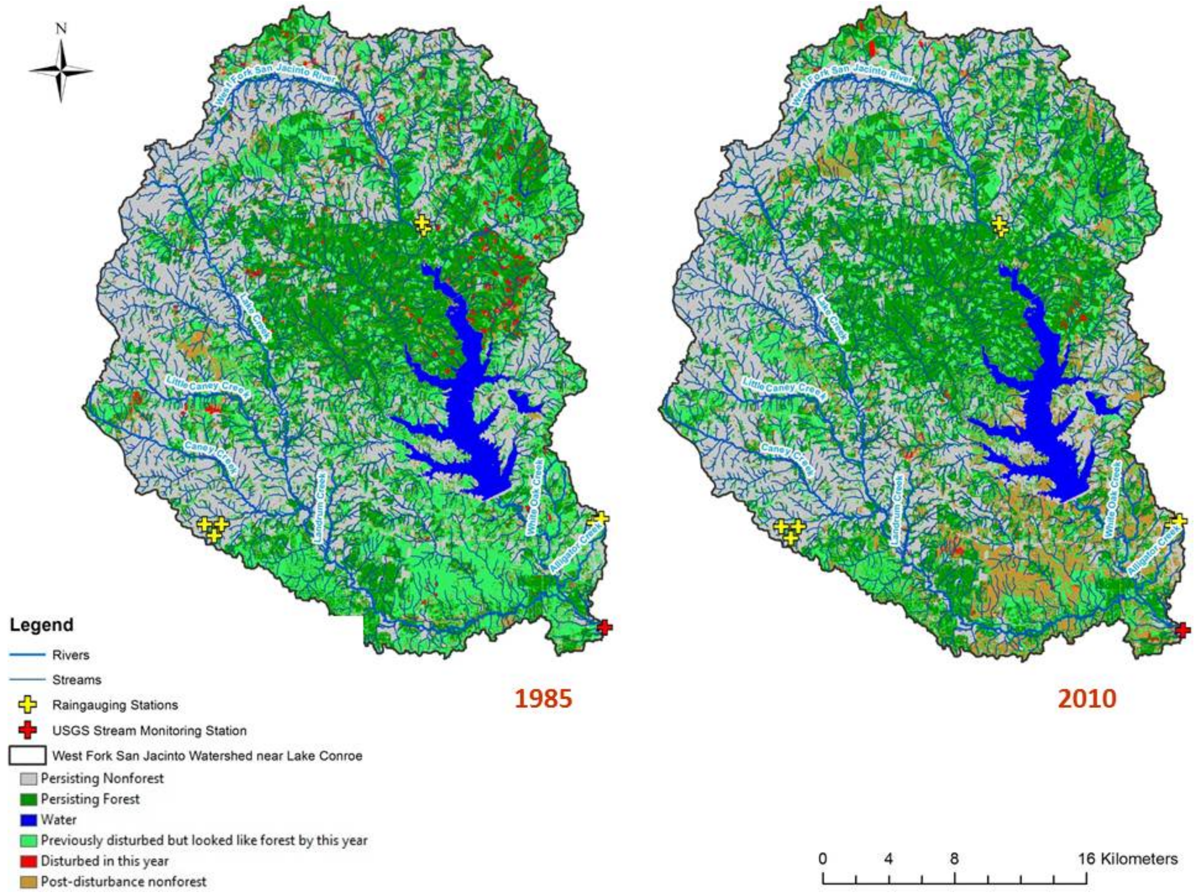


Fig. 3.16 Forest cover change in the West Fork San Jacinto Watershed near Lake Conroe from 1985 through 2010

of 2010 (Fig. 3.16). From the time series analysis (Fig. 3.17), there was a 1% decrease in forest cover from 1985-1988, after which forest cover rose through 1992 when 58.3% of the watershed area was under forest cover. The years 1989 (0.77), 1990 (0.8) and 1991(0.7) had the minimum forest disturbance which must have contributed to the peak forest area in 1992. After 1992, forests declined to 46.9% by 1999, an 11% decrease. There was a recovery in forest cover during 1999-2004, reaching a maximum forest cover of ~53%. The declines in forest cover were preceded by disturbance in the catchment, with a maximum in 1999 was the

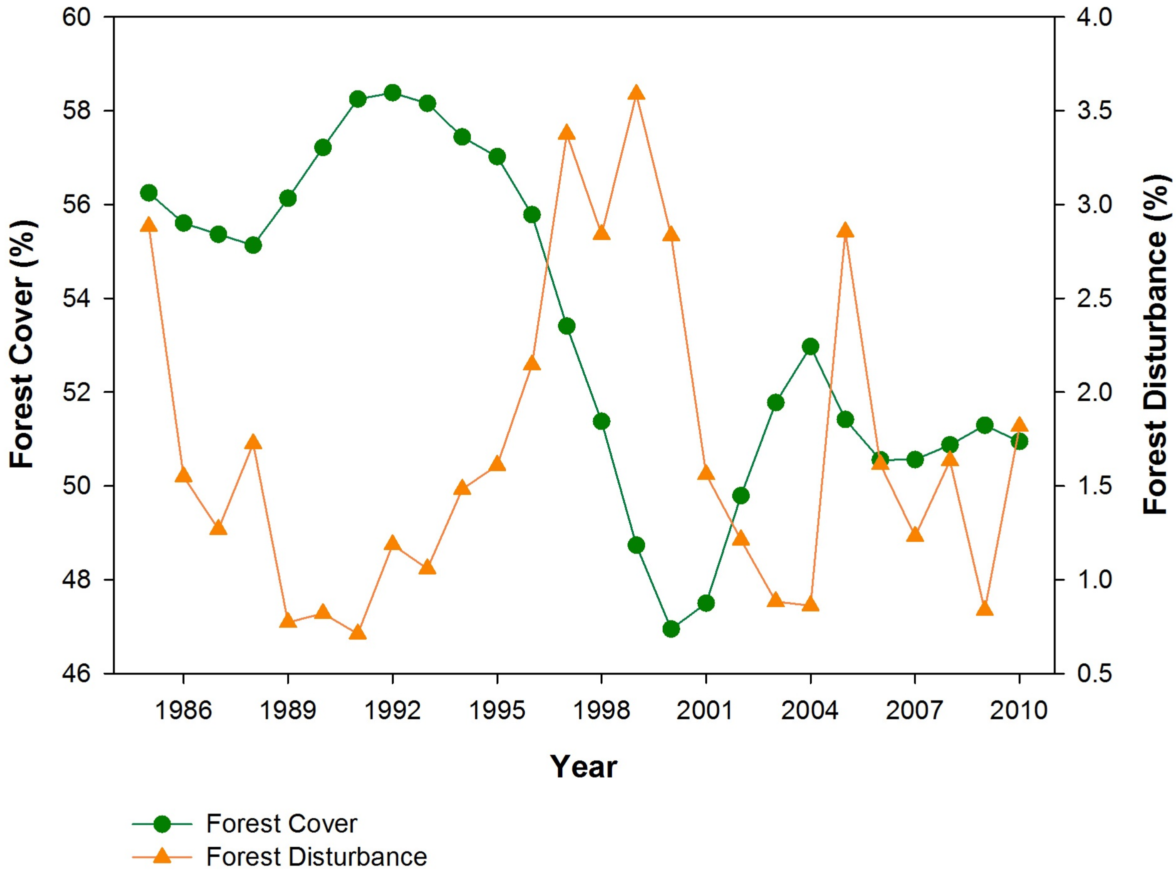


Fig. 3.17 Time Series plots showing the trends in Forest Cover Change and Forest Disturbance for the West Fork San Jacinto Watershed from 1985 through 2010

minimum in forest cover. During 2004-2010 the forested area in the watershed fluctuated between 52.9% and 50.9% with changes caused by forest disturbance.

3.5.2 Trends in water yield and water chemistry

The average annual stream discharge (cubic feet per second) as reported by USGS was converted to water yield (m y^{-1} = m^3 m^{-2} y^{-1}) for all stations using the watershed area (m^2). This was followed by regression analysis of year vs water yield to look for trends in stream flow over time. The water quality analysis involved examining inter-annual trends in nutrient concentration (TN, nitrate and TP) for all the four rivers.

Bray's Bayou (Fig. 3.18) showed an increasing trend in annual discharge after 1966, indicating higher water yields over time. Water yields after 1990 are equivalent to 100% of rainfall, indicating tapping of other freshwater resources. Greens Bayou (Fig. 3.19) showed a linear increasing trend in water yield from 1953-2010, approaching annual rainfall values. This trend indicates the results of deforestation and urbanization, inter-basin transfers or deep groundwater pumping. No significant trend in water yield was observed for either the East Fork San Jacinto and West Fork San Jacinto watersheds.

In the case of water quality, a significant increase in nitrate concentrations can be seen in the Brays Bayou watershed (Fig. 3.18). There were no significant trends in TP. Similarly significant increase in TN and nitrate concentrations was observed in Greens Bayou but no significant trend in TP (Fig. 3.19). Decreasing trends in TN and TP over time from the early 1980's till 2010 was observed for the East Fork San Jacinto River (Fig. 2.10) which was in sharp contrast to trends in nutrient concentrations for West Fork of the same river. There has been a steady increase in N, nitrate and P concentrations (Fig. 3.20) in the West Fork San Jacinto River near Conroe. These are likely to be the result of variations in agricultural development, population growth and waste water discharges from urban areas.

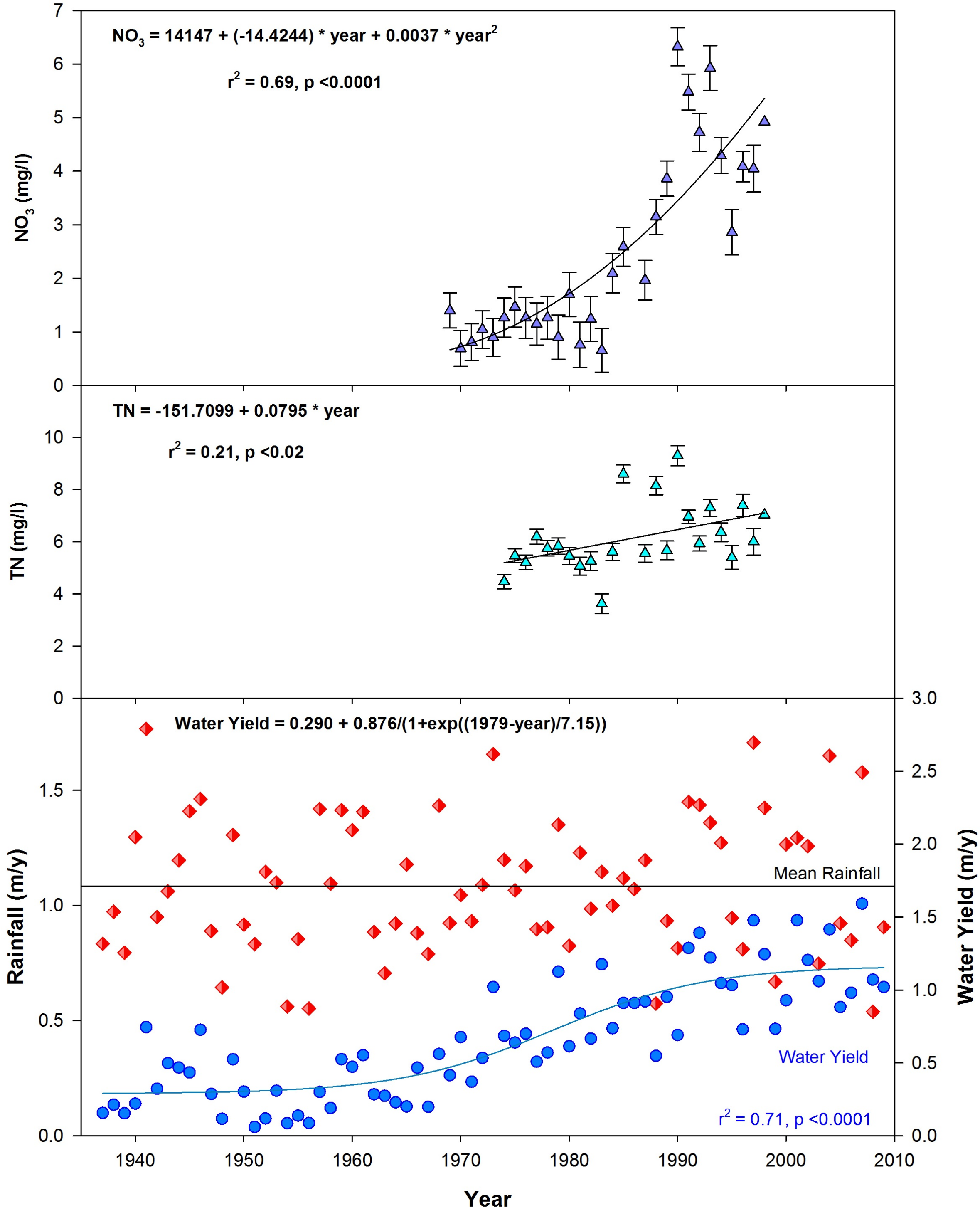


Fig. 3.18 Time series plots of rainfall, water yield, TN and nitrate in the Brays Bayou Watershed

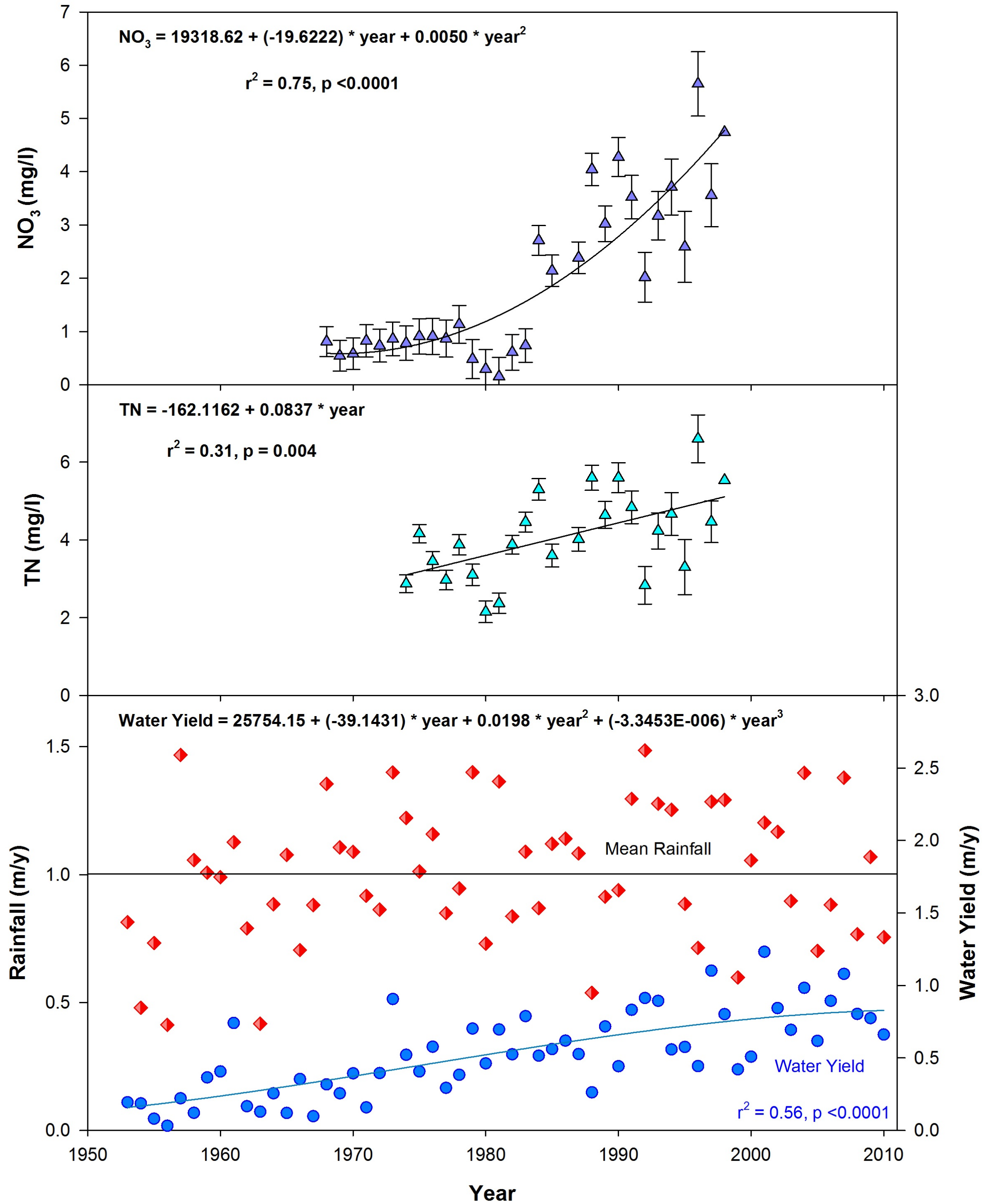


Fig. 3.19 Time series plots of rainfall, water yield, TN and nitrate in the Greens Bayou Watershed

3.5.3 Regression Analysis

Variables for the regression analysis were annual water yield (m/y), annual average Total Nitrogen (mg/l), annual average Nitrate (mg/l), and annual average Total Phosphorus (mg/l) calculated from USGS stream flow data; percent forest cover, percent forest disturbance derived from remote sensing imagery, and precipitation data (m/y) from rain gauging stations obtained from NCDC for all four catchments in the watershed. The multiple linear regression models were constructed as follows:

$$\text{Water Yield} = a + b\,(\text{annual rainfall}) + c\,(\%\text{ forest cover}) + d\,(\%\text{ forest disturbance}) \quad (\text{eq. } 1)$$

$$TN = a + b\,(\%\text{ forest cover}) + c\,(\%\text{ forest disturbance}) \quad (\text{eq. } 2)$$

$$NO_3 = a + b\,(\%\text{ forest cover}) + c\,(\%\text{ forest disturbance}) \quad (\text{eq. } 3)$$

$$TP = a + b\,(\%\text{ forest cover}) + c\,(\%\text{ forest disturbance}) \quad (\text{eq. } 4)$$

where,

a,b,c,d = constants

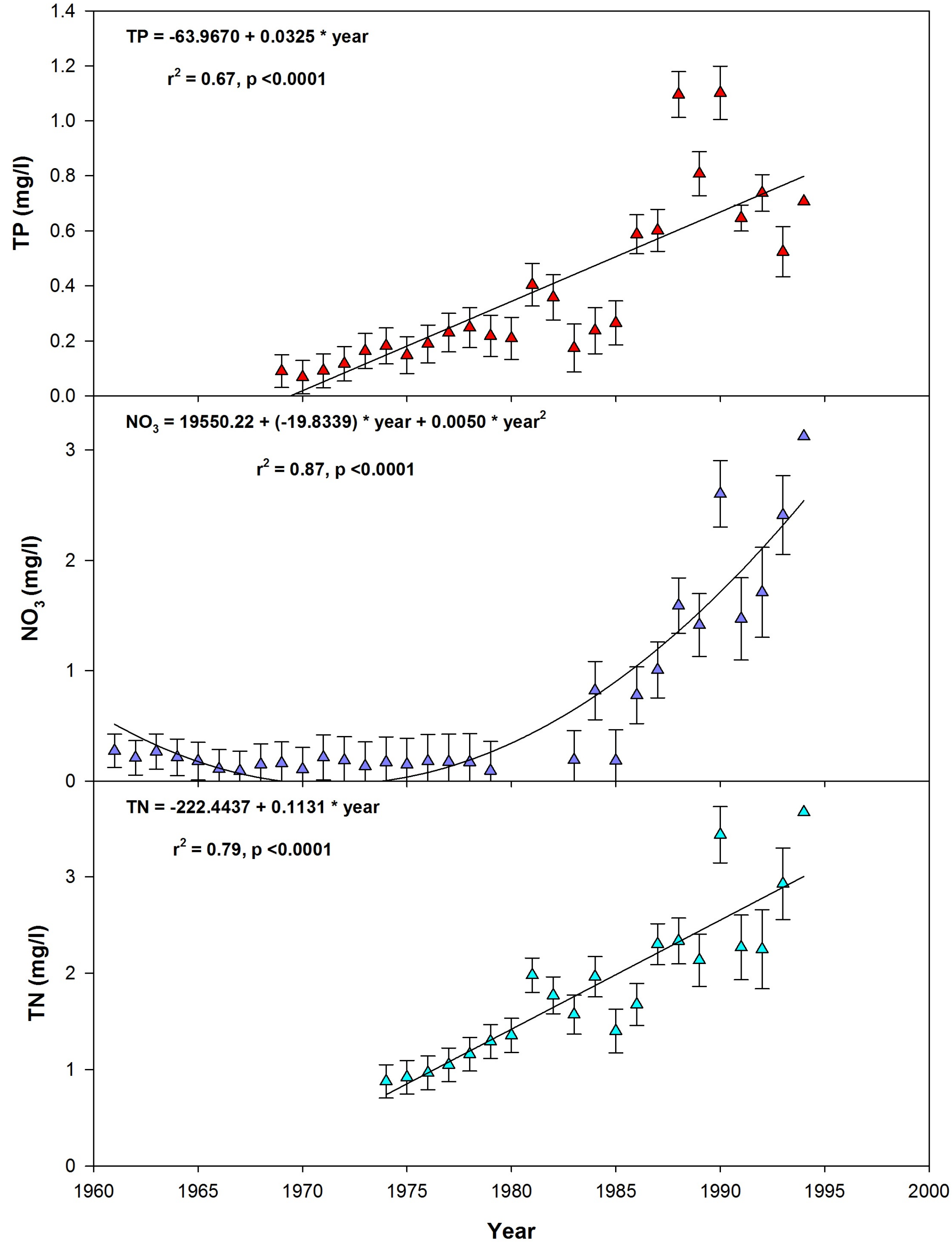


Fig. 3.20 Time series plots of TN, nitrate and TP in the West Fork San Jacinto Watershed

The multiple linear regression models were initially run with all variables. If some independent variables were not significant, the models were rerun without the variables that were not significant (Table 3.3). In addition, individual linear regression models were run to check for a simple significant relationship between each variable. Results of the trends and relationships between variables are listed in Tables 3.4, 3.5, 3.6 and 3.7. A brief description of the results of the regression analyses for the 4 catchments follows:

Brays Bayou: Brays Bayou had an r^2 of 0.76 for regression (1) with water yield showing a highly significant positive linear relationship with rainfall and an inverse relationship with forest cover (Table 3.3). Forest disturbance was not significant, and hence the regression model was rerun with only rainfall and forest cover as independent variables. Rainfall explained 65% of the variability in water yield (Fig. 3.21) in Brays Bayou (Table 3.6). Forest cover did not show any direct significant relationship with water yield (Table 3.6) although it contributed significantly to the multiple linear regression in Table 3.3. Regression (2) for TN did not show any significant results relating the impact of forests on TN. An r^2 of 0.48 was observed for Regression (3) for TP with forest cover showing a positive relationship. Even though the regression was significant, the forest cover variable had a p-value of 0.07, indicating only as statistically marginal effect on TP. However a linear regression model of TP vs. Forest cover showed a positive correlation between the variables with an r^2 of 46 ($p = 0.01$) which is very unusual. There could be various reasons for this relationship. For example, waste disposal on forested areas could cause

Catchment	**Multiple Linear Regression Model**	**R^2**	**p-value**
Brays Bayou	Water Yield = 0.699 + 0.674 * Rainfall - 0.0424 * Forest Cover	0.76	<0.001
Greens Bayou	Water Yield = 0.435 + 0.667 * Rainfall - 0.0154 * Forest Cover	0.55	<0.001
East Fork San Jacinto	Water Yield = -0.114 + (0.386 * Rainfall)	0.48	<0.001
West Fork San Jacinto	Water Yield = -0.258 + (0.462 * Rainfall)	0.68	<0.001

Table 3.3 Results of the Multiple Linear Regression Model

Watershed Name	USGS ID	Km^2 Area	**Water Yield**				m/y Rainfall	**Forest Cover**				**Forest Disturbance**			
			m/y Ave	Trends	r^2	p		% Ave	Trends	r^2	p	% Ave	Trends	r^2	p
Brays Bayou	08075000	253.6	1.07	No Trend	0.27	NS	1.11	8.9	Decreasing	0.95	<0.0001	0.67	No Trend	0.18	NS
Greens Bayou	08076000	153.3	0.72	Increasing	0.16	0.04	1.04	26.6	Decreasing	0.90	<0.0001	1.75	No Trend	0.16	NS
East Fork San Jacinto	08070200	984.9	0.27	No Trend	0.14	NS	1.02	67.1	Curvilinear Decrease	0.3	0.03	2.38	No Trend	0.1	NS
West Fork San Jacinto	08068000	2147.6	0.22	No Trend	0.12	NS	1.0	53.4	Decreasing	0.83	<0.0001	1.7	No Trend	0.1	NS

Table 3.4 Trends in water yield, forest cover and forest disturbance

Watershed Name	USGS ID	Km^2 Area	**TN**				**NO_3**				**TP**			
			mg/l Ave	Trends	r^2	p	mg/l Ave	Trends	r^2	p	mg/l Ave	Trends	r^2	p
Brays Bayou	08075000	253.6	6.15	Linear increase in TN	0.21	0.02	2.51	Increasing trend in nitrate	0.69	<0.0001	1.92	Curvilinear decrease in TP	0.24	0.02
Greens Bayou	08076000	153.3	4.11	Linear increase in TN	0.3	0.004	1.96	Increasing trend in nitrate	0.75	<0.0001	1.72	No significant trend	0.08	NS
East Fork San Jacinto	08070200	984.9	0.81	Decreasing trend in TN	0.25	0.01	0.14	No significant trend	0.22	NS	0.06	Curvilinear decrease in TP	0.8	<0.0001
West Fork San Jacinto	08068000	2147.6	1.87	Linear increase in TN	0.79	<0.0001	0.66	Curvilinear increase in nitrate	0.87	<0.0001	0.39	Linear increase in TP	0.66	<0.0001

Table 3.5 Trends in TN, nitrate and TP

Watershed Name	USGS ID	**Water Yield vs Rainfall**			**Water Yield vs Forest Cover**			**Water Yield vs Forest Disturbance**			**TN vs Forest Cover**			**TN vs Forest Disturbance**		
		Relationship	r^2	p	Relationship	r^2	p	Relationship	r^2	P	Relationship	r^2	p	Relationship	r^2	p
Brays Bayou	08075000	Positive	0.65	<0.001	Negative	0.06	NS	Positive	0.01	NS	Positive	0.02	NS	None	0.0	NS
Greens Bayou	08076000	Positive	0.44	<0.001	Negative	0.02	NS	Positive	0.01	NS	Positive	0.01	NS	Negative	0.06	NS
East Fork San Jacinto	08070200	Positive	0.47	<0.001	Positive	0.01	NS	Positive	0.01	NS	Positive	0.02	NS	None	0.00	NS
West Fork San Jacinto	08068000	Positive	0.67	<0.001	Positive	0.04	NS	Negative	0.02	NS	Positive	0.17	NS	Negative	0.22	NS

Table 3.6 Relationships between water yield and rainfall, forest cover, forest disturbance and TN

Watershed Name	USGS ID	**NO_3 vs Forest Cover**			**NO_3 vs Forest Disturbance**			**TP vs Forest Cover**			**TP vs Forest Disturbance**		
		Relationship	r^2	p	Relationship	r^2	p	Relationship	r^2	p	Relationship	r^2	p
Brays Bayou	08075000	None	0.07	NS	None	0.0	NS	Positive	0.46	0.01	Negative	0.25	NS
Greens Bayou	08076000	None	0.06	NS	None	0.06	NS	Positive	0.06	NS	Negative	0.33	0.03
East Fork San Jacinto	08070200	None	0.0	NS	None	0.03	NS	None	0.00	NS	Positive	0.01	NS
West Fork San Jacinto	08068000	None	0.28	NS	None	0.28	NS	Negative	0.01	NS	Negative	0.24	NS

Table 3.7 Relationships between river nutrients (NO_3 and TP) and forest cover and forest disturbance

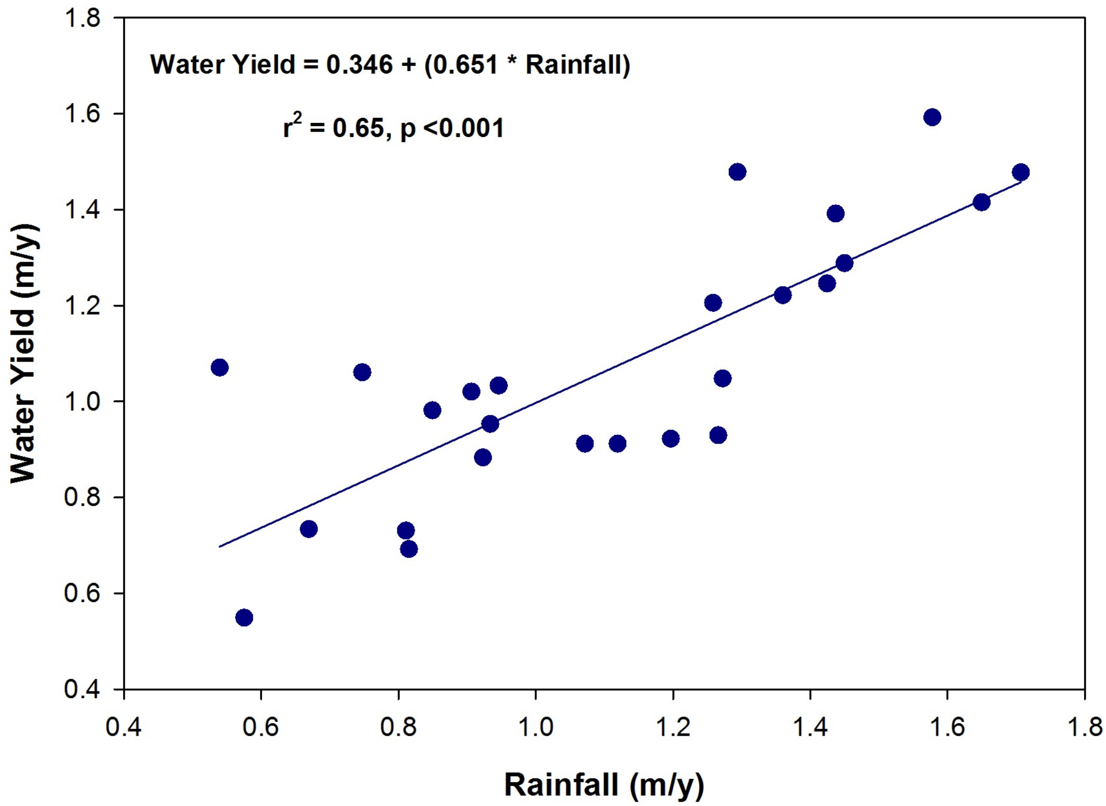


Fig. 3.21 Relationship between rainfall and water yield in the Brays Bayou watershed

phosphorus levels to increase. Second, forested wetlands can also mobilize P due to hypoxic soils.

Greens Bayou: Similarly Greens Bayou (Table 3.3) showed a positive relationship with rainfall and an inverse relationship with forest cover with an r^2 of 0.56 for regression (1). A rerun of the model with only the significant variables—rainfall and forest cover yielded an r^2 of 0.55. Rainfall explained 44% of the variability in water yield, whereas the impact of forest cover alone on water yield was not significant. Regressions (2) and (3) did not yield any significant results. Forest cover did not seem to have an impact on TN, NO_3 or TP. However, a negative correlation with an r^2

of 33 ($p = 0.04$) between forest disturbance and TP was observed for Greens Bayou. There may be a statistical relationship but no obvious underlying cause and effect.

East Fork San Jacinto Watershed near New Caney: Results of the multiple linear regression model for the East Fork San Jacinto watershed showed an r^2 of 0.48 with rainfall being the only significant variable that explained 48% of the variability in water yield (Table 3.3). There was no impact of forest cover and forest disturbance on TN, NO_3 and TP.

West Fork San Jacinto Watershed near Lake Conroe: The West Fork San Jacinto watershed had results similar to the East Fork with rainfall being the only significant variable explaining 68% of the variability in water yield (Table 3.3). The regression had an r^2 of 0.68 with a highly significant p value of <0.001. Forests did not explain any variability in TN and TP for this catchment.

3.5.4 Regression Analysis of combined data for all catchments

Forest cover effect on water yield and water chemistry could not be seen due to the limited number of observations in the data. Therefore, the data for all four catchments—*Brays Bayou*, *Greens Bayou*, *East Fork San Jacinto* and *West Fork San Jacinto* watersheds were combined for "space for time-substitution" analysis (Pickett, 1989) to check for correlations between forest cover and stream hydrology and stream chemistry. Figs. 3.22-3.26 using the combined results for land use effects across the watersheds with broad ranges of land use are "space for time swaps", which assume that the combined data of multiple watersheds reflect the trajectory that an individual watershed would take if it underwent a large change in land use.

Variables for the regression analysis were annual water yield (m/y), annual average Total Nitrogen (mg/l), annual average nitrate (mg/l), and annual average Total Phosphorus (mg/l) calculated from USGS stream flow data; percent forest cover, percent forest disturbance derived from remote sensing imagery, and precipitation data (m/y) from rain gauging stations obtained from NCDC for all four catchments in the watershed. The multiple linear regression models were constructed as follows:

Water Yield = a + b (annual rainfall) + c (% forest cover) + d (% forest disturbance)   (eq. 5)

TN = a + b (water yield) + (% forest cover) + c (% forest disturbance) (eq. 6)

NO_3 = a + b (water yield) + (% forest cover) + c (% forest disturbance) (eq. 7)

TP = a + b (water yield) + (% forest cover) + c (% forest disturbance)   (eq. 8)

where,

a,b,c,d = constants

The multiple linear regression models were initially run with all variables. If some independent variables were not significant, the models were rerun without the variables that were not significant (Table 3.8). In addition, individual linear regression models were run to check for a simple significant relationship between each variable. Results of the relationships between variables are listed in Tables 3.9 and 3.10.

Regression (5) had an r^2 of 0.84 (Table 3.8) with water yield showing a significant positive linear relationship with rainfall and an inverse relationship with forest cover (Table 3.9). Forest disturbance was not significant and hence the regression model was rerun with only rainfall and forest cover as independent variables. Rainfall explained 23% of the variability in water yield (Fig. 3.22) while forest cover contributed 68% of the total variability in water yield for all four catchments (Fig. 3.23). Forest Cover and forest disturbance were negatively correlated with TN and explained 89% of the total variability in Regression (6). Forest cover alone explained 88% of the total variability in TN (Fig. 3.24). A highly significant negative relationship between forest cover and nitrate was observed in Regression (7) where forest cover explained 75% of the variability in NO_3 (Fig. 3.25). Water yield and forest cover together explained 47% of the variability in TP for all 4 catchments. Water yield showed a positive relationship (Table 3.10) while forest cover showed a negative relationship contributing 39% of the variability in TP (Fig. 3.26).

Regression	Multiple Linear Regression Model	R^2	p-value
5	Water Yield = 0.492 + (0.586 * Rainfall) - (0.0137 * Forest Cover)	0.84	<0.001
6	TN = 8.033 - (0.0950 * Forest Cover) - (0.297 * Forest Disturbance)	0.89	<0.001
7	NO_3 = 5.197 - (0.0706 * Forest Cover)	0.75	<0.001
8	TP = 3.442 - (1.214 * Water Yield) - (0.0432 * Forest Cover)	0.47	<0.001

Table 3.8 Results of the Multiple Linear Regression Model

	Rainfall			**Forest Cover**			**Forest Disturbance**		
	Relationship	r^2	p	Relationship	r^2	p	Relationship	r^2	p
Water Yield	Positive	0.23	<0.001	Negative	0.68	<0.001	Negative	0.2	<0.001

Table 3.9 Relationships between water yield and rainfall, forest cover and forest disturbance

	Water Yield			Forest Cover			Forest Disturbance		
	Relationship	r^2	p	Relationship	r^2	p	Relationship	r^2	p
TN	Positive	0.51	<0.001	Negative	0.88	<0.001	Negative	0.48	<0.0001
NO_3	Positive	0.5	<0.001	Negative	0.75	<0.001	Negative	0.41	<0.0001
TP	Positive	0.2	0.007	Negative	0.39	<0.001	Negative	0.38	<0.0001

Table 3.10 Relationships between river nutrients (TN, NO_3 and TP) and water yield, forest cover and forest disturbance

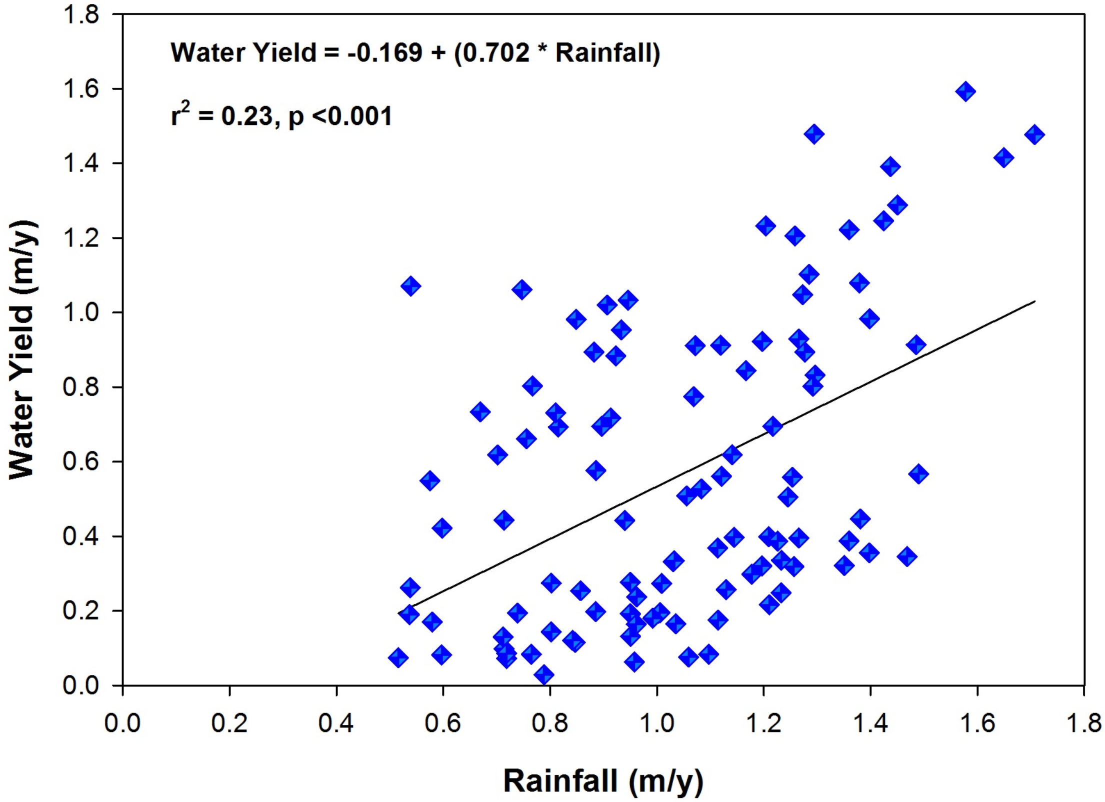


Fig. 3.22 Relationship between rainfall and water yield for all catchments from 1985-2010

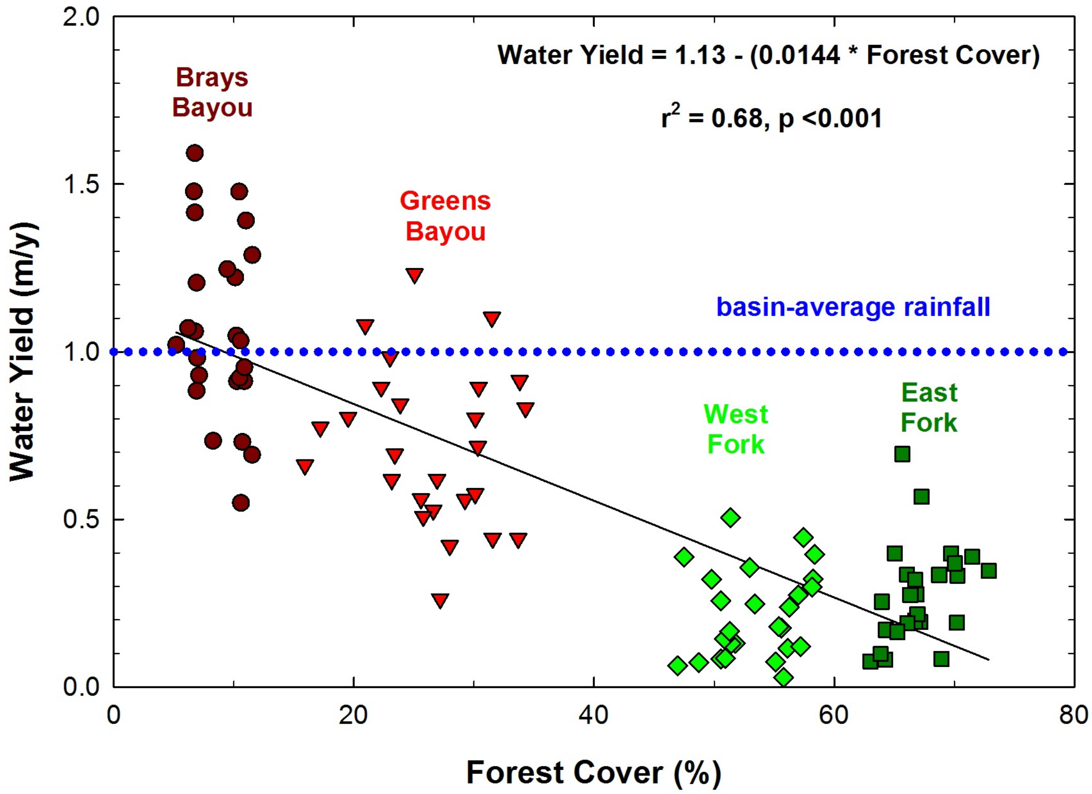


Fig. 3.23 Plot showing the relationship between forest cover and water yield for all catchments from 1985-2010. Brays Bayou and Greens Bayou are highly urbanized watersheds experiencing increasing trends in water yields. East Fork San Jacinto and West Fork San Jacinto are largely forested watersheds thereby experience low water yields.

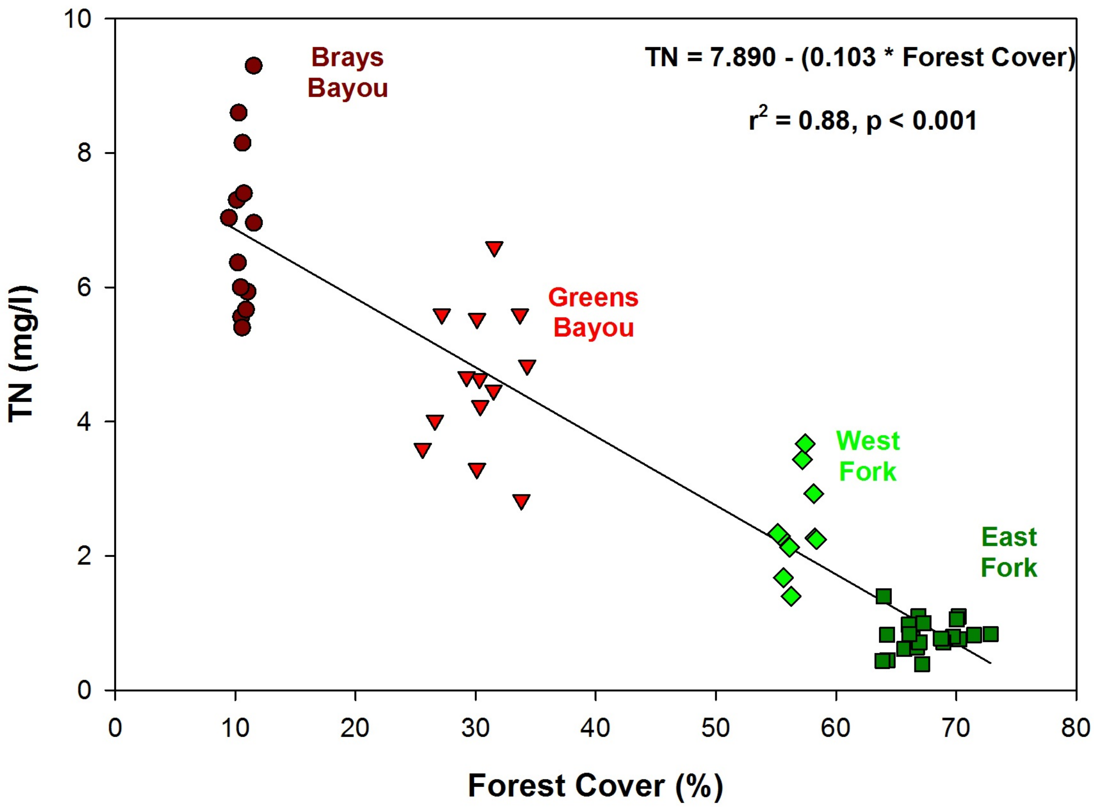


Fig. 3.24 Relationship between forest cover and TN for all catchments

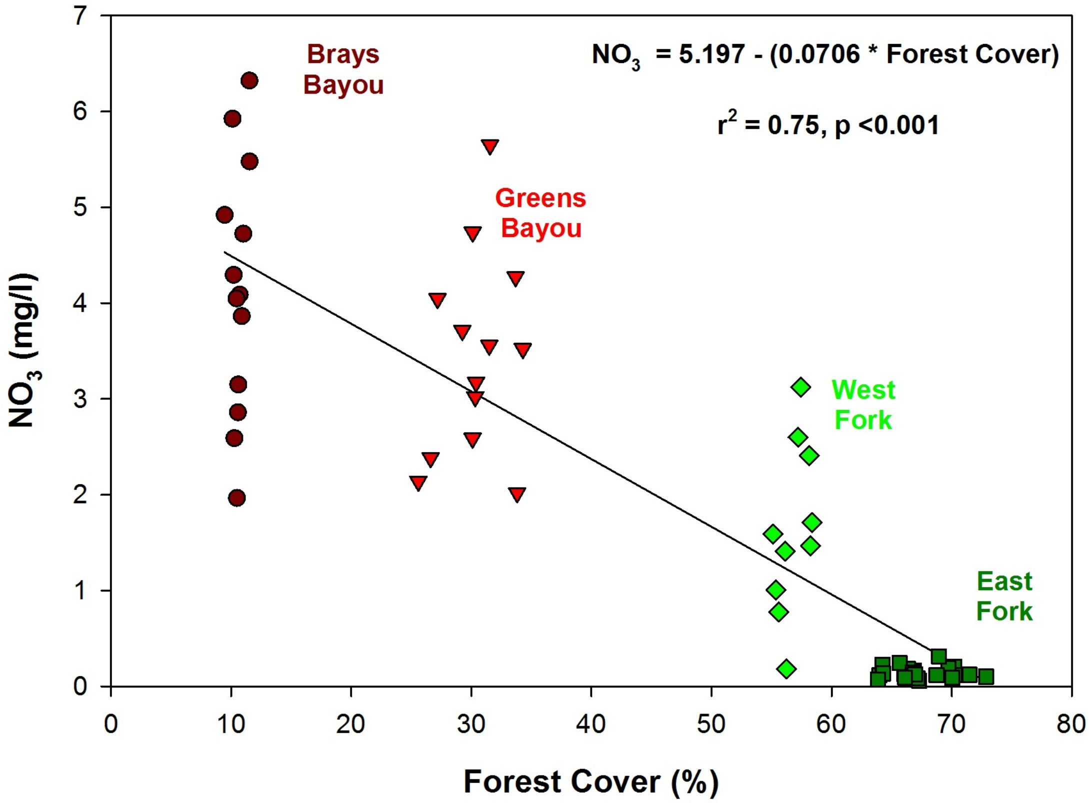


Fig. 3.25 Relationship between forest cover and nitrate for all catchments

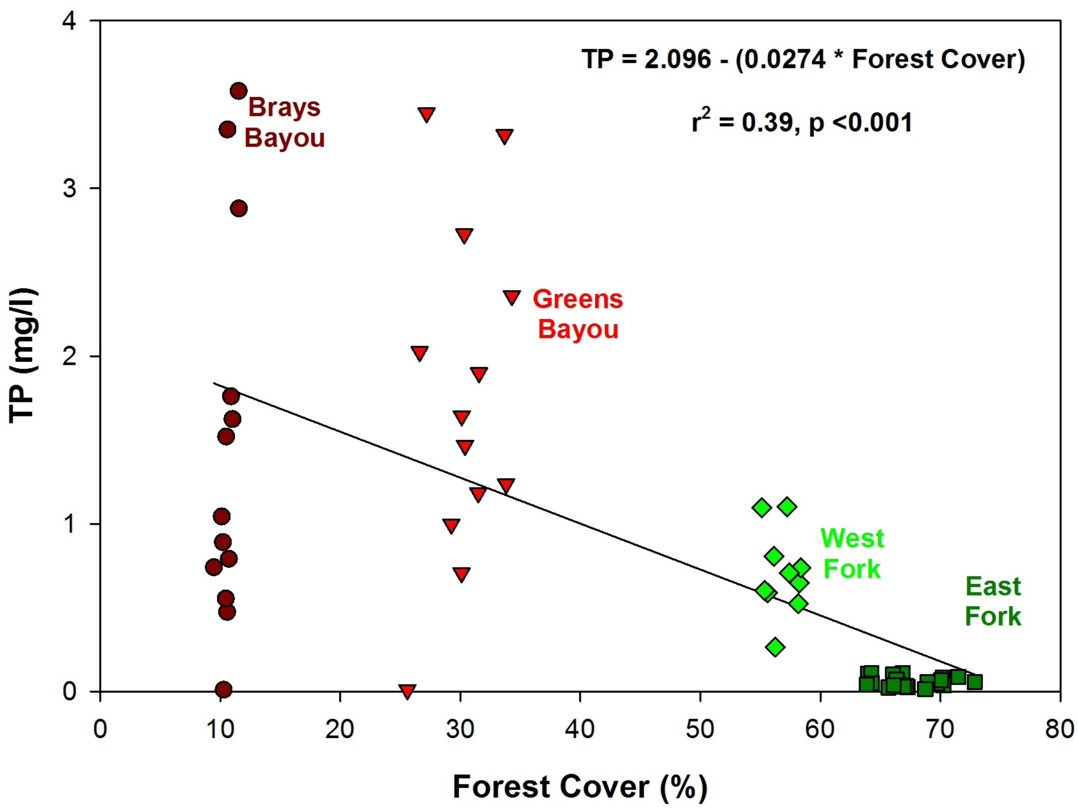


Fig. 3.26 Relationship between forest cover and TP for all catchments

3.6 Discussion

Based on the results of the regression analysis for each individual watershed on a temporal scale, variations in forest cover did not influence stream hydrology or stream chemistry. Results of the Regression (1) for Brays Bayou showed that rainfall is the primary driver of water yield, followed by percent forest cover, which was the secondary cause with a significant land use effect. However a linear regression analysis between forest cover and water yield did not yield any significant results. The same phenomenon was observed in the case of Greens Bayou that showed a positive relationship with rainfall and a negative relationship with forest cover. Rainfall explained 44% of the variability in water yield, whereas the impact of forest cover alone on water yield was not significant. Both Brays Bayou and Greens Bayou are highly urbanized catchments located in and around the Houston Metropolitan Area and appear to have similar characteristics in terms of land use and water yield. These catchments are undergoing rapid urban development causing a decrease in forest cover and an increase in water yields (Figs. 3.11 and 3.18). Fig. 3.27 illustrates the trends in water yield, forest cover and rainfall in the Brays Bayou watershed. No significant land cover effect was observed for TN and NO_3 for both Brays Bayou and Greens Bayou. However, unusual relationships were observed between forest cover and TP for Brays Bayou and forest disturbance and TP for Greens Bayou. A significant positive relationship was observed between TP and forest cover for the Brays Bayou catchment which was puzzling. There could be several reasons that could result in this relationship. For example, waste disposal on forested areas could cause phosphorus levels to

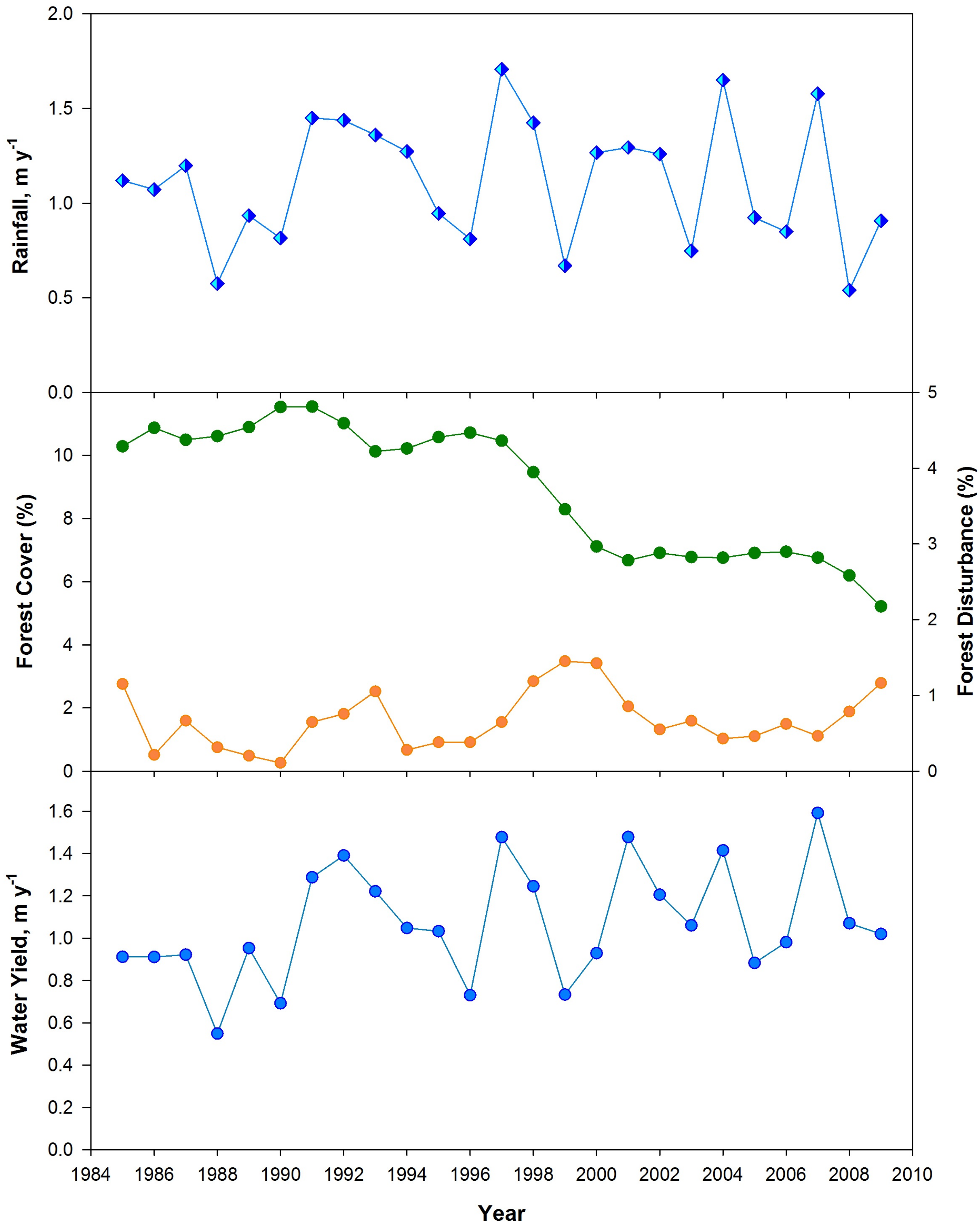


Fig. 3.27 Time Series plots showing the trends in Water Yield, Forest Cover and Forest Disturbance and Rainfall for the Brays Bayou Watershed from 1985-2009

increase. Second, phosphorus is being liberated from forested wetlands due to hypoxic soils. The negative correlation (r^2 of 33, p = 0.04) observed between TP and forest disturbance for the Greens Bayou catchment, was also puzzling. There may be a statistical relationship but no obvious underlying cause and effect.

Contrary to the Brays Bayou and Greens Bayou which are highly urbanized with similar characteristics, the two forested watersheds East Fork San Jacinto and West Fork San Jacinto did not show any trends in water yield and had totally different trends in stream water quality (Figs. 2.10 and 3.20). The East Fork San Jacinto watershed showed decreasing trends in both TN and TP while the West Fork San Jacinto had increasing trends in TN, NO_3 and TP. Forest cover and forest disturbance did not have any significant effect on water yield for both these catchments.

Rainfall was the only significant variable that explained 48% of the variability in water yield for East Fork San Jacinto and 68% for the West Fork San Jacinto watersheds. No significant relationship between forest cover and forest disturbance with TN, NO_3 and TP was observed for both these catchments. The water quality data were limited that could have hindered the statistical relationship. An analysis on water yield versus nutrient data showed increased TN with higher flows in the East Fork San Jacinto watershed, which is very typical for forested catchments (Fig. 3.28). No significant relationships were found between water yield and nutrient data in the West Fork San Jacinto watershed.

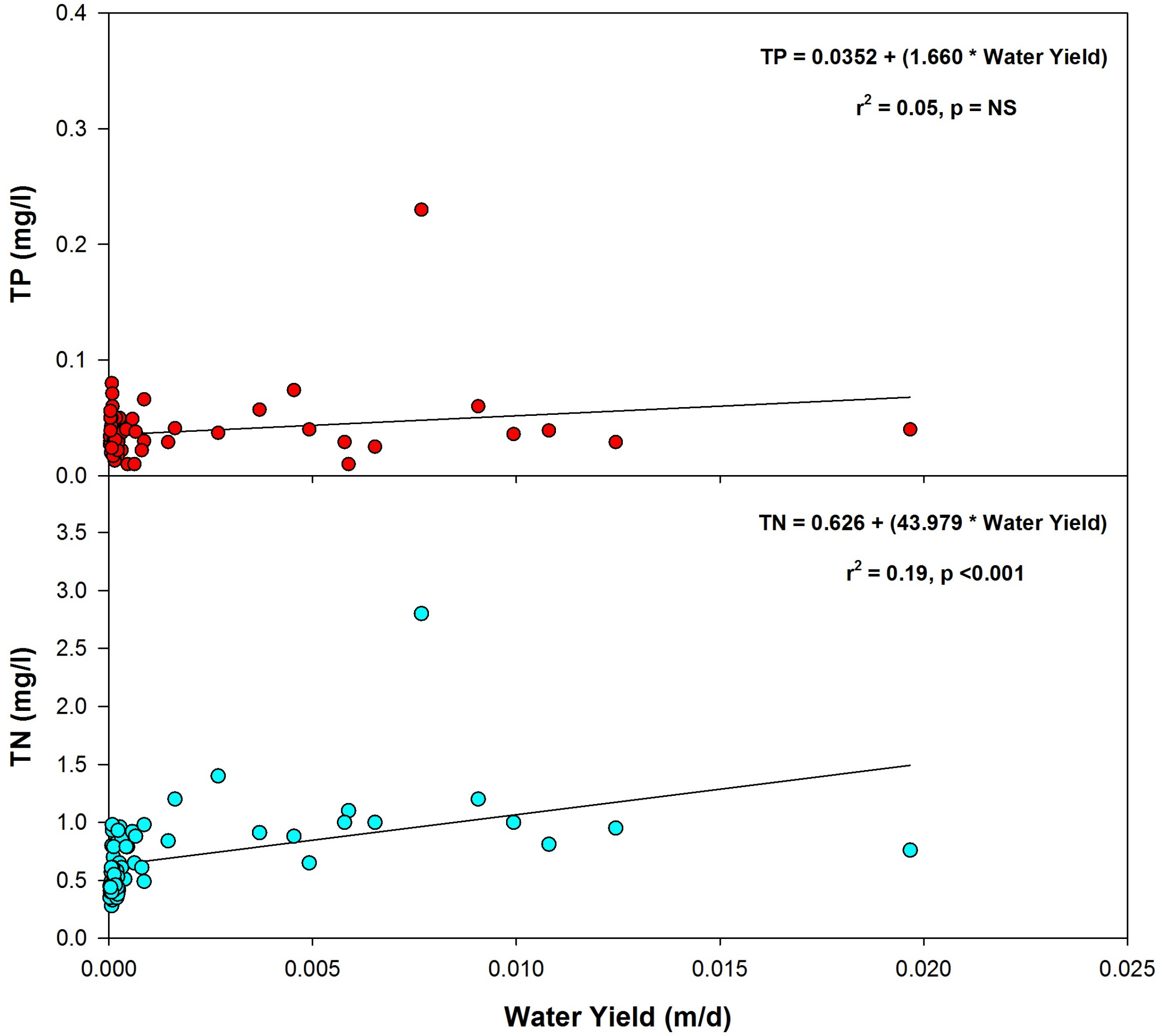


Fig. 3.28 Relationship between water yield and river nutrients (TN and TP) in the East Fork San Jacinto watershed

The results of the multiple regression analyses (1-4) showed that the data only partially supported hypotheses H1 and H2 for the respective study areas. The first hypothesis (There is an inverse relationship between annual water yield and annual forest cover) is partially supported by the data in two watersheds whereas the second hypothesis (Forest cover and river nutrients (TN and TP) are inversely related) is not supported. Based on the analysis for all individual catchments, rainfall is the primary driver influencing water yield in the catchments of the lower Galveston Bay Watershed. It was obvious from the results of the regression analyses, that the limited number of observations in the data had hindered the statistical analyses. The urbanized catchments were experiencing increasing trends in water yields and river nutrients. All four catchments were experiencing a decreasing trend in forest cover (Table 3.4).

A longer historical data record is necessary to see the effect of land use/land cover change on hydrology and river chemistry on a temporal scale. The longer the time period, the better is the chance of a significant correlation. Most of the changes in the water yield in Brays Bayou and Greens Bayou were observed for the time period between1970-1990. The forest cover dataset that was used only ranged from 1985-2010. Second, based on the forest cover time series maps, the most intensive period of deforestation in all four catchments were observed towards the late 1990's. There were no river nutrient data beyond 1994 for the West Fork San Jacinto watershed; no nutrient data were available beyond 1998 for the Brays Bayou and Greens Bayou catchments. The nutrient data for the East Fork San Jacinto watershed were inconsistent. All these factors resulted in low correlations and regressions not being significant.

In order to see the effect of land cover on the hydrology and river chemistry the data for all four catchments—*Brays Bayou*, *Greens Bayou*, *East Fork San Jacinto* and *West Fork San Jacinto* watersheds were combined to increase the number of observations and check for correlations between forest cover and stream hydrology and stream chemistry. Results of the multiple regression analyses (5-8) from the data for all catchments combined confirmed that both hypotheses H1 and H2 are supported by the data. Forest cover had a highly significant negative relationship with water yield indicating increasing water yields with decreasing forest cover. Forest cover was the primary driver of water yield followed by rainfall which was secondary in this case. This is in sharp contrast to what was observed for the regression analysis for all four catchments on an individual basis where rainfall was the primary driver and only significant variable explaining water yield in these catchments. Forest disturbance was not significant in Regression (5) but individual regression analysis between forest disturbance and water yield showed that it had a significant negative relationship ($r^2 = 0.48$, $p < 0.0001$) with water yield which was unusual. Both forest cover and forest disturbance negatively influenced TN. Forest cover alone explained 88% of the total variability in TN indicating decreasing levels in TN with increasing forest cover. However the negative effect of forest disturbance on TN was puzzling that had no obvious underlying cause and effect. A highly significant negative relationship was observed between NO_3 and forest cover indicating decreasing levels in nitrate concentrations with increasing forest cover. As for TP, both water yield and forest cover together explained 47% of the variability for all four catchments from 1985-2010. Forest cover was the primary driver negatively influencing TP ($r^2 = 0.39$, $p < 0.001$) followed by water yield that had a small but significant positive effect ($r^2 = 0.2$, $p = 0.007$) indicating increasing TP with higher water yields.

Individual regression analysis from this dataset showed that both forest cover and forest disturbance were negatively correlated with water yield, TN, NO_3 and TP. Decreasing forest cover was associated with increasing water yields and high levels of TN, NO_3 and TP concentrations. However the negative relationship between forest disturbance and water yield, TN, NO_3 and TP could not be explained.

Results of this research show that anthropogenic changes in the watershed have a significant impact on the river flow and stream water quality. If development continues, there will be less forest cover and hence more impervious surface leading to higher water yields. This results in faster flowing streams and flooding during storm events. This study has shown that increasing water yields cause higher nutrient flow into the streams. Besides water yield, decreasing forest cover would lead to higher nutrient inputs (TN, NO_3 and TP) as observed in this study. Increasing freshwater flow in the streams in the lower Galveston Bay watershed cause stratification in the estuary downstream. Stratification along with higher nutrient inputs make the Bay vulnerable to eutrophication. With rising temperatures as a result of global warming, eutrophication in the Bay will become more severe and lead to increased hypoxia during the warm summer months.

CHAPTER 4: LAND USE/LAND COVER CHANGE AND POPULATION GROWTH

ABSTRACT

Land use and land cover change play a dominant role in water quantity and quality. Land cover change and human population growth are two major forces reshaping freshwater flows to estuaries worldwide. Land use conversion directly modifies the nature of watershed runoff into streams and rivers ultimately affecting the health of estuaries. The nature of society's relationship with coastal environments is illustrated well by the Galveston Bay watershed. High rates of inter-basin transfer of water was observed from the USGS stream gauging station data for those stations lying within the highly urbanized area with increasing trends in river discharge. Results of the land cover classification for the lower Galveston Bay watershed from 1989-2009 show an increase in urban growth followed by a decrease in agriculture and forest cover. Regression analyses relating water yield to land cover classes for four different time periods—1989, 1996, 2002 and 2009 for Brays Bayou, Greens Bayou, East Fork San Jacinto and West Fork San Jacinto watersheds did not yield significant results. The small number of land use observations hindered the statistical analyses. However, in the case of the projected land cover data (1986-2009) for the Brays Bayou watershed, rainfall and urban land cover together explained 78% of the variability in water yield. This was followed by combining the data for all four catchments—Brays Bayou, Greens Bayou, East Fork San Jacinto and West Fork San Jacinto watersheds for "space for time swaps" to increase the number of observations and check for correlations between land cover and stream hydrology and stream

chemistry. Highly significant relationships were found between land use/ land cover and stream hydrology and stream chemistry. Urban, forest, pasture and wetlands explained most of the variability in water yield followed by rainfall which had a small but significant effect. Results of the analysis clearly demonstrated increasing water yields and nutrient inputs with increasing urban land use. Watersheds with a larger percent of forest cover and wetlands had low water yields and low nutrient concentrations in their streams. Catchments with more area under barren land had high levels of TP in the rivers. Population explained the increasing trends in water yields for the highly urbanized catchments of Brays Bayou and Greens Bayou. Similarly, highly significant positive relationships were observed between river nutrients and total population for Brays Bayou, Greens Bayou, and the West Fork San Jacinto catchments. Results from this research show that anthropogenic changes in the watershed have a significant impact on the river flow and stream water quality. Continued development leads to higher water yields resulting in faster flowing streams and flooding during storm events. Future population growth in the highly urbanized areas near Houston will cause increasing water demand from adjacent watersheds resulting in higher downstream flows in the estuary. With rising temperatures as a result of global warming, eutrophication in the Bay could get worse. Higher rates of stratification caused by rising temperatures and larger freshwater inflow with increased nutrient inputs due to increasing population and urban growth may increase eutrophication in the Bay. Thus, increasing freshwater flow in the estuary may have serious implications from a global warming perspective.

4.1 Introduction

4.1.1 Land Use/Land Cover and its effects

4.1.1.1 General Background

Land cover and land use are two important determinants of water supply on its transit through a landscape (Mustard and Fisher, 2004). The use and condition of land has a profound influence on water quality (Wear et al., 1998), and land use conversion directly modifies the nature of watershed runoff into streams and rivers (Hopkinson and Vallino, 1995). The sequence of land use change is from natural land (forest or grassland) to community land (urbanization), from natural land to agricultural land (agriculturalization for energy/tree harvest or crop production), agricultural land to additional community land (urbanization), and occasionally from agricultural land back to natural land (abandonment) (Hopkinson and Vallino, 1995). A number of environmental changes occur with each conversion disrupting original patterns of water and material output from watersheds to rivers. Changes ultimately influencing the metabolism of estuaries are the timing and magnitude of water runoff from the land surface, sediment erosion, alteration of organic matter export and nutrient runoff. Land use composition and its spatial pattern can also influence the fate of precipitation inputs to the watershed (Hopkinson and Vallino, 1995).

Land use and land cover influence water yields. For instance, forests have much higher rates of evapotranspiration due to higher plant biomass than agricultural or urban land uses, leaving less water available for groundwater or overland flows to streams. As a result, forested landscapes retain more water as well as particulates and dissolved materials, producing the most steady and smallest stream discharges of any land cover (Mustard and Fisher, 2004). Thus, the conversion of forest land cover to anthropogenic land uses not only results in increased water yields with increasing volume and erosive power of storm flows and decreasing base flows but also increasing export of dissolved and particulate material (Mustard and Fisher, 2004). Urban land cover in particular increases water yields due to impervious surfaces such as roads, roofs and parking lots, causing storm responses to be faster with higher discharges and power for bank erosion. Besides overland flow, impervious surfaces prevent infiltration to groundwater causing a rapid drop in flows after the end of the rain event as well as lower evapotranspiration due to reduced abundance of plant biomass. This results in urban areas experiencing a larger volume of water over a shorter period of time with reduced base flows between storm events (Mustard and Fisher, 2004).

Besides quantity, land use and land cover are significant determinants of water quality (Griffith et al., 2002). Land uses within a watershed can account for a relatively high percentage of the variability in stream and estuary water quality (Jones et al., 2001). The local linkages between land use and water quality have cumulative effects on the watershed and the receiving coastal waters (Turner and Rabalais, 2003), and the effects of these linkages vary with changes in the cultural and ecological landscape, with population growth, and with changes in land use and climatic events (Peierls et al. 1991). Fisher et al. (2006) observed three main watershed characteristics determining the magnitude of increased nutrient export to coastal waters: (1) human population density; (2) intensive agricultural production; and (3) the ratio of terrestrial drainage area to aquatic area. Watersheds with high amounts of impervious surface and roads can yield high loadings of nutrients and sediment to streams (Jones et al, 2001). Soil erosion and NO_3 losses to groundwater caused by agriculture can lead to increases in nutrient and sediment loadings to surface waters (Jones et al, 2001). Urban and agricultural land use result in increased inorganic N concentrations in drainage waters via wastewater, fertilizer use, cultivation of N-fixing crops and atmospheric deposition (Pellerin et al., 2004). Wastewater discharge and runoff from intensive agricultural activity may contain elevated concentrations of dissolved organic Nitrogen (Pellerin et al., 2004).

Anthropogenically disturbed areas have higher nutrient yields than forests and hence conversion of forest to agricultural or urban land uses leads to increased concentrations of N and P (Lee et al, 2001). The land cover classes for this research were selected based upon the information summarized in the literature on the contribution of different land use types to water quality in the Bay. Nitrogen fixation in pastures and rangelands accounts for less than 7 % of the total fixation by agricultural biota in the United States (Jordan and Weller, 1996). Barren land is a key contributor to total phosphorus loadings in streams (Lopez et al., 2008). Wetlands play an important role in reducing nutrient concentrations to surface waters acting as filters removing particulate material, as sinks accumulating nutrients or as transformers converting nutrients to different forms such as gaseous compounds of nitrogen (N) and carbon (C) (Jones et al, 2001; Jordan et al., 2003). Because of this ecological role, wetlands are being restored in agricultural watersheds to provide wildlife habitat and improve water quality (Jordan et al., 2003). Land use and land cover data for this research have been classified under 7 categories:

Urban/Developed, *Agriculture*, *Bare land*, *Pasture/Shrub*, *Forest*, *Open Water*, and *Wetlands*.

4.1.1.2 Land Use/Land Cover in the Galveston Bay Watershed

The following is a brief account of the historical changes in human activity and land use in the Galveston Bay watershed based on Lester and Gonzalez, (2002):

Dating back to the late 1800's agricultural production was the dominant land use of the coastal prairies. The arrival of Japanese immigrants after 1900 to farm rice in Harris, Galveston and Brazoria counties (Fig. 1.4) introduced cultivation methods that revolutionized local farming practices. The Japanese cultivation methods were employed to establish large citrus farms in many parts of the western side of the Bay. Following World War II, many returning soldiers left farms and went to work for industries around Galveston Bay (Fig. 1.3). After 1900, increasing quantities of shell, soil and sand resources were used for the construction of roads and buildings. River sand from the San Jacinto and Trinity rivers (Fig. 1.2) was made available by the hydraulic dredge. The mining of bank sand from ancient river tributaries gave rise to "sand pits" creating new pond habitats and wetlands on the coastal prairies.

Oil production came to Galveston in the early 1900's and the growth of the petroleum industry led to changes of land use in and around Galveston Bay. With the demand for petroleum during the World War I, lumber barons were investing their fortunes in drilling for oil and cattlemen who owned large acreage of rangeland began leasing to oil companies. The construction of the first oil refinery along the Houston Ship Channel on Buffalo Bayou (Figs. 2, 3) began in 1918, and by 1927 eight oil refineries were in operation on the channels in Galveston Bay. New oil refineries were built after 1930 on the upper reaches of the Houston Ship Channel and on the southwestern shore of the Bay at Texas City (Fig. 1.3). The growth of the petroleum industry in the early 20th century was the beginning of a trend that led to the highest concentration of refineries and petrochemical plants in the world and a very high concentration of oil and gas wells in and around the Bay. Increased industrial and residential growth resulted in increased use of groundwater that caused land subsidence and taxed the limits of aquifers.

There is not much literature available documenting historical trends on land cover change in the Galveston Bay watershed. The major land use categories in the watershed are developed upland comprised of industrial and municipal land use, cultivated upland and undeveloped lands which include uplands, wetlands and transitional lands (Fig. 4.1).

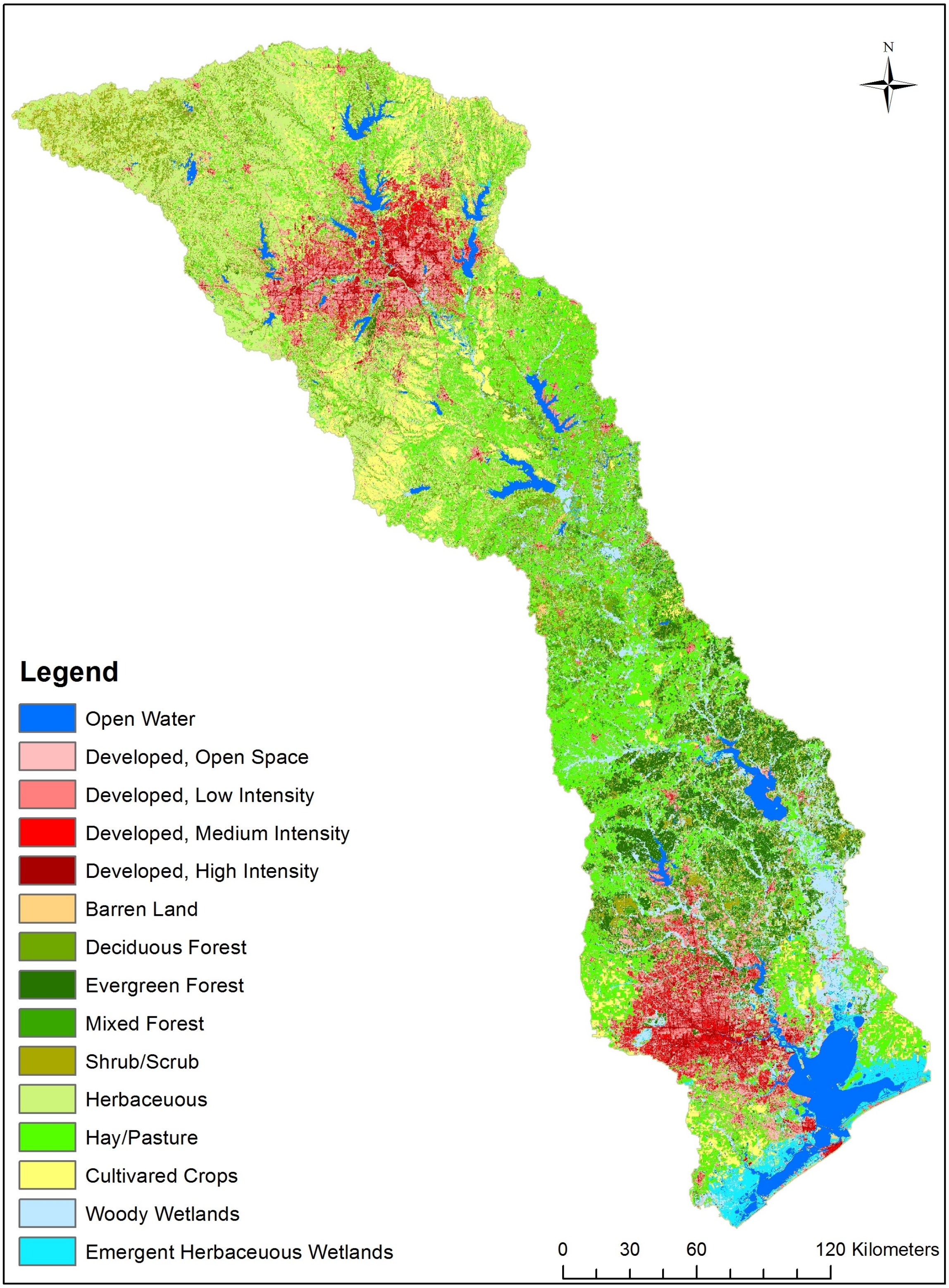


Fig. 4.1 Land Cover map of the Galveston Bay Watershed derived from NLCD (2006)

Based on the information derived from the Galveston Bay Estuary Program report GBEP-T7 (Lester and Gonzalez, 2002), there is extensive residential and commercial use of coastal land in the Galveston Bay watershed. Many industries and shipping concerns located on the Houston Ship Channel are concentrated in the channel area. There has been significant urban development along the western edge of the Bay while the lands east of Trinity and north of West Bay are primarily rural. Suburban and industrial development is interspersed with grazing and agricultural operations in the western shore of the Bay. The report (Lester and Gonzalez, 2002) also states that the effects of non-point source loadings as a result of increased surface runoff caused by impervious surfaces such as roads and parking lots has been a problem that is generating more concern in recent years.

There are five counties surrounding the Bay: — Brazoria, Chambers, Galveston, Harris and Liberty Counties (Fig 4.1). Refining and petrochemical industries are most prominent in the eastern portion of Harris County around the Houston Ship Channel. Galveston County is highly urbanized where land available for development is limited due to development and natural barriers. Land use in Chambers County is primarily agricultural with rice and soybean as the main agricultural crops, but the area also has some petrochemical plants near the border with Harris County. Large areas of Chambers County have been reserved for conservation and recreational parks. Most parts of Brazoria County are rural with a few medium communities—large areas are under conservation and recreation. Among all five counties, Liberty County is the fastest growing county with land use primarily under ranching and agriculture. With the increase in Houston's population, development has moved beyond Harris County, and Liberty is now experiencing suburban development.

Each of the five counties has agricultural land use. However, it is more prominent in Liberty and Brazoria Counties, with livestock grazing and crop production being the primary activities. According to the GBEP-T7 (Lester and Gonzalez, 2002) report there are more than 5, 500 farms located within the five counties surrounding the Bay resulting in more than 2549.52 km^2 of cropland with greater than 323.75 km^2 under irrigation.

Agricultural crops basically include soybeans, rice, sorghum and cotton out of which soybeans represent the largest crop harvested from more than 242.81 km^2 in 1997. The GBEP-T7 (Lester and Gonzalez, 2002) states that despite the fact that a variety of crops are cultivated in all five counties, each county has one main crop — crop yields in 1997 included more than 84.98 km^2 of rice in Chambers County, more than 149.73 km^2 of soybean in Liberty and more than 56.66 km^2 of sorghum in Brazoria. Just like agriculture, livestock grazing operations (primarily cattle) are present in every county with Brazoria leading all others followed by Harris in 1997. According to the GBEP-T7 (Lester and Gonzalez, 2002) report agricultural land use surrounding the Bay has been declining for many years.

4.1.2 Population Growth and its effects

4.1.2.1 General Background

Human population growth is one of the most important factors impacting global land use (Heilig, 1994) reshaping freshwater flows to estuaries worldwide (Montagna, 2002). More people require more food, more houses, more power generation and more roads and railways (Heilig, 1994), and the carrying capacity of land is not a natural constant but a variable strongly influenced by human activity (Heilig, 1994). The coastal areas are heavily populated, with 60% of the people in the United States living within 60 km of the coast and 17 of the 20 fastest growing counties being located in coastal areas (Montagna, 2002). Increasing population growth results in increasing demand for freshwater for municipal, industrial and agricultural uses ; since 1940, water use in the United States has doubled and is likely to double again by 2015 (Montagna, 2002). Reservoirs are constructed in order to meet the growing demands for water and energy that affects the hydrology of the river as a result of modifications by dams, diversions and withdrawals (Montagna, 2002). These large watershed-scale structures severely limit inflow to estuaries, resulting in altered functioning of these ecosystems (Montagna, 2002). On the other hand, water use can produce important beneficial flows by providing a substantial stream flow base during dry seasons when little natural flow may occur (Longley, 1994). There have been reports (Solis and Longley, 1993) regarding USGS gauges in the Galveston Bay drainage basin showing increasing stream flow trends from 1968 to 1987. Two of the possibilities among other causes cited in the report were the increases in ground water return flows from wastewater injection and import of water across watershed boundaries.

Population growth not only affects water yields but water quality as well. Large volumes of nutrient-rich wastewater are generated by dense human populations that are delivered by public sewer systems quickly and directly to aquatic systems (Fisher et al, 2006). If the land is heavily populated, large terrestrial areas draining into small enclosed seas can potentially reduce salinity and increase nutrients and turbidity (Fisher et al, 2006). Peierls et al., (1991) provided evidence that human population within a river's watershed is strongly related to the concentration of nitrate in rivers that discharge to coastal ecosystems. Increase in the amount of nitrogen introduced in point source discharges is a direct result of population growth in the Galveston Bay watershed (Jensen et al., 1991). Besides influencing point source loadings, population growth results in intensive agricultural production for increasing food and energy consumption leading to increased nutrient export to coastal waters (Fisher et al., 2006). Watersheds with greater proportions of agricultural land tend to discharge greater amounts of nitrogen (Jordan et al., 1997).

4.1.2.2 Population Distribution in the Galveston Bay Watershed

The Galveston Bay is adjacent to one of the most urbanized and industrialized areas in the U.S (Lester and Gonzalez, 2002). Approximately four million people reside in the five counties surrounding Galveston Bay (Brazonia, Chambers, Galveston, Harris and Liberty Counties), and Harris County is the most populous in the state with 3.4 million people (Fig. 4.2). The land around the Bay has become increasingly urbanized over the years, and population growth is expected to continue in the region. Per the GBEP-T7 (Lester and Gonzalez, 2002) report, the average population density in the five-county area is 211 persons per km^2, with Harris County (760 persons per km^2) being the most densely populated and Chambers County (17 persons per km^2) the most sparsely populated county in the Bay area. Out of the 4 million people in the five-county area, around 20 percent of the population lives within a two-mile buffer zone around the Bay and its tidally influenced tributaries, and over the last 50 years, the region has exhibited continuous immigration and economic expansion. Much of the growth in this area has been attributed to the construction of the Houston Ship Channel and the discovery of oil in the early part of the twentieth century. The Houston metropolitan area grew to be a major population and industrial center after World War II, with huge population increases during the 1970s and 1980s. A large part of Houston's population growth is due to immigration from within and outside the US and the strength of the region’s economy and its ability to provide jobs has continually attracted new residents from national and international sources.

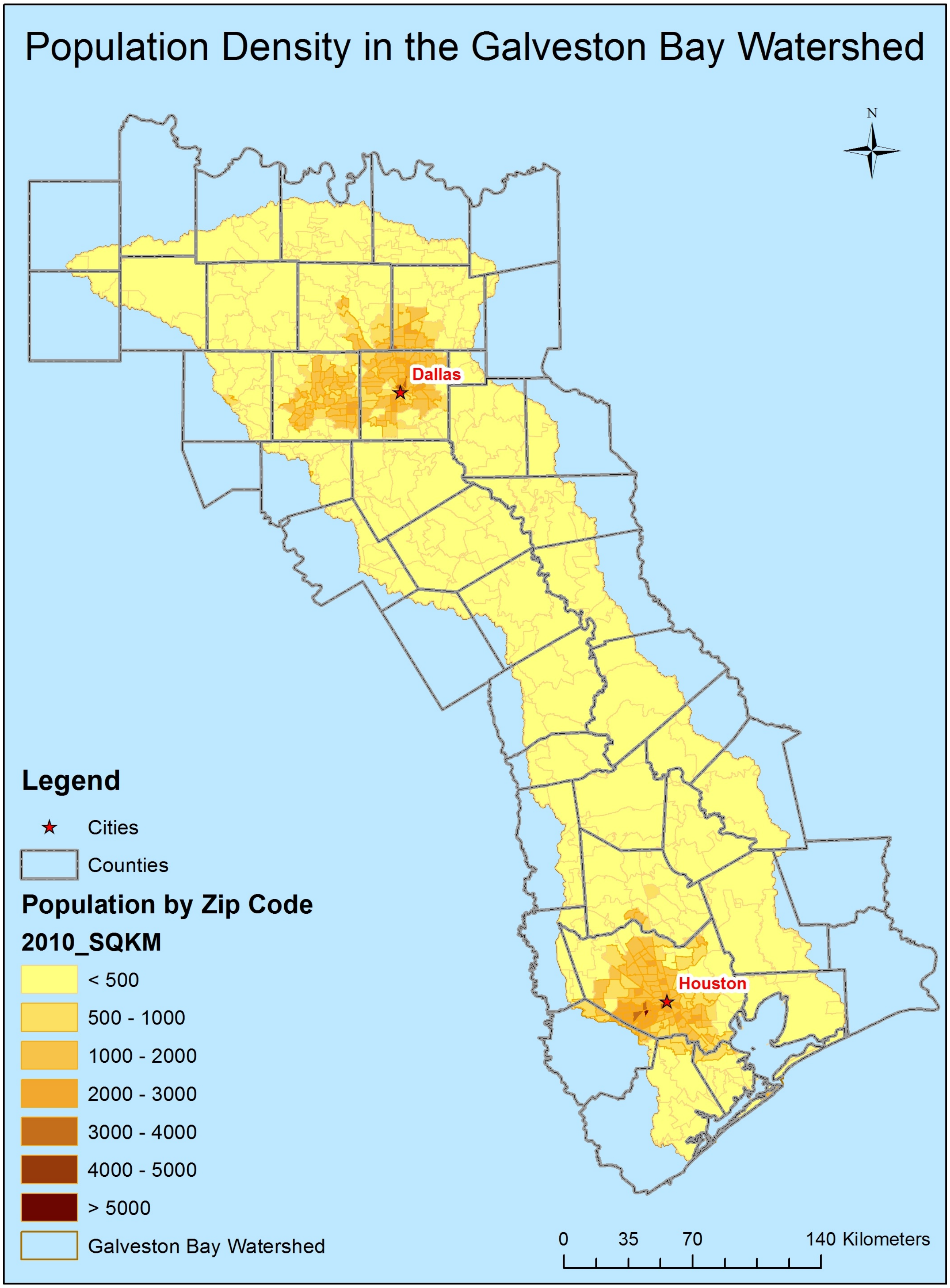


Fig. 4.2 Population Density by Zipcode in the Galveston Bay Watershed

4.1.3 Hypotheses

This chapter analyzes the variations in land use/ land cover and population growth and their influence on stream hydrology and stream chemistry in selected catchments in the Galveston Bay watershed. The hypotheses for this research are as follows:

H1: Increase in urban land use is associated with increase in water yields

H2: Increases in human populations cause increases in water yields in urban areas

H3: There is a positive correlation between increasing population growth and concentration of river nutrients

4.2 Watershed Description

The impact of land cover change and population growth on stream hydrology and chemistry was analyzed for four selected catchments within the Galveston Bay watershed—the *Brays Bayou* and the *Greens Bayou* watersheds near Houston, the *East Fork San Jacinto River watershed near New Caney* and the *West Fork San Jacinto River watershed near Lake Conroe* (Fig. 4.3). Each of these catchments is described in Chapter 3.

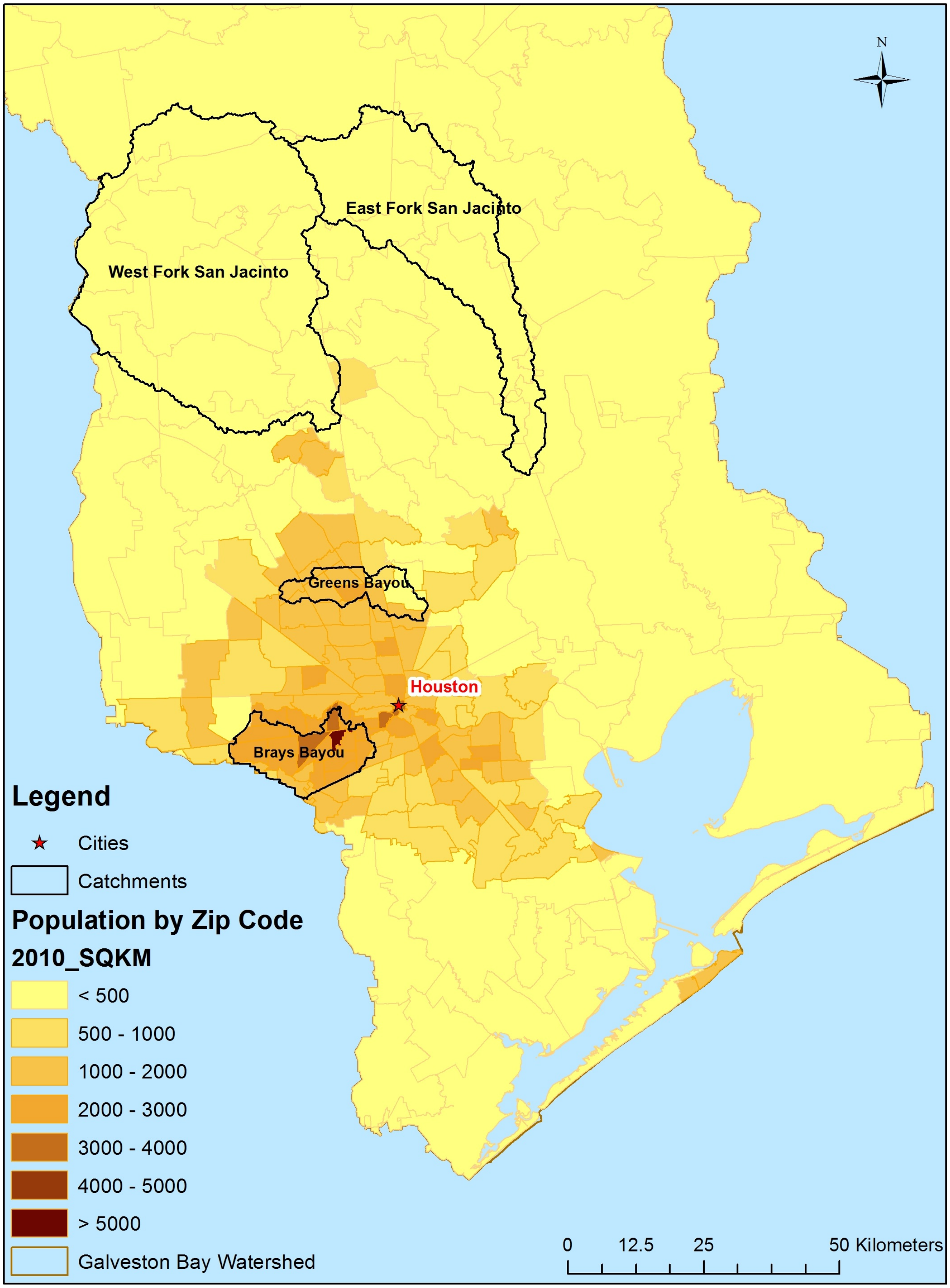


Fig. 4.3 Population Density by Zipcode for Brays Bayou, Green Bayou, East Fork San Jacinto and West Fork San Jacinto catchments

4.3 Datasets

4.3.1 Landsat TM

Landsat TM data were used to generate land cover maps for the lower Galveston Bay watershed for 1989, 1996, 2002 and 2009. This data were downloaded from GLOVIS during the leaf-on period—May-October, when vegetation is at its peak (pers comm. Huang, C.,). This was necessary to maintain a consistent seasonal landscape condition from one time period to the next. This dataset was part of the Landsat Time Series Stack which was processed to generate the Forest Cover Change maps using the Vegetation Change Tracker (VCT) algorithm. High quality Landsat acquisitions are needed to constitute a Landsat Time Series Stack (LTSS) which refers to a sequence of Landsat images acquired at a nominal temporal interval for a particular Worldwide Reference System (WRS) path/row tile (Huang et al., 2009b). The Galveston Bay watershed constitutes a total of 8 path/row tiles (Fig. 4.4). The Forest Cover Change maps were generated for the entire watershed using the automated VCT algorithm while land cover was classified for only 3 path/row tiles—path025row039, path025row040 and path026row039. The Vegetation Change Tracker (VCT) forest cover product was derived from a highly automated change detection algorithm which was already validated for accuracy assessments. The training sites for the land cover classification involved assigning samples of pixels from the Landsat TM data to the respective classes using ancillary data from Google Earth, C-CAP (Coastal Change Analysis Program) data and aerial photos. The Land

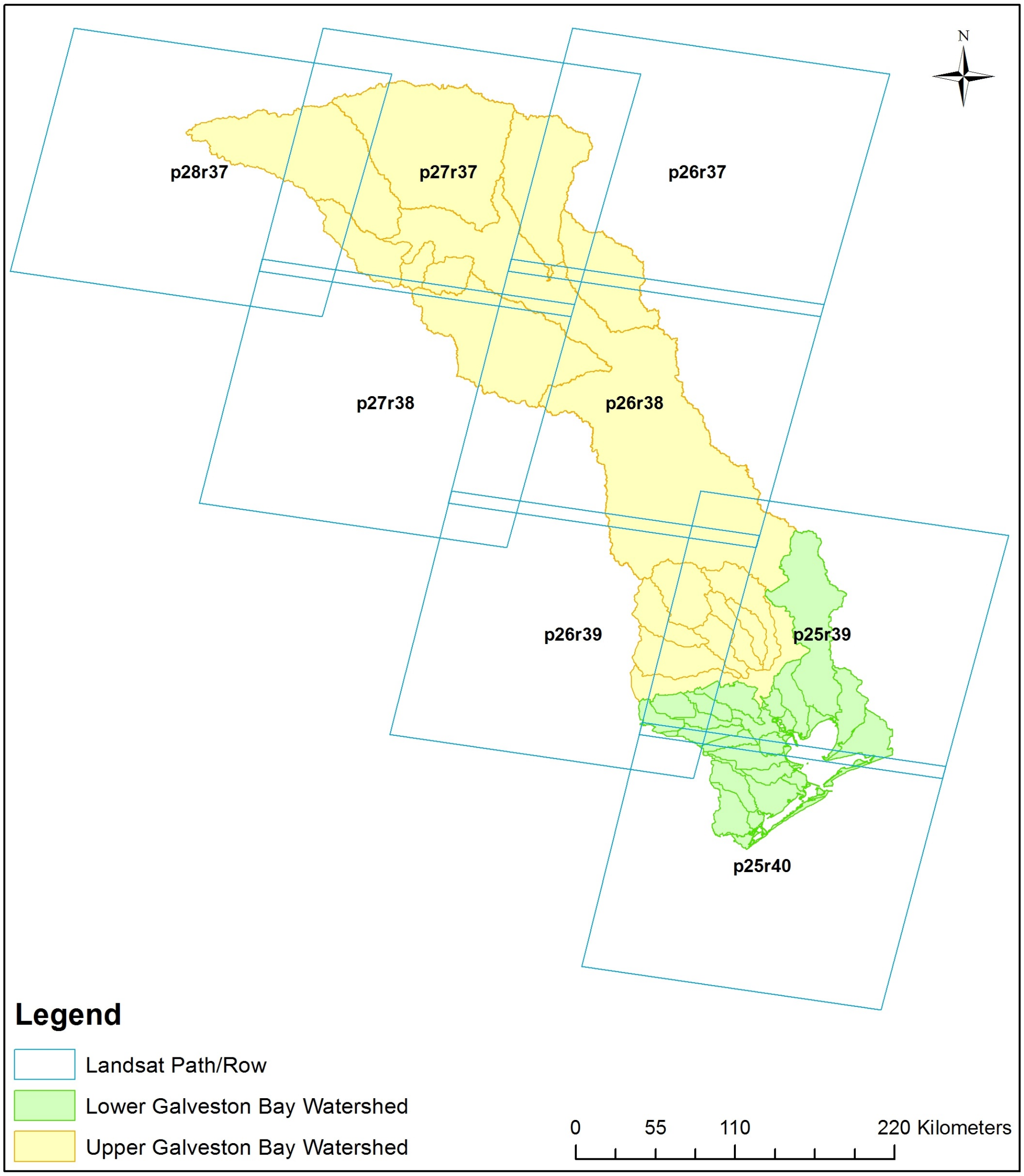


Fig. 4.4 Landsat TM path/rows for the Galveston Bay Watershed

Cover Classification involved selecting training sites manually by using data from various sources. There was no adequate ancillary information for the entire Galveston Bay Watershed for training and validation for the earlier time periods e.g. 1989 and 1996. Second, most of the streams showing increasing trends in water yield and river nutrients were located in the lower watershed particularly in and around the Houston Metropolitan Area. Third, land use/land cover change within the catchments in the lower part of the watershed adjacent to the Bay has the maximum impact on the estuary. According to Steven Johnston (pers comm.) at GBEP/TCEQ (Galveston Bay Estuary Program/ Texas Commission on Environmental Quality), lakes do a lot of modification on the nutrient loading and hence the upper Galveston Bay watershed stops at *Lake Houston* and *Lake Livingston* (Todd Running, H-GAC, pers comm.). The lower watershed more directly contributes runoff and runoff-borne detritus and pollutants to the Bay than the upper watershed (Lester and Gonzalez, 2002). Hence, due to above reasons coupled with the limitations in the ancillary data to support training and validation, the land cover classification had to be limited to just 3 path/row tiles comprising of the lower part of the Galveston Bay Watershed.

The Landsat TM data were classified for 4 land cover classes: *Urban/Developed*, *Agriculture*, *Pasture/Shrub* and *Barren*. The classification was initially intended for five classes—*Urban/Developed*, *Agriculture*, *Pasture/Shrub*, *Barren* and *Wetlands*. One of the major problems in classifying these 5 categories was differentiating *Wetlands* from *Urban* and *Bare soil* with high moisture content. After running the classification with the training sites, large parts of the urban areas as well as agricultural plots with bare soil were classified as wetlands. The spectral

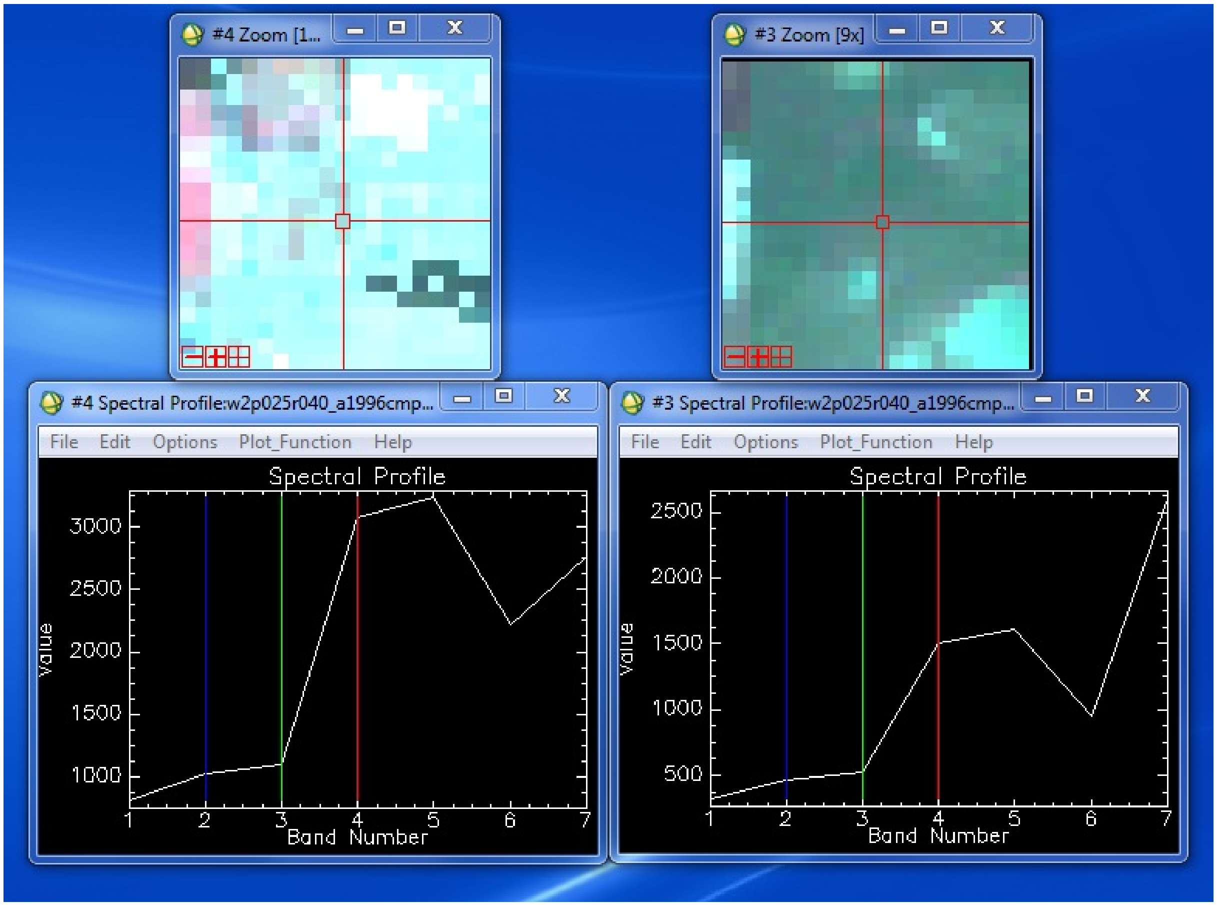


Fig. 4.5 Figure showing the similarity in the shape of the spectral signatures for the *Urban* (left) and *Wetland* (right) classes. Owing to this similarity many *urban* pixels were misclassified as *wetlands* in the classified image

signatures for these classes demonstrated the shape of the spectra to be very similar for both the *Urban* and *Wetland* classes (See Fig. 4.5). Further attempts to improve the classification and the accuracy proved futile—the Producers Accuracy increased for one or two classes but further deteriorated the accuracies for the other classes bringing down the overall accuracy. Hence the decision to use the *Wetland* class from

NOAA CCAP (Coastal Change Analysis Program) and NLCD (National Land Cover Database) Land cover products proved to be a better solution to the classification problem.

4.3.2 VCT Forest Cover Product

The VCT forest cover product has been derived from the *Vegetation Change Tracker (VCT)* algorithm developed by Huang et al.,(2010a). It is a highly automated change detection algorithm which can be used to analyze simultaneously all images in a time series stack of Landsat (LTSS). The derived disturbance maps (Fig. 3.8) had overall accuracy values of about 80% with most of the disturbance classes having user's accuracies ranging from 70% to 95 % (Huang et al., 2009a).

The VCT algorithm comprises two major steps (Thomas et al., 2011): (1) individual image analysis and (2) time series analysis. The forest disturbance year maps produced from VCT identify three static classes—persisting forest, persisting non forest and water, in addition to flagging the year of disturbance for all pixels where forest change was detected. The following is a description of the mapped classes:

- Persistent Forest – This class comprises of pixels that remained forested throughout the time series.
- Persistent Nonforest – It consists of pixels that were never forested during the entire observing period of the time series
- Persistent Water – This class consists of pixels that were water pixels throughout the observing period.

- Forest Disturbance – This constitutes pixels that are not classified as one of the persisting land cover classes. It corresponds to the time step in which the disturbance event occurred.
- Pre-series Disturbance – It comprises pixels that are classified as nonforest during time 1 of the series but change to forest at some point during the observation period. This category includes both forest regrowth and afforestation processes. It is categorized as *previously disturbed but looked like forest by this year* in the map legend.
- Post Disturbance Nonforest – This class includes pixels that indicate forest disturbance long ago and have been converted into another land cover class

The forest disturbance year map product summarizes forest cover changes in the study area that have occurred during the observation period from 1985-2010 (Thomas et al., 2011). Once the maps were derived from VCT (Fig. 3.8), the percentage area was calculated for the forest cover and disturbance classes. The *persistent forest* and *previously disturbed but looked like forest by this year* classes were combined to derive the total forest cover for each year. The *forest* and *water* classes for the land cover maps were derived from this dataset.

4.3.3 Coastal Change Analysis Program (C-CAP)

The C-CAP dataset (Fig. 4.6) is a land cover product generated by the Coast Change Analysis Program (C-CAP) at NOAA which produces a nationally standardized database of land cover and land change information for the coastal regions of the United States. The C-CAP land cover product for the Texas coast has been classified into 22 classes from Landsat TM data for 1996, 2001 and 2006. As per the C-CAP website (http://www.csc.noaa.gov/crs/lca/gulfcoast.html), the products are produced to meet an 85% overall accuracy specification. The *wetland* class for 1996, 2002 and 2009 was derived from the C-CAP land cover products for 1996, 2001 and 2006 respectively. There are six different wetland classes in the land cover product—*Palustrine Forested*, *Palustrine Scrub/Shrub*, *Palustrine Emergent*, *Estuarine Forested*, *Estuarine Scrub/Shrub* and *Estuarine Emergent Wetland*. All these six classes have been combined as one *wetland* class to be merged with the classified land cover product. The 1996 wetland from the C-CAP dataset was used for the 1996 land cover classification, 2001 wetland for the 2002 classified product and 2006 wetland for the 2009 classified map product respectively.

4.3.4 National Land Cover Database (NLCD) 1992-2001 Retrofit Product

The NLCD 1992-2001 Land Cover Change Retrofit product (Fig. 4.7) was developed by the Multi-Resolution Land Characteristics Consortium (MRLC: http://www.mrlc.gov/faq_rlc.php) to provide more accurate and useful land cover change data than by direct comparison of NLCD 1992 and NLCD 2001 (Fry et al., 2008). Data from both Landsat Thematic Mapper (TM) and the Enhanced Thematic Mapper Plus (ETM+) were used by MRLC to generate this product. It has a 30 m resolution, containing unchanged pixels from the NLCD 2001 land cover dataset that have been cross-walked to a modified Anderson Level I classcode, and changed pixels labeled with a “from-to” class code (Fry et al., 2008). There are 56 land cover classes for the state of Texas—that includes a class for changing pixels for every class that has changed from 1992-2001. According to the literature on the NLCD 1992-

2001 Retrofit product, no formal accuracy assessment has been completed (Fry et al., 2008). The *wetland* class for the 1989 classified land cover map was derived from the 1992-2001 Retrofit Product.

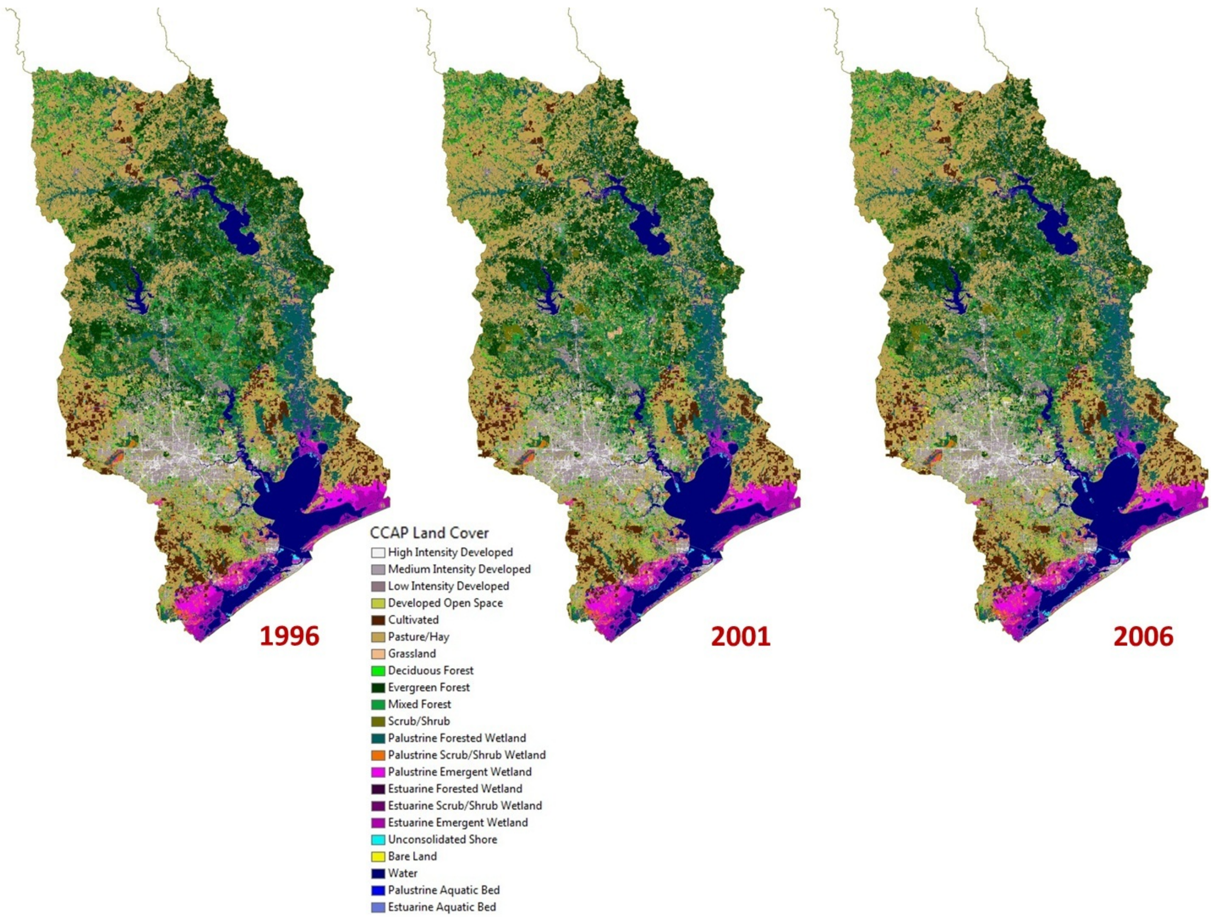


Fig. 4.6 Land Cover Maps from NOAA C-CAP (Coastal Change Analysis Program) for 1996, 2001 and 2006. The *Wetland* data for the 1996, 2002 and 2009 land cover maps were derived from these products

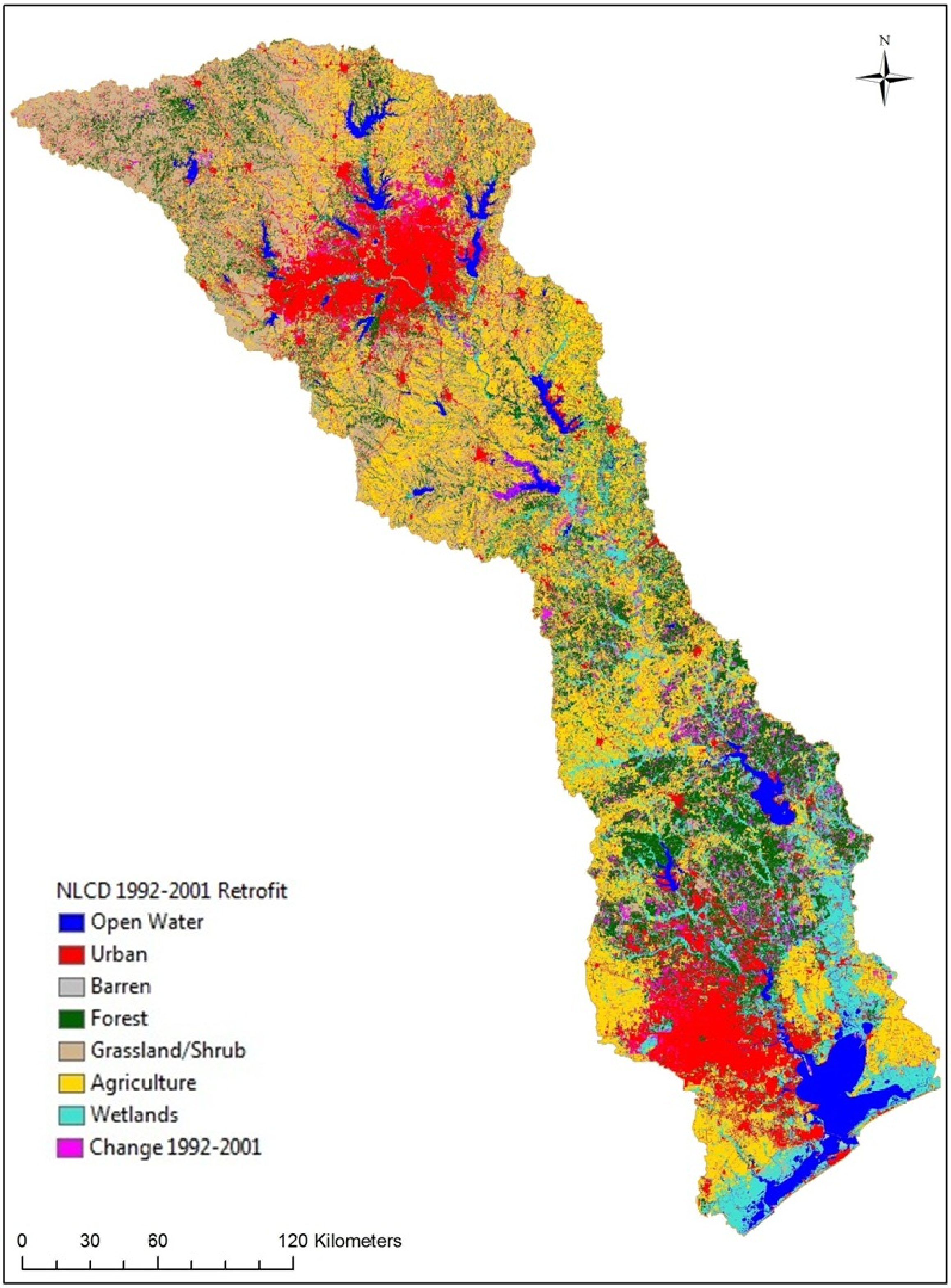


Fig. 4.7 NLCD 1992-2001 Land Cover Change Retrofit product. This dataset provided the *Wetland* data for the 1989 land cover map

4.3.5 National Wetland Inventory (NWI)

The National Wetland Inventory (NWI) dataset (Fig. 4.8) comprises wetland geospatial data providing on-line map information for 82 percent of the conterminous United States; 31 percent of Alaska and 100 percent of Hawaii (http://www.fws.gov/wetlands/Data/Products.html). This dataset is provided by the U.S. Fish and Wildlife Service as a vector file. This wetland dataset was used for the 1989 classified image after merging the NLCD product. The wetland product from NLCD underestimated the percentage wetland area for the lower Galveston Bay watershed and hence this product was used as ancillary data to fill up the gaps for the NLCD 1992 retrofit product. Since NWI did not cover the entire study area, the NLCD data had to be retained for parts of the upper Galveston Bay watershed. The NWI wetland data for the lower Galveston Bay watershed were based on image data derived between 1982 and 1993.

4.3.6 Census Data

This dataset comprises the total population data from the US Census Bureau for each county within and bordering the Galveston Bay Watershed from 1900-2010 (www.census.gov). Block level data for 2000 and 2010 were also obtained, but analysis of the block level data demonstrated an underestimation of county level population data for the previous years in the Brays Bayou watershed (Figs. 4.9, 4.10). Hence, in order to keep the analysis consistent for all the study catchments, only county level data were used for all the years for *Brays Bayou*, *Greens Bayou*, *East Fork San Jacinto* and *West Fork San Jacinto* watersheds.

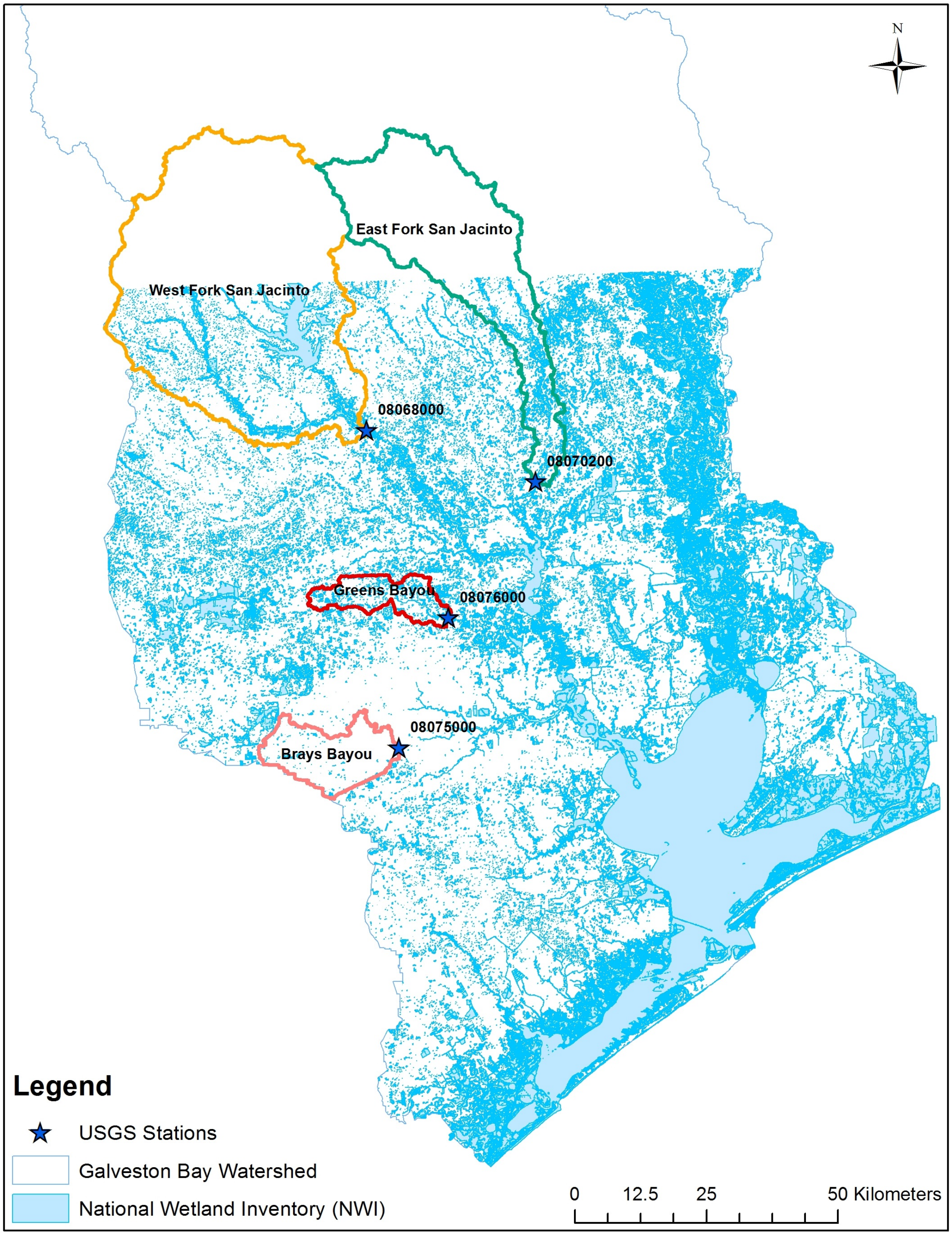


Fig. 4.8 Wetland product derived from the National Wetland Inventory (NWI). This dataset was used to update the 1989 *Wetland* area for the classified image that NLCD had underestimated

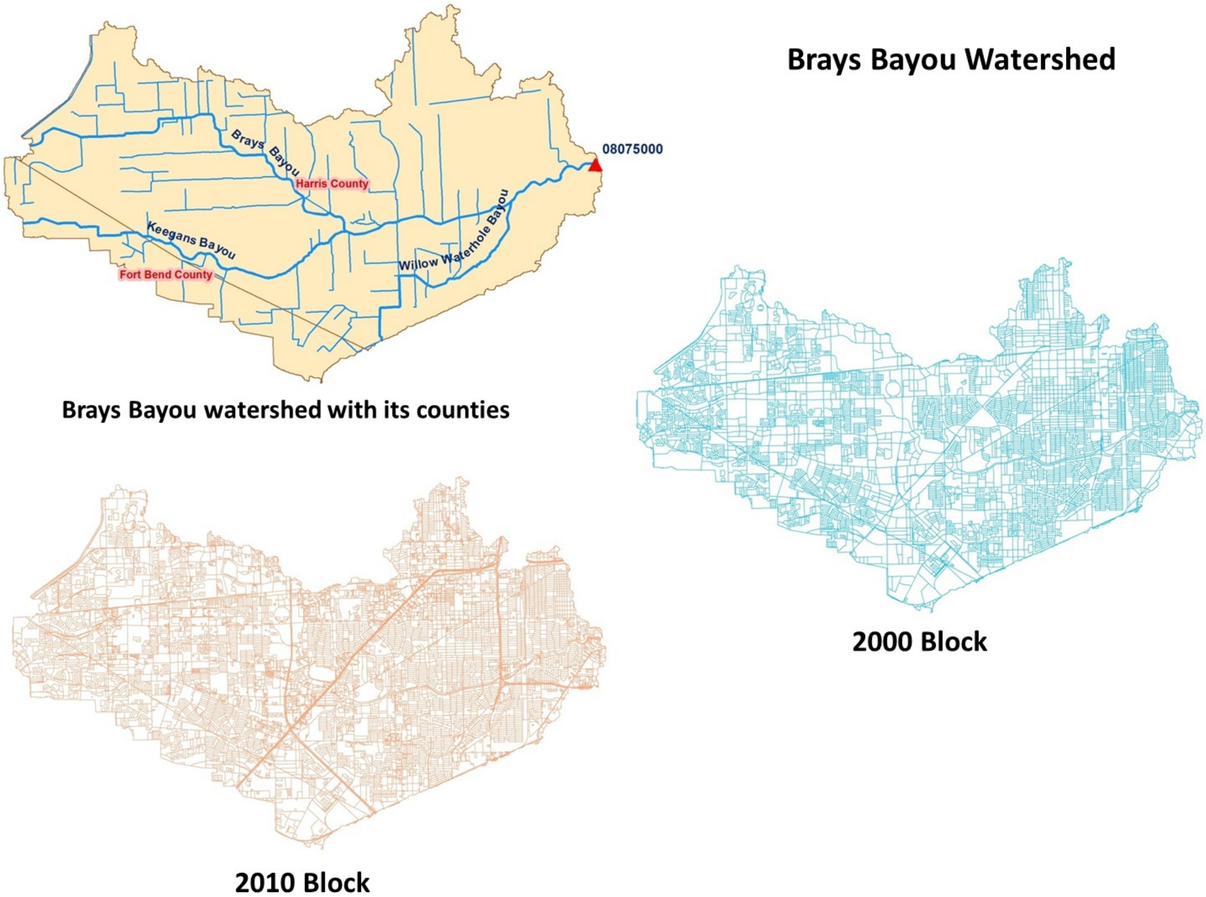
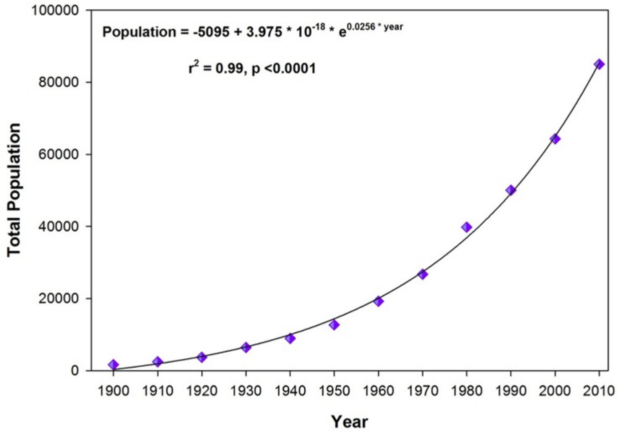


Fig. 4.9 Counties and Blocks for the Brays Bayou Watershed



Year	County Population	Block Population	Difference	Percent_Difference
2000	64317.1754	600538	536220.8318	89.29007413
2010	85041.7176	653231.2	568189.4734	86.98137524

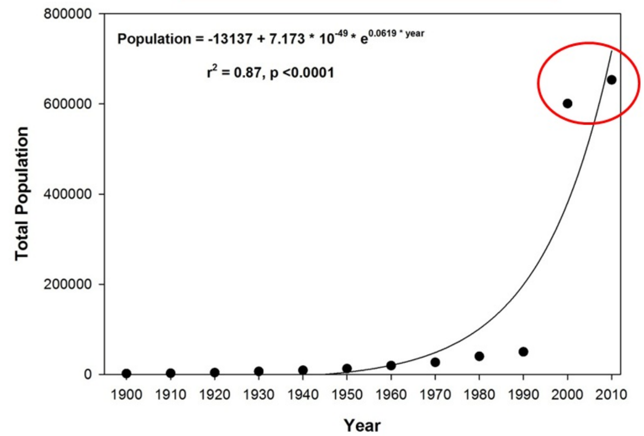


Fig. 4.10 Analysis showing data at the Block level underestimating the county population data for the Brays Bayou Watershed

4.3.7 Precipitation

Daily rainfall data were acquired from the National Climatic Data Center for 10 stations located in and around the 4 catchments—*Brays Bayou*, *Greens Bayou*, *East Fork San Jacinto near New Caney* and *West Fork San Jacinto near Conroe* (Fig. 3.1). Appendix I describes the station locations and their period of record. The mean annual rainfall (m/year) computed from the daily precipitation dataset (inches/day) was used as an independent variable for multiple linear regression models.

4.3.8 Streamflow

Stream flow data were acquired from USGS (www.water.usgs.gov) located at the mouth of the four watersheds (Fig. 3.1). The stream gauging stations for the 4 catchments with their period of record are listed in Table 3.2. The average annual stream discharge (cubic feet per second) as reported by USGS was converted to water yield ($m\ y^{-1} = m^3\ m^{-2}\ y^{-1}$) for all stations using the watershed area (m^2) for comparison with annual rainfall (also $m\ y^{-1}$). This was followed by regression analysis of year vs water yield to look for trends in stream flow over time.

4.3.9 Stream Water Quality

The water quality data were computed as annual averages of TN, nitrate and TP data from the stream gauging stations for *Brays Bayou*, *Greens Bayou*, *East Fork San Jacinto* and *West Fork San Jacinto* watersheds. Table 3.2 lists the USGS stations, their respective basins and their period of record for TN, nitrate and TP data.

4.3.10 GIS Data

The GIS data included the watershed boundaries of the upper and lower Galveston Bay watersheds, TCEQ Bay segments, stream network, lakes and reservoirs, USGS stream monitoring stations, rain gauging stations, county boundaries, blocks, urban areas, cities, ship channels and wastewater outfalls. This data have been obtained from several sources: Trinity River Authority (TRA), Texas Commission on Environmental Quality (TCEQ), Houston-Galveston Area Council

(H-GAC), United States Geological Survey (USGS), U. S. Census Bureau and the National Climatic Data Center (NCDC). The list of GIS data and their respective sources are described in Appendix VIII. The catchment boundaries for Brays Bayou, Greens Bayou, East Fork San Jacinto and West Fork San Jacinto watersheds have been delineated using the USGS EDNA viewer (http://edna.usgs.gov/EDNA_Viewer/viewer.php). Using the monitoring stations as the watershed outlet, the four catchments were delineated for each individual station upstream of the gauge.

4.4 Methods

The proposed research is based on studying the effect that land cover change and population growth has on stream hydrology and stream chemistry in the Galveston Bay Watershed. The percentages of land cover types were used as independent variables along with precipitation and total population data in multiple linear regression models of water yield and water quality for *Brays Bayou*, *Greens Bayou*, *East Fork San Jacinto* and *West Fork San Jacinto* watersheds. These were delineated for the USGS stream gauging stations within the Galveston Bay watershed, and the methodology that was adopted to produce the land cover classification maps for the multiple linear regression analysis is described in a flowchart in Fig. 4.11.

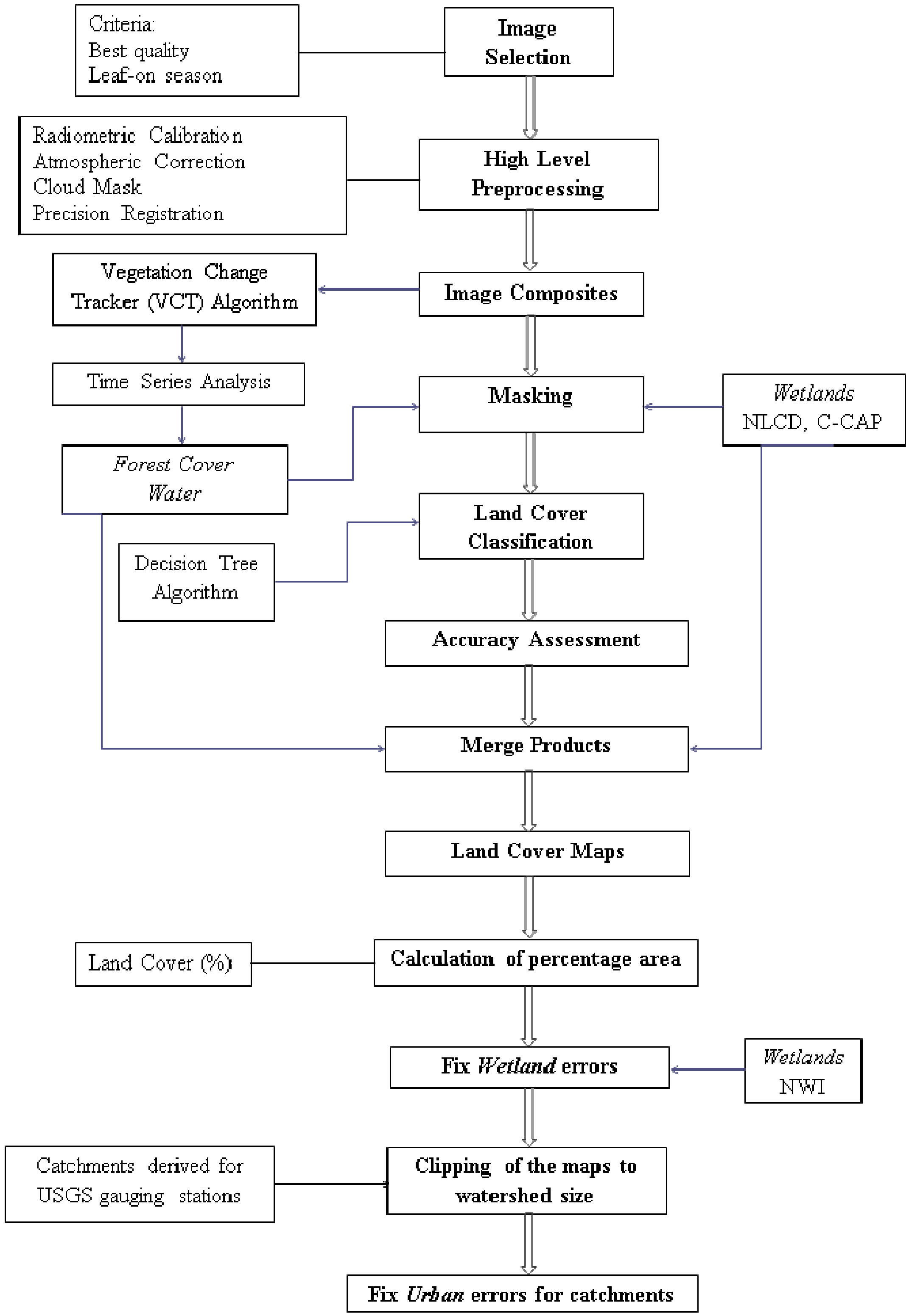


Fig. 4.11 Flowchart describing the method used for the Land Cover Classification from Landsat TM data

4.4.1 Remote Sensing Analysis

4.4.1.1 Image Pre-Processing and Calibration

The Landsat TM Level 1 data consist of digital numbers (DN) which are pre-processed to a reflectance product. The pre-processing steps include calibration of the DNs to at-sensor radiance (watts per square meter per steradian per micron) using the published coefficients for Landsat 5 (Masek et al., 2006). The radiance was corrected to top-of-atmosphere (TOA) reflectance by correcting for solar zenith, Sun-Earth distance, TM bandpass and solar irradiance with the help of the MODTRAN solar output model (Masek et al., 2006). Finally the Landsat surface reflectance product is derived from TOA reflectance using the MODIS/6S methodology for atmospheric corrections. This atmospheric correction scheme assumes that: 1) the target is Lambertian and infinite and 2) the gaseous absorption and particle scattering in the atmosphere can be decoupled (Masek et al., 2006). This was followed by the application of a cloud mask algorithm (Huang et al., 2010b) to flag clouds and their shadows in the images. The cloud mask algorithm uses clear view forest pixels as a reference to define cloud boundaries for separating cloud from clear view surfaces in a spectral temperature space. Shadow locations are predicted based on the cloud location, cloud height estimates and sun illumination geometry (Huang et al., 2010b). The shadow pixels have been identified by searching the darkest pixels surrounding the predicted shadow location (Huang et al., 2010b). Masks derived using this algorithm had overall accuracies ranging from 86% to 99%, while visual assessments indicated that most cloud and shadow were detected properly at the patch level

(Huang et al., 2010b). Following the cloud masks, image composites were created which were used for the Land Cover classification.

4.4.1.2 Land Cover Classification

Prior to the classification, masks were created for *forest*, *water* and *wetlands* from the VCT maps (forest and water for all four time periods) and the NLCD (wetlands for 1989 image) and C-CAP products (wetlands for 1996, 2002 and 2006 image) and then applied to the pre-processed Landsat TM reflectance data to mask out those pixels. This was followed by sub-setting the image to the Galveston Bay watershed boundary to reduce the data size and increase the processing speed. After sub-setting the image, training areas for four land cover classes—*Urban*, *Agriculture*, *Pasture* and *Barren* were selected for each tile for 1989, 1996, 2002 and 2009. The validation for training areas was done using Google Earth and in some cases C-CAP data. Then the RuleGen tool in ENVI (*The Environment for Visualizing Images*) (http://www.exelisvis.com/ProductsServices/ENVI/Capabilities.aspx) image processing software was used as a classifier to classify the reflectance product. The RuleGen tool is an implementation of classification and regression trees (CART) making use of ENVI's native Decision Tree tool (RuleGen_Instructions_v1.01.doc). The CART algorithms are machine learning or expert systems which provide a means to non-parametrically determine statistical relationships between many data layers in order to produce a binary decision tree. The RuleGen tool uses freeware CART algorithms that provide similar functionality to commercially available software such as CART™ (RuleGen_Instructions_v1.01.doc).

Once the image was classified, accuracy assessments were done using stratified random sampling for validation followed by calculation of the statistics on accuracy assessment. Google Earth was used for validating the random samples. Then the *forest*, *water* and *wetland* classes from the respective sources for those years were merged with the classified image. After classifying and merging the data for all the 3 path/row tiles—path025row039, path025row040 and path026row039, they were mosaicked into one single image for each time period. The percentage area for each land cover class—*Urban*, *Agriculture*, *Pasture*, *Barren*, *Forest*, *Water* and *Wetlands* was calculated for the entire image to look for trends in land cover over a 20 year period (1989-2009). Then followed the clipping of the images using catchment boundaries for each study watershed—*Brays Bayou*, *Greens Bayou*, *East Fork San Jacinto near New Caney* and the *West Fork San Jacinto near Conroe*.

4.4.2 Population Analysis

4.4.2.1 <u>Population Analysis</u>

Total population data at the county level were analyzed from 1900-2010 for all the counties lying within the Galveston Bay watershed including the bordering counties that are partly included in the watershed (Fig. 4.12). First, the counties overlapping the Galveston Bay watershed were intersected using the Intersecting tool in ArcGIS. The Galveston Bay Watershed has a total of 45 counties intersecting the watershed boundary—11 of them are completely within the watershed boundary while the remaining 34 counties lie on the boundary. This was followed by

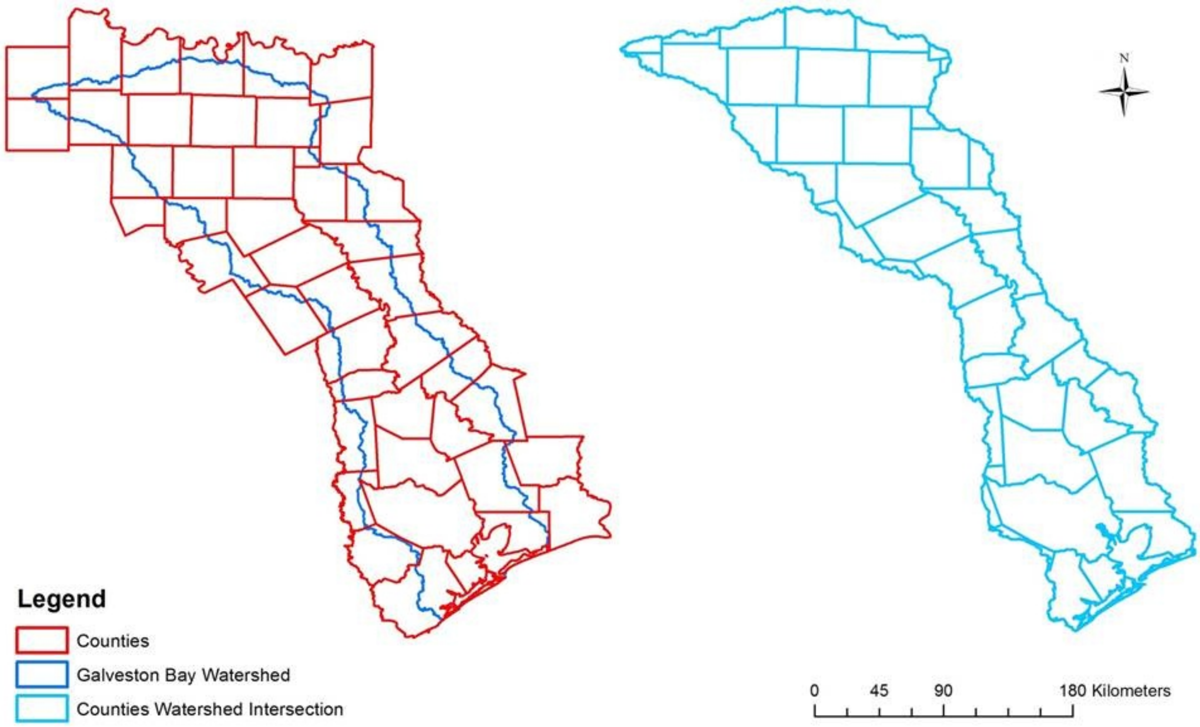


Fig. 4.12 Maps showing intersection of counties with the Galveston Bay Watershed boundary. There are a total of 45 counties intersecting the boundary—11 of them are completely within the watershed while 34 of them are lying on the boundary.

calculating the total population for each decade for all counties lying totally within the watershed. For the bordering counties, first the percentage area that lies within the watershed was calculated. This percentage was then used to calculate the percent population that falls within the watershed; e.g., if 25% of the county lies within the Galveston Bay watershed, then 25% of that county's population was included in the population of the whole watershed. Finally, all the data were totaled to get the final figure for total population for each decade. The same method was adopted for calculating the population for all the four catchments—*Brays Bayou*, *Greens Bayou*, *East Fork San Jacinto near New Caney* and *West Fork San Jacinto near Conroe* from 1900 to 2010. The counties included in these catchments, with the in percent area in the watershed have been listed on Table 4.1.

Catchments	**Counties**	**Area (%)**
Brays Bayou	Harris County	4.8
	Fort Bend County	1.39
Greens Bayou	Harris County	3.33
East Fork San Jacinto	Walker County	13.4
	San Jacinto County	34.6
	Montgomery County	1.05
	Liberty County	3.7
	Harris County	0.1
West Fork San Jacinto	Walker County	32.2
	Grimes County	19.2
	Montgomery County	38.3

Table 4.1 Catchments with their respective counties and their percent area

4.4.3 Regression Analysis

4.4.3.1 Regression Analysis for Land Cover Change

Variables for the regression analysis for land cover change relating to hydrology were water yield (m/y) for 1989, 1996, 2002 and 2009 calculated from USGS stream flow data; percent land cover derived from remote sensing imagery, human population data from US Census Bureau and precipitation data (m/y) from rain gauging stations obtained from NCDC for all four catchments in the watershed. The multiple linear regression model was constructed as follows:

Water Yield = a + b (% urban) + c (% agriculture) + d (% pasture) + e (% bare land) + f (% forest) + g (% wetland) + h (annual rainfall) + i (human population)   (eq. 1)

where y = water yield (m/y), and a,b,c,d,e,f,g,h,i are constants

4.4.3.2 Regression Analysis for Population Growth

Variables for the regression analysis were water yield (m/y) calculated from USGS stream flow data; human population data from US Census Bureau and precipitation data (m/y) from rain gauging stations acquired from NCDC for all four catchments in the watershed. Multiple linear regression analysis correlating water yield and nutrient data with total population was done using Sigma Plot VII on projected population data for all catchments. First an exponential regression model was run for the decadal population data from 1900 to 2010. Then the coefficients of the exponential growth equation were used to project (interpolate) the population data for each catchment (Table 4.2). The reason for projecting the population data was basically for the purpose of correlating water yield and nutrient data with total population. The nutrient data was severely limited and a large number of observations are required to get a significant statistical relationship. The linear regression models were constructed as follows:

$$\text{Water Yield} = a + b\,(\text{Total Population}) + c\,(\text{annual rainfall}) \quad (1)$$

$$TN = a + b\,(\text{Total Population}) \quad (2)$$

$$NO_3 = a + b\,(\text{Total Population}) \quad (3)$$

$$TP = a + b\,(\text{Total Population}) \quad (4)$$

where, y = water yield (m/y), a,b,c = constants.

Catchment	Year	Equation	R^2	p-value
Brays Bayou	1930-2010	=-17076+0.00000000000012893*EXP(0.0205*year)	0.99	<0.0001
Greens Bayou	1960-2010	=-364745+122.2656*EXP(0.0041*year)	0.99	0.0002
East Fork San Jacinto	1970-2010	=-458810+57798.1313*EXP(0.0011*year)	0.99	0.002
West Fork San Jacinto	1960-2010	=-22338+2.877E-25*EXP(0.03425*year)	0.99	<0.001

Table 4.2 Equations for Population Projections for Brays Bayou, Greens Bayou, East Fork San Jacinto and West Fork San Jacinto watersheds

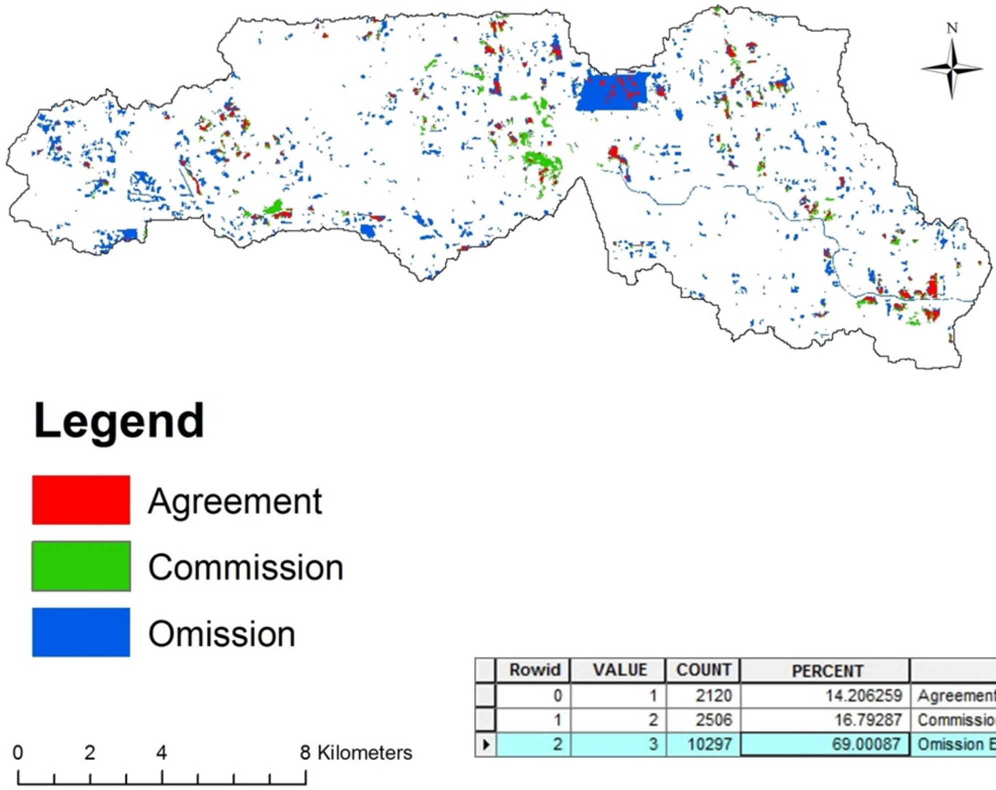
4.5 Results

4.5.1 Accuracy Assessments of the Classified Land Cover maps

The accuracy assessments used the stratified random sampling method to select validation points gathered from the Google Earth tool. Fewer aerial images and black and white photos of land cover for the earlier dates (1989, 1996) made validation difficult. Validation samples were very limited for 1989 which affected the overall accuracy of the Landsat TM tiles for 1989.

The maximum overall accuracy for 1989 achieved for path/row 025/040 was 67% followed by 026/039 with 63% and 025/039 with 62% (Appendix X: Table 1). Results for the 1996 classification were more or less the same—69% for 025/039, 65% for 025/040 and 62% for 026/039 (Appendix X: Table 2). A large improvement in the overall accuracies was observed for 2002 with 80% overall accuracy for 025/040 followed by 025/039 with 79% and 77% for 026/039 (Appendix X: Table 3). An 81% overall accuracy was observed for path/row 025/039 in 2009, 71% for 025/040 and 66% for 026/039 (Appendix X: Table 4). In most cases, urban and pasture had the maximum producer and user accuracy with agriculture and barren the lowest. The lower part of the Galveston Bay watershed is highly urbanized and pasture dominates a major part of the watershed. Moreover, there were very few validation sample points for bare land which could have affected the accuracies for this class. The accuracy assessment statistics for all the path/rows for the four time periods are described in four separate tables in Appendix X.

One anomaly that was observed from the trends in the time series maps was the percentage of wetlands in the Galveston Bay watershed. This land cover class appeared to be 9.8% in 1989 while it was 10.3% in 1996. Although, it is not very different from the previous time period, it is unlikely that wetlands increased, which was a clear indication of an underestimation of the wetland class in the 1992 NLCD Retrofit product. A comparison of the NLCD and NWI wetlands for the Greens Bayou watershed showed that 69% of the wetland area classified by the NWI was classified as other classes (See Fig. 4.13): 43.7% of the wetland pixels were classified as urban, 16.3% as forest and 16% as agriculture by the NLCD 1992 Retrofit product. Hence, the wetland dataset from the NWI was used to update the wetland class. The NWI wetland vectors were converted into a raster grid and then merged with the 1989 classified image. This increased the total wetland percentage to a 22.4% in 1989 followed by a decreasing trend of 19.6%, 19.4% and 19.1% in 1996, 2002 and 2009 respectively. One drawback with the NWI wetland dataset is that it does not cover the entire watershed (Fig. 4.8). Thus, almost half the catchment area for the East Fork San Jacinto and West Fork San Jacinto watersheds had to depend on the NLCD wetlands only for the 1989 classification.



	Rowid	VALUE	COUNT	PERCENT	CLASS
	0	1	2120	14.206259	Agreement
	1	2	2506	16.79287	Commission Errors
▸	2	3	10297	69.00087	Omission Errors

Fig. 4.13 Figure showing an accuracy assessment that was done to test for commission and omission errors between the *wetland* products derived from the NLCD 1992-2001 Land Cover Change Retrofit product and NWI for the Greens Bayou catchment. There was only 14% agreement between NLCD and NWI. Omission errors accounted for 69% which was classified as other land cover types by the NLCD land cover product.

Some discrepancies in the urban class at the catchment scale were observed for Brays Bayou and the East Fork San Jacinto watershed. This could be attributed to tree cover affecting the signal since these images were obtained during the peak summer leaf-on period. The East Fork San Jacinto watershed is also a heavily forested catchment which includes a large part of the Sam Houston National Forest. A simple procedure to fix this discrepancy was adopted whereby the urban pixels for the previous time period was added to the current year where the percentage is low, and then again these pixels were added to the subsequent years assuming whatever was urban stays urban.

4.5.2 Land Cover Trends

Time series maps (Fig. 4.14) of land cover class—*Urban*, *Agriculture*, *Pasture*, *Barren*, *Forest*, *Water* and *Wetlands* for the classified image of the Galveston Bay Watershed have been constructed to analyze the trends in land cover classes from 1989 to 2009. Urbanization continued to grow from 8.7% in 1989 to 14.1 in 2009 (Table 4.3). Agriculture declined from 10.6% in 1989 to 9.3 in 1996; it slightly increased to 9.5% in 2002 and then decreased to 9.4% in 2009. Pasture was more or less constant with minor fluctuations in between—20.6% in 1989 and 21.6% in 2009. Bare land increased from 0.9% in 1989 to 1.6% in 2009 while forest cover decreased from 27.9% in 1989 to 25.5% in 2009. The trends in land cover change are described in Table. 4.4.

For hypothesis testing, the annual variations in land cover types and their influence on stream hydrology was analyzed for the four selected catchments in the Galveston Bay Watershed. The percentage area for land cover have been calculated for each year for *Brays Bayou*, *Greens Bayou*, *East Fork San Jacinto River watershed near New Caney* and the *West Fork San Jacinto River watershed near Lake Conroe*.

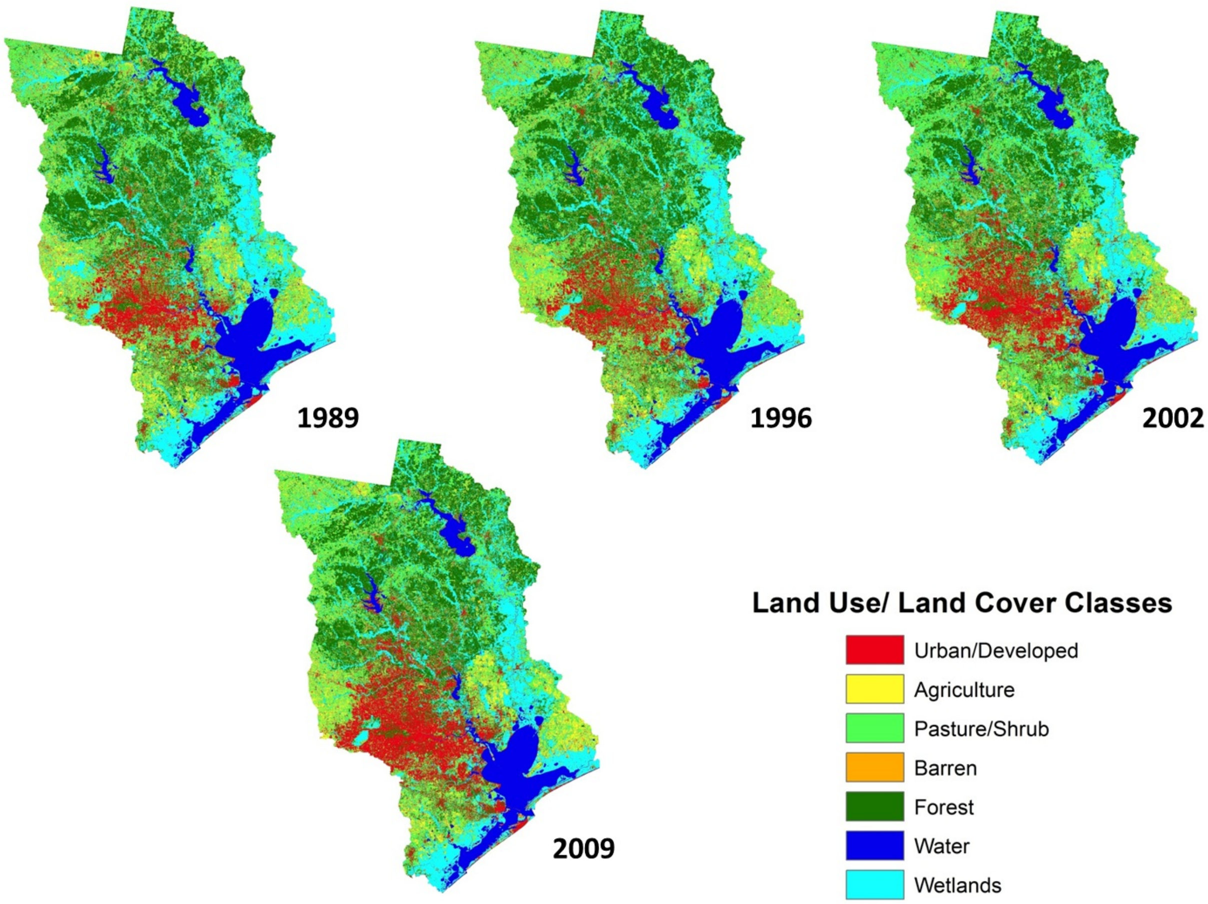


Fig. 4.14 Land Cover maps derived from Landsat TM data using the Decision Tree Algorithm for 1989, 1996, 2002 and 2009**.** This classification was done for only 4 classes—*Urban*, *Agriculture*, *Pasture* and *Barren*. The *Forest* and *Water* classes were derived from the VCT Forest Cover maps while the *Wetlands* were acquired from NLCD, NWI and C-CAP data.

Land Use/ Land Cover	**Year**			
	1989 (%)	**1996 (%)**	**2002 (%)**	**2009 (%)**
Urban/Developed	8.7	9.6	11.5	14.1
Agriculture	10.6	9.3	9.5	9.4
Pasture/Shrub	20.6	22.8	23.7	21.6
Bare Land	0.9	0.5	0.9	1.6
Forest	27.9	29.2	26.2	25.5
Water	8.8	8.9	8.9	8.8
Wetlands	22.4	19.6	19.4	19.1

Table 4.3 Land Use/ Land Cover in the Lower Galveston Bay Watershed

Land Use/ Land Cover	**Galveston Bay Watershed**		
	Trend	R^2	p-value
Urban/Developed	Increasing	0.96	0.02
Agriculture	No Trend	0.87	NS
Pasture/Shrub	No Trend	0.97	NS
Bare Land	No Trend	0.97	NS
Forest	No Trend	0.71	NS
Wetlands	No Trend	0.96	NS

Table 4.4 Trends in Land Use / Land Cover Change in the Lower Galveston Bay Watershed

Land Use/ Land Cover	Year			
	1989 (%)	**1996 (%)**	**2002 (%)**	**2009 (%)**
Urban/Developed	64.5	73.3	81.8	89.3
Agriculture	7.2	4.1	2.7	0.9
Pasture/Shrub	15.6	11.7	8.2	4.2
Bare Land	1.1	0.3	0.5	0.6
Forest	10.8	10.1	6.4	4.7
Water	0.01	0.01	0.01	0.01
Wetlands	0.8	0.5	0.3	0.2

Table 4.5 Land Use/ Land Cover Change in the Brays Bayou Watershed

Land Cover Change in the Brays Bayou Catchment: The Brays Bayou catchment had a total urban land cover of 64.5% in 1989 and 61.2% in 1996 (Table 4.5). Partly located in the Houston Metropolitan Area, this is a heavily urbanized catchment. It is very unusual for an urban land cover to change into another land cover class. Assuming that whatever was urban stays urban, the 1989 urban land cover class was added to the 1996 urban class, which increased the percentage to 73.3% in 1996. Thus, in order to keep the urban growth consistent, the 1989 and 1996 urban area was added to the 2002 urban class, which resulted in 81.8% total urban area in 2002. Similarly, for 2009 the urban area from all the previous years was added to the 2009 urban pixels, resulting in 89.3% of urban area in 2009 (Fig. 4.15). The Brays Bayou watershed being a highly urbanized catchment experienced significant increase in urbanization with decreasing trends in agriculture, pasture, forests and wetlands (Fig. 4.16).

Land Cover Change in the Greens Bayou Catchment: Greens Bayou experienced an increasing trend in urban area from 32.8% in 1989 to 58.5% in 2009 (Table 4.6). Land cover change for all classes is described in Table 4.6.

Land Cover Change in the East Fork San Jacinto Watershed near New Caney: The 2002 classification showed a decrease in the urban area for the East Fork San Jacinto watershed. This is a largely forested watershed with a major part of the Sam Houston National Forest (TPWD) lying within the catchment and hence this could have affected the spectral signature since the image dataset was derived during the leaf-on season. Therefore, in order to rectify the urban class, a similar procedure was adopted for this catchment as in the Brays Bayou watershed where the urban pixels

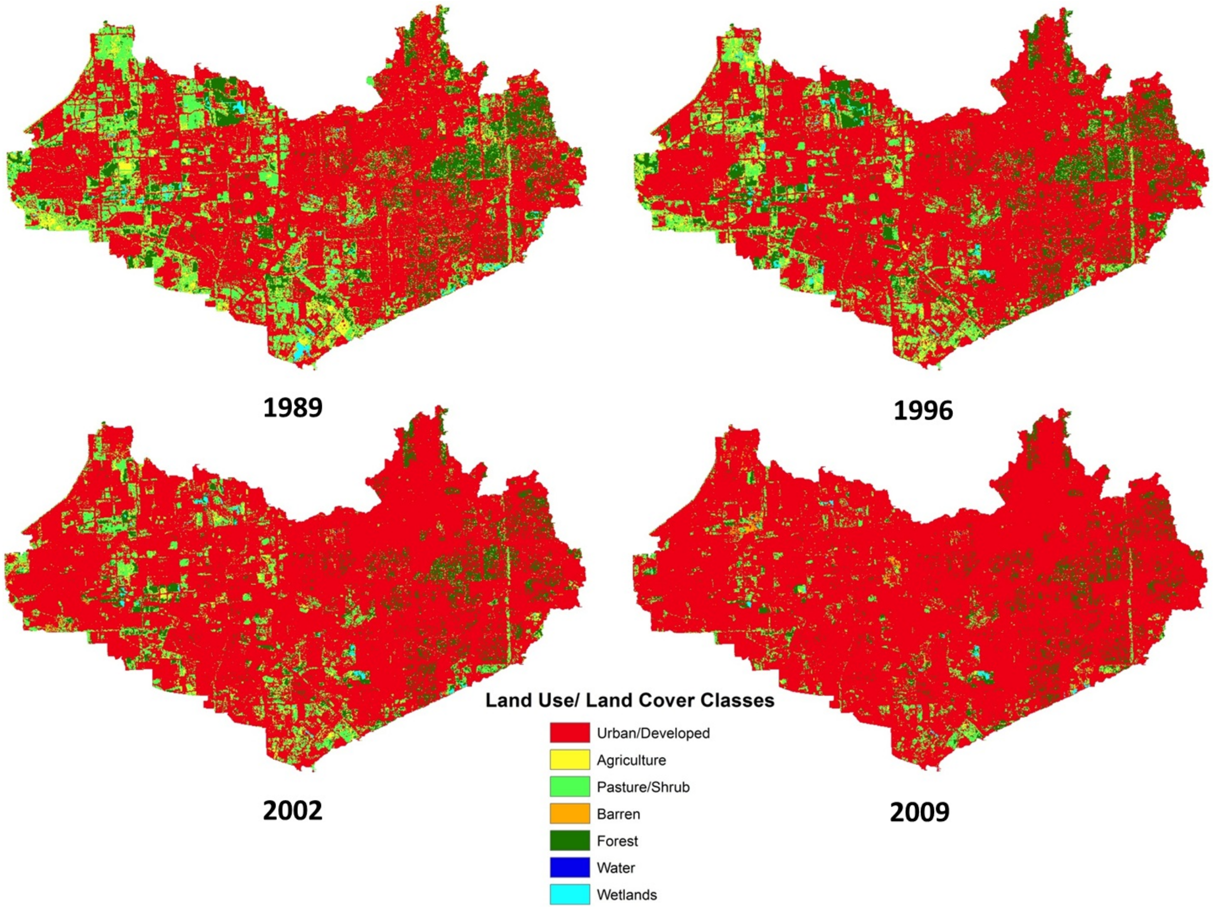


Fig. 4.15 Land Cover time series maps for the Brays Bayou catchment derived from the classified Landsat TM data

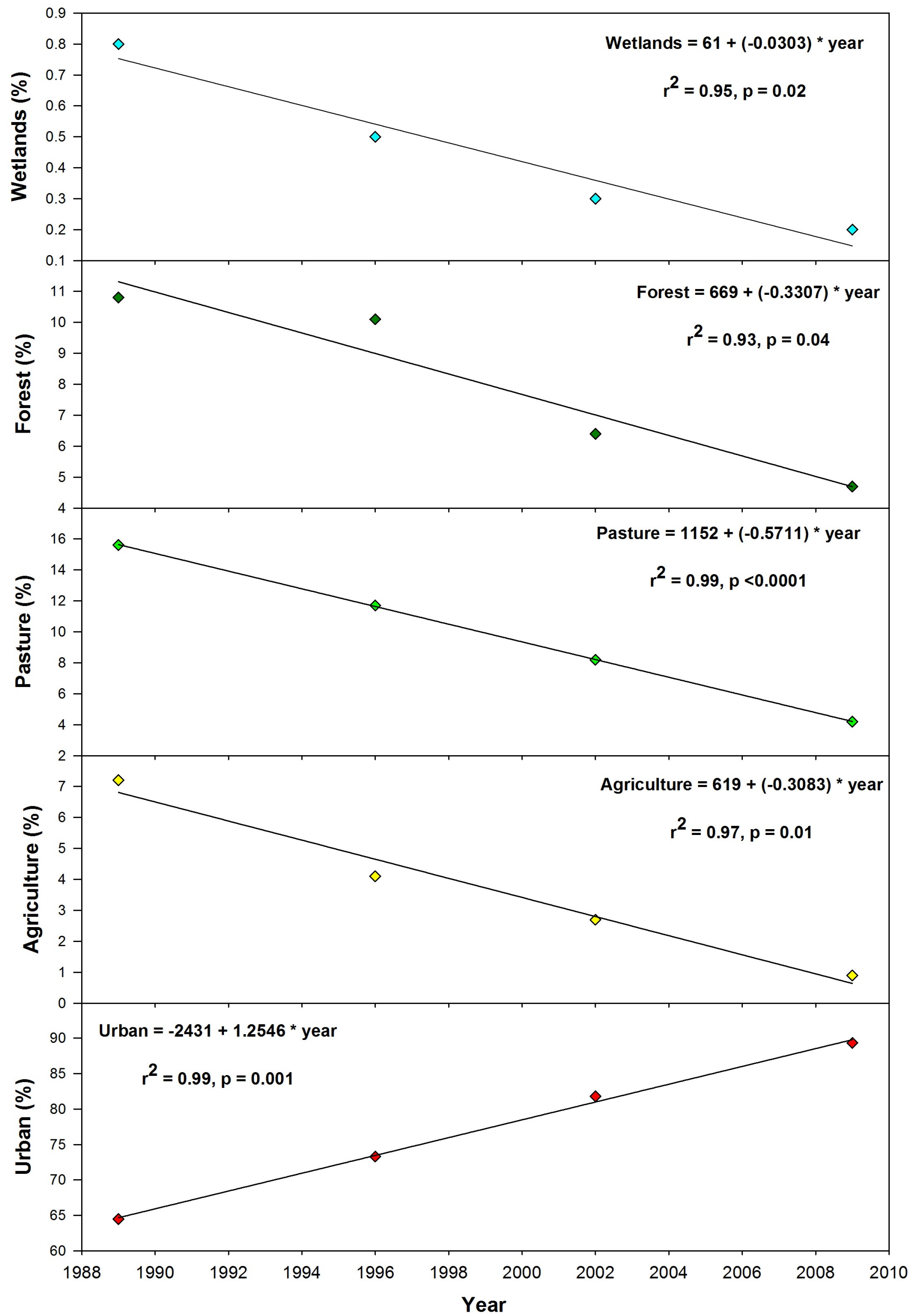


Fig. 4.16 Land Cover trends in the Brays Bayou watershed from 1989-2009. *Urban* land cover is on the rise while *Agriculture*, *Pasture*, *Forest* and *Wetlands* continue on a declining trend which is very typical of watersheds located in a highly urbanized area.

Land Use/ Land Cover	**Year**			
	1989 (%)	**1996 (%)**	**2002 (%)**	**2009 (%)**
Urban/Developed	32.8	37.5	48.3	58.5
Agriculture	11.8	5.9	6.2	3.9
Pasture/Shrub	19.2	22.4	15.9	13.5
Bare Land	2.1	0.9	2	2.8
Forest	25.3	29.4	23.8	17.9
Water	0.03	0.03	0.03	0.03
Wetlands	8.7	3.8	3.6	3.3

Table 4.6 Land Use/ Land Cover in the Greens Bayou Watershed

for the previous year were added to the subsequent periods. For this catchment, the 1996 urban land cover class was added to the 2002 urban class which increased the percentage from 1.9% to 3.9% in 2002 and this was further added to the 2009 urban class that accounted for a total of 6.1% of urban area. Table 4.7 describes the changes in land cover for all classes in the East Fork San Jacinto Watershed.

Land Cover Change in the West Fork San Jacinto Watershed near Conroe: Urban area in the West Fork San Jacinto watershed followed an increasing trend 3.1% in 1989 to 4.9% in 2009 while wetlands continued to decline from 15.4% in 1989 to 13.9% in 2009 (Table 4.8). The trends in land cover change for all four catchments are described in Table. 4.9.

Land Use/ Land Cover	**Year**			
	1989 (%)	**1996 (%)**	**2002 (%)**	**2009 (%)**
Urban/Developed	1.5	2.7	3.9	6.1
Agriculture	7.3	3.8	5.6	4.9
Pasture/Shrub	18.8	17.7	18.4	17.1
Bare Land	0.7	0.3	0.2	0.9
Forest	51.5	55.4	52.5	51.8
Water	0.2	0.2	0.2	0.2
Wetlands	19.9	19.9	19.1	18.9

Table 4.7 Land Use/ Land Cover in the East Fork San Jacinto Watershed

Land Use/ Land Cover	**Year**			
	1989 (%)	**1996 (%)**	**2002 (%)**	**2009 (%)**
Urban/Developed	3.1	3.5	4.2	4.9
Agriculture	8.3	7.8	7.4	7.8
Pasture/Shrub	24	24.4	29.9	27.5
Bare Land	0.4	0.2	0.4	0.9
Forest	44.9	45.9	40	40.9
Water	3.8	3.9	3.9	3.9
Wetlands	15.4	14.2	14.1	13.9

Table 4.8 Land Use/ Land Cover in the West Fork San Jacinto Watershed

Land Use/ Land Cover (%)	Brays Bayou			Greens Bayou			East Fork San Jacinto			West Fork San Jacinto		
	Trend	**R^2**	p-value	Trend	**R^2**	p-value	Trend	**R^2**	p-value	Trend	**R^2**	p-value
Urban/Developed	Increasing	0.99	0.001	Increasing	0.97	0.02	Increasing	0.98	0.01	Increasing	0.98	0.009
Agriculture	Decreasing	0.97	0.01	No Trend	0.81	NS	No Trend	0.55	NS	No Trend	0.93	NS
Pasture/Shrub	Decreasing	0.99	<0.0001	No Trend	0.76	NS	No Trend	0.59	NS	No Trend	0.52	NS
Bare Land	No Trend	0.83	NS	No Trend	0.80	NS	No Trend	0.96	NS	No Trend	0.99	NS
Forest	Decreasing	0.93	0.04	No Trend	0.92	NS	No Trend	0.57	NS	No Trend	0.6	NS
Wetlands	Decreasing	0.99	0.03	No Trend	0.69	NS	No Trend	0.85	NS	No Trend	0.96	NS

Table 4.9 Trends in Land Use / Land Cover in the Brays Bayou, Greens Bayou, East Fork San Jacinto and West Fork San Jacinto watersheds

4.5.3 Results of the Multiple Linear Regression Model for Land Cover Change

No significant relationships were observed between water yield and any of the land cover classes including rainfall and population for Brays Bayou, Greens Bayou, East Fork San Jacinto and West Fork San Jacinto watersheds. Equation (1) did not yield any significant results (Table 4.10), primarily because only four time periods were available, yielding a low power for statistical tests.

In the case of the Brays Bayou watershed, the trends for urban, agriculture, pasture, forest and wetlands had an r^2 that was greater than 0.9 from 1989-2009 (Fig. 4.16). Thus, the land cover for Brays Bayou was projected (interpolated) to increase the number of years (observations) based on the following equations:

$$\text{Urban} = -2430.6947 + (1.2546 * \text{Year})$$

$$\text{Agriculture} = 619.9305 + (-0.3083 * \text{Year})$$

$$\text{Pasture} = 1151.5557 + (-0.5711 * \text{Year})$$

$$\text{Forest} = 699.1372 + (-0.3307 * \text{Year})$$

$$\text{Wetlands} = 60.9702 - (0.0303 * \text{Year})$$

A multiple linear regression analysis was done with water yield as the dependent variable and urban, agriculture, pasture, forest, wetlands and rainfall as the independent variables. Results of the analysis showed

Catchment	Multiple Linear Regression Model	R^2	p-value
Brays Bayou	Water Yield = -7.177 + (0.0896 * Urban) + (0.331 * Agriculture)	0.68	NS
	Water Yield (m/y) = 1.060 - (0.0279 * Pasture) + (0.312 * Bare)	0.40	NS
	Water Yield (m/y) = 1.504 - (0.114 * Forest) + (0.851 * Wetlands)	0.59	NS
	Water Yield (m/y) = -0.0830 + (0.858 * Rainfall (m/y)) + (0.00000359 * Total Population)	0.88	NS
Greens Bayou	Water Yield (m/y) = -0.829 + (0.0240 * Urban) + (0.0665 * Agriculture)	0.84	NS
	Water Yield (m/y) = 1.064 - (0.0275 * Pasture) + (0.0608 * Bare)	0.75	NS
	Water Yield (m/y) = 1.323 - (0.0291 * Forest) + (0.0152 * Wetlands)	0.59	NS
	Water Yield (m/y) = 0.0283 + (0.978 * Rainfall (m/y)) - (0.00000242 * Population)	0.97	NS
East Fork San Jacinto	Water Yield (m/y) = -0.177 + (0.0118 * Urban) + (0.0641 * Agriculture)	0.66	NS
	Water Yield (m/y) = -1.793 + (0.110 * Pasture) + (0.0480 * Bare)	0.54	NS
	Water Yield (m/y) = 2.215 - (0.0440 * Forest) + (0.0165 * Wetlands)	0.49	NS
	Water Yield (m/y) = 0.690 + (0.489 * Rainfall (m/y)) - (0.0000151 * Population)	0.77	NS
West Fork San Jacinto	Water Yield (m/y) = 1.452 + (0.0260 * Urban) - (0.178 * Agriculture)	0.42	NS
	Water Yield (m/y) = -0.934 + (0.0419 * Pasture) - (0.0347 * Bare)	0.85	NS
	Water Yield (m/y) = 1.277 - (0.0452 * Forest) + (0.0570 * Wetlands)	0.87	NS
	Water Yield (m/y) = -0.472 + (0.772 * Rainfall (m/y)) - (0.000000841 * Population)	0.99	NS

Table 4.10 Results of the Multiple Linear Regression Model for Water Yield vs Land Cover Classes, Rainfall and Human Population for the study watersheds

rainfall ($p < 0.001$) and urban ($p = 0.002$) as the only significant variables together explaining 78% of the variability in water yield. Regression analyses between water yield and rainfall and water yield and urban land cover was run separately to understand how well these variables correlated with water yield. Rainfall ($p < 0.001$) explained 66% of the variability in water yield. The urban land cover class explained 11% of water yield but the regression was not significant. The percent urban land cover did not explain water yield; however it helped contribute a significant increase in r^2 along with rainfall to explain water yield. A significant positive effect of urban land use on river discharge can be observed from this analysis which is probably due to impervious surfaces.

4.5.4 Regression Analysis of combined data for all catchments

Land cover effect on hydrology and river chemistry could not be seen due to the limited number of observations in the data. Therefore, the data for all four catchments—*Brays Bayou*, *Greens Bayou*, *East Fork San Jacinto* and *West Fork San Jacinto* watersheds were combined for "space for time-substitution" analysis (Pickett, 1989) to check for correlations between land cover and stream hydrology and stream chemistry.

Variables for the regression analysis were annual water yield (m/y), annual average Total Nitrogen (mg/l), annual average nitrate (mg/l), and annual average Total Phosphorus (mg/l) calculated from USGS stream flow data; percent land cover derived from remote sensing imagery, and precipitation data (m/y) from rain gauging stations obtained from NCDC for all four catchments in the watershed. The multiple linear regression models were constructed as follows:

Water Yield = a + b (annual rainfall) + c (% urban) (eq. 2)

Water Yield = a + b (annual rainfall) + c (% forest) (eq. 3)

Water Yield = a + b (annual rainfall) + c (% wetlands) (eq. 4)

Water Yield = a + b (annual rainfall) + c (% urban) + d (% agriculture) (eq. 5)

where,

a,b,c,d = constants

The multiple linear regression models were initially run with all variables. If some independent variables were not significant, the models were rerun without the variables that were not significant (Table 4.11). In addition, individual linear regression models were run to check for a simple significant relationship between each variable. Results of the trends and relationships between variables are listed in Tables 4.12 and 4.13.

Regression (2) had an r^2 of 0.93 (Table 4.11) with water yield showing a significant positive linear relationship with urban which is the primary driver followed by rainfall. Regression analyses between water yield and rainfall and water yield and urban land cover was run separately to understand how well these variables correlated with water yield. Percent urban ($p < 0.001$) explained 88% of the variability in water yield. Rainfall explained 12% of water yield but the regression was not significant. Annual rainfall did not explain water yield; however it helped contribute

Regression	Multiple Linear Regression Model	R^2	p-value
2	Water Yield = -0.307 + (0.495 * Rainfall) + (0.0105 * Urban)	0.93	<0.001
3	Water Yield = 0.674 + (0.453 * Rainfall) - (0.0188 * Forest)	0.91	<0.001
4	Water Yield = 0.364 + (0.570 * Rainfall) - (0.0412 * Wetlands)	0.85	<0.001
5	Water Yield = -0.536 + (0.519 * Rainfall) + (0.0117 * Urban) + (0.0281 * Agriculture)	0.96	<0.001

Table 4.11 Results of the Multiple Linear Regression Model for the combined land cover data

	Urban (%)			Agriculture (%)			Pasture (%)			Barren (%)			Forest (%)			Water (%)			Wetland (%)		
	Relationship	r^2	p	Relationship	r^2	p	Relationship	r^2	p	Relationship	r^2	p	Relationship	r^2	p	Relationship	r^2	p	Relationship	r^2	p
Water Yield	Positive	0.88	<0.001	None	0.14	NS	Negative	0.57	<0.001	None	0.15	NS	Negative	0.86	<0.001	Negative	0.34	0.02	Negative	0.78	<0.001
TN	Positive	0.84	0.004	None	0.0	NS	None	0.14	NS	None	0.06	NS	Negative	0.85	0.003	None	0.12	NS	Negative	0.95	<0.001
NO_3	Positive	0.85	0.02	None	0.0	NS	None	0.02	NS	None	0.09	NS	Negative	0.8	0.04	None	0.09	NS	Negative	0.89	0.01
TP	Curvilinear decrease	0.88	0.01	None	0.42	NS	None	0.02	NS	Positive	0.73	0.02	Curvilinear decrease	0.81	0.04	None	0.04	NS	Curvilinear decrease	0.84	0.03

Table 4.12 Relationships between percent land cover and water yield and river nutrients (TN, NO_3 and TP) for all four catchments combined

Watershed Name	USGS ID	Km^2 Area	Water Yield				m/y Rainfall	Human Population				TN				NO_3				TP			
			m/y Ave	Trends	r^2	p		Ave (County Level)	Trends	r^2	p	mg/l Ave	Trends	r^2	p	mg/l Ave	Trends	r^2	p	mg/l Ave	Trends	r^2	p
Brays Bayou	08075000	253.6	1.07	No Trend	0.27	NS	1.11	26754.2	Increasing	0.99	<0.0001	6.89	No Trend	0.17	NS	2.5	Increasing	0.69	<0.0001	1.47	Curvilinear Decrease	0.44	0.05
Greens Bayou	08076000	153.3	0.72	Increasing	0.16	0.04	1.04	49303.4	Increasing	0.99	<0.0001	4.6	No Trend	0.1	NS	1.9	Increasing	0.76	<0.0001	1.77	No Trend	0.28	NS
East Fork San Jacinto	08070200	984.9	0.27	No Trend	0.14	NS	1.02	12289.4	Increasing	0.98	<0.0001	0.8	Decreasing	0.4	0.02	0.14	No Trend	0.2	NS	0.05	Decreasing	0.80	<0.0001
West Fork San Jacinto	08068000	2147.6	0.22	No Trend	0.12	NS	1.0	53839.8	Increasing	0.99	<0.0001	2.43	Increasing	0.59	0.009	0.7	Increasing	0.87	<0.0001	0.7	Curvilinear Decrease	0.55	NS

Table 4.13 Trends in water yield, human population, TN, NO_3 and TP for Brays Bayou, Greens Bayou, East Fork San Jacinto and West Fork San Jacinto catchments

a significant increase in r^2 along with percent urban to explain water yield. Regression (3) had an r^2 of 0.91 (Table 4.11) with water yield showing a significant negative linear relationship with forest which is the primary driver followed by a positive relationship with rainfall. Percent forest ($p < 0.001$) explained 86% of the variability in water yield. Annual rainfall by itself was not significant but helped contribute a significant increase in r^2 along with percent forest to explain water yield. Similar results were seen from regression (4) that had an r^2 of 0.85 where significant negative land cover effect was seen from wetlands on water yield. Percent wetlands explained 78% of the variability in water yield for all four catchments combined. Regression (5) yielded an r^2 of 0.96 ($p < 0.001$) with significant positive relationships between water yield and rainfall, urban and agriculture. Regression analysis between water yield and agriculture did not yield significant results; however agriculture like rainfall helped contribute a significant increase in r^2 along with percent urban to explain water yield.

4.5.5 Population Trends

The population growth in the Galveston Bay watershed (Fig. 4.17) in general and all the four catchments *Brays Bayou*, *Greens Bayou*, *East Fork San Jacinto near New Caney* and *West Fork San Jacinto near Conroe* had very similar trends with exponential growth from 1900 to 2010 (Fig. 4.18). The Galveston Bay watershed and all the catchments except for the East Fork San Jacinto watershed had an r^2 of 0.99 with $p < 0.0001$ (Fig. 4.18). The East Fork San Jacinto catchment had an r^2 of 0.98 with $p < 0.0001$ (Fig. 4.18). These trends in population for all four catchments are described in Table. 4.13.

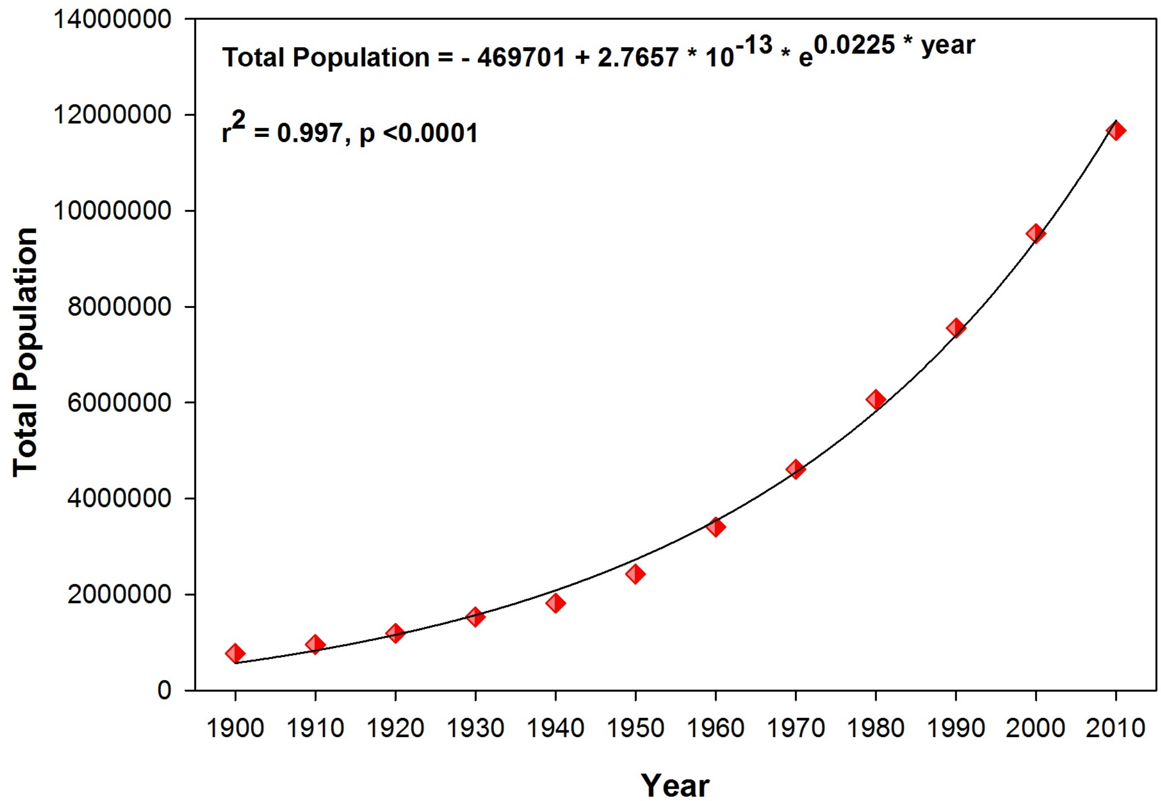


Fig. 4.17 Population growth in the Galveston Bay Watershed based on County level census data from 1900-2010

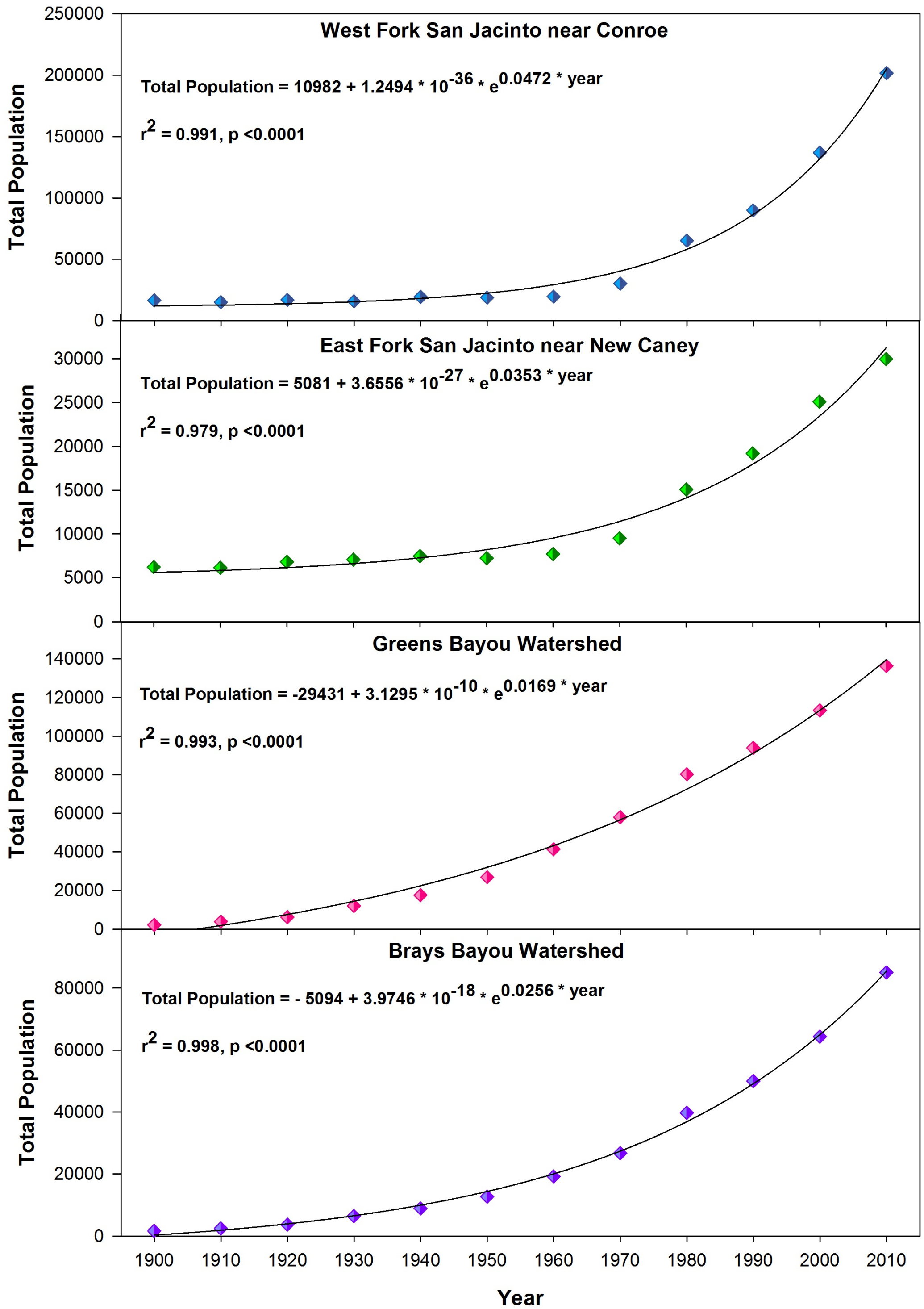


Fig. 4.18 Trends in Population growth for the Brays Bayou, Greens Bayou, East Fork San Jacinto and West Fork San Jacinto watersheds based on County level census data from 1900-2010

4.5.6 Results of the Multiple Linear Regression Model for Population Growth

Brays Bayou: Brays Bayou had a long data record for annual water yield (Fig. 3.19). A linear regression model was run with water yield as the dependent variable and the decadal population data as the independent variable from 1940-2010. This analysis resulted in an r^2 of 0.94 with a $p = 0.007$ (Fig. 4.19). The population was then projected using the equation (Table 4.14) for the data ranging from 1930-2010 as follows:

$$\text{Population} = -9195 + 3.3824 \times 10^{-16} * e^{0.0234 * \text{year}}$$

Then the projected population data ranging from 1937-2009 were used for equation (1) that resulted in an r-square of 0.87 with $p < 0.001$ (Table 4.15). Linear regression models were run separately to check for their contribution to water yield. The projected population data explained 67% of the water yield in Brays Bayou while rainfall contributed 24% of the water yield in the catchment (Table 4.16). As for equations (2), (3) and (4), positive significant relationships were observed between population and TN and nitrate whereas TP showed a declining trend with increasing population (Table 4.16). This was a significant correlation, but not necessarily cause and effect. Phosphorus reduction could be a result of change in legislation relating to a ban in phosphorus for detergent use (Todd Running, Houston-Galveston Area Council (H-GAC), pers comm.). Increasing population causes a higher demand for water resulting in increasing return flows over time as can be seen from the Fig. 4.19.

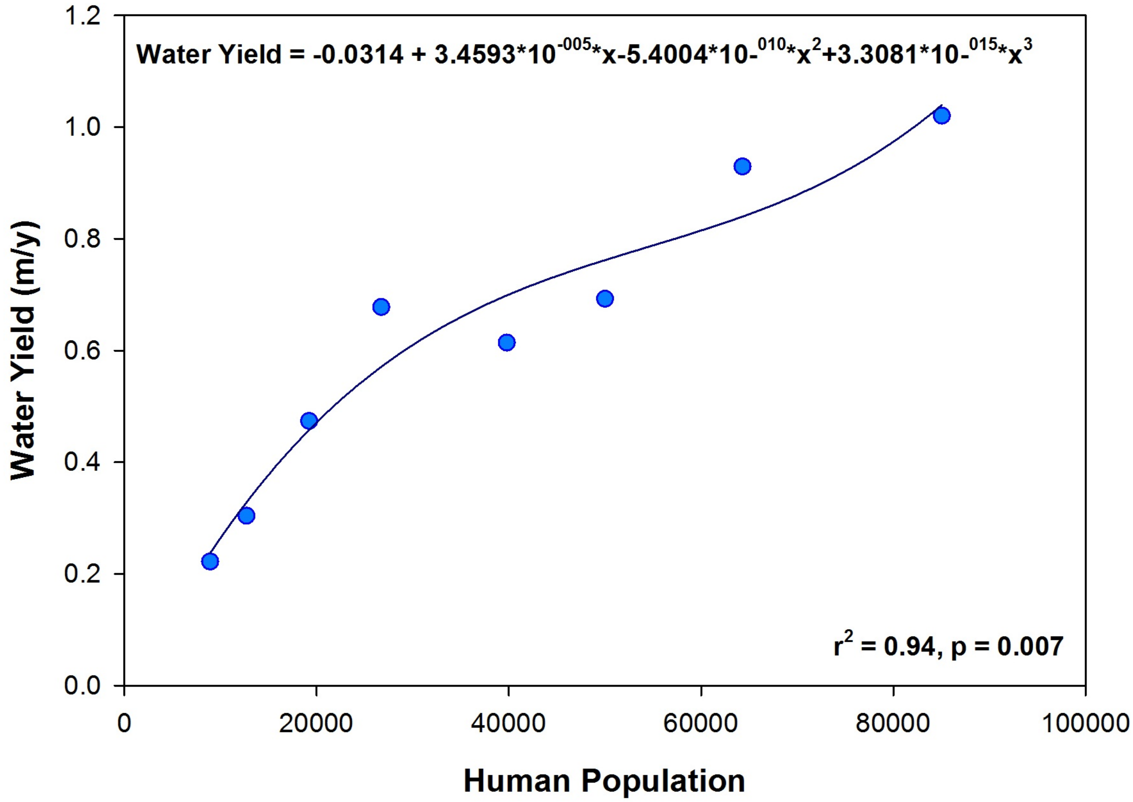


Fig. 4.19 Plot showing the relationship between decadal Human Population vs Water Yield from 1940-2010 in the Brays Bayou Watershed

Catchment	Year	Equation	R^2	p-value
Brays Bayou	1930-2010	=-17076+0.00000000000012893*EXP(0.0205*year)	0.99	<0.0001
Greens Bayou	1960-2010	=-364745+122.2656*EXP(0.0041*year)	0.99	0.0002
East Fork San Jacinto	1970-2010	=-458810+57798.1313*EXP(0.0011*year)	0.99	0.002
West Fork San Jacinto	1960-2010	=-22338+2.877E-25*EXP(0.03425*year)	0.99	<0.001

Table 4.14 Equations for Population Projections for Brays Bayou, Greens Bayou, East Fork San Jacinto and West Fork San Jacinto watersheds

Catchment	Multiple Linear Regression Model	R^2	p-value
Brays Bayou	Water Yield = -0.527 + (0.620 * Rainfall) + (0.0000153 * Total Population)	0.87	<0.001
Greens Bayou	Water Yield = -0.461 + (0.476 * Rainfall) + (0.00000619 * Total Population)	0.74	<0.001
East Fork San Jacinto	Water Yield (m/y) = -0.114 + (0.386 * Rainfall (m/y))	0.48	<0.001
West Fork San Jacinto	Water Yield (m/y) = -0.235 + (0.443 * Rainfall (m/y))	0.61	<0.001

Table 4.15 Results of the Multiple Linear Regression Model for Water Yield vs Rainfall and Human Population for the listed catchments

Watershed Name	USGS ID	**Water Yield vs Rainfall**			**Water Yield vs Human Population**			**TN vs Human Population**			**NO_3 vs Human Population**			**TP vs Human Population**		
		Relationship	r^2	p	Relationship	r^2	p	Relationship	r^2	p	Relationship	r^2	p	Relationship	r^2	p
Brays Bayou	08075000	Positive	0.24	<0.0001	Positive	0.67	<0.001	Positive	0.19	0.03	Positive	0.68	<0.0001	Curvilinear Decrease	0.3	0.007
Greens Bayou	08076000	Positive	0.31	<0.0001	Positive	0.55	<0.001	Positive	0.3	0.004	Positive	0.75	<0.0001	No Trend	0.08	NS
East Fork San Jacinto	08070200	Positive	0.48	<0.0001	No Trend	0.14	NS	Negative	0.25	0.01	No Trend	0.2	NS	Negative	0.81	<0.0001
West Fork San Jacinto	08068000	Positive	0.61	<0.0001	No Trend	0.04	NS	Positive	0.8	<0.0001	Positive	0.9	<0.0001	Positive	0.67	<0.0001

Table 4.16 Relationships between water yield and human population; river nutrients and human population for the four study catchments

Greens Bayou: The decadal population data explained 95% of the water yield in the Greens Bayou watershed. The population was then projected using the equation for the data ranging from 1950-2010 as follows:

$$\text{Population} = -\ 271121 + 11.7954 * e^{0.0052 * \text{year}}$$

Rainfall and projected population explained 74% of the water yield with rainfall contributing 31% and population explaining 55% of the total water yield. Positive relationships were observed between population and TN and NO_3 with population contributing 30% of TN and 75% of the nitrate in the Greens Bayou catchment. There was no relationship between TP and total population.

East Fork San Jacinto Watershed: Human population was projected from 1983-2010 using the equation for the population data ranging from 1970-2010

$$\text{Population} = -\ 458810 + 57798.1313 * e^{0.0011 * \text{year}}$$

An r-square of 0.49 ($p < 0.001$) was observed for Equation (1) for the East Fork San Jacinto watershed. Rainfall explained 48 % of the water yield while no relationship was observed between the projected human population and water yield. Both TN and TP showed a declining trend with increasing population which is a clear indication of no cause and effect. According to a local contact at Houston-Galveston Area Council (H-GAC), this could probably be a result of a shift from onsite sewage facilities (septic tanks) of various stages of efficiency to centralized treatment plants but that has not been confirmed as yet. No significant relationship was observed between nitrate and total population for the East Fork San Jacinto catchment.

West Fork San Jacinto Watershed: The projected population for the West Fork San Jacinto watershed was calculated using the data ranging from 1960-2010 based on the following equation:

$$\text{Population} = -\ 22338 + 2.877 \times 10^{-25} * e^{0.03425 * \text{year}}$$

The West Fork San Jacinto watershed had an r-square of 0.61 with $p < 0.001$ for Equation (1) where rainfall explained 61% of the variability in water yield. Total population during 1961 and 2010 had no significant impact on the water yield of the West Fork San Jacinto River, but population had significant positive relationships with TN, nitrate and TP in the watershed. Human population explained 81% of the TN, 90% of nitrate and 67% of TP in the West Fork San Jacinto catchment indicating increase in river nutrients with increasing population growth (Fig. 4.20).

4.6 Discussion

Test of the Hypothesis

I observed no significant relationships between water yield and land cover for Brays Bayou, Greens Bayou, East Fork San Jacinto and West Fork San Jacinto watersheds based on the time series data for the four respective time periods—1989, 1996, 2002 and 2009 on an individual watershed basis. Therefore, hypothesis H1 (Increase in urban land use is followed by an increase in water yield) was not supported by the data for equation (1). However, in the case of the projected land cover data (1986-2009) for the Brays Bayou watershed, rainfall and urban land cover together explained 78% of the variability in water yield.

In order to see the effect of land cover the data for all four catchments—*Brays Bayou*, *Greens Bayou*, *East Fork San Jacinto* and *West Fork San Jacinto* watersheds were combined to increase the number of observations and check for correlations between percent land cover and stream hydrology and stream chemistry. Results of the multiple regression analyses (2-5) from the data for all the catchments combined confirmed that hypothesis H1 (Increase in urban land use is followed by an increase in water yield) is supported by the data. Percent urban had a highly significant positive relationship with water yield (r^2 of 0.88, $p < 0.001$) indicating increasing water yields with increasing urban land use (Fig. 4.21). Contrary to the results of the regression analysis for the projected land cover data for the Brays Bayou watershed where rainfall was the primary driver of water yield, in this case urban land cover played the primary role in explaining water yield.

Results of the regression analysis between water yield and the other land cover classes also showed significant relationships. Pasture ($r^2 = 0.57$, $p < 0.001$), forest ($r^2 = 0.86$, $p < 0.001$) and wetlands ($r^2 = 0.78$, $p < 0.001$) negatively correlated with water yield (Figs. 4.22, 4.23 and 4.24). Percent water also showed a significant negative correlation with water yield ($r^2 = 0.34$, $p < 0.02$) indicating low water yield with higher percentage of water body within the watershed.

Significant relationships were also observed between river nutrients (TN, NO_3 and TP) and percent land cover (Figs. 4.25, 4.26, 4.27 and 4.28). A highly significant positive relationship was observed between TN and percent urban (Fig. 4.25) that had an $r^2 = 0.85$ ($p = 0.004$). TN decreased with increasing forests ($r^2 = 0.85$, $p = 0.003$)

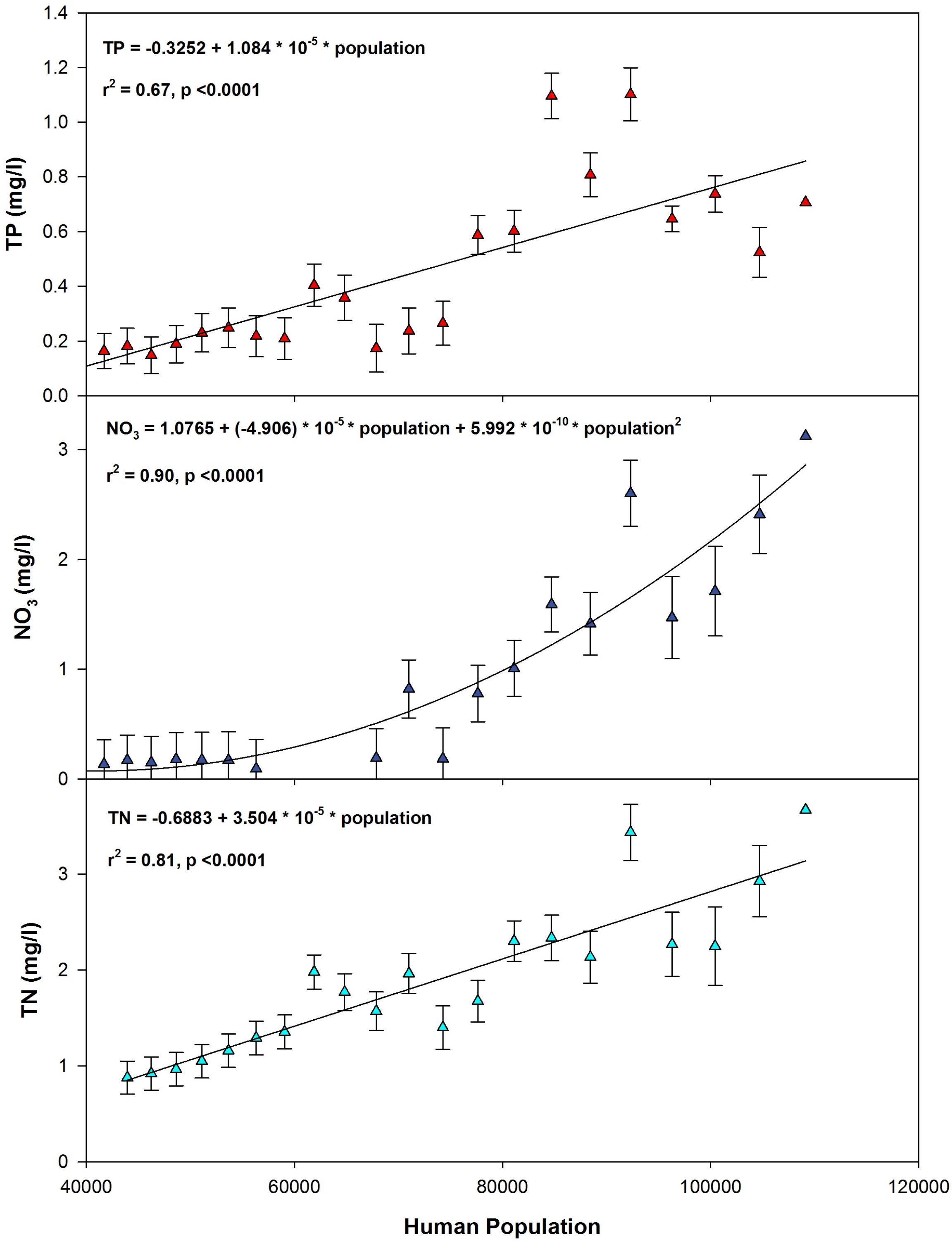


Fig. 4.20 Plot showing the relationships between Human Population vs TN, NO_3 and TP from 1961-2010 in the West Fork San Jacinto Watershed. Projected population data have been used from 1960-2010.

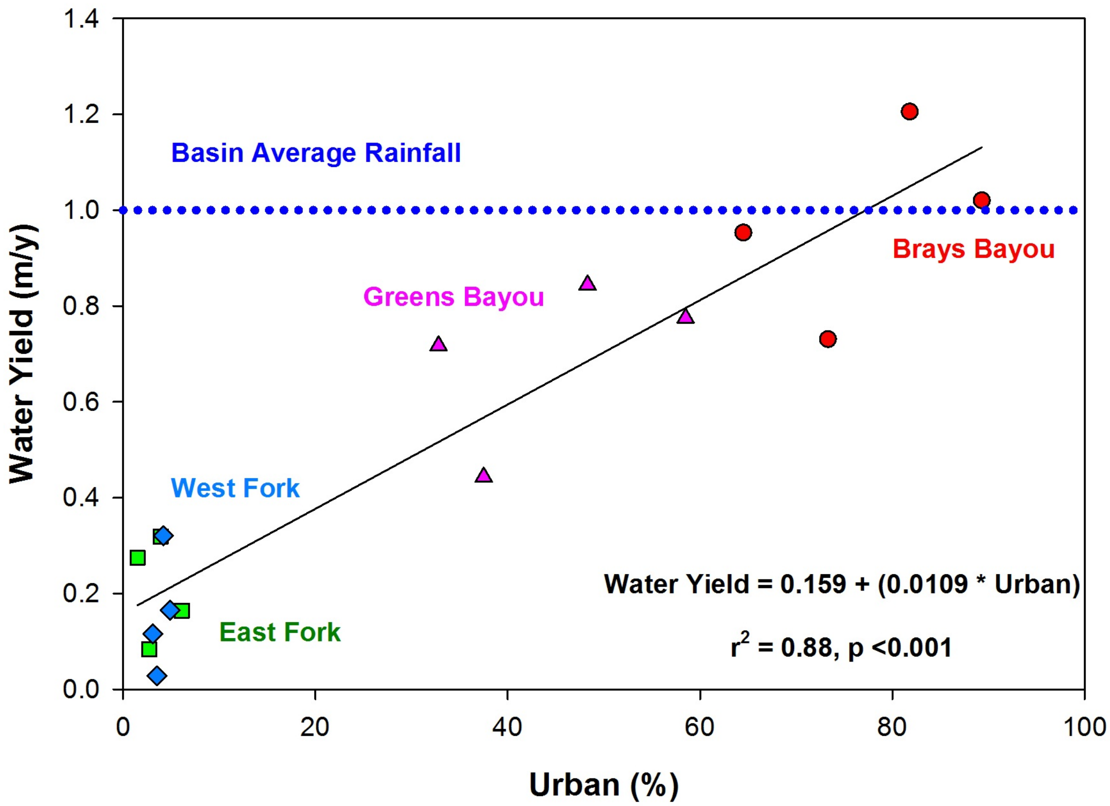


Fig. 4.21 Plot showing the relationship between percent urban and water yield for all catchments from 1989-2009. Brays Bayou and Greens Bayou are highly urbanized watersheds experiencing high water yields with increasing urban land cover. East Fork San Jacinto and West Fork San Jacinto are largely forested watersheds thereby experiencing low water yields.

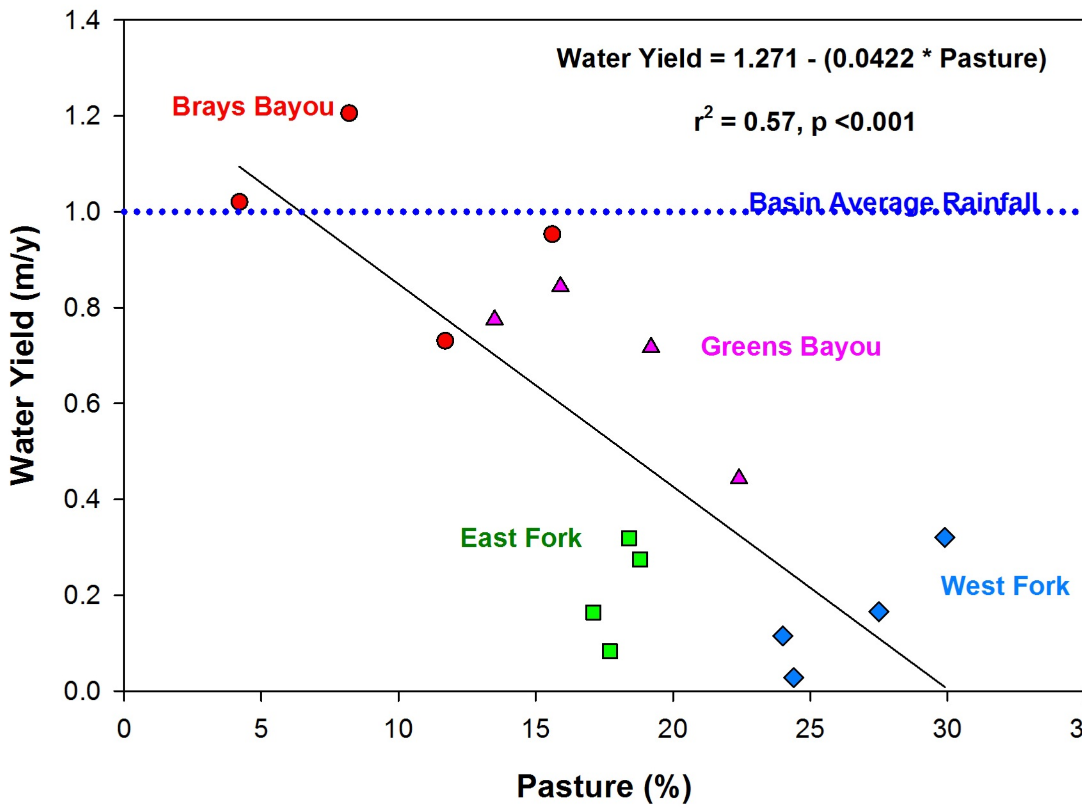


Fig. 4.22 Plot showing the negative relationship between pasture and water yield for all catchments from 1989-2009. West Fork San Jacinto has the highest percentage of watershed area under pasture among all the 4 catchments and hence experiences low water yields followed by the East Fork San Jacinto watershed which is primarily forested. Brays Bayou and Greens Bayou are highly urbanized watersheds with a lower percentage of watershed area under natural lands thus experiencing high water yields.

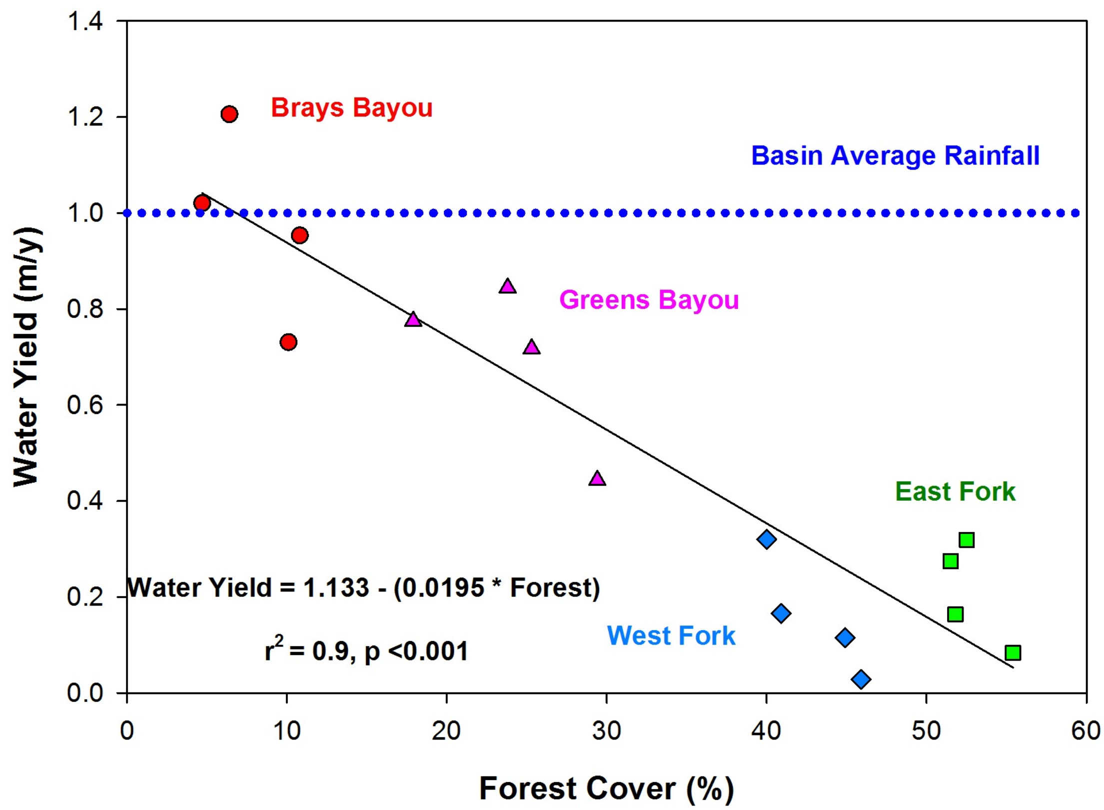


Fig. 4.23 Plot showing the negative relationship between forest cover and water yield for all catchments from 1989-2009. The East Fork San Jacinto watershed is the least densely populated out of all four catchments and has the maximum watershed area under forest cover. Both the East Fork and the West Fork San Jacinto watersheds fall under the Sam Houston National Forest and hence they experience low water yields as compared to the Brays Bayou watershed which has the minimum forest cover followed by Greens Bayou.

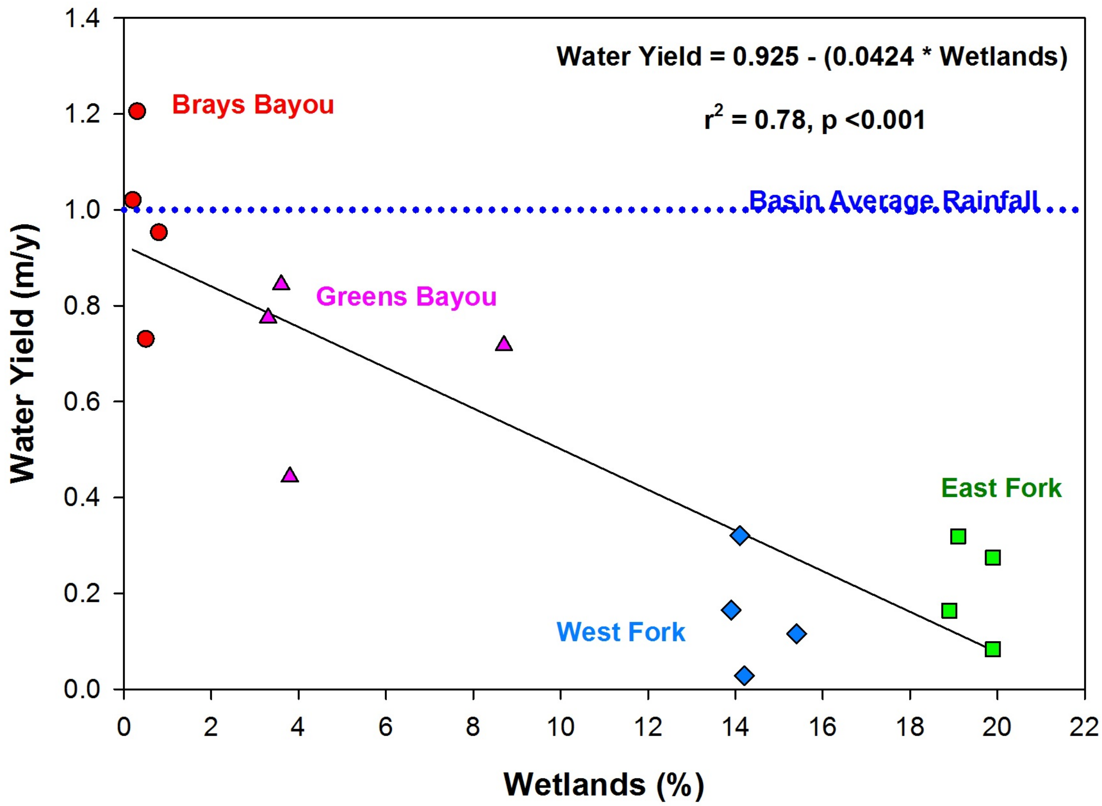


Fig. 4.24 Plot showing the negative relationship between wetlands and water yield for all four catchments from 1989-2009. The higher percentage of area under wetlands in the East Fork and West Fork San Jacinto watersheds contribute to lower water yields in these basins. The highly urbanized catchments with less area under wetlands experience higher water yields.

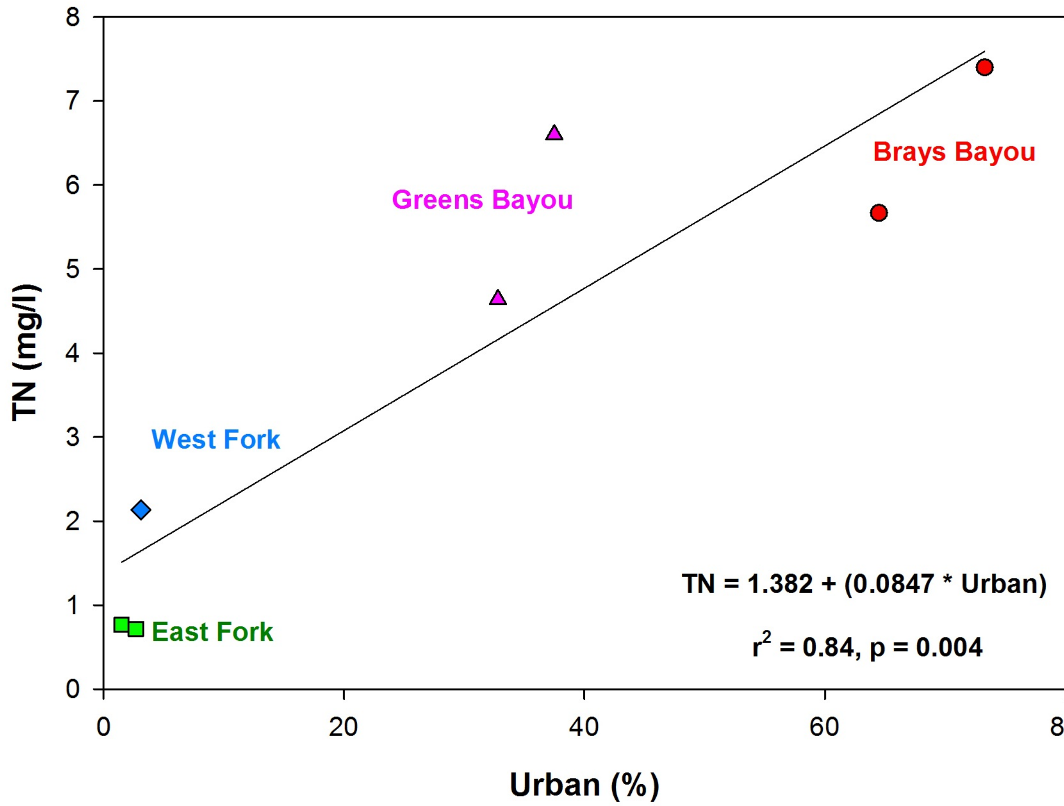


Fig. 4.25 Plot showing the highly significant positive correlation between percent urban land cover and TN. Brays Bayou yields the maximum TN followed by Greens Bayou. Minimum TN levels are seen for the East Fork and the West Fork San Jacinto watersheds which have more forest cover and pasture that filters out the river nutrients.

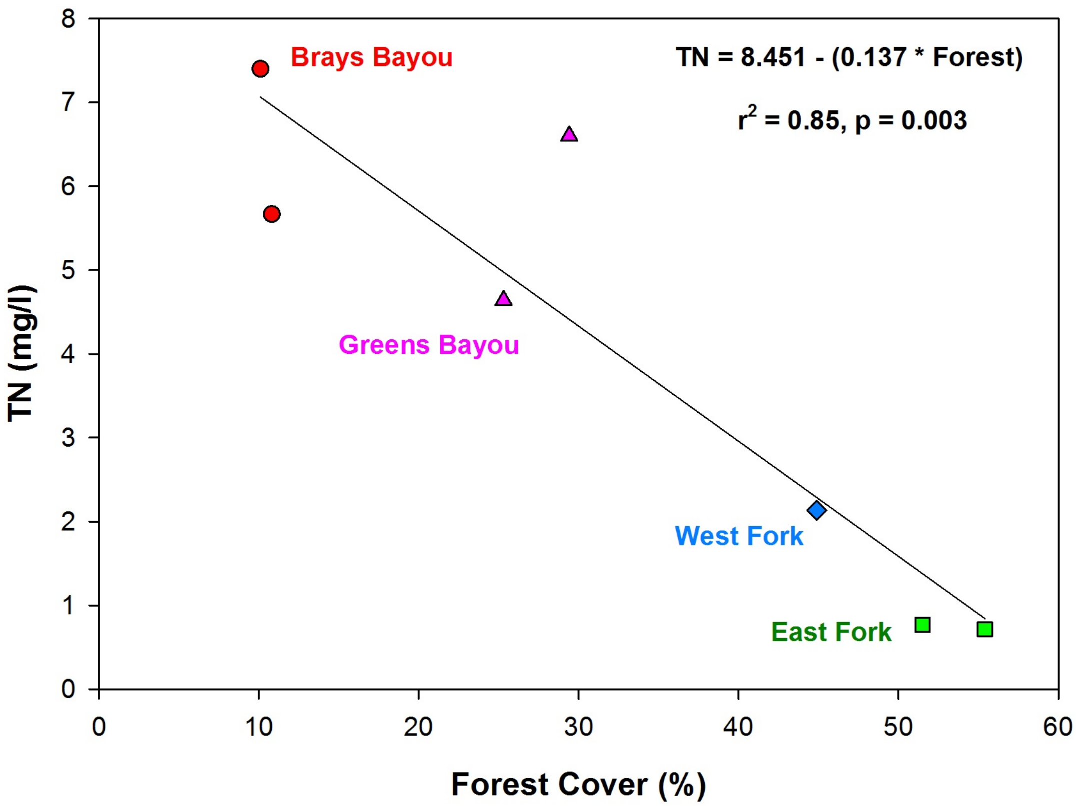


Fig. 4.26 High significant negative correlation can be seen between forest cover and TN. Brays Bayou yields the maximum TN followed by Greens Bayou. Minimum TN levels are seen for the East Fork San Jacinto watershed with the highest percentage of watershed area under forest cover followed by the West Fork San Jacinto catchment. Brays Bayou with the minimum forest cover experiences the maximum nutrient yield.

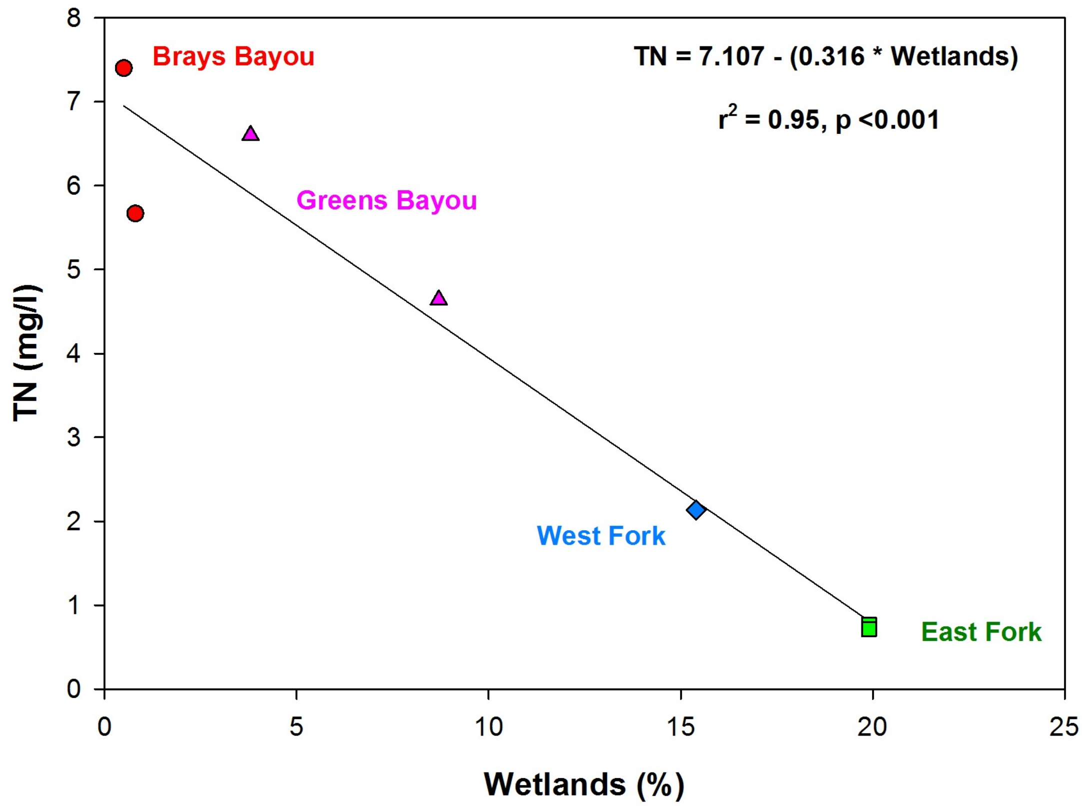


Fig. 4.27 Wetlands filter out nutrients from flowing into the streams and estuaries. High significant negative correlation can be seen between wetlands and TN. Brays Bayou yields the maximum TN followed by Greens Bayou. These watersheds have very small percentage of wetlands as compared to the East Fork and the West Fork San Jacinto watersheds.

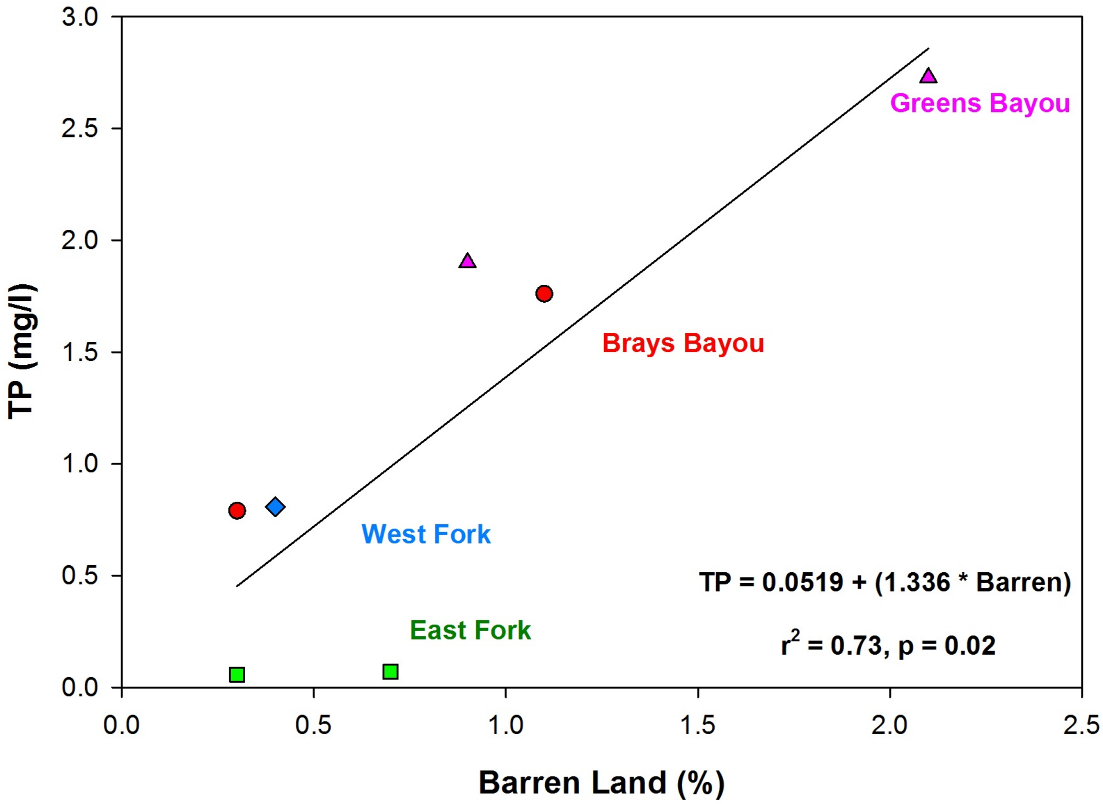


Fig. 4.28 Based on the results of the land cover classification, Greens Bayou had the maximum percentage of bare land (2.1% and 0.9 Table 4.6) in 1989 and 1996 among all four catchments. Barren land is a key contributor to total phosphorus loadings in streams (Lopez et al., 2008). Nutrient data for Greens Bayou showed high phosphorus loadings for both 1989 (2.7 mg/L) and 1996 (1.9 mg/L) which were the maximum values for TP among all four watersheds for both time periods. Brays Bayou ranks second in terms of bare land and TP loadings. East Fork San Jacinto is largely under forest cover and hence contributes to the minimum yield in TP.

and wetlands (r^2 = 0.95, p <0.001). Similarly, nitrate concentrations increased with increasing urban land use (r^2 = 0.85, p = 0.02) and showed decreasing trends with increasing forest cover (r^2 = 0.8, p = 0.04) and wetlands (r^2 = 0.89, p = 0.01). TP showed a highly significant positive relationship with barren land (Fig. 4.28) that had an r^2 = 0.73 (p = 0.02). Non linear relationships were observed between TP and percent urban (r^2 = 0.88, p = 0.01); TP and percent forest (r^2 = 0.81, p = 0.04) and TP and wetlands (r^2 = 0.84, p = 0.03) where the trend shows a curvilinear decrease. In general, urban, forest and wetland played a significant role if explaining the variability in water yield and stream chemistry.

Water yield and total population were positively correlated and explained 67% and 55% of the water yield for Brays Bayou and Greens Bayou respectively. Hence, the second hypothesis H2: Increase in human population growth cause an increase in water yield in urban areas is supported by the data.

Highly significant positive relationships were observed between river nutrients and total population for Brays Bayou, Greens Bayou, and the West Fork San Jacinto catchments. 19% of the TN variance and 68% of nitrate variance was explained by the population in Brays Bayou.

Human population explained 30% of TN and 75% of nitrate variance in Greens Bayou while in the case of the West Fork San Jacinto watershed, population explained 81% of TN, 90% of nitrate and 67% of TP variance in the watershed. Certain anomalies like the inverse relationship between total population and TP in the Brays Bayou and total population and TN and TP in the East Fork San Jacinto catchments were observed but the decline in TP has been largely attributed to the phosphorus ban on detergents (Todd Running, H-GAC, pers comm.). Based on the fact that majority of the catchments have a significant high positive correlation between river nutrients and total population, the third hypothesis H3: There is a positive correlation between increasing population growth and river nutrients was supported by the data.

Interpretation of the Data

The small number of land use observations hindered the statistical analyses for equation (1). H1 was based on the results derived from the regression analysis for land cover and population data for only 4 time periods. I observed no significant relationships between water yield and any of the land cover classes (1989, 1996, 2002 and 2009) including rainfall and population for Brays Bayou, Greens Bayou, East Fork San Jacinto and West Fork San Jacinto watersheds. However, after projecting the land cover data (1986-2009) for the Brays Bayou catchment, rainfall ($p < 0.001$) and urban ($p = 0.002$) together explained 78% of the variability in water yield. The urban land cover helped contribute a significant increase in r^2 along with rainfall to explain water yield. A significant positive effect of urban land use on river discharge was observed from this analysis which is due to the percent impervious surface. Similarly, I did not see any impact of forest cover on the water yield for any of the catchments using the data for the 4 time periods. Brays Bayou had an r^2 of 0.76 for Regression (1) in Chapter 3 with water yield showing a positive relationship with rainfall and a negative relationship with forest cover. In this case, forest cover was the secondary cause showing land use effect. Both forest and urban land classes did not show any direct significant relationship with water yield, but they helped contribute a significant increase in r^2 along with rainfall to explain water yield.

Most of the changes in the water yield in Brays Bayou and Greens Bayou were observed for the time period between1970-1990. The land cover data that were used only ranged from 1989-2009. There were no river nutrient data beyond 1994 for the West Fork San Jacinto watershed; no nutrient data were available beyond 1998 for the Brays Bayou and Greens Bayou catchments. The nutrient data for the East Fork San Jacinto watershed were inconsistent and no TN, TP or nitrate data were available for 2002 and 2009 which made it impossible to correlate land cover with river nutrient data for individual catchments on a temporal scale. All these factors resulted in low correlations and regressions not being significant.

Results of the land cover classification in the lower Galveston Bay watershed showed increasing trends in percent urban for all four catchments. The urbanized catchments were experiencing increasing trends in water yields and river nutrients. All four catchments were experiencing a decreasing trend in forest cover as was observed from the forest cover time series maps in Chapter 3. Thus, it was evident from these results that the statistical analysis was hindered as a result of limited number of observations.

In order to see the effect of land cover on the hydrology and river chemistry the data for all four catchments—*Brays Bayou*, *Greens Bayou*, *East Fork San Jacinto* and *West Fork San Jacinto* watersheds were combined for “space for time swaps” that increased the number of observations. Figs. (4.22-4.28) using the combined results for land use effects across the watersheds with broad ranges of land use are “space for time swaps”, which assume that the combined data of multiple watersheds reflect the trajectory that an individual watershed would take if it underwent a large change in land use. Results of the multiple regression analyses (2-5) from the data for all the catchments combined confirmed that hypothesis 1 (Increase in urban land use is followed by an increase in water yield) is supported by the data. Percent urban explained 88% of the variability in water yield while the effect of rainfall was of secondary importance. Forest cover had a highly significant negative relationship with water yield indicating increasing water yields with decreasing forest cover. Forest cover was the primary driver of water yield followed by rainfall. Same was the case with wetlands where water yields increased with decreasing wetlands.

Urban land cover also helped explain the increasing levels in nutrient concentrations (TN and NO_3) with increasing urban growth. Forests and wetlands contributed negatively to river nutrients (TN, NO_3 and TP) as expected. Bare soil helped explain the variability in TP. Results from this study show that a longer historical data record is necessary to see the effect of land use/land cover change on hydrology and river chemistry for small watersheds on a temporal scale. In this study a large spatial dataset helped derive significant relationships between land cover variables and hydrology and river chemistry as expected. The increase in the number of observations provided for the larger variations in land cover that increased the statistical power to detect the effects of land use/land cover change on river hydrology and chemistry.

Human population growth and water yield are highly correlated as can be seen in the case of the urban catchments — Brays Bayou and Greens Bayou whereas no correlation was observed between water yield and total population as well as rainfall data for 1989, 1996, 2002 and 2009 for these two catchments. The high correlation between water yield and population growth indicates higher return flows due to increasing population in the urban areas.

The data range for the multiple linear regression model for water yield, total population and rainfall for the Brays Bayou watershed was 73 years (1937-2009) which was a very large sample size as compared to the four years of land cover data. In the Greens Bayou dataset, water yield, rainfall and population data ranged from 1953-2010 which is about 58 years of data. Thus, in order to see a correlation between land cover and water yield or river nutrients, more time periods of land cover data are necessary and probably with larger changes when looking for land cover effect for individual catchments.

Conclusion

Anthropogenic effects have a significant impact on the hydrology and water quality in the Galveston Bay watershed. With continued development water yields will continue to increase with increasing impervious surface and decreasing forests and wetlands. Impervious surface increase overland flow and together with higher return flows in the stream, the rivers flow faster during large storm events. Urban growth will result in increased nutrient inputs to the streams ultimately affecting the health of the Bay.

Results of the study showed that increasing population growth leads to higher water demand in the urban areas leading to intense groundwater pumping or inter-basin transfer from adjacent watersheds. Higher return flows increases the overall flow as can be seen in the downstream areas. Increasing population growth is also followed by an increase in urban growth and changes in land cover from natural lands to impervious surface. Future population growth in the highly urbanized areas near Houston will cause higher water demand from adjacent watersheds resulting in higher downstream flows in the estuary.

The health of the Galveston Bay is largely determined by the volume, timing and quality of freshwater inflows into the estuary from the surrounding watersheds (Solis and Longley, 1993). The nutrient budget of the Bay is dominated by the nutrients derived from freshwater inflows that account for over 80% of the nutrients reaching the estuary (Armstrong, 1982). Increasing freshwater flow in the estuaries can result in stratification leading to eutrophication and ultimately hypoxia in the Bay bottom. Second, the transport of nutrients from overland flow and sewage from urban areas by the rivers to the estuary cause algal blooms which are another big factor resulting in bay eutrophication. Hypoxia in the Bay is at its peak during the warm summer months as a result of stratification and algal bloom. With rising temperatures as a result of global warming, eutrophication in the Bay could get worse. Higher rates of stratification caused by rising temperatures and larger freshwater flow and increased nutrient inputs due to increasing population and urban growth would lead to severe eutrophication in the Bay. Thus, increasing freshwater flow in the estuary may have serious implications from a global warming perspective.

CHAPTER 5: CONCLUSIONS

The Galveston Bay Watershed illustrates well the nature of society's relationship with the coastal environment. The estuary is an important economic, recreational and environmental asset; however due to its location in the heart of the fast growing Houston metropolitan area, the Galveston Bay has been heavily impacted by industrial and municipal development, discharge of pollutants and wastewater effluent, channelization and dredging projects, subsidence, and alterations in bay-water circulation dynamics. The Galveston Bay receives the second-highest freshwater inflow of any Texas estuary with the San Jacinto, Buffalo Bayou and the Trinity rivers being the principal sources of freshwater flow. It receives nutrient inputs mainly from the Trinity and San Jacinto rivers along with treated and untreated domestic sewage which is released into the water from surrounding areas. Atmospheric inputs also contribute to its eutrophic state. The Bay is shallow and resuspension of bottom sediments caused by intensive trawling and dredging activity makes the Bay turbid.

Time series analysis for stream hydrology showed increasing trends in river discharge for those USGS stations lying within the highly urbanized area which is an indication of high rates of inter-basin transfer. In order to meet the demands of the growing population, more water has been pumped from the Trinity River, as was observed from the trends in discharge for the station 08067070 on the CWA Canal in the lower Trinity basin. As for stream water quality, some of the stream gauging stations did not show any significant trends in water quality, while a few of them did have decreasing trends particularly in TP. This could be a result of improved waste water treatment and the ban on phosphorus on laundry detergents.

Time series analysis of the bay water quality showed more or less similar trends in Chl *a* and TSS for most of the sections of the Bay in general. The *in situ* data exhibited high seasonal and interannual variability in Chl *a* and TSS for the Galveston Bay. Chlorophyll *a* values appeared to be high in the early 1970s, leading to a drop in the 1990s, and then it rose again from 2000 onwards. TSS follows a similar pattern with comparatively higher values in the 1970s followed by an all time low in the 1990s and then it rose again after 1995. The mean monthly plots for both Chl *a* and TSS indicated a strong Spring maximum (Feb) probably reflecting the peak Spring streamflow. The declining Chl *a* and TSS probably reflect the combined effects of reductions in industrial nitrogen loads, improved waste water treatment, altered land use, and impoundments on the principal rivers (San Jacinto and Trinity).

Land use and land cover classification for the lower Galveston Bay watershed from 1989-2009 showed an increase in urban growth followed by a decrease in agriculture and forest cover. Regression analyses relating water yield to land cover classes for four different time periods—1989, 1996, 2002 and 2009 for Brays Bayou, Greens Bayou, East Fork San Jacinto and West Fork San Jacinto watersheds did not yield significant results. The small number of land use observations hindered the statistical analyses. However, in the case of the projected land cover data (1986-2009) for the Brays Bayou watershed, rainfall and urban land cover together explained 78% of the variability in water yield. A land use (forest cover) effect on hydrology was also observed in the highly urbanized watersheds of Brays Bayou and Greens Bayou for the analysis that involved the 25 year forest cover data relating water yield. In order to see a correlation between land cover and water yield or river nutrients, more time periods of land cover data are necessary with larger changes. There was no river nutrient data beyond 1994 for the West Fork San Jacinto watershed; no nutrient data were available beyond 1998 for the Brays Bayou and Greens Bayou catchments. The nutrient data for the East Fork San Jacinto watershed were inconsistent and no TN, TP or nitrate data were available for 2002 and 2009 which made it impossible to correlate land cover with river nutrient data for individual catchments on a temporal scale. All these factors resulted in low correlations and regressions not being significant.

Results of the land cover classification in the lower Galveston Bay watershed showed increasing trends in percent urban for all four catchments. The urbanized catchments were experiencing increasing trends in water yields and river nutrients. All four catchments were experiencing a decreasing trend in forest cover as was observed from the forest cover time series maps in Chapter 3. Thus, it was evident from these results that the statistical analysis was hindered as a result of limited number of observations. In order to see the effect of land cover the data for all four catchments—*Brays Bayou*, *Greens Bayou*, *East Fork San Jacinto* and *West Fork San Jacinto* watersheds were combined for "space for time-substitution" analysis (Pickett, 1989) to increase the number of observations and check for correlations between percent land cover and stream hydrology and stream chemistry. "Space for time swaps", assume that the combined data of multiple watersheds reflect the trajectory that an individual watershed would take if it underwent a large change in land use.

Results of the multiple regression analyses (Chapter 4) from the data for all the catchments combined confirmed the hypothesis: increase in urban land use is followed by an increase in water yield. Percent urban explained 88% of the variability in water yield while the effect of rainfall was of secondary importance. Forest cover had a highly significant negative relationship with water yield indicating increasing water yields with decreasing forest cover. Forest cover was the primary driver of water yield followed by rainfall for the combined land cover dataset. Same was the case with wetlands where water yields increased with decreasing wetlands. Urban land cover also helped explain the increasing levels in nutrient concentrations (TN and NO_3) with increasing urban growth. Forests and wetlands contributed negatively to river nutrients (TN, NO_3 and TP) as expected. Bare soil helped explain the variability in TP. Results from the study showed that a longer historical data record is necessary to see the effect of land use/land cover change on hydrology and river chemistry for small watersheds on a temporal scale. A large spatial dataset (land cover, hydrology and river nutrient data for all the four watersheds combined for the "space-time-swap") helped derive significant relationships between land cover variables and hydrology and river chemistry as expected. The increase in the number of observations provided for the larger variations in land cover that increased the statistical power to detect the effects of land use/land cover change on river hydrology and chemistry.

Population growth in the Galveston Bay watershed exhibited exponential growth from 1900 to 2010. All four catchments (Brays Bayou, Greens Bayou, East Fork San Jacinto near New Caney and West Fork San Jacinto near Conroe) had very similar exponential trends. Water yield and the projected total population were positively correlated and explained 67% and 55% of the water yield for Brays Bayou and Greens Bayou respectively. The high correlation between water yield and population growth indicates inter-basin transfer as a result of higher consumptive water use due to increasing population in the urban areas. Highly significant positive relationships were observed between river nutrients and total population for Brays Bayou, Greens Bayou, and the West Fork San Jacinto catchments.

Anthropogenic effects have a significant impact on the hydrology and water quality in the Galveston Bay watershed. With continued development water yields will continue to increase with increasing impervious surface and decreasing forests and wetlands. Impervious surface increases overland flow and together with increasing base flow (due to return flows) in the stream, the rivers flow faster during large storm events. Urban growth will result in increased nutrient inputs to the streams ultimately affecting the health of the Bay. Results from this study showed that increasing population growth leads to higher water demand in the urban areas leading to intense groundwater pumping or inter-basin transfer from adjacent watersheds. This results in increasing base flows due to higher return flows, thus increasing the overall flow as can be seen in the downstream areas. Increasing population growth is also followed by an increase in urban growth and changes in land cover from natural lands to impervious surface. Future population growth in the highly urbanized areas near Houston will cause higher water demand from adjacent watersheds resulting in higher downstream flows in the estuary.

The health of the Galveston Bay is largely determined by the volume, timing, and quality of freshwater inflows into the estuary from the surrounding watersheds (Solis and Longley, 1993). The nutrient budget of the Bay is dominated by the nutrients derived from freshwater inflows that account for over 80% of the nutrients reaching the estuary (Armstrong, 1982). Increasing freshwater flow in the estuaries results in higher nutrient loading and stratification, leading to eutrophication, algal blooms, and ultimately hypoxia in the Bay bottom. Hypoxia in the Bay is at its peak during the warm summer months as a result of stratification and algal blooms. With rising temperatures as a result of global warming, eutrophication in the Galveston Bay could get worse. Higher rates of stratification caused by rising temperatures and larger freshwater flow and increased nutrient inputs due to increasing population and urban growth will lead to more severe eutrophication in the Bay. Thus, increasing freshwater flow from the streams may have serious implications for the Galveston Bay from a global warming perspective.

Findings from this research can be summarized as follows:

- A longer historical data record is necessary to see the effect of land use/land cover change on hydrology and river chemistry for small catchments. The longer the time period, the better is the chance of a significant correlation.
- “Space for time-substitution” technique can be used to see the land cover effect on hydrology and river chemistry for catchments within a smaller time frame. Data from individual catchments within the watershed can be combined to increase the number of observations that would provide for

the larger variations in land cover over space. A large spatial dataset provides more statistical power to detect the effects of land use change as was observed in this research.

- Most of the changes in the water yield in Brays Bayou and Greens Bayou were observed for the time period between 1970 and 1990. Land cover data for these catchments need to be analyzed to check for trends in land use/land cover change for this period to explain water yield.
- High rates of urbanization and exponential population growth in the lower Galveston Bay watershed have led to higher rates of inter-basin water transfers increasing the baseflow of streams. This results in faster flowing streams and flooding during storm events carrying more sediment and increased nutrients into the receiving waters of Galveston Bay.
- Larger freshwater flow into the Bay affects the health of the Bay and its ecosystem as a result of nutrient enrichment and stratification. With rising temperatures as a result of global warming, along with increased freshwater flow and nutrients, the Bay will become more vulnerable to eutrophication, resulting in increased hypoxia during the warm summer months.

APPENDICES

APPENDIX I

Cooperative Station ID	Location		Period of Record	Location within Basin Area
	Latitude	Longitude		
410271	33°26'26"	-98°22'15"	1950-2010	Upper Galveston Bay Watershed Upper Trinity River Watershed
413047	31°43'56"	-96°12'28"	1950-2007	Middle Galveston Bay Watershed Middle Trinity River Watershed
412086	31°46'18"	-97°49'26"	1950-1951 1992-2010	
418126	29°40'57"	-96°51'23"	1950-2010	Lower Galveston Bay Watershed
411911	29°41'56"	-96°34'23"	1948-2010	Brays Bayou Catchment
418160	29°46'17"	-96°08'44"	1937-1972 1978-2003	
410655	30°01'54"	-96°13'00"	1979-1993 1995-2010	Greens Bayou Catchment
414903	29°55'02"	-96°52'31"	1953-2010	
411314	30°31'56	-96°42'08"	1985-2010	East Fork San Jacinto near New Caney
412462	30°21'38"	-96°50'44"	1985-2010	
413525	30°11'14"	-96°51'34"	1985-2010	
411889	30°35'21"	-96°21'53"	1973-1996 1999-2010	West Fork San Jacinto near Conroe
419491	30°19'25"	-96°09'34"	1973-2010	
418446	30°20'12"	-96°32'25"	1973-2010	
416280	30°08'15"	-95°10'42"	1982-2009	Lower Trinity River Watershed

Appendix I Rain gauging stations with their locations and period of record

APPENDIX II

	USGS Station	Location		Basin	Drainage Area (km^2)
		Latitude	Longitude		
1	08042800	33°17'30"	98°04'49"	W Fk Trinity Rv nr Jacksboro, TX	1703.4
2	08044000	33°13'54"	97°41'40"	Big Sandy Ck nr Bridgeport, TX	862.9
3	08044500	33°05'07"	97°33'30"	W Fk Trinity Rv nr Boyd, TX	4430.7
4	08044800	32°56'44"	97°34'58"	Walnut Ck at Reno, TX	162.1
5	08045850	32°44'25"	97°39'06"	Clear Fk Trinity Rv nr Weatherford, TX	313.4
6	08047000	32°39'54"	97°26'30"	Clear Fk Trinity Rv nr Benbrook, TX	1117.6
7	08047050	32°41'42"	97°26'49"	Marys Ck at Benbrook, TX	139.6
8	08047500	32°43'56"	97°21'31"	Clear Fk Trinity Rv at Ft Worth, TX	1341.4
9	08048000	32°45'39"	97°19'56"	W Fk Trinity Rv at Ft Worth, TX	6738.9
10	08048543	32°45'06"	97°17'21"	W Fk Trinity Rv at Beach St, Ft Worth, TX	6920.7
11	08048970	32°36'12"	97°15'53"	Village Ck at Everman, TX	234.1
12	08049500	32°45'45"	96°59'40"	W Fk Trinity Rv at Grand Prairie, TX	7903.1
13	08049580	32°29'27"	97°07'22"	Mountain Ck nr Venus, TX	65.8
14	08049700	32°34'51"	97°06'06"	Walnut Ck nr Mansfield, TX	162.9
15	08050100	32°44'51"	96°55'32"	Mountain Ck at Grand Prairie, TX	768.7
16	08050400	33°37'27"	97°09'22"	Elm Fk Trinity Rv at Gainesville, TX	459.2
17	08050800	33°33'16"	96°56'49"	Timber Ck nr Collinsville, TX	101.5
18	08050840	33°31'34"	96°48'25"	Range Ck nr Collinsville, TX	75.6
19	08051500	33°20'10"	97°10'45"	Clear Ck nr Sanger, TX	763
20	08052700	33°17'00"	96°53'33"	Little Elm Ck nr Aubrey, TX	190.1
21	08052745	33°13'09"	96°53'30"	Doe Br at US Hwy 380 nr Prosper, TX	100.2
22	08053000	33°02'44"	96°57'39"	Elm Fk Trinity Rv nr Lewisville, TX	4337.9
23	08053500	33°07'08"	97°17'25"	Denton Ck nr Justin, TX	1035.7
24	08055000	32°59'13"	97°00'45"	Denton Ck nr Grapevine, TX	1824.1
25	08055500	32°57'57"	96°56'39"	Elm Fk Trinity Rv nr Carrollton, TX	6375.3
26	08056500	32°48'26"	96°48'08"	Turtle Ck at Dallas, TX	16.3
27	08057000	32°46'29"	96°49'18"	Trinity Rv at Dallas, TX	15675.1
28	08057200	32°53'21"	96°45'23"	White Rk Ck at Greenville Ave, Dallas, TX	172.8
29	08057410	32°42'27"	96°44'08"	Trinity Rv bl Dallas, TX	16228.6
30	08057445	32°42'17"	96°40'11"	Prairie Ck at US Hwy 175, Dallas, TX	23.1
31	08059000	33°12'13"	96°35'44"	E Fk Trinity Rv nr McKinney, TX	491.1
32	08059400	33°17'40"	96°28'58"	Sister Grove Ck nr Blue Ridge, TX	215.2
33	08061540	32°57'35"	96°36'51"	Rowlett Ck nr Sachse, TX	310
34	08061750	32°46'27"	96°30'12"	E Fk Trinity Rv nr Forney, TX	2894.1
35	08062000	32°38'19"	96°29'06"	E Fk Trinity Rv nr Crandall, TX	3245.5
36	08062500	32°25'35"	96°27'46"	Trinity Rv nr Rosser, TX	21038.2

37	08062700	32°08'51"	96°06'08"	Trinity Rv at Trinidad, TX	22069.8
38	08062800	32°30'12"	96°06'45"	Cedar Ck nr Kemp, TX	490.3
39	08063100	31°56'18"	96°40'52"	Richland Ck nr Dawson, TX	863.5
40	08063800	32°14'36"	96°38'24"	Waxahachie Ck nr Bardwell, TX	452.2
41	08064100	32°11'54"	96°31'12"	Chambers Ck nr Rice, TX	2126.6
42	08064700	31°50'54"	96°17'23"	Tehuacana Ck nr Streetman, TX	369.6
43	08065000	31°38'54"	95°47'21"	Trinity Rv nr Oakwood, TX	33322.3
44	08065200	31°34'11"	95°53'17"	Upper Keechi Ck nr Oakwood, TX	386.7
45	08065350	31°20'18"	95°39'22"	Trinity Rv nr Crockett, TX	35969.5
46	08065800	30°53'05"	95°46'40"	Bedias Ck nr Madisonville, TX	856.3
47	08066000	30°51'33"	95°23'55"	Trinity Rv at Riverside, TX	40360
48	08066170	30°54'25"	95°05'18"	Kickapoo Ck nr Onalaska, TX	157.9
49	08066200	30°42'58"	94°57'31"	Long King Ck at Livingston, TX	364.2
50	08066250	30°34'19"	94°56'55"	Trinity Rv nr Goodrich, TX	43619.5
51	08066300	30°28'53"	94°46'47"	Menard Ck nr Rye, TX	391.6
52	08066500	30°25'30"	94°51'02"	Trinity Rv at Romayor, TX	44422.2
53	08067070	29°57'40"	94°48'36"	CWA Canal nr Dayton, TX	45451.2
54	08067500	29°58'21"	94°59'08"	Cedar Bayou nr Crosby, TX	733.7
55	08067525	29°46'14"	94°59'58"	Goose Ck at Baytown, TX	37.6
56	08067650	30°20'31"	95°32'34"	W Fk San Jacinto Rv bl Lk Conroe nr Conroe, TX	1183.1
57	08068000	30°14'40"	95°27'25"	W Fk San Jacinto Rv nr Conroe, TX	2147.6
58	08068090	30°05'09"	95°17'59"	W Fk San Jacinto Rv abv Lk Houston nr Porter, TX	2535.9
59	08068275	30°07'11"	95°38'45"	Spring Ck nr Tomball, TX	480.9
60	08068390	30°11'26"	95°29'28"	Bear Br at Research Blvd, The Woodlands, TX	40.1
61	08068400	30°11'31"	95°29'01"	Panther Br at Gosling Rd, The Woodlands, TX	66.3
62	08068450	30°07'51"	95°28'52"	Panther Br nr Spring, TX	88.6
63	08068500	30°06'37"	95°26'10"	Spring Ck nr Spring, TX	970.2
64	08068720	29°57'00"	95°48'29"	Cypress Ck at Katy-Hockley Rd nr Hockley, TX	29.5
65	08068740	29°57'32"	95°43'03"	Cypress Ck at House-Hahl Rd nr Cypress, TX	329.2
66	08068780	30°00'57"	95°41'50"	Little Cypress Ck nr Cypress, TX	112.9
67	08068800	29°58'24"	95°35'54"	Cypress Ck at Grant Rd nr Cypress, TX	570.3
68	08069000	30°02'08"	95°25'43"	Cypress Ck nr Westfield, TX	775.4
69	08069500	30°01'37"	95°15'28"	W Fk San Jacinto Rv nr Humble, TX	4574.9
70	08070000	30°20'11"	95°06'14"	E Fk San Jacinto Rv nr Cleveland, TX	840.9
71	08070200	30°08'43"	95°07'27"	E Fk San Jacinto Rv nr New Caney, TX	984.9
72	08070500	30°15'34"	95°18'08"	Caney Ck nr Splendora, TX	272.9
73	08071000	30°13'57"	95°10'05"	Peach Ck at Splendora, TX	303.3

74	08071280	30°06'34"	95°03'35"	Luce Bayou abv Lk Houston nr Huffman, TX	18.4
75	08072300	29°44'35"	95°48'24"	Buffalo Bayou nr Katy, TX	176.9
76	08072730	29°49'50"	95°41'12"	Bear Ck nr Barker, TX	55.7
77	08072760	29°52'01"	95°38'47"	Langham Ck at W Little York Rd nr Addicks, TX	52.8
78	08073500	29°45'42"	95°36'20"	Buffalo Bayou nr Addicks, TX	721.8
79	08073600	29°45'43"	95°33'27"	Buffalo Bayou at W Belt Dr, Houston, TX	753.9
80	08073700	29°44'48"	95°31'24"	Buffalo Bayou at Piney Point, TX	792.5
81	08074000	29°45'36"	95°24'30"	Buffalo Bayou at Houston, TX	873.3
82	08074020	29°52'14"	95°28'49"	Whiteoak Bayou at Alabonson Rd, Houston, TX	85.2
83	08074150	29°51'04"	95°29'16"	Cole Ck at Deihl Rd, Houston, TX	37.3
84	08074250	29°49'40"	95°28'09"	Brickhouse Gully at Costa Rica St, Houston, TX	29.8
85	08074500	29°46'30"	95°23'49"	Whiteoak Bayou at Houston, TX	231
86	08074540	29°47'34"	95°22'05"	Little Whiteoak Bayou at Trimble St, Houston, TX	52.3
87	08074800	29°39'23"	95°33'43"	Keegans Bayou at Roark Rd nr Houston, TX	37
88	08074810	29°40'21"	95°31'41"	Brays Bayou at Gessner Dr, Houston, TX	133.1
89	08075000	29°41'49"	95°24'43"	Brays Bayou at Houston, TX	253.6
90	08075400	29°37'07"	95°26'45"	Sims Bayou at Hiram Clarke St, Houston, TX	49.7
91	08075500	29°40'27"	95°17'21"	Sims Bayou at Houston, TX	161.9
92	08075730	29°41'40"	95°12'58"	Vince Bayou at Pasadena, TX	17.6
93	08075770	29°47'35"	95°16'04"	Hunting Bayou at IH 610, Houston, TX	42.9
94	08075900	29°57'24"	95°25'04"	Greens Bayou nr US Hwy 75 nr Houston, TX	81.1
95	08076000	29°55'05"	95°18'24"	Greens Bayou nr Houston, TX	153.3
96	08076700	29°50'13"	95°13'59"	Greens Bayou at Ley Rd, Houston, TX	471.1
97	08076180	29°56'01.1"	95°14'01.5"	Garners Bayou nr Humble, TX	70.9
98	08076500	29°51'42"	95°20'05"	Halls Bayou at Houston, TX	77.2
99	08078000	29°22'09"	95°19'14"	Chocolate Bayou nr Alvin, TX	218.3

Appendix II USGS Station locations and their watersheds

APPENDIX III

USGS Station	Period of Record	Observed Changes in Streamflow	R^2	p-value
08042800	1974-2010	Fairly consistent flow with wet years in the early 80's and 90's	0.05	NS
08044000	1956-1995 2005-2010	No significant trend; peak flow in 1982	0.01	NS
08044500	1948-2010	No significant trend; peak flows during wet years in 1982 and 1990	0.02	NS
08044800	1996-2010	No significant decreasing trend in discharge	0.01	NS
08045850	1981-1985 1999-2005	No significant trend in discharge; peak flow in 1982	0.1	NS
08047000	1953-2010	Curvilinear increase in discharge with peak flow in 1992	0.1	0.0418
08047050	1999-2010	No significant trend; high flows in 2010	0.15	NS
08047500	1953-2010	Curvilinear increase in discharge; high flows in 1992	0.1	0.0473
08048000	1921-2010	No significant trend in discharge	0.0	NS
08048543	1977-2010	No significant trend in discharge	0.09	NS
08048970	1990-2010	High flows in the early 90's followed by a dry period in the late 90's and early 2000 after which the flow starts increasing till 2010; does not show any significant trend	0.22	NS
08049500	1926-2010	No significant trend in discharge	0.07	NS
08049580	1986-1987 2002-2010	Curvilinear increase in discharge from 2002-2010 not significant	0.18	NS
08049700	1961-2010	Curvilinear increase in discharge	0.19	0.0068
08050100	1961-2010	Linear increase in discharge	0.14	0.0055

08050400	1986-2010	No significant trend in discharge	0.02	NS
08050800	1986-2010	No significant trend in discharge	0.16	NS
08050840	1993-2010	No significant trend in discharge	0.09	NS
08051500	1981-2010	No significant decrease in discharge	0.07	NS
08052700	1957-1976 1980-2010	No significant trend in discharge	0.01	NS
08052745	2005-2010	No significant trend in discharge	0.26	NS
08053000	1955-2010	No significant trend in discharge	0.04	NS
08053500	1965-2010	No significant trend in discharge	0.04	NS
08055000	1953-1990 2004-2010	No significant trend in discharge	0.1	NS
08055500	1955-2010	No significant trend in discharge; peak flow in 1982	0.03	NS
08056500	1985-1991	No significant trend in discharge	0.1	NS
08057000	1914-2010	Curvilinear increase in discharge	0.06	0.0450
08057200	1962-1980 1985-2010	Curvilinear increase in discharge	0.3	0.0006
08057410	1958-1999 2003-2010	Linear increase in discharge	0.12	0.0136
08057445	1976-1980 1985-2010	Linear increase in discharge	0.28	0.0018
08059000	1950-1975	Curvilinear increase in discharge	0.23	0.0490
08059400	1976-2001	Linear increase in discharge	0.23	0.0128
08061540	1969-2010	Linear increase in discharge	0.33	<0.0001
08061750	1974-2010	No significant trend in discharge	0.02	NS
08062000	1954-2010	No significant trend in discharge	0.04	NS
08062500	1925 1940-2010	Linear increase in discharge	0.07	0.0192

08062700	1965-2010	No significant trend in discharge	0.04	NS
08062800	1964-2010	No significant trend in discharge	0.0087	NS
08063100	1964-2010	No significant trend in discharge	0.01	NS
08063800	1964-2010	No significant trend in discharge	0.06	NS
08064100	1984-2010	No significant trend in discharge	0.01	NS
08064700	1969-2010	No significant trend in discharge	0.03	NS
08065000	1925-2010	No significant trend in discharge	0.04	NS
08065200	1963-2010	No significant trend in discharge	0.02	NS
08065350	1965-2010	No significant trend in discharge	0.03	NS
08065800	1968-1994 2001-2010	No significant trend in discharge	0.00	NS
08066000	1924-1968	No significant trend in discharge	0.02	NS
08066170	1967-2010	No significant trend in discharge; unusually high flow in 1995	0.03	NS
08066200	1964-2010	No significant trend in discharge	0.11	NS
08066250	1967-2010	No significant trend in discharge	0.04	NS
08066300	1967-2010	Increasing trend in discharge from 1967 till 1992 after which it follows a decreasing trend	0.18	0.0169
08066500	1925-2010	No significant trend in discharge	0.03	NS
08067070	1982-2010	Curvilinear increase in discharge	0.98	<0.0001
08067500	1972-1991 2002-2010	No significant trend in discharge	0.01	NS
08067650	1975-1989 1998-2000	No significant trend in discharge	0.05	NS
08068000	1973-2010	No significant trend in discharge	0.01	NS
08068090	1985-2010	No significant trend in discharge	0.08	NS
08068275	2000-2010	No significant trend in discharge	0.17	NS

08068390	2000-2010	No significant trend in discharge	0.03	NS
08068400	1975 2000-2010	No significant trend in discharge	0.07	NS
08068450	1973-1976 2000-2010	No significant trend in discharge	0.23	NS
08068500	1940-2010	Curvilinear increase in discharge	0.12	0.0115
08068720	1976-1980 1981-1982 1985-2010	No significant trend in discharge	0.01	NS
08068740	1976-2010	No significant trend in discharge	0.00	NS
08068780	1983-1992 2002-2010	No significant trend in discharge	0.03	NS
08068800	1983-1992 2002-2010	No significant trend in discharge	0.1	NS
08069000	1945-2010	Curvilinear increase in discharge	0.19	0.0010
08069500	1929-1954	No significant trend in discharge	0.06	NS
08070000	1940-2009	No significant trend in discharge	0.01	NS
08070200	1985-2009	No significant trend in discharge	0.06	NS
08070500	1945-2009	No significant trend in discharge	0.03	NS
08071000	1944-1977 2000-2010	No significant trend in discharge	0.03	NS
08071280	1985-2001 2004 2006-2009	No significant trend in discharge	0.04	NS
08072300	1978-2010	No significant trend in discharge	0.01	NS
08072730	1978-2010	Linear increase in discharge	0.14	0.0306
08072760	1978-1980 2003-2004	No significant trend in discharge	0.56	NS

	2006-2010			
08073500	1946-2010	Linear increase in discharge	0.25	<0.0001
08073600	1972-2010	Linear increase in discharge	0.13	0.0235
08073700	1964-1976 1985-1986 1988-2010	Linear increase in discharge	0.27	0.0008
08074020	2003-2010	No significant trend in discharge	0.04	NS
08074150	1965-1986	No significant trend in discharge	0.24	NS
08074250	1965-1981	Curvilinear increase in discharge	0.42	0.0203
08074500	1937-2010	Curvilinear increase in discharge	0.51	<0.0001
08074800	1965-1981	Linear increase in discharge	0.35	0.0113
08074810	2002-2010	No significant trend in discharge	0.04	NS
08075000	1937-2010	Curvilinear increase in discharge	0.71	<0.0001
08075400	1965-1991 1997-2010	Linear increase in discharge	0.20	0.0034
08075500	1953-1995	Linear increase in discharge	0.43	<0.0001
08075730	1972-2010	No significant trend in discharge	0.05	NS
08075770	1965-2004 2006-2010	Linear increase in discharge	0.22	0.0010
08075900	1966-1992 2007-2010	Linear increase in discharge	0.55	<0.0001
08076000	1953-2010	Linear increase in discharge	0.56	<0.0001
08076180	1987-1993 2001-2010	No significant trend in discharge	0.17	NS
08076500	1953-1993 2002-2010	Linear increase in discharge	0.42	<0.0001
08078000	1960-2010	No significant trend in discharge	0.00	NS

APPENDIX IV

USGS Station	Period of Record		Observed Changes in Stream Water Quality		R^2		p-value	
	TN	TP	TN	TP	TN	TP	TN	TP
08047000	1981-1982 1990-1996	1981-1982 1990-1996	No significant trend	Linear decrease in TP not significant	0.26	0.41	NS	NS
08048000		1969-1976		Curvilinear decrease in TP not significant		0.63		NS
08048543	1976-1994	1976-1994	Curvilinear decrease in TN	Curvilinear decrease in TP not significant	0.55	0.2	0.002	NS
08048970	1989-2002	1989-2002	No significant trend	High concentrations in TP in the early 90's followed by a drop in the mid-90's after which it starts rising again from 2000 onwards	0.2	0.59	NS	0.006
08049500	1974-2010	1969-2010	Curvilinear increase in TN not significant	Significant decreasing trend in TP	0.12	0.81	NS	<0.0001
08049580	1985-1993 2003 2006-2007	1985-1993 2003 2004-2007	No significant trend in TN	No significant trend in TP	0.02	0.35	NS	NS
08049700	1985-1993 2003 2006-2007	1985-1993 2003 2004-2007	Curvilinear increase in TN not significant	High concentrations in TP in the mid- 80's followed by a drop in the early-90's after which it starts rising again till 2007	0.18	0.4	NS	0.04
08051500	1984-2003 2009-2010	1984-2006 2009-2010	High TN concentrations in the 80's followed by a	High TP concentrations in the mid-80's	0.4	0.36	0.007	0.007

			drop till 2003 after which it starts rising aging from 2003	followed by a drop in the late 90's after which it begins to rise again				
08052700	1984-1997	1984-1997	Linear decrease in TN	Linear decrease in TP	0.76	0.3	<0.0001	0.03
08053000	1981-1997	1981-1997	No significant decrease in TN; unusually high concentrations in 1989	No significant trend in TP; unusually high concentratio ns in 1989	0.15	0.19	NS	NS
08053500	1980-1982 1997-2003	1980-1982 1997-2003	Very high concentrations in TN in the early 1980's with a drop in the late 90's after which it starts to rise again	No significant trend in TP	0.6	0.27	0.03	NS
08055000	1981-1982 1998-2003	1981-1982 1998-2003	No significant trend	No significant trend	0.4	0.34	NS	NS
08057200	1995 1997-2003 2009	1995 1997-2010	No significant increase in TN	No significant increase in TP	0.19	0.26	NS	NS
08057410	1974-1999 2001-2003 2009-2010	1969-1999 2001-2010	High values in TN in the mid-70's followed by a drop in the mid-90's after which it starts rising again till late 2000	Steady decreasing trend in TP from the early 70's till 2010	0.27	0.68	0.01	<0.0001
08059400	1985-1987 1995-1999 2001	1985-1987 1995-1999 2001	High TN concentrations in mid-80's followed by a	High TP concentratio ns in mid-80's with a	0.78	0.7	0.001	0.02

			declining trend till 2001	steep decline in the mid-90's after which it slowly begins to rise				
08061750	1981-1992	1981-1992	Curvilinear decrease in TN not significant	Curvilinear increase in TP	0.39	0.6	NS	0.01
08062000	1974-1981 1986-2000	1969-1981 1986-2000	Curvilinear decrease in TN	Curvilinear decrease in TP	0.3	0.58	0.01	<0.0001
08062500	1974-2010	1969-2010	No significant trend	Curvilinear decrease in TP	0.12	0.7	NS	<0.0001
08062700	1974-1994	1969-1994	Linear decrease in TN	Linear decrease in TP	0.33	0.56	0.005	<0.0001
08063100	1981-1982 2000-2003	1981-1982 2000-2004	No significant trend	Decreasing trend in TP not significant	0.68	0.4	NS	NS
08063800	1981-1982 1993-1994 1999-2003	1981-1982 1993-1994 1999-2003	No significant trend	No significant trend	0.14	0.19	NS	NS
08064100	1983-2010	1983-2010	High TN concentrations in the 80's followed by a drop in the mid-90's and it starts to rise again	Curvilinear decrease in TP	0.38	0.3	0.002	0.01
08064700	1990-2010	1990-2010	High TN concentrations in the early 90's followed by a drop in early 2000 and it starts to rise again towards late 2000	No significant trend	0.5	0.16	0.001	NS
08065350	1974-2010	1969-2010	No significant trend	Curvilinear decrease in TP	0.01	0.58	NS	<0.0001
08065800		1970-1974 1993-1995		No significant trend		0.36		NS
08066000		1970-1974		Decrease in		0.58		NS

				TP not significant				
08066170		1970-1974		Decrease in TP not significant		0.68		NS
08066500	1974-1995	1969-1995	Increase in TN in the mid-80's followed by a decreasing trend in the 1990's	Decreasing trend in TP	0.43	0.28	0.004	0.003
08067500	1974-1979	1971-1979	Decrease in TN not significant	No significant trend	0.83	0.36	NS	NS
08067650	1974-1986 1988-1989	1972-1986 1988-1989	No significant trend	No significant trend	0.08	0.04	NS	NS
08068000	1974-1994	1969-1994	Linear increase in TN	Linear increase in TP	0.79	0.66	<0.0001	<0.0001
08068090	1984-1999	1984-1999	Increase in TN not significant	No significant trend	0.2	0.01	NS	NS
08068450		1972-1975 1999		Linear increase in TP		0.99		0.0002
08068500	1996-1999 2005-2008 2010	1996-1999 2005-2008 2010	No significant trend	No significant trend	0.05	0.03	NS	NS
08068740	1977-1991	1977-1991	No significant increase in TN	No significant trend in TP	0.23	0.27	NS	NS
08069000	1978 1983-1999 2004 2008	1978 1983-1999 2004 2008	No significant trend	Decreasing trend in TP not significant	0.02	0.1	NS	NS
08070000	1983-1989	1983-1989	Low TN values in the early and late 80's with a peak in the mid 80's	No significant trend	0.4	0.19	NS	NS
08070200	1983-1999 2004-2008 2010	1983-1999 2004-2008 2010	Decreasing trend in TN	Curvilinear decrease in TP	0.25	0.8	0.01	<0.0001
08070500	1983-1999 2002-2004	1983-1999 2002-2004	Decreasing trend in TN	No significant trend	0.35	0.06	0.02	NS
08071280	1984-1999	1984-1999	No significant trend	No significant	0.19	0.02	NS	NS

				trend				
08073500	1974-1982	1970-1982	Curvilinear increase in TN not significant	Curvilinear increase in TP	0.5	0.45	NS	0.04
08073600	1978-1998	1978-1998	Decrease in TN not significant	Increasing trend in TP from 1978 till it peaks in 1990 after which it follows a decreasing trend	0.25	0.34	NS	0.02
08073700	1974-1978 1998	1970-1978 1998	Decrease in TN not significant	Increase in TP from 1970 till 1976 followed by a decreasing trend till 1998	0.7	0.59	NS	0.04
08074000	1975-1981 1993 1998	1969-1981 1993 1998	Significant decrease in TN	Curvilinear decrease in TP	0.75	0.5	0.002	0.01
08074250	1974-1983	1970-1983	No significant trend	No significant trend	0.05	0.03	NS	NS
08074540	1979-1984 2003-2004	1979-1984 2003-2004	High TN concentration in the early 80's followed by decreasing trends from 1984 onwards	No significant trend; high TP concentratio n in 1984	0.7	0.4	0.005	NS
08074800	1974-1983	1969-1983	Decreasing trend in TN not significant	Increase in TP from 1968 till 1977 after which it starts to decrease till 1983	0.26	0.66	NS	0.001
08075000	1974-1985 1987-1998	1969-1985 1987-1998	Linear increase in TN	Curvilinear decrease in TP	0.21	0.24	0.02	0.02
08075400	1974-1985	1970-1985	No significant trend	Linear decrease in TP	0.003	0.43	NS	0.005
08075500	1974-1998	1969-1998	No significant	Linear	0.006	0.49	NS	<0.0001

			trend	decrease in TP				
08075730		1971-1973 1977-1979		No significant trend		0.11		NS
08075770	1974-1998	1969-1998	No significant trend	Decreasing trend in TP	0.06	0.5	NS	<0.0001
08076000	1974-1985 1987-1998	1969-1985 1987-1998	Linear increase in TN	No significant trend	0.3	0.08	0.004	NS
08076500	1974-1984	1969-1984	No significant trend	No significant trend	0.14	0.14	NS	NS
08076700	1974-1981	1970-1981	Curvilinear decrease in TN not significant	Linear decrease in TP	0.66	0.85	NS	<0.0001
08078000	1974-1985	1971-1985	No significant trend	Decreasing trend in TP not significant	0.27	0.2	NS	NS

Appendix IV USGS Stream water quality data analysis showing the trends in TN and TP over time. No volume-weighting of river nutrients has been done for this analysis.

APPENDIX V

	Station_ID	Location		Site description	Agency
		Latitude	Longitude		
1	11421	29° 13' 48"	-95° 1' 11.9994"	West Bay	TCEQ
2	13303	29° 32' 23.9994"	-94° 54' 0"	Upper Galveston Bay	TCEQ
3	13305	29° 34' 12"	-94° 57' 35.9994"	Upper Galveston Bay	TCEQ
4	13306	29° 36' 35.9994"	-94° 55' 12"	Upper Galveston Bay	TCEQ
5	13307	29° 36' 0"	-94° 57' 0"	Upper Galveston Bay	TCEQ
6	13308	29° 37' 12"	-94° 57' 35.9994"	Upper Galveston Bay	TCEQ
7	13310	29° 38' 59.9994"	-94° 58' 48"	Upper Galveston Bay	TCEQ
8	13314	29° 41' 24"	-94° 43' 48"	Trinity Bay	TCEQ
9	13315	29° 39' 36"	-94° 46' 48"	Trinity Bay	TCEQ
10	13316	29° 43' 48"	-94° 49' 47.9994"	Trinity Bay	TCEQ
11	13317	29° 45' 0"	-94° 48' 36"	Trinity Bay	TCEQ
12	13318	29° 37' 47.9994"	-94° 44' 23.9994"	Trinity Bay	TCEQ
13	13320	29° 30' 36"	-94° 37' 47.9994"	East Bay	TCEQ
14	13324	29° 12' 36"	-95° 0' 0"	West Bay	TCEQ
15	13325	29° 11' 59.9994"	-95° 0' 0"	West Bay	TCEQ
16	13326	29° 9' 36"	-95° 7' 12"	West Bay	TCEQ
17	13327	29° 9' 36"	-95° 7' 47.9994"	West Bay	TCEQ
18	13328	29° 7' 12"	-95° 7' 12"	West Bay	TCEQ
19	13329	29° 8' 59.9994"	-95° 4' 47.9994"	West Bay	TCEQ
21	13331	29° 16' 11.9994"	-94° 55' 12"	West Bay	TCEQ
22	13336	29° 40' 47.9994"	-94° 57' 35.9994"	Upper Galveston Bay	TCEQ
24	13346	29° 10' 47.9994"	-95° 8' 24"	Chocolate Bay	TCEQ
25	13347	29° 12' 4.9998"	-95° 10' 40.0074"	Chocolate Bay	TCEQ
26	13348	29° 5' 23.9994"	-95° 10' 12"	Bastrop Bay	TCEQ

27	13350	29° 3' 0"	-95° 11' 23.9994"	Christmas Bay	TCEQ
28	13352	29° 2' 23.9994"	-95° 12' 0"	Christmas Bay	TCEQ
29	13356	29° 21' 35.9994"	-94° 49' 47.9994"	Lower Galveston Bay	TCEQ
30	13364	29° 30' 36"	-94° 52' 12"	Lower Galveston Bay	TCEQ
31	13366	29° 26' 24"	-94° 52' 12"	Lower Galveston Bay	TCEQ
32	13367	29° 27' 36"	-94° 42' 35.9994"	Lower Galveston Bay	TCEQ
33	13368	29° 21' 0"	-94° 47' 24"	Lower Galveston Bay	TCEQ
34	13373	29° 19' 47.9994"	-94° 50' 24"	Lower Galveston Bay	TCEQ
35	14560	29° 36' 0"	-94° 57' 0"	Upper Galveston Bay	TCEQ
36	14622	29° 16' 40.0038"	-94° 53' 57.0114"	West Bay	TCEQ
37	15180	29° 19' 47.9994"	-94° 50' 24"	West Bay	TCEQ
38	15215	29° 18' 35.9994"	-94° 52' 12"	Lower Galveston Bay	TCEQ
39	15216	29° 21' 29.2026"	-94° 48' 5.3388"	Lower Galveston Bay	TCEQ
40	15217	29° 23' 24"	-94° 47' 24"	Lower Galveston Bay	TCEQ
41	15218	29° 20' 39.7032"	-94° 45' 17.4126"	Lower Galveston Bay	TCEQ
42	15219	29° 28' 15.099"	-94° 56' 19.503"	Lower Galveston Bay	TCEQ
43	15220	29° 28' 48"	-94° 49' 47.9994"	Lower Galveston Bay	TCEQ
44	15221	29° 28' 48"	-94° 50' 24"	Lower Galveston Bay	TCEQ
45	15222	29° 30' 0"	-94° 52' 12"	Lower Galveston Bay	TCEQ
46	15223	29° 31' 48"	-94° 48' 36"	Lower Galveston Bay	TCEQ
47	15225	29° 24' 36"	-94° 52' 12"	Lower Galveston Bay	TCEQ
48	15226	29° 15' 0"	-94° 57' 0"	West Bay	TCEQ
49	15227	29° 14' 23.9994"	-95° 0' 0"	West Bay	TCEQ
50	15228	29° 8' 24"	-95° 5' 24"	West Bay	TCEQ
51	15229	29° 32' 23.9994"	-94° 38' 24"	East Bay	TCEQ
52	15230	29° 30' 0"	-94° 38' 24"	East Bay	TCEQ
53	15231	29° 29' 23.9994"	-94° 38' 24"	East Bay	TCEQ

54	15232	29° 27' 26.103"	-94° 42' 25.8078"	Lower Galveston Bay	TCEQ
55	15234	29° 40' 47.9994"	-94° 47' 24"	Trinity Bay	TCEQ
56	15235	29° 43' 48"	-94° 49' 47.9994"	Trinity Bay	TCEQ
57	15236	29° 43' 48"	-94° 45' 36"	Trinity Bay	TCEQ
58	15237	29° 45' 0"	-94° 43' 48"	Trinity Bay	TCEQ
59	15238	29° 40' 47.9994"	-94° 43' 11.9994"	Trinity Bay	TCEQ
60	15239	29° 38' 59.9994"	-94° 42' 35.9994"	Trinity Bay	TCEQ
61	15240	29° 36' 0"	-94° 46' 11.9994"	Trinity Bay	TCEQ
62	15241	29° 37' 47.9994"	-94° 49' 11.9994"	Trinity Bay	TCEQ
63	15242	29° 35' 23.9994"	-94° 49' 47.9994"	Upper Galveston Bay	TCEQ
64	15243	29° 34' 12"	-94° 57' 0"	Upper Galveston Bay	TCEQ
65	15244	29° 39' 36"	-94° 58' 48"	Upper Galveston Bay	TCEQ
66	15245	29° 36' 35.9994"	-94° 54' 35.9994"	Upper Galveston Bay	TCEQ
67	15246	29° 31' 11.9994"	-94° 55' 48"	Upper Galveston Bay	TCEQ
68	15898	29° 43' 11.9994"	-94° 47' 24"	Trinity Bay	TCEQ
69	15899	29° 42' 36"	-94° 42' 35.9994"	Trinity Bay	TCEQ
70	15900	29° 41' 24"	-94° 49' 11.9994"	Trinity Bay	TCEQ
71	15901	29° 40' 12"	-94° 47' 59.9994"	Trinity Bay	TCEQ
72	15902	29° 38' 24"	-94° 42' 35.9994"	Trinity Bay	TCEQ
73	15903	29° 38' 24"	-94° 53' 24"	Upper Galveston Bay	TCEQ
74	15904	29° 37' 47.9994"	-95° 0' 0"	Upper Galveston Bay	TCEQ
75	15905	29° 37' 12"	-94° 47' 59.9994"	Trinity Bay	TCEQ
76	15906	29° 36' 35.9994"	-94° 51' 35.9994"	Upper Galveston Bay	TCEQ
77	15908	29° 36' 35.9994"	-94° 58' 48"	Upper Galveston Bay	TCEQ
78	15909	29° 35' 23.9994"	-94° 52' 47.9994"	Upper Galveston Bay	TCEQ
79	15910	29° 33' 0"	-94° 54' 0"	Upper Galveston Bay	TCEQ
80	15911	29° 32' 23.9994"	-94° 48' 36"	Upper Galveston Bay	TCEQ

81	15912	29° 31' 48"	-94° 31' 48"	East Bay	TCEQ
82	15913	29° 31' 11.9994"	-94° 58' 48"	Upper Galveston Bay	TCEQ
83	15915	29° 30' 0"	-94° 51' 35.9994"	Lower Galveston Bay	TCEQ
84	15916	29° 29' 23.9994"	-94° 42' 35.9994"	East Bay	TCEQ
85	15917	29° 28' 48"	-94° 38' 24"	East Bay	TCEQ
86	15918	29° 27' 36"	-94° 46' 11.9994"	Lower Galveston Bay	TCEQ
87	15919	29° 27' 36"	-94° 50' 59.9994"	Lower Galveston Bay	TCEQ
88	15920	29° 27' 36"	-94° 45' 0"	Lower Galveston Bay	TCEQ
89	15921	29° 25' 47.9994"	-94° 45' 36"	Lower Galveston Bay	TCEQ
90	15923	29° 24' 36"	-94° 49' 47.9994"	Lower Galveston Bay	TCEQ
91	15924	29° 22' 47.9994"	-94° 47' 59.9994"	Lower Galveston Bay	TCEQ
92	15925	29° 21' 0"	-94° 44' 23.9994"	Lower Galveston Bay	TCEQ
93	15926	29° 19' 47.9994"	-94° 49' 47.9994"	Lower Galveston Bay	TCEQ
94	15928	29° 11' 24"	-95° 1' 48"	West Bay	TCEQ
95	15929	29° 8' 59.9994"	-95° 7' 12"	West Bay	TCEQ
96	15930	29° 6' 35.9994"	-95° 8' 24"	West Bay	TCEQ
97	15931	29° 3' 35.9994"	-95° 10' 48"	Christmas Bay	TCEQ
98	16196	29° 43' 48"	-94° 49' 47.9994"	Trinity Bay	TCEQ
99	16197	29° 43' 11.9994"	-94° 49' 47.9994"	Trinity Bay	TCEQ
100	16198	29° 41' 24"	-94° 45' 0"	Trinity Bay	TCEQ
101	16200	29° 39' 36"	-94° 51' 35.9994"	Trinity Bay	TCEQ
102	16201	29° 39' 36"	-94° 56' 23.9994"	Upper Galveston Bay	TCEQ
103	16202	29° 38' 59.9994"	-94° 42' 35.9994"	Trinity Bay	TCEQ
104	16203	29° 38' 59.9994"	-94° 56' 23.9994"	Upper Galveston Bay	TCEQ
105	16204	29° 38' 24"	-94° 47' 24"	Trinity Bay	TCEQ
106	16206	29° 35' 23.9994"	-94° 47' 59.9994"	Trinity Bay	TCEQ
107	16207	29° 34' 12"	-94° 52' 12"	Upper Galveston Bay	TCEQ

108	16208	29° 34' 12"	-94° 58' 11.9994"	Upper Galveston Bay	TCEQ
109	16209	29° 34' 12"	-94° 55' 12"	Upper Galveston Bay	TCEQ
110	16210	29° 33' 35.9994"	-94° 45' 36"	Trinity Bay	TCEQ
111	16211	29° 33' 0"	-94° 34' 11.9994"	East Bay	TCEQ
112	16212	29° 32' 10.6002"	-94° 29' 49.7004"	East Bay	TCEQ
113	16213	29° 32' 23.9994"	-94° 57' 35.9994"	Upper Galveston Bay	TCEQ
114	16214	29° 30' 36"	-94° 39' 0"	East Bay	TCEQ
115	16215	29° 31' 11.9994"	-94° 52' 12"	Upper Galveston Bay	TCEQ
116	16216	29° 30' 0"	-94° 41' 23.9994"	East Bay	TCEQ
117	16217	29° 28' 11.9994"	-94° 47' 24"	Lower Galveston Bay	TCEQ
118	16218	29° 27' 36"	-94° 50' 24"	Lower Galveston Bay	TCEQ
119	16219	29° 26' 59.9994"	-94° 45' 36"	Lower Galveston Bay	TCEQ
120	16220	29° 26' 59.9994"	-94° 53' 24"	Lower Galveston Bay	TCEQ
121	16221	29° 22' 47.9994"	-94° 47' 59.9994"	Lower Galveston Bay	TCEQ
122	16222	29° 22' 57.9"	-94° 47' 16.8072"	Lower Galveston Bay	TCEQ
123	16223	29° 22' 58.7022"	-94° 50' 28.6008"	Lower Galveston Bay	TCEQ
124	16224	29° 21' 0"	-94° 52' 47.9994"	Lower Galveston Bay	TCEQ
125	16225	29° 18' 0"	-94° 52' 47.9994"	Lower Galveston Bay	TCEQ
126	16226	29° 13' 11.9994"	-95° 1' 11.9994"	West Bay	TCEQ
127	16227	29° 11' 59.9994"	-95° 1' 48"	West Bay	TCEQ
128	16228	29° 9' 36"	-95° 7' 47.9994"	West Bay	TCEQ
129	16230	29° 37' 47.9994"	-94° 55' 48"	Upper Galveston Bay	TCEQ
130	16495	29° 45' 36"	-94° 46' 11.9994"	Trinity Bay	TCEQ
131	16497	29° 45' 0"	-94° 45' 0"	Trinity Bay	TCEQ
132	16498	29° 44' 23.9994"	-94° 45' 36"	Trinity Bay	TCEQ
133	16500	29° 42' 26.103"	-94° 41' 46.3914"	Trinity Bay	TCEQ
134	16501	29° 41' 59.9994"	-94° 48' 36"	Trinity Bay	TCEQ

135	16502	29° 39' 36"	-94° 49' 11.9994"	Trinity Bay	TCEQ
136	16503	29° 39' 36"	-94° 57' 0"	Upper Galveston Bay	TCEQ
137	16504	29° 38' 59.9994"	-94° 43' 48"	Trinity Bay	TCEQ
138	16505	29° 38' 24"	-94° 50' 24"	Trinity Bay	TCEQ
139	16506	29° 38' 24"	-94° 47' 59.9994"	Trinity Bay	TCEQ
140	16507	29° 37' 12"	-94° 55' 48"	Upper Galveston Bay	TCEQ
141	16509	29° 34' 47.9994"	-94° 45' 0"	Trinity Bay	TCEQ
142	16510	29° 34' 47.9994"	-94° 50' 24"	Upper Galveston Bay	TCEQ
143	16511	29° 34' 12"	-94° 58' 48"	Upper Galveston Bay	TCEQ
144	16512	29° 33' 0"	-94° 54' 0"	Upper Galveston Bay	TCEQ
145	16514	29° 31' 48"	-94° 35' 24"	East Bay	TCEQ
146	16515	29° 31' 48"	-94° 42' 0"	East Bay	TCEQ
147	16516	29° 31' 11.9994"	-94° 58' 11.9994"	Upper Galveston Bay	TCEQ
148	16517	29° 31' 11.9994"	-94° 48' 36"	Lower Galveston Bay	TCEQ
149	16518	29° 30' 0"	-94° 49' 11.9994"	Lower Galveston Bay	TCEQ
150	16519	29° 29' 23.9994"	-94° 54' 0"	Lower Galveston Bay	TCEQ
151	16520	29° 28' 11.9994"	-94° 49' 11.9994"	Lower Galveston Bay	TCEQ
152	16521	29° 28' 11.9994"	-94° 51' 35.9994"	Lower Galveston Bay	TCEQ
153	16522	29° 27' 36"	-94° 43' 11.9994"	Lower Galveston Bay	TCEQ
154	16523	29° 25' 47.9994"	-94° 47' 59.9994"	Lower Galveston Bay	TCEQ
155	16524	29° 25' 12"	-94° 45' 0"	Lower Galveston Bay	TCEQ
156	16525	29° 23' 59.9994"	-94° 50' 24"	Lower Galveston Bay	TCEQ
157	16526	29° 23' 24"	-94° 48' 36"	Lower Galveston Bay	TCEQ
158	16528	29° 18' 34.5024"	-94° 51' 23.3136"	Lower Galveston Bay	TCEQ
159	16529	29° 13' 48"	-95° 0' 0"	West Bay	TCEQ
160	16531	29° 8' 59.9994"	-95° 3' 36"	West Bay	TCEQ
161	16565	29° 13' 48"	-95° 1' 11.9994"	West Bay	TCEQ

162	17969	29° 25' 12"	-94° 52' 47.9994"	Lower Galveston Bay	TCEQ

Appendix V TCEQ Stations for Bay water quality

APPENDIX VI

Year	Number of samples			Agency
	Chl *a* (ug/l)	TSS (mg/l)	Salinity (ppt)	
1969		13		TCEQ
1970		38		TCEQ
1971		29		TCEQ
1972	32	32		TCEQ
1973	37	51		TCEQ
1974	13	59		TCEQ
1975	21	60		TCEQ
1976	57	57		TCEQ
1977	53	55		TCEQ
1978	57	57		TCEQ
1979	46	50		TCEQ
1980	3	64	9	TCEQ
1981		67	20	TCEQ
1982	4	55	19	TCEQ
1983	1	49	13	TCEQ
1984	7	97	23	TCEQ
1985	42	103	468	TCEQ
1986	69	79	406	TCEQ
1987	65	109	765	TCEQ
1988	99	99	953	TCEQ
1989	61	72	904	TCEQ
1990	78	82	960	TCEQ
1991	85	85	1159	TCEQ
1992	80	80	999	TCEQ

1993	65	65	1485	TCEQ
1994	65	62	1310	TCEQ
1995	65	65	873	TCEQ
1996	81	81	959	TCEQ
1997	137	137	1442	TCEQ
1998	139	139	1483	TCEQ
1999	131	142	1142	TCEQ
2000	128	135	1205	TCEQ
2001	125	145	540	TCEQ
2002	136	161	1007	TCEQ
2003	131	139	728	TCEQ
2004	125	127	292	TCEQ
2005	112	113	261	TCEQ
2006	115	115	536	TCEQ
2007	114	125	250	TCEQ
2008	111	113	281	TCEQ
2009	106	121	276	TCEQ

Appendix VI Water quality samples from 1969-2009

APPENDIX VII

Year	East Bay			West Bay			Upper Galveston Bay			Lower Galveston Bay			Trinity Bay			Chocolate Bay			Bastrop Bay			Christmas Bay		
	Chl	**TSS**	**Salinity**	**Chl**	**TSS**	**Salinity**	**Chl**	**TSS**	**Salinity**	**Chl**	**TSS**	**Salinity**	**Chl**	**TSS**	**Salinity**	**Chl**	**TSS**	**Salinity**	**Chl**	**TSS**	**Salinity**	**Chl**	**TSS**	**Salinity**
1969		2			2			2			4			3										
1970		6			5			5			12			9									1	
1971		3			4			4			8			7									3	
1972	4	4		3	3		4	4		10	10		8	8								3	3	
1973	3	4		3	5		6	8		9	12		13	17						1		3	4	
1974	1	4		3	8		2	8		3	12		4	16			3			4			4	
1975	2	4		4	8		3	9		6	12		3	15		1	4		1	4		1	4	
1976	4	4		7	7		8	8		11	11		16	16		4	4		4	4		3	3	
1977	4	4		4	5		12	12		8	8		15	16		4	4		4	4		2	2	
1978	4	4		5	5		15	15		9	9		16	16		4	4		4	4				
1979	4	4		3	5		10	11		9	9		16	16		2	2		2	3				
1980		4		1	10	5	2	12			14	4		16			4			4				
1981		4			12	9		11			16	11		16			4			4				
1982		3			9	9	1	9		3	18	10		9			5			2				
1983		3			14	8		10			11	5	1	9			1						1	
1984		4			11	11	7	47			18	12		12			4			1				
1985	2	4	34	4	12	62	20	51	105	7	18	206	6	12	49	2	5		1	1	6			6
1986	3	3	25	8	9	31	29	34	121	16	18	192	11	11	37	2	3			1				
1987	4	6	84	7	11	87	23	44	218	14	22	308	14	22	56	2	3	3	1	1	5			4
1988	5	5	74	10	10	65	43	43	359	21	21	341	16	16	95	3	3	10	1	1	5			4

1989	3	4	103	3	4	38	24	30	298	15	18	326	13	13	122	2	2	8	1	1	5			4
1990	4	4	91	3	4	14	32	34	317	20	20	408	16	16	114	3	3	12		1	2			2
1991	4	4	127	4	4	105	34	34	317	20	20	499	16	16	83	4	4	15	1	1	6	2	2	7
1992	4	4	87	5	5	47	28	28	259	17	17	507	15	15	75	4	4	12	3	3	5	4	4	7
1993	4	4	197	5	5	121	20	20	332	12	12	665	12	12	134	4	4	12	4	4	12	4	4	12
1994	4	3	169	4	3	96	20	20	315	13	12	557	12	12	122	4	4	15	4	4	18	4	4	18
1995	4	4	126	4	4	36	21	21	230	12	12	382	12	12	66	4	4	14	4	4	10	4	4	9
1996	7	7	117	8	8	103	21	21	243	17	17	338	18	18	126	4	4	13	3	3	10	3	3	9
1997	15	15	194	17	17	105	28	28	345	37	37	612	34	34	167	2	2	8			3	4	4	8
1998	12	12	166	17	17	105	39	39	418	38	38	642	30	30	137						6	3	3	9
1999	11	11	116	14	25	114	34	34	315	35	35	346	37	37	235						8			8
2000	9	9	137	15	24	137	27	27	282	38	36	373	39	39	257						10			9
2001	12	12	31	15	26	71	27	27	151	35	44	170	36	36	115						1			1
2002	9	12	99	20	26	76	36	44	298	38	45	429	29	30	93						4	4	4	8
2003	11	11	43	12	16	63	33	35	228	35	37	184	37	37	201						3	3	3	6
2004	9	9	15	15	15	21	23	25	59	39	39	109	38	38	87	1	1	1						
2005	9	9	17	14	14	24	23	23	62	32	31	82	30	30	66	4	5	10						
2006	12	12	38	17	17	114	24	24	98	35	34	171	20	20	98	4	6	14				3	2	3
2007	6	10	18	12	16	68	23	23	35	36	36	36	29	29	55	8	11	25						
2008	8	8	12	16	15	35	14	15	34	37	37	37	28	28	69	8	8	21						
2009	6	7	13	16	16	34	25	26	47	26	38	96	27	28	77	6	6	9						

Appendix VII Water quality samples from 1969-2009 in the TCEQ bay segments

APPENDIX VIII

GIS Data	Source
Upper Galveston Bay Watershed Boundary	Trinity River Authority (TRA)
Lower Galveston Bay Watershed Boundary	Houston-Galveston Area Council (H-GAC)
Ship Channels	
Wastewater Outfalls	
Bay Segments	Texas Commission on Environmental Quality (TCEQ)
Bay Water Quality Monitoring Stations	
Streams	United States Geological Survey (USGS)
Lakes and Reservoirs	
Urban Areas	
Cities	
Counties	U. S. Census Bureau
Blocks	
Population by Zip Code	ESRI
Rain Gauging Stations	National Climatic Data Center (NCDC)

Appendix VIII GIS datasets and their sources

APPENDIX IX

Bay	**Salinity**			**TSS**			**Chl *a***		
	Period of Record	**R^2**	**p-value**	**Period of Record**	**R^2**	**p-value**	**Period of Record**	**R^2**	**p-value**
Bastrop Bay	1985 1987-2003	0.07	NS	1973-1996	0.34	0.01	1975-1979 1985 1987-1989 1991-1996	0.08	NS
Chocolate Bay	1987-1997 2004-2009	0.28	NS	1974-1997 2004-2009	0.24	0.02	1975-1979 1985-1997 2004-2009	0.15	NS
Christmas Bay	1985 1987-2003 2006	0.2	NS	1970-1977 1983 1991-1998 2002-2003 2006	0.16	NS	1972-1973 1975-1977 1991-1998 2002-2003 2006	0.24	NS
Trinity Bay	1985-2009	0.0	NS	1969-2009	0.27	0.002	1972-1979 1983 1985-2009	0.47	<0.0001
Upper Galveston Bay	1985-2009	0.04	NS	1969-2009	0.17	0.03	1972-1980 1982 1984-2009	0.58	<0.0001
Lower Galveston Bay	1980-2009	0.13	NS	1969-2009	0.14	0.05	1972-1979 1982 1985-2009	0.3	0.003
East Bay	1985-2009	0.27	0.03	1969-2009	0.1	NS	1972-1979 1985-2009	0.29	0.006
West Bay	1980-2009	0.22	0.03	1969-2009	0.17	0.03	1972-1980 1985-2009	0.38	0.0006

Appendix IX TCEQ Bay Segments and their water quality data analysis

APPENDIX X

Year	Path/Row	Overall Accuracy (%)	Kappa Coefficient	Class	Commission Errors (%)	Omission Errors (%)	Producer Accuracy (%)	User Accuracy (%)
1989	025039	62	0.4	Urban	28	14	86	72
				Agriculture	60	78	22	40
				Pasture	42	42	58	58
				Barren	57	63	38	43
	025040	66.7	0.5	Urban	29	3	97	71
				Agriculture	31	55	45	69
				Pasture	52	48	52	48
				Barren	0	46	54	100
	026039	63.25	0.5	Urban	23	31	69	77
				Agriculture	28	47	53	72
				Pasture	54	19	81	46
				Barren	50	88	13	50

Appendix X: Table 1 Statistics on Accuracy Assessment 1989

Year	Path/Row	Overall Accuracy (%)	Kappa Coefficient	Class	Commission Errors (%)	Omission Errors (%)	Producer Accuracy (%)	User Accuracy (%)
1996	025039	68.8	0.5	Urban	22	17	83	79
				Agriculture	72	31	69	28
				Pasture	19	37	64	82
				Barren	67	80	20	33
	025040	64.6	0.5	Urban	34	17	83	66
				Agriculture	65	44	56	35
				Pasture	17	44	56	83
				Barren	44	58	42	56
	026039	62.2	0.5	Urban	16	23	77	84
				Agriculture	58	71	29	42
				Pasture	52	11	89	48
				Barren	25	75	25	75

Appendix X: Table 2 Statistics on Accuracy Assessment 1996

Year	Path/Row	Overall Accuracy (%)	Kappa Coefficient	Class	Commission Errors (%)	Omission Errors (%)	Producer Accuracy (%)	User Accuracy (%)
2002	025039	78.8	0.6	Urban	14	5	95	86
				Agriculture	53	39	62	47
				Pasture	21	32	69	79
				Barren	33	75	25	67
	025040	80	0.71	Urban	14	3	97	86
				Agriculture	27	45	55	73
				Pasture	27	19	81	73
				Barren	0	36	64	100
	026039	76.7	0.5	Urban	28	20	79	72
				Agriculture	72	56	44	28
				Pasture	11	18	82	89
				Barren	33	63	38	67

Appendix X: Table 3 Statistics on Accuracy Assessment 2002

Year	Path/Row	Overall Accuracy (%)	Kappa Coefficient	Class	Commission Errors (%)	Omission Errors (%)	Producer Accuracy (%)	User Accuracy (%)
2009	025039	80.8	0.7	Urban	10	4	96	91
				Agriculture	60	17	83	40
				Pasture	11	35	65	89
				Barren	40	67	33	60
	025040	71.1	0.6	Urban	21	10	90	79
				Agriculture	42	36	64	58
				Pasture	31	32	68	69
				Barren	29	64	36	71
	026039	65.6	0.4	Urban	18	18	82	82
				Agriculture	84	49	51	16
				Pasture	12	34	66	88
				Barren	75	93	7	25

Appendix X: Table 4 Statistics on Accuracy Assessment 2009

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