GENESIS: GEOSPATIAL ENVIRONMENTAL NUTRIENT EVALUATION SYSTEM FOR INLAND STREAMS

A Thesis

Presented to

the Faculty of the Department of Civil and Environmental Engineering

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in Environmental Engineering

by

Tiffany Swann Schmidt

August 2013

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ABSTRACT

Nutrients in natural water systems are necessary and not inherently harmful; however, in excess, they pose environmental harm and are thus considered “pollutants” necessitating management and control. While numerous models exist for simulating nutrients and their sources, no tools exist presently for understanding nutrient impacts on water quality or ecological resources at multiple spatial and temporal scales. This research addresses this gap by developing a framework for decision-makers in the site-specific management of nutrients. Using a geospatial decision support system approach, the developed framework integrates contextual geospatial information; pollutant sources; monitoring data; and analysis and modeling tools using Digital Earth visualization. GENESIS was demonstrated in the Spring Creek watershed within the San Jacinto River Basin in southeast Texas. GENESIS provided the capability of investigating total phosphorus and dissolved oxygen at multiple spatial scales and developing the input for models used in a total maximum daily load assessment for water quality.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

ADD	antecedent dry days
AU	assessment unit
BCFU	billion colony forming units
CAFO	concentrated animal feeding operations
CFR	Code of Federal Regulations
CRP	Clean Rivers Program
CWA	Clean Water Act
EPA	Environmental Protection Agency (US)
DSS	decision support system
FDC	flow duration curve
GDSS	geospatial decision support system
GIS	geographic information system
HCFCD	Harris County Flood Control District
H-GAC	Houston-Galveston Area Council
HUC	Hydrologic Unit Code
KML	Keyhole Markup Language
KMZ	Keyhole Markup language Zipped
LA	load allocation
LDC	load duration curve
mL	milliliter
MOS	margin of safety
MS4	municipal separate storm sewer system
MUD	municipal utility district
NLCD	National Land Cover Dataset

NPDES	National Pollutant Discharge Elimination System
NPS	non-point source
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
OLS	ordinary least-squares
OSSF	on-site sewage facility
SOD	sediment oxygen demand
SSO	stormsewer system overflow
TCEQ	Texas Commission on Environmental Quality
TKN	Total Kjeldahl Nitrogen
TMDL	total maximum daily load
TN	total nitrogen
TP	total phosphorus
TPDES	Texas Pollutant Discharge Elimination System
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WLA	waste load allocation
WQM	water quality monitoring
WQMP	Water Quality Management Plan
WWTF	wastewater treatment facility

CHAPTER 1 – INTRODUCTION

An emerging issue in water quality is the challenge of nutrients. Nutrients are a vital part of the environment and of an ecosystem's biological and physical cycles, yet excess nutrients cascade reactions that propagate other environmental problems. Paracelsus (1493 – 1541) famously stated that all substances are poisons in the sense that the materials themselves are not inherently toxic; rather, the dose determines a substance's toxicity. In a similar way, nutrients themselves are necessary and are not inherently harmful in the environment; however, when in excess, these necessary and nourishing compounds pose environmental harm. Thus, nutrients may be considered "pollutants" and necessitate management and control in order to maintain their levels in water bodies within acceptable limits; given their vital role in ecosystems, however, their loads into water bodies must be kept at levels that are supportive of biota and ecological resources such as bays and estuaries.

Managing and controlling nutrients and understanding their role in ecosystems is a challenging problem that requires analyzing large datasets that encompass physical, chemical, and biological characteristics of water bodies and their watersheds and that exhibit spatial and temporal variation. At present, while there are numerous water quality models that can be used to simulate nutrients in streams, such models tend to be complex and require specialized knowledge, training, and expertise to implement them and to understand what their results mean. As of this writing, there are no user friendly tools that aid decision-makers in understanding nutrient sources, their fate and transport in watersheds, and their role in associated ecological resources.

This thesis addresses this gap and develops a geospatial framework to aid decision-makers in the site-specific management and control of nutrients at multiple scales. Using a geospatial decision support system approach, the developed framework promotes a methodology that takes into account environmental data across multiple geospatial scales, ranging from the assessment unit[1] to the river basin scale. Decision Support Systems (DSS) are systems that integrate databases with analysis and modeling tools in a framework that is supportive of decision-making. This thesis enhances the DSS concept by utilizing a geospatial framework that allows incorporation of geospatial datasets (e.g., land cover and soil maps) and geospatial data analysis and modeling tools as well as providing users with open-source visualization tools such as Google Earth to visualize their data.

This thesis is composed of six chapters. The following chapter, Chapter 2, will outline the specific objectives of this research. Chapter 3 includes a detailed description of decision support systems and nutrient water quality considerations. Chapter 4 describes the geospatial decision support system framework development of GENESIS: Geospatial Environmental Nutrient Evaluation System for Inland Streams. Chapter 5 demonstrates the application of GENESIS to the river basin, watershed, and sub-watershed scales. Chapter 6 presents the conclusions that were drawn from this research.

[1] An assessment unit refers to a sub-section of a stream segment.

CHAPTER 2 – OBJECTIVES

The overall goal of this research is to create a geospatial decision support system to aid decision-makers in developing site-specific nutrient management and control strategies for nutrient loads in surface waters. This spatial decision support system, titled GENESIS: Geospatial Environmental Nutrient Evaluation System for Inland Streams, (Figure 2-1:), integrates: i) contextual geospatial information, ii) pollutant sources, iii) monitoring data, and iv) modeling and analysis tools. This thesis uses a Digital Earth visualization system, specifically Google Earth Keyhole Markup Language (KML), as a geospatial means of displaying large surface water quality datasets in order to support the understanding of environmental water quality conditions by decision-makers.

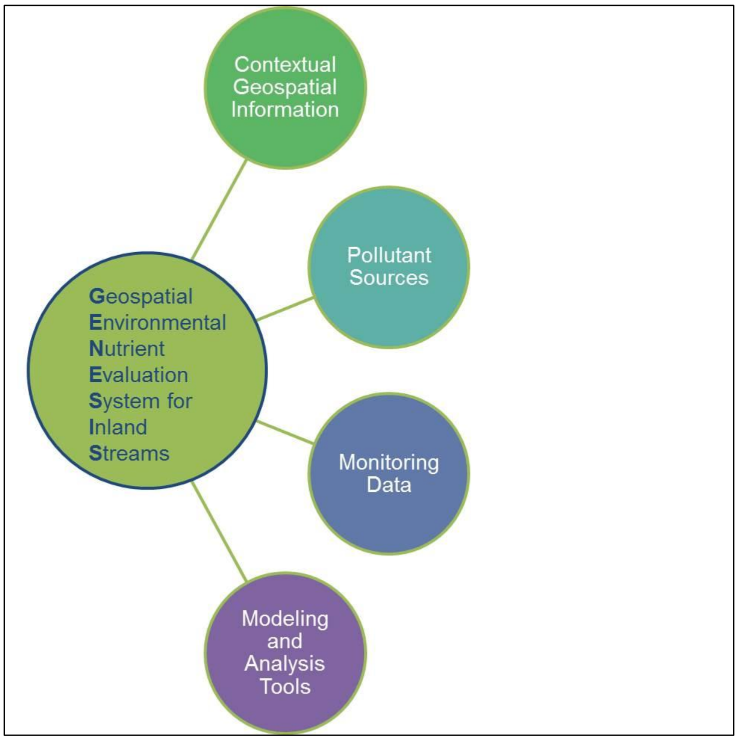

Figure 2-1: The components of GENESIS.

CHAPTER 3 – BACKGROUND

3.1 Decision Support Systems

Decision Support Systems (DSS) originated in the business and management fields as a new group of software tools aimed at aiding management decision-making without requiring computation for everyday operational problems. While many definitions of DSS exist, mutual descriptions stemming from Gorry and Scott-Morton's (1971) framework include the integration of data, models, and a sophisticated user interface such that the resulting combined system is easier to use than the individual parts (Newell 1989). More specifically, DSS may be characterized by the following distinguishing features: i) design intended to solve poorly structured, incompletely defined problems; ii) powerful and easy-to-use graphical interface; iii) ability to combine analytical models and data; iv) potential solutions are presented as multiple feasible alternatives; v) accommodation of various decision-making styles is supported, with modification after initial creation possible; and vi) problem solving using such a system is interactive and iterative rather than unidirectional and linear (Sprague and Carlson 1982; Geoffrion 1983).

Applications of DSS are broad, and DSSs have been applied to environmental data analysis and water quality since the late 1980s when Newell introduced a DSS for groundwater contaminant modeling (Newell 1989; Newell, Haasbeek et al. 1990). Many other applications in water quality and management followed, including USGS's SPARROW, a web-based DSS for nutrient prediction of stream water quality (Booth, Everman et al. 2011); a GIS-based DSS for assessing water quality management alternatives (Assaf and Saadeh 2008); WATERSHEDSS, a DSS for agriculturally dominated watersheds with non-point source pollution (Osmond, Cannon et al. 1997);

and USEPA's SUSTAIN, a DSS for stormwater management and urban flow abatement (Lee, Selvakumar et al. 2012).

These DSS have met widespread adoption because they use a process-oriented rather than a product-oriented approach, which has historically characterized the field of environmental modeling (Loucks, Kindler et al. 1985). Process-oriented functionality allows decision-makers to directly become the users, which results in the ability of the user to better understand, trust, and recognize the limitations of the model output (Newell 1989). Newell identified that in order for process-oriented DSSs to be optimally used, i) their incorporation of modeling software capabilities must be broadened and ii) their facilitated human/computer interaction must be of increasingly high quality. Newell's first requirement presently is addressed by many authors' systems capable of incorporating a wide range of data and model sources across the web into the DSS (Zhang, Zhao et al. 2010). The second requirement, increasingly improved human/computer interaction, is addressed by the computer mapping and visualization techniques augmented by the prevalence of desktop geographic information systems (GIS) and geospatial visualization systems such as Google Earth. Digital, visually aesthetic rendering of numerous types of geospatial information has become ubiquitous so much so that the term "Digital Earth" came into being.

The use of Digital Earth, a term coined in 1998 by former US Vice President Al Gore, has many definitions but for scientists, engineers, and modelers can be thought of as "a multi-resolution, three-dimensional representation of the planet, into which we can embed vast quantities of geo-referenced data" (Gore 1998), (Grossner, Goodchild et al. 2008). The use of Digital Earth as a visualization medium addresses Newell's second requirement by providing users with a three-dimensional, easy-to-use tool. More specifically, in this thesis, Google Earth is chosen as a type of Digital Earth browser because of its ability to display a wide range of data via extensive symbology options, all within a freeware package accessible via the web. This broader Digital Earth type of a system is called a Spatial DSS or a Geospatial DSS. The term Geospatial DSS (GDSS) is preferred here, as it specifies that the spatial frame is referenced to the Earth.

3.2 Geospatial Decision Support Systems

Geospatial Decision Support Systems (GDSS), or Spatial Decision Support Systems (SDSS), are spatial analogues of DSSs and provide a framework for integrating geospatially referenced databases, analytical models, graphical and geospatial visualization, and expert knowledge (Densham 1991), and these systems have been used across many fields successfully. In studies measuring time-to-complete and accuracy, SDSS increased performance efficiency of decision-makers, resulting in shorter decision times and fewer errors as tested across tasks at two different levels of complexity (Crossland, Wynne et al. 1995). Some of the fields in which these spatial systems have been applied are community resource density and spatial distribution (Bodurow, Creech et al. 2009); health systems for malaria elimination (Kelly, Tanner et al. 2012); college admission recruitment using Google Earth (Deligiannidis, Werner et al. 2008); structural geology visualization using Google Earth (Blenkinsop 2012). More specific applications of GDSS/SDSS to scientific fields are in water resources: Uran and Janssen evaluate SDSSs used in the Netherlands for coastal zone management (Uran and Janssen 2003); groundwater management (Fürst, Girstmair et al. 1993); arctic science (Johnson 2011); and managed ecosystem vulnerability (Beier, Patterson et al. 2008).

While many GDSS for water quality use ArcGIS or ArcGIS Explorer (e.g., water quality linked with land cover and elevation, (Wang and Yin 1997)), few applications make use of freeware-based Digital Earth-linked GDSS such as Google Earth. The GDSS that do use Google Earth for water quality make little use of the extensive symbology and display capabilities available (Sharma, Naidu et al. 2012). Google Earth, along with many other Digital Earth web browsers that use the *OpenGIS KML 2.2 Encoding Standard (OGC KML)*, an international standard for visual representation of geographic information (Wernecke 2009), is not being used to its full potential as part of a GDSS framework for assessing surface water quality. The research described in this thesis begins to address this gap and utilize the full potential offered by Google Earth for environmental decision making and display of large geospatially referenced datasets.

The increasing complexity of environmental issues can be addressed using a geospatial decision support system framework and visualization tools such as Google Earth. For example, the Total Maximum Daily Loads (TMDL) program is a regulatory program that estimates allowable pollution limits for water bodies and distributes the allowable pollution capacity among the dischargers within a watershed. These regulatory limits are calculated according to a detailed process that involves data gathering, statistical analysis, graphical rendering of flow and load exceedance curves, watershed based and in-stream fate and transport modeling, and other tools. These types of problems are especially suited for geospatial DSS, especially given the extensive stakeholder involvement that is typically associated with watershed level analyses and decision-making. More complex environmental problems encompass the one addressed in this research: the need to develop nutrient management and control strategies to sustain water quality and healthy ecosystems, a problem that hinges on the delicate and requisite balance of nutrients within a watershed and/or an ecosystem.

3.3 Nutrient Pollution and Land Use/Land Cover

While nitrogen and phosphorus are naturally occurring elements and are vital for healthy ecosystems, excess concentrations pose environmental damage and contribute to human health problems. In surface waters, excess nitrogen and phosphorus promote algae and aquatic flora growth more rapidly than the ecosystem can stabilize, and this process is called eutrophication. This unbounded growth rapidly causes an imbalance in other parameters such as dissolved oxygen (DO). Rapid growth of algae is called an algal bloom. DO may be drastically reduced resulting in hypoxia, or DO may be depleted, resulting in anoxia. In addition to requiring further oxygen demand in the decomposition of organic matter, algal blooms can introduce toxins and bacteria into surface waters. These toxins and bacteria pose human health problems if humans ingest or come into contact with polluted water or consume affected fish or shellfish.

3.3.1 Nutrient Sources

Nutrient pollution is one of the most widespread and challenging environmental problems in the U.S., in part because of the wide range of anthropogenic sources (USEPA 2013a). Sources of nutrient pollution include agriculture; stormwater, including runoff from impervious surfaces and bank erosion of some soils; wastewater; fossil fuel emissions; and household products. This wide range of inputs introduces nutrients through many means, making regulation and reduction of these sources particularly challenging.

Nutrient pollution results from both point sources and non-point sources. The CWA historically has focused on reducing nutrient discharge to surface waters from point sources, particularly wastewater treatment facilities (WWTFs). As a result, almost ninety percent of the funding allocated to water pollution prevention has been applied to point source regulation (USEPA 2004). While point source effluent from WWTFs can overwhelm receiving water bodies and can drive nutrient interactions in streams (Carey and Migliaccio 2009), non-point sources are also important and less understood drivers of nutrient induced stream impairment.

The most recent EPA National Water Quality Inventory reports that 44 percent of assessed rivers are impaired (Figure 3-1, USEPA 2004). The leading causes of impairments are pathogens, habitat alterations, and organic enrichment (Figure 3-2, USEPA 2004).

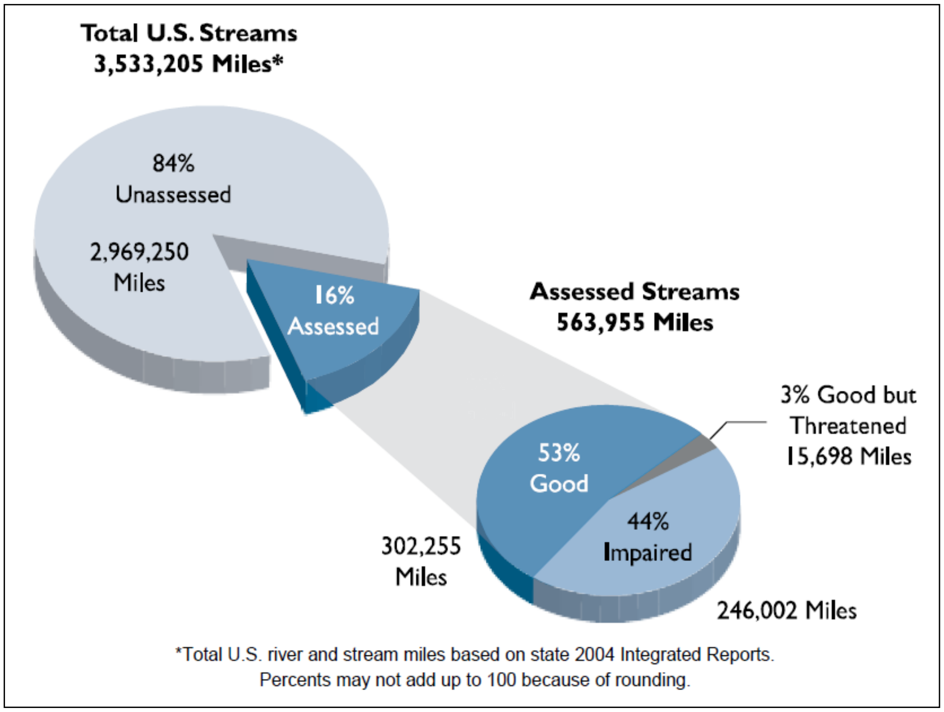

Figure 3-1: Stream impairments in the U.S. (source: USEPA 2004).

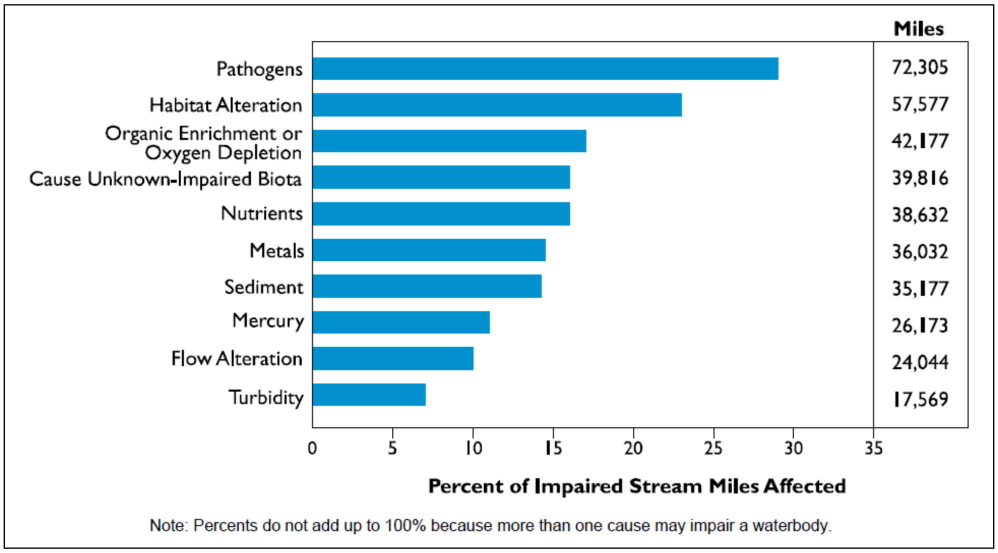

Figure 3-2: Top ten causes of assessed stream and river impairments (source: USEPA 2004).

Organic enrichment refers to the presence of high levels of biochemical oxygen demanding substances, which cause oxygen depletion or low levels of DO, when they degrade. Sources of biochemical oxygen demand (BOD), for example, include leaves and woody debris; dead plants and animals; animal manure; effluents from pulp and paper mills, wastewater treatment plants, feedlots, and food-processing plants; failing septic systems; and urban stormwater runoff (USEPA 2012). While urban nutrient non-point sources are major contributors (Carey, Hochmuth et al. 2013), the occurrence of organic enrichment as the third leading cause of U.S. river and stream impairment paired with the information that agriculture, hydromodification, and unknown reasons due to insufficient information are the leading sources of impairments implies that agriculturally sourced nutrient enrichment can be connected to many of the identified stream impairments (USEPA 2004).

Agriculture sources of nutrient pollution are largely non-point sources, or diffuse and intermittent sources. Commercial fertilizer application is the primary agricultural non-point source of nutrients (Puckett 1995). It is estimated that farmers apply 24 to 38 percent more fertilizer than crops require because of uncertainties regarding soil nutrient content and weathering (Babcock and Blackmer 1992; Trachtenberg and Ogg 1994). Fertilizer applications are primarily in rural locations. Other rural non-point sources include silvicultural activities, application of pesticides, tillage, concentrated animal feeding operations (CAFOs), and logging (Newell, Rifai et al. 1992). Loading from these sources may vary significantly over time and with season, as runoff events and seasonal agricultural practices may be the driving factors in nutrient sourcing. For example, watersheds having a high percentage of riparian forest coverage exhibit high sediment and nutrient retention and little runoff (Basnyat, Teeter et al. 1999), but extensively forested watersheds with silvicultural activity produce high levels of nutrient- and sediment-laden runoff (Newell, Rifai et al. 1992).

Atmospheric inputs of nitrogen are significantly large sources of nitrogen in urban watersheds and significantly small sources of nitrogen in agricultural watersheds (Puckett 1995). Forested and mixed use watershed land use/land cover showed no statistically significant correlation in comparison with other land uses. The large sources of nitrogen in urban watersheds are predominately due to nitrogen oxides emissions. Phosphorus inputs followed these atmospheric nitrogen trends with the exception that phosphorus was not significantly higher in urban watersheds than in agricultural watersheds.

3.3.2 Effects, Regulation, and Measuring Excess Nutrients

Excess nutrients in surface waters are primarily nitrogen and phosphorus. Total Nitrogen (TN) is the sum of all forms of inorganic and organic nitrogen present in water. These forms include nitrate (NO_3), nitrite (NO_2), organic nitrogen (N), and ammonia (NH_4). Organic nitrogen and ammonia may be measured together by the Total Kjeldahl Nitrogen (TKN) analytical method (Newell, Rifai et al. 1992). Total Phosphorus (TP) is the sum of orthophosphate and organic phosphorus in surface waters. While several other parameters relating to nutrient pollution may be monitored, this work focuses on TN and TP because they are causal parameters rather than response parameters, such as chlorophyll-a (USEPA 2013b).

Nutrients are regulated in the U.S. under the Clean Water Act (CWA), but numeric criteria have not yet been developed and adopted across all states. Non-numeric criteria take the form of narrative and antidegradation criteria. The CWA allows states to develop numeric nutrient criteria, which are then reviewed by the EPA. Much progress has been made since 1998, when EPA introduced its strategy for helping states develop and adopt numeric criteria (USEPA 2013b). However, several states, including Texas, have yet to develop numeric criteria (Figure 3-3; USEPA 2013b).

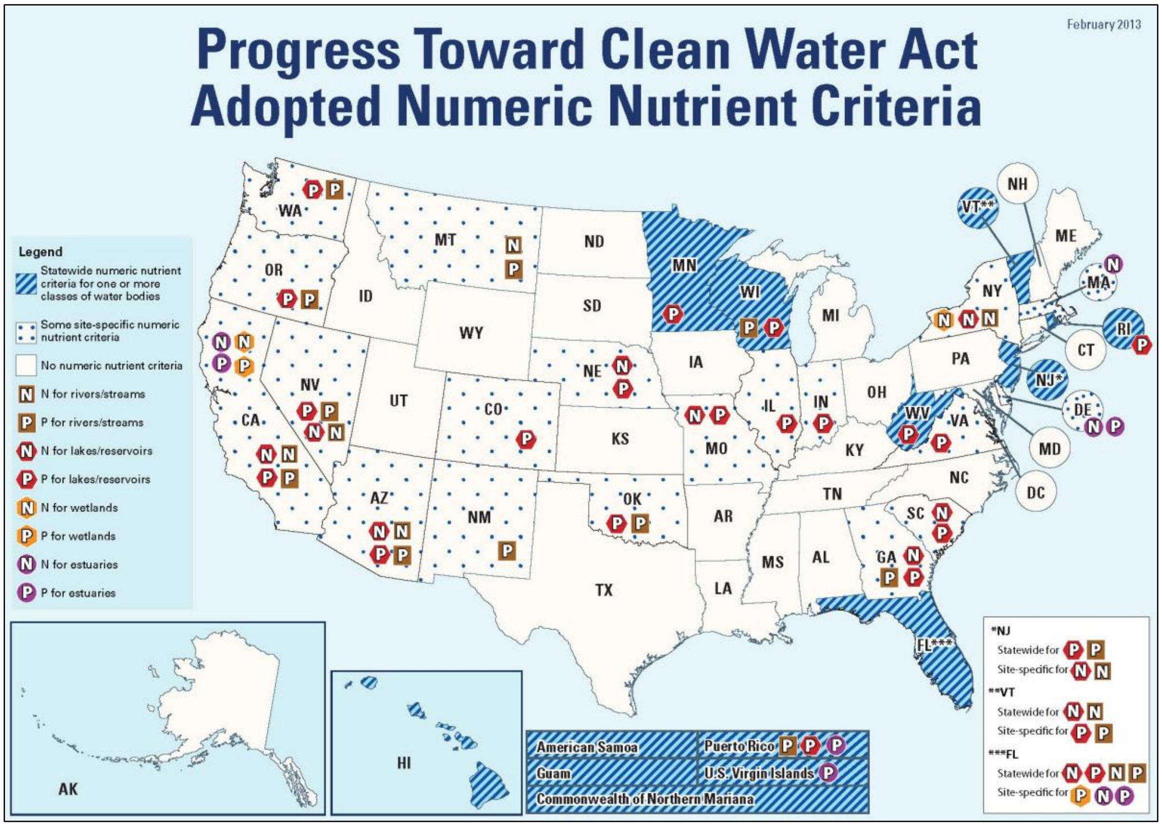

Figure 3-3: Status of USEPA progress toward CWA adopted numeric nutrient criteria by state (source: USEPA 2013b).

Measuring nutrients may result in varying values according to seasonal effects. Santschi (1995), for instance, reported that a strong seasonal effect was observed for phosphorus and chlorophyll-a in upper and mid-Galveston Bay stations. Phosphate maxima occurred in September, while chlorophyll-a maxima occurred in March and April. In this bay setting, it was hypothesized that phosphate maxima may be caused by a benthic source of phosphate despite possible buffering by physical and geochemical mechanisms, such as particle sorting and particle-colloid interactions (Santschi 1995).

3.3.3 Correlation of Nutrient Pollution and Land Use/Land Cover

Land use and land cover play important roles in the management of water quality. While land use and land cover are very similar descriptors, these two categories can differ in their environmental influences. Land use is the economic and cultural activities that occur at a particular place (USEPA 2008). Examples of land uses are agricultural, residential, industrial, and recreational uses. Land cover differs in that it is the physical cover for a given area, but that physical covering does not always convey its use at a given time. For example, the land use for a given plot of land may be silvicultural, but its timber (the land cover) may not be harvested for many years. While land cover may be helpful in correlating present water quality conditions, land use may be a better predictor of future water quality effects. For example, Roberts and Prince (2010) demonstrated the significance of riparian land cover/land use and landscape metrics on water quality simulations for Chesapeake Bay using SPARROW. Future urban land cover was also used to predict nitrogen and phosphorus runoff to Chesapeake Bay (Roberts, Prince et al. 2009). In this way, both land use and land cover affect water quality and can provide predictive water quality information.

Nitrogen and phosphorus loads follow similar patterns based on land use (Puckett 1995). Ahearn, Sheibley et al. (2005) report that in the western Sierra Nevada of California, nitrate is positively correlated to grasslands during average water years and negatively correlated during dry water years. Overall, the largest nutrient loads were observed in mixed use watersheds; the smallest loads were observed in forested watersheds; and no statistically significant difference was observed in agricultural and urban watersheds (Puckett 1995). Despite this finding, joint contributions from mixed land uses have not been widely studied (Basnyat, Teeter et al. 1999).

Nutrient retention, defined as the fraction of total nitrogen and phosphorus inputs from fertilizer, manure, atmospheric deposition, and point sources not found in stream loads, was higher in agricultural dominated watersheds compared with forested and urban watersheds. This finding is consistent with Puckett's (1995) assumption that more nutrients would be retained by crops, while lower retention rates would be expected in higher elevation, forested land where atmospheric deposition would play a greater role and/or steeper, shallower soils would not be retained. Emili and Greene (2013) also note that soil erodability, while not captured in land use classifications, may be the dominant driver of stream water quality because of lack of soil retention. Additionally, urban watersheds are expected to have low nutrient retention rates because of the high percentage of impervious surfaces promoting rapid runoff of atmospheric inputs (Puckett 1995).

Another land use correlation to nutrient pollution is that fertilizer nitrogen inputs per area of agricultural land were related to the dominant land use of the watershed (Puckett 1995). More specifically, lands classified as predominately agricultural received higher nitrogen fertilizer inputs per area than agricultural lands in predominantly urban watersheds. Puckett postulates that these findings may illustrate the varying intensity of agricultural practices within the same land use classification. Not only is the land use important for understanding water quality issues, but also the intensity and specific type of use employed.

Thus, it can be concluded that sources of nutrients within a natural water system originate from both point and non-point sources, depend on land use/land cover practices within a watershed, and are associated with both rural and urban activities. This diverse sourcing, when combined with the complex chemical and biological interactions associated with the presence of nutrients in water bodies (described in the next section) is a problem that is well suited for geospatial DSS and GENESIS.

3.3.4 Chemical and Biological Interactions of Nutrients in Natural Waters

Nutrient cycles in natural waters are inextricably linked to aquatic productivity, which greatly influences dissolved oxygen levels. Nitrogen and phosphorus are viewed as the limiting nutrients for primary productivity. Nitrogen occurs in the biosphere in several different oxidation states ranging from positive five to negative three. Nitrogen occurs as inorganic nitrogen primarily in the forms of oxidized nitrite and nitrate, reduced ammonia, and molecular nitrogen. While nitrogen gas and other nitrous oxide gases are important in the atmosphere, they play minimal roles in natural waters. Rather, natural waters primarily contain organic nitrogen, in the form of amino and amide nitrogen; heterocyclic compounds such as purines; cellular constituents; non-living particulate matter; soluble organic compounds, and inorganic ions in solution (Brezonik 1972). These compounds cycle via chemical, and biologically mediated, reactions: nitrate assimilation; ammonia assimilation; ammonification; nitrification; denitrification; and nitrogen fixation. With the exception of ammonia exchange with sediments, all reactions in the nitrogen cycle occur in the presence of microorganisms. These reactions in surface waters are dominated by ammonia and nitrate assimilation, which are mediated primarily by phytoplankton and macrophytes. The predominant form of inorganic nitrogen in surface waters is nitrate, which is readily used by plants. Some evidence suggests planktonic assimilation of inorganic nitrogen favors ammonia.

Phosphorus occurs in the biosphere, hydrosphere, and lithosphere. In the biosphere, it is one of the major elements required for zooplankton and phytoplankton growth (Kramer 1972). Phosphorus is the limiting nutrient in many systems, as it is less abundant on the surface of the earth than carbon and nitrogen despite its wider distribution throughout the earth. Phosphorus in natural waters is present in dissolved, colloidal, or particulate forms. Inorganic phosphorus primarily occurs in natural waters as orthophosphate, and organic phosphorus occurs primarily as dissolved organic phosphorus, composed of acid-soluble, lipid, inorganic, polyanionic, and nucleic acid phosphorus content. Utilization of phosphorus by microorganisms is dependent upon the activity of its phosphatase enzymes.

Phosphorus and sediment interactions are important for the relative abundance of phosphorus in natural waters and sediments. Clays, such as iron an aluminum hydroxides and oxides, adsorb phosphorus readily and quickly (e.g., adsorption by aluminum oxides is about 10 minutes; Kar 1958). Thus, phosphorus is transported along with sediments (Kramer 1972). The oxidation-reduction potential, pH, calcium concentration, and suspended particles control the adsorption-desorption relationship in the water column. In addition to phosphorus, sediments can sorb other compounds that may deplete DO, adding to the total sediment oxygen demand. These compounds exerting a DO load on the water body may cause impairment, leading to irreversible sinks for DO in the short-term and requiring specific management and control strategies over the long-term.

CHAPTER 4 – A FRAMEWORK FOR WATER QUALITY DECISION-MAKING FOR NUTRIENTS IN INLAND STREAMS

4.1 Current Water Quality Regulations

The current regulatory framework for surface waters is based on the water body's presumed or designated use(s). The water quality is evaluated using parameters which indicate the degree to which the water body supports its designated use. Each classified segment (segments are sections of streams that are given a specific alphanumeric designation by the State) is assigned designated use(s), such as aquatic life, recreation, or public water supply. For each regulated water quality parameter, such as dissolved oxygen, the water body is categorized as fully supporting, not supporting, or not assessed for its designated uses. The US EPA requires that each state compile a list of impaired (or not supporting the designated use) surface water bodies. This list, for example in Texas, is called the Texas Integrated Report of Surface Water Quality (formerly the Texas Water Quality Inventory and 303(d) List), and is issued biennially (TCEQ 2013). To illustrate how segments are described within such listing, Assessment Unit (AU) 1008-02 (one particular section of Segment 1108, Spring Creek) is designated as fully supporting for public water supply and general uses. However, the same AU has been listed as not supporting since 1996 for aquatic life use due to depressed dissolved oxygen (TCEQ 2012). In order to improve a water body's condition such that is may be considered fully supporting of its designated use(s), a "budget" is developed of inputs of a particular pollutant that will allow the applicable water quality standards to be met. This "budget" is typically given in units of mass per time and is called the TMDL.

Developing a TMDL for a given water quality parameter involves a relatively predictable process of data acquisition and analysis as established under guidance from EPA's 1972 Clean Water Act (CWA) and Part 130 of Title of the Code of Federal

Regulations (40 CFR 130). Each state, in developing a TMDL for a particular water quality variable in a given stream segment, must consider: problem definition; endpoint identification; source analysis; linkage analysis; seasonal variation; margin of safety (MOS); pollutant load allocation; public participation; and implementation and reasonable assurance in EPA's guidance. In order to receive required approvals from EPA, and thus modify the state's Water Quality Management Plan (WQMP), the state's waste treatment plan used in planning and permitting activities affecting water quality control, a TMDL must consider a pre-determined, core set of information.

Because development of each TMDL makes use of a similar set of data and undertakes a similar set of analyses, a framework supporting the process can be established. Overall, the components considered in TMDL development can be grouped into the following categories: i) contextual geospatial information, ii) sources of pollutant of interest, iii) monitoring data, and iv) modeling and analysis of the data. In the TMDL context, the first category, contextual geospatial information, includes geospatially dependent characteristics of the study area. This information typically includes watershed characteristics such as topographic, hydrologic, and hydrogeologic properties; land use and land cover, including agriculture; population density and projected population growth; climatic data; and any relevant municipal or jurisdictional boundaries. The second category, pollutant source characterization, is composed of regulated sources such as wastewater treatment plants and permitted sewer outfalls and on-site sewage facilities (OSSFs), and non-regulated sources; the latter includes non-point sources, stormsewer system overflows (SSOs), contributions from wildlife, domesticated animals, cattle, and avian life forms within watersheds. This thesis does not address non-regulated sources, such as sanitary sewer overflows, but these and other similar sources can be readily integrated into GENESIS.

The third category of information is monitoring data. This category includes monitoring data for the parameter of interest as well as contemporaneous flow and other ambient water quality parameters, such as pH and temperature. States typically maintain relatively extensive monitoring networks for their streams and watersheds, and they also collect data for various water quality parameters. Such data collection efforts, while extensive, do not exhibit spatial or temporal uniformity or consistency in collection methodology and laboratory analytical methods. Thus, compiling available data is a time-consuming and complex process that can be significantly aided by using geospatial DSS.

The fourth category is modeling and analysis. Modeling and analysis varies from the simple – such as simple MS Excel spreadsheets – to complex detailed hydrologic models such as the Water Quality Analysis Simulation Program (WASP), QUAL2K, and others (USEPA 2013c). As models become more complex, however, they are less amenable to stakeholders and decision-makers that may not have the necessary training and experience to use these models. Furthermore, the geographic scale of the model may limit its usefulness when evaluating nutrients at a different spatial scale. Incorporating mid-level complexity modeling tools such as regression-based modeling, as is proposed in GENESIS, expands the toolbox and facilitates decision-making, data sharing, and accessibility of information to stakeholders and decision-makers.

The aforementioned four categories of information upon which decisions are made are common across TMDL development and form the basis of the geospatial decision support system proposed here. The key advantage of GENESIS is the ability to undertake multiple TMDLs and other water quality studies for a given water body using the same GENESIS framework and datasets, thus eliminating the need for repeating the first three categories of a TMDL study for each water quality parameter that is not in attainment. More importantly, GENESIS provides the capability of analyzing co- and inter-dependent water quality variables, such as nutrients and dissolved oxygen, and the capability for understanding water body behavior at multiple spatial (e.g., segment, stream, watershed, basin) and temporal (e.g., daily versus annual) scales. Finally, GENESIS facilitates the development of datasets that would be used as input for the analysis and modeling category of TMDL development and water quality studies, and it allows spatial visualization of monitored data. Thus, users and decision-makers can observe the spatial and temporal changes in water quality variables within a given system and potentially link those to changes in contextual geospatial data such as land use or soil types.

4.2 GENESIS Framework

Because of the multifaceted nature of water quality regulation and management, decision-makers need tools for depicting extensive data in a highly functional yet easy to use technology. This need can be addressed by the use of a geospatial decision support system, which integrates geospatial contextual, pollutant source, monitoring, and analysis and modeling tools using a sophisticated graphical user interface. This framework, Geospatial Environmental Nutrient Evaluation System for Inland Streams (GENESIS), is an architecture to organize the process of analysis typified by TMDL development, although it also can be applied to other surface water quality regulation processes. The cornerstone of this framework is the consideration of basin-wide information applied to the watershed and sub-watershed scales, and this information is viewable in a sophisticated graphical user interface, Google Earth.

4.2.1 Graphical User Interface

Geospatial information may be displayed in Google Earth to enhance visualization and to easily transport and share the visualization with a wider audience. To display in Google Earth, geospatial data is first imported into or created in a geographic information system (GIS) such as ESRI's ArcMap. Geoprocessing may be performed to modify or prepare the information for Google Earth visualization. In ArcMap 10, a tool may be used to convert the vector or raster data into KML or KMZ, which can be displayed in Google Earth using the same symbology used in the geoprocessed vector or raster data. The KML or KMZ file(s) may then be transported or transferred via typical data transfer methods such as internet websites and hardware storage devices. For example, KMZ files may be easily presented in a stakeholder meeting by viewing the files in a free version of Google Earth. By using this readily transportable visualization technique, complex geospatial information may be viewed and shared in a simple and effective manner.

The GENESIS framework makes use of a "Digital Earth" visualization system, which is demonstrated in this work using Google Earth. This freeware visualization and mapping tool is ideal for use in GENESIS because it serves as a free, easy to use medium for displaying multiple scales of geospatial information, including the information necessary for water quality management decision-making. In a fully developed application of the GENESIS framework, users would access a river basin-based KML or KMZ file. For example, users would access a San Jacinto River Basin KMZ file. By opening the file, Google Earth automatically runs, and users see a fly-through to the San Jacinto River Basin in southeast Texas. Upon hovering over the river basin, users can see available layers of stream segments, land cover, monitoring station points, NPDES permit outfall locations, and other relevant information, and users have the option to view detailed information, such as monitoring point metadata (e.g., date range, parameters available, number of data points) and LDCs for specific AUs, by clicking on points, lines, or polygons. The selected information could then be exported or converted into shapefiles and associated attribute information displayed in ArcMap. Detailed records could then be exported to Excel if desired, for input into water quality models or for further data processing and analysis. In this way, Google Earth serves as a helpful visualization tool for considering multiple scales and types of data simultaneously.

Further, the flexibility of the GENESIS framework allows for information to be centralized and updated repeatedly. This framework would simplify a decision-makers access to relevant information by allowing a central repository and system of viewing relevant water quality data, metadata, and hydrologic units. This proposed framework is in contrast to the current method of gathering data from disparate databases in various formats, processing that data, and then viewing the information in a compartmentalized fashion. Also, this central repository could be updated regularly since Google Earth allows for hyperlinks to be embedded within the dialog box of a point, line, or polygon. Users could click on the links and visit the website through which updated information could be appended to the existing files. In this way, organizing all relevant data for a river basin in the GENESIS framework would allow KMZ files viewable in Google Earth to serve as a data management medium for water quality decision-making.

4.2.2 Geospatial Context

In order to consider basin-wide information at the watershed and sub-watershed levels, geospatial contextual information is used for the area under study. In this framework, the most basic geospatial area unit selected is either a regionally delineated watershed or a USGS hydrologic unit. In some cases, regional entities may develop more detailed watershed boundaries given local information. For example, H-GAC (Houston-Galveston Area Council) provides detailed watershed boundaries as part of the Clean Rivers Program (CRP). These boundaries take into account data from Harris County Flood Control District (HCFCD), USGS 10-digit hydrologic unit codes (HUC), and H-GAC CRP. In many cases, however, more comprehensive boundaries are unavailable; the USGS HUC should be used in such instances. HUCs identify hydrologic units using distinct numbers of varying 2-digit increments, which correspond to the scale of the unit. The region is identified with two digits; the subregion, with four digits; the basin, with six digits; the subbasin, with eight digits; and the watershed, with ten digits. For example, the San Jacinto River Basin's 6-digit HUC is 120401. Within the San Jacinto River Basin are Buffalo-San Jacinto, East Fork San Jacinto, Spring, and West Fork San Jacinto subbasins (12040104, 12040103, 12040102, and 12040101, respectively). These USGS HUCs or other locally derived hydrologic units form the geospatial area unit in the GENESIS framework.

In addition to the area base unit, other geospatial contextual information is important in TMDL development. Hydrologic-relevant information such as topography; soils; hydraulic features including dams and pump stations; and reach cross sectional information may be considered during the watershed characterization. Atmospheric and biological information may also be considered. Climate data, such as average annual precipitation, and locations of atmospheric monitoring stations may also be collected. Biologic information such as ecoregion, land use and land cover, aquatic vegetation, specific agricultural, and biological monitoring information may prove relevant. Further, jurisdictional and residential information can be included. Relevant information would include municipal boundaries as well as current and projected population statistics. These hydrologic, atmospheric, biological, jurisdictional, and residential data provide important geospatial context in TMDL development and other water quality studies irrespective of the specific parameter or variable under study.

4.2.3 Pollutant Sources

Pollutant source characterization is a central aspect of TMDL development and, therefore, of GENESIS. Sources are grouped into the following subcategories: regulated and non-regulated sources, as mentioned previously. This thesis does not address non-regulated sources, such as sanitary sewer overflows (SSOs) and wildlife and domestic pet contributions, but these can be readily integrated into GENESIS. Point sources are regulated under the CWA's National Pollution Discharge Elimination System (NPDES), which is administered in Texas by TCEQ under the Texas Pollutant Discharge Elimination System (TPDES). The TPDES includes permitted wastewater discharges (e.g., municipal WWTFs) and stormwater discharges (e.g., Municipal Separate Storm Sewer Systems or MS4s). Specifically, permitted flows and locations of permitted facilities are commonly relied upon in TMDL and water quality studies to develop loads of a given pollutant entering a segment, stream, watershed, or basin. Other source considerations include known enforcement actions under TPDES, legacy sediment contamination contributing to soil oxygen demand (SOD), backwater introduction of pollutants, and high suspended sediment loading. All of the aforementioned source information, much like monitoring data as will be seen below, resides in disparate databases; compiling these data is costly and time-consuming and would greatly accelerate and facilitate water quality management when readily available in a searchable, viewable framework such as GENESIS.

4.2.4 Parameter Monitoring Data

Monitoring data is the third category of information addressed in GENESIS. This category includes monitoring data for the parameter of interest as well as contemporaneous flow and other ambient water quality parameters, such as pH and temperature. Flow conditions not only provide contextual information for parameter concentrations but also allow for generation of synthetic data in the case of intermittent monitoring records (Vieux and Moreda 2003). Flow-related parameters may be available directly from monitoring databases in the form of antecedent dry days (ADD) or may be derived statistically. Further, other parameters, such as water temperature, pH, and chlorophyll-a, may be available and of interest to the study.

Monitoring information can be obtained by searching databases for monitoring locations. Monitoring location metadata is then accessed, providing information about the parameters, the number of measurements, and the date ranges for which data are available. The data of interest must then be downloaded, cleaned, and processed to composite a dataset of all data for a given monitoring location. This process is time-consuming and must be repeated many times to obtain the data needed to undertake water quality studies encompassing an entire river basin. The GENESIS framework changes this paradigm of monitoring data acquisition, processing, and compilation by allowing users to select and sort data geospatially.

4.2.5 Modeling and Analysis Tools

Modeling and analysis tools in GENESIS vary from simple to complex. The simplest tool in this context is monitoring data fitted with a trendline in a spreadsheet program such as MS Excel. This simple linear regression tool makes use of the ordinary least-squares (OLS) regression, which minimizes the sum of the squared differences between modeled and observed data points. Regressions methods may also be used in ArcMap 10.1 by using the spatial statistics toolbox. More complex modeling and analysis tools include water quality models such as LDCurve, WASP, and QUAL2K (USEPA 2013c), among others. Many models are currently available and additional models for water quality will likely continue be developed in the future; GENESIS allows for flexibility in the choice of modeling and analysis tools while maintaining the overall architecture. Users can develop dataset generation capabilities from GENESIS to any water quality model or analysis tool of their choice for a given basin or watershed.

CHAPTER 5 – DEMONSTRATION OF GENESIS

5.1 Geospatial Context

As previously described, the GENESIS framework is composed of four categories of information and tools: i) contextual geospatial information, ii) sources of pollutant of interest, iii) monitoring data, and iv) analysis and modeling tools. Information falling under the first three categories can be used repeatedly for a given water body to undertake study and analysis of various water quality parameters. The first category, geospatial context, addresses various spatial scales (basin, subbasin, watershed) as well as other geospatial information such as land use and land cover.

5.1.1 Hydrologic Scales

The first step of the framework is to determine the hydrologic area base unit and the geospatial scales of interest. This step is important because geospatial contextual information should be collected at the broadest scale to capture the maximum data needed for a study or set of studies. For example, clipping state-wide county boundary GIS shapefiles to the maximum extent needed before adding the clipped files into a file geodatabase ensures the largest area of interest is maintained while considering file management limitations. While the GENESIS framework allows for a variety of scales, it is recommended that nutrient-related studies maintain basin (or 6-digit HUC) scale datasets for two reasons: i) nutrients cycle on a broader scale than that of the watershed, and ii) river basin or HUC-6 scale boundaries represent the largest hydrologic scales typically within state boundaries, thus lending itself to simplified regulatory management.

In the selected demonstration case study for this thesis, the basin (corresponding to the “San Jacinto River Basin,” Figure 5-1), the watershed/basin (corresponding to the

“Lake Houston Watershed/Upper San Jacinto River Basin,” Figure 5-2), and the subbasin (corresponding to the “Spring Creek Watershed”) scales are considered. The San Jacinto River Basin (TCEQ River Basin number ten) is located in southeast Texas and is composed of eighteen watersheds, listed in Table 5-1 (H-GAC 2010). This river basin spans Fort Bend, Grimes, Harris, Liberty, Montgomery, San Jacinto, Walker, and Waller Counties and includes the Houston metropolitan area. It contributes 28 percent of the annual freshwater inflow into Galveston Bay, making it the second highest contributing basin after the Trinity River Basin (TWDB 2001). The San Jacinto River Basin includes two major reservoirs, Lake Conroe and Lake Houston, and two smaller state park reservoirs, Lake Raven and Sheldon Reservoir.

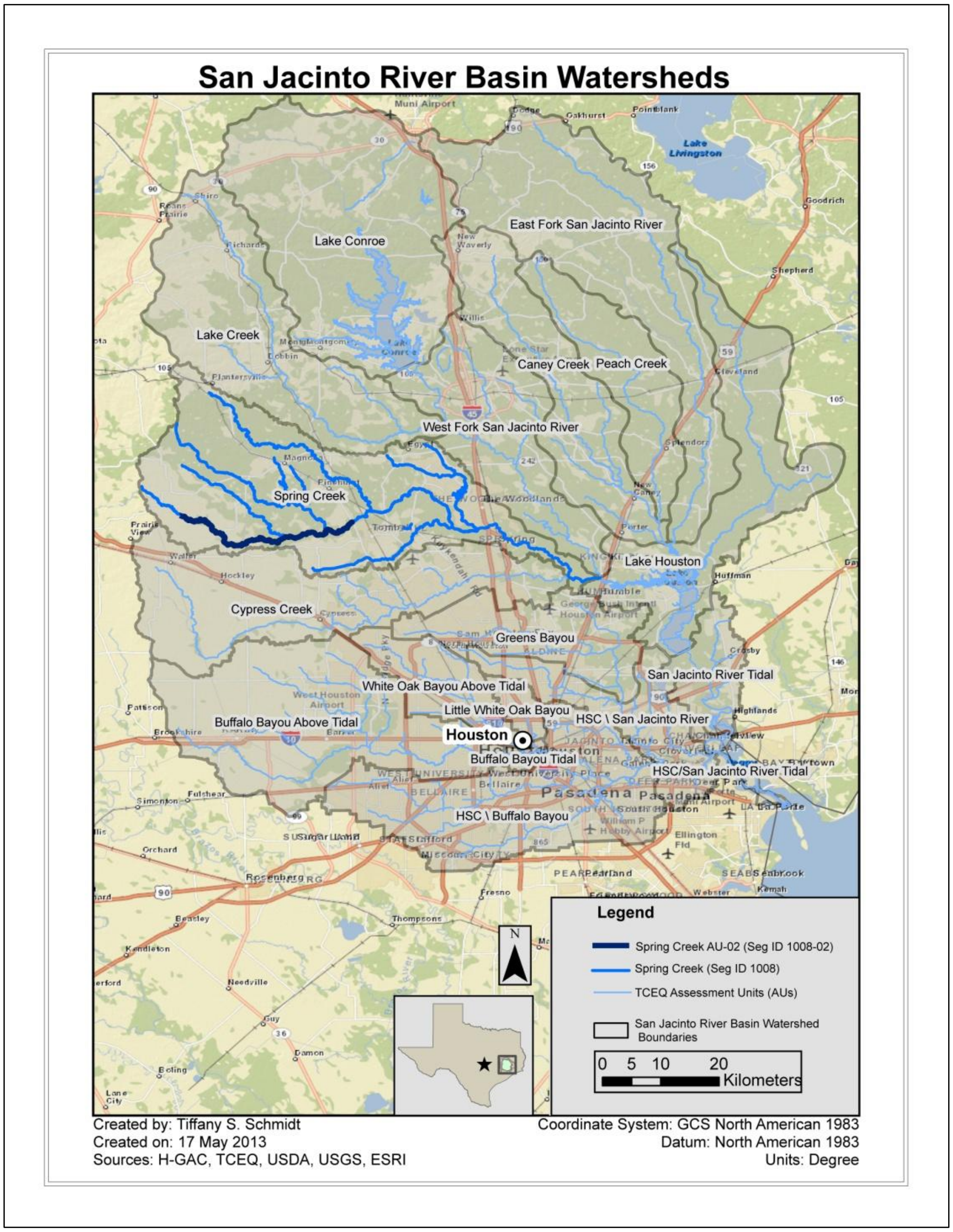

Figure 5-1: The San Jacinto River Basin and its watersheds in southeast Texas.

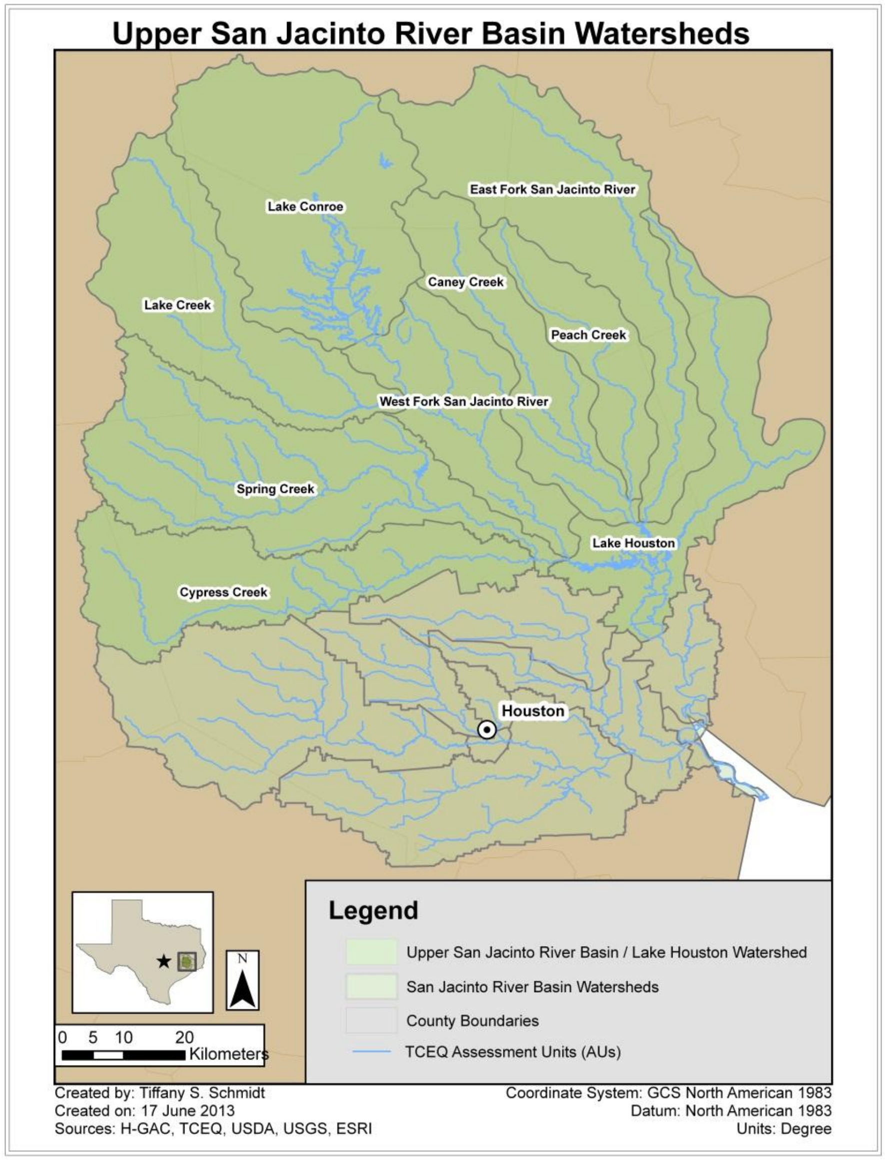

Figure 5-2: The San Jacinto River Basin and the Upper San Jacinto River Basin Watershed.

Table 5-1: Areas of the San Jacinto River Basin Watersheds.

Watershed	*Watershed ID*	*Area (Sq Mi)*	*Area (Acres)*
Buffalo Bayou Above Tidal	1014	351.35	224,861.22
Buffalo Bayou Tidal	1013	9.04	5,785.36
Caney Creek	**1010**	**221.98**	**142,064.57**
Cypress Creek	**1009**	**319.47**	**204,461.84**
East Fork San Jacinto River	**1003**	**403.54**	**258,264.83**
Greens Bayou	1016	143.34	91,734.69
HSC / Buffalo Bayou	1007	295.98	189,429.55
HSC / San Jacinto River	1006	122.20	78,206.94
HSC / San Jacinto River Tidal	1005	16.92	10,828.34
Lake Conroe	**1012**	**455.78**	**291,697.74**
Lake Creek	**1015**	**328.22**	**210,058.01**
Lake Houston	**1002**	**278.75**	**178,399.49**
Little White Oak Bayou	1013A	22.02	14,090.68
Peach Creek	**1011**	**150.74**	**96,474.38**
San Jacinto River Tidal	1001	67.44	43,164.04
Spring Creek	**1008**	**441.44**	**282,524.28**
West Fork San Jacinto River	**1004**	**216.33**	**138,452.83**
White Oak Bayou Above Tidal	1017	87.88	56,241.01
San Jacinto River Basin Area:		3,932	2,516,740
Upper San Jacinto River Basin Area:		2,816	1,802,398
Upper San Jacinto River Basin as Percent of Total River Basin:		72%	72%

Bold text indicates watersheds of the Upper San Jacinto River Basin

Source: Clean Rivers Program, H-GAC GIS Clearinghouse (2010)

In 2006, the San Jacinto River was named one of the ten most endangered rivers because of habitat damage caused by watershed development and sand and gravel dredging (RFHP 2009). Lake Conroe, a 21,000-acre reservoir constructed in 1973 by the San Jacinto River Authority and the City of Houston, is enriched by nutrients due to development of nearby lands and is plagued by exotic aquatic vegetation. Lake Houston is affected primarily by sedimentation resulting from upstream gravel and sand dredging, and this additional suspended and dissolved solids load results in decreased primary productivity. The association between nutrients at the watershed scale and water quality in Lake Houston as well as the attenuation capacity for nutrients within the Lake have significant ramifications on nutrient availability for ecosystems in Galveston Bay. Thus, using a framework such as GENESIS would allow management of nutrients within the watersheds that drain to Lake Houston to maintain Lake water quality while ensuring sufficient nutrient loads to support biota in Galveston Bay.

5.1.2 Geospatial Data

The San Jacinto River Basin is characterized by four EPA Level III ecoregions: East Central Texas Plains in the west; South Central Plains predominantly in the northern areas; Texas Blackland Prairies in the west; and Western Gulf Coastal Plain in the southern areas (Figure 5-3). The 2006 NLCD land use/land cover is dominated by high and medium intensity developed areas in the southern and central regions; by hay/pasture in the west and northwestern regions; by evergreen forest primarily in the northern areas; and by a mixture of evergreen forest and shrub/scrub in the eastern areas (Figure 5-4). Of note, several watersheds within the basin, especially the Buffalo Bayou Above Tidal, Cypress Creek, and Spring Creek watersheds, are characterized by rather abrupt transitions between agriculture-related cover to the west and high and medium intensity developed cover to the east (Figure 5-5).

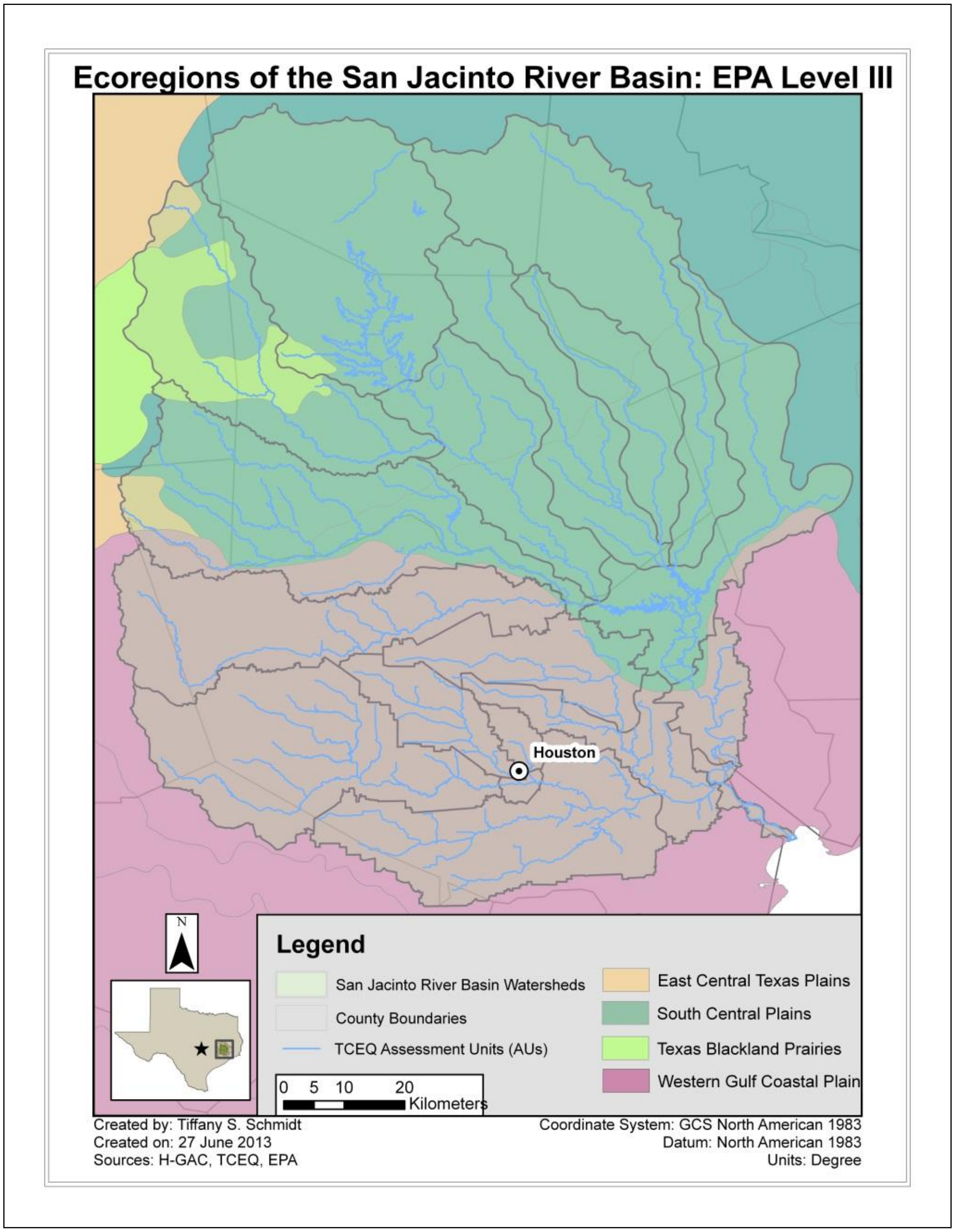

Figure 5-3: EPA Level III Ecoregions of the San Jacinto River Basin.

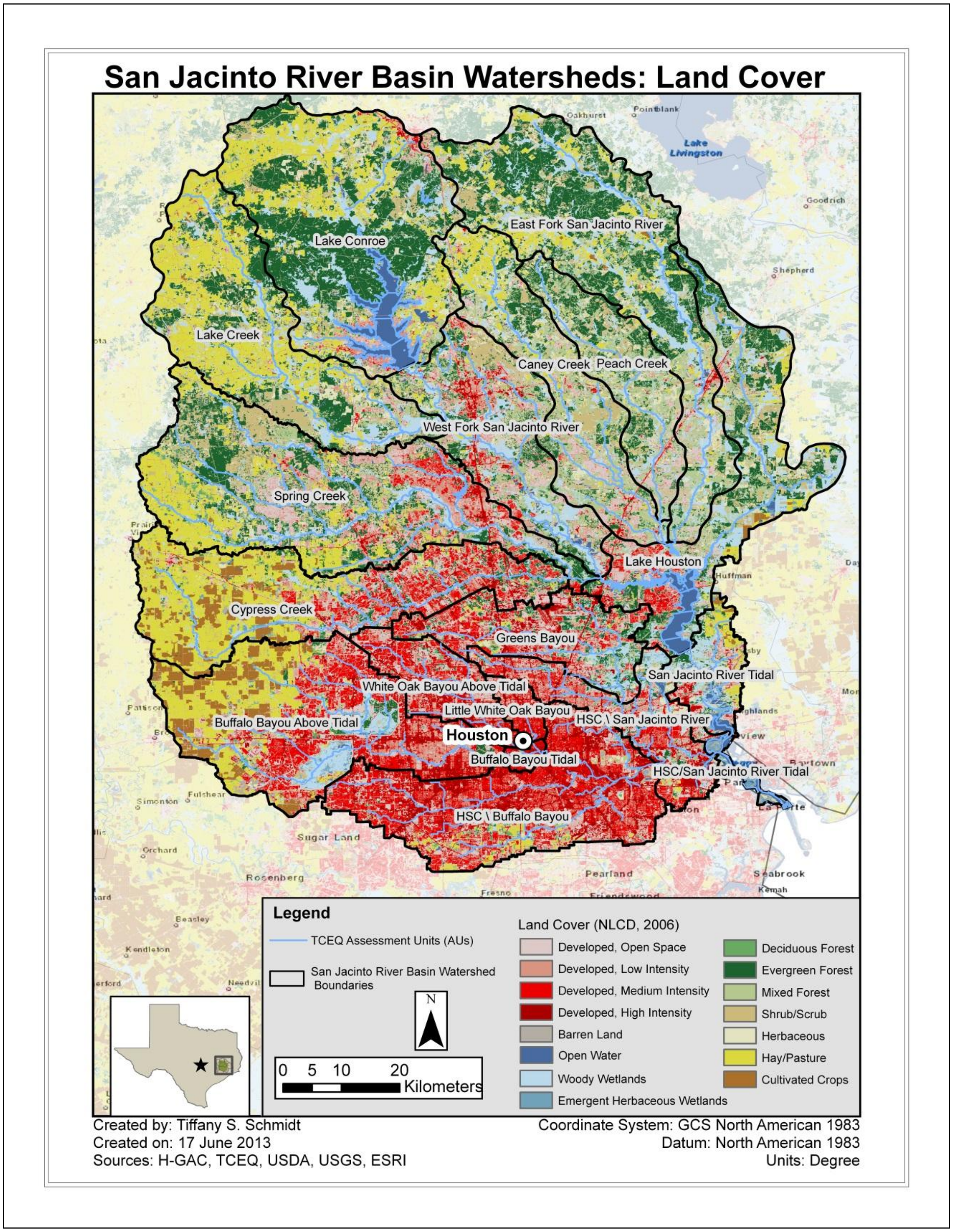

Figure 5-4: Land cover of the San Jacinto River Basin watersheds.

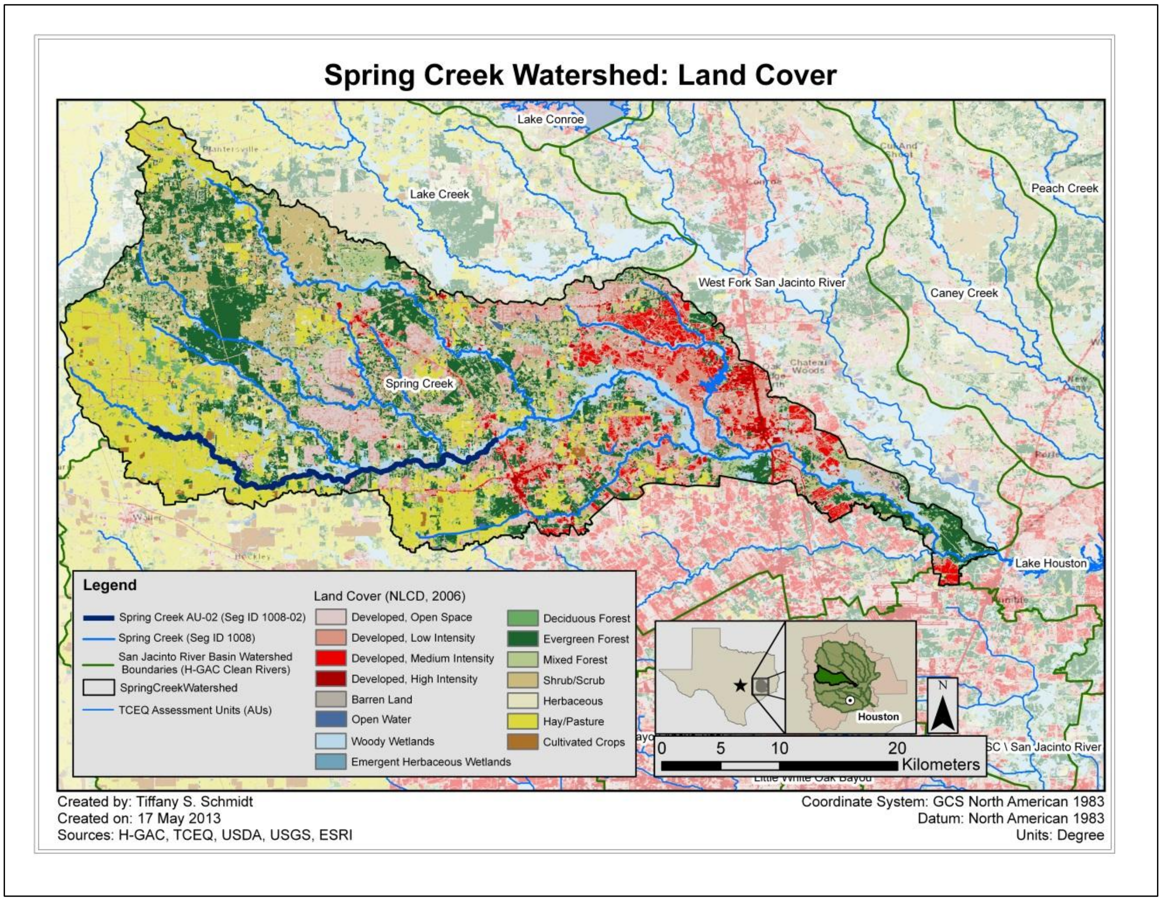

Figure 5-5: Land cover of the Spring Creek Watershed.

The Upper San Jacinto River Basin or Lake Houston watershed is composed of 13 watersheds which drain into Lake Houston, the main reservoir for the Houston metropolitan area. The total drainage area of the Lake Houston watershed is over 2,800 square miles. The drainage area is composed primarily of Harris and Montgomery Counties, but portions of Grimes, Liberty, San Jacinto, Walker, and Waller Counties also fall within the Lake Houston Watershed. The largest municipalities within the Lake Houston watershed include portions of the City of Houston, Conroe, and The Woodlands. The Woodlands, Spring, and the northern Houston suburbs make up the developed areas in the easternmost areas of the Spring Creek watershed.

The Spring Creek watershed is located in the west-central San Jacinto River Basin. Using H-GAC watershed boundaries, it measures about 440 square miles. Spring Creek and its tributaries flow from west to east before joining with Cypress Creek and West Fork San Jacinto River. The West and East Forks of the San Jacinto River then converge to form Lake Houston. Spring Creek defines the boundary between Harris County and Montgomery County.

The Spring Creek watershed is of interest because Spring Creek (TCEQ Segment 1008) AUs 1008-02, 1008-03, and 1008-04 first appeared on the 303(d) list in 1996, and AU 1008-02 has been listed consistently since then for depressed dissolved oxygen (Figure 5-5) (TCEQ 2012). Of note, Cypress Creek (Segment 1009) also has 303(d) AUs listed since 1996. While a bacteria TMDL has been developed and approved for Spring Creek, a dissolved oxygen TMDL has not yet been developed.

5.2 Source Characterization

Source characterization is a central aspect of TMDL development and water quality studies and, therefore, of GENESIS. This demonstration of GENESIS, as mentioned previously, does not address non-regulated sources, such as SSOs and wildlife and domestic pet contributions; rather, only regulated sources are incorporated here. NPDES/TPDES permitted discharges include wastewater discharges such as outfalls from WWTFs (Figure 5-6). While stormwater discharges such as Municipal Separate Storm Sewer Systems (MS4s) are also included under NPDES/TPDES, they are not incorporated into the demonstration for brevity.

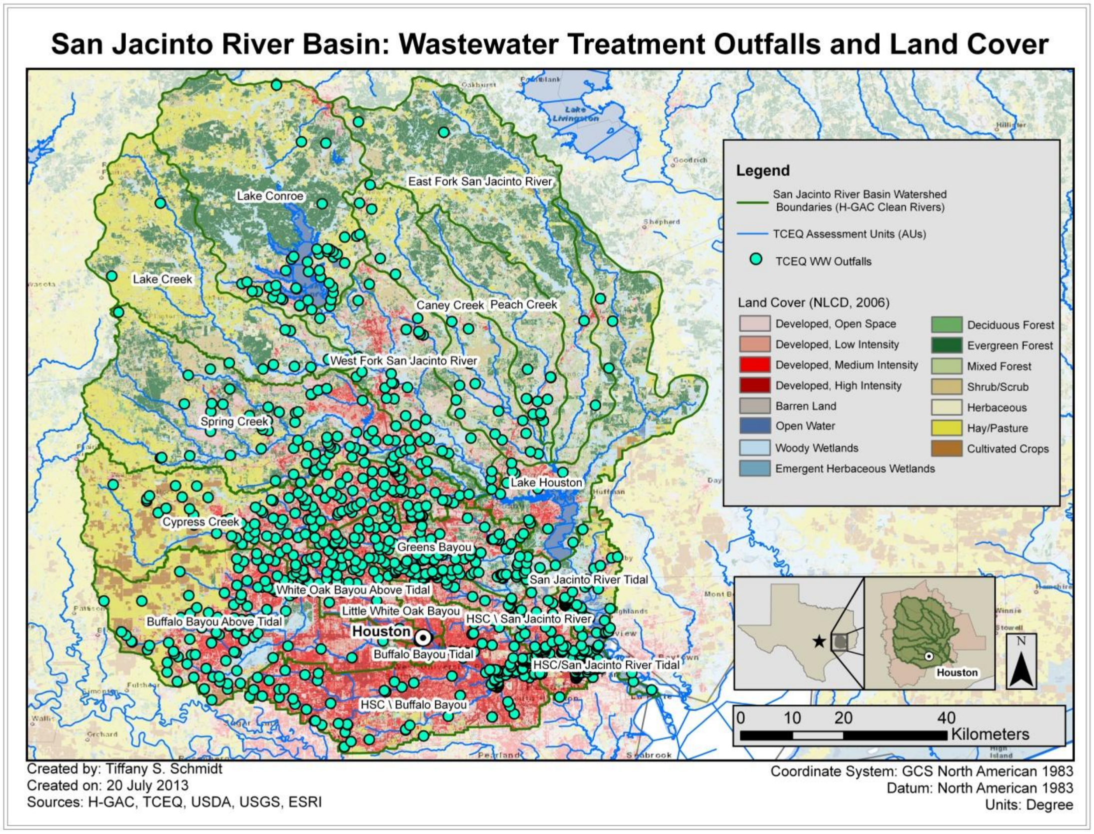

Figure 5-6: Wastewater treatment outfalls and land cover of the San Jacinto River Basin.

Source characterization includes information about other allocated (or managed pollutant) loads within the same watershed or river basin. For example, it is important to take into account all existing TMDLs within the basin of study in order to take a more holistic approach towards additional TMDL development. By using Google Earth as a medium in GENESIS, AUs, stream segments, and basin and subbasin boundaries, along with water quality impairments and existing TMDLs can be viewed across the entire basin. Thus, a group of stakeholders and decision-makers can be aware of the existing water quality impairments and management efforts for the entire river basin.

To integrate this information, the EPA ATTAINS database is used as a starting point since it provides a searchable database of all approved TMDLs. However, it is not geospatially searchable beyond the state level. This information is also available from TCEQ on a webpage of all existing Texas TMDLs, but it does not integrate any type of geographic search function at present. For this case study, the EPA ATTAINS database was queried for all TMDLs in Texas, and this table is included in APPENDIX I: TEXAS TOTAL MAXIMUM DAILY LOADS FROM EPA ATTAINS. The ATTAINS database information was integrated into GENESIS such that decision-makers can visually examine which segments within the San Jacinto River Basin have existing TMDLs and their corresponding parameters and waste load allocations (WLAs or permit limits imposed on wastewater treatment facilities for a specific water quality parameter, e.g., indicator bacteria), as well as impaired segments lacking TMDLs (symbolized as red steam segments in Figure 5-7). This integration was achieved by joining the EPA ATTAINS output; 303(d) listed impairments; and geospatial stream segment information to yield dialog boxes including data such as TMDL name, document web address, parameter name, and WLA, viewable by clicking on segments in Google Earth (Figure 5-7).

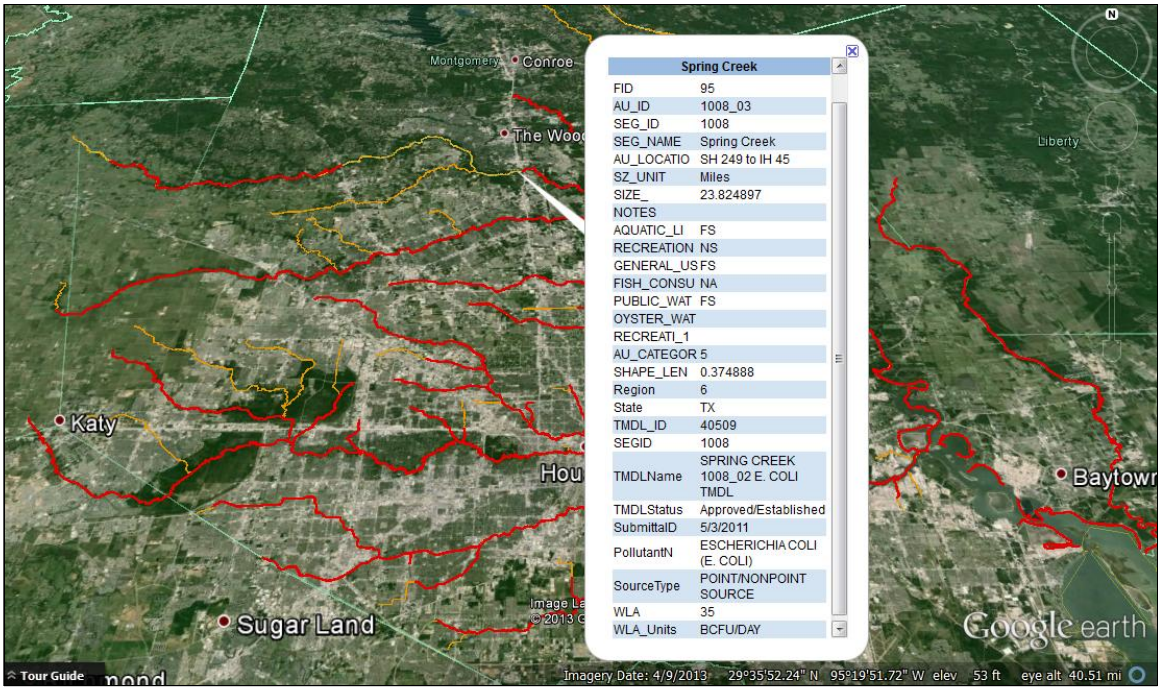

Figure 5-7: Screenshot in Google Earth of impaired stream segments with TMDLs. Dialog boxes contain data such as TMDL name, parameter name, and waste load allocation. In this example, dialog box shows Spring Creek (AU 1008-03) information, including bacteria TMDL and WLA of 35 BCFU/day.

5.3 Monitoring Data

The GENESIS framework allows decision-makers to simultaneously view water quality monitoring data for co- or inter-dependent variables such as nutrients and dissolved oxygen. In the selected application of GENESIS, dissolved oxygen and total phosphorus are the parameters of interest. While separate TMDLs would be developed for each, these parameters were chosen because AU 1008-02 in Segment 1008, Spring Creek, has been listed as not supporting its aquatic life designated use since 1996 due to depressed dissolved oxygen (Figure 5-8) (TCEQ 2012). A TMDL has been developed for this AU and fourteen others in the Lake Houston Watershed for bacteria, but DO impairments and numeric nutrient criteria have not yet been addressed.

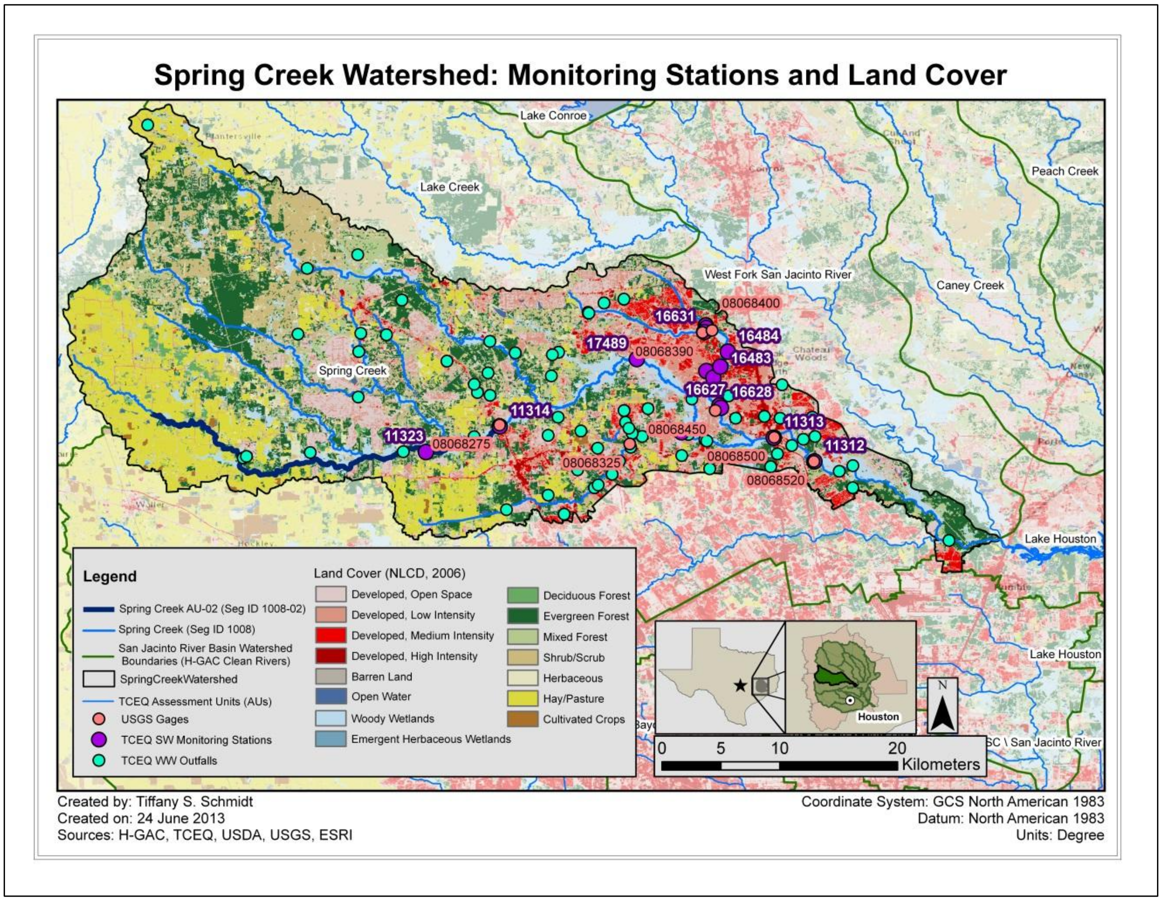

Figure 5-8: Water quality and flow stations and land cover of the Spring Creek Watershed.

In the development of a TMDL, the monitoring data component for AUs of interest, or for all AUs impaired for a given parameter in an entire river basin, can easily become unwieldy because of the number of monitoring locations and date ranges and frequency of monitoring points. For example, Figure 5-9 depicts available surface water monitoring stations within the San Jacinto River Basin. This high degree of data availability is beneficial from a data accessibility perspective but easily becomes cumbersome from a data management standpoint. Typically, monitoring data is downloaded from databases and imported and manipulated using data management tools, such as Microsoft Access. The data are then analyzed for trends in time and space and/or with other variables. This process, however, is time consuming and repetitive, and the user is unable to consider metadata or to visualize information that would prove relevant to the specific analysis needed. Associated geospatial information, such as latitude and longitude of sampling locations, is used more as an afterthought rather than as a tool to help inform the analysis itself.

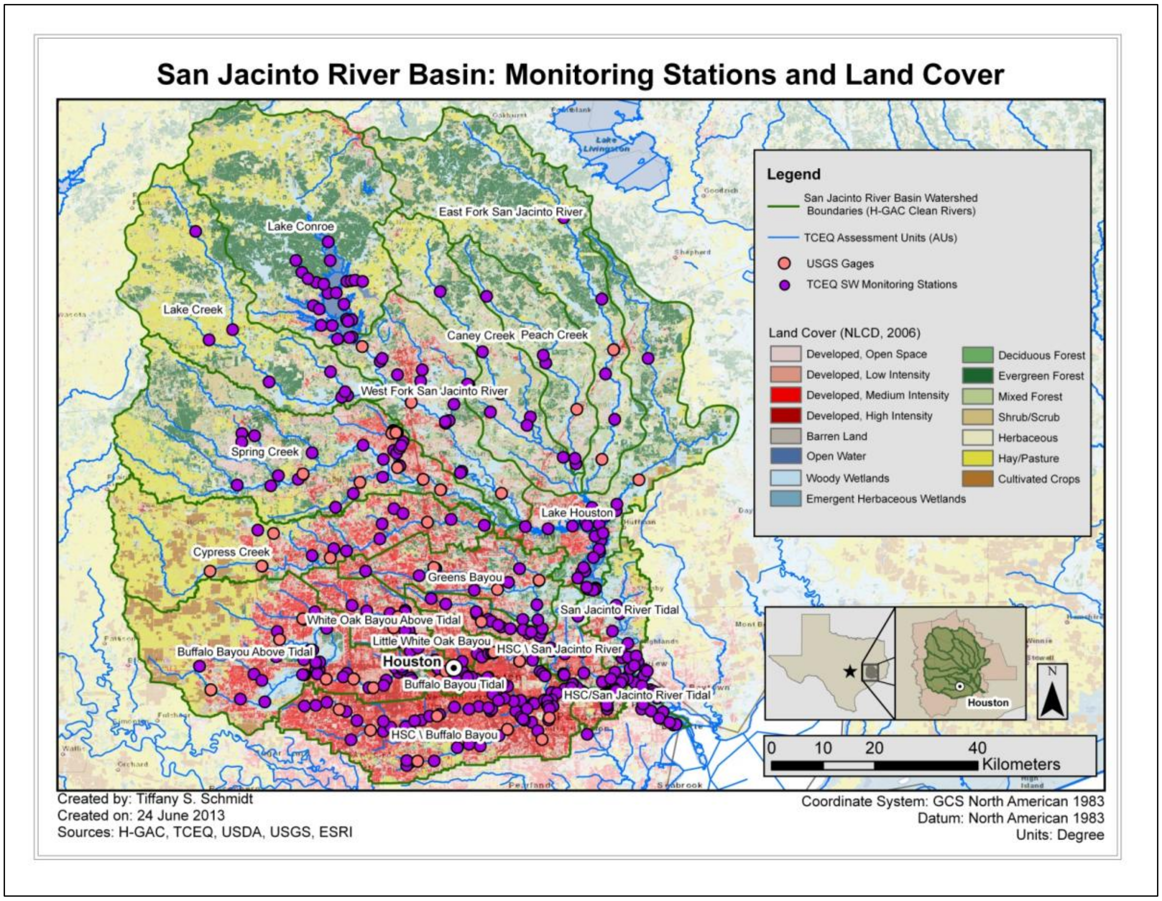

Figure 5-9: Surface water monitoring stations and flow gages in the San Jacinto River Basin.

The GENESIS framework, in contrast, offers a method for visualizing and geospatially selecting relevant monitoring stations and corresponding data. GENESIS allows users to join disparate databases of information using a common field, the monitoring station identifier. This joining of sampled water quality information with sample location/geospatial information can be done in GIS software or in database software by visual basic coding. Another option would be to use the USGS's NWIS Mapper web application, which provides metadata organized by station for date ranges, parameters, and data point counts; however, limited methods for station search and selection limit the ease of use of the USGS database.

This demonstration uses GIS software, ArcMap, to perform a "join" between two tables downloaded from the USGS Water Quality Portal. This freely accessible database allows USGS NWIS and EPA STORET water quality monitoring data to be easily downloaded; however, it is not possible at the time of this thesis to simultaneously download water quality data and geospatial data, such as the latitude and longitude of the monitored stations from the USGS Water Quality Portal. Thus, it is necessary for the user to join these two datasets under the GENESIS framework. Then, parameter data, in this case DO and TP, can then be graphed within ArcMap or MS Excel and inserted as image files to provide graphical display of concentration data over time in the context of geospatial location (Figure 5-10). If desired, users can also view simple summary statistics, such as date range and counts of datapoints, for a given station location. Figure 5-10, for example, depicts a dialog box indicating the monitoring station information for which DO data graphically appears on the left. The dialog box details monitoring station metadata for the parameter selected, in this case DO. For this particular station, there are 47 measurements for DO in the time range searched (1990 to 2012). Measurements are available only from 1990 to 2008.

By viewing monitoring data and its metadata simultaneously, the GENESIS framework allows users to organize their approach by geospatial location and hydrologic scale such that relevant monitoring stations may be selected geospatially at the watershed and basin scales, taking into account relative abundance or lack of intervals of interest. To integrate this information into GENESIS, a table of station metadata, such as parameter codes, datapoint counts, and date ranges was generated from the USGS

NWIS webportal. This information can be easily imported into ArcMap as a table and displayed geospatially such that a user can choose sampling stations which include the parameter of study for a specific range of time.

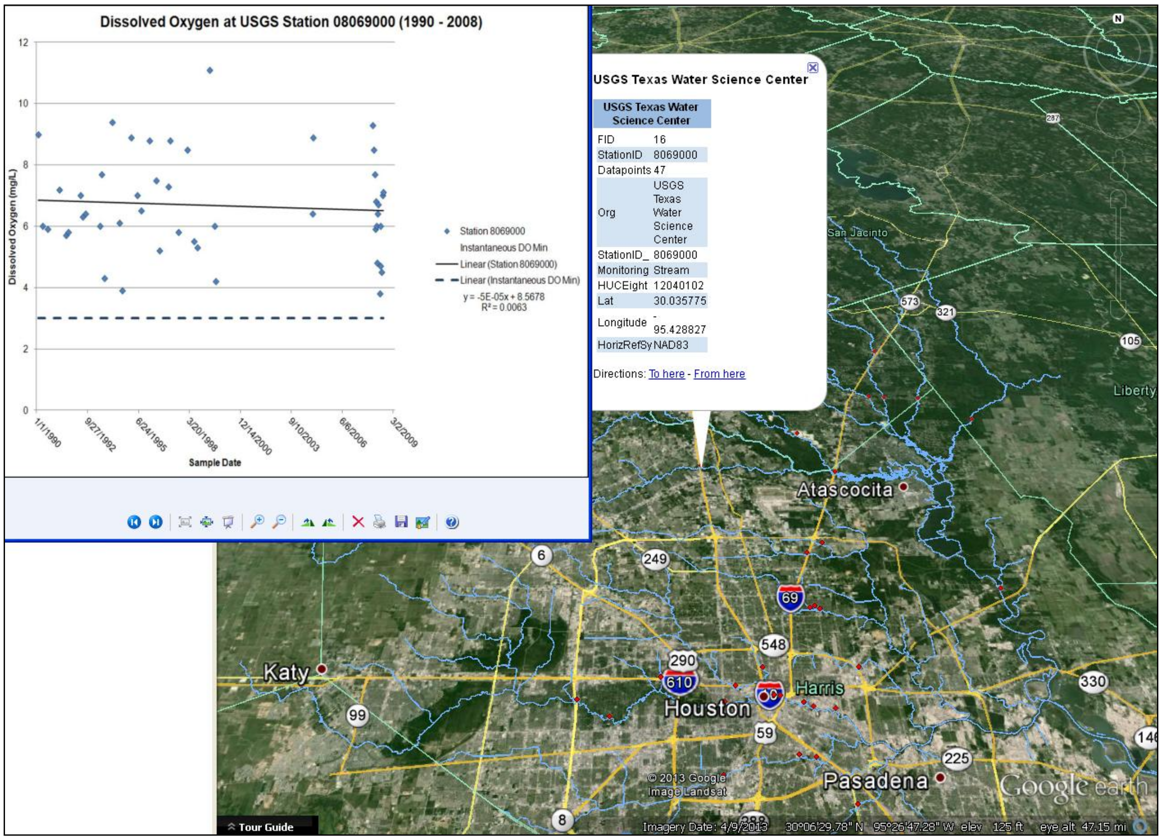

Figure 5-10: Dissolved oxygen water quality data graphed and simultaneously viewed in Google Earth.

The monitoring station for which DO data is described in the following section was chosen in the following way. Based on the availability of sampling data and of locations of TCEQ surface water quality monitoring stations, USGS flow gages, and the assessment unit of interest (AU 1008-02; see Figure 5-5 and Figure 5-8), TCEQ station 11314 and USGS gage 08068275 were chosen because this location provided the only coincidence of water quality and flow data that was directly hydrologically relevant to the AU of interest. Overall, however, the GENESIS framework allows geospatial determination of monitoring station collocation with AU or stream segment boundaries by applying small radial buffers to AUs or stream segments and calculating intersections between buffered areas and monitoring points.

5.4 Modeling and Analysis Tools

The GENESIS framework can accommodate water quality models of varying complexity. This demonstration makes use of linear regression modeling, Flow Duration Curves (FDCs present flow data gathered at a specified stream location statistically in terms of flow exceedance percentiles), and Load Duration Curves (LDCs present the measured pollution for a specific flow value in a FDC). At the most basic level, regression modeling may be nutrient or DO data monitored at a specific location over time, fitted with a linear trendline in a simple spreadsheet tool such as MS Excel. This regression relationship may serve as the input for more complex water quality models or provide insight into variable relationships so as to inform further study.

Linear regression is demonstrated using the GENESIS framework here by examining DO and TP concentrations measured over time. Monitoring stations corresponding to hydrologic unit boundaries were selected, and DO and TP concentrations were plotted versus time (sample date). Specifically, DO measurements at USGS station 08069500, located at the mouth of the West Fork San Jacinto River, are shown in Figure 5-11, and TP measurements at the same location are shown in Figure 5-12. Using this data and Excel's linear regression trendline tool, DO and TP were plotted against each other Figure 5-13. TP was set as the independent variable and DO as the dependent variable to indicate the possibility of DO concentrations responding to excess nutrient TP. The resulting correlation, however, indicates that as TP increases, DO also increases somewhat.

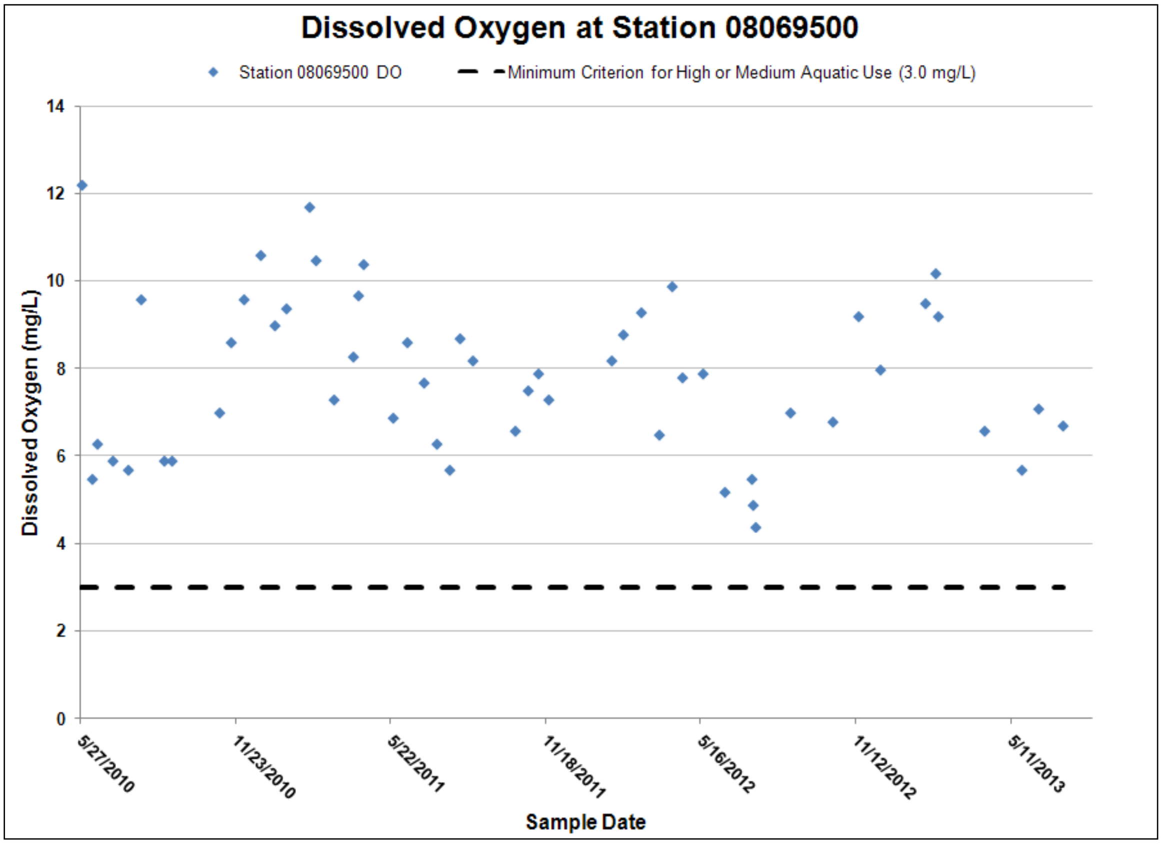

Figure 5-11: Dissolved oxygen concentrations over time at the mouth of the West Fork San Jacinto River.

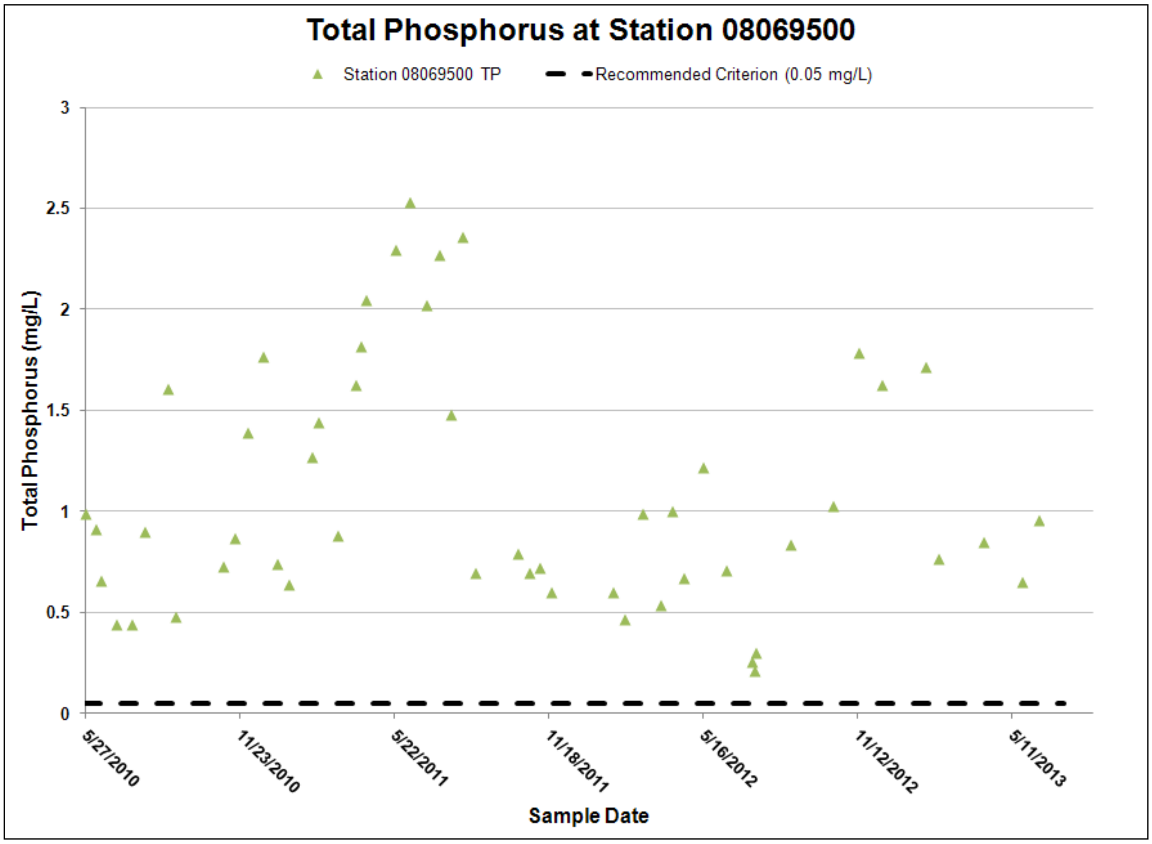

Figure 5-12: Total phosphorus concentrations over time at the mouth of the West Fork San Jacinto River.

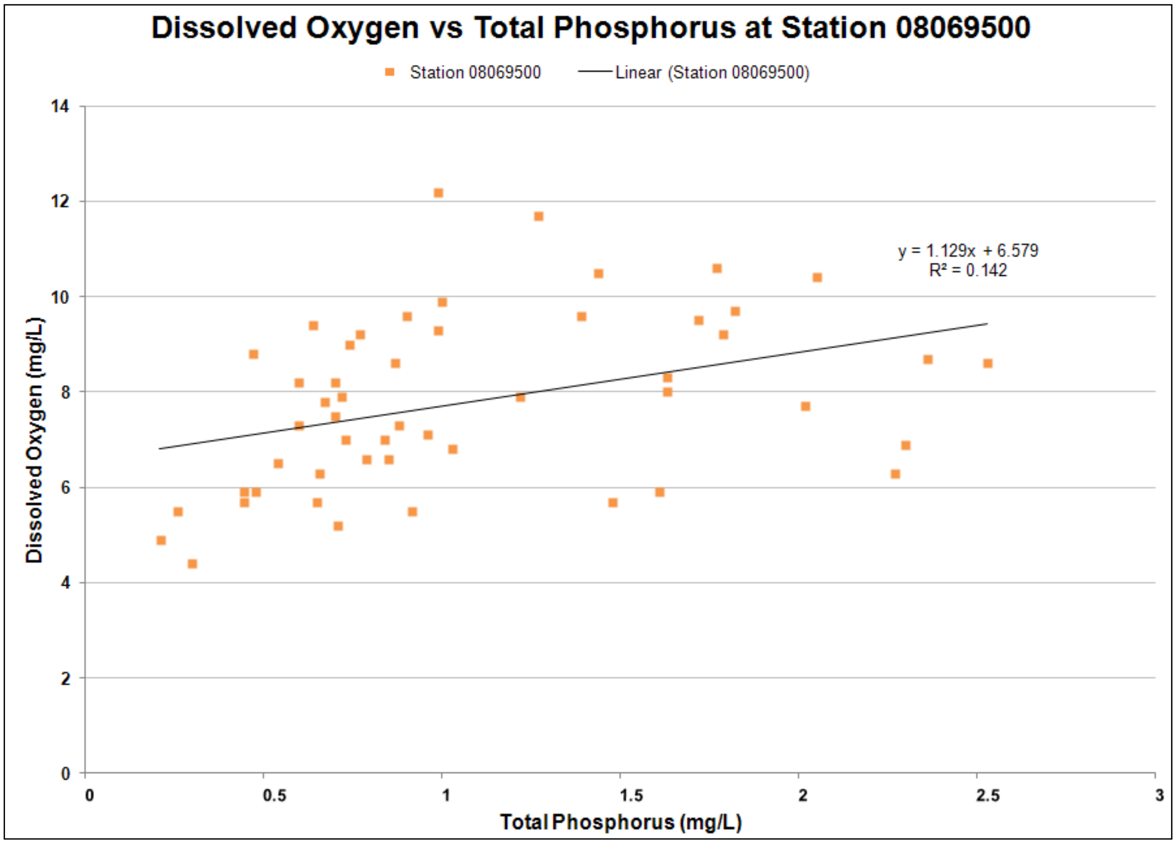

Figure 5-13: Dissolved oxygen and total phosphorus correlation at the mouth of the West Fork San Jacinto River.

Hypothesis testing was performed to check whether the DO-TP relationships indicated by trendline equations were statistically significant despite the low R^2 values. To accomplish the hypothesis testing, the trendline equations relating DO and TP concentrations for each selected station were used to generate "predicted" DO concentrations given observed TP concentrations. Then, the null hypothesis and alternate hypothesis were written. Geometric means, standard deviations, and P-values were calculated in Excel for each predicted dataset. P-values were compared with the chosen acceptable probability (0.05). In all datasets examined in this work, the P-values were greater than 0.05, so the null hypothesis corresponding to the observed and predicted DO concentrations being statistically the same failed to be rejected. This finding indicates that the trends observed between DO and TP concentrations are statistically significant at the 95% confidence limit.

The application of linear regression also demonstrates the value of using multiple spatial scales as part of the GENESIS framework. Three monitoring stations were chosen to demonstrate the importance of considering multiple spatial scales. One station at the mouth of the West Fork San Jacinto River (USGS 08069500) was chosen to represent the basin scale; USGS station 08068500, located on Spring Creek near its confluence with the West Fork San Jacinto River, was selected to represent the stream segment scale; and USGS station 08068275/TCEQ station 11314, located at the terminus of AU 1008-02, was chosen to represent the AU scale. DO and TP concentrations over time were plotted, and DO versus TP were plotted to correlate total phosphorus and dissolved oxygen. Figure 5-11, Figure 5-12, and Figure 5-13 depict DO versus time, TP versus time, and DO versus TP, respectively, for the river basin scale. Figure 5-14, Figure 5-15, and Figure 5-16 depict DO versus time, TP versus time, and DO versus TP, respectively, for the stream segment scale. Figure 5-17, Figure 5-18, and Figure 5-19 depict DO versus time, TP versus time, and DO versus TP, respectively, for the AU scale.

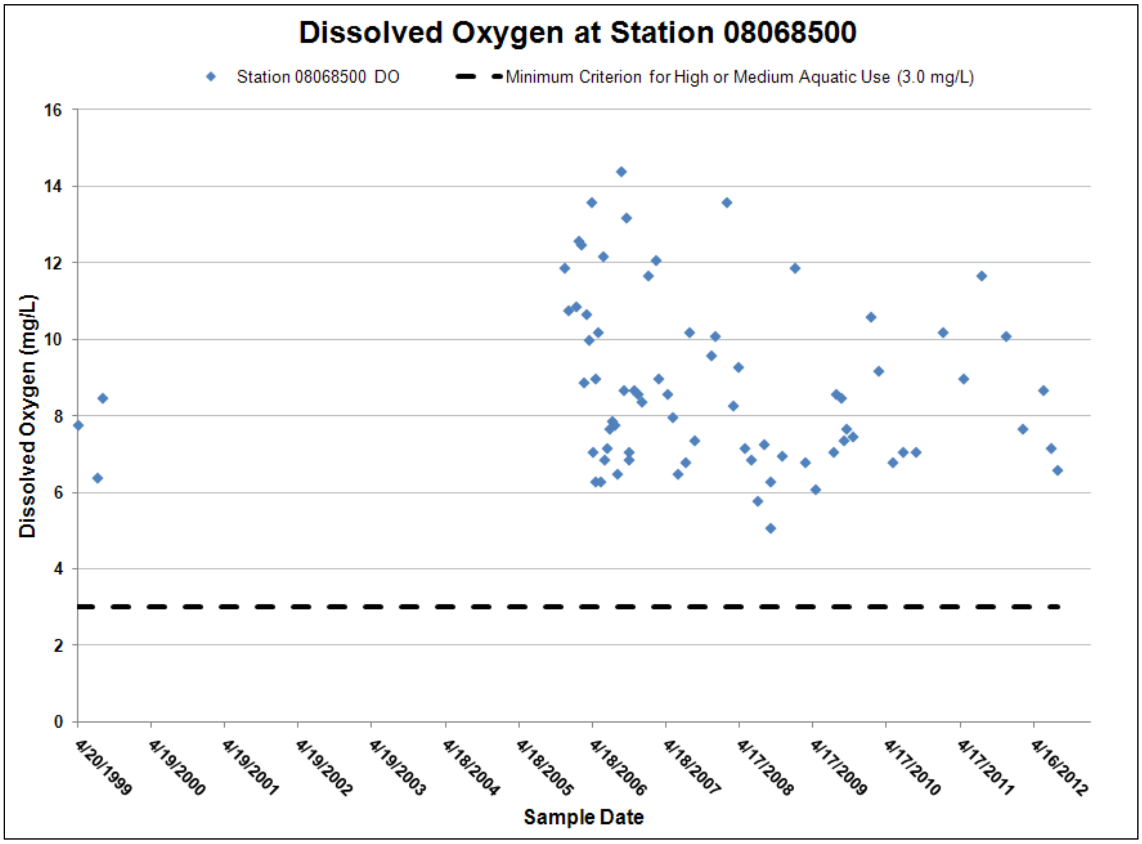

Figure 5-14: Dissolved oxygen concentrations over time on Spring Creek near its confluence with the West Fork San Jacinto River.

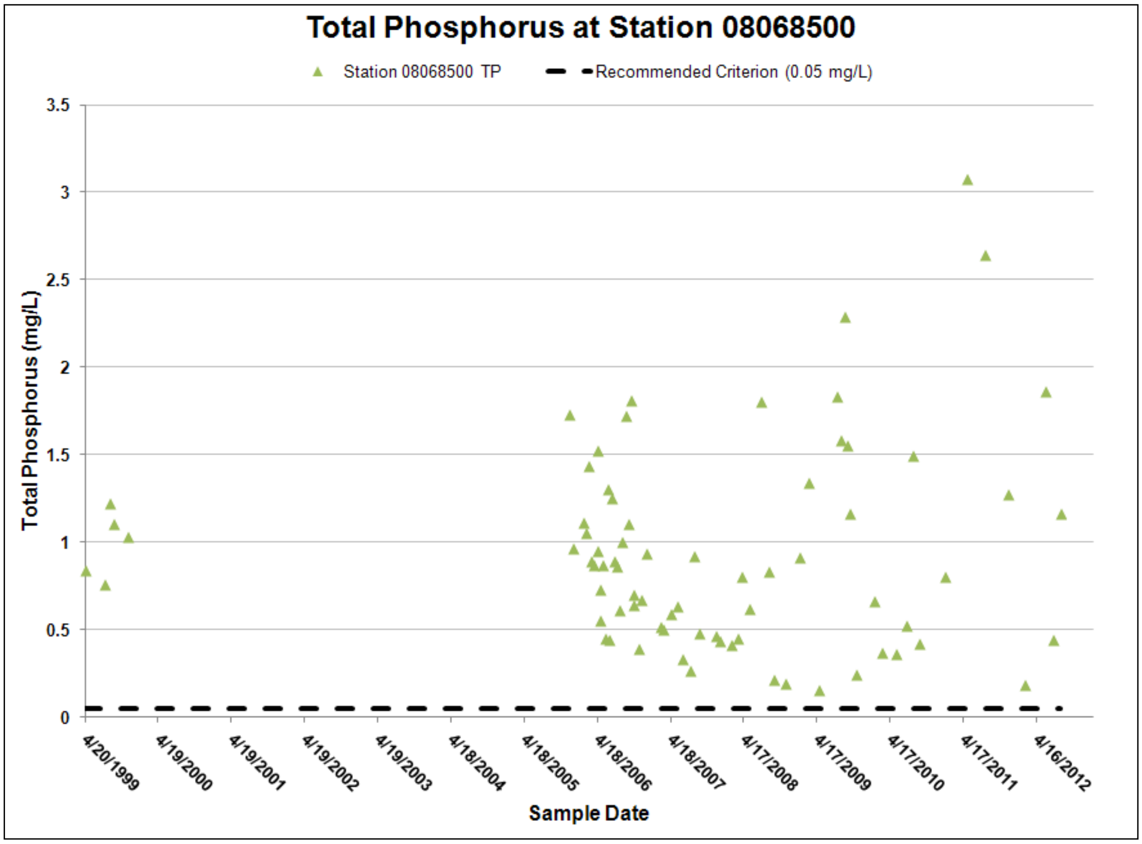

Figure 5-15: Total phosphorus concentrations over time on Spring Creek near its confluence with the West Fork San Jacinto River.

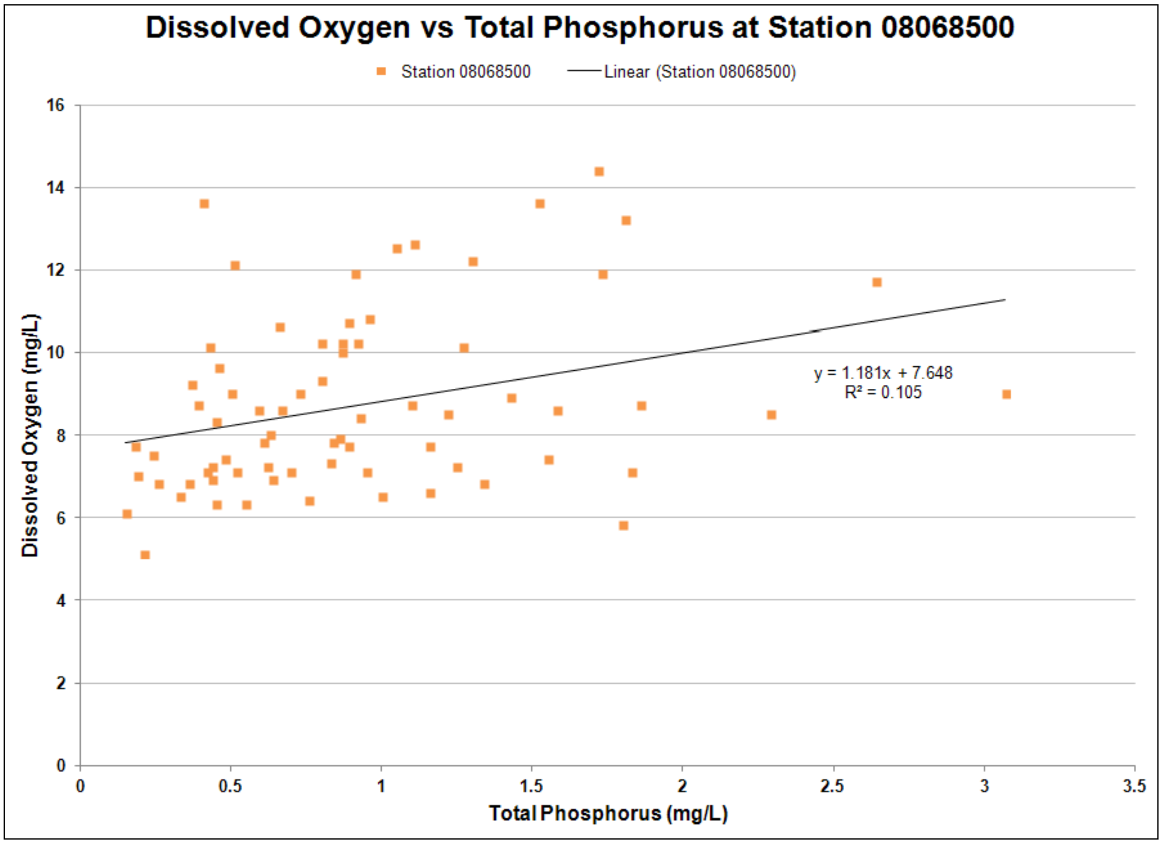

Figure 5-16: Dissolved oxygen and total phosphorus correlation on Spring Creek near its confluence with the West Fork San Jacinto River, representing the stream segment scale.

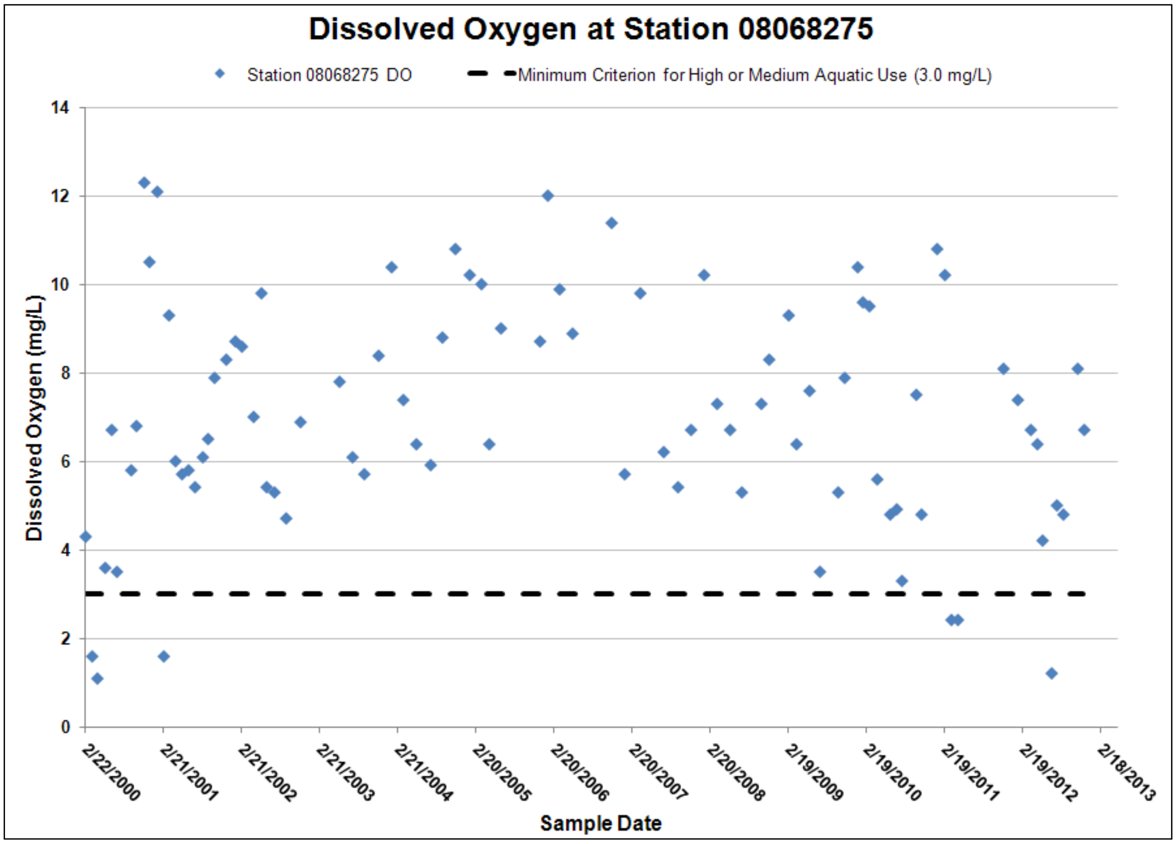

Figure 5-17: Dissolved oxygen concentrations over time at the terminus of AU 1008-02.

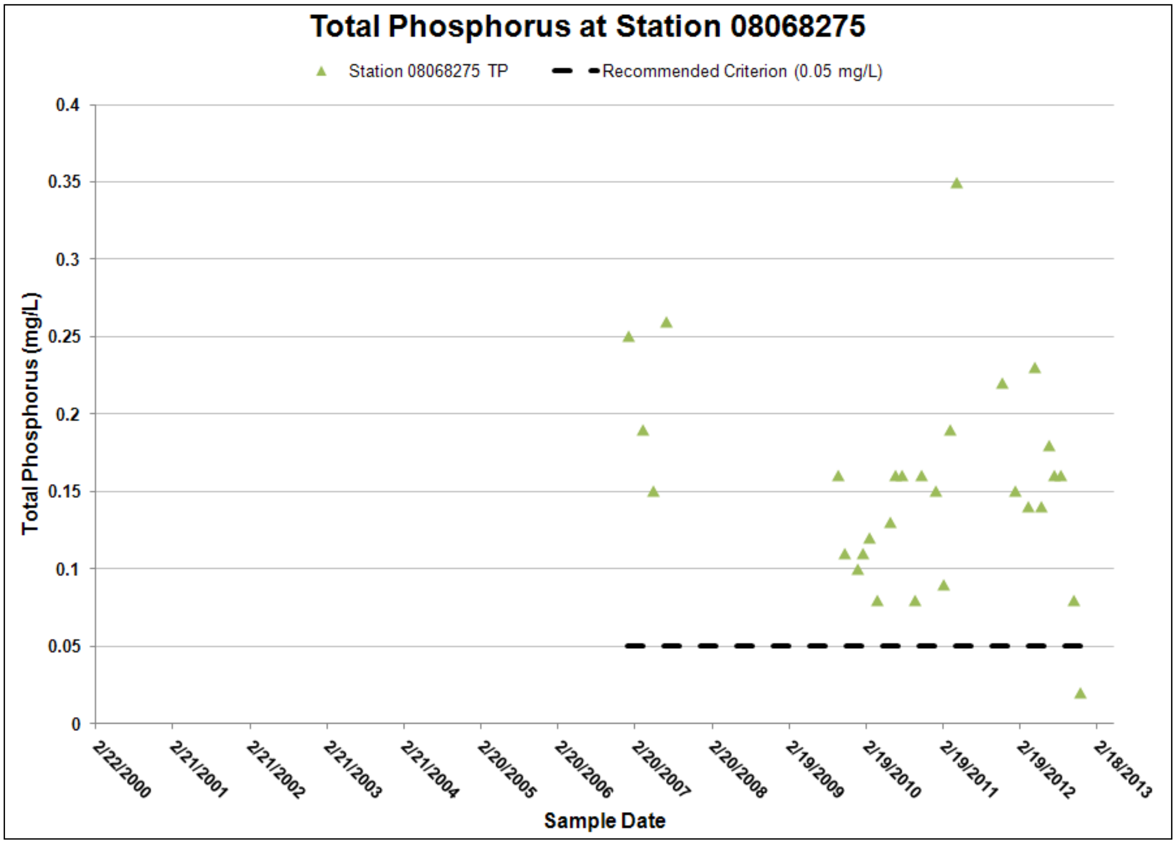

Figure 5-18: Total phosphorus concentrations over time at the terminus of AU 1008-02.

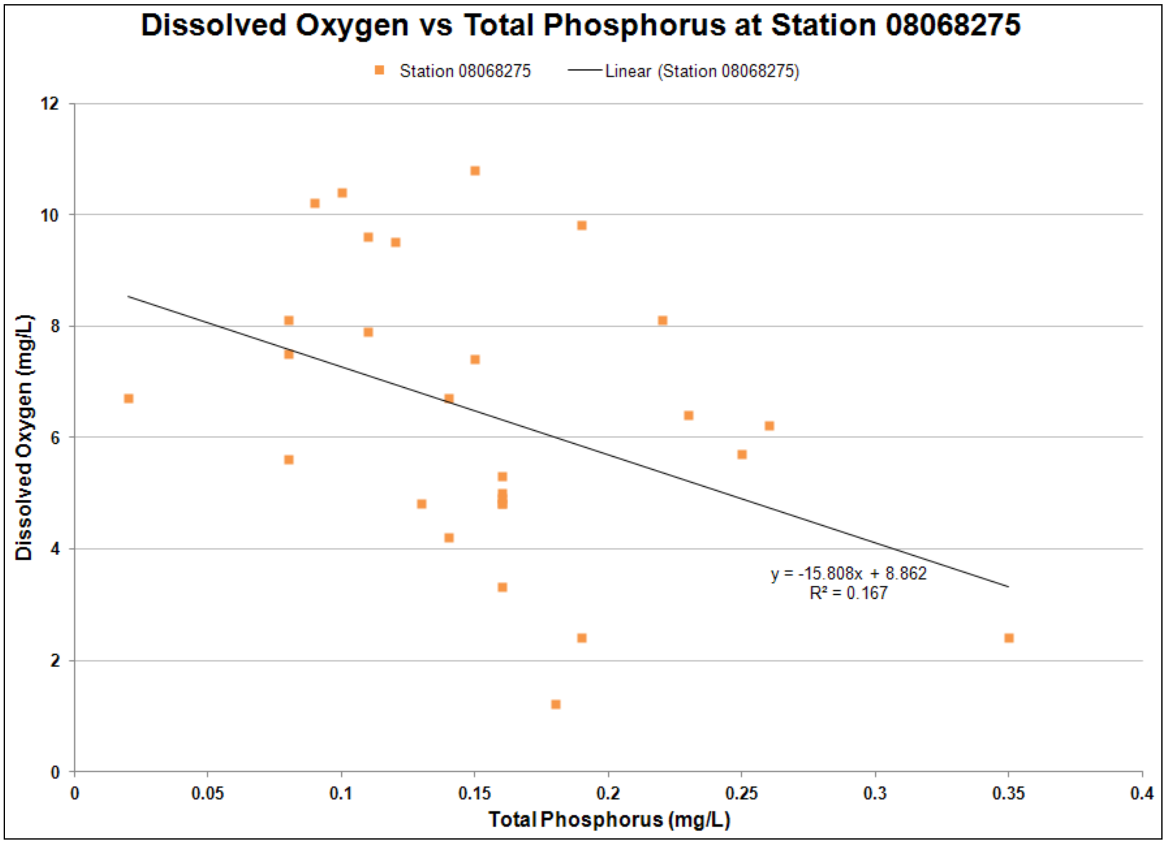

Figure 5-19: Dissolved oxygen and total phosphorus correlation at the terminus of AU 1008-02, representing the AU scale.

From these simple linear regressions, several conclusions can be drawn. First, consideration of multiple spatial scales is important because parameters may not hold the same relationship across different spatial scales. For example, the DO and TP correlation on the AU scale depicts the relationship expected, that higher concentrations of TP correlate to lower concentrations of DO, or that TP may be related to depleted DO within the assessment unit. However, DO and TP correlations on both the river basin and stream segment scales indicate a slightly positive relationship between TP and DO, that as TP concentrations increase, DO concentrations also increase. While this result is not expected based on the simple relationship between excess nutrients and reduced DO, there may be other factors with greater influence on DO concentrations on these scales. For example, it may be possible that dilution of TP on the stream and basin scales is sufficient to minimize DO depletion. Further, flow rates and/or turbulence downstream may be sufficient such that waters become aerated sufficiently so that TP has little influence on DO. Alternatively, suspended sediment loads, to which TP may absorb, may have sufficient settling as waters move downstream. Regardless of the cause(s), consideration of parameter correlation at various spatial scales can provide insight into other processes that may be influencing water quality.

Secondly, the AU-scale TP and DO relationship depicted here indicates that the AU is an appropriate scale on which to regulate nutrients. While boundaries between assessment units theoretically reflect changes in hydrology, this synthetic designation used in management and regulation of water quality does not always represent boundaries between hydrologically distinct units. However, the relationship between TP and DO on the AU scale underscores that AU-based management decisions are appropriate for this particular water body. This linear regression approach applied through GENESIS, therefore, can inform water quality management decisions.

As part of the GENESIS framework, Excel can also be used for the development of FDCs and LDCs. FDCs are useful for characterizing the frequency of flows occurring in a stream segment, and they depict average daily streamflow versus the percent of time that a specific magnitude of flow is exceeded. In this case study, daily mean flow data in the form of discharge (cubic feet per second, cfs) was downloaded from the USGS online NWIS database and imported into MS Excel. The years 1999 to 2012 were chosen as the period of interest so that a flow record exceeding one decade would to take into account potential flow fluctuations caused by drought and other short-term hydrologic influences. Using the PERCENTRANK function in Excel, a percentile for each datapoint as a percent of the dataset (1999 – 2012) was generated. Then, the flow exceedance was calculated by subtracting the percent rank from 100% to determine the frequency with which the specified flow rate would be exceeded. An FDC was then generated by ordering the data from smallest to largest and graphing the percentiles and corresponding flow values (inset, Figure 5-20).

An LDC was generated by multiplying the regulated criterion in the form of concentration, or mass per volume, by flow (volume per time) to create graphs of mass per time for each parameter of interest. Because a numeric criterion for total phosphorus is not yet available for Texas, a recommended value of 0.05 mg/L was used for illustrative purposes (Vieux and Moreda 2003). For instantaneous dissolved oxygen, however, LDCs are not applicable because a range of values is appropriate. In this case, DO concentrations were compared to 3.0 mg/L to determine if concentrations ever fell below it, as this value is the minimum value allowed for classified freshwater segments with high or intermediate aquatic use in Texas (TCEQ 2010). This graph, Figure 5-21, shows that the DO concentrations were below the minimum criteria in six measurements, so further analysis of TP was of interest to determine whether there was a relationship between DO depletion and TP. An LDC for TP was then developed and monitoring data were added (Figure 5-22). Figure 5-22 shows that TP loads are consistently in excess of recommended daily loads when varying flow regimes are considered.

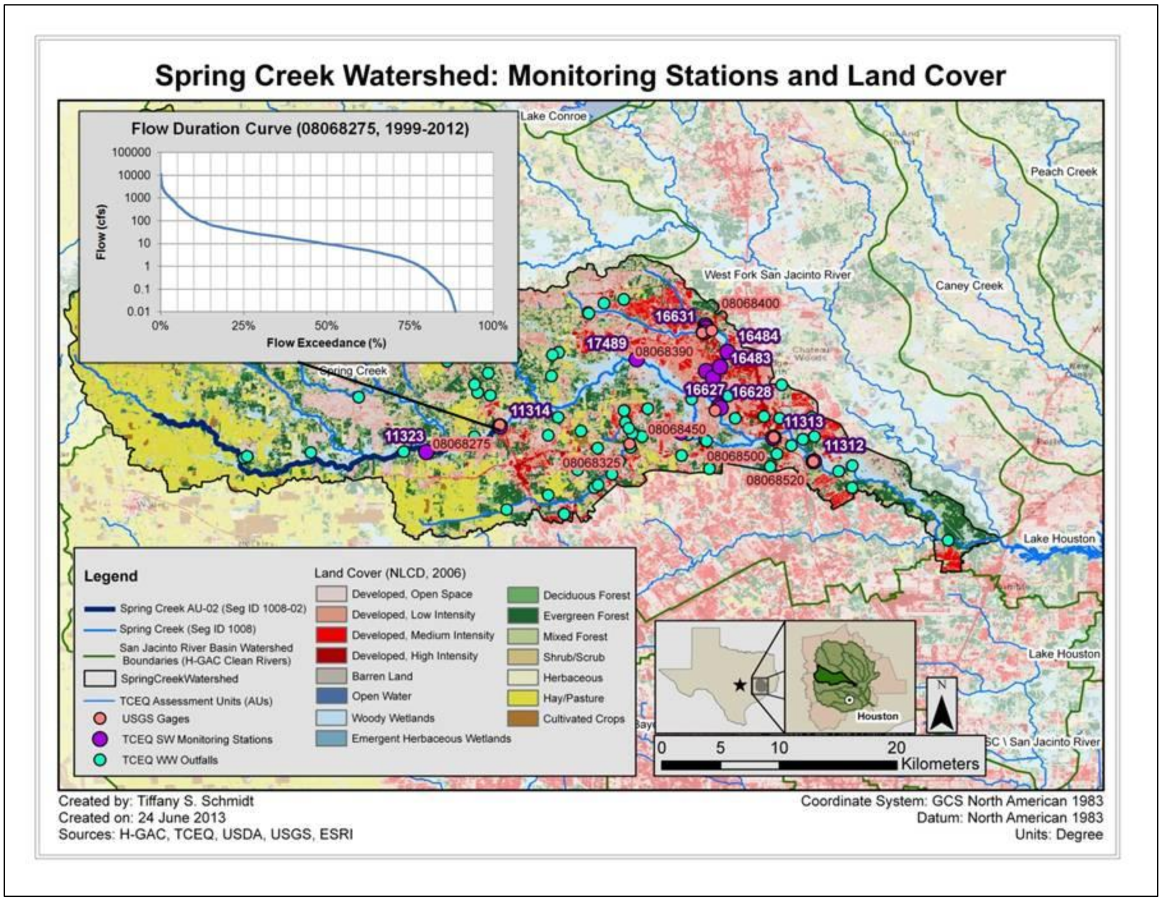

Figure 5-20: Flow duration curve for 1999-2012 at USGS station 08068275, located at the terminus of AU 1008-02.

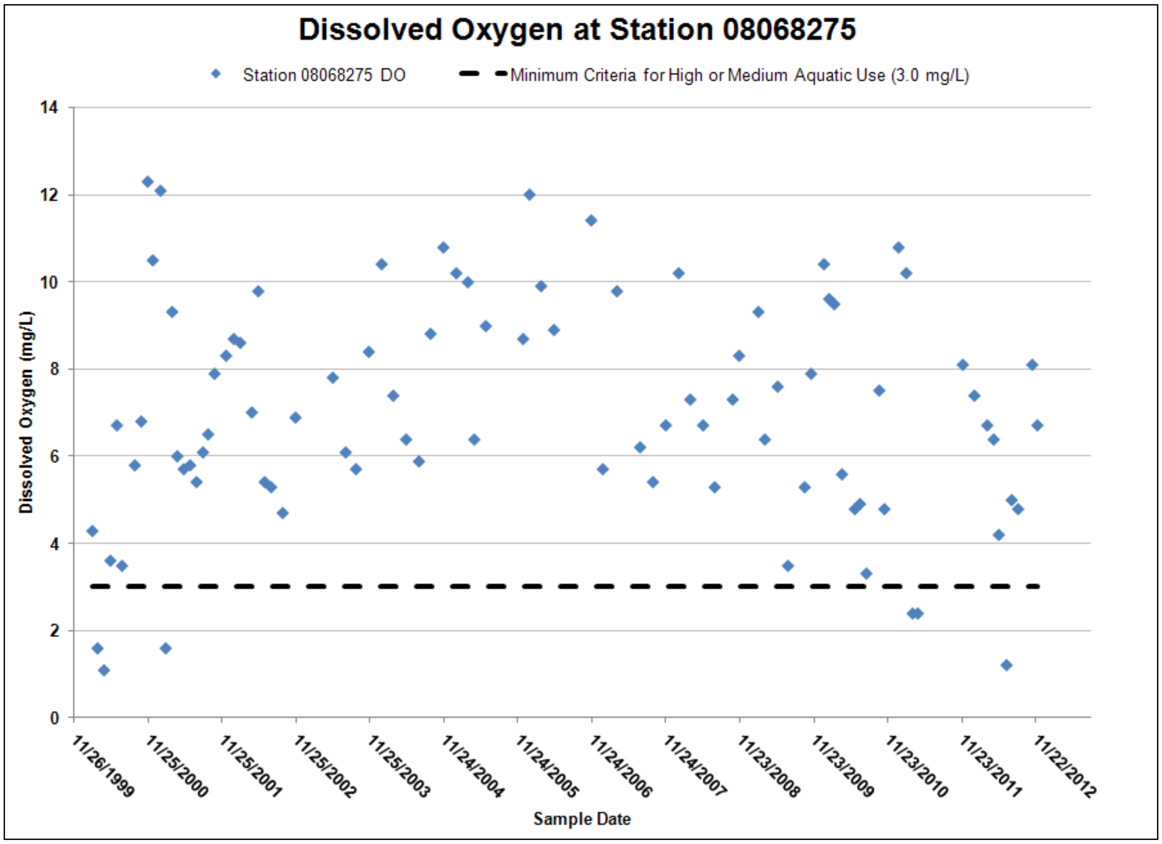

Figure 5-21: Dissolved oxygen for 1999-2012 at USGS station 08068275, located at the terminus of AU 1008-02, compared to the minimum criteria for high or medium aquatic use (3.0 mg/L).

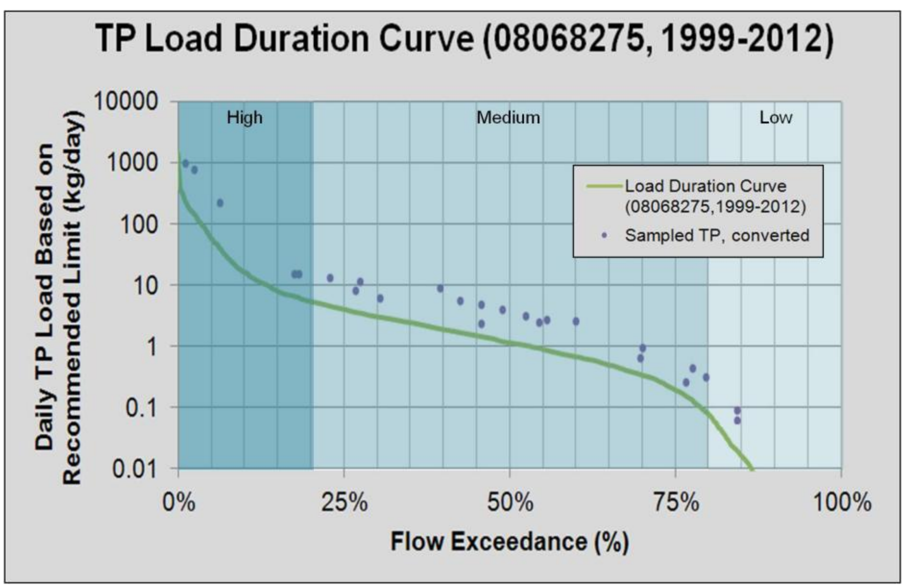

Figure 5-22: Load duration curve for total phosphorus for 1999-2012 at USGS station 08068275, located at the terminus of AU 1008-02.

Despite the ability to generate FDCs and LDCs manually, this process can be automated. Existing tools, such as LDCurve (Johnson, Whiteaker et al. 2009), may be used as well as user-specific developed spreadsheet tools using visual basic code and a webscraper. The GENESIS framework seeks to minimize manual, repetitive data processing and model input preparation and therefore recommends decision-makers incorporate such tools.

The value of the GENESIS framework is further demonstrated by linking the correlation between TP and DO on the AU scale (Figure 5-19) to land cover change in the Spring Creek watershed. To begin, a geodatabase containing land cover changes from 1992 to 2011 was downloaded from H-GAC's GIS Clearinghouse website. The land cover change raster, depicting land cover changes from 1992 NLCD to NOAA 2011 data, was then loaded into ArcMap and geoprocessed. To gain a sense for overall land cover change in the entire river basin, a map was created depicting land cover change across the San Jacinto River Basin (Figure 5-23). Zero change in land cover classification in the San Jacinto River Basin is depicted as gray cells. Other colors symbolize change from a particular land cover class to various other classes. For example, dark red indicates areas forested in 1992 changed to any other cover type (such as developed, cultivated, or wetlands) in 2011. A map was also created to show land cover change in the Spring Creek watershed using the same symbology (Figure 5-24).

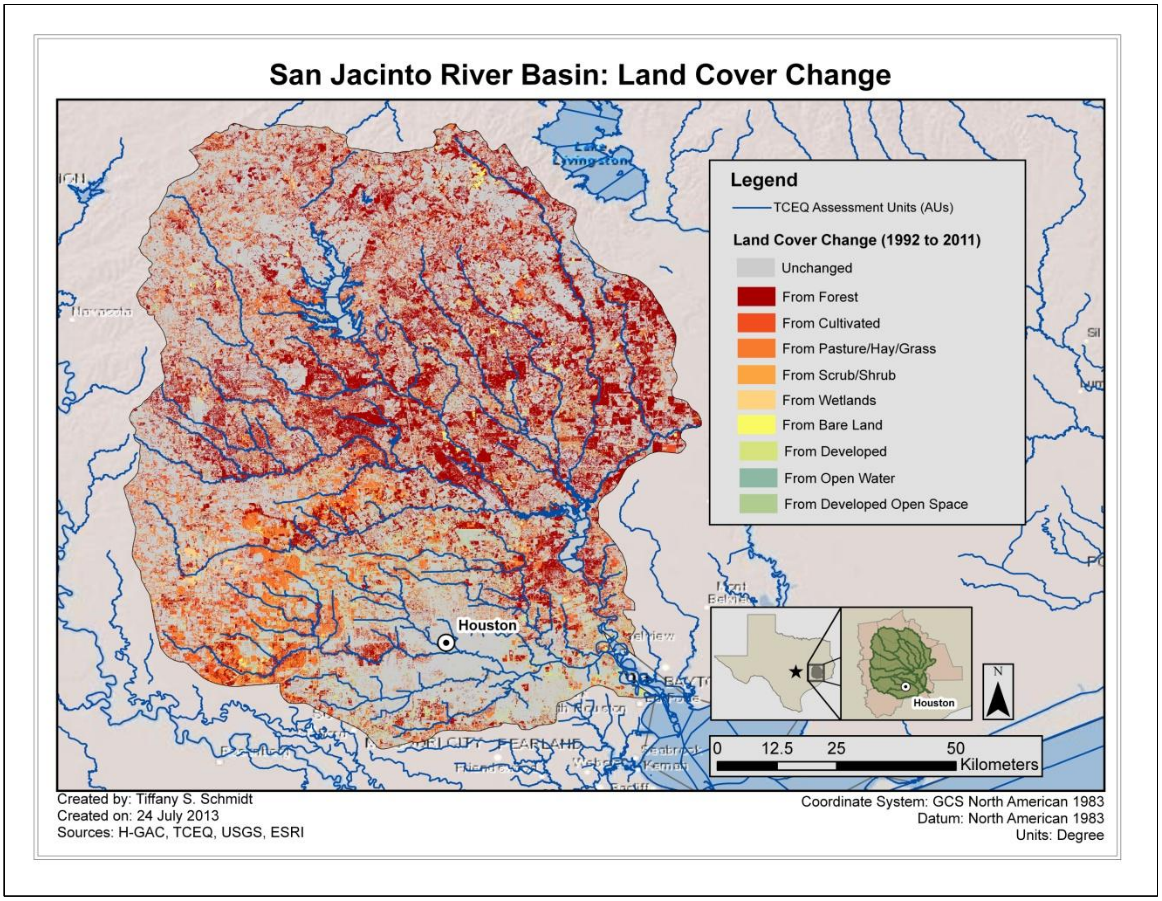

Figure 5-23: Land cover change between 1992 and 2011 in the San Jacinto River Basin.

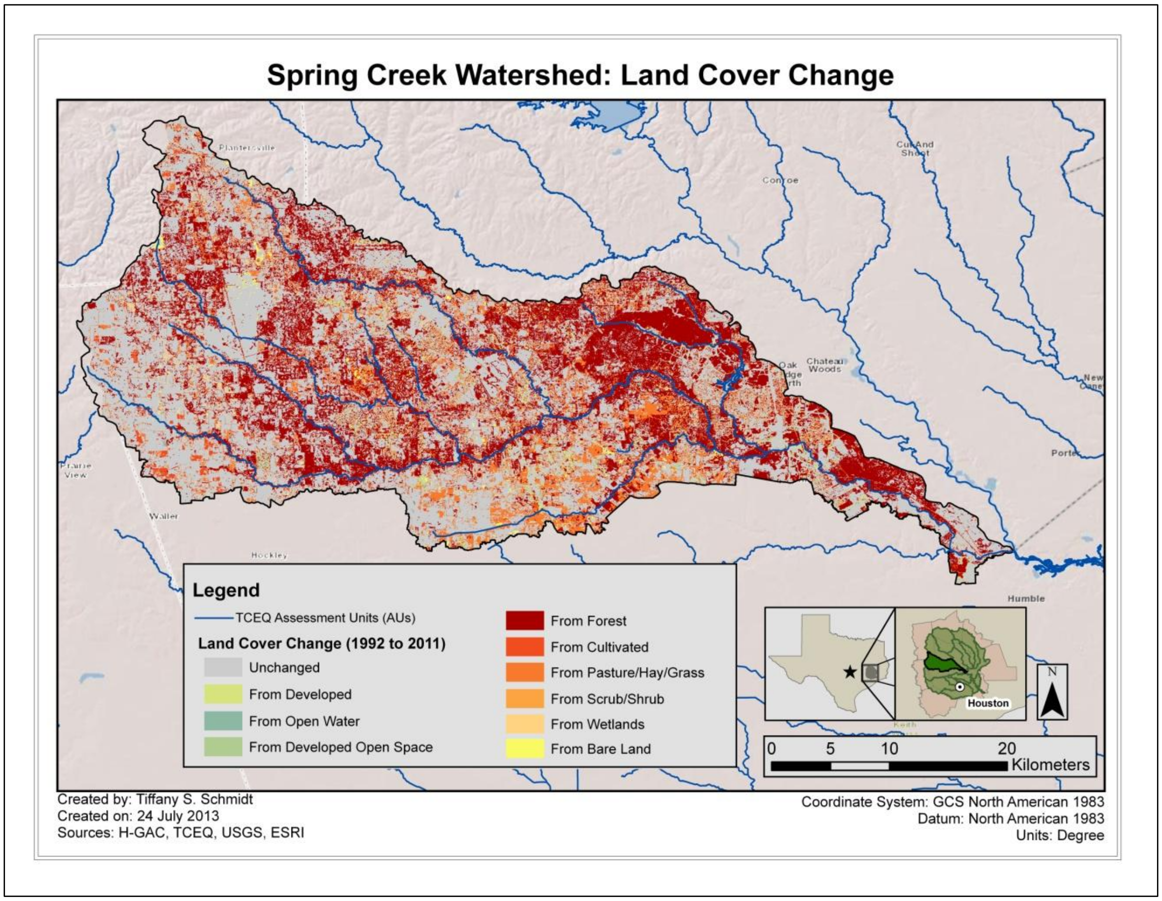

Figure 5-24: Land cover change between 1992 and 2011 in the Spring Creek Watershed.

To further investigate land cover change in the Spring Creek watershed, a map was created depicting removal of forested areas (i.e., land cover change from forest to any other category) because the literature reviewed in Section 3.3.1 indicated that presence of riparian buffers influences nutrients and forests aid in nutrient and soil retention (Figure 5-25). As part of the forest removal investigation, the area of land cover changed from forest was calculated in ArcMap. The summed results appear in Table 5-2. This type of geospatial calculation is possible in the GENESIS framework, and the output values can serve as input into other water quality studies or other models. For example, land cover maps can be merged with subbasin or subwatershed boundaries such that land use percentages for each hydrologic unit can be developed as input for models. Similarly, other geospatial data such as soil maps can be used to generate soil types or infiltration variables that would be input into hydrologic models. In this way, GENESIS facilitates the development of datasets that can be used as input for the analysis and modeling category of TMDL development and water quality studies, all while allowing spatial visualization of monitored and other geospatial data.

In this demonstration, Figure 5-25 represents potentially increased nutrient loads into watershed streams associated with land cover change from forest. There are two particular observations of interest from this figure. The first is the observed removal of concentrated areas of forest (presumably riparian buffer) along the AU of interest. The second is that areas changing from forest to pasture/hay/grass in the western portions of the watershed, which serve as the catchment areas for the AU of interest, may indicate not only nutrient and soil losses into the streams but also additional nutrient loads stemming from runoff of fertilizer application. To consider land cover changes potentially decreasing nutrient loads into streams, a map was created depicting the addition of forest in the Spring Creek watershed (Figure 5-26). This information, paired with the summed area calculations in Table 5-2, indicates an overall loss of forest across the entire watershed.

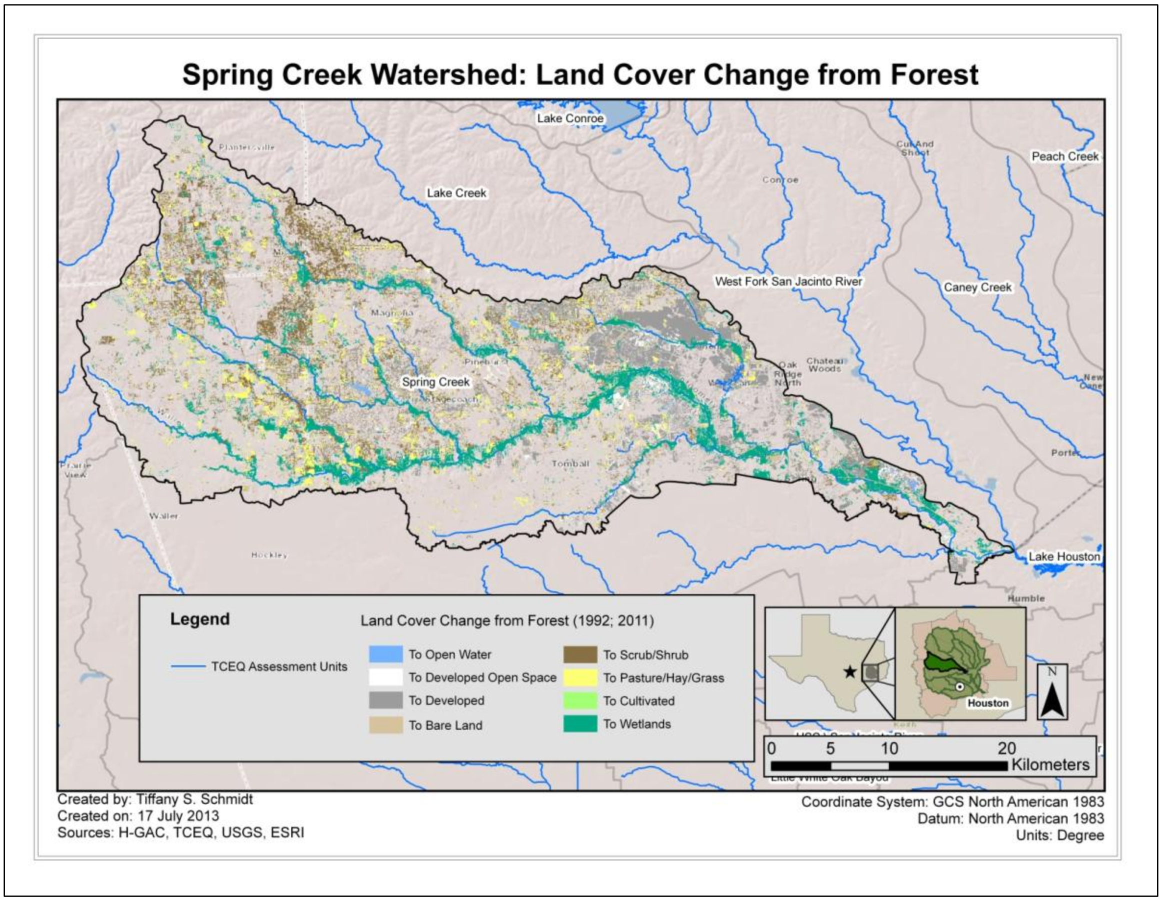

Figure 5-25: Land cover change from forest to other categories between 1992 and 2011 in the Spring Creek watershed.

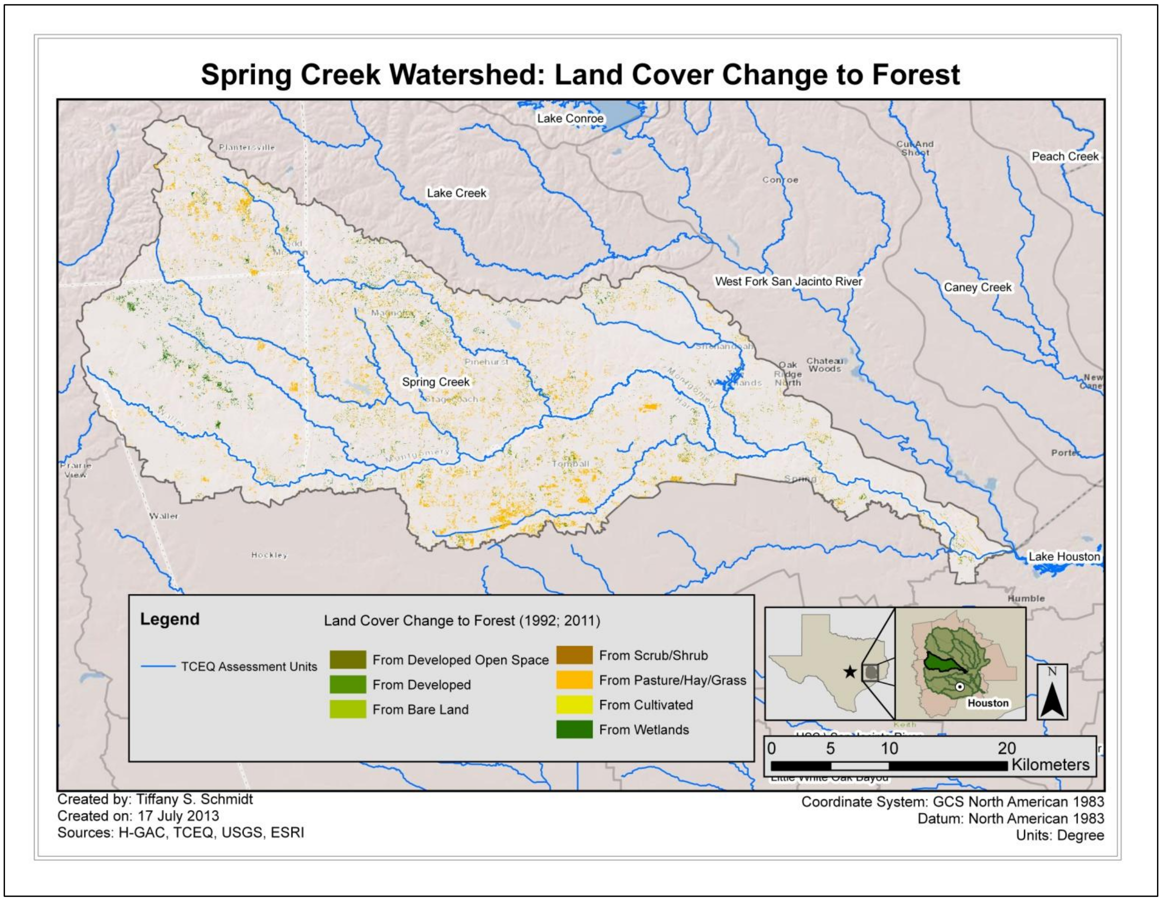

Figure 5-26: Land cover change to forest from other categories between 1992 and 2011 in the Spring Creek watershed.

Table 5-2: Land cover change area calculations in the Spring Creek watershed.

Land Cover Change (1992 to 2011)	Area (acres)
From Forest	**89,373.21**
To Open Water	1,041.72
To Developed Open Space	4,340.45
To Developed	22,910.26
To Bare Land	1,407.95
To Scrub / Shrub	23,742.03
To Pasture / Hay / Grass	14,604.07
To Cultivated	30.91
To Wetlands	21,295.82
To Forest (Sum)	**14,236.36**
From Developed Open Space	102.39
From Developed	879.36
From Bare Land	54.71
From Scrub / Shrub	3.11
From Pasture / Hay / Grass	10,524.39
From Cultivated	68.22
From Wetlands	2,604.18

Land cover change between 1992 and 2011 can be better understood at the AU scale by considering DO and TP concentrations in AU 1008-02 in the Spring Creek watershed. While datapoints are few during these timeframes, the DO concentrations in 2011 show a wider range than those in 1992, with the lowest measurement being below the 3.0 mg/L criteria (Figure 5-27). The range of TP concentrations in 2011 is also wider than the range of TP concentrations in 1992, with the maximum concentration in 2011 being over twice as high as the maximum in 1992 (Figure 5-28). Further, the TP and DO correlation for 1992 and 2011 measurements (Figure 5-29) depicts an inverse correlation between TP and DO; as TP increases, DO decreases. This relationship was also observed for a wider range of timeframes at the same station (Figure 5-19). This finding supports the possibility that a net loss of forested land cover in the Spring Creek watershed between 1992 and 2011 can be correlated to decreased concentrations in DO on the AU scale, leading to impairment of AU 1008-02. This finding suggests that water quality management decisions for AU 1008-02 should consider watershed-scale changes in land cover such as forest that may influence the retention of nutrients. Further, management decisions could include increasing such land cover acreage, specifically increasing or restoring riparian buffer coverage along AUs impaired due to excess nutrients, in attempt to minimize nutrient loads into the surface water body.

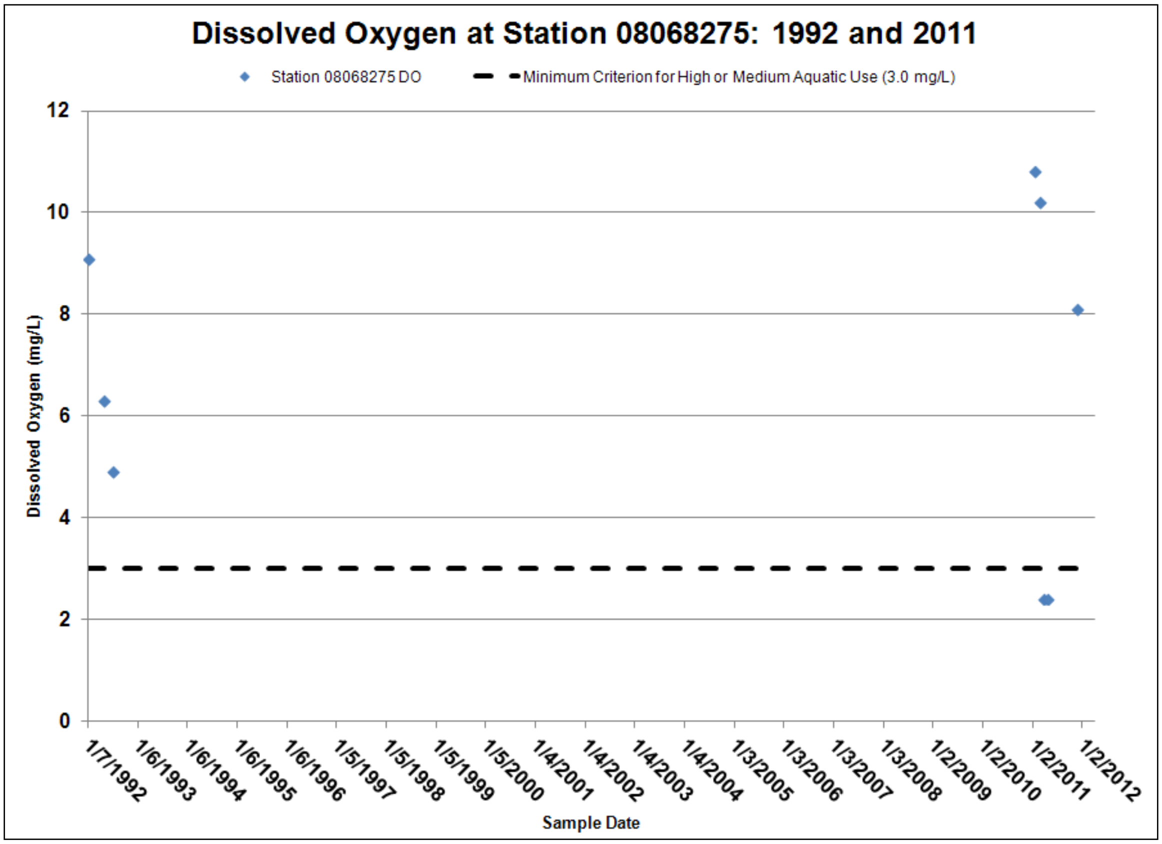

Figure 5-27: Dissolved oxygen in 1992 and in 2011 at USGS station 0806825, located at the terminus of AU 1008-02.

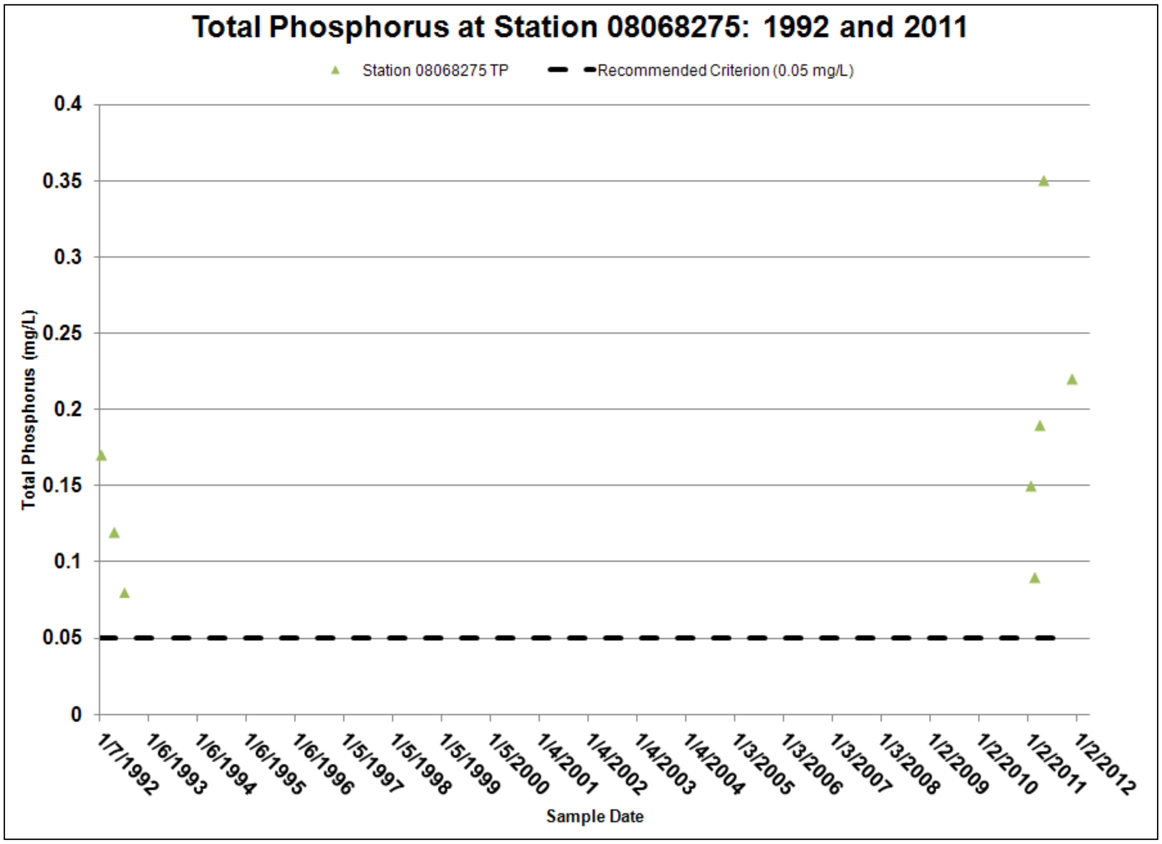

Figure 5-28: Total phosphorus concentrations in 1992 and 2011 at USGS station 0806825, located at the terminus of AU 1008-02.

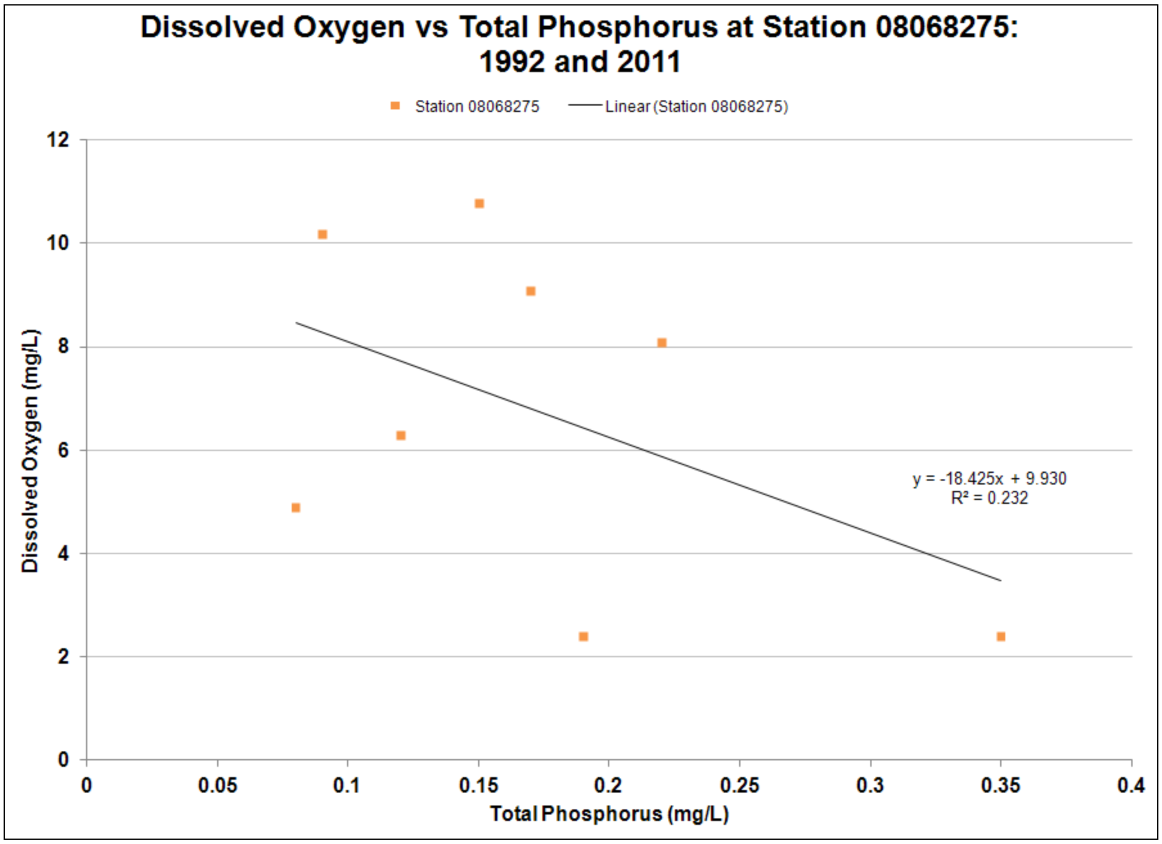

Figure 5-29: Dissolved oxygen and total phosphorus correlation at USGS Station 08068275, located at the terminus of AU 1008-02.

Depicting land cover change simultaneously with water quality information can aid decision-makers in making water quality management decisions. In this demonstration of GENESIS, land cover change in the Spring Creek watershed between 1992 and 2011 can be viewed alongside water quality data, such as nutrient concentrations. This information, along with linear regression modeling, FDCs, and LDCs, can be used to inform water quality management decisions.

CHAPTER 6 – CONCLUSIONS

This thesis addresses the gap in user friendly tools that aid decision-makers in understanding nutrient sources, their fate and transport in watersheds, and their role in associated ecological resources such that they can manage and control nutrients at multiple scales. This work was achieved by developing a framework and methodology that take into account environmental data across multiple geospatial scales, ranging from the assessment unit to the river basin scale, as well as multiple temporal scales. The developed framework, GENESIS, is a geospatial decision support system that allows the incorporation of geospatial datasets and analysis and modeling tools as well as open-source visualization tools such as Google Earth.

This work demonstrated this geospatial framework and its usefulness for water quality studies, TMDLs, management, and regulation by examining the relationships between DO and TP on the river basin, watershed, and AU geospatial scales. Varying temporal scales were also considered. Further, land cover change over time and DO and TP data were paired in order to provide additional insights that could be used in water quality and land cover management decisions.

This demonstration underscores the importance of harnessing the capabilities offered by recent computer technologies, GIS, databases, visualization techniques, remote sensing, and web resources. This demonstration also highlights the need for restructuring environmental and monitoring databases such that they lend themselves to being fully searchable geospatially and therefore easily accessed in the GENESIS framework. Jurisdictional entities can further enhance their systems to allow sharing and cross-coordination thus facilitating transfer of information between as well as promoting understanding of water quality considerations among many stakeholders.

The GENESIS framework developed possesses both positive and negative aspects. Its strengths lie in its flexibility and corresponding ability to be continuously updated as more data becomes available or as management strategies change. Additionally, the open architecture approach allows adaptation to changing technology and water quality management paradigms. The negative aspect of the framework is its limitation in handling migration of large datasets to cloud-based storage. While some users might consider the lack of automation within GENESIS a negative aspect, this feature (or lack of feature) was intentional during development in order to prevent GENESIS from quickly becoming obsolete. Rather, visualization tools other than Google Earth may be incorporated as technology continues to change.

Overall, the GENESIS GDSS framework and Google Earth visualization feature provide a visually appealing and geospatially informed methodology for applying modeling and analysis tools. Simple, easy to use and understand models and analysis tools are amenable to data sharing and stakeholder communication and decision-making. Furthermore, the flexibility of geographic scale in GENESIS promotes its usefulness when evaluating nutrients at different spatial scales. Incorporating mid-level complexity modeling tools such as regression-based modeling, as in GENESIS, expands the toolbox and facilitates decision-making, data sharing, and accessibility of information to stakeholders and decision-makers.

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APPENDIX I: TEXAS TOTAL MAXIMUM DAILY LOADS FROM EPA ATTAINS DATABASE

Region	State	TMDL ID	TMDL Name	TMDL Status	TMDL Submittal Date	Pollutant Name	TMDL Type	Total Waste Load Allocation (WLA)	WLA Units
6	TX	32996	ADAMS BAYOU TIDAL TMDL	Approved / Established	20-Jul-07	AMMONIA NITROGEN	POINT/NONPOINT SOURCE	14	Not given
6	TX	32996	ADAMS BAYOU TIDAL TMDL	Approved / Established	20-Jul-07	CARBONACEOUS BOD	POINT/NONPOINT SOURCE	29	Not given
6	TX	32996	ADAMS BAYOU TIDAL TMDL	Approved / Established	20-Jul-07	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	10	Not given
6	TX	9670	AQUILLA RESERVOIR	Approved / Established	12-Apr-01	DDE	POINT SOURCE	22	Not given
6	TX	36181	BEAR CREEK 1014A_01 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	164,000,000,000	CFU/DAY
6	TX	41935	BENSONS BAYOU 1103A_01 ENTEROCOCCUS TMDL	Approved / Established	22-Mar-12	ENTEROCOCCUS BACTERIA	POINT/NONPOINT SOURCE	4,250,000,000	BCFU/DAY
6	TX	39289	BERRY BAYOU ABOVE TIDAL 1007F_01 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	155	BCFU/DAY
6	TX	39287	BIG GULCH ABOVE TIDAL 1006F_01 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	9	BCFU/DAY
6	TX	41936	BORDENS GULLY 1103B_01 ENTEROCOCCUS TMDL	Approved / Established	22-Mar-12	ENTEROCOCCUS BACTERIA	POINT/NONPOINT SOURCE	564,000,000	BCFU/DAY
6	TX	39308	BRAYS BAYOU ABOVE TIDAL 1007B_01 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	2,264	BCFU/DAY
6	TX	39309	BRAYS BAYOU ABOVE TIDAL 1007B_02 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	151	BCFU/DAY
6	TX	36202	BRICKHOUSE GULLY 1017A_01 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	157,000,000,000	CFU/DAY
6	TX	36182	BUFFALO BAYOU 1014B_01 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	531,000,000,000	CFU/DAY
6	TX	36180	BUFFALO BAYOU ABOVE TIDAL 1014_01 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	874,000,000,000	CFU/DAY
6	TX	36177	BUFFALO BAYOU TIDAL 1013_01 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	268,000,000,000	CFU/DAY
6	TX	42528	BURTON CREEK E. COLI TMDL	Approved / Established	21-Sep-12	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	153	BCFU/DAY
6	TX	40548	CANEY CREEK 1010_02 E. COLI TMDL	Approved / Established	3-May-11	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	16	BCFU/DAY
6	TX	40549	CANEY CREEK 1010_04 E. COLI TMDL	Approved / Established	13-May-11	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	39	BCFU/DAY
6	TX	42529	CARTERS CREEK TX-1209C_01 E. COLI TMDL	Approved / Established	21-Sep-12	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	317	BCFU/DAY
6	TX	40797	CEDAR CREEK 0805_04 E. COLI TMDL	Approved / Established	23-May-11	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	1,480	BCFU/DAY
6	TX	35921	CHIGGER CREEK 1101B_01 E. COLI TMDL	Approved / Established	17-Oct-08	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	7,140,000,000	CFU/DAY
6	TX	35922	CHIGGER CREEK 1101B_02 ENTEROCOCCUS TMDL	Approved / Established	17-Oct-08	ENTEROCOCCUS BACTERIA	POINT SOURCE	680,000,000,000	CFU/DAY
6	TX	4211	CLEAR CREEK ABOVE TIDAL	Approved / Established	5-Mar-01	1,1,2-TRICHLOROETHANE	POINT/NONPOINT SOURCE	0	
6	TX	4211	CLEAR CREEK ABOVE TIDAL	Approved / Established	5-Mar-01	1,2-DICHLOROETHANE	POINT/NONPOINT SOURCE	0	
6	TX	35925	CLEAR CREEK ABOVE TIDAL 1102_01 E. COLI TMDL	Approved / Established	17-Oct-08	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	11,100,000,000	CFU/DAY
6	TX	35926	CLEAR CREEK ABOVE TIDAL 1102_02 E. COLI TMDL	Approved / Established	17-Oct-08	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	4,000,000,000	CFU/DAY

Region	State	TMDL ID	TMDL Name	TMDL Status	TMDL Submittal Date	Pollutant Name	TMDL Type	Total Waste Load Allocation (WLA)	WLA Units
6	TX	35927	CLEAR CREEK ABOVE TIDAL 1102_03 E. COLI TMDL	Approved / Established	17-Oct-08	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	50,500,000,000	CFU/DAY
6	TX	35928	CLEAR CREEK ABOVE TIDAL 1102_04 E. COLI TMDL	Approved / Established	17-Oct-08	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	692,000,000	CFU/DAY
6	TX	35930	CLEAR CREEK ABOVE TIDAL 1102_05 ENTEROCOCCUS TMDL	Approved / Established	17-Oct-08	ENTEROCOCCUS BACTERIA	POINT/NONPOINT SOURCE	1,630,000,000,000	MCFU/DAY
6	TX	4210	CLEAR CREEK TIDAL	Approved / Established	5-Mar-01	1,1,2-TRICHLOROETHANE	POINT/NONPOINT SOURCE	0	
6	TX	4210	CLEAR CREEK TIDAL	Approved / Established	5-Mar-01	1,2-DICHLOROETHANE	POINT/NONPOINT SOURCE	0	
6	TX	35918	CLEAR CREEK TIDAL 1101_01 ENTEROCOCCUS TMDL	Approved / Established	17-Oct-08	ENTEROCOCCUS BACTERIA	POINT/NONPOINT SOURCE	1,310,000,000,000	CFU/DAY
6	TX	35918	CLEAR CREEK TIDAL 1101_01 ENTEROCOCCUS TMDL	Approved / Established	17-Oct-08	ENTEROCOCCUS BACTERIA	POINT/NONPOINT SOURCE	1,310,000,000,000	MCFU/DAY
6	TX	35919	CLEAR CREEK TIDAL 1101_02 ENTEROCOCCUS TMDL	Approved / Established	17-Oct-08	ENTEROCOCCUS BACTERIA	POINT/NONPOINT SOURCE	7,000,000,000	CFU/DAY
6	TX	35920	CLEAR CREEK TIDAL 1101_03 ENTEROCOCCUS TMDL	Approved / Established	17-Oct-08	ENTEROCOCCUS BACTERIA	POINT/NONPOINT SOURCE	3,070,000,000,000	CFU/DAY
6	TX	35920	CLEAR CREEK TIDAL 1101_03 ENTEROCOCCUS TMDL	Approved / Established	17-Oct-08	ENTEROCOCCUS BACTERIA	POINT/NONPOINT SOURCE	3,070,000,000,000	MCFU/DAY
6	TX	36203	COLE CREEK 1017B_02 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	103,000,000,000	CFU/DAY
6	TX	32225	COLORADO RIVER BELOW E. V. SPENCE RESERVOIR TMDL FOR CL AND TDS	Approved / Established	9-Mar-07	CHLORIDE	POINT/NONPOINT SOURCE	5,700	LBS/DAY
6	TX	32225	COLORADO RIVER BELOW E. V. SPENCE RESERVOIR TMDL FOR CL AND TDS	Approved / Established	9-Mar-07	TOTAL DISSOLVED SOLIDS (TDS)	POINT/NONPOINT SOURCE	15,900	LBS/DAY
6	TX	33038	COON BAYOU TMDL	Approved / Established	20-Jul-07	AMMONIA NITROGEN	POINT/NONPOINT SOURCE	5	Not given
6	TX	33038	COON BAYOU TMDL	Approved / Established	20-Jul-07	CARBONACEOUS BOD	POINT/NONPOINT SOURCE	3	Not given
6	TX	33038	COON BAYOU TMDL	Approved / Established	20-Jul-07	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	10	Not given
6	TX	41764	COTTONWOOD BRANCH 0822A_02 TMDL FOR E.. COLI	Approved / Established	12-Mar-12	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	158	BCFU/DAY
6	TX	39293	COUNTRY CLUB BAYOU 1007K_01 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	37	BCFU/DAY
6	TX	42527	COUNTRY CLUB BRANCH E. COLI TMDL	Approved / Established	21-Sep-12	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	5	BCFU/DAY
6	TX	33048	COW BAYOU ABOVE TIDAL	Approved / Established	20-Jul-07	AMMONIA NITROGEN	POINT/NONPOINT SOURCE	5	Not given
6	TX	33048	COW BAYOU ABOVE TIDAL	Approved / Established	20-Jul-07	CARBONACEOUS BOD	POINT/NONPOINT SOURCE	103	Not given
6	TX	33049	COW BAYOU TIDAL TMDL	Approved / Established	20-Jul-07	AMMONIA NITROGEN	POINT/NONPOINT SOURCE	22	Not given
6	TX	33049	COW BAYOU TIDAL TMDL	Approved / Established	20-Jul-07	CARBONACEOUS BOD	POINT/NONPOINT SOURCE	420	Not given
6	TX	33049	COW BAYOU TIDAL TMDL	Approved / Established	20-Jul-07	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	18	Not given
6	TX	35931	COWART CREEK 1102A_01 E. COLI TMDL	Approved / Established	17-Oct-08	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	24,300,000,000	CFU/DAY
6	TX	35932	COWART CREEK 1102A_02 ENTEROCOCCUS TMDL	Approved / Established	17-Oct-08	ENTEROCOCCUS BACTERIA	POINT SOURCE	152,000,000,000	CFU/DAY
6	TX	40540	CYPRESS CREEK 1009_01 E. COLI TMDL	Approved / Established	3-May-11	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	69	BCFU/DAY

Region	State	TMDL ID	TMDL Name	TMDL Status	TMDL Submittal Date	Pollutant Name	TMDL Type	Total Waste Load Allocation (WLA)	WLA Units
6	TX	40542	CYPRESS CREEK 1009_02 E. COLI TMDL	Approved / Established	3-May-11	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	201	BCFU/DAY
6	TX	40543	CYPRESS CREEK 1009_03 E. COLI TMDL	Approved / Established	3-May-11	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	441	BCFU/DAY
6	TX	40544	CYPRESS CREEK 1009_04 E. COLI TMDL	Approved / Established	3-May-11	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	516	BCFU/DAY
6	TX	51281	Clear Creek and Tributaries Watershed nps/ps	Approved / Established	6-Feb-13	ENTEROCOCCUS BACTERIA	POINT/NONPOINT SOURCE	7	BCFU/DAY
6	TX	51281	Clear Creek and Tributaries Watershed nps/ps	Approved / Established	6-Feb-13	ESCHERICHIA COLI (E. COLI)	POINT SOURCE	46	BCFU/DAY
6	TX	41938	DICKINSON BAYOU ABOVE TIDAL 1104_01 E. COLI TMDL	Approved / Established	22-Mar-12	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	4,030,000,000	BCFU/DAY
6	TX	41945	DICKINSON BAYOU ABOVE TIDAL 1104_02 ENTEROCOCCUS TMDL	Approved / Established	22-Mar-12	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	4,650,000,000	BCFU/DAY
6	TX	41946	DICKINSON BAYOU TIDAL 1103_02 ENTEROCOCCUS TMDL	Approved / Established	22-Mar-12	ENTEROCOCCUS BACTERIA	POINT/NONPOINT SOURCE	7,390,000,000	BCFU/DAY
6	TX	41921	DICKINSON BAYOU TIDAL 1103_03 ENTEROCOCCUS TMDL	Approved / Established	22-Mar-12	ENTEROCOCCUS BACTERIA	POINT/NONPOINT SOURCE	36,000,000,000	BCFU/DAY
6	TX	41920	DICKINSON BAYOU TIDAL 1103_04 ENTEROCOCCUS TMDL	Approved / Established	22-Mar-12	ENTEROCOCCUS BACTERIA	POINT/NONPOINT SOURCE	17,200,000,000	BCFU/DAY
6	TX	4190	EV SPENCE RESERVOIR	Approved / Established	13-Dec-00	SULFATES	POINT/NONPOINT SOURCE	10	TONS/DAY
6	TX	4190	EV SPENCE RESERVOIR	Approved / Established	13-Dec-00	TOTAL DISSOLVED SOLIDS (TDS)	POINT/NONPOINT SOURCE	45	TONS/DAY
6	TX	40545	FAULKEY GULLY 1009C_01 E. COLI TMDL	Approved / Established	3-May-11	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	16	BCFU/DAY
6	TX	40796	FIVEMILE CREEK 0805_03 E. COLI TMDL	Approved / Established	23-May-11	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	2,600	BCFU/DAY
6	TX	9513	FOURTEEN TOTAL MAXIMUM DAILY LOADS FOR NICKEL IN THE HOUSTON	Approved / Established	1-Sep-00	NICKEL	POINT/NONPOINT SOURCE	101	LBS/DAY
6	TX	39032	GARNERS BAYOU 1016A_02 E. COLI TMDL	Approved / Established	28-Jun-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	182	BCFU/DAY
6	TX	39033	GARNERS BAYOU 1016A_03 E. COLI TMDL	Approved / Established	28-Jun-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	367	BCFU/DAY
6	TX	41937	GEISLER BAYOU 1103C_01 ENTEROCOCCUS TMDL	Approved / Established	22-Mar-12	ENTEROCOCCUS BACTERIA	POINT/NONPOINT SOURCE	1,040,000,000	BCFU/DAY
6	TX	36049	GILLELAND CREEK 1428C BACTERIA TMDL	Approved / Established	31-Aug-07	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	55,500,000,000	CFU/DAY
6	TX	41765	GRAPEVINE CREEK 0822B_01 TMDL FOR E. COLI	Approved / Established	12-Mar-12	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	35	BCFU/DAY
6	TX	39028	GREENS BAYOU ABOVE TIDAL 1016_01 E. COLI TMDL	Approved / Established	28-Jun-10	ESCHERICHIA COLI (E. COLI)	POINT SOURCE	380	BCFU/DAY
6	TX	39030	GREENS BAYOU ABOVE TIDAL 1016_02 E. COLI TMDL	Approved / Established	28-Jun-10	ESCHERICHIA COLI (E. COLI)	POINT SOURCE	972	BCFU/DAY
6	TX	39031	GREENS BAYOU ABOVE TIDAL 1016_03 E. COLI TMDL	Approved / Established	28-Jun-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	1,459	BCFU/DAY
6	TX	39283	HALLS BAYOU ABOVE US 59 1006_02 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	265	BCFU/DAY
6	TX	39283	HALLS BAYOU ABOVE US 59 1006_02 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	265	CFU/DAY
6	TX	39282	HALLS BAYOU BELOW US 59 1006D_01 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	437	BCFU/DAY
6	TX	35934	HICKORY SLOUGH 1102C_01 E. COLI TMDL	Approved / Established	17-Oct-08	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	18,500,000,000	CFU/DAY

Region	State	TMDL ID	TMDL Name	TMDL Status	TMDL Submittal Date	Pollutant Name	TMDL Type	Total Waste Load Allocation (WLA)	WLA Units
6	TX	39297	HUNTING BAYOU ABOVE TIDAL 1007R_01	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	22	BCFU/DAY
6	TX	39298	HUNTING BAYOU ABOVE TIDAL 1007R_02 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	30	BCFU/DAY
6	TX	39299	HUNTING BAYOU ABOVE TIDAL 1007R_03 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	159	BCFU/DAY
6	TX	39300	HUNTING BAYOU ABOVE TIDAL 1007R_04 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	212	BCFU/DAY
6	TX	39312	KEEGANS BAYOU ABOVE TIDAL 1007C_01 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	302	BCFU/DAY
6	TX	39290	KUHLMAN GULLY ABOVE TIDAL 1007G_01 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	35	BCFU/DAY
6	TX	36183	LANGHAM CREEK 1014E_01 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	210,000,000,000	CFU/DAY
6	TX	40547	LITTLE CYPRESS CREEK 1009E_01 E. COLI TMDL	Approved / Established	3-May-11	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	13	BCFU/DAY
6	TX	36178	LITTLE WHITE OAK BAYOU 1013A_01 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	234,000,000,000	CFU/DAY
6	TX	35917	LOWER GALVESTON BAY 2439_01 FECAL COLIFORM TMDL	Approved / Established	19-Sep-08	FECAL COLIFORM	POINT/NONPOINT SOURCE	81,800,000,000	CFU/30DAYS
6	TX	35917	LOWER GALVESTON BAY 2439_01 FECAL COLIFORM TMDL	Approved / Established	19-Sep-08	FECAL COLIFORM	POINT/NONPOINT SOURCE	81,800,000,000	CFU/DAY
6	TX	35639	LOWER SAN ANTONIO RIVER 1901_03 E.COLI	Approved / Established	16-Sep-08	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	1,600,000,000	CFU/DAY
6	TX	35641	LOWER SAN ANTONIO RIVER 1901_04 E. COLI	Approved / Established	19-Sep-08	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	11,000,000,000	CFU/DAY
6	TX	35640	LOWER SAN ANTONIO RIVER 1901_05 E. COLI	Approved / Established	19-Sep-08	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	300,000,000	CFU/DAY
6	TX	35933	MARY'S CREEK 1102B_01 E. COLI TMDL	Approved / Established	17-Oct-08	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	166,000,000,000	CFU/DAY
6	TX	36189	MASON CREEK 1014L_01 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	48,800,000,000	CFU/DAY
6	TX	35936	MUD GULLY 1102E_01 FECAL COLIFORM TMDL	Approved / Established	17-Oct-08	FECAL COLIFORM	POINT/NONPOINT SOURCE	120,000,000,000	CFU/DAY
6	TX	36190	NEIMANS BAYOU 1014M_01 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	34,800,000,000	CFU/DAY
6	TX	9682	NORTH BOSQUE RIVER	Approved / Established	13-Mar-01	PHOSPHORUS	POINT/NONPOINT SOURCE		LBS/DAY
6	TX	23011	ONE TMDL FOR DO IN LAKE O' THE PINES	Approved / Established	2-May-06	DISSOLVED OXYGEN	POINT/NONPOINT SOURCE	27,000	Not given
6	TX	12358	ONE TMDL FOR NITRATE-NITROGEN IN THE LOWER SABINAL RIVER	Approved / Established	20-Sep-05	NITROGEN, TOTAL	POINT/NONPOINT SOURCE	42	LBS/DAY
6	TX	34498	OSO BAY 2485 TMDL FOR BACTERIA	Approved / Established	31-Aug-07	ENTEROCOCCUS BACTERIA	POINT/NONPOINT SOURCE	4	TCFU/DAY
6	TX	40550	PEACH CREEK 1011_02 E. COLI TMDL	Approved / Established	3-May-11	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	6	BCFU/DAY
6	TX	32088	PETRONILA CREEK ABOVE TIDAL TMDL FOR CL, SO4, AND TDS	Approved / Established	12-Feb-07	CHLORIDE	POINT/NONPOINT SOURCE	6,900	LBS/DAY
6	TX	32088	PETRONILA CREEK ABOVE TIDAL TMDL FOR CL, SO4, AND TDS	Approved / Established	12-Feb-07	SULFATE	POINT/NONPOINT SOURCE	10	LBS/DAY
6	TX	32088	PETRONILA CREEK ABOVE TIDAL TMDL FOR CL, SO4, AND TDS	Approved / Established	12-Feb-07	TOTAL DISSOLVED SOLIDS (TDS)	POINT/NONPOINT SOURCE	50	LBS/DAY
6	TX	39291	PINE GULLY ABOVE TIDAL 1007H_01 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	10	BCFU/DAY

Region	State	TMDL ID	TMDL Name	TMDL Status	TMDL Submittal Date	Pollutant Name	TMDL Type	Total Waste Load Allocation (WLA)	WLA Units
6	TX	39292	PLUM CREEK ABOVE TIDAL 1007I_01 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	26	BCFU/DAY
6	TX	35923	ROBINSON BAYOU 1101D_01 ENTEROCOCCUS TMDL	Approved / Established	17-Oct-08	ENTEROCOCCUS BACTERIA	POINT/NONPOINT SOURCE	43,900,000,000	CFU/DAY
6	TX	35924	ROBINSON BAYOU 1101D_02 ENTEROCOCCUS TMDL	Approved / Established	17-Oct-08	ENTEROCOCCUS BACTERIA	POINT/NONPOINT SOURCE	35,300,000,000	CFU/DAY
6	TX	36192	RUMMEL CREEK 1014N_01 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	68,500,000,000	CFU/DAY
6	TX	9687	SALADO CREEK	Approved / Established	7-Nov-01	DISSOLVED OXYGEN	POINT/NONPOINT SOURCE	250	LBS/DAY
6	TX	33746	SALADO CREEK TMDL FOR BACTERIA	Approved / Established	15-Aug-07	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	2,980,000,000,000	CFU/DAY
6	TX	39301	SIMS BAYOU ABOVE TIDAL 1007D_01 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	203	BCFU/DAY
6	TX	39302	SIMS BAYOU ABOVE TIDAL 1007D_02 E.COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	467	BCFU/DAY
6	TX	39304	SIMS BAYOU ABOVE TIDAL 1007D_03E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	631	BCFU/DAY
6	TX	36185	SOUTH MAYDE CREEK 1014H_01 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	33,000,000,000	CFU/DAY
6	TX	36186	SOUTH MAYDE CREEK 1014H_02 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	147,000,000,000	CFU/DAY
6	TX	36195	SPRING BRANCH 1014O_01 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	209,000,000,000	CFU/DAY
6	TX	40509	SPRING CREEK 1008_02 E. COLI TMDL	Approved / Established	3-May-11	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	35	BCFU/DAY
6	TX	40510	SPRING CREEK 1008_03 E. COLI TMDL	Approved / Established	3-May-11	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	220	BCFU/DAY
6	TX	40538	SPRING CREEK 1008_04 E. COLI TMDL	Approved / Established	3-May-11	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	249	BCFU/DAY
6	TX	40546	SPRING GULLY 1009D_01 E. COLI TMDL	Approved / Established	3-May-11	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	7	BCFU/DAY
6	TX	39288	SPRING GULLY ABOVE TIDAL 1006H_01 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	29	BCFU/DAY
6	TX	31982	TMDL FOR ZINC IN OYSTER TISSUE IN NUECES BAY	Approved / Established	15-Nov-06	ZINC IN SHELLFISH	POINT/NONPOINT SOURCE	33	KG/DAY
6	TX	35913	TRINITY BAY 2422_01 FECAL COLIFORM TMDL	Approved / Established	19-Sep-08	FECAL COLIFORM	POINT/NONPOINT SOURCE	5,990,000,000	CFU/DAY
6	TX	36187	TURKEY CREEK 1014K_01 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	30,000,000,000	CFU/DAY
6	TX	36188	TURKEY CREEK 1014K_02 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	13,200,000,000	CFU/DAY
6	TX	35935	TURKEY CREEK 1102D_01 FECAL COLIFORM TMDL	Approved / Established	17-Oct-08	FECAL COLIFORM	POINT SOURCE	54,700,000,000	CFU/DAY
6	TX	30416	TWO TMDLS FOR TDS AND CHLORIDES IN CLEAR CREEK ABOVE TIDAL	Approved / Established	12-May-06	CHLORIDES	POINT/NONPOINT SOURCE	3,677	LBS/DAY
6	TX	30416	TWO TMDLS FOR TDS AND CHLORIDES IN CLEAR CREEK ABOVE TIDAL	Approved / Established	12-May-06	CHLORIDES	POINT/NONPOINT SOURCE	3,677	Not given
6	TX	30416	TWO TMDLS FOR TDS AND CHLORIDES IN CLEAR CREEK ABOVE TIDAL	Approved / Established	12-May-06	TOTAL DISSOLVED SOLIDS (TDS)	POINT/NONPOINT SOURCE	6,800	LBS/DAY
6	TX	30416	TWO TMDLS FOR TDS AND CHLORIDES IN CLEAR CREEK ABOVE TIDAL	Approved / Established	12-May-06	TOTAL DISSOLVED SOLIDS (TDS)	POINT/NONPOINT SOURCE	6,800	Not given
6	TX	39307	UNNAMED NON-TIDAL TRIBUTARY BRAYS BAYOU 1007L_01 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	10	BCFU/DAY

Region	State	TMDL ID	TMDL Name	TMDL Status	TMDL Submittal Date	Pollutant Name	TMDL Type	Total Waste Load Allocation (WLA)	WLA Units
6	TX	39296	UNNAMED NON-TIDAL TRIBUTARY BUFFALO BAYOU 1007O_01 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	0	BCFU/DAY
6	TX	39295	UNNAMED NON-TIDAL TRIBUTARY HUNTING BAYOU 1007M_01	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	31	BCFU/DAY
6	TX	39306	UNNAMED NON-TIDAL TRIBUTARY SIMS BAYOU_1007N_01 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	24	BCFU/DAY
6	TX	39036	UNNAMED TRIBUTARY GREENS BAYOU 1016D_01 E. COLI TMDL	Approved / Established	28-Jun-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	69	BCFU/DAY
6	TX	39285	UNNAMED TRIBUTARY HALLS BAYOU 1006I_01 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	2	BCFU/DAY
6	TX	39286	UNNAMED TRIBUTARY HALLS BAYOU 1006J_01 ECOLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	35	BCFU/DAY
6	TX	39034	UNNAMED TRIBUTARY OF GREENS BAYOU 1016B_01 E. COLI TMDL	Approved / Established	28-Jun-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	12	BCFU/DAY
6	TX	39035	UNNAMED TRIBUTARY OF GREENS BAYOU 1016C_01 E. COLI TMDL	Approved / Established	28-Jun-10	ESCHERICHIA COLI (E. COLI)	POINT SOURCE	89	BCFU/DAY
6	TX	36204	UNNAMED TRIBUTARY OF WHITEOAK BAYOU 1017D_01 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	9,140,000,000	CFU/DAY
6	TX	36205	UNNAMED TRIBUTARY OF WHITEOAK BAYOU 1017E_01 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	9,140,000,000	CFU/DAY
6	TX	35911	UPPER GALVESTON BAY 2421_01 FECAL COLIFORM TMDL	Approved / Established	19-Sep-08	FECAL COLIFORM	POINT/NONPOINT SOURCE	57,200,000,000	CFU/DAY
6	TX	35912	UPPER GALVESTON BAY 2421_02 FECAL COLIFORM TMDL	Approved / Established	19-Sep-08	FECAL COLIFORM	POINT/NONPOINT SOURCE	43,400,000,000	CFU/DAY
6	TX	39144	UPPER OYSTER CREEK 1245_03 CBOD5 AND AMMONIA TMDLS	Approved / Established	9-Aug-10	AMMONIA	POINT/NONPOINT SOURCE	23	KG/DAY
6	TX	39144	UPPER OYSTER CREEK 1245_03 CBOD5 AND AMMONIA TMDLS	Approved / Established	9-Aug-10	CARBONACEOUS BOD	POINT/NONPOINT SOURCE	101	KG/DAY
6	TX	33557	UPPER OYSTER CREEK TMDL FOR BACTERIA 1245	Approved / Established	31-Aug-07	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	1,070,000,000,000	Not given
6	TX	33747	UPPER SAN ANTONIO RIVER FOR BACTERIA	Approved / Established	15-Aug-07	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	10,900,000,000,000	CFU/DAY
6	TX	36179	UT NON-TIDAL TRIB. OF BUFFALO BAYOU TIDAL 1013C_01 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	16,400,000,000	CFU/DAY
6	TX	33745	WALZEM CREEK TMDL FOR BACTERIA	Approved / Established	15-Aug-07	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	83,600,000,000	Not given
6	TX	35915	WEST BAY 2424_02 FECAL COLIFORM TMDL	Approved / Established	19-Sep-08	FECAL COLIFORM	POINT/NONPOINT SOURCE	45,100,000,000	CFU/DAY
6	TX	36196	WHITEOAK BAYOU ABOVE TIDAL 1017_01 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	125,000,000,000	CFU/DAY
6	TX	36199	WHITEOAK BAYOU ABOVE TIDAL 1017_02 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	46,900,000,000	CFU/DAY
6	TX	36200	WHITEOAK BAYOU ABOVE TIDAL 1017_03 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	132,000,000,000	CFU/DAY
6	TX	36201	WHITEOAK BAYOU ABOVE TIDAL 1017_04 E. COLI TMDL	Approved / Established	22-Apr-09	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	483,000,000,000	CFU/DAY
6	TX	39313	WILLLOW WATERHOLE BAYOU ABOVE TIDAL 1007E_01 E. COLI TMDL	Approved / Established	24-Sep-10	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	123	BCFU/DAY
6	TX	40539	WILLOW CREEK 1008H_01 E. COLI TMDL	Approved / Established	3-May-11	ESCHERICHIA COLI (E. COLI)	POINT/NONPOINT SOURCE	29	BCFU/DAY

Source: EPA ATTAINS Database; TX