Plum Creek Watershed Management: A survey and synthesis of management strategies within the context of watershed-scale changes in land use, hydrology, and water quality

by

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1. Introduction

The watershed (or drainage basin) is the fundamental landscape unit for understanding surface water quantity and quality (Chorley et al. 1964; Winter 2001). While the watershed's external conditions are set by geologic and climatic forces, the historical and contemporary land use and management that exert a substantial control on the internal water quantity/quality patterns (Briggs et al. 2006; Lewis et al. 2006; Grimm et al. 2008; James 2017). Rapid urbanization and increased migration to cities have stressed water resources. Drinking water and sanitation issues have been declared one of the greatest challenges of this century (United Nations 2010).

The United States (U.S.) has experienced tremendous urban expansion in the past few decades with roughly 115 million acres of rural land converted into newly developed urban areas between 1982 - 2015 (Natural Resource Inventory: Summary Report, 2018). Urban landscape area is increasing as populations migrate to large cities and surrounding suburbs (Grimm et al. 2008; Kaushal and Belt 2012; Martin-Mikle et al. 2015). The amount of urban land use quadrupled between 1945 and 2010 and reports estimate that 50 - 60% of the global population will live within cites in the next 15 years (USCB 2012; USDA 2011; Grimm et al. 2008). This trend has been observed all over the U.S., and Texas is no exception. Developed land in Texas increased from 5.2 million acres in 1982, to 9.2 million acres in 2015 (NRI 2018). This difference is roughly an increase of 2.33 percent per year over the four decades. Conversely, rural land area showed a decreasing trend between 1982 – 2015. Total rural land in Texas dropped from 159.1 million acres in 1982 to 154.5 million acres in 2015. The movement and distribution of people on the landscape has impacted use and ownership patterns across the state.

Data suggests population density increase in urban centers may influence private, rural ownership followed by changes in land uses due to increased demand for development, resulting in urban sprawl outside city limits (Texas Land Trends 2017; NRI 2018). Texas Land Trends (2017) used state migration scenarios and predicted the fastest population growth to take place between 2010 – 2050. This growth is predicted to occur in the suburban ring surrounding large urban counties, including Travis County. Data reports have shown a decreasing trend in the number of farms and number of acres of farms between 100 and 2000 acres in size for Caldwell County, TX (Texas Land Trends 2019).

Land development can affect the environment and landscape in three major ways: habitat fragmentation, water quality impairment, and flow regime (Grimm et al. 2008; Shah et al. 2019). Habitat fragmentation occurs through the conversion of natural to modified land cover types (e.g., impervious surfaces, utilities, structures) which interrupts the feeding, dispersal, and breeding patterns of wildlife. The construction of a single roadway that cuts through wilderness can have a widespread effect on population and species diversity (EPA 2001; Grimm et al. 2008). Land development alters water quality as buildings, parking lots, and other forms of impervious surfaces disrupt the natural flows of water within a watershed (EPA 2001). The total impervious surface area in a watershed, in addition to the location of infrastructure in relation to specific natural resources, can be correlated to the health of an area's surface waters (EPA 2001). Impervious surfaces, with associated stormwater conveyance and wastewater discharge, are significant sources of water quality impairment and alterations to stream discharge. Expansion of human water infrastructure and increased water consumption has resulted in a greater number of rivers around the world being dominated by effluent discharge. Effluent discharge has also been reported as sources of groundwater impairments and has altered stream hydrology (Brooks et al.

2006; Grimms et al. 2008). Seasonal and spatial variations also influence how non-effluent sources interact with wastewater inputs to mediate both water quantity and quality (Shah et al. 2019).

The effects of anthropogenic activities can have enduring impacts on the landscape, termed legacy effects. Legacy effects can be thought of as long-term environmental changes resulting from previous human disturbances. These disturbances can vary based on previous land use and land cover, water diversions, introductions of chemicals, disruptions in natural systems, or a combination of these changes within a watershed (Grimm et al. 2008; James 2017). This phenomenon includes legacy pollution, legacy changes to ecosystems or individual species, and legacy sediment. In any case, all result from changes to landscape composition by antecedent human disturbances such as land development or intense agriculture (James 2017). Legacy effects are often moderate to large scale, long term events within varying geographic extents (i.e., existing at multiple scales and crossing delineated boundaries). For instance, the temporal setting for this concept can be thought of as lasting decades or longer while the spatial reach is usually beyond that of the watershed and ecosystem of a specific or singular site (James 2017). Grimm et al. (2008) describes this phenomenon in urban areas as leaving a legacy of impact in the ecological characteristic of a landscape. Furthermore, soil-nutrient concentrations may vary due to urban structure (impervious cover) and landscape choice (e.g., lawns, tree cover, crop type) (Kaye et al. 2008). Long-lasting legacy effects have also been found in agriculture land use soils. Previous agrarian land in Phoenix contained biogeochemical properties after 40 years (Lewis et al. 2006) and other locations in the region showed agriculture legacies after centuries (Briggs et al. 2006). Legacy effects are important because they incorporate a dynamic environmental system that must recognize the history and direction of change. Integrating land use and land cover from a historical view of ecological, geomorphic, hydrological, and biogeochemical processes is needed for watershed-scale analyses.

Intense and high runoff volumes caused by impervious surfaces erode stream beds and banks, increase sediment/pollutant loads, degrade stream ecosystems, and displace organisms (Julian and Torres 2006; Palmer 2009; Paul and Meyer 2001; Walsh et al. 2005; Grimm et al. 2008). Accordingly, streams that run though urban landscapes can be placed within the context of the *Urban Stream Syndrome*, which considers the vulnerability of ecosystems in these areas. Walsh (2005) describes the *Urban Stream Syndrome* to consist of the following symptoms: flashier hydrographs, elevated concentrations of nutrients and contaminants, altered channel morphology and stability, and reduced biotic richness, with increased dominance of tolerant species. Other researchers have used this concept to describe similar findings that have affected urban stream functionality due to developed landscapes (Paul and Meyer 2001; Meyer et al. 2005; Grimm et al. 2008; Kaushal and Belt 2012). This syndrome ultimately influences the physiochemical processes (e.g., hydrologic and water chemistry) and ecosystem processes (e.g., nutrient processing and primary production) in urban areas. Watersheds with large areas of impervious cover also tend to display low water infiltration (Wolman and Schick 1967).

The urban watershed continuum (Kaushal and Belt 2012) is another important concept, which examines how urban infrastructure affects stream flow, especially when located at the headwaters. The urban watershed continuum is an inclusive watershed approach in water discharge and water quality analysis. For example, this concept takes into consideration the urban infrastructure (e.g., storm drains, gutters, ditches) that contribute to and influence the hydrography and health of streams. This concept describes the transformation and transportation of energy and materials that is dependent on hydrologic processes. Over time, the biogeochemical cycles and ecosystem functions evolve as land use and urban infrastructure change (Kaushal and Belt 2012). Contaminants may enter aquifers or groundwater sources through subsurface infrastructure, creating a source of water quality impairment for urban rivers (Brooks and Lemon 2007; Kaushal et al. 2011; Hopkins et al. 2015; Hall et al. 2016; Gabor et al. 2017). Increasing engineered inputs (wastewater effluent) alters the natural flow of water sources, such as increased flow. Conversely, agricultural practices, like irrigation, will cause a decline in the natural flow of water sources. Significant shifts in water inputs and outputs must be addressed in order to meet demands for growing populations and response to greater volumes of water diverted for human consumption (Shah et al. 2019)

Holistic and interdisciplinary approaches to watershed management have gained attention in the past few decades (Mitchell 1990; Cairns and Crawford 1991; Noss 1995; Karr 1996; Kenney 1997; Hull et al. 2003; Plum Creek Watershed Protection Plan 20018; Kusler 2004; Flotemiersch 2016). From a watershed perspective, the entire basin becomes the focus of management, which is important because human activities are frequently associated with nonpoint source (NPS) pollution entering surface water networks and ultimately impairing water quality in these streams. This scale enables incorporation of all potential pollution sources. Many studies have been cited showing a response lag time equal to or in excess of 10 years, for both large and small watersheds (Medalie 2010). From a water quality perspective, headwaters are arguably the most important reaches of a stream network. These streams provide aquatic habitat, clean drinking water, and are “hotspots” for the overall maintenance of water quality and ecosystem function with respect to downstream rivers, reservoirs, and estuaries (Peterson et al. 2001; Kemp et al. 2005; Kaushal et al. 2006; Wigington et al. 2006; Freeman et al. 2007). Land management strategies, from a local to regional scale, are being used by municipalities, farm/ranch owners, cities, and residents to combat the negative effects of point and nonpoint source pollutions caused by land development, wastewater discharges, and agricultural overland flow. These strategies have been termed by the EPA as best management practices (BMPs) and limited impact development (LID).

The purpose of this project was to survey management strategies within the Plum Creek watershed and synthesize them within the context of watershed-scale changes in land use, hydrology, and water quality. The benefit of this synthesis is that it provides a reference for future monitoring sites, data collection, management practices, governmental policies, and sustainable development goals.

2. Literature Review

2.1 Hydrologic Landscapes

This report focuses on a geographic perspective for studying watersheds, with a focus on spatial and temporal patterns. Spatial and temporal scales are important from this perspective, but so are the terrestrial and aquatic ecosystems within these landscapes. Ecological understanding of how these systems interact within a spatial context is important for a comprehensive approach to studying diverse landscapes. Researchers have defined ‘landscapes’ as heterogenous areas of land composed of interacting ecosystems, which include aquatic systems almost inherently, focusing primarily on the terrestrial perspective (Hobbs 1995; Zonneveld 1995). Landscape ecology has traditionally looked at land, but much can be learned from studies of aquatic systems. Wiens (2002) describes limitations that fluvial landscape ecology faces in dealing with issues like those found in terrestrial landscapes. Accordingly, fluvial landscapes operate within a particular framework of rules (Townsend 1996). Poole (2002) describes these rules as patchy and hierarchal systems interacting between structure and function. That is, the foundation of fluvial landscapes are hydrology, fluvial geomorphology, and stream ecology, which creates a fundamentally different field of study from landscape ecology. In either discipline, water is an effective medium for linking landscape elements in both space and scale. Spatial patterns, relationships, and processes are critical elements in understanding how terrestrial and aquatic ecosystems, and how their physical geography, interact and effect the other (Stanford 1996; Wiens 2002). Landscape ecology has grown to include aquatic systems as a key component, but also includes the role human activities play in shaping landscapes that subsequently affect riverine landscapes. Forman (1995) placed an emphasis on the relationship between human activities (land use and resource management) and landscapes, highlighting how these pattern-process relationships influence watershed functions. Watershed analyses must take into consideration the social and anthropogenic characteristics in hydrologic landscapes.

The concept of hydrologic landscapes lends itself to the characteristics of earth and its climate that affect the location, movement, and chemistry of water (Winter 2001). The fundamental hydrologic landscape unit (FHLU) is a hydrologic framework aimed to distinguish the movement of water that is unique to specific landscapes. The FHLU can be defined by: (1) its land surface form of an upland adjacent to a lowland separated by a steeper slope, (2) its geologic framework, and (3) its climatic setting. This system is controlled by surface water (the slope and permeability of the unit’s surface), groundwater (the hydraulic characteristics of the unit), and atmospheric water (the exchanges of water within the unit that is controlled by climate). The concept of hydrologic landscapes provides a framework for developing hypotheses for water movement in a drainage basin. It can be used to evaluate many different physical, chemical, or biological issues related to natural or anthropogenic processes effecting watershed systems (Winter 2001). Hydrologic connectivity within a basin is defined as the passage of water from one part of a landscape to another, generating a watershed runoff response (Bracken and Croke 2007). It is influenced by factors such as storm characteristics, antecedent wetness conditions, topography, soils, and vegetation (Bracken and Croke 2007). Understanding how this connectivity interacts between landscape elements and how it varies both spatially and temporally is important when examining watershed response before, during, and after rainfall events (Jencso et al. 2009). Wiens (2002) outlines 6 themes situated in riverine landscape ecology: (1) patches differ in quality, (2) patch boundaries affect flows, (3) patch context matters, (4) connectivity is critical, (5) organisms are important, and (6) the importance of scale. The ‘patches’ described here are scale-defined areas of land (e.g., hectares, square miles, acres) composed of interacting ecosystems (Hobbs 1995). These themes are not discussed in detail here, but they highlight a general conceptual framework linking riverine ecology with a watershed-scale approach for water quality management within the context of hydrologic landscapes.

2.2 Low Impact Development & Best Management Practices

Urban areas may only cover about 3% of the U.S. land area (USCB, 2012), but this land use type has the most intensive impacts on stream health (Fuhrer 1999; Hoffman et al. 2000; Omernik 1967; FLOW 2003). The impervious areas and stormwater infrastructure of urban areas alter the hydrology, surface runoff, and functionality of a watershed (Wolman & Schick 1967; Paul & Meyer 2001; Kaushal & Belt 2012; EPA 2018). Stormwater management approaches for dealing with urban stream impacts include Best Management Practices (BMPs) and the BMP subcategory, Low Impact Development (LID). Increased recognition for the need to improve water quality resulted in the concept of BMPs, which are measures aimed at providing an on-the-ground solution to diffuse pollution issues from all sources and sectors (D'Arcy and Frost 2001). These land management techniques vary in purpose, design, scale, implementation, and across different land use types. The EPA has placed BMPs into two categories: nonstructural or source control BMPs and structural or treatment BMPs. These two categories refer broadly to operational activities, physical controls, or educational measures aimed at reducing or eliminating the discharge of pollutants and to minimize potential impacts to receiving waters (Muthukrishnan 2004). Structural and nonstructural BMPs refer to practices that have direct impacts on the release, transport, or discharge of pollutants. LID strategies are considered nonstructural or source control BMP and will be discussed further in section 2.2.2. Many of these can be thought of as have public centered or engagement focus rather than management through engineering practices alone. Table 1 details specific types of nonstructural BMPs. Structural BMPs are different because they are designed to treat stormwater either at the point of pollutant generation or the point of discharge. A structural BMP implies a physically constructed area of land or filtration-type structures that may also treat stormwater and facility discharge at a specific collection site (e.g. retention or detention ponds and constructed wetlands). Target sources are either stormwater conveyance or sewer systems that discharge to receiving waters. Table 2 details these structural BMPs based on standard definitions outlined in the American Society of Civil Engineers (ASCE) National Stormwater Database and the EPA's National Menu of BMPs (Schueler, 1987; EPA 2018; ASCE 2019).

Table 1. Nonstructural Best Management Practices (BMPs) for urban stormwater runoff. Adapted from Muthukrishnan (2004; Table 2-1).

Major Categories	**Nonstructural Practices**
Public Education	Public Education & Outreach

Planning & Management	Better Site Design, Vegetation Controls, Reduction/Disconnection of Impervious Areas, Green Roofs*, Low-Impact Development**
Materials Management	Alternative Production Substitution, Housekeeping Practices
Street/Storm Drain Maintenance	Street Cleaning, Catch basin Cleaning, Storm Drain Flushing, Road & Bridge Maintenance, BMP Maintenance, Storm Channel & Creek Maintenance
Spill Prevention & Cleanup	Above Ground Tank Spill Control, Vehicle Spill Control
Illegal Dumping Controls	Illegal Dumping Controls, Storm Drain Stenciling, Household Hazardous Waste Collection, Used Oil Recycling
Illicit Connection Control	Illicit Connection Prevention, Illicit Connection-Detection & Removal, Leaking Sanitary Sewer & Septic Tank Control
Stormwater Reuse	Landscape Watering, Toilet Flushing, Cooling Water, Aesthetic & Recreational Ponds

**Considered a structural BMP based on engineering principles*
***Combination of both nonstructural and structural BMP*

Table 2. Structural or treatment Best Management Practices (BMPs) for urban stormwater. Adapted from Muthukrishnan (2004; Table 2-2).

Major Categories	**Structural BMPs**
Ponds	Dry Detention Ponds, Dry-Extended Detention Ponds, Wet (retention) Ponds
Stormwater Wetlands	Constructed Wetlands
Vegetated Biofilters	Grass Swales (Wet/Dry), Filter Strip/Buffer, Bioretention Cells
Infiltration Practices	Infiltration Trench, Infiltration Basin, Porous Pavement
Sand and Organic Filters	Surface Sand Filter, Perimeter Filter, Media Filter, Underground Filter
Technology Options and Others	Water Quality Inlets, Multi-Chambered Treatment Train, Vortex Separation/Continuous Deflection Systems

It is important to consider the location at which these BMP strategies are being implemented. A mixed-use watershed can consist of a diverse set of constraints (e.g., resources, land use, ecosystems, governmental rules and regulations). The identification for LID and BMP siting benefits from using tools and known processes are included in concepts like hydrologically sensitive areas (HSA), critical source areas (CSA), and variable source area (VSA) hydrology (Qiu 2009; Martin-Mikle 2015; Giri et al. 2016). These areas, collectively, are known to have a high runoff (stormwater and saturated overland flow) and pollutant load source potential (Dickinson et al. 1990; Pionke et al. 2000; Walter et al. 2000; Srinivasan and McDowell 2009; Qiu 2009; Shen et al. 2011; Ghebremichael et al. 2013). LID and BMP strategies are effective in mitigating nonpoint and point source pollutions that enter water systems. However, their location, using siting strategies based on hydrological function and land use, had the greatest effect when used in conjunction with identifying HSA, CSA, and VSA in studies previously mentioned. The mechanism (e.g., sedimentation, sorption, precipitation) for which these strategies are designed is important since each is unique to a range of pollutants removed and the conditions in which they are promoted (Table 3).

Table 3. Pollutant removal mechanisms in common urban stormwater BMPs. Adapted from Muthukrishnan (2004; Table 2-3).

Mechanism	**Pollutants Affected**	**Promoted by**
Sedimentation	Solids, BOD, pathogens, COD (chemical oxygen demand) Phosphorus, Nitrogen, Metals	Low turbulence
Filtration	Solids, BOD, pathogens, COD (chemical oxygen demand) Phosphorus, Nitrogen, Metals	Fine, dense herbaceous plants
Sorption	Dissolved Phosphorus, metals, synthetic organics	High soil aluminum, iron, organics
Oxidation	COD, petroleum, hydrocarbons, synthetic organics	Aerobic conditions
Precipitation	Dissolved Phosphorus, metals	High alkalinity
Biological Nitrification	Ammonia	Dissolved oxygen > 2.0 mg/L, low toxics, temp. > 41-45 °F

Microbial Decomposition	BOD, COD, petroleum hydrocarbons, synthetic organics	High plant surface area and soil organics
Phytoremediation	Aromatics, chlorinated aliphatics, hydrocarbons, nutrients	rhizosphere microbial degradation, plant-produced enzymes
Volatilization	Volatile petroleum, hydrocarbons & synthetic organics	High temperature and air movement

2.2.1 BMP Strategies

Best Management Practices (BMPs) encompass LID strategies, but generally focus on a broader scope of water quality management measures, including wastewater and industrial use discharges (i.e., point source pollutions). The purpose of a BMP is aimed towards protecting water systems from point and nonpoint source pollutions with the latter being more difficult to pinpoint and mitigate. These voluntary management practices are best measured at direct use and discharge points at site-specific pollution sources. However, identification of critical source areas (CSA), discussed earlier, for BMP siting have long been recognized as an effective and efficient way to control nonpoint source pollutions (Maas et al. 1985; Duda and Johnson 1985; Fox et. al. 1990; Gburek et al. 2002).

BMPs are primarily engineered to remove TSS and pollutants sorbed to particles using gravitational settling as the predominate process for pollutant removal and are most effective at removing heavy metal pollutants from stormwater (Schueler et al. 1992; Muthukrishnan 2004). BMP efficiency is largely determined by TSS particle size, storm intensity, loading rate, and geometry and age of BMP facility (Muthukrishnan 2004). Increased storm intensity may attribute to an increase in TSS metal concentrations due to large particle size fractions, resulting in better removal efficiency (Ferrara and Witkowski 1983). Sedimentation rate is influenced by pond geometry where finer particles do not settle out when length-to-width ratio is insufficient. In detention ponds draining a commercial complex, sediment was observed to sort coarsest particles and settling was nearest the inlet (Marsalek et al. 1997). Schueler et al. (1992) reported a moderate to high removal efficiency for wet detention basins, constructed wetlands, and combined wetland-pond systems. Sediment concentration indicates the benefit that BMPs have on stormwater quality (Marsalek et al. 1997). Furthermore, BMP efficiency is limited by the available storage volume, hydraulic loading rate of runoff to BMP, and the age of the BMP (EPA 1993; Muthukrishnan 2004). The Texas Water Development Board (TWDB) provides a BMP strategies guide for 5 categories of water users: (1) agriculture, (2) commercial and institutional, (3) industrial, (4) municipal water providers, and (5) wholesale water providers. The foundation of this guide is based on conservation within these categories of water users. The TWDB states that many successful conservation efforts have occurred in Texas, but a more comprehensive effort by all water use sectors is needed in the state (TWDB 2013).

BMP facilities are designed to provide sedimentation for particle-phase nutrients and biological uptake for soluble nutrients to improve stormwater quality that is polluted with excessive nutrient levels (Martin 1988). BMPs designed to capture large amounts of stormwater (e.g., detention ponds, retention ponds, constructed wetlands) act as a sink, source, or transformer of nutrients, but their performance for nutrient-enriched stormwater is unpredictable (Muthukrishnan 2004). Like TSS removal efficiency, BMP nutrient removal is largely based on particle size, quality of substrate, and age of BMP. Performance is highly variable for nutrient removal compared to TSS and is largely determined by particulate dissolved phase and species of nutrient (Tanner et al. 1997). The most effective phosphorus removal constituents are absorption, complexation, precipitation reactions with Al, Fe, Ca, and clay particles, and by peat accretion (Muthukrishnan 2004). Nitrogen removal efficiency is based on pond conditions responsive to nitrification-denitrification processes (Muthukrishnan 2004).

2.2.2 LID Strategies

Low impact development (LID) is a wide-ranging set of land use planning/design techniques used to mitigate negative impacts to the environment caused by land development. Table 4 outlines major stormwater pollutants and their sources. These site design strategies are aimed at maintaining, replacing, or minimizing the change in pre-development hydrologic regime through techniques that create functionally equal landscapes (Muthukrishnan 2004). LID strategies are continuously being regarded as an effective method to decrease runoff and pollutant loadings in streams (Van Roon 2005; Dietz 2007; Martin-Mikle et al. 2015; EPA 2019) and a popular technique aimed at improving water quality in urban watersheds (Dietz 2007; Pyke et al. 2011; Roy et al. 2008; Urbonas and Stahre 1993). The EPA describes LID as a set of systems and practices that use or mimic a natural process "resulting in the infiltration, evapotranspiration, or use of stormwater", aimed at protecting the quality of water that enters or is associated with aquatic habitats. The EPA refers to these designs broadly as green infrastructure. This approach to land development (or re-development) refers mainly to the network of natural areas that provide habitat, flood protection, and cleaner water, among other benefits. These techniques can be applied at multiple scales, with the most popular approach being the preservation, restoration, or creation of functional semi-natural spaces that take advantage of soils, vegetation, and rainwater harvesting techniques (EPA 2019). Hydrologic functions (e.g., storage, infiltration, groundwater recharge, runoff) are maintained or reduced through the use of cohesive and dispersed micro-scale stormwater retention and detention areas, impervious cover area reduction, and the lengthening of flow paths and runoff time (EPA 2000) Specific LID examples include rainwater cisterns, bioswales, raingardens, permeable pavers, and artificial wetlands which are aimed at collecting, storing, and filtering stormwater strategies (EPA 2019; Martin-Mikle 2015). Martin-Mikle (2015) looked at many different types of LID techniques and their site suitability (Table 5). Purpose, scale, and location was important when determining what type of LID technique could be effectively implemented in an area.

Table 4. Major categories of stormwater pollutants, sources, and related impacts. Adapted from Muthukrishnan (2004; Table 1-1).

Stormwater Pollutant	**Major Sources**	**Related Impacts**
Nutrients: Nitrogen & Phosphorus	Urban runoff, failing septic systems, croplands, livestock operations, gardens, lawns, fertilizers, construction site soil	Algae growth, reduced water clarity, lower dissolved oxygen, recreational and water supply impairment.
Solids: Sediment	Construction sites, disturbed and/or non-vegetated lands, urban runoff, streambank erosion	Increased turbidity, reduced water clarity, lower dissolved oxygen, increased sediment load, smothering of aquatic habitat
Pathogens: Bacteria, Viruses, Protozoans	Domestic and natural animal waste, urban runoff, failing septic systems, landfills	Human health risks through drinking supplies and contact recreation

Table 5. Common LID Techniques Grouped According to Generalized Site Suitability. Adapted from Martin-Mikle (2015; Table 2).

LID Type	Land use Characteristics	Scale for Implementation	Effective in Implementation
Rain barrel/cistern	Collecting rooftop runoff	Local	Yes
Green roof	Collecting rooftop runoff	Local	Yes
Porous Pavement	Highly developed areas: parking lots, driveways, and low-volume roads	Local	Yes, intended to replace impervious surface
Rain garden/Bioretention	Collecting runoff from impervious surfaces and yards.	Intermediate	Intercepts runoff from impervious areas but requires land for construction
Vegetated swale	Collecting sheet flow runoff from roads and highways. Also good for collecting runoff from subdivisions.	Intermediate	Intercepts runoff from impervious areas but requires land for construction
Infiltration Trench	Ideal for collecting rainwater from adjacent surfaces. Not appropriate for construction sites or areas with a high solids source which may cause premature clogging	Intermediate	Moderate. Highly permeable soils create temporary subsurface storage of runoff, enhancing natural capacity of the ground to store, filter, and drain water. Maintenance required to prevent clogging.
Detention pond	Ideal for detaining runoff from large catchments ($\leq$ 75 acres)	Catchment	Intercepts runoff from impervious areas but requires a large area of land for construction
Retention pond	Ideal for retaining water from parking lots and residential areas	Catchment	Intercepts runoff from impervious areas but requires a large area of land for construction
Stormwater wetland	Widely applicable for land development sites. May provide wildlife habitat and aesthetic features. Also used to reduce peak runoff rates when designed as a multi-stage, multi-function facility	Catchment	Temporarily stores runoff in relatively shallow pools that support conditions suitable of wetland plants
Riparian buffer	Ideal for land directly adjacent to streams and rivers	Stream Reach	Intercepts runoff from impervious areas but requires a large area of land adjacent to stream for implementation

Studies have shown that LID techniques can have a significant effect in removing nitrogen, phosphorous, total suspended solids (TSS), and other pollutants from stormwater that may enter surface and groundwater (Oklahoma Conservation Commission 2008). Although their primary intent is not to remove Nitrate ($NO3^-$), LID techniques have been shown to reduce $NO3^-$ levels in freshwater systems (Passeport et al. 2012), which generally enter through subsurface sources. Research has reported retention ponds and riparian buffers to remove the highest and most consistent percentages of total nitrate, total phosphorus, and total suspended solids (Oklahoma Conservation Commission 2008). Table 6 outlines LID effectiveness found in the literature (Mayer et al. 2007; Hoffman et al. 2009; Zhang et al. 2010; Collins et al. 2010). Green roof techniques removed the highest total nitrogen concentrations, up to 91% (Collins et al. 2010) and permeable pavers were the second most effective in removing total nitrogen concentrations (25-50%). All LID techniques mentioned show nutrient or sediment removal potential. Riparian buffers and retention ponds were estimated to consistently remove TP, $NO3^-$, and TSS concentrations. All LID techniques listed in Table 6 showed the greatest potential for removing TSS from stormwater. Phosphorus was not removed by green roofs and vegetated swales, while nitrogen was not removed in detention ponds.

Table 6. Estimated percent nutrient and sediment removal by LID techniques.

LID Type	Phosphorus	Nitrate	TSS
Green roof	0	0-91%	0-93%
Porous Pavement	25-50%	0-42%	68-86%
Rain garden/Bioretention	0-42%	0-58%	69-59%
Vegetated swale	0	0-32%	6-55%
Detention pond	4-37%	0	50-75%
Retention pond	48-61%	15-40%	75-85%
Riparian buffer	41-93%	56-87%	58-100%

Researchers have identified a great potential for ecological improvements in urban streams through the application of LID strategies (Booth 2005; Walsh et al. 2005). These techniques provide the benefit of reducing risks from human activities (e.g., spilled pollutants on impervious surfaces within the catchment) by reducing the direct connection of upland areas from receiving waters (Walsh et al. 2005). Many LID practices are designed to decrease the volume of stormwater to receiving waters to alleviate stream bank erosion and altered hydrology associated with urban and suburban landcover. Restoration and/or conservation of riparian and wetland areas can also significantly improve stream banks, restore natural hydrology, and improve water quality entering stream networks. Benefits from riparian and wetland services for river networks are discussed in the following sections.

2.3 Riparian Restoration and Conservation

Riparian ecosystems are the transitional areas between terrestrial and aquatic environments (Gregory et al. 1991). Hillslopes and riparian zones are the most basic units of a watershed that influence how water is received, stored, and delivered within the hydrologically connected makeup of a watershed (McGlynn and McDonnell 2003; McGlynn et al. 2004; Bieger et al. 2019). Riparian zones are different from hillslopes based on their proximity to streams, topography, soils and vegetation, and are characterized as having higher soil moisture and prolonged periods of saturation (McGlynn and McDonnell 2003). These characteristics allow a riparian zone to have a disproportionate effect on the hydrology and connectedness within a watershed (Bieger et al. 2019). Further, riparian zones have the potential to buffer the delivery of water from hillslopes to streams which can have a large influence on a watershed’s hydrologic response after a precipitation event (Jensco et al. 2010; McGuire and McDonnell 2010) and improve the quality of water entering streams through subsurface flow. These transitional zones experience an intrinsically drastic change from many environmental factors and are influenced by both aquatic and terrestrial processes (Gregory et al. 1991). The riparian zone boundaries can be thought of as extending outward into the floodplain and into the canopy of the neighboring riverside vegetation, however their composition may not always be as clearly delineated (Gregory et al. 1991). These areas also perform a disproportionately large amount of ecosystem services in comparison to their size (Brauman et al. 2007; Jones et al. 2010). Ecosystem services are the benefits that humans receive from functioning ecosystems, and these services can be widespread. Supporting Services is one category of particular focus in environmental policy/management which are environmental services centered around natural processes that provide for good water quality (National Wildlife Federation 2019). Wetlands are a good example of Supporting Services because they provide carbon sequestration, natural water regulation, water filtration, flood mitigation, and diverse habitats.

Nonpoint source (NPS) pollution remains a significant issue for maintaining good water quality. Two thirds of this pollution affecting waters of the U.S. can be attributed to agriculture sources (Lee et al. 2003). Runoff filtration is one service provided by riparian buffers that has been observed to be successful in the removal of sediments and nutrients before they enter surface water systems and during overbank floods (Lee et al. 2003; Lowrance et al. 1997; Mayer et al. 2007). Studies have shown that riparian buffer width and soil depth are important factors that influence filtering potential for NPS pollution runoff and improving water quality, however these areas demonstrate an overall effective function for water quality (Lowrance et al. 1997; Mayer et al. 2007). Riparian restoration and conservation offer two avenues benefiting water resources: (1) improving water quality by protecting and restoring riparian habitat, while also (2) increasing a historically naturally vegetated connectivity network. This is done by structurally joining disconnected habitat patches along stream networks. The reconstruction or preservation of riparian buffers are often incorporated into the local land-use planning process through ordinances requiring buffer width maintenance to control diffuse water pollution (Qui 2009). Riparian restoration can be utilized in different areas like urban, suburban or agricultural settings that lack vegetation buffers.

2.4 Wetlands

The National Wetlands Inventory (NWI) of the U.S. Fish and Wildlife Service reported that wetland area in the U.S. originally covered 391 million acres. The most current survey reported only 104 million of those wetland acres remain (Dahl 1990). 5.5 million of these wetland acres were found in Texas as of 2010 (NRCS 2018). A Houston area study highlighted this loss in a growing metropolitan area, reporting a total loss of 447,949 total acres of wetland loss across 8 counties between 1992 – 2010 (Jacob et al. 2014). Over 70% of the wetland loss reported in this study was attributed to development (Cooley 2014). The loss of wetland areas leads to loss of the associated ecosystem services they provide.

Ameli and Creed (2019) found that wetlands located closer to the main stem of a river system had a greater effect in reducing peakflow, leading to lowered flood risk during extreme precipitation events. Wetlands have been recognized as flood reduction mechanisms by storing, holding, and percolating water (Bullock and Acreman 2003; Acreman and Holden 2013). Wetlands have not only been found to help in flood mitigation but have offered other ecosystem services like creating habitats for flora and fauna, improving water quality (filtration, nutrient processing), and providing opportunities for recreation and public aesthetics (Chescheir et al.

1991; Miller et al. 2017). A class of constructed wetlands can offer both habitat and a wastewater treatment opportunity with the benefit of selecting an optimal location for a desired purpose or function. In other words, wetlands can be constructed near wastewater treatment plants (WWTP), offering a tertiary level (nutrient filtration) of wastewater treatment. They have also been used to help mitigate water quality impairments near parking lots by collecting and filtering volumes of polluted stormwater caused by impervious surface cover. Wetlands provide a Regulating Service (NWF 2019), which includes decomposition, water purification, erosion and flood control, carbon storage, and climate control (House et al. 1998). Wetland functions and values depend on the context of the watershed and landscape they are situated. Table 7 outlines interrelationships between watershed contexts and specific wetland functions**.**

Table 7. Examples of interrelationships between watershed contexts and specific functions/values. Adapted from Kusler (2004; Box 1).

Flood storage	Protections of wetlands alone will not protect much of its flood storage unless topographic contours are also protected
Flood conveyance	Flood conveyance of a riverine wetland depends on flood characteristics of the entire river, topography, and vegetations
Pollution prevention and control	Pollution prevention and control capabilities depend on overall surface water regime and a wetland's connection to these waters, soils, and vegetation
Fisheries	Wetland fisheries depend wetland characteristics and whether it is connected to a larger body of water where fish live, feed, and breed.
Waterfowl	Waterfowl feeding and breeding depends on whether the wetland is adjacent to a river or lake and its locational relationship to other wetlands for nesting, feeding, and breeding
Songbird habitat	Bird habitat depends on the adjacent buffer and upland areas
Mammal habitat	Mammal use wetlands for feeding. This water depends on upland habitat and adequate connectedness between wetlands and upland habitats
Reptile and amphibian habitat	Reptiles and amphibians use wetlands for habitat, breeding, and feeding. Habitat depends on uplands habitats connected to wetland habitats.
Recreational use	Wetland use by boaters and paddlers depends on the proximity of the wetland to open water and the ability of recreational users to enter these spaces

2.5 Watershed-scale Approach to Water Quality Management

Rivers and the lands they drain cannot be separated neither in theory nor in practice (Hynes 1975). Historically, large-scale river basin management was based on economical drivers but have evolved to consider regional watershed management, organized around smaller watersheds (Schalger and Blomquist 2008). Sustainable river basin management should be based on a comprehensive understanding of water resource systems and their internal relations like surface and groundwater quality and quantity, along with biotic components between upstream and downstream interactions (Jain and Singh 2003). River basins should be integrated and managed based on a broader environment and in relation to socio-economic demands and potentials, that are influenced by cultural and political settings (Jain and Singh 2003). Therefore, the management of water should incorporate both local (farm, city, county) and regional (catchment and river basin) scale techniques in decision-making processes (Jain and Singh 2003; Pulido-Velazquez and Ward 2017).

Stanford (1996) and Grumbine (1994) use concepts found in ecosystem management and restoration that pinpoint collective watershed characteristics important to a watershed-scale approach to water quality management. A watershed defines the spatial dimensions of a river network, and subsequently, is composed of interactive, biophysical resources (e.g., water, minerals, nutrients, habitats) (Stanford 1996) and land use/resource (development, agriculture, municipal water supply). Historically, river management was based on minimizing flooding risks while increasing water supply potential for irrigation, power, and domestic use (Allan et al. 2008; Karr and Chu 2000; Newson 2009). Sustainable watershed-scale management should address the role of governance frameworks in the context of changing traditional approaches so that spatial and temporal scales, along with the scope of actors, are accounted for in decision-making processes (Biermann et al. 2009; Genskow 2009; Medd and Marvin 2008; Moss 2004; Pahl-Wostl et al. 2007). Adaptive, sustainable river management and experimental ethos promotes the development of a progressive watershed-scale approach to water quality management (Gregory 2011; Doyle and Drew 2008).

The “strategies” outlined previously operate at different scales. Researchers have analyzed how these techniques can vary from a local to regional scale (Martin-Mikle et al. 2015). For example, replacing a parking lot with permeable pavers increases stormwater infiltration allowing the soil to filter nutrients and pollutants that would otherwise enter the surface water system. From a watershed-scale, the total area of perviousness may be disproportionately smaller compared to the total area of imperviousness. In either case, the size does not negate a porous paver’s potential for stormwater filtering, but it can have a notable effect on the scale at which it is capable of mitigating stormwater pollutants at (i.e. local scales). Conversely, increasing riparian buffer zones or creating a network of constructed or restored wetlands could have a larger or even regional mitigation effect within a watershed. However large or small of a scale these strategies operate at, it is important to consider the collective and cumulative impact these techniques have on surface water and groundwater sources within a basin. A multi-scale network of management, restoration, and mitigation strategies is the ideal when attempting to improve watershed health.

3. Study Area and Background

3.1 Study Area

The Plum Creek watershed offers an excellent case study in terms of watershed management because it is composed of mixed-land use, multiple management authorities, and concentrations of significant population changes at the headwaters and throughout the watershed (Figure 1). The entire stream channel was listed as a Section 303(d) impaired waterway due to high bacteria levels in 2004 (Plum Creek Watershed Protection Plan 2018). Practically all baseflow upstream of Luling is supplied by effluent from domestic and municipal WWTP discharges. Its headwaters drain from the Hill Country one of the fastest growing cities in Texas (Kyle) and one of the fastest growing counties in the U.S. (Hays County). The headwaters begin south of the Balcones Escarpment in the gently sloping Northern Blackland Prairies. Downstream, the landscape transforms into the Southern Post Oak Savanna. Land use is dominated by agriculture with large increases in developed, built-up land occurring throughout the study period. The recently constructed 130 Toll Way bisects the watershed, increasing habitat fragmentation, vehicle transportation, and impervious pollutant input. Table 8 outlines a basic area and land use summary of the Plum Creek watershed.

Plum Creek runs through the cities of Kyle and Luling, and adjacent to Lockhart, exacerbating the negative effects of urbanization due to the proximity of land development near the main stem of the watercourse. This stream is also hydrologically important because it drains directly into the San Marcos River, carrying all pollutants and sediments to this iconic river, which flows downstream to the Guadalupe River, that drains to the San Antonio Bay. Rapid development, water diverted for irrigation, and federal requirements to maintain the physical, chemical, and biological integrity of our nation's waters, has led to a shift in how the Plum Creek watershed is being managed today.

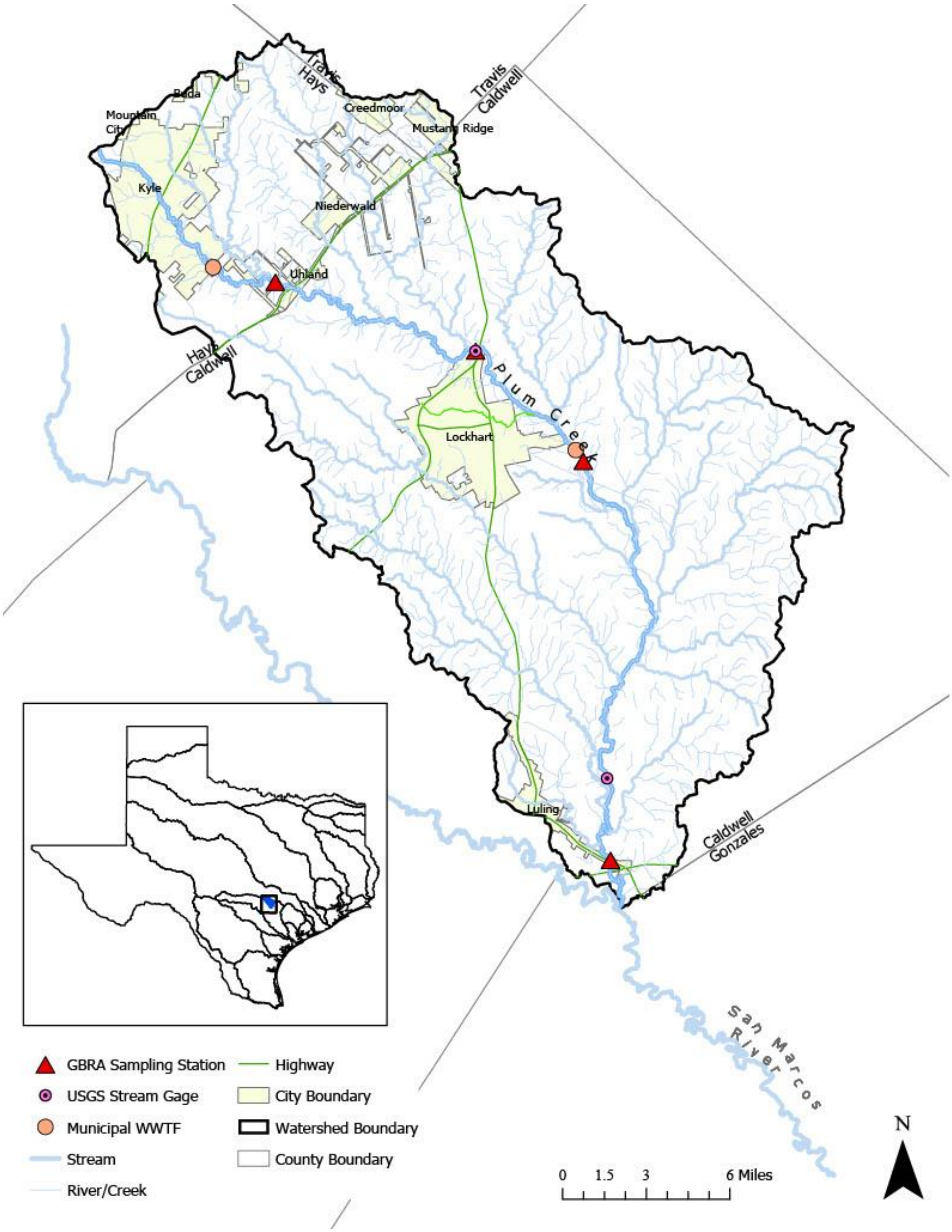

Figure 1. Plum Creek Watershed study area.

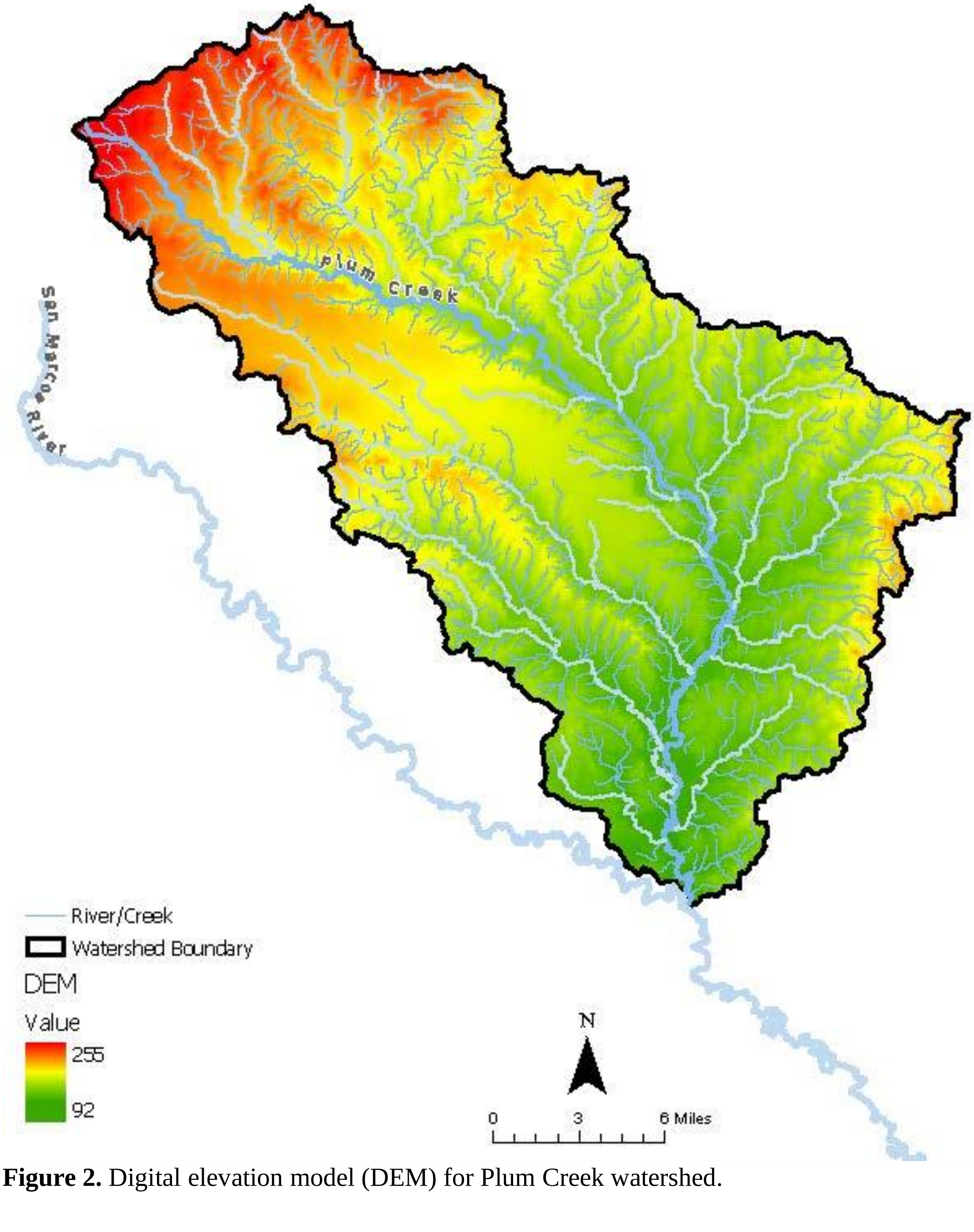

Figure 2. Digital elevation model (DEM) for Plum Creek watershed.

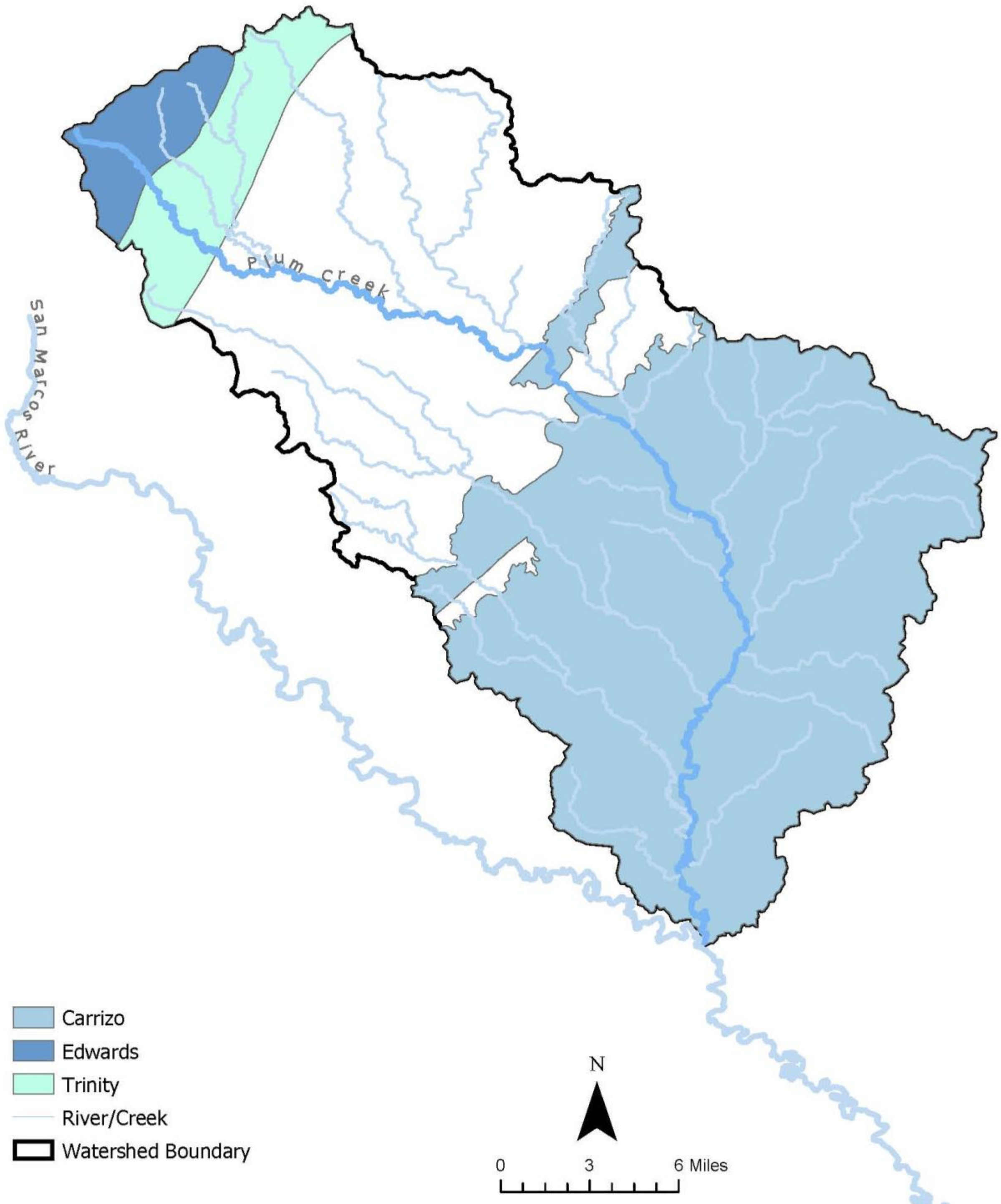

Figure 3. Major aquifers in Plum Creek watershed.

Figure 4. Omernik Level IV ecoregions in Plum Creek watershed.

Table 8. Plum Creek Watershed summary.

Drainage Area	397 square miles
Streams	Plum Creek, Clear Fork Creek, Town Branch, San Marcos River
Aquifers	Edwards-Balcones, Carrizo Wilcox
Guadalupe River Basin Segment ID – Water Body Name	1810 – Plum Creek
Cities	Kyle, Buda, Luling, Lockhart
Counties	Hays, Caldwell, Travis
Ecoregions	Texas Blackland Prairies, Post Oak Savannah, Edwards Plateau
Climate	Average annual rainfall: 33 inches
	Average annual temperature: January 40°F, July 95°F
Land Use	Industry, Urban, Oil & Gas Production, Cattle, Hog, and Poultry Productions, Agriculture, Crops (sorghum, hay, cotton, wheat, and corn)
Water Body Uses	Aquatic Habitat, Contact Recreation, Water Supply, Fish Consumption
Soils	Black, waxy soil to sandy soil, limestone to black waxy chocolate and grey loam

3.2 Watershed Protection Plans Summary and Supporting Documents

Several water quality studies have been conducted within the Plum Creek watershed. The first watershed protection plan was published in 2008, followed by several updates published in 2012, 2014, and 2018. Clean River Basin Summaries were published in 2013 and 2018, providing additional information and analyses conducted in Plum Creek watershed.

3.2.1 2008 Plum Creek Watershed Protection Plan

The 2008 Plum Creek Watershed Protection Plan (PCWPP) was the initial document accepted by the EPA as a guideline for addressing water quality and water quantity management measures. The goal was to identify and address water pollutants and potential pollutant sources in Plum Creek Watershed (Plum Creek Watershed Protection 2008). Studies in this plan identified potential pollutant sources within urban, agricultural, and wildlife settings. Scientific analysis concluded that E. coli, phosphorus, and nitrate should be reduced in three regions within the watershed: Uhland, Lockhart, and Luling. Management measures were outlined to address four specific pollutant source categories – urban nonpoint source pollution (NPS), wastewater, agricultural NPS, and wildlife and non-domestic animals.

Urban runoff contributes to the level of bacteria concentrations in Plum Creek. A study determined that bacteria levels in urban runoff can be extremely high, especially in areas with large concentrations of impervious surfaces (City of Austin 1997). This pattern is observed at significantly higher concentrations in Kyle, Lockhart, and Luling compared to the entire watershed (Plum Creek Watershed Protection Plan 2008). Water quality analysis determined high concentrations of E. coli for the upper reach of Plum Creek. The Partnership found significant potential of urban bacteria loading within subwatersheds containing these three cities.

Census data from 2000 estimated that about 9,000 dogs reside within the watershed. According to the plan's analysis, E. coli containing bacteria load potential from pet waste was also concentrated in highly urbanized subwatersheds for the cities Lockhart, Kyle, and Luling.

Septic systems are common in rural areas of the watershed. These systems require adequate maintenance to maintain proper working conditions and to eliminate leaking septic contaminants into groundwater sources. When these systems fail, the wastewater is not properly treated and can become a source for bacteria, pathogens, and nutrients. One study determined that in the counties within and around the Plum Creek Watershed, approximately 12% of reported septic systems are chronically malfunctioning (Reed, Stowe, and Yanke 2001). This study also determined the highest densities of septic systems were located in the northern portion of the watershed.

Wastewater treatment plants (WWTPs) are permitted point sources in the watershed. Plum Creek Watershed contains 12 WWTPs and 2 water treatment facilities that averaged 12 MGD (Plum Creek Watershed Protection Plan, 2008). Permitting totals were expected to increase in order to meet demands of an increasing population and the expansion of development within the watershed. Larger permits and the potential for additional WWTP permits to meet the growing need is expected to lead to an increase in total effluent discharge to Plum Creek. Several WWTP malfunctions were reported in Plum Creek (Plum Creek Watershed Protection Plan 2008). Effluent violations included several treatment bypasses at WWTPs that resulted in untreated waste being transported to Plum Creek. Sewage bypass occurred from excessive sludge build-up that was eventually released to the stream resulting in high concentrations of bacteria loads. Urbanization has changed upper reaches of the landscape, but much of the watershed, particularly Caldwell County, was and still is dominated by agriculture land use.

Farms and ranches consisted of various livestock and forage production. The reported majority of agricultural land use types were beef cattle, hay production, and row cropping. Goats, sheep, horses, and chickens are other types of livestock within the watershed. Urine and feces from livestock can act as bacterial and nutrient pollutant sources. Pollutants may be transported during runoff events or when livestock are confined in areas near streams or drainage areas. Potential impacts can also occur when livestock is permitted direct access to stream and riparian corridors. Wild game like deer and feral hogs were found to be a significant source of E. coli loads found in the southern reaches of the watershed. Row crops were determined to have a potential contribution in high levels of nutrients from fertilizer used in crop production. These nutrients may be carried downstream during runoff events or irrigation practices. The majority of row crop types reported were corn, sorghum, wheat, and cotton. The Plan mentions that row crop production is slowly declining as agricultural land undergoes development. Despite this trend, crop production may still have been a source of high nutrient concentrations found in a prior water quality assessment conducted in 2006 (Plum Creek Watershed Protection Plan 2008). High concentrations of orthophosphates and total phosphorus were concentrated in the lower reach, south of Uhland at Highway 21. Nitrate was considered a concern for the entire Plum Creek stream segment.

Additional watershed protection measures include outreach and education programs utilized to inform student and locals on how to practice water stewardship within the local community.

3.2.2 2012 Update to the Plum Creek Watershed Protection Plan

The 2012 update of the Plum Creek Watershed Protection Plan served two purposes: to report current water quality and quantity trends since 2008 and to outline specific watershed-scale management measures to be implemented in the region. Detailed management measures are outlined to address large-scale pollutant source inputs previously mentioned (urban stormwater, wastewater, and agricultural and wildlife). Management measures in this plan are Best Management Practices and Low Impact Development strategies. These strategies have shown to aid in the mitigation of pollutant loads and reinforce water quantity levels. The efficacy of these strategies were discussed in Section 2. Literature Review.

Table 9. Summary of management measures in the 2012 Update to the Plum Creek Watershed Protection Plan.

Management Measure Category	Management Measure
Urban Stormwater Management	Street Sweeping
	Urban Stormwater Assessment and Mapping
	Urban Stormwater Markers, Inlet Protection Devices, and No Dumping Campaigns
	Retention Retrofits
	Luling Stormwater Structure
	Ordinance to Include the Use of Mulch Tubes
	Stormwater and Illicit Discharge Survey
	Urban Waterfowl Management
	Dog Waste Management
	Hays County Development Regulations
Wastewater Management	Regional Water and Wastewater Planning Studies
	Kyle Water Reuse Feasibility Study
	Buda Water Reuse Projects
	Regional Wastewater Compact
	Sewer Pipe Replacement and New Sewer Service
	New Discharge Permit in Plum Creek Watershed
	Voluntary Effluent Monitoring by WWTPs
	Phosphorus Removal
	Recommended Facility Upgrades and SCADA
	Plum Creek Community Install Wet Well with Bar Screens to Reduce TSS in Effluent for Reuse
	Septic System Connection to Sewer
	Wastewater in the Counties
Agricultural NPS Management	Adapted from EPA list of approved practices for funding*
Wildlife and Non-domestic Animal Management	Feral Hog Control
	Wildlife Surveys

**Found in Table 20. Financial Incentive-Based Agricultural BMPs*

Table 10. Public outreach and education management measures for the 2012 Update to the Plum Creek Watershed Protection Plan.

Management Category	Management Sub-Category	Management Measure
Outreach and Education	Public Education	Plum Creek Watershed Protection Plan
		Watershed Protection Campaign Brochure
		Partnership Website
		News Releases
		Newsletter
		Texas Watershed Steward Workshop
		Volunteer Monitoring
		GBRA's Plum Creek School Water Quality Project
		Plum Creek Watershed Kiosks in Kyle, Lockhart, and Luling
		Outreach at Local Events
		Rainwater Harvesting Education
	Urban Outreach	NEMO Workshops
		Online Stormwater Management Module
		Stormwater Management Demonstrations
		Site Assessment Visits
		Urban Sector Turf and Landscape Management
		Household Hazardous Waste Collection Events
	Septic System Outreach	Septic System Online Module
		Septic System Workshops
	Municipal Wastewater Outreach	Online Wastewater Treatment Facility Module
		Online Fats, Oils, and Grease Modules
		Fats, Oils, and Grease Modules
	Agricultural Outreach	Soil and Water Testing Campaigns
		Nutrient, Crop, and Livestock Grazing Management Education
		Lonestar Healthy Steams Program
		Agricultural Waste Pesticide Collection Events
	Feral Hog Management Outreach	Feral Hog Control
		Feral Hog Management Workshops
		Technical Assistance
		Feral Hog Reporting System
		Feral Hog Management Factsheets

Additionally, the 2012 Update provides sections dedicated to *Measures of Success* towards implementing management measures outlined in the 2008 plan. Measures of success provides specific efforts taken by the Partnership, including several water quality studies, analyses, and results. Table 11 describes these efforts in greater detail, outlining the diversity of work towards implementation goals. Table 13 describes the projected progress from the 2008 Plum Creek Watershed Protection Plan's management measures with actual progress of implementation as of 2012. These are broken down into 3-year block, starting from 2008.

Table 11. Progress toward management measure goals from 2008 to 2012 Plum Creek Watershed Protection Plans.

Measures of Success	Description
Routine Water Quality Monitoring Data	Increased the number of water quality monitoring sites from 3 to 47 for routine (monthly) data collection which provides a higher understanding of spatial and temporal trends of pollutant loadings.
GBRA Routine Monitoring Results	The number of routine monthly testing stations increased from 3 to 8. At this time 35 sites were added and were sampled twice per season during dry and wet weather conditions; 6 WWTPs are sampled once per season, and 3 springs are sampled seasonally.
Analysis of Water Quality Trends at CRP Stations	E. coli, Nitrate Nitrogen, and Total Phosphorous trended downward from upstream monitoring stations to downstream monitoring stations.
GBRA Targeted Monitoring Results	Results indicated great variations between stations depending on pollutant load: E. coli, Total Phosphorus, and Nitrates continued to be a concern throughout the Plum Creek segment
Rainfall Patterns from January 2008 – November 2011	Rainfall data during this period recorded the lowest precipitation totals resulting in a historical drought period.
Stream Biological Assessments	Aquatic Life Monitoring (ALM) protocol used by TCEQ provided baseline data on environmental conditions
Soil and Water Assessment Tool (SWAT)	SWAT analysis was inconclusive and was noted that this form of analysis will may be performed at a later date.
Bacterial Source Tracking (BST)	At this time, the BST technique was not useful and will be reconsidered at a later date.

Nitrate Nitrogen Isotope Study	Nitrate Nitrogen mean concentrations increased at water quality sites going downstream. This concern led the Partnership to adopt numeric water quality standards developed by TCEQ. Isotope signatures in water quality samples are being analyzed to determine specific sources of nitrates in groundwater and surface water.
Bacteria Reductions	Expected load reductions per management measure category*
Adaptive Management	The Partnership plans to apply 'Adaptive Management' in which decisions are made as part of an ongoing science-based process. Instream monitoring data will be compared with interim milestones and water quality criteria to determine progress in achieving WQS. If water quality improvement is not being demonstrated within the proposed time frames, efforts will be made to increase adoption of BMPs and/or adjust strategies or focus areas if and when necessary.

*Found in Table 12. Expected load reductions per management measure

Table 12. Expected load reductions per management measure category.

Management Measure	Expected Load Reductions					
	Uhland		Lockhart		Luling	
	E.coli (cfu/yr)	Phosphorus (Kg/yr)	E.coli (cfu/yr)	Phosphorus (Kg/yr)	E.coli (cfu/yr)	Phosphorus (Kg/yr)
Urban Stormwater Management Measures						
Pet Waste Collection Stations	7.20E+12	8.2	7.30E+12	18	6.00E+14	N/A
Comprehensive Urban Stormwater Assessment; Retrofit Urban Stormwater Detention Basins; Initiate Street Sweeping Program; Manage Urban Waterfowl Populations; Rehabilitate Stormwater Retention Pond	4.30E+13	19.1	1.90E+13	33	1.80E+15	N/A
Wastewater Management Measures						
Wastewater Upgrade (TSS Reductions); Wastewater Upgrade (Phosphorus Removal)	3.50E+10	N/A	2.10E+10	N/A	3.20E+12	N/A

Voluntary Monthly E.coli Monitoring						
Voluntary Monthly Phosphorus Monitoring						
Sanitary Sewer Pipe Replacement						
Lift Station SCADA Installation						
Initiate Sanitary Sewer Inspection Program						
Septic System Inspection/Enforcement	6.10E+10	13.3	5.00E+12	24.2	3.80E+14	N/A
Septic System Repair						
Septic System Replacement						
Septic System Connection to Sewer						
Agricultural Management Measures						
WQMP Technician	9.60E+12	827	2.1EE+13	4772	5.60E+15	N/A
Livestock Water Quality Management Plans						
Cropland Water Quality Management Measures						
Non-Domestic Animal and Wildlife Management Measures						
Feral Hog Control (New Position)	7.30E+12	327	1.20E+13	1163	4.00E+15	N/A
Feral Hog Control (equipment)						

Table 13. Projected management measures progress from 2008 PCWPP and 2012 progress status

Management Measure	Responsible Party	Projections from 2008 (Years)			
		1 - 3	Status though Nov 30, 2011	4 - 6	7 - 10
Urban Stormwater Management Measures		**Total Number of Management Measures per Type**			
Pet Waste Collection Stations	City of Kyle	13	16	4	4
Pet Waste Collection Stations	City of Lockhart	10	16	4	4
Pet Waste Collection Stations	City of Luling	6	6	2	2
Pet Waste Collection Stations	City of Buda	10	18	4	4

Comprehensive Urban Stormwater Assessment	City of Kyle	1	Completed	-	-
Retrofit Stormwater Detention Basins	City of Kyle	2	2 Completed	-	-
Initiate Street Sweeping Program	City of Kyle	-	Initiated and Continuing	-	-
Comprehensive Urban Stormwater Assessment and Illicit Discharge Survey	City of Lockhart	1	In progress	-	-
Manage Urban Waterfowl Populations	City of Lockhart	-	Ongoing	-	-
Comprehensive Urban Stormwater Assessment	City of Luling	1	0	-	-
Rehabilitate Stormwater Retention Pond	City of Luling	1	0	-	-
Initiate Street Sweeping Program	City of Buda	1	Initiated and Continuing	-	-
Wastewater Management Measures					
Wastewater Upgrade (TSS Reduction)	WWTP Operators	-	0	3	3
Wastewater Upgrade (Phosphorus Removal)	WWTP Operators	-	0	7	7
Voluntary Monthly E.coli Monitoring	WWTP Operators	-	3	-	-
Voluntary Monthly Phosphorus Monitoring	WWTP Operators	-	2	-	-
Sanitary Sewer Pipe Replacement	City of Kyle	2400 ft	4660 ft	2400 ft	3200 ft
Lift Station SCADA Installation	City of Kyle	3	1	4	-
Sanitary Sewer Pipe Replacement	City of Lockhart	1800 ft	4000 ft	1800 ft	2400 ft
Initiate Sanitary Inspection Program	City of Luling	1	1	-	-
Sanitary Sewer Pipe Replacement	City of Luling	2400 ft	16672 ft	2400 ft	3200 ft
Lift Station SCADA Installation	City of Luling	4	0	1	-
Sanitary Sewer Pipe Replacement	City of Buda	-	2652 ft	8523 ft	-
Septic System Inspection/Enforcement (New Position)	Caldwell County	2	0	-	-
Septic System Repair/Replacement	Hays County	300	208	300	400

Septic System Repair/Replacement	Caldwell County	150	34	150	200
Septic System Connection to Sewer	City of Uhland	100	0	100	150
Agricultural Management Measures					
WQMP Technician (New Position)	SWCD	-	Funded through FY 2012	-	-
Livestock Water Quality Management Plans	SWCD	65	8 Certified 4 In-progress	70	102
Cropland Water Quality Management Plans	SWCD	6	1	9	9
Non-Domestic Animal and Wildlife Management Measures					
Feral Hog Education (New Position)	AgriLife Extension	-	Funded through FY 2012	-	-
Feral Hog (Demonstration Equipment)	AgriLife Extension	-	$10,000 of Equipment	-	-
Monitoring Component					
Targeted Water Quality Monitoring	GBRA	-	Funded through FY 2013	-	-
Comprehensive Stream Assessment	GBRA	12	8	12	16
Bacterial Source Tracking	TAMU	1	0	-	-

The increased number of monitoring stations and data collection provided a higher level of understanding of the spatial and temporal trends of pollutant loadings. This monitoring strategy served to refine the focus of management measures while tracking the performance of ongoing implementation activities.

3.2.3 2014 Update to the Plum Creek Watershed Protection Plan

The 2014 update to the PCWPP served as a progress report on efforts toward implementing management measures since its initial release in 2008, with a primary focus on activities and updates from December 2011 through March 2014. Modifications to strategies and goals are also found in the 2014 PCWPP. Analysis of collected water quality data was performed to determine interim progress in reaching water quality restoration goals. Ongoing management measures were retained while others were added in this report. Urban stormwater management remained at the forefront of these efforts. Public education and outreach efforts increased during this period.

Table 14. Summary of management measures in the 2014 Update to the Plum Creek Watershed Protection Plan

Management Measure Category	Management Measure	Update	
Urban Stormwater Management	Street Sweeping	City of Kyle	164 mi/month
		City of Buda	55.9 miles (every 3-4 months)
		City of Lockhart	50-60 mi/month
		City of Luling	All streets swept monthly
	Urban Stormwater Assessments, Mapping, and Illicit Discharge Survey	The City of Kyle incorporated comprehensive stormwater assessments to identify the most effective locations for installations of structural stormwater controls.	2058 storm drain inlets
			291 storm drain outlets
			825 stormwater manholes
		The City of Lockhart developed a "Stormwater and Drainage Management Plan" to improve water quality in Plum Creek	The city also mapped out their existing stormwater system. 288 inlets were identified during this analysis
	Urban Stormwater Markers, Inlet Protection Devices, and No Dumping Campaigns	The cities of Buda, Kyle, and Lockhart installed "no dumping" markers on the majority of storm drain inlets.	
	Ordinance to Include the Use of Mulch Tubes	The City of Kyle passed an ordinance requiring the use of mulch tubes in areas of high runoff or that were environmentally sensitive. This included the installation of about 500 linear feet throughout the city.	

	Urban Waterfowl Management	The City of Lockhart removed and relocated 50% of the waterfowl population at the City Park pond
	Dog Waste Management	50 pet waste stations now exist in cities throughout Plum Creek watershed
	Hays County Development Regulations	Hays county adopted regulations to provide for the orderly and efficient development of rural and suburban areas outside of city limits. The regulations were considered to be consistent with PCWPP goals.
	Caldwell County Development Regulations	In January 2011, Caldwell County adopted an ordinance for the purpose of providing a framework for, "the safe, orderly, and healthful development of the unincorporated areas, these issues being hereby declared to be worthwhile public purposes and in the public interest."

The 2014 PCWPP update transitioned its focus to public outreach and education efforts to increase community engagement. Management measure activities were incorporated into public outreach programs, local workshops, online modules, and other public education events. This shift to a community-effort focus addressed the significant impact of locally led river stewardship. The 2014 update notes that, "Many of the resources developed through this project have been adapted and utilized in other watersheds across the state, and the effort has received multiple awards for its creativity and effectiveness" (Plum Creek Watershed Protection Plan 2014). Local, state, and national media efforts were conducted at this time to spread information on watershed education resources.

3.2.4 2018 Update to the Plum Creek Watershed Protection Plan

The 2018 PCWPP focused on education and outreach activities being conducted within Plum Creek watershed. Management measures, previously mentioned, were updated to reflect current concerns surrounding water quality issues in Plum Creek. Low Impact Development (LID) and Best Management Practices (BMPs) also became a focal point in urban stormwater management measures. Wastewater management strategies concentrated on the continued effort to replace dated sewer pipes and addressing septic system issues in the area. Feral hog management measures were the focus of the wildlife and non-domestic animal efforts. Despite major changes within the watershed, with rapid development, and significant years of drought, the Partnership continues to be actively engaged in implementation activities. Continued implementation is evident with the increasing number of new projects within the watershed including LID implementation in Caldwell County and the City of Kyle, as well as the riparian restoration project in Lockhart. This document update is discussed in-depth later in the Analysis section.

3.2.5 Clean Rivers Basin Summary Report (2013 and 2018)

The Clean Rivers Basin Summary Report provides additional analysis and recommendations for improved water quality in Plum Creek watershed. These summaries were put out by the Guadalupe-Blanco River Authority to further address issues within Plum Creek, and the collective, Guadalupe River Basin. These summaries supported data and analyses consistent in all PCWPPs. Similar concerns for contact recreation and biological integrity were discussed. These summaries agreed that urban development, agriculture, and septic system issues are major factors effecting water quality in Plum Creek (Clean Rivers Program Basin Summary Report 2013 and 2018).

4. Data and Methods

4.1 Watershed-Scale Mitigation Strategies Content Review

Plum Creek Watershed Protection Plans, TCEQ watershed projects database, Plum Creek Conservation District (PCCD) rules and regulations, and information gathered from interviews with local landowners and managers was used to create a comprehensive database of current and past land-water management strategies. These data will be important in understanding spatial and temporal relationships between land management, water quality, and discharge.

4.2 Water Quality Analysis

Water quality data from four Guadalupe-Blanco River Authority (GBRA) sampling station sites was used to create box plot summaries (Appendix A) of total phosphorus (TP), nitrate ($NO3^-$), and total suspended solid (TSS) for each month and water year for the study period (2008 – 2018). Effluent discharge and water quality data was analyzed by mean and total for the water year only since the available sampling was performed only quarterly each year.

Water quality measures were chosen to examine trends between each variable based on annual and seasonal temporal ranges. Annual water quality trends were based on the water year (WY) (WY2018 = October 1, 2017- September 30, 2018) to observe water quality patterns compared to landcover/land use change. Seasonal patterns were analyzed by grouping monthly data for all water years between 2008 – 2018 to observe differences between wet and dry periods throughout the year. Discharge data from the United States Geological Survey (USGS) was used to analyze discharge data trends between 2008 - 2018. Data from the National Climatic Data Center (NCDC) was used to characterize temperature and precipitation patterns.

Figure 5 shows each sampling station starting at Station 1 downstream consecutively to Station 4. Station 1 was chosen because of its location near the headwaters. Station 4 was chosen because it was the most downstream sampling site providing total load concentrations in Plum

Creek for this study. Station 2 was chosen because it is directly south of a major tributary that is dominated by wastewater point source discharge. Station 3 was chosen because it is south of the Town Branch riparian restoration project in Lockhart, TX. All stations were compared to each other to observe trends in nutrient and sediment concentration loads throughout the main channel.

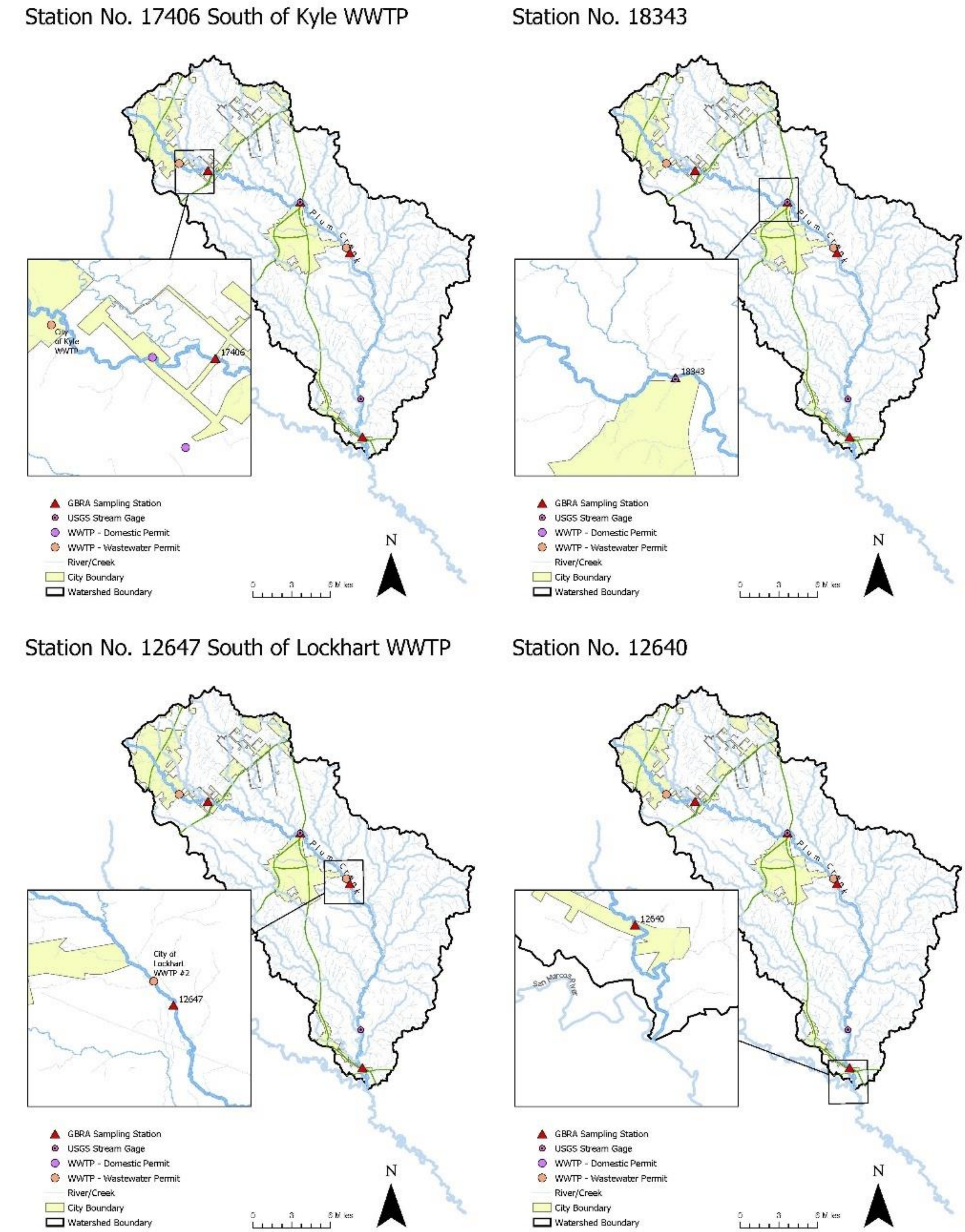

Figure 5: Study area sampling stations (1-4) and WWTP discharge locations.

4.3 Land Use/Land Cover Change Analysis

Geospatial data was retrieved and analyzed to assess land cover changes from 2001 to 2016. The National Land Cover Database (NLCD) was used to analyze the percent change in land cover, specifically urban, barren-agriculture, forest, grassland, open water, and wetlands. Raster metadata was recorded in 30m x 30m cell sizes. Each land cover/land use type was converted to square kilometers by multiplying cell counts by square kilometers (cell count x 0.0009 km^2) for each land classification. Table 15 describes the land classification system used for the LULC change analysis.

Table 15. Land use/land cover classifications from the NLCD classification system.

Classification	Description
Open Water	Areas of open water, generally with less than 25% cover of vegetation or soil.
Developed, Open Space	Areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.
Developed, Low Intensity	Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing
Developed, Medium Intensity	Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units.
Developed High Intensity	Highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover.
Barren Land (Rock/Sand/Clay)	Areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.
Deciduous Forest	Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.
Evergreen Forest	Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.
Mixed Forest	Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.
Shrub/Scrub	Areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true

	shrubs, young trees in an early successional stage or trees stunted from environmental conditions.
Grassland/Herbaceous	Areas dominated by graminoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling but can be utilized for grazing.
Pasture/Hay	Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation.
Cultivated Crops	Areas used to produce annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.
Woody Wetlands	Areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.
Emergent Herbaceous Wetlands	Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.

5. Analysis/Results

5.1. Land Management Strategies for Water Quality and Quantity

LID and BMP concepts outlined in the EPA publication *Smart Growth* (2001) are a set of strategies that presently exist or are in development for the Plum Creek watershed. Completed and current mitigation projects and strategies in the Plum Creek watershed are detailed in Table 16.

Table 16. Management strategies in Plum Creek watershed.

Project Type	Location	Description	Project Period
Riparian Restoration	Town Branch in Lockhart, TX	The City of Lockhart will conduct an evaluation of Town Branch's riparian areas and institute improvements in managing them, including low impact development (LID) features in a park within the Town Branch riparian area. The City will also provide outreach activities and permanent educational signs to involve the community in better riparian practices. The project study area includes approximately 177 acres of land divided into five named reaches for the evaluation.	9/1/2017 – 8/31/2020
Implementing a Watershed Protection Plan (WPP) - Illicit Discharge Monitoring	City of Lockhart, TX	One management measure in the Plum Creek WPP is to detect and address non-stormwater discharges into the municipal separate storm sewer system. GBRA monitored the City of Lockhart's stormwater conveyance system for illicit discharges during dry weather. When water was present under those conditions and water quality sampling identifies an illicit discharge, the City of Lockhart was notified to enforce the city's drainage ordinance.	9/15/2014 – 11/30/2016
Implementing a Watershed Protection Plan in Lockhart	City of Lockhart, TX	To implement the WPP, the City of Lockhart mapped its stormwater system, identifying and prioritizing improvements in this system that will prevent pollution in the creek, and implemented several other activities.	8/17/2010 – 8/17/2013
Implementing Low Impact Development at the Caldwell County Justice Center	City of Lockhart, TX	•This project is retrofitting the Caldwell County Justice Center in Lockhart with xeriscaping*, cisterns for rainwater harvesting*, a rain garden*, and a porous pavement parking lot*. •The county will estimate how much the pollutants are reduced by these measures. •An education campaign will include a workshop, tours, permanent signs at the site to identify the LID features, and a brochure to explain them.	11/9/2015 – 5/31/2019
Implementing Low Impact Development in the City of Kyle	City of Kyle's waste-water treatment facility	This project includes the installation of rainwater harvesting, bioretention, and permeable concrete or pavers at the City of Kyle's wastewater treatment plant. The City of Kyle will host site tours and distribute educational materials to residents, local businesses, and community leaders. This project implements the Plum Creek Watershed Protection Plan by installing low impact development (LID) best management practices at the City of Kyle's wastewater treatment plant.	1/11/2017 – 2/29/2020
Implementing the Watershed Protection Plan at the Headwaters in Kyle	City of Kyle, TX	•In this project, the City of Kyle reduced nonpoint source (NPS) pollution by implementing activities in the Plum Creek WPP. These activities reduced bacteria and nutrient loads to the headwaters of the Plum Creek watershed. •Project activities included mapping and evaluating the existing stormwater system, retrofitting detention facilities to improve the quality of discharged water, implementing education and increasing awareness about storm sewers, installing dog-waste stations, facilitating creek clean-up days, and implementing city street sweeping.	8/18/2009 – 8/31/2011

Healthy Lawns and Healthy Waters Education Project	Regional watersheds of the Guadalupe River	This project delivers the "Healthy Lawns and Healthy Waters" citizen education training program to areas in the region. This includes the watersheds of Cypress Creek, Upper Cibolo Creek, Plum Creek, Geronimo Creek, and the Upper San Antonio River. The program will focus on rainwater harvesting and proper use of fertilizers for residential homes. Participants will also receive a free soil analysis	1/30/2017 – 2/28/2020
Plum Creek Site 6 Rehabilitation Project	NRCS, PCCD, and TSSWCD	Originally built in 1967, the Site 6 rehabilitation project is the largest dam project in Texas. The upgrade includes a concrete labyrinth spillway that reduces the velocity of flood waters during high rainfall events while also allowing for controlled release at a safer engineered rate. The Site 6 dam provides flood protection and environmental benefits to the area.	9/10/2015 – 9/20/2018

*Sites found in Figure 6. Locations of restoration and mitigation strategies in the Plum Creek watershed.

There are 14 Texas Pollutant Discharge Elimination System (TPDES) permitted wastewater point sources that discharge directly into the streams of Plum Creek watershed (Table 17). These point sources range in discharge from 0.075 to 4.5 millions of gallons per day (MGD). Permitted E. coli concentrations for all these discharge limits are 126 cfu/100mL daily average as the mean of all effluent samples within a month. The daily maximum E. coli concentration permitted is 399 cfu/100mL. Discharge monitoring schedules range from once per day, week, month, or quarter. All wastewater permits listed were reevaluated in February 2020.

Table 17. TPDES Wastewater permits in the Plum Creek watershed

FACILITY NAME	Disinfectant	Max Permitted Flow (MGD)	Permit Number	Effective Date	Expiration Date	E. coli effluent limits	E. coli effluent monitoring requirements
KYLE	Chlorine	3/4.5	WQ0011041-002	10/07/2015	02/01/2020	126 cfu/100mL daily avg[1]; 399 cfu/100mL daily max	once per week
LOCKHART NO. 2	UV	1.5	WQ0010210-002	05/13/2015	02/01/2020	126 cfu/100mL daily avg[1]; 399 cfu/100mL daily max	once per day
BUDA	Chlorine	1.5	WQ0011060-001	03/30/2015	02/01/2020	126 cfu/100mL daily avg[1]; 399 cfu/100mL daily max	once per week
LOCKHART NO. 1	Chlorine	1.1	WQ0010210-001	02/12/2015	02/01/2020	126 cfu/100mL daily avg[1]; 399 cfu/100mL daily max	once per week
LULING-NORTH	Chlorine	0.9	WQ0010582-002	08/18/2017	02/01/2020	126 cfu/100mL daily avg[1]; 399 cfu/100mL daily max	twice per month
RANCH AT CLEAR FORK	Chlorine	0.33/0.7	WQ0014439-001	04/20/2016	02/01/2020	126 cfu/100mL daily avg[1]; 399 cfu/100mL daily max	once per month
RAILYARDS-VILLAGE HOMES	Chlorine	0.075/0.12375	WQ0014060-001	09/10/2015	02/01/2020	126 cfu/100mL daily avg[1]; 399 cfu/100mL single grab	once per quarter
GOFORTH	Chlorine	0.0424	WQ0013293-001	04/30/2015	02/01/2020	126 cfu/100mL daily avg[1]; 399 cfu/100mL single grab	once per week
SUNFIELD	Chlorine	0.25/0.5/0.99	WQ0014377-001	05/04/2017	02/01/2020	126 cfu/100mL daily avg[1]; 399 cfu/100mL daily max	once per month
SHADOW CREEK	Chlorine	0.162/0.486	WQ0014431-001	05/21/2015	02/01/2020	126 cfu/100mL daily avg[1]; 399 cfu/100mL single grab	once per month
CROSSWINDS	Chlorine	0.20/0.40	WQ0015011-001	06/24/2015	02/01/2020	126 cfu/100mL daily avg[1]; 399 cfu/100mL single grab	once per month
WINDY HILL	Chlorine	0.45	WQ0015478-001	10/25/2016	02/01/2020	126 cfu/100mL daily avg[1]; 399 cfu/100mL single grab	once per quarter
CAMINO REAL	Chlorine	0.42	WQ0015323-001	11/2/2015	02/01/2020	126 cfu/100mL daily avg[1]; 399 cfu/100mL single grab	Once per month
CALDWELL VALLEY	Chlorine	1.55	WQ0015064-001	05/19/2017	02/01/2020	126 cfu/100mL daily avg[1]; 399 cfu/100mL single grab	Once per month

[1]defines daily avg as the mean of all effluent samples as required by the permit within a period of one calendar month consisting of at least four separate measurements

There are 20 permitted wastewater treatment plants (Figure 6) that discharge directly into the streams of Plum Creek watershed. These include the 14 previously mentioned WWTPs that have acquired voluntary TPDES permits. A riparian restoration project began in September 2017 on the Town Branch reach in Lockhart. This project began by conducting a riparian evaluation to plan and design improved sustainable riparian zone creeks. The restoration project also includes plans to build urban riparian BMPs, build sustainable LID infrastructure in a park along Town Branch, and to conduct public outreach activities and education in support of the Plum Creek WPP. Retrofitting LID projects were completed in May 2019 at the Caldwell County Justice Center including xeriscaping, rainwater cistern, rain garden, and porous pavement parking lot.

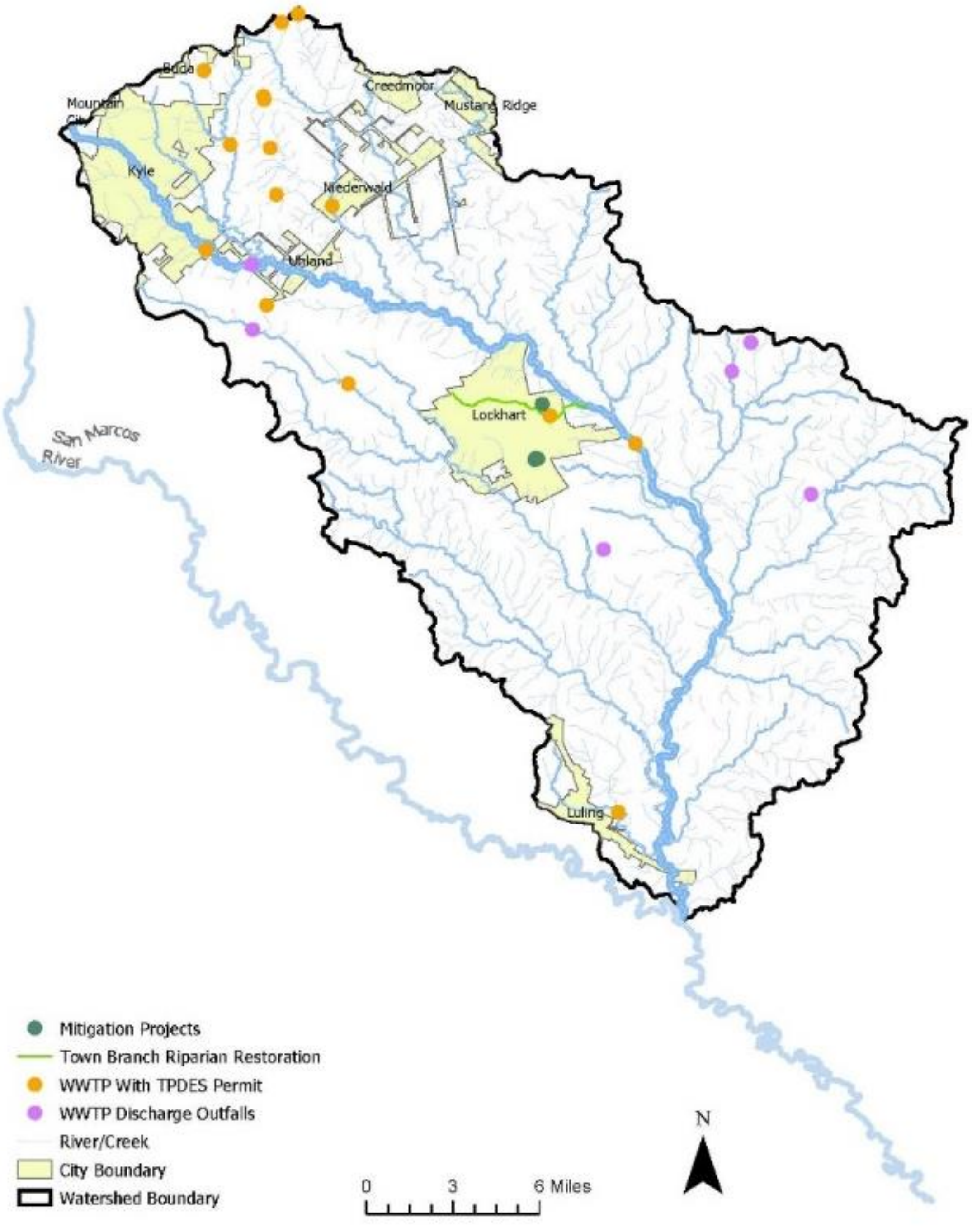

Figure 6. Locations of restoration and mitigation strategies in the Plum Creek watershed.

Table 18 details past and ongoing education and outreach efforts described in the Plum Creek Watershed Protection Plan (PCWPP). The PCWPP has been printed over 750 times and distributed throughout the watershed. Outreach efforts that implement PCWPP components include local, state, and national media outlets that provide stakeholder specific information and contact list information. Local meetings, workshops, and events centered on strong environmental stewardship are scheduled to continue throughout Lockhart. Environmental stewardship events include the annual GBRA Youth Education and Plum Creek School Water Quality Project, annual household hazardous waste and recycling programs, and the annual Keep Lockhart Beautiful Cleanup and Environmental Fair. Education programs provide rural landowners and agricultural producers with nutrient, crop, livestock management, and bacteria source reduction education. Workshops have targeted property owners and managers of land adjacent to Plum Creek to focus on management practices for riparian restoration. GBRA provide education modules for reducing and preventing targeted pollutant source inputs. These modules are available to both municipalities and to the public for stormwater management, wastewater treatment plant operations, septic system owners, and a general fats, oils and grease module for home and business owners. Additional water quality monitoring is maintained by volunteers through the Texas Stream Team program.

Table 18. Watershed education and outreach in Plum Creek watershed.

Education and Outreach	**Description**
Plum Creek Watershed Protection Plan	176-page document available to the public. Over 750 copies have been printed and distributed throughout the watershed
Plum Creek Contact List and Target Outreach	Contact information for watershed protection and target program events for user-specific (stakeholders) electronic communication. Network development strategy for bringing together professional and volunteer organizations that implement Plum Creek WPP components

Local Meetings, Workshops & Events	Events centered on strong environmental stewardship components outlined in the PCWPP
Local, State, and National Media	Increased outreach via local and regional media outlets that provide stakeholder-specific information on events, workshops, and program schedules
GBRA Youth Education and Plum Creek School Water Quality Project	Annual water quality monitoring conducted by students within Hays ISD, Lockhart ISD, and Luling ISD. Classroom instruction and hands-on investigation to educate students about water quality monitoring purposes and techniques
Volunteer Monitoring	Texas Stream Team volunteers monitor 18 locations throughout the Plum Creek watershed
Targeted Pollutant Source Outreach Efforts	-Stormwater Management Module -Online Septic System Module -Online Wastewater Treatment Facility Module -Online Fats, Oils, and Grease Module
Household Hazardous Waste & Recycling Programs	The City of Lockhart hosts annual hazardous and electronic waste collection days
Nutrient, Crop, and Livestock Grazing Management Education	Agricultural and Natural Resource education programs for Caldwell County and Hays County residents and producers
The Lone Star Healthy Streams Program	Provides rural landowners with education on reducing the number of bacteria entering Texas water bodies
Soil and Water Testing Campaigns	Annual soil testing campaigns provided by the Caldwell-Travis Soil and Water Conservation District
Stream & Riparian Workshops	Targeted owners and managers of property adjacent to Plum Creek and its tributaries to focus on management practices to restore and maintain riparian health.
Keep Lockhart Beautiful	The City of Lockhart has partnered with GBRA and The Plum Creek Watershed Partnership to continue the annual Keep Lockhart Beautiful Cleanup and Environmental Fair. Volunteer efforts include annual cleanups both upstream and downstream of Lockhart's WWTPs

City funds were budgeted to replace aging wastewater conveyance infrastructure. The cities of Buda, Kyle, Lockhart have replaced outdated clay pipes but the city of Luling has not reported any replacement or repairs. Buda replaced or repaired a total of 30,977 linear feet between 2008 - 2017. Lockhart reported 5,470 for the 2008 – 2013 period and no replacements were reported for 2014 – 2017 period. Kyle reported the largest amount of wastewater piping replacement or repair of 126,761 linear feet. The city of Luling has reported no replacements or repairs throughout the project period.

Table 19. Sewer lines replaced or repaired by cities in the Plum Creek Watershed. NR means none reported.

City	**2008 - 2013**	**2014 - 2017**
	Sewer Line Repaired/ Replaced (linear feet)	Sewer Line Repaired/ Replaced (linear feet)
Buda	10,023	20,954
Kyle	4,660	122,101
Lockhart	5,470	NR
Luling	NR	NR
Totals	**20,153**	**143,055**

A CWA §319 nonpoint source grant has provided financial incentives and technical assistance for implementation of certain BMPs (Table 20). These BMPs are prescribed in the TSSWCB-certified Water Quality Management Plans (WQMPs) and are approved for funding through the §319 grant. Table 20 summarizes the total number of farms, number of conservation plans needed, and completed conservation plans in Plum Creek watershed. There are a total of 702 livestock operation farms and 142 cropland farms in Plum Creek watershed. There are 235 livestock operation conservation plans needed and 120 plans have been completed. A total of 24 conservation plans are needed for cropland farms with 5 that have been completed though the study period.

Table 20. Financial incentive-based agricultural BMPs.

Approved Practices through § 319(h) Grant	**BMP**
Prescribed Grazing	Manages the controlled harvest of vegetation with grazing animals to improve or maintain vegetation composition
Riparian Herbaceous Buffers	Establishes an area of grasses and forbs along water courses to reduce sediment and nutrient inputs from runoff pollutants
Grassed Waterways	Natural or constructed channel shaped or graded and established with suitable vegetation to protect and improve water quality
Riparian Forest Buffers	Established an area predominated by trees and shrubs located adjacent to and up-gradient form watercourses to reduce pollutants associated with agricultural practices (organic material, nutrients, and pesticides) from shallow groundwater flow
Watering Facilities	Places a tank, trough, or other watertight container for providing animal access to water and protects streams ponds, and water supplies from contamination
Field Borders	Establishes a strip of permanent vegetation at the edge or around the perimeter of a field to protect soil and water quality
Filter Strips	Establishes a strip or area of herbaceous vegetation between agricultural lands and environmentally sensitive areas to reduce pollutant loading in runoff
Nutrient Management	Manages the amount, source, placement, form, and timing of the application of plant nutrients and soil amendments to reduce agricultural nonpoint source pollution from surface and groundwater sources
Conservation Cover	Establishes permanent vegetative cover to protect soil and water resources
Stream Crossings	Creates a stabilized area or structure across a stream providing access for people, livestock, equipment, or vehicles to protect soil and water resources
Cross-Fencing	Facilitates implementation of a rotational grazing system by creating multiple fields for forage utilization by livestock. This practice improves forage and stream health by restricting livestock for a given period
Pipelines	Facilitates the transportation of water source to a watering facility for livestock
Water Well	Provides groundwater for livestock

Pasture and Hayland Planting	Establishes a permanent vegetative cover of improved grasses (seeded or vegetative) for livestock forage
Rangeland Planting	Establishes a permanent vegetative cover of native grasses for livestock forage

Table 21. Agricultural conservation plans.

Type of Agricultural Operation	Total farms	Conservation Plans Needed	Completed Plans
Livestock Operation	702	235	120
Cropland	142	24	5

Several local cleanup projects took place throughout Plum Creek watershed to mitigate illegal dumping. A total of six sites along Plum Creek, Salt Branch, and Copperas Creek were the targeted site locations. The total clean yielded 14,320 lbs. of refuse, 62 tires, and 3 car batteries over the three-day period. The next year, 5 sites were added to the cleanup efforts which yielded 8,500 pounds of refuse, 82 tires, 6 car batteries, 2 sofas, 1 drier, 1 refrigerator, 1 motorcycle, 1 television, and 6 mattresses. The Keep Lockhart Beautiful event in 2012 yielded 2,130 lbs. of refuse and 310 lbs. of recyclables; and 1,580 lbs. of refuse and 840 lbs. of recyclables in 2013. The Plum Creek Watershed Clean-Up in Kyle yielded 2,000 lbs. of refuse in 2012, 740 lbs. of refuse in 2013, and 1,800 lbs. of refuse in 2014. Caldwell and Hays Counties volunteers removed 155 tons of solid waste in 2017.

Table 22. The 2008 cleanup efforts along Plum Creek and its tributaries.

Dates	**03/25/2008-03/28/2008**
Cleanup Site Location	• Plum Creek @ Whisper Road (CR 135) • Plum Creek @ Biggs Road (CR 131)

	• Salt Branch @ Salt Flat Road (Spruce Avenue) • Copperas Creek @ Wattsville Road (CR 140) • Plum Creek @ Old McMahon Road (CR 202) • Plum Creek @ Old Kelly Road (CR 186)
Total Cleanup Yield	• 14,320 lbs. of refuse • 62 tires • 3 car batteries

Rules and regulations for groundwater use are managed and enforced by the PCCD. River basin management by the PCCD focuses on groundwater regulations and permitting (Table 23) for any person(s) or entity that desire to obtain a well permit. The purpose of groundwater management here is to regulate the use and purpose of groundwater sources. Groundwater management areas (GMA) and desired future conditions (DFC) were created in 2010 (Table 24) to preserve and conserve groundwater supplies in Plum Creek watershed.

Table 23. Plum Creek Conservation District's Rules and Regulations for River Basin Management.

Rule
Waste, Pollution
Test Holes
Well Applications & Registrations
Non-Exempt Agricultural Use Well Permits and Dewatering Well Permits
Test Well Permits
Additional Permit Applications
Transport Permit Applications
Miscellaneous Applications
Exempt Wells
Well Requirements
Drilling Permits
Issuance of New or Amended Permits
Permit Duration and Transfer

Location of Well Deposits and Administrative Fees Reporting & Record Keeping Requirements Water Well Driller/Pump Installer Licenses Classification, Spacing, and Production Provisions Rate of Decline Reworking or Replacing a Well Protections of Groundwater Quality - Required Equipment on Wells Transportation of Groundwater from the District Recharge Wells and Facilities, Including Aquifer Storage and Recovery Wells and Projects Right to Inspect and Test Wells Notice Requirements Permit Consideration Permit Conditions

Table 24. Desired future conditions (DFC) for Groundwater Management Areas (GMA) 10 and 13.

GMA	Aquifers	Adopted DFC	Adoption Date
10	Trinity Group	A regional average well drawdown during average recharge conditions that does not exceed 25 ft.	8/23/2010
10	Saline Edwards	Well drawdown at the saline-freshwater interface that averages no more than 5 feet and does not exceed a maximum of 25 ft.	8/4/2010
13	Carrizo - Wilcox	An average drawdown of 23 ft.	4/9/2010

5.2 Water Quality and Discharge Results

Box plot analyses showed nutrient and sediment concentrations varying each year (Appendix A). Overall annual nutrient concentration decreased downstream while annual sediment concentration fluctuated at the southernmost sampling station (Station 4). The highest annual mean concentration of TSS showed a consistent trend recorded at Station 2 for each year.

Mean nutrient concentrations were highest at Station 1. Relatively consistent trends of increasing concentrations of $NO3^-$, TP, and TSS were observed at all four stations from 2016 – 2018. Interquartile ranges (IQR) and median nutrient levels showed a pattern of decreasing $NO3^-$ concentration between the two northern most sampling stations (Station 1 and Station 2) and between two southern most sampling stations (Station 3 and Station 4) while increasing between the central sampling stations (Station 2 and Station 3) for water year 2018. Median concentration levels increased from 2.67 mg/L to 6.38 mg/L between the two central stations then decreased to 3.86 mg/L downstream at Station 4 in 2018. The same pattern was observed with total phosphorus (TP) concentrations. Conversely, total suspended solids (TSS) increased downstream between Station 1 and Station 2 and again between Station 3 and Station 4. TSS concentrations decreased between Station 2 and Station 3 in 2018. All three sampling stations upstream from Station 4 had the highest TP and $NO3^-$ concentration in 2011. Station 4 recorded the highest median and overall IQR for $NO3^-$ concentrations in 2018 and highest median TP concentration of 1.23 mg/L in 2009. Lowest concentration ranges of TSS were recorded in 2011 at all stations. All four stations showed a trend of increasing TP and $NO3^-$ concentrations between 2016 – 2018. Median and IQR for TSS concentrations decreased between 2013 – 2016.

Annual mean flow at Station 1 ranged from 1.67 – 33.94 cubic feet per second (cfs) (Table 25). Annual mean TSS ranged from 18.43 – 52.10 mg/L. The annual mean TP ranged from 0.93 – 3.29 mg/L and $NO3^-$ ranged from 4.00 – 21.24 mg/L. The highest rate of annual mean flow occurred in 2016 at 33.94 cfs and the lowest was recorded in 2011 at 1.67 cfs. Highest annual TSS load occurred in 2010 and lowest annual mean load occurred in 2011 at 18.43 mg/L. The highest annual mean TP concentration occurred in 2009 and lowest was recorded in 2016. The highest annual mean $NO3^-$ concentration occurred in 2011 and lowest was recorded in 2016.

Table 25. Annual means summary at Station No. 17406 (Station 1).

Water Year	Mean Flow (cfs)	Mean Total Suspended Solids (mg/L)	Mean Total Phosphorus (mg/L)	Mean Nitrate-N (mg/L)
2008	3.90	26.21	2.99	12.12
2009	4.84	27.21	3.29	13.34
2010	25.78	52.10	1.29	7.91
2011	1.67	18.43	3.06	21.24
2012	17.90	41.23	2.17	13.49
2013	2.84	26.27	2.44	11.98
2014	10.30	21.83	1.86	10.77
2015	17.84	25.11	1.65	6.85
2016	33.94	25.03	0.93	4.00
2017	22.63	26.99	1.19	4.25
2018	30.25	34.18	1.49	8.10
Annual Mean	**15.66**	**29.11**	**2.00**	**10.12**

Station 2 recorded annual mean flow ranging from 2.17 – 215.67 cfs. The greatest annual mean discharge was recorded in 2010 and least annual mean discharge was recorded 2011. Annual mean summary for TSS ranged from 13.50 – 86.25 mg/L. No TSS data were available for years 2008 – 2010. The annual mean TSS ranged from 0.27 – 2.23 mg/L occurring in 2016 and 2011 respectively. Annual mean $NO3^-$ concentrations ranged from 0.74 mg/L in 2008 to 8.34 mg/L in 2011.

Table 26. Annual means summary at Station No. 18343 (Station 2).

Water Year	Mean Flow (cfs)	Mean Total Suspended Solids (mg/L)	Mean Total Phosphorus (mg/L)	Mean Nitrate-N (mg/L)
2008	5.32	-	1.45	0.74
2009	9.88	-	1.70	3.48
2010	215.67	-	0.95	1.72
2011	2.17	13.50	2.23	8.34
2012	48.70	86.25	1.44	4.50
2013	8.36	20.16	2.04	5.20
2014	121.43	85.55	1.29	3.74
2015	80.26	55.72	0.58	2.17
2016	85.68	35.82	0.27	1.53
2017	103.01	58.09	0.90	3.26
2018	119.13	66.13	0.90	4.14
Yearly Mean	**72.01**	**55.07**	**1.22**	**3.53**

Table 27 describes annual means summaries for flow, sediment, and nutrient concentration loads at Station 3. Annual mean flow ranged from 4.05 cfs in 2009 to 244.79 cfs in 2017. Annual mean TSS ranged from 13.78 mg/L to 153.98 mg/L in 2011 and 2017 respectively. Mean TP concentrations ranged from 0.56 mg/L in 2016 – 1.77 mg/L in 2009. Annual mean $NO3^-$ concentrations ranged from 4.01 – 9.15 mg/L in 2016 and 2011 respectively.

Table 27. Annual means summary at Station No. 12467 (Station 3).

Water Year	Mean Flow (cfs)	Mean total Suspended Solids (mg/L)	Mean Total Phosphorus (mg/L)	Mean Nitrate-N (mg/L)
2008	8.82	19.76	1.10	4.49
2009	4.05	14.88	1.77	6.89
2010	126.54	52.64	0.61	4.09
2011	4.68	13.78	1.51	9.15
2012	56.17	56.31	1.12	5.38
2013	5.87	23.67	1.52	5.82
2014	36.59	29.27	1.06	4.09
2015	112.69	40.82	0.70	4.02
2016	75.16	27.73	0.56	4.01
2017	244.79	153.98	0.66	4.61
2018	70.17	72.77	0.95	5.81
Yearly Mean	**65.34**	**46.57**	**1.03**	**5.23**

Table 28 shows annual means summary at Station 4. Annual mean flow ranged from 7.36 cfs in 2009 to 260.70 cfs in 2017. Annual mean TSS ranged from 14.73 mg/L in 2011 to 83.58 mg/L in 2012. Annual mean TP concentrations ranged from 0.34 to 1.25 mg/L in 2016 and 2009 respectively. Annual mean $NO3^-$ ranged from 1.05 mg/L in 2008 to 4.25 mg/L in 2018.

Table 28. Annual means summary at Station No. 12640 (Station 4)

Water Year	Mean Flow (cfs)	Mean Total Suspended Solids (mg/L)	Mean Total Phosphorus (mg/L)	Mean Nitrate-N (mg/L)
2008	19.88	62.43	0.99	1.05
2009	7.36	16.23	1.25	1.67
2010	152.73	60.81	0.45	2.41
2011	7.38	14.73	0.87	2.53
2012	76.98	83.58	0.65	1.61
2013	20.67	30.03	1.14	2.25
2014	44.57	70.12	0.82	2.81
2015	121.31	63.29	0.40	1.60
2016	150.14	53.55	0.34	1.93
2017	260.70	49.58	0.50	3.70
2018	61.45	42.59	0.68	4.24
Yearly Mean	**85.09**	**49.89**	**0.73**	**2.33**

Monthly concentrations between 2008 – 2018 varied by sampling station. Station 1 trends showed highest $NO3^-$ concentration ranges between August – October and lowest concentrations between February – April. Concentration ranges were highest in October at Station 2, October – November at Station 3, and January – February at Station 4. TSS concentrations were highest between August and October at Station 1, August – November at Stations 2 and 3, and July – September at Station 4. Summaries for monthly mean concentrations and mean discharge can be found in tables 22 – 25.

Monthly mean flow at Station 1 ranged from 4.58 to 28.88 cfs. Large flow ranges (18.65 – 28.88 cfs) occurred between January and May. The lowest flow ranges occurred between June and August. Moderate flow ranges (10.45 – 16.08 cfs) occurred during September through December. The highest concentrations of monthly TSS were observed in July and April. The lowest concentrations of TSS ranges occurred during November through January. Monthly mean TP ranged from 1.26 – 3.58 mg/L. The highest TP concentrations were recorded during July through October and lower concentrations were observed outside of those months. The highest monthly mean $NO3^-$ concentrations were recorded during August through November.

Table 29. Monthly mean summary at Station No. 17406 (Station 1).

Month	Mean Flow (cfs)	Mean Total Suspended Solids (mg/L)	Mean Total Phosphorus (mg/L)	Mean Nitrate-N (mg/L)
January	20.93	19.73	1.60	9.98
February	26.65	30.57	1.47	7.04
March	18.65	25.12	1.42	6.10
April	24.75	44.45	1.62	8.67
May	28.88	30.41	1.87	8.91
June	6.44	31.06	1.74	8.96
July	8.95	44.84	2.16	9.89
August	4.58	21.36	3.58	15.32
September	10.45	33.60	2.61	15.01
October	10.49	33.42	2.51	12.27
November	16.08	15.27	1.99	10.51
December	11.21	13.50	1.26	8.27
Monthly Mean	**15.66**	**29.11**	**2.00**	**10.12**

Table 30 describes monthly mean summaries at Station 2. Monthly mean flow ranged from 3.30 to 165.79 cfs. Monthly mean TSS ranged from 9.00 to 104.28 mg/L. Monthly mean TP ranged from 0.22 to 2.76 mg/L and monthly mean $NO3^-$ ranged from 1.50 to 6.05 mg/L.

Table 30. Monthly mean summary at Station No. 18343 (Station 2)

Month	Mean Flow (cfs)	Mean Total Suspended Solids (mg/L)	Mean Total Phosphorus (mg/L)	Mean Nitrate-N (mg/L)
January	122.00	77.25	0.89	3.69
February	40.28	33.90	1.40	5.26
March	24.48	39.57	0.59	1.99
April	93.19	46.09	1.18	4.10
May	165.79	104.28	0.83	2.13
June	54.90	34.85	1.35	4.91
July	23.21	88.24	1.21	2.15
August	12.77	82.05	1.82	3.42
September	156.94	75.67	1.27	2.41
October	6.55	13.55	1.67	6.05
November	3.30	9.00	2.76	5.48
December	68.00	38.05	0.22	1.50
Monthly Mean	**72.01**	**55.07**	**1.22**	**3.53**

Table 31 shows monthly mean summaries at Station 3. Mean monthly flow ranged from 6.65 to 166.98 cfs. Mean monthly TSS ranged from 16.82 to 111.43 mg/L. Mean monthly TP ranged from 0.78 to 1.37 mg/L. Mean monthly $NO3^-$ ranged from 2.74 to 7.57 mg/L.

Table 31. Monthly mean summary at Station No. 12467 (Station 3).

Month	Mean Flow (cfs)	Mean Total Suspended Solids (mg/L)	Mean Total Phosphorus (mg/L)	Mean Nitrate-N (mg/L)
January	68.24	46.62	0.89	5.80
February	128.64	111.43	0.86	5.31
March	166.98	39.97	0.78	4.20
April	86.82	50.05	0.80	2.74
May	30.65	31.88	0.85	3.30
June	50.68	53.69	1.01	3.88
July	13.38	46.62	1.07	5.39
August	6.65	32.29	1.37	6.70
September	92.57	45.53	1.29	5.43
October	44.99	70.63	1.25	7.57
November	68.11	19.65	1.07	7.25
December	22.68	16.82	1.10	5.77
Monthly Mean	**65.34**	**46.57**	**1.03**	**5.23**

Table 32 describes monthly mean summaries at Station 4. Monthly mean flow ranged from 12.11 to 149.31 cfs. Monthly mean TSS ranged from 17.74 to 88.21 mg/L. Monthly mean TP ranged from 0.51 to 1.11 mg/L. Monthly mean $NO3^-$ concentrations ranged from 1.08 to 4.49 mg/L.

Table 32. Monthly mean summary at Station No. 12640 (Station 4).

Month	Mean Flow (cfs)	Mean Total Suspended Solids (mg/L)	Mean Total Phosphorus (mg/L)	Mean Nitrate-N (mg/L)
January	87.14	70.17	0.66	4.49
February	58.43	24.33	0.57	3.34
March	167.62	79.74	0.68	2.23
April	122.77	70.62	0.59	1.49
May	100.57	74.22	0.70	1.48
June	117.82	46.57	0.84	1.51
July	18.55	36.35	0.83	1.97
August	12.11	17.74	0.89	1.08
September	72.11	35.01	1.11	2.75
October	149.41	88.21	0.69	2.12
November	74.43	32.81	0.51	2.49
December	40.27	20.23	0.59	2.86
Monthly Mean	**85.09**	**49.89**	**0.73**	**2.33**

The flood of record was a discharge rate of 20,700 cfs in August 2017 which corresponded with the highest rain fall event of 6.9 inches. Monthly precipitation data indicated wet seasons to range between the months of September - January and March – May. Drier months occurred in February and in June through August. The wettest years were 2009, 2010, 2012, 2013, 2015, and 2017. The highest precipitation total over the study period was 41.85 inches in the 2015 water year. Based on the collective sum of precipitation data, the overall wettest month during the study period occurred in September. Tables 33 and 34 show summaries based on monthly and yearly mean discharge, total precipitation, and mean temperature.

Total monthly mean discharge ranged from 12.73 to 309.24 cfs with median discharge ranging from 0.80 to 10.4 cfs. Total precipitation for every month between 2008 – 2018 ranged from 11.30 to 45.50 inches. The month of May had the highest cumulative amount of precipitation and the month of July had the lowest cumulative amount of precipitation throughout the study period. Monthly precipitation totals ranged from 11.30 inches in July to 44.23 inches in September. Monthly mean temperatures displayed a seasonal increase from 48.9°F in January to 85.5 °F August. Mean monthly temperatures then began to decrease to 79.3 °F in September and continued to decrease to 51.6 °F in December.

Table 33. Monthly mean and median summary at USGS Gage 0817300. Total monthly precipitation between 2008 – 2018 at USC00415285 at Lockhart State Park.

Month	Mean Q (cfs)	Median Q (cfs)	Total Precipitation (in)	Mean Temperature (°F)
January	136.73	9.57	30.90	48.9
February	102.28	7.80	13.02	54.7
March	141.83	10.40	29.72	61.6
April	125.30	6.13	28.02	68.4
May	309.24	6.52	45.50	75.8
June	125.80	3.22	15.03	83.3
July	12.73	1.88	11.30	84.9
August	169.67	0.80	28.23	85.5
September	56.03	2.74	44.23	79.3
October	101.24	3.19	32.39	69.6
November	160.34	5.95	18.18	59.9
December	47.95	8.90	25.28	51.6

The mean discharge between water year 2008 and 2018 ranged from 7.78 to 299.69 cfs and median discharge ranged from 1.27 to 22.75 cfs. Total annual precipitation between 2008 - 2018 ranged from 12.87 to 45.15 inches. The wettest year occurred in 2010 and conversely, the driest year occurred in 2011 based on total annual precipitation. Mean annual temperatures displayed a relative increasing pattern from 2008 – 2018. These temperatures ranged from 66.9 to 72.1 °F in 2018. The 3 highest recorded temperatures occurred between the 2016 and 2018 water year.

Table 34. Annual mean and median summary discharge with total precipitation and mean temperature by Water Year.

Water Year	Mean Q (cfs)	Median Q (cfs)	Total Precipitation (in)	Mean Temperature (°F)
2008	11.45	2.81	18.26	68.1
2009	7.78	1.61	17.43	68.7
2010	175.59	19.10	45.15	67.2
2011	9.02	1.69	12.87	69.5

2012	140.81	1.27	37.81	69.5
2013	12.40	2.82	22.41	67.7
2014	116.48	5.38	28.15	66.9
2015	267.23	10.60	41.85	67.6
2016	299.69	22.75	30.76	69.6
2017	263.18	13.30	37.56	70.7
2018	63.62	8.79	29.55	72.1

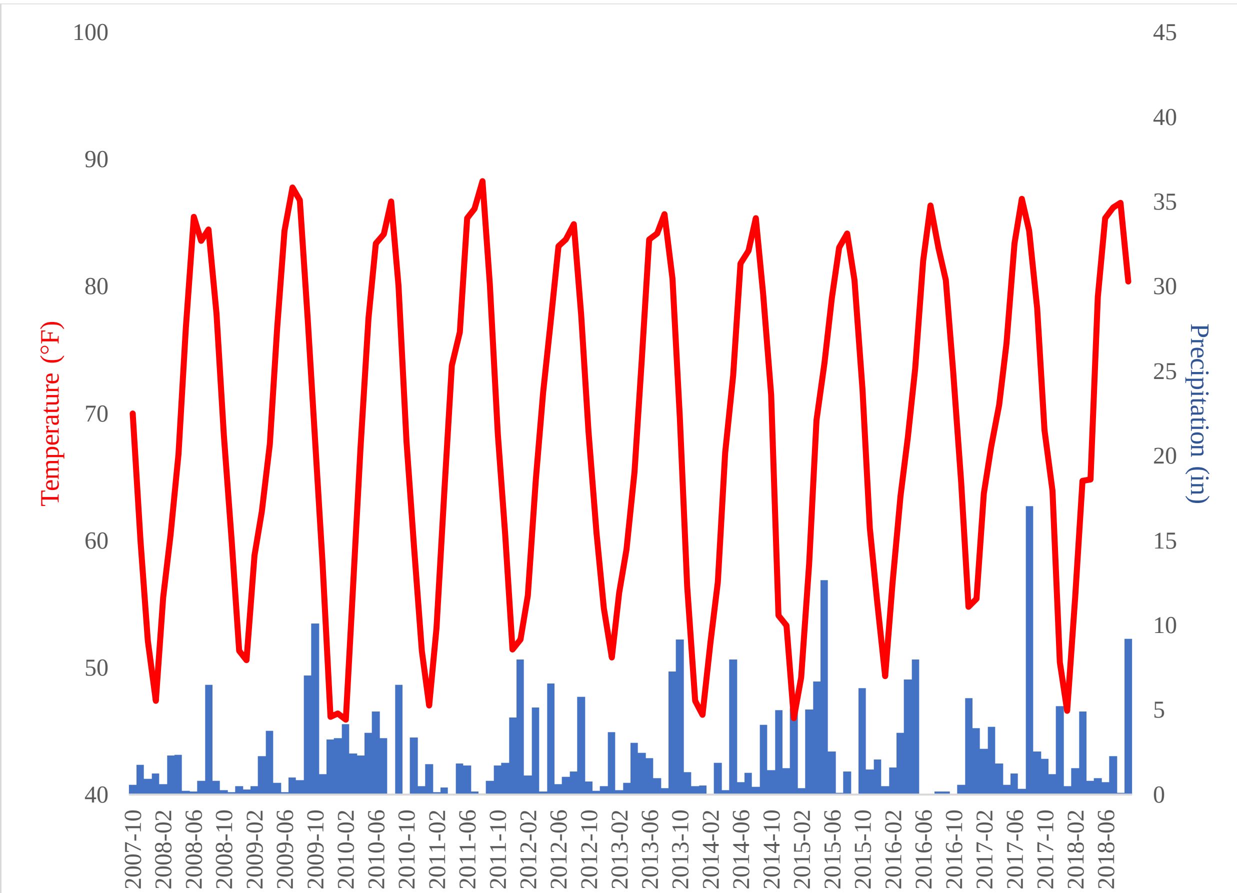

Figure 7. Monthly Climograph for the Plum Creek watershed area. Mean monthly temperature and total monthly precipitation were obtained from USC00415285 at Lockhart State Park.

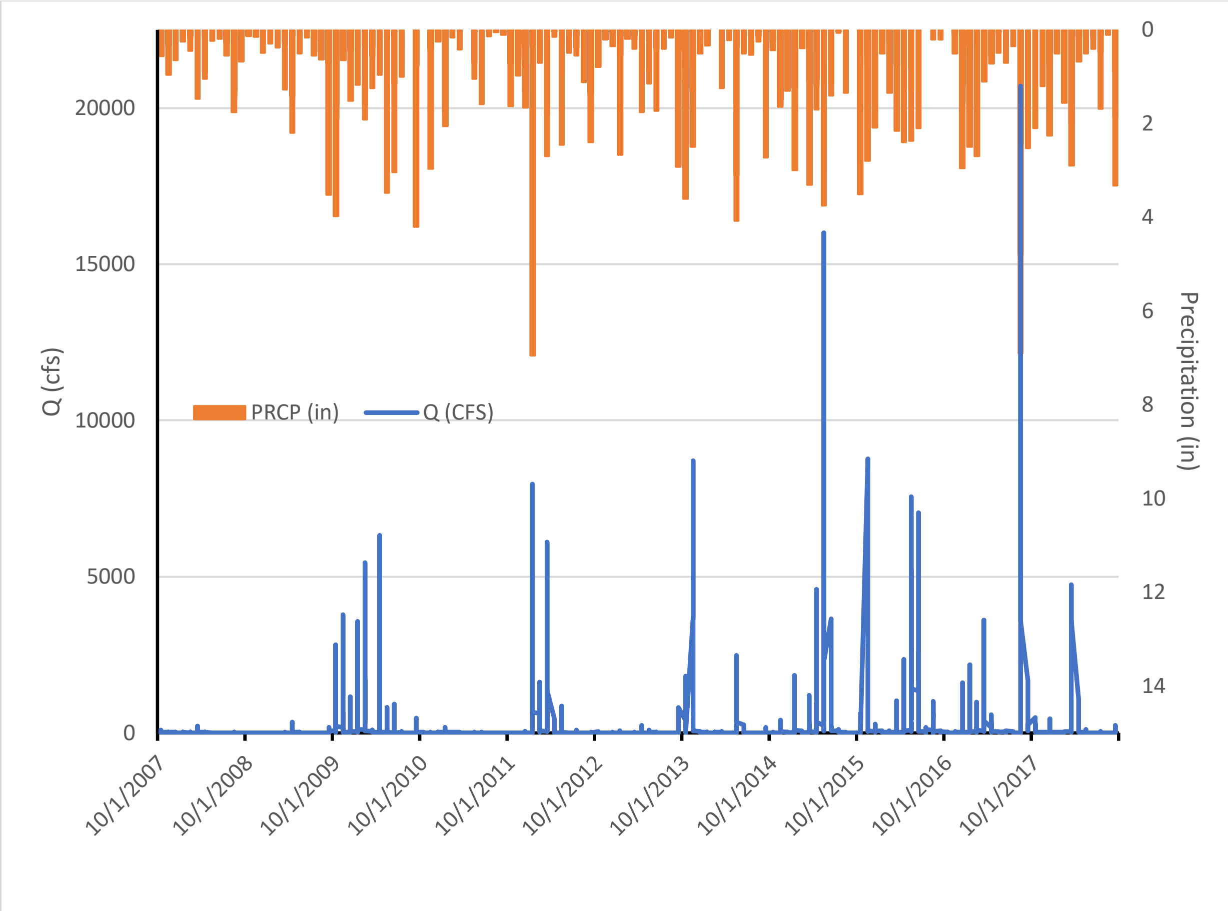

Figure 8. Daily discharge time Series for Plum Creek at XX (USGS 008173000). Daily total precipitation was obtained from Weather Station USC00415285 at Lockhart State Park.

Kyle WWTP (Station No. 20486) data summaries in Table 35 displayed a moderately consistent flow ranging between 2.15 to 3.67 cfs from 2008 – 2018. Mean flow deviated from this range in 2016 when discharge rates reached a mean of 4.26 cfs. Mean discharge flows were greatest in 2016, 2017, and 2018. Total suspended solid (TSS) mean and annual concentrations were highest in 2012. Mean TSS varied by year with the highest means recorded in 2011 (14.43 mg/L) and 2012 (25.39 mg/L), while mean discharge flow was relatively low compared to other years. Mean TP remained within a range of 3.19 to 4.89 mg/L outside of 2016 and 2017. Mean TP was 221.97 mg/L in 2016 when mean discharge flow was greatest. Mean TP was recorded highest in 2017 at 839.46 mg/L when mean discharge flow was relatively high compared to other years. Conversely, mean $NO3^-$ was lowest in 2017, recorded at 4.31 mg/L. Mean $NO3^-$ ranged from 13.08 to 27.00 mg/L for all other years. Mean TSS and $NO3^-$ were independent of mean discharge flow while the highest mean TP was recorded during 2 out of the 3 highest mean flow rates.

Table 35. Annual mean concentrations and discharge summary at City of Kyle WWTP.

Water Year	Mean Flow (cfs)	Data Count Flow	Mean TSS (mg/L)	Data Count TSS	Mean TP (mg/L)	Data Count TP	Mean $NO3^-$ (mg/L)	Data Count $NO3^-$
2008	3.17	2	4.15	2	4.89	2	19.45	2
2009	2.57	2	7.50	2	4.37	2	13.80	2
2011	2.15	6	14.43	6	4.06	6	27.00	6
2012	2.93	12	25.39	12	4.37	12	23.01	12
2013	2.15	14	8.26	12	3.42	12	18.56	12
2014	2.83	12	5.99	12	3.95	12	22.07	12
2015	2.97	12	7.41	12	3.40	12	14.12	12
2016	4.26	11	5.12	11	221.97	11	13.08	11
2017	3.53	12	9.82	12	839.46	12	4.31	12
2018	3.67	9	8.24	9	3.19	9	20.07	9

The same annual mean discharge values from Table 35 were used to visually compare total annual concentrations in Table 36. Total annual TSS concentrations varied significantly each year, ranging from 15.00 to 304.71 mg/L. The greatest annual concentration was recorded in 2012 when mean discharge flow was a moderate 2.93 cfs. Annual TP concentrations varied less when compared to TSS concentrations but recorded two significantly high values in 2016 (2441.69 mg/L) and in 2017 (10073.48 mg/L). Annual $NO3^-$ concentrations displayed an increased trend from 2008 to 2014 then decreased from 2014 to 2017. Annual $NO3^-$ concentrations more than doubled from 51.67 mg/L in 2017 to 180.60 mg/L in 2018.

Table 36. Annual concentrations and mean discharge summary at City of Kyle WWTP.

Water Year	Mean Flow (cfs)	Annual TSS Concentration (mg/L)	Annual TP Concentration (mg/L)	Annual $NO3^-$ Concentration (mg/L)
2008	3.17	8.30	9.77	38.90
2009	2.57	15.00	8.74	27.60
2011	2.15	86.60	24.36	162.00
2012	2.93	304.70	52.41	276.10
2013	2.15	99.10	40.99	222.67
2014	2.83	71.90	47.44	264.85
2015	2.97	88.90	40.77	155.30

2016	4.26	56.30	2441.69	143.90
2017	3.53	117.80	10073.48	51.67
2018	3.67	74.20	28.74	180.60
Total	**-**	**922.78**	**12768.39**	**1523.59**

Lockhart WWTP#2 (Station No. 20494) data show the highest discharge mean flow (cfs) occurring in 2015 and 2016. The highest suspended solids concentration mean occurred in 2009 and mean TP concentration was highest in 2008. It should be noted that these years consisted of only two data entries. Mean annual $NO3^-$ ranged from 4.34 to 10.80 mg/L. A relatively high trend of mean $NO3^-$ was recorded from 2014 to 2018.

Table 37. Water quality and mean discharge summary for City of Lockhart WWTP #2.

Water Year	Mean Flow (cfs)	Data Count Flow	Mean TSS (mg/L)	Data Count TSS	Mean TP (mg/L)	Data Count Total Phosphorus	Mean $NO3^-$ (mg/L)	Data Count $NO3^-$
2008	1.29	2	4.65	2	3.87	2	8.08	2
2009	1.34	2	13.35	2	3.31	2	10.80	2
2011	1.58	6	4.81	6	2.51	6	6.24	6
2012	1.28	12	5.99	12	2.54	12	4.96	12
2013	1.35	12	3.84	12	2.21	12	4.34	12
2014	1.18	12	4.64	12	2.18	12	7.23	12
2015	2.09	12	5.17	12	2.30	12	7.93	12
2016	2.24	12	5.46	12	2.89	12	9.86	12
2017	1.40	12	4.63	12	2.84	12	9.01	12
2018	1.37	9	5.97	9	2.89	9	6.16	9
Overall Mean	**-**	**91**	**5.22**	**91**	**2.58**	**91**	**7.14**	**91**

The same annual mean flows were used from Table 37 to visually compare annual sediment and nutrient concentrations at the City of Lockhart WWTP #2 in table 38. Overall concentrations were independent of mean annual flow discharge at the wastewater point source. Annual TSS, TP, and $NO3^-$ were also independent from each other. That is to say that there were no observable trends of one measure increasing/decreasing for a particular pollutant that caused another pollutant to increase/decrease in that same water year. Annual TSS loads ranged from 9.30 to 71.87 mg/L with the highest annual concentration occurring in 2012. Annual TP loads ranged from 6.62 to 34.70 mg/L in 2009 and 2016 respectively. Annual $NO3^-$ concentrations showed the largest range of 16.15 mg/L in 2008 to 118.28 mg/L in 2016. Annual $NO3^-$ concentrations were also significantly high in 2017 at 108.12 mg/L. It should be noted that for water year 2008 and 2009, only two data entries were available.

Table 38. Water quality and total discharge summary for City of Lockhart WWTP #2.

Water Year	Mean Flow (cfs)	Annual TSS Concentrations (mg/L)	Annual TP Concentrations (mg/L)	Annual $NO3^-$ Concentrations (mg/L)
2008	1.29	9.30	7.74	16.15
2009	1.34	26.70	6.62	21.60
2011	1.58	28.86	15.04	37.41
2012	1.28	71.87	30.45	59.51
2013	1.35	46.10	26.47	52.03
2014	1.18	55.63	26.17	86.71
2015	2.09	56.90	27.54	87.22
2016	2.24	65.50	34.70	118.28
2017	1.40	55.60	34.02	108.12
2018	1.37	53.70	25.99	55.43
Overall Total Loads	**-**	**470.16**	**234.74**	**642.46**

5.3 Land use/Land Cover Change Analysis

Table 39 illustrates land use as a percent of total watershed area in years 2001, 2006, 2011, and 2016. Change in percentage points was calculated from percent values in 2001 and 2016. Percentage points were used to represent actual change in land use/landcover (LULC) during this period instead of percent change (rate of change). Developed open space, deciduous forest, shrub/scrub, grassland/herbaceous, and pasture/hay were the major land use and land cover types in 2001. Cultivated crops were also a notable land use type in 2001, making up 6.88% of Plum Creek watershed. Similar trends in LULC were observed in 2006 but showed slight increases in all developed land types, deciduous forest, pasture/hay, and cultivated crops. Developed, open space decreased significantly from 10.36% to 6.0% between year 2006 and 2016 resulting in a decrease of 4.36 percentage points. Shrub/scrub and grassland/herbaceous landcover decreased between each year of record. Pasture/hay increased each year of record between 2001 and 2016. Percentage points increases from 2001 to 2016 for all developed land types. Pasture/hay land use showed the highest percentage point increase of 16.06 from 2001 to 2016. Promotion of financial incentives outlined in Approved Practices through § 319(h) Grant (Table 20) may explain why pasture/hay land use trends increased during this period. Financial incentives fail to explain increased cultivated crops land use. Shrub/scrub landcover had the largest decrease in percentage points, followed by developed, open space. Developed, open space and shrub/scrub land decreased while developed low, medium, and high intensity land use increased. Slight increases in baren land (areas <15% vegetation cover) and mixed forest land area increased between 2001-2016. Population increased significantly during this study period and may have influenced the loss of developed, open space and shrub/scrub land in Plum Creek watershed.

Table 39. Percent land use/land cover change from 2001 – 2016

Classification	2001	2006	2011	2016	Percentage Point Change between 2006-2016
Open Water	0.55%	0.54%	0.53%	0.63%	0.09
Developed, Open Space	10.36%	10.44%	10.58%	6.00%	-4.36
Developed, Low Intensity	0.93%	1.13%	1.36%	1.66%	0.73
Developed, Medium Intensity	0.31%	0.61%	0.86%	1.10%	0.80
Developed High Intensity	0.11%	0.16%	0.24%	0.31%	0.20
Barren Land (Rock/Sand/Clay)	0.08%	0.21%	0.26%	0.18%	0.10
Deciduous Forest	11.21%	11.30%	10.94%	10.74%	-0.48
Evergreen Forest	1.32%	1.30%	1.26%	0.93%	-0.39
Mixed Forest	1.51%	1.50%	1.44%	2.49%	0.98
Shrub/Scrub	31.53%	30.79%	29.64%	17.95%	-13.58
Grassland/Herbaceous	11.37%	10.64%	10.86%	7.22%	-4.15
Pasture/Hay	20.83%	21.35%	21.64%	36.89%	16.06
Cultivated Crops	6.88%	7.03%	7.39%	11.19%	4.31
Woody Wetlands	3.01%	2.99%	2.99%	2.66%	-0.35
Emergent Herbaceous Wetlands	0.01%	0.02%	0.02%	0.05%	0.04

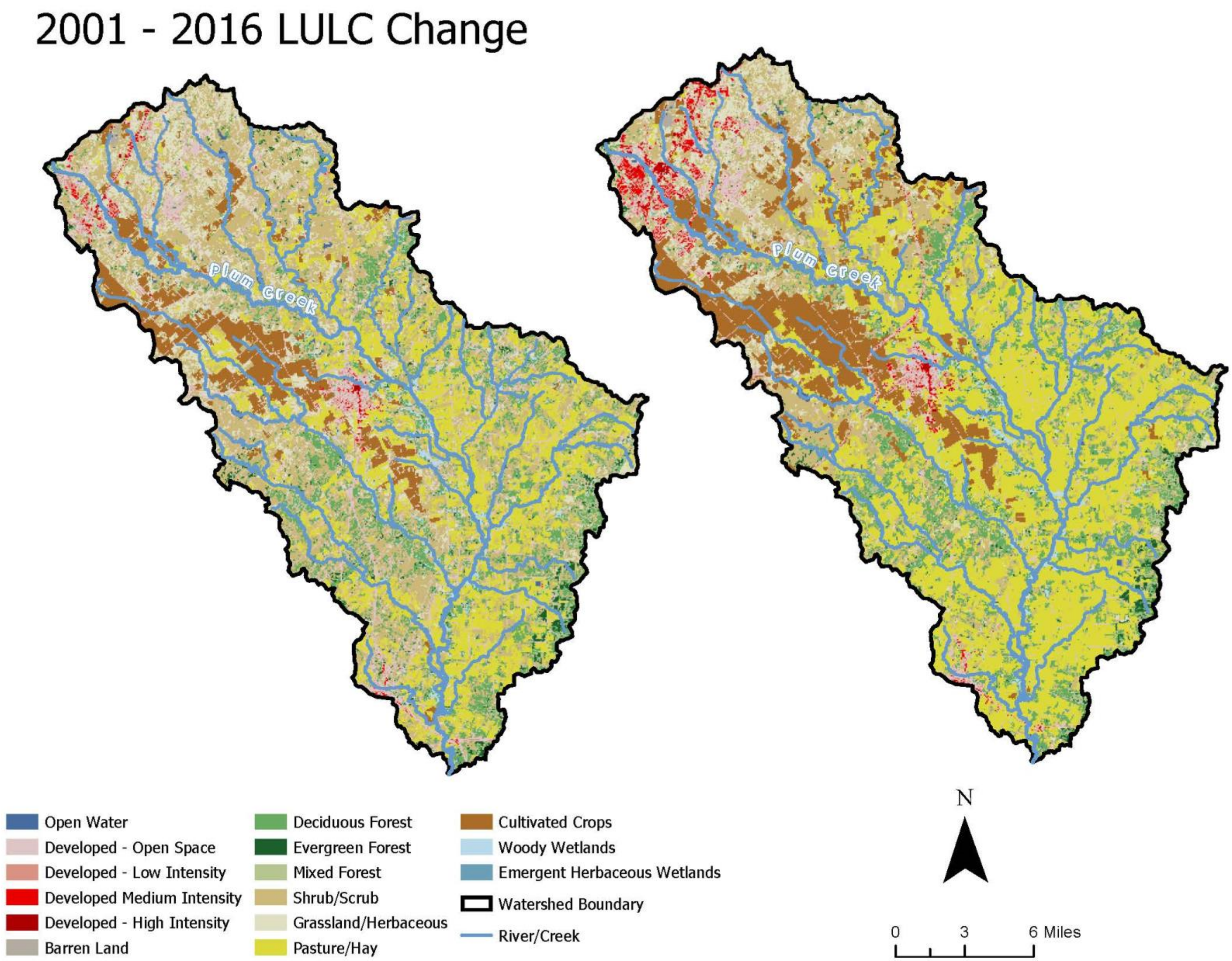

Figure 9. Land use/land cover change from 2001 to 2016. Note the increased development around the headwaters in the northwestern part of the watershed.

6. Discussion and Conclusions

6.1 Continuing Watershed-scale Management in Plum Creek

Watershed planning in the Plum Creek watershed in central Texas has been a combination of federal, state, and local efforts using a wholistic approach to maintaining good water quality and sufficient water quantity. Watershed-scale mitigation strategies were concentrated in years following 2010 and are planned to continue through 2020. Many of these efforts are geared towards retrofitting sewer infrastructure and managing WWTP effluent discharges to meet higher water quality standards set by the EPA. Management measures continue to focus on improving agricultural land use practices through BMP incentive-based strategies. Education and outreach efforts continue to engage the public in environmental stewardship and watershed protection practices.

6.2 Urban Impacts on Water Quality and Quantity

Although most of the land use in the watershed is agricultural, two towns (Luling and Lockhart) have shown increases in population accompanied by increased impervious surface land cover. Land use/land cover (LULC) analyses (Table 38 and Figure 10) showed increased urban land development and decreased open space between 2001 – 2016. Urban development may have contributed to increased impervious surface runoff, resulting in degraded water quality from stormwater inputs. WWTPs in the upper watershed have been stressed during this study period due to significant population increases in Kyle, Buda, and Uhland (Plum Creek Watershed Protection Plan 2014). Significant population increases in these areas may also explain trends in the upsurge of urban development.

The LULC Change Analysis results reported an increase in all development types (low, medium, and high intensity) throughout the study period. Further investigation may show that development in the area to be a factor influencing trends in total pollutant loads entering the river networks from urban stormwater inputs. Increased stress on WWTPs along with continued urban development reported throughout all PCWPPs, support Walsh's *Urban Stream Syndrome* symptom of elevated concentrations of nutrients and contaminants. Results from data collected on targeted WWTPs all show an increasing trend in annual mean pollutant concentrations for TSS, $NO3^-$, and TP during the period of greatest population growth found in the 2010 census.

The Plum Creek Watershed Protection Plan includes concepts outlined by Kaushal and Belt (2012) by addressing the urban infrastructure of wastewater point source inputs that contribute to and influence the hydrography and health of streams. Cities within Plum Creek watershed have budgeted funds to replace aging wastewater conveyance infrastructure (Table 18) which may lead to improved water quality in Plum Creek. However, data collected from the three WWTPs in this study reflected a more consistent trend in annual flow discharge (cfs) compared to pollutant concentrations. Significant fluctuations in pollutant concentrations compared to consistent WWTP discharge rate indicate that other factors (agriculture, urban stormwater, wildlife) are influencing water quality in Plum Creek. Wastewater point sources can generally be identified more easily than stormwater inputs since wastewater is collected and treated at specific sites. Stormwater conveyance systems, although generally ending at point source outflows, collect numerous nonpoint source pollution contaminates draining from multiple areas like urban roads and parking lots (Hong et al. 2018; Shao et al. 2018; Barbier 2018), making this NPS more difficult to mitigate. Projects like porous pavement parking lots, raingardens, xeriscaping, and rain cisterns at the Comal County Justice Center in Lockhart, TX are strategies that could have a larger impact if utilized for all future development in Plum Creek watershed. Agricultural land use must also be considered to address pollutant inputs in Plum Creek, especially NPS.

6.3 Agricultural Impacts on Water Quality and Quantity

Increases in land use for cultivated crops could be a source for increased nutrient concentrations during the 2018 water year and overall nutrient inputs during the study period. Agricultural land use is a significant source of TP and $NO3^-$ NPS pollution entering waterbodies through groundwater or saturated overland flow (Boyer et al. 2002; Foley et al. 2005; Serio et al. 2018; Chotpantarat and Boonkaewwan 2018; Li et al. 2018). Increased implementation of BMP strategies of approved practices though the CWA § 319(h) grant could help to mitigate these nutrient input sources. Septic systems also pose as a groundwater nitrate pollutant source (Clean Rivers Program Basin Summary, 2018). Fluxes of nutrient inputs from urban area stormwater sources must also be considered as a significant source of load inputs during large rain events (Groffman et al. 2014; Janke et al. 2014).

The largest and most consistent precipitation patterns were between 2015 – 2017, which likely accounts for increased nutrient and suspended solids loads for those years. Indeed, watershed nutrient runoff is typically higher during wet periods (Poor and McDonnell 2007; Sharpley et al. 2007; Pellerin et al. 2011; Meybeck and Moatar 2012; Dhillon and Inamdar 2013; Lian et al. 2019), which may account for large pollutant loadings at that time. Total and mean precipitation decreased in 2018, but nutrient levels were highest during this period compared to 2016 and 2017. These patterns may indicate stormwater inputs from developed land imperviousness during large rain events and total WWTP discharge, contributing to the increases in nutrient and TSS loads. Seasonal inputs from large precipitation events account for higher discharge rates and concentrations in those months. Based on these patterns, climate variability may play a large role in affecting water quality and discharge rates. Increases in mean annual temperature and total annual precipitation implies increased atmospheric temperatures and large rain events with extended periods of dry months. Heavier but less frequent rain events can lead to large nutrient and sediments loads entering river systems at one time within a year (Chaplot et al. 2005; Hopkins et al. 2017; Frazar 2019).

The increase of open water landcover between 2001 – 2016 may be attributed to increased precipitation and collective WWTP discharges. BMP practices are dependent on whether stream flow in the area is classified as ephemeral, intermittent, or perennial (Svec et al. 2005). Definitions for each stream flow type are generalized as (Helms 1998; Stringer and Thompson 2000; Stringer and Perkins 2001; Svec 2005):

Perennial: Steams that hold water throughout the year.

Intermittent: Streams that hold water during wet periods of the year

Ephemeral: Channel formed by water during or immediately after precipitation events as indicated by an absence of forest litter and exposure of mineral soil.

Texas defines perennial streams as flowing 90% of the time, intermittent streams flowing between 30 and 90% of the time, and ephemeral streams flowing less than 30% of the time (Texas Forest Service 2000). Watersheds like Plum Creek contain ephemeral, intermittent, and perennial steams, therefore affecting pollutant dilution potential depending on where point source and nonpoint source inputs occur along the stream channel.

Plum Creek was historically intermittent north of Lockhart, TX, running dry during periods of drought but flowing after heavy rain events (GBRA 2019). Plum Creek, south of

Lockhart is spring fed and flows year-round, therefore considered a perennial section of the main channel (GBRA 2019). Today, urban development has led to an increase in the number of WWTPs at the northern headwaters and has transformed this once intermittent section above Lockhart into an effluent dominated perennial stream, flowing year-round (Plum Creek Watershed Protection Plan 2018). Svec (2005) points out that generally, as flow duration increases, the potential for NPS potential increases due to soil disturbances. The input of persistent wastewater point sources to create perennial flow combined with potential increase of soil erosion of a once historically intermittent stream may give evidence for the consistently high mean and median nutrient loads that were recorded at Station 1. These inputs may also give reason to why annual nutrient median and mean values did not always decrease downstream from Station 2 and Station 3 since both stations are located south of large urban areas and WWTPs.

Large rain events followed by periods of drought stress a river's system to maintain good water quality standards and consistent discharge patterns. Historical agricultural land use along with large precipitation events between 2014 – 2017 may account for persistent increases of annual mean and median TP and $NO3^-$ concentrations between 2016 – 2018 at Station 4. The increase of cropland/hay land use between 2001 – 2016 could also increase legacy potential patterns of TP and $NO3^-$ loads from groundwater sources in the future.

Collective increases from developed land and agriculture land use are exacerbated by large precipitation events which may have led to the large concentrations of $NO3^-$, TP, and TSS recorded at Station 4 on Plum Creek between 2016 - 2018. Effects from future development will have continued impacts on water quality and quantity. Proper mitigation for water quality must be considered for all future development and continued agricultural practices in the Plum Creek watershed to ensure healthy riverine landscapes and continued river network functionality. Therefore, the management of water should incorporate both local (farm, city, county) and regional (catchment and river basin) scale techniques in decision-making processes (Jain and Singh 2003; Pulido-Velazquez and Ward 2017).

6.4 Watershed Management Plan

The City of Lockhart has experienced urban growth and is expected to have future development dominated by single-family residential development (Plum Creek Watershed Protection Plan 2018). Many of the land and watershed-scale management strategies previously discussed have been completed, are currently being practiced, or have been planned to be implemented in the 2018 Plum Creek Watershed Protection Plan (PCWPP). The PCWPP has outlined watershed-scale strategy efforts aimed at mitigating the stresses that a sustainable river management concept faces for future economic, social, and environmental goals (Table 9). Mitigation strategies were developed for both agricultural and urban settings.

River basin management strategies for flood control and groundwater management are implemented through rules, regulations, and permitting outlined in the municipal work of the Plum Creek Conservation District (PCCD). The PCCD operates, manages, and maintains 28 flood control structures that were built by the Soil Conservation Service. In 1989, legislation was amended which gave the PCCD the responsibility of regulating multiple aquifer resources for the conservation, preservation, protection, recharging, and prevention of groundwater waste. All current rules, regulations, and permitting requirements were made effective December 16th, 2018 (Plum Creek Conservation District Rules, 2018). Development of these rules implies an approach to traditional river basin management for minimizing flood risk and preserving water supply for irrigation, power, and domestic use (Allan et al. 2008; Karr and Chu 2000; Newson 2009). The PCCD is currently developing a document (Water Control and Improvement District Rules) aimed at water quality control implementation within their jurisdiction. The PCCD has also outlined goals in their *2017 Groundwater Management Plan*, designed to extend the quantity and preserve the quality of water available in aquifers in Caldwell and Hays county. Their mission is to protect, conserve, and prevent waste of groundwater through the use of permitting requirements and creating management strategies in conjunction with household, livestock, and municipal water users.

The *Lockhart Comprehensive 2020 Plan* outlines future growth goals consistent with sustainable land development strategies that would help improve water quality and quantity by discouraging “leap-frog” development and promoting the enhancement and expansion of open spaces and environmentally sensitive areas through new land development policy considerations. These three documents show a transition from a singular traditional water management (flood prevention and secured water supply) style to a newer, more holistic river basin management strategy. They involve decision makers and the role of governance frameworks to create a more sustainable watershed-scale management approach that recognizes spatial and temporal scales previously discussed (Biermann et al. 2009; Genskow 2009; Medd and Marvin 2008; Moss 2004; Pahl-Wostl et al. 2007). These documents also possess experimental ethos that promote the development of adaptive, sustainable river management that is considered necessary for future watershed-scale approaches to water quality and quantity (Gregory 2011; Doyle and Drew 2008). The riparian restoration project on the Town Branch tributary in Lockhart represents an effective BMP strategy that can potentially intercept runoff from impervious areas and control sediment and nutrient load inputs (Oklahoma Conservation Commission 2008; Martin-Mikle 2015).

The majority of agricultural land use is managed through traditional farming techniques, but some local landowners (ranch/farmland) have used conservation plans developed through efforts of the Plum Creek Watershed Partnership when growing and/or maintaining crops or livestock (Table 20). These BMPs are prescribed in the TSSWCB-certified Water Quality Management Plans (WQMPs) and are approved for funding through the CWA §319 grant. Annual soil testing is performed by the Caldwell – Travis Soil and Water Conservation District. Grant funding through a Clean Water Act (CWA) Section 319(h) grant was used to pay for 70 soil samples in Plum Creek watershed. Soil testing campaigns were meant to provide environmental benefits by reducing nutrient loadings to the soil and subsequently water resources. This campaign also sought to create an opportunity for an economic impact through agricultural BMP incentives. These strategies also highlight efforts involving decision-makers and local farmers, utilizing federal funding for BMPs practices, and implementation of aforementioned agricultural BMP practices (Table 20). These conservation farming plans were made possible through a system of local, state, and federal involvement of experimental ethos promoting the development of adaptive, sustainable river management by sustainably managing the further reaching landscape (Gregory 2011; Doyle and Drew 2008). Additionally, efforts have been made to create local workshops to educate and inform local landowners on how to manage their land for beneficial watershed health, tax breaks, and how to reach the appropriate contacts for those who want to gain more knowledge or information about the watershed and beneficial land practices.

The efforts by municipal, local, and private organizations towards watershed – scale management for water quality and quantity is present in Plum Creek watershed. But the growth of developed land and the continued practice of traditional till agriculture will continue to impair water resources in this watershed. Water quality analyses performed in this study do not indicate the desired mitigation of TSS, TP, and $NO3^-$ pollutant inputs. It should be noted that these pollutants were not the reason for Plum Creek to be a federally listed impaired water segment. They do indicate a potential for future ecosystem impairments for aquatic life and diminished ecosystem services.

Watershed management is challenged by the environmental, social, and economic characteristics within its region, as well as the larger river basin characteristics of the San Marcos and Guadalupe Rivers. Regional to local scale management measures must include broad, collective strategies to secure the biological, chemical and physical integrity of our nation's waters for present and future generations. A watershed-scale approach to water quality management includes these facets by creating a holistic strategy of federal, state, and local involvement.

This study applied concepts outlined in the literature review such as the *Urban Stream Syndrome* and *Legacy Effect* to analyze water quality in Plum Creek. This study can also be used as a resource for finding past and ongoing water quality studies that have taken place in Plum Creek watershed. Additionally, water quality and LULC change analysis could be used as an interim report on the current condition of Plum Creek. A major emphasis for this study was placed on the synthesis of a collection of reports, studies, and analyses conducted by multiple stakeholders in order to progress water quality analysis needs in Plum Creek. This report allows other researchers access to a database for Plum Creek watershed protection. Although similar analyses have been conducted, the data presented here offers a focus on TSS, $NO3^-$, and TP, which provides a beneficial reference to further understanding watershed characteristics in the region.

6.5 Future Work

A subwatershed analysis for TSS, TP, and NO3- would benefit the comprehensive water quality analysis of the Plum Creek watershed. The GBRA has performed extensive analyses on sources of E. coli in the area, estimating subwatersheds that contribute the highest levels of E. coli concentrations. This same analysis should be done for other known water quality impairments to manage subwatersheds based on impairment sources. Water quality from stormwater inputs would benefit from city ordinances for future development requiring retention/detention ponds based on an imperviousness to undeveloped land ratio. The Lockhart 2020 Comprehensive plan addresses the need for better stormwater conveyance, increased WWTP effluent discharge quality, and water storage, but none are currently in effect. The City of Kyle only requires development in flood zones to acquire proper development permits and insurance. As these cities increase in size, so do the areas of impervious surfaces and water use/consumption.

Cost-effective and incentive based agricultural BMP strategies could help to mitigate water use/storage and nutrient inputs form subsurface flows in agricultural land use areas by requiring larger riparian areas. Numerous water quality sampling sites exist within the Plum Creek watershed but do not report monthly water quality data. These sites would help pinpoint seasonal nutrient inputs if water quality data was reported once a month as opposed to quarterly year reports. Areas north of Lockhart are dominated by effluent discharge. If land development for a WWTP required tertiary treatment through constructed wetlands, the discharge would mimic historical intermittency and help treat effluent discharges more naturally while providing potential wildlife habitat, flood conveyance/storage, and pollutant filtration potential outlined by Kusler (2004; table 7). Watershed-scale management is important because it is inclusive, considering natural and built environments, climate, and political decisions that affect water quantity and water quality. Need a concluding sentence that captures the importance of watershed-scale management.

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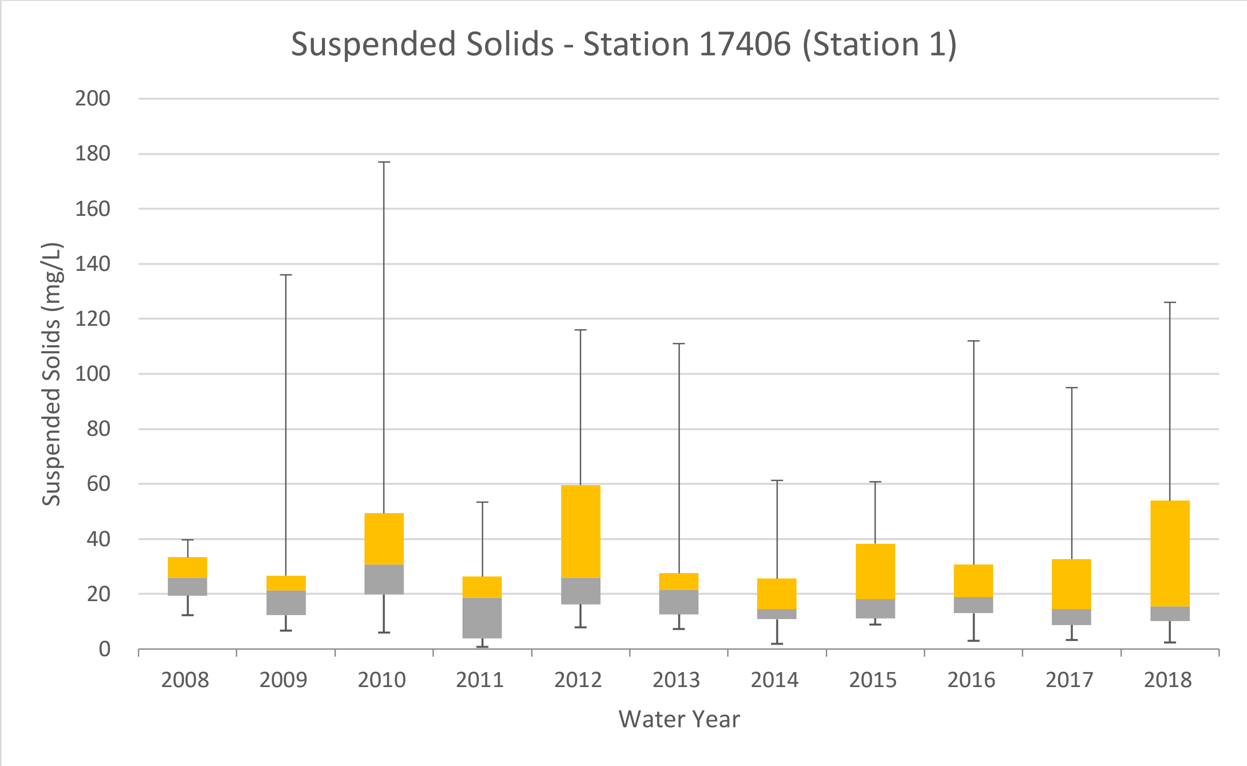
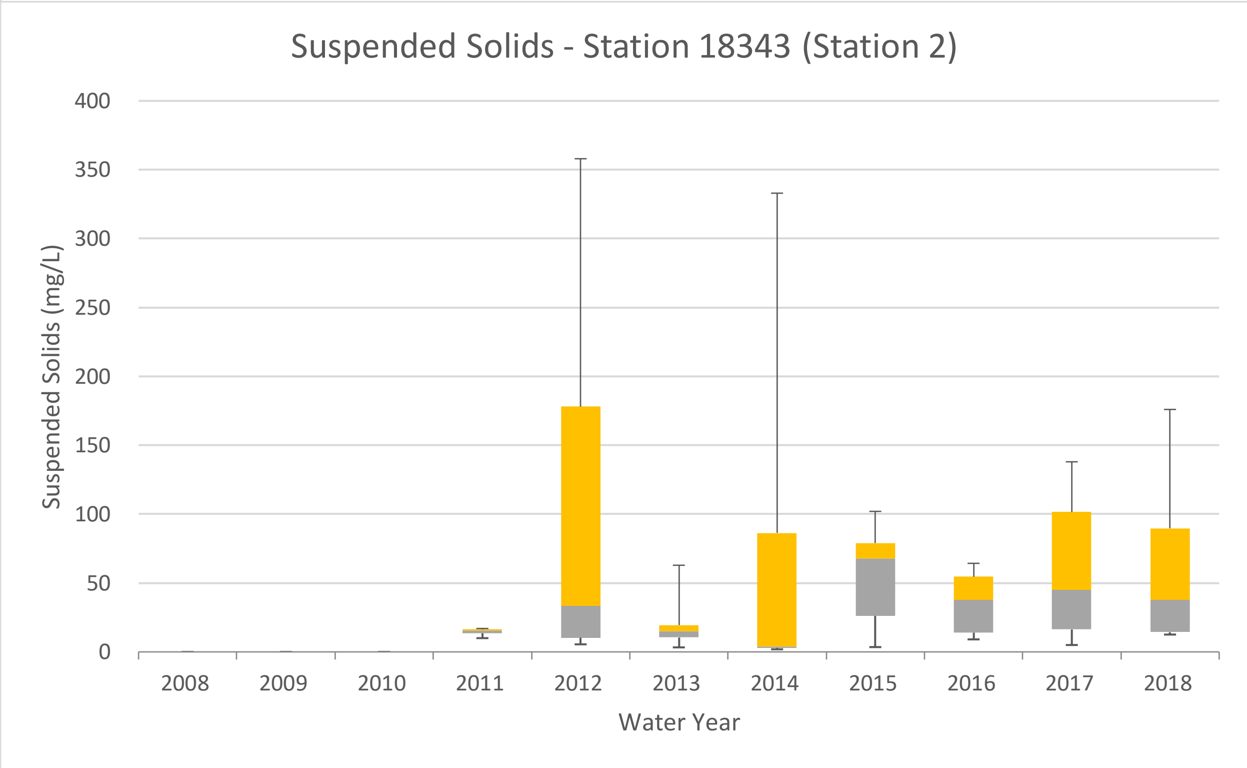
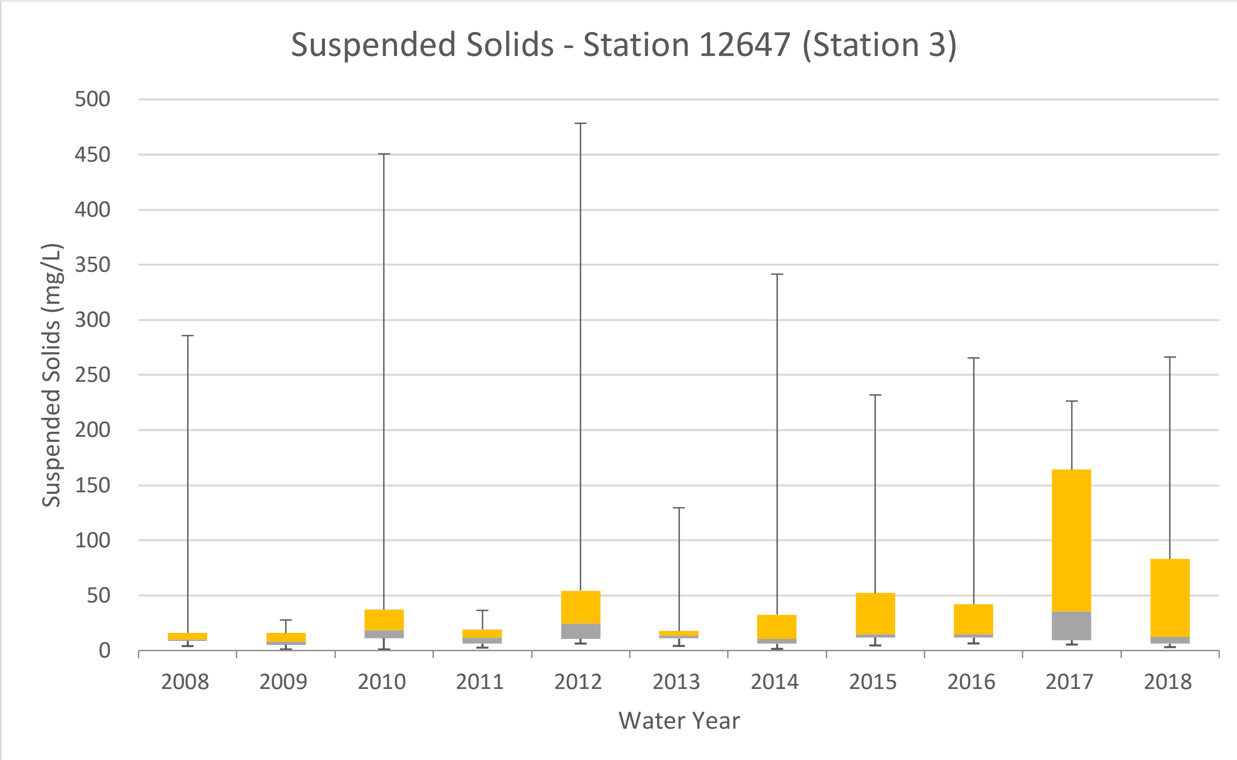
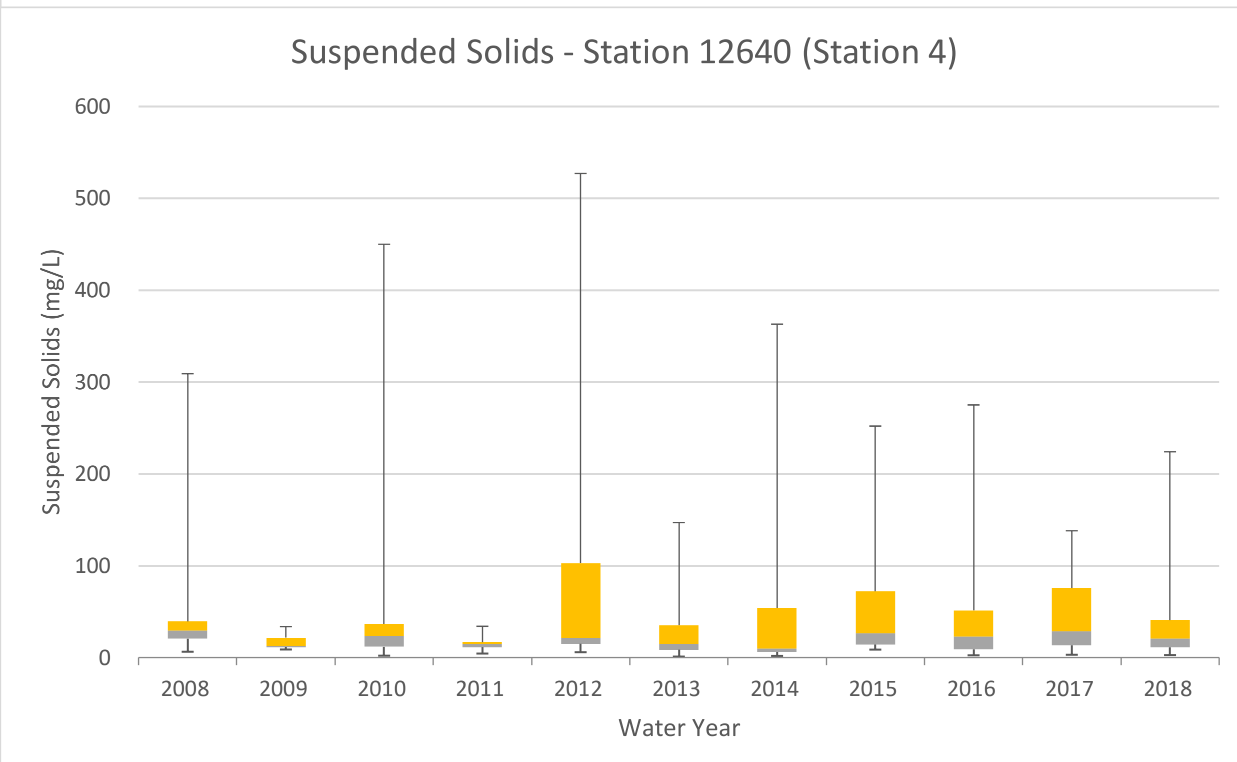
Appendices

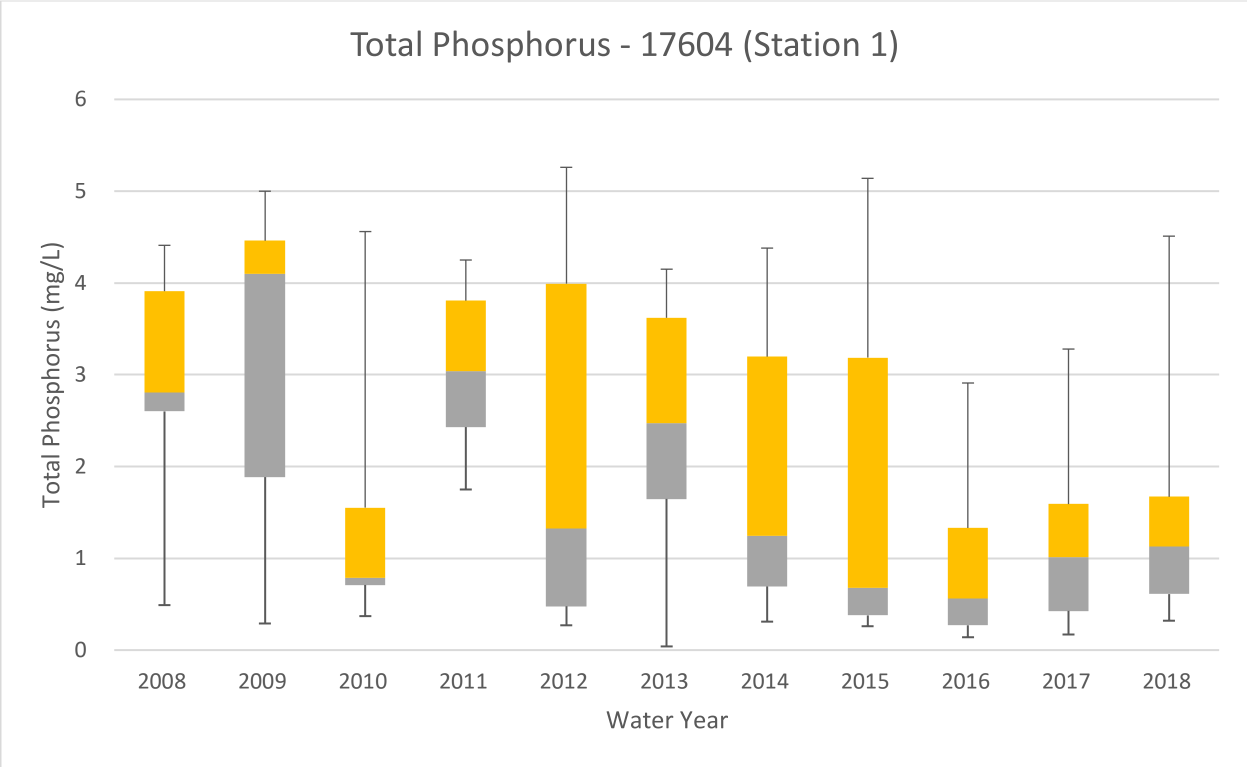
Appendix A – Box Plot Analysis



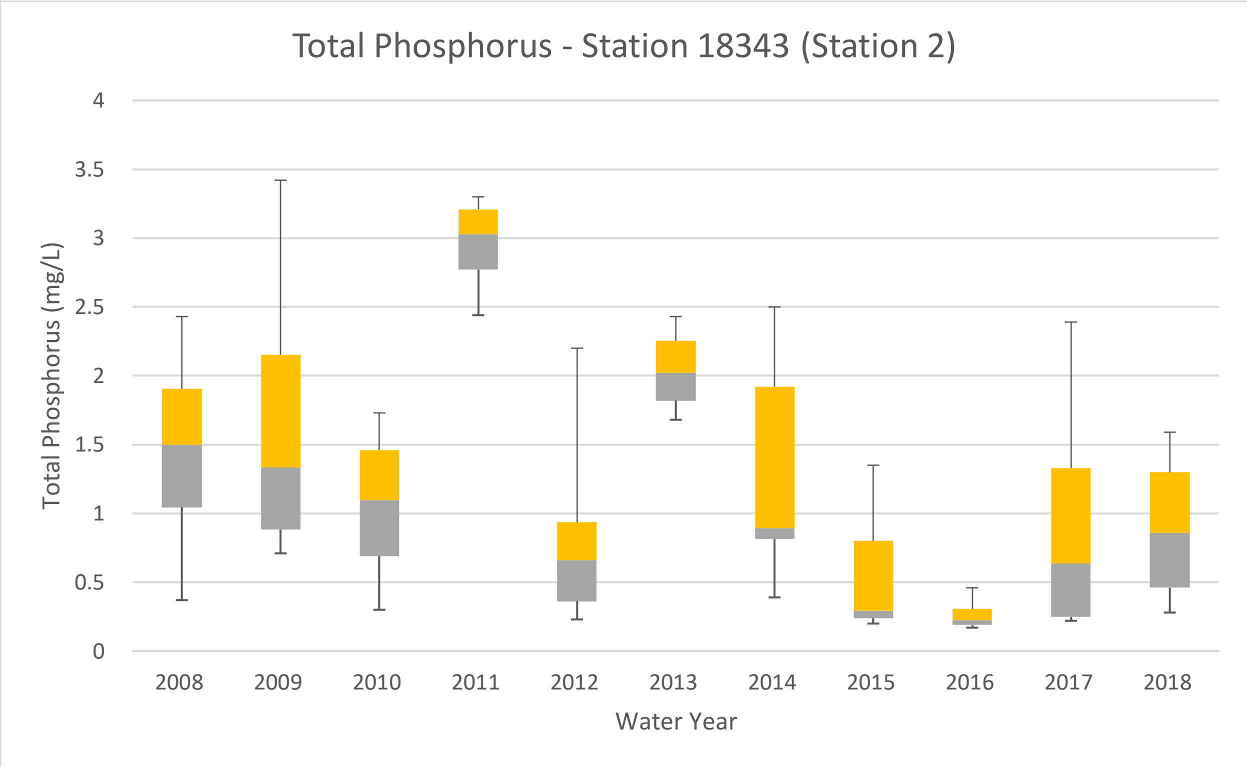



Suspended Solids - Station 12647 (Station 3)
Suspended Solids (mg/L)
500
450
400
350
300
250
200
150
100
50
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Water Year

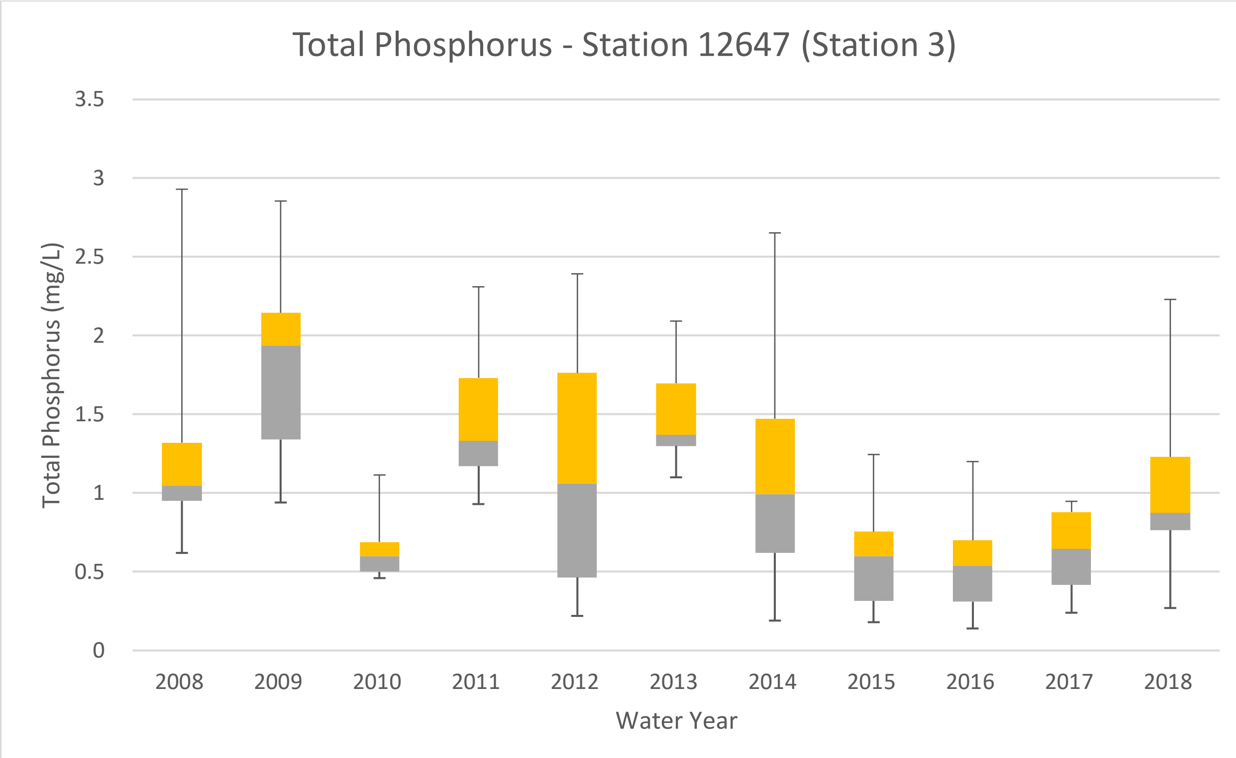

Suspended Solids - Station 12640 (Station 4)
Suspended Solids (mg/L)
600
500
400
300
200
100
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Water Year

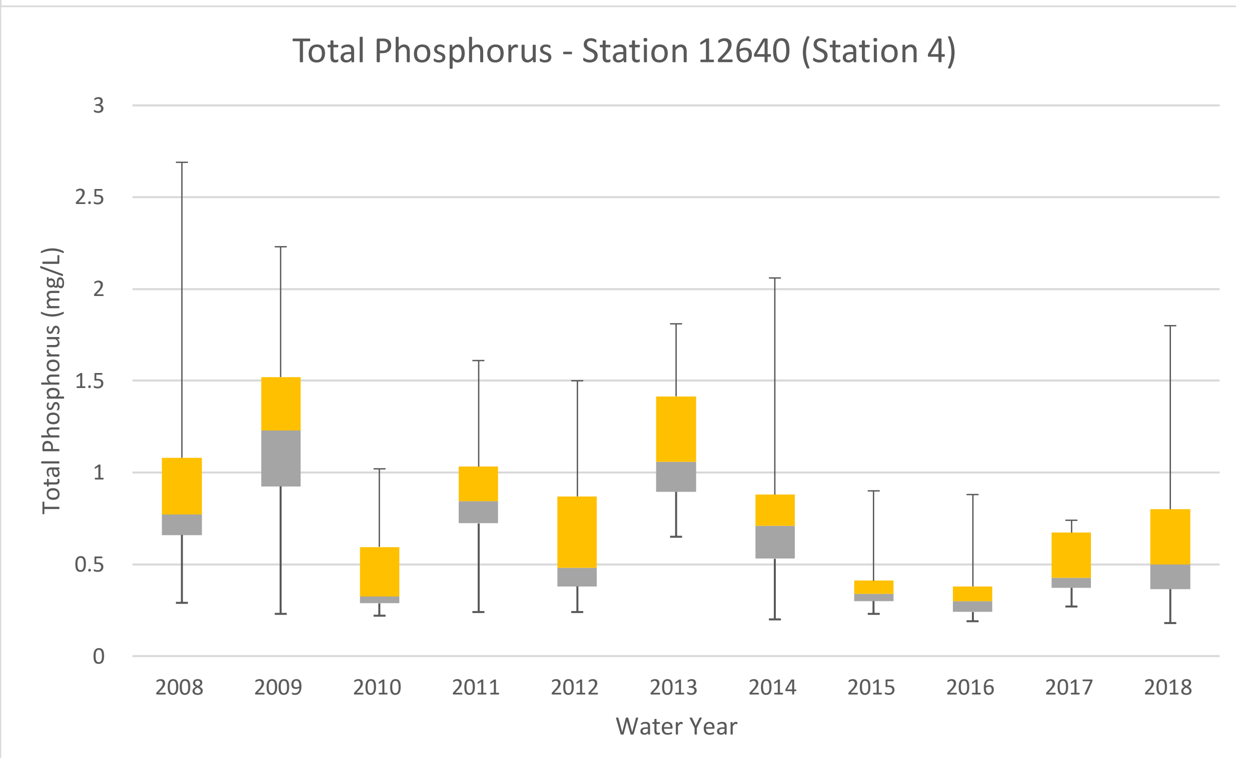


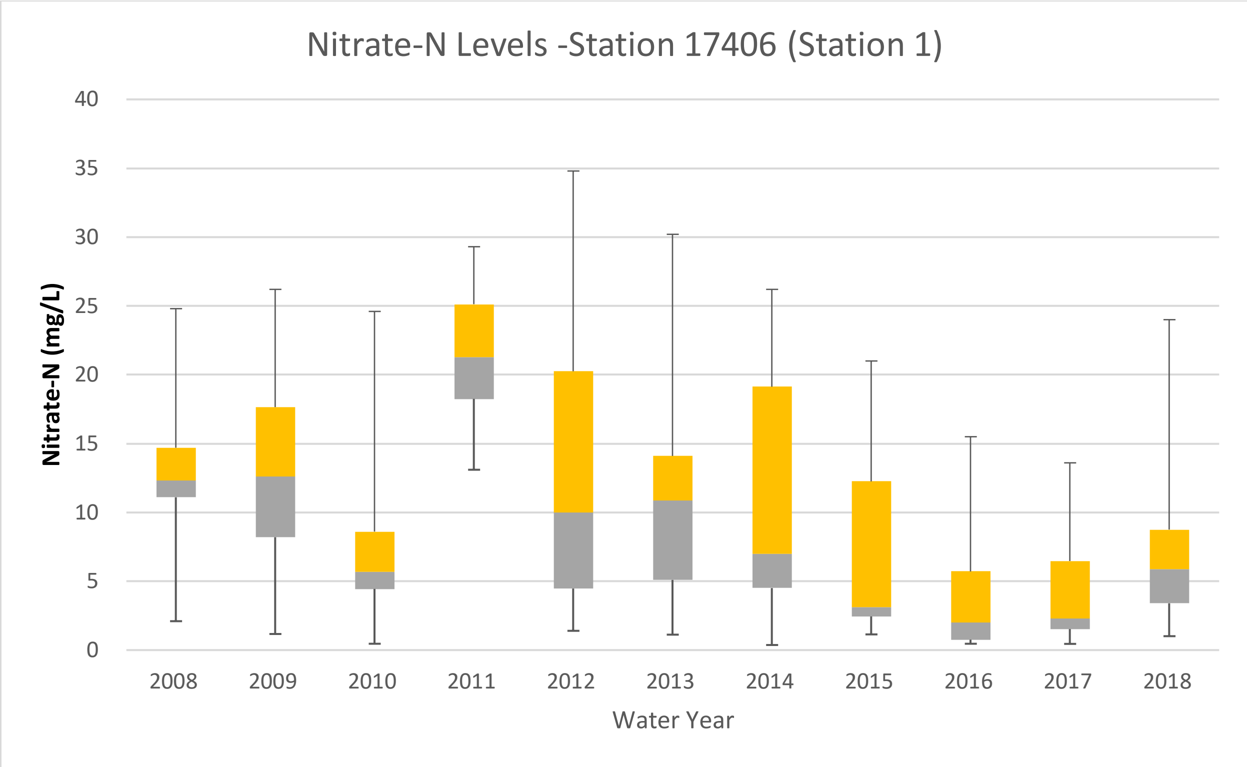
Total Phosphorus - 17604 (Station 1)
Total Phosphorus (mg/L)
6
5
4
3
2
1
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Water Year

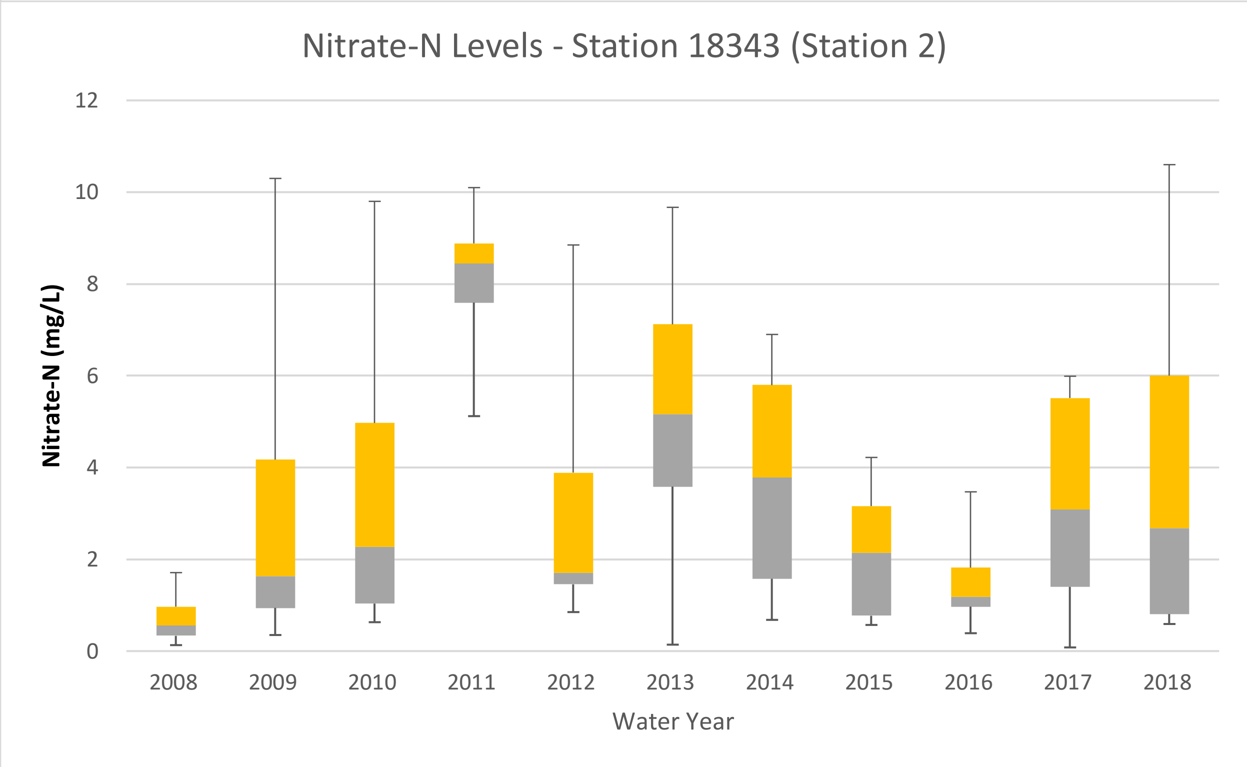


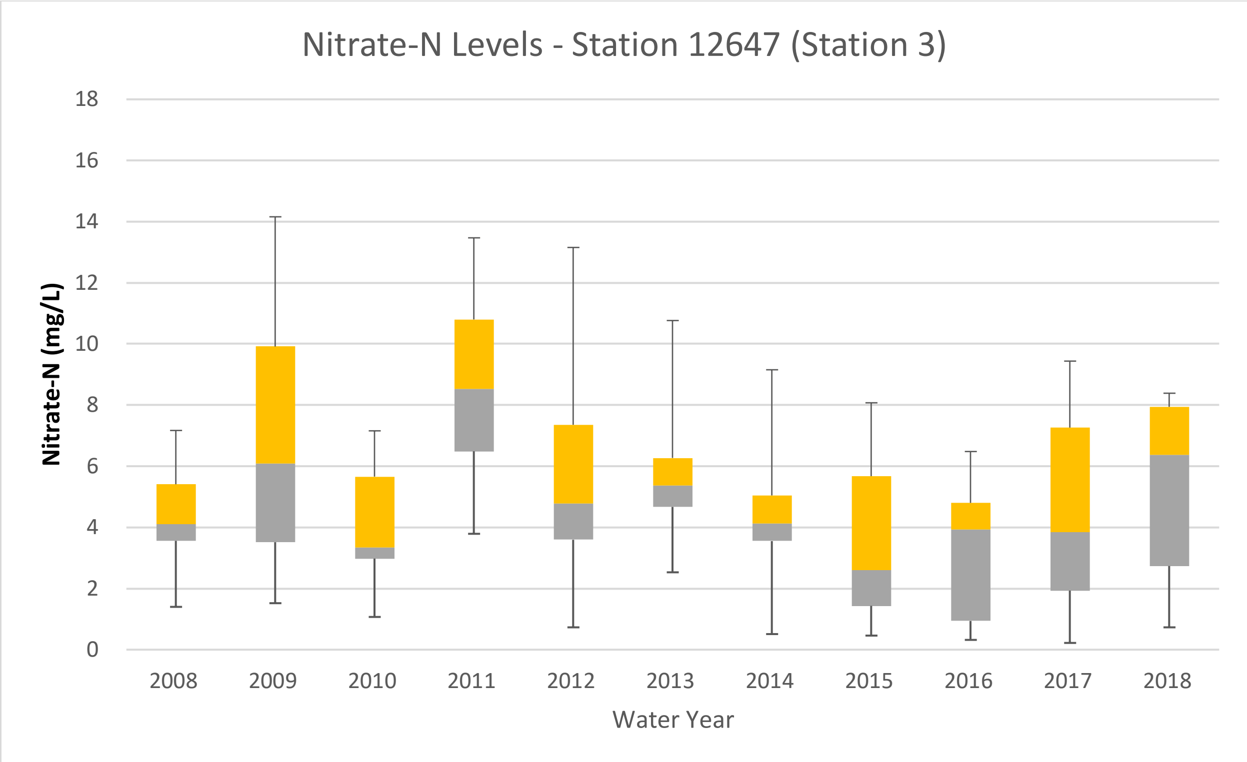
Total Phosphorus - Station 18343 (Station 2)
Total Phosphorus (mg/L)
4
3.5
3
2.5
2
1.5
1
0.5
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Water Year

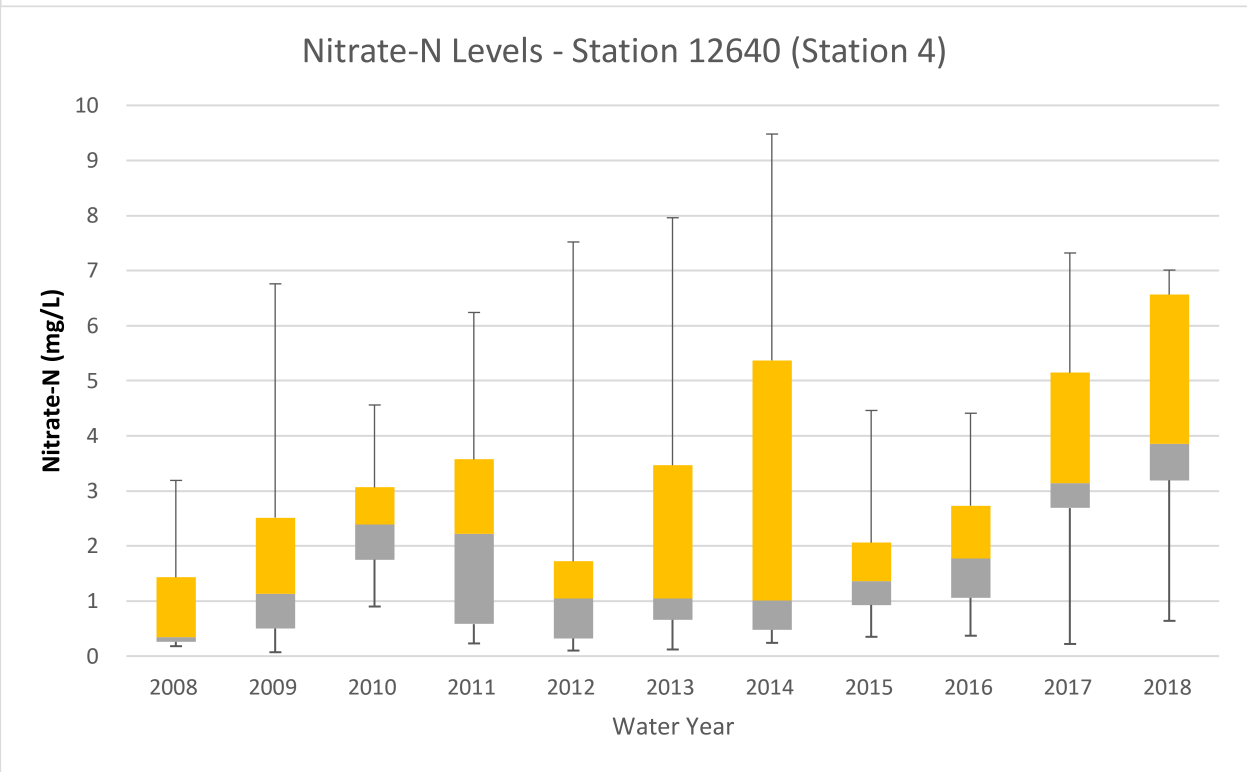

Total Phosphorus - Station 12647 (Station 3)
Total Phosphorus (mg/L)
3.5
3
2.5
2
1.5
1
0.5
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Water Year

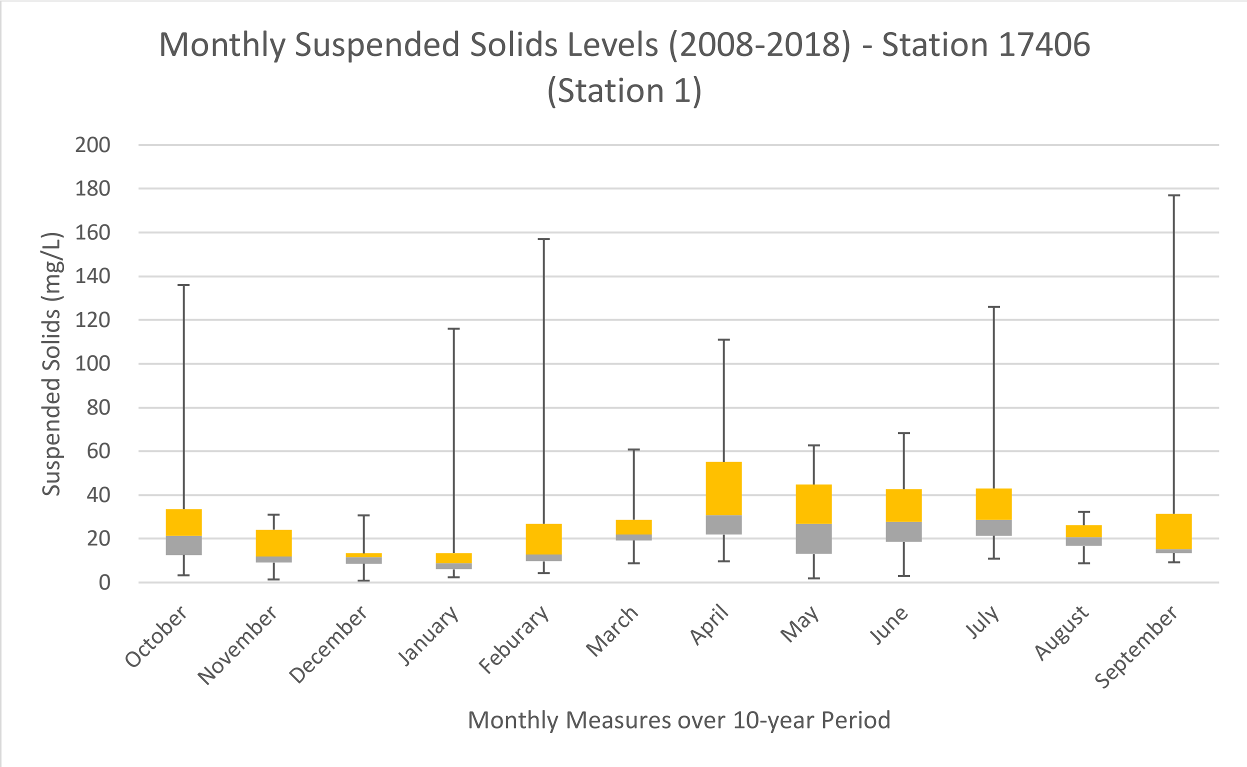

Total Phosphorus - Station 12640 (Station 4)
Total Phosphorus (mg/L)
3
2.5
2
1.5
1
0.5
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Water Year


Nitrate-N Levels -Station 17406 (Station 1)
Nitrate-N (mg/L)
40
35
30
25
20
15
10
5
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Water Year

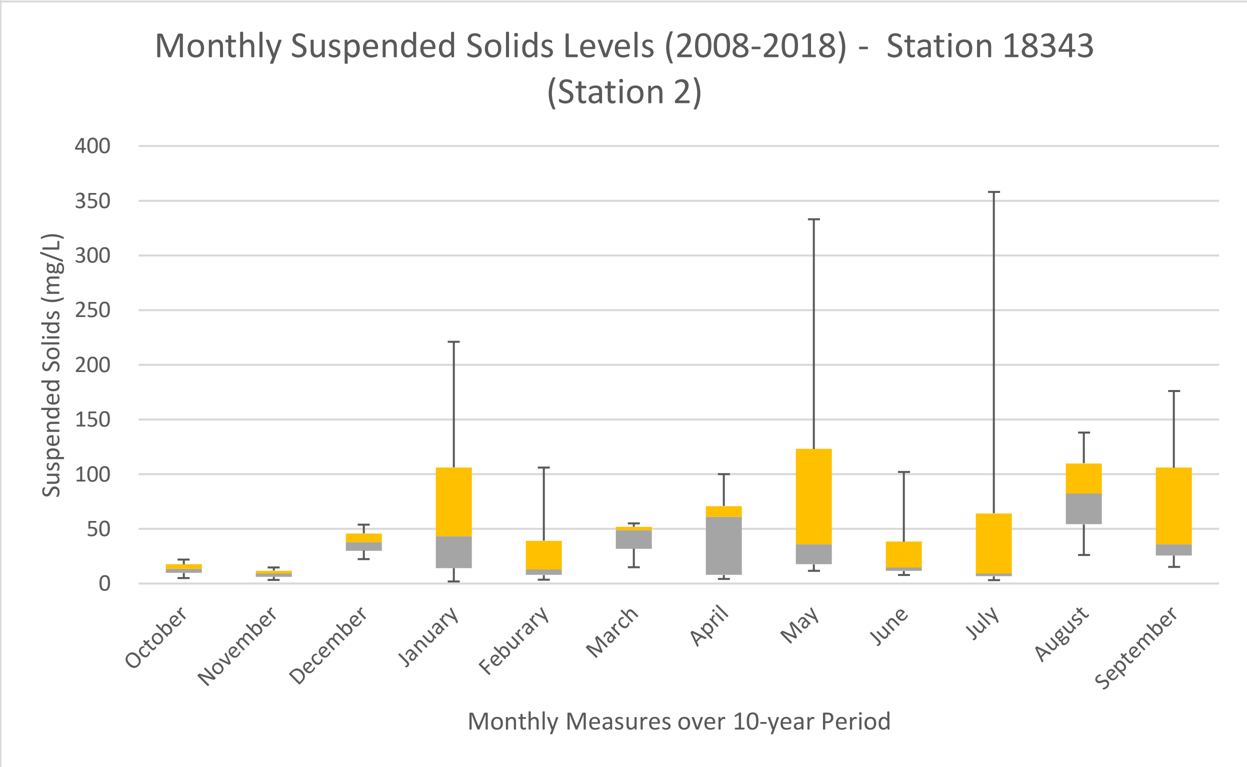

Nitrate-N Levels - Station 18343 (Station 2)
Nitrate-N (mg/L)
12
10
8
6
4
2
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Water Year


Nitrate-N Levels - Station 12647 (Station 3)
Nitrate-N (mg/L)
18
16
14
12
10
8
6
4
2
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Water Year

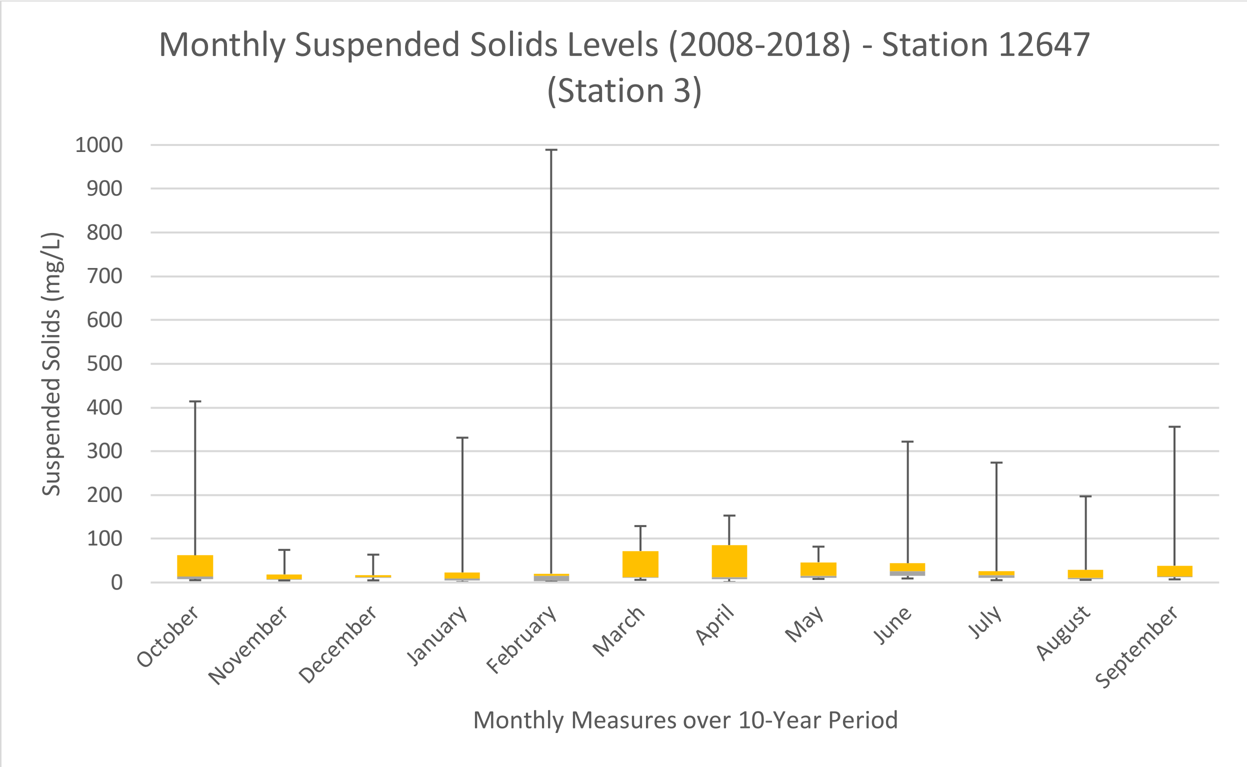

Nitrate-N Levels - Station 12640 (Station 4)
Nitrate-N (mg/L)
10
9
8
7
6
5
4
3
2
1
0
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Water Year

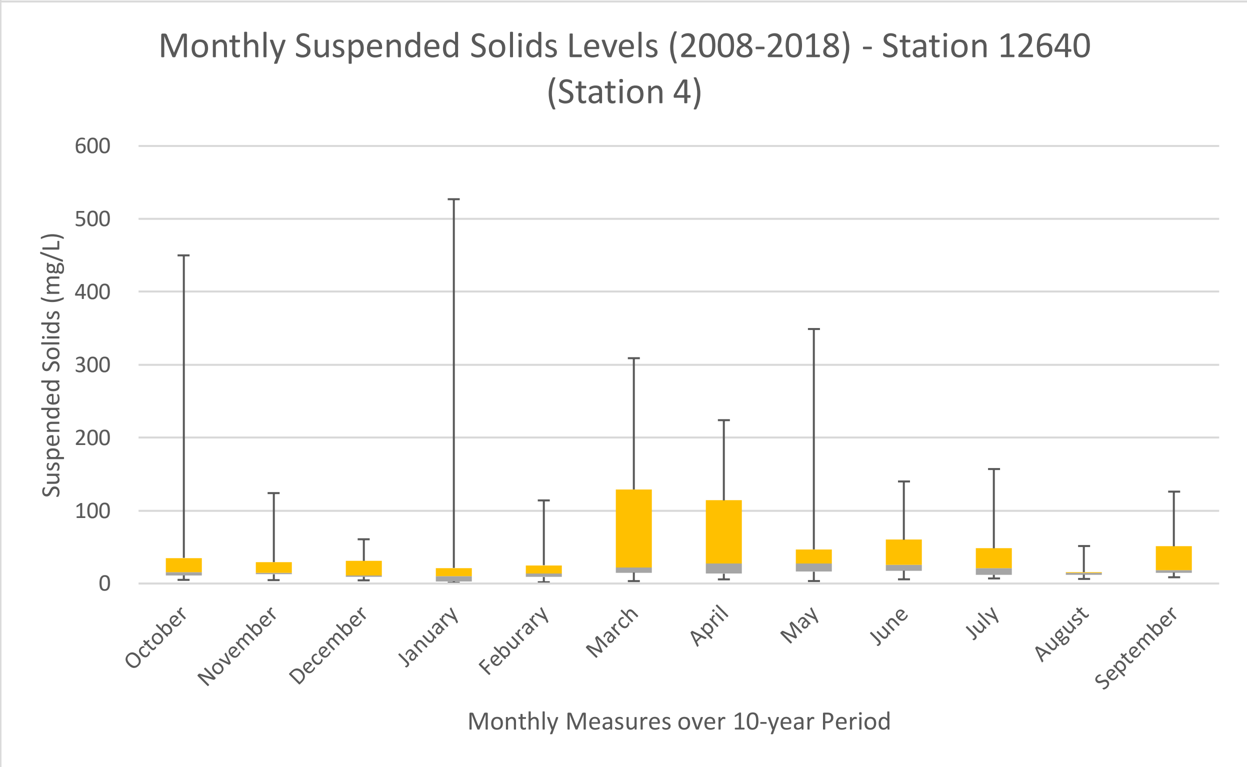


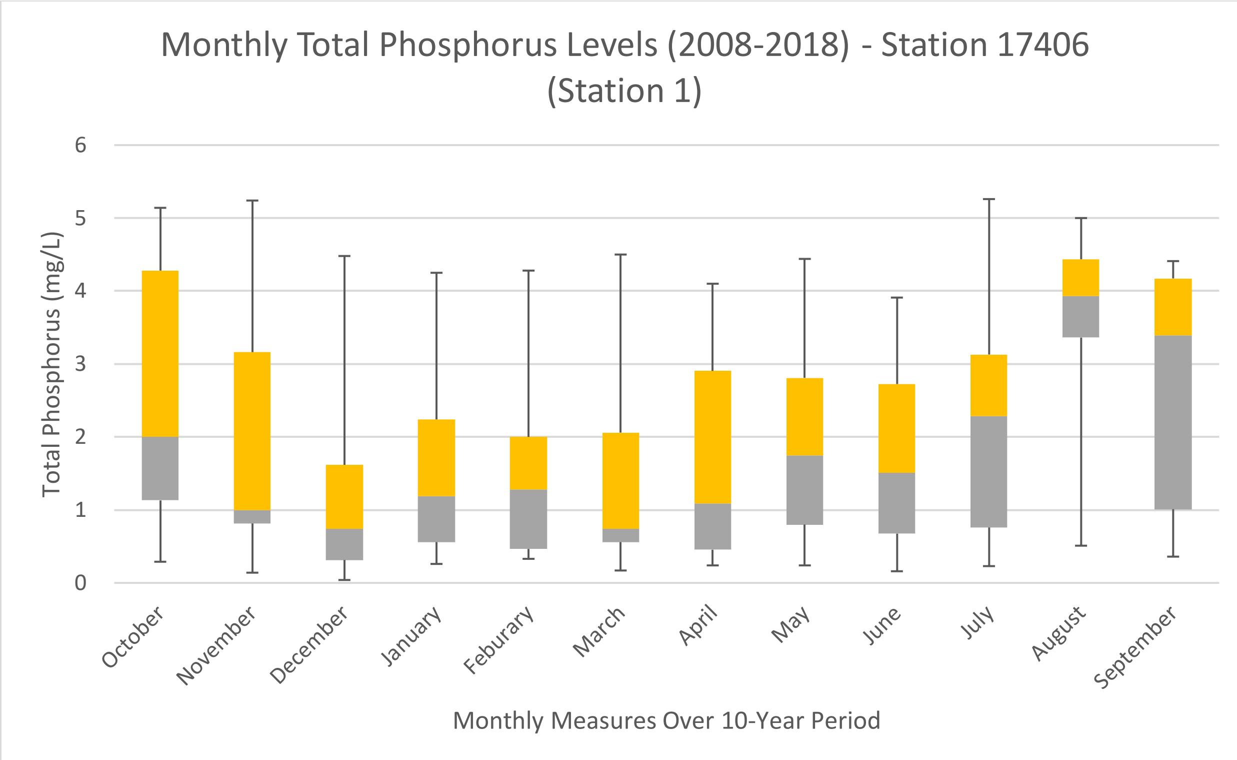
Monthly Suspended Solids Levels (2008-2018) - Station 17406 (Station 1)
Suspended Solids (mg/L)
200
180
160
140
120
100
80
60
40
20
0
October
November
December
January
Feburary
March
April
May
June
July
August
September
Monthly Measures over 10-year Period

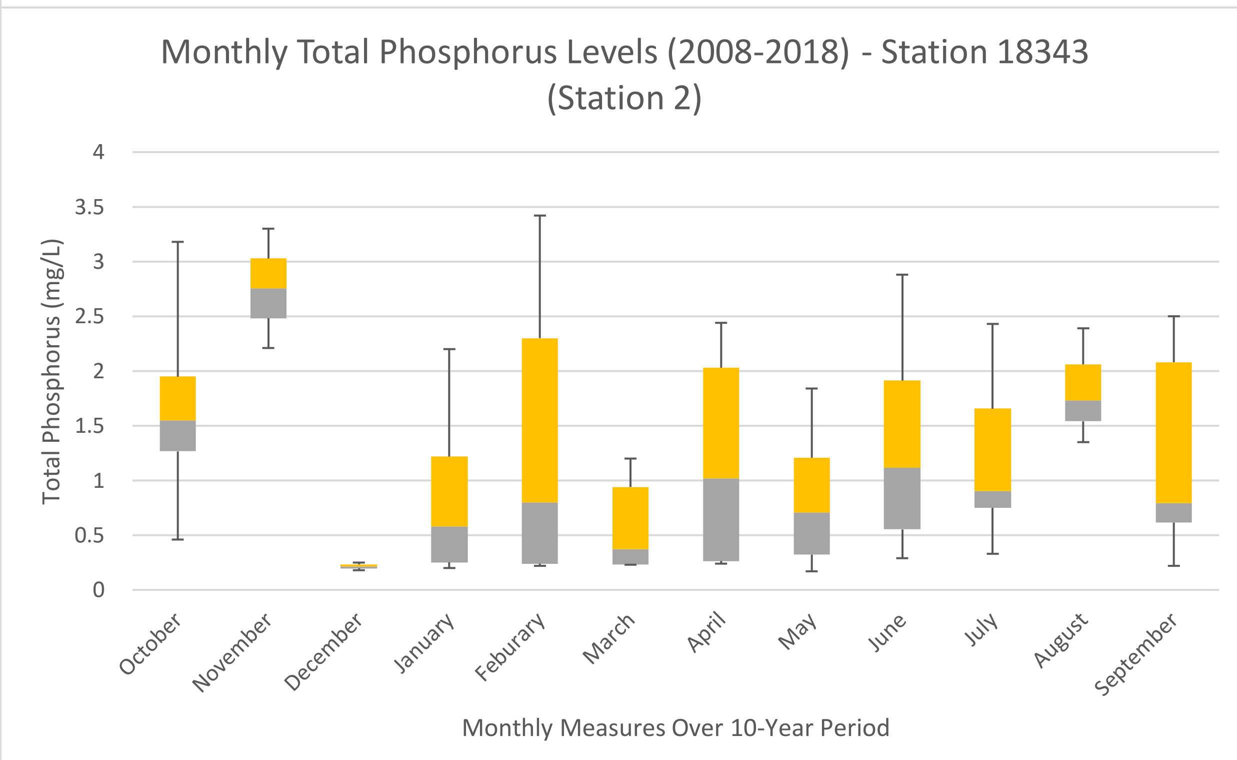


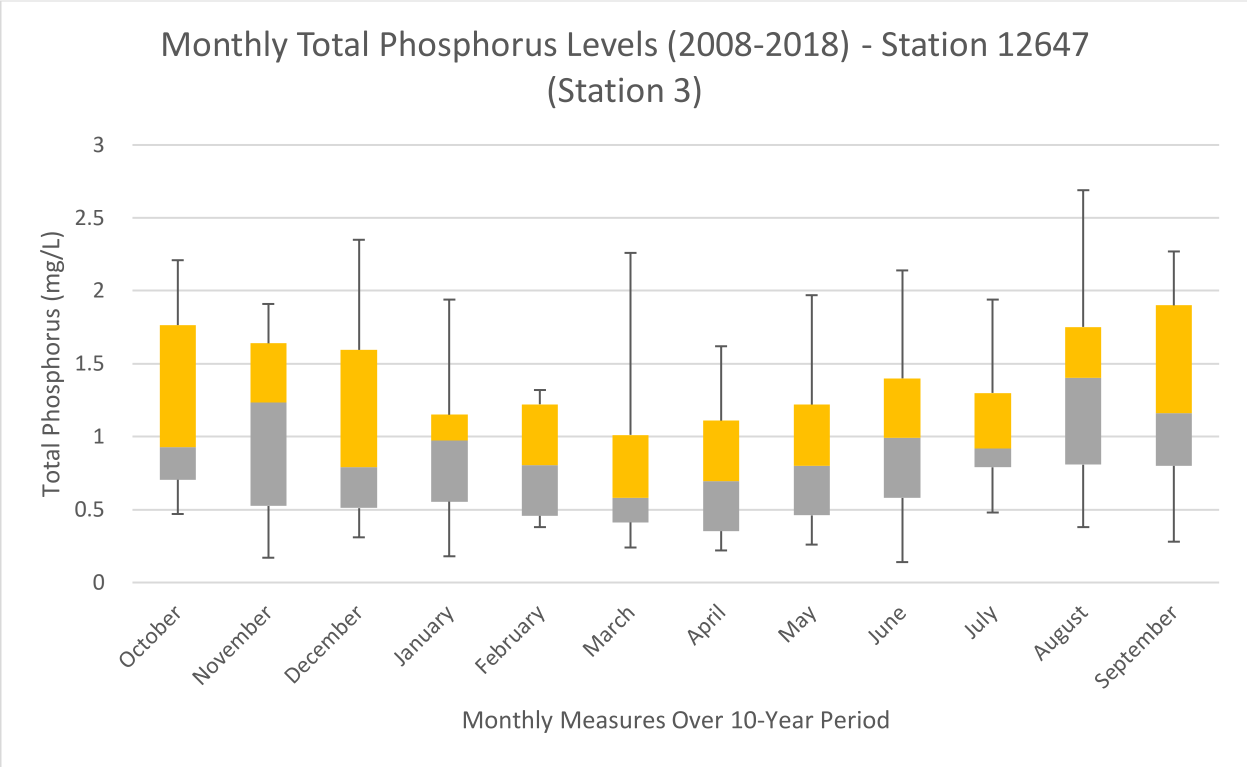
Monthly Suspended Solids Levels (2008-2018) - Station 18343 (Station 2)
Suspended Solids (mg/L)
400
350
300
250
200
150
100
50
0
October
November
December
January
Feburary
March
April
May
June
July
August
September
Monthly Measures over 10-year Period

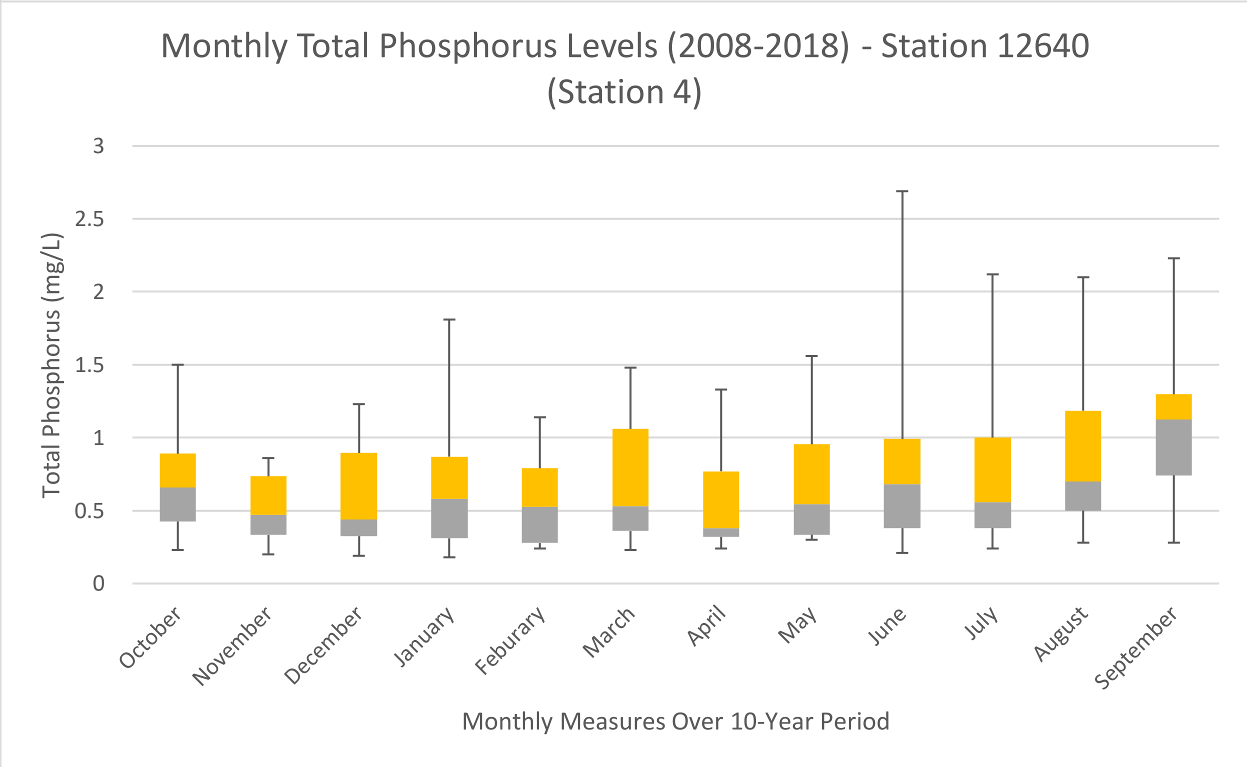

Monthly Suspended Solids Levels (2008-2018) - Station 12647 (Station 3)
Suspended Solids (mg/L)
1000
900
800
700
600
500
400
300
200
100
0
October
November
December
January
February
March
April
May
June
July
August
September
Monthly Measures over 10-Year Period

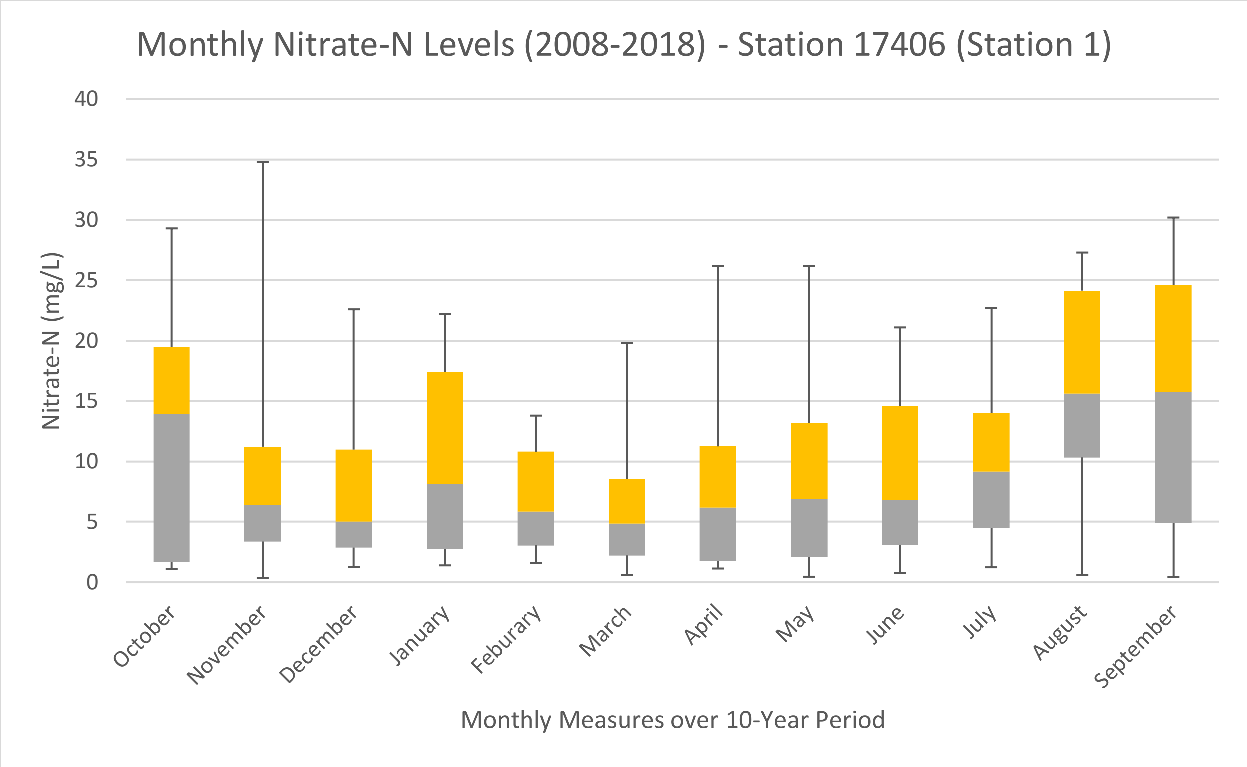

Monthly Suspended Solids Levels (2008-2018) - Station 12640 (Station 4)
Suspended Solids (mg/L)
600
500
400
300
200
100
0
October
November
December
January
Feburary
March
April
May
June
July
August
September
Monthly Measures over 10-year Period

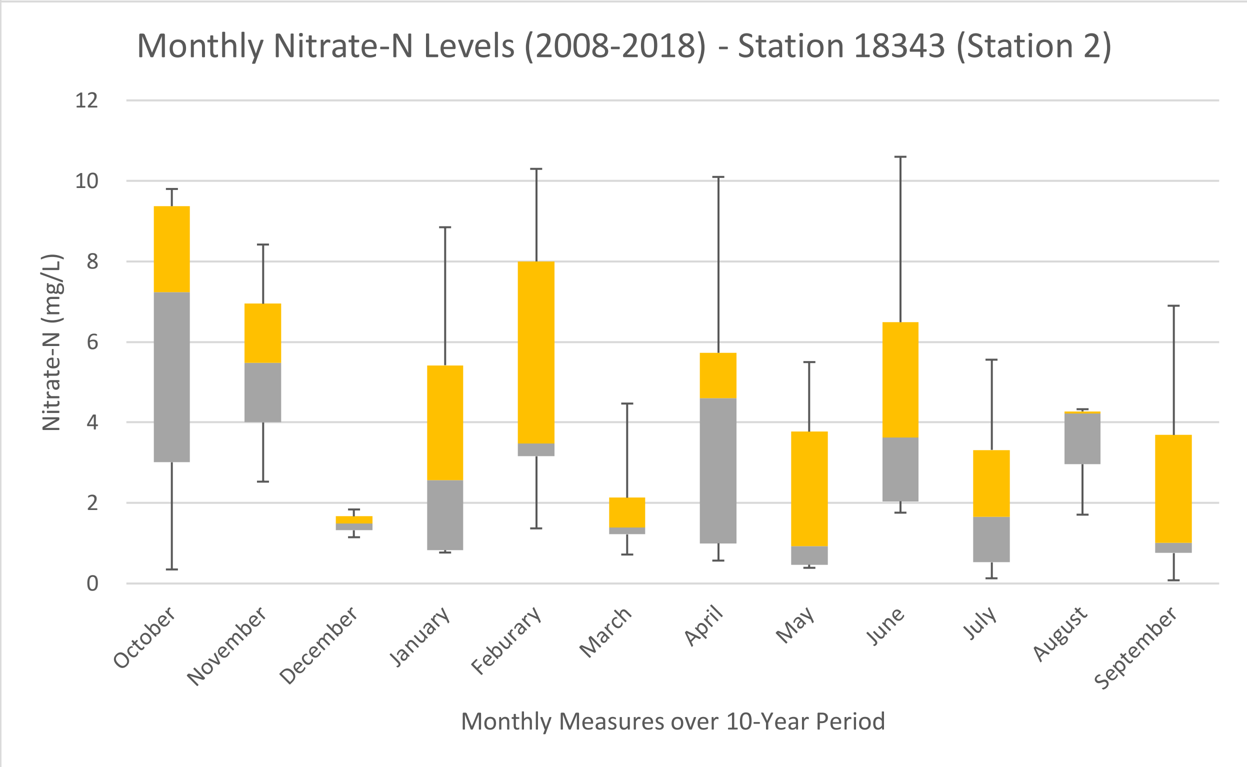

Monthly Total Phosphorus Levels (2008-2018) - Station 17406 (Station 1)
Total Phosphorus (mg/L)
0
1
2
3
4
5
6
October
November
December
January
Feburary
March
April
May
June
July
August
September
Monthly Measures Over 10-Year Period

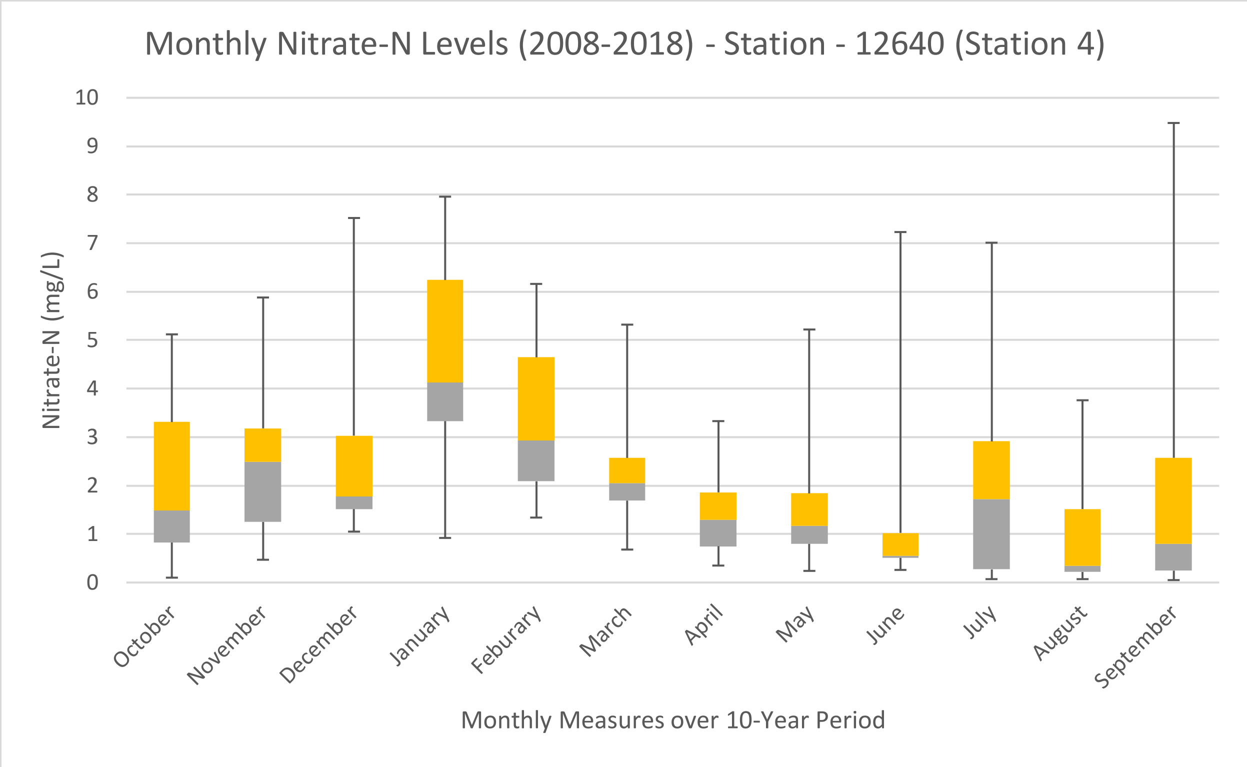

Monthly Total Phosphorus Levels (2008-2018) - Station 18343 (Station 2)
Total Phosphorus (mg/L)
0
0.5
1
1.5
2
2.5
3
3.5
4
October
November
December
January
Feburary
March
April
May
June
July
August
September
Monthly Measures Over 10-Year Period


Monthly Total Phosphorus Levels (2008-2018) - Station 12647 (Station 3)
Total Phosphorus (mg/L)
0
0.5
1
1.5
2
2.5
3
October
November
December
January
February
March
April
May
June
July
August
September
Monthly Measures Over 10-Year Period

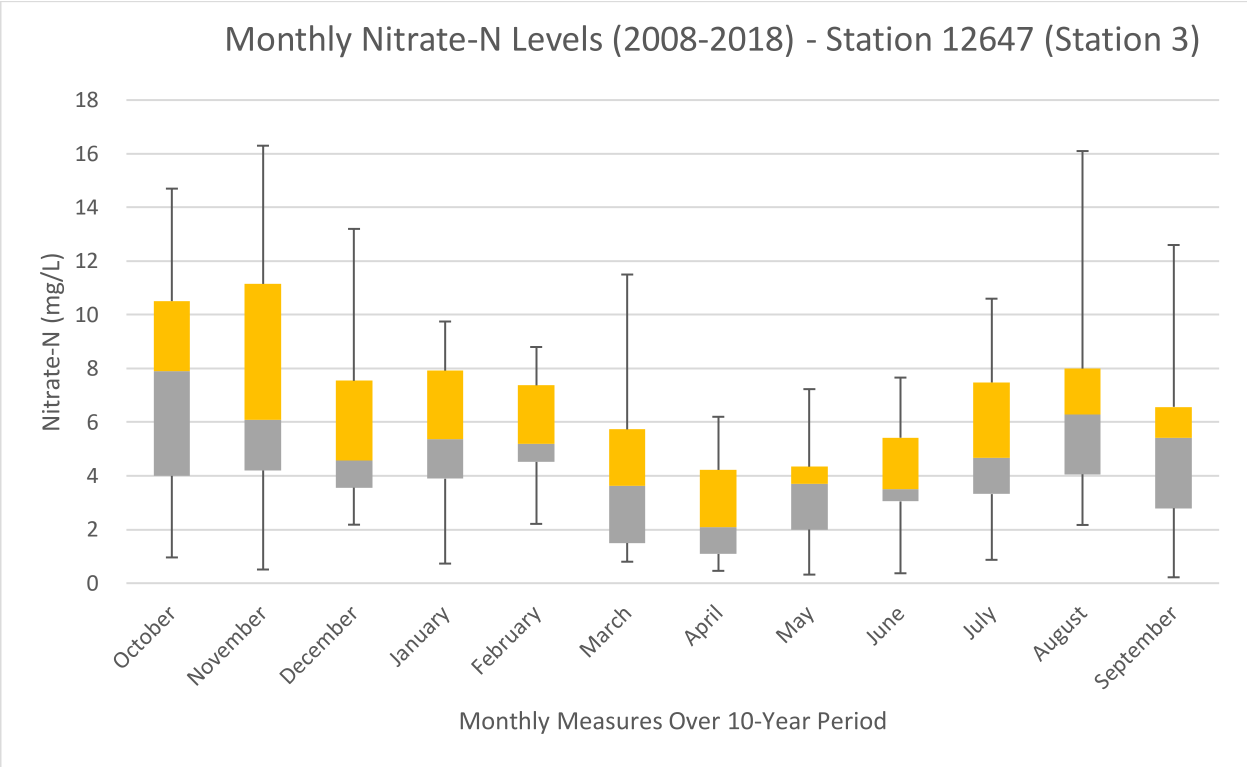

Monthly Total Phosphorus Levels (2008-2018) - Station 12640 (Station 4)
Total Phosphorus (mg/L)
0
0.5
1
1.5
2
2.5
3
October
November
December
January
Feburary
March
April
May
June
July
August
September
Monthly Measures Over 10-Year Period


Monthly Nitrate-N Levels (2008-2018) - Station 17406 (Station 1)
40
35
30
25
20
15
10
5
0
Nitrate-N (mg/L)
October
November
December
January
Feburary
March
April
May
June
July
August
September
Monthly Measures over 10-Year Period


Monthly Nitrate-N Levels (2008-2018) - Station 18343 (Station 2)
12
10
8
6
4
2
0
Nitrate-N (mg/L)
October
November
December
January
Feburary
March
April
May
June
July
August
September
Monthly Measures over 10-Year Period



Monthly Nitrate-N Levels (2008-2018) - Station - 12640 (Station 4)
Nitrate-N (mg/L)
10
9
8
7
6
5
4
3
2
1
0
October
November
December
January
Feburary
March
April
May
June
July
August
September
Monthly Measures over 10-Year Period



Monthly Nitrate-N Levels (2008-2018) - Station 12647 (Station 3)
Nitrate-N (mg/L)
18
16
14
12
10
8
6
4
2
0
October
November
December
January
February
March
April
May
June
July
August
September
Monthly Measures Over 10-Year Period

Appendix B - 5-Number Summary Tables of Pollutant Concentrations

	Gage	Station ID	5-Number Summary	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
	1	17406												
			Minimum	0.49	0.29	0.37	1.75	0.27	0.04	0.31	0.26	0.14	0.17	0.32
			Q1	2.6	1.885	0.71	2.43	0.4775	1.6475	0.6925	0.3775	0.27	0.4275	0.61
			Median	2.81	4.1	0.79	3.04	1.325	2.47	1.245	0.68	0.56	1.01	1.13
			Q3	3.91	4.46	1.5525	3.8075	3.9925	3.62	3.1975	3.1875	1.33	1.59	1.67
			Maximum	4.41	5	4.56	4.25	5.26	4.15	4.38	5.14	2.91	3.28	4.51
	2	18343												
			Minimum				10	5.5	3.3	1.9	3.5	9.1	5	12.6
			Q1				13.525	10.375	10.4	2.8	26.1	13.975	16.275	14.325
			Median				15.4	33.45	15.2	3.65	68	37.65	44.8	37.95
			Q3				16.325	177.95	19.45	86.4	79	54.5	101.5	89.75
TSS			Maximum				17	358	62.9	333	102	64.3	138	176
	3	12647												
			Minimum	4	1	1	2.6	6.3	4.14	1.5	4.6	6.4	5.4	3.1
			Q1	8.825	5.3	11.425	6.175	10.675	10.85	6.1	11.9	11.675	9.35	6.05
			Median	9.8	8.3	18.5	11.7	24.15	13.3	10.3	14.6	14.75	35.25	12.35
			Q3	16.025	15.7	37.2	19.125	54.4	17.8	32.5	52	41.9	164	83.05
			Maximum	84.5	41.7	414	30.8	331	86	161	130	74.6	989	356
	4	12640												
			Minimum	6.3	8.7	2	4.3	5.8	1	1.8	8.6	2.4	3	2.7
			Q1	20.45	11.525	11.6	11.4	15	8.565	6.1	14.15	8.8	13.25	11
			Median	29	12.3	23.35	15.1	21.4	14.6	9.8	26.6	22.5	28.45	20.5
			Q3	39.275	21.7	36.6	16.725	103	35.3	54	72.1	51.4	75.675	40.75
			Maximum	309	33.7	450	34	527	147	363	252	275	138	224

	Gage	Station ID		2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
	1	17406												
			Minimum	0.49	0.29	0.37	1.75	0.27	0.04	0.31	0.26	0.14	0.17	0.32
			Q1	2.6	1.885	0.71	2.43	0.4775	1.6475	0.6925	0.3775	0.27	0.4275	0.61
			Median	2.81	4.1	0.79	3.04	1.325	2.47	1.245	0.68	0.56	1.01	1.13
			Q3	3.91	4.46	1.5525	3.8075	3.9925	3.62	3.1975	3.1875	1.33	1.59	1.67
			Maximum	4.41	5	4.56	4.25	5.26	4.15	4.38	5.14	2.91	3.28	4.51
	2	18343												
			Minimum	0.37	0.71	0.3	2.44	0.23	1.68	0.39	0.2	0.17	0.22	0.28
			Q1	1.045	0.8825	0.69	2.77	0.3625	1.82	0.815	0.24	0.19	0.2475	0.46
			Median	1.5	1.335	1.095	3.03	0.66	2.02	0.895	0.29	0.225	0.635	0.86
			Q3	1.905	2.1525	1.46	3.21	0.935	2.255	1.92	0.8	0.305	1.33	1.2975
TP			Maximum	2.43	3.42	1.73	3.3	2.2	2.43	2.5	1.35	0.46	2.39	1.59
	3	12647												
			Minimum	0.62	0.94	0.46	0.93	0.22	1.1	0.19	0.18	0.14	0.24	0.27
			Q1	0.95	1.34	0.5	1.1725	0.465	1.3	0.62	0.315	0.31	0.4175	0.765
			Median	1.05	1.94	0.6	1.33	1.06	1.37	0.995	0.6	0.54	0.645	0.875
			Q3	1.32	2.145	0.69	1.7325	1.7625	1.6975	1.4725	0.755	0.7	0.88	1.23
			Maximum	1.46	2.26	0.86	2.69	2.21	2.35	1.97	1.91	1.88	1.11	1.68
	4	12640												
			Minimum	0.29	0.23	0.22	0.24	0.24	0.65	0.2	0.23	0.19	0.27	0.18
			Q1	0.37	0.695	0.0675	0.4825	0.14	0.245	0.33	0.07	0.05	0.1025	0.185
			Median	0.11	0.305	0.0375	0.1225	0.1	0.165	0.18	0.04	0.06	0.0525	0.135
			Q3	0.31	0.29	0.27	0.1875	0.39	0.355	0.17	0.07	0.08	0.2475	0.3
			Maximum	1.61	0.71	0.425	0.5775	0.63	0.395	1.18	0.49	0.5	0.0675	1

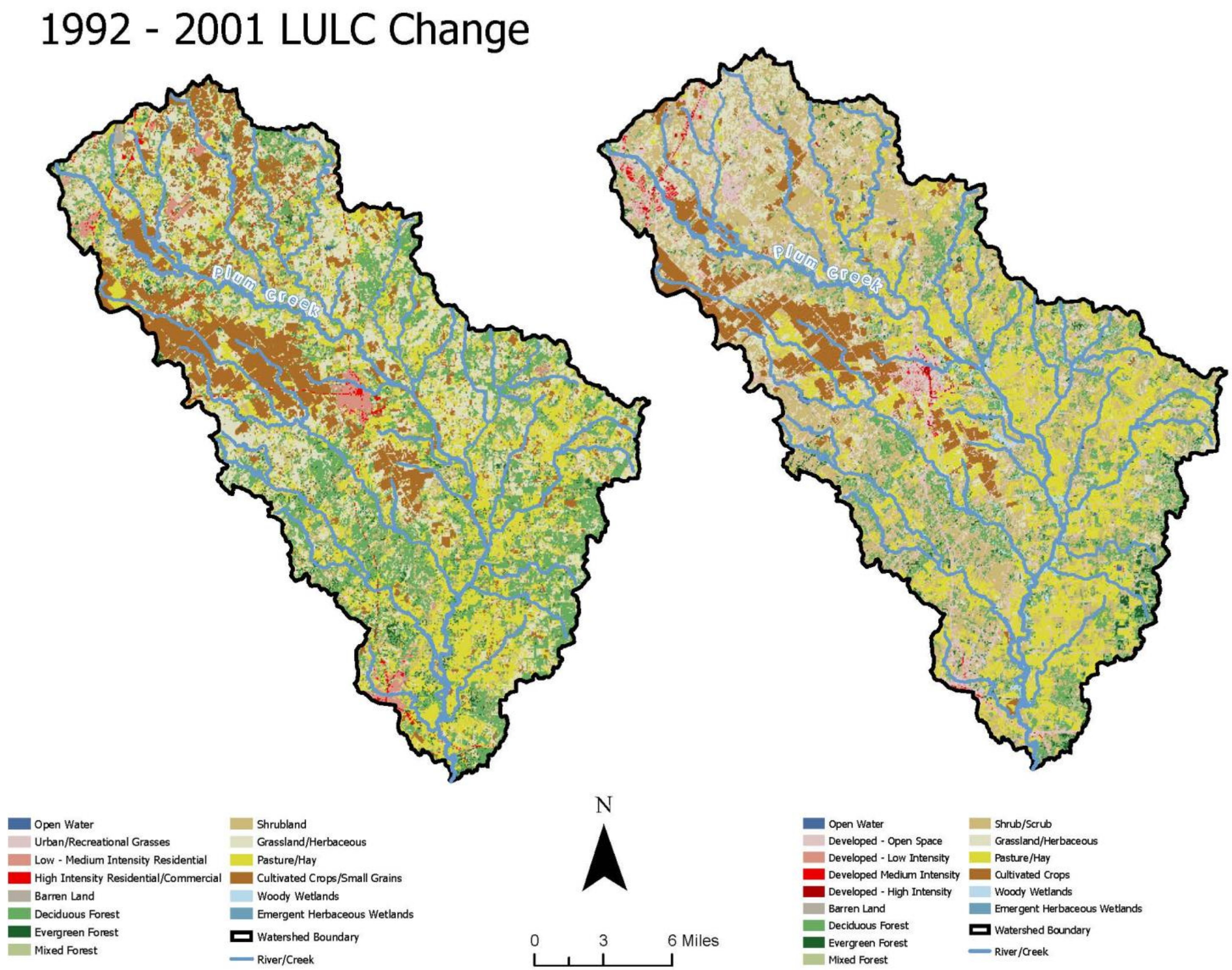
	Gage	Station ID		2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
	1	17406												
			Minimum	2.1	1.17	0.46	13.1	1.4	1.12	0.37	1.14	0.46	0.45	1.01
			Q1	11.1	8.2	4.445	18.25	4.47	5.1	4.505	2.445	0.76	1.5275	3.4
			Median	12.3	12.6	5.665	21.3	10	10.85	6.98	3.13	2.02	2.315	5.9
			Q3	14.7	17.65	8.61	25.125	20.25	14.1	19.125	12.25	5.71	6.47	8.755
			Maximum	24.8	26.2	24.6	29.3	34.8	30.2	26.2	21	15.5	13.6	24
	2	18343												
			Minimum	0.13	0.35	0.63	5.12	0.85	0.14	0.68	0.57	0.39	0.08	0.59
			Q1	0.3325	0.9425	1.035	7.595	1.455	3.585	1.5775	0.77	0.97	1.4	0.8075
			Median	0.56	1.635	2.265	8.45	1.705	5.16	3.78	2.14	1.185	3.085	2.675
			Q3	0.9675	4.1725	4.97	8.885	3.89	7.12	5.795	3.16	1.82	5.515	6.0025
			Maximum	1.71	10.3	9.8	10.1	8.85	9.67	6.9	4.22	3.47	5.99	10.6
NO_3^-	3	12647												
			Minimum	1.4	1.52	1.07	3.79	0.73	2.53	0.51	0.46	0.32	0.22	0.73
			Q1	3.56	3.515	2.98	6.49	3.595	4.67	3.55	1.435	0.94	1.9325	2.7375
			Median	4.1	6.08	3.34	8.53	4.78	5.36	4.12	2.6	3.92	3.835	6.375
			Q3	5.41	9.9125	5.66	10.8	7.355	6.27	5.045	5.675	4.8	7.2625	7.9425
			Maximum	8	13.6	8.4	16.3	12.6	11.6	7.8	11.9	14.7	10.6	12.4
	4	12640												
			Minimum	0.18	0.07	0.9	0.23	0.1	0.12	0.24	0.35	0.37	0.22	0.64
			Q1	0.26	0.5	1.7525	0.58	0.32	0.66	0.4775	0.93	1.06	2.6875	3.1925
			Median	0.34	1.125	2.39	2.215	1.04	1.05	1.015	1.36	1.77	3.14	3.855
			Q3	1.43	2.515	3.0625	3.57	1.72	3.465	5.37	2.06	2.73	5.145	6.565
			Maximum	3.19	6.76	4.56	6.24	7.52	7.96	9.48	4.46	4.41	7.32	7.01

	Gage	Station ID	5-Number Summary	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	Jun.	July	Aug.	Sep.
	1	17406													
			Minimum	3.3	1.4	0.8	2.4	4.3	8.8	9.7	1.9	3	10.9	8.8	9.25
			Q1	12.65	9.05	8.6225	6	9.625	19.225	21.85	13	18.55	21.4	16.65	13.5
			Median	21.3	12	11.5	8.9	12.9	21.95	30.65	26.9	27.7	28.8	20.7	15.3
			Q3	33.55	24.175	13.3	13.5	26.825	28.725	55.075	44.8	42.65	43	26.2	31.4
			Maximum	136	31	30.7	116	157	60.8	111	62.7	68.3	126	32.3	177
	2	18343													
			Minimum	5	3.3	22.3	1.9	3.5	14.9	4.2	11.6	7.8	3.1	26.1	15.2
			Q1	9.65	6.15	30.175	14.05	7.7	31.85	7.75	17.525	11.4	6.6	54.075	25.5
			Median	13.65	9	38.05	43.05	13.05	48.8	61	36.25	14.8	9.2	82.05	35.8
			Q3	17.55	11.85	45.925	106.25	39.25	51.9	70.95	123	38.25	64.3	110.025	105.9
TSS			Maximum	21.9	14.7	53.8	221	106	55	100	333	102	358	138	176
	3	12647													
			Minimum	5.4	4.9	5	1	1.5	6.1	1	8.2	9.3	5.4	6	7.2
			Q1	7.9	6.05	11.05	4.13	3.85	11.3	8.05	10.9	15.1	10.8	8	12
			Median	14.2	8.15	12	8.9	15.7	12.7	12.1	15.4	26.3	17	10	13.7
			Q3	62.25	18.725	16.55	23.225	20.35	72.15	85.5	46.5	44.2	25.8	29.1	38.5
			Maximum	414	74.6	63.7	331	989	129	153	82	322	274	197	356
	4	12640													
			Minimum	5	4.7	4.4	1	1.8	3.33	5.7	3.4	5.8	7	6.3	8.6
			Q1	11.15	12.625	9.25	3	8.875	15.1	13.425	16.175	17.7	12	12.25	15.1
			Median	15.7	14.85	11.2	10.2	14	22.3	27.35	27.7	26	21.5	14.3	18.1
			Q3	35.2	29.4	31.05	21.4	25.175	129	114	46.825	59.95	48.3	15.55	51.1
			Maximum	450	124	60.7	527	114	309	224	349	140	157	51.4	126

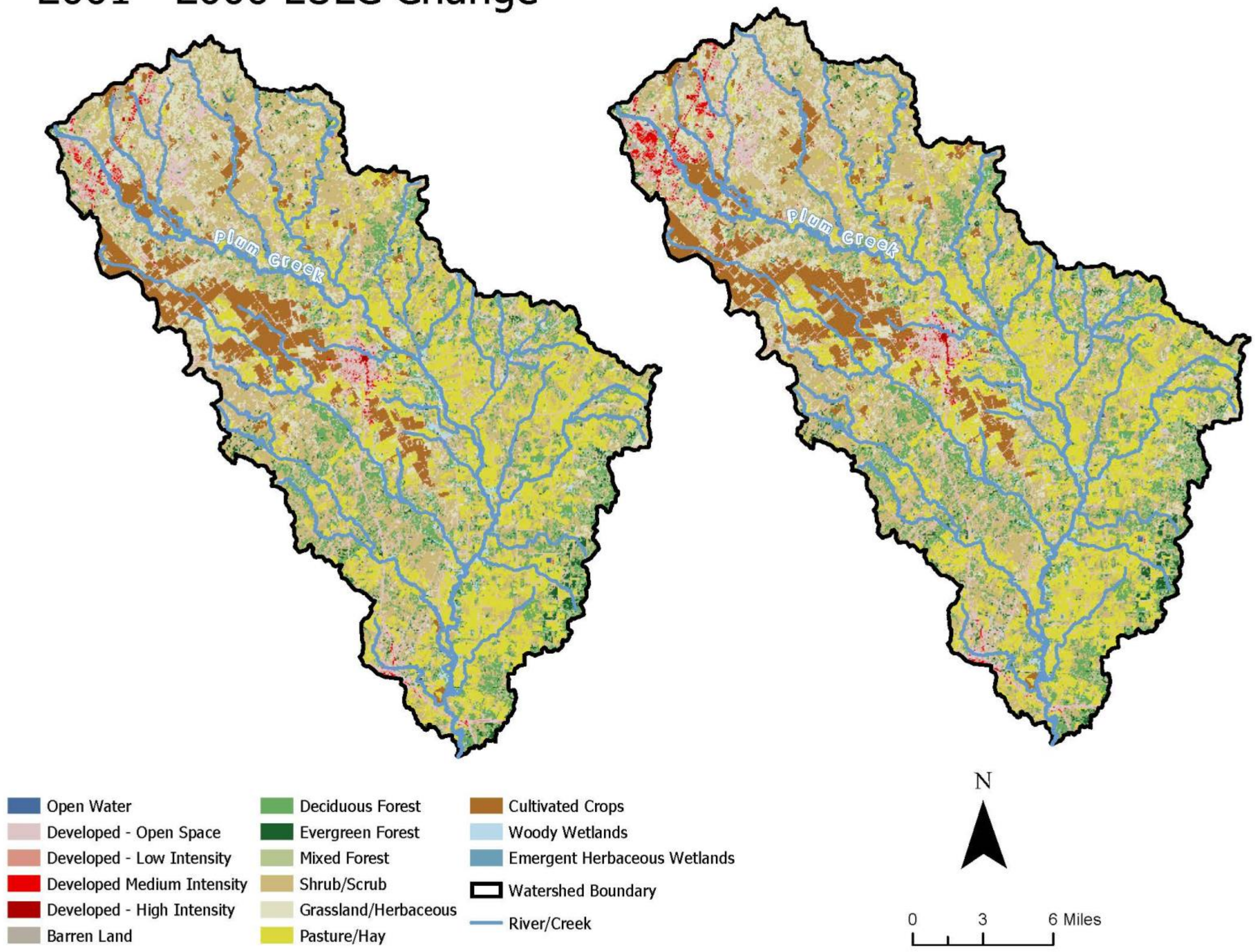
	Gage	Station ID	5-Number Summary	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Aug.	Sep.
	1	17406													
			Minimum	0.29	0.14	0.04	0.26	0.33	0.17	0.24	0.24	0.16	0.23	0.51	0.36
			Q1	1.13	0.815	0.315	0.56	0.465	0.56	0.455	0.8	0.675	0.76	3.3625	1.01
			Median	2	0.995	0.74	1.19	1.28	0.74	1.085	1.75	1.51	2.29	3.935	3.395
			Q3	4.28	3.1625	1.6175	2.24	2	2.06	2.905	2.81	2.725	3.13	4.435	4.1725
			Maximum	5.14	5.24	4.48	4.25	4.28	4.5	4.1	4.44	3.91	5.26	5	4.41
	2	18343													
			Minimum	0.46	2.21	0.18	0.2	0.22	0.23	0.24	0.17	0.29	0.33	1.35	0.22
			Q1	1.265	2.4825	0.1975	0.2525	0.24	0.23	0.265	0.3225	0.5525	0.75	1.54	0.615
			Median	1.55	2.755	0.215	0.58	0.8	0.37	1.02	0.705	1.115	0.9	1.73	0.79
			Q3	1.9475	3.0275	0.2325	1.2175	2.3	0.94	2.03	1.2075	1.9125	1.655	2.06	2.08
			Maximum	3.18	3.3	0.25	2.2	3.42	1.2	2.44	1.84	2.88	2.43	2.39	2.5
TP	3	12647													
			Minimum	0.47	0.17	0.31	0.18	0.38	0.24	0.22	0.26	0.14	0.48	0.38	0.28
			Q1	0.705	0.525	0.51	0.555	0.4575	0.4125	0.3525	0.46	0.58	0.79	0.8075	0.8
			Median	0.93	1.235	0.79	0.975	0.805	0.58	0.695	0.8	0.99	0.92	1.405	1.16
			Q3	1.765	1.64	1.595	1.15	1.2225	1.0125	1.11	1.22	1.4	1.3	1.7525	1.9
			Maximum	2.21	1.91	2.35	1.94	1.32	2.26	1.62	1.97	2.14	1.94	2.69	2.27
	4	12640													
			Minimum	0.23	0.2	0.19	0.18	0.24	0.23	0.24	0.3	0.21	0.24	0.28	0.28
			Q1	0.425	0.3325	0.325	0.31	0.2775	0.36	0.32	0.335	0.38	0.38	0.5	0.7425
			Median	0.66	0.47	0.44	0.58	0.525	0.53	0.38	0.545	0.68	0.56	0.7	1.125
			Q3	0.89	0.735	0.895	0.87	0.79	1.06	0.77	0.955	0.99	1	1.185	1.2975
			Maximum	1.5	0.86	1.23	1.81	1.14	1.48	1.33	1.56	2.69	2.12	2.1	2.23

	Gage	Station ID	5-Number Summary	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Aug.	Sep.
	1	17406													
			Minimum	1.12	0.37	1.27	1.4	1.59	0.6	1.14	0.46	0.76	1.24	0.61	0.45
			Q1	1.66	3.38	2.88	2.76	3.0625	2.23	1.7475	2.11	3.105	4.5	10.345	4.905
			Median	13.9	6.38	5.05	8.1	5.87	4.84	6.18	6.9	6.8	9.14	15.6	15.75
			Q3	19.5	11.225	10.9875	17.4	10.8	8.56	11.25	13.2	14.6	14	24.15	24.6
			Maximum	29.3	34.8	22.6	22.2	13.8	19.8	26.2	26.2	21.1	22.7	27.3	30.2
	2	18343													
			Minimum	0.35	2.53	1.15	0.77	1.37	0.72	0.57	0.39	1.76	0.13	1.71	0.08
			Q1	3.0125	4.0025	1.3225	0.83	3.16	1.22	1	0.47	2.045	0.525	2.965	0.755
			Median	7.235	5.475	1.495	2.565	3.47	1.39	4.6	0.925	3.63	1.65	4.22	1.01
			Q3	9.3725	6.9475	1.6675	5.4225	8	2.13	5.73	3.7725	6.49	3.32	4.275	3.69
			Maximum	9.8	8.42	1.84	8.85	10.3	4.47	10.1	5.5	10.6	5.56	4.33	6.9
$NO3^-$	3	12647													
			Minimum	0.96	0.51	2.18	0.73	2.21	0.8	0.46	0.32	0.37	0.87	2.17	0.22
			Q1	4	4.1975	3.56	3.89	4.52	1.4975	1.09	2	3.045	3.32	4.06	2.795
			Median	7.89	6.085	4.56	5.36	5.2	3.62	2.095	3.7	3.5	4.67	6.28	5.41
			Q3	10.51	11.15	7.54	7.92	7.37	5.73	4.22	4.34	5.42	7.48	7.995	6.57
			Maximum	14.7	16.3	13.2	9.75	8.8	11.5	6.2	7.23	7.66	10.6	16.1	12.6
	4	12640													
			Minimum	0.1	0.47	1.05	0.92	1.34	0.68	0.35	0.24	0.26	0.07	0.07	0.05
			Q1	0.825	1.25	1.515	3.33	2.0875	1.69	0.75	0.7975	0.51	0.27	0.2175	0.245
			Median	1.49	2.49	1.77	4.12	2.93	2.05	1.3	1.175	0.55	1.72	0.34	0.8
			Q3	3.31	3.18	3.03	6.24	4.645	2.57	1.86	1.8375	1.025	2.91	1.515	2.5725
			Maximum	5.12	5.88	7.52	7.96	6.16	5.32	3.33	5.22	7.23	7.01	3.76	9.48

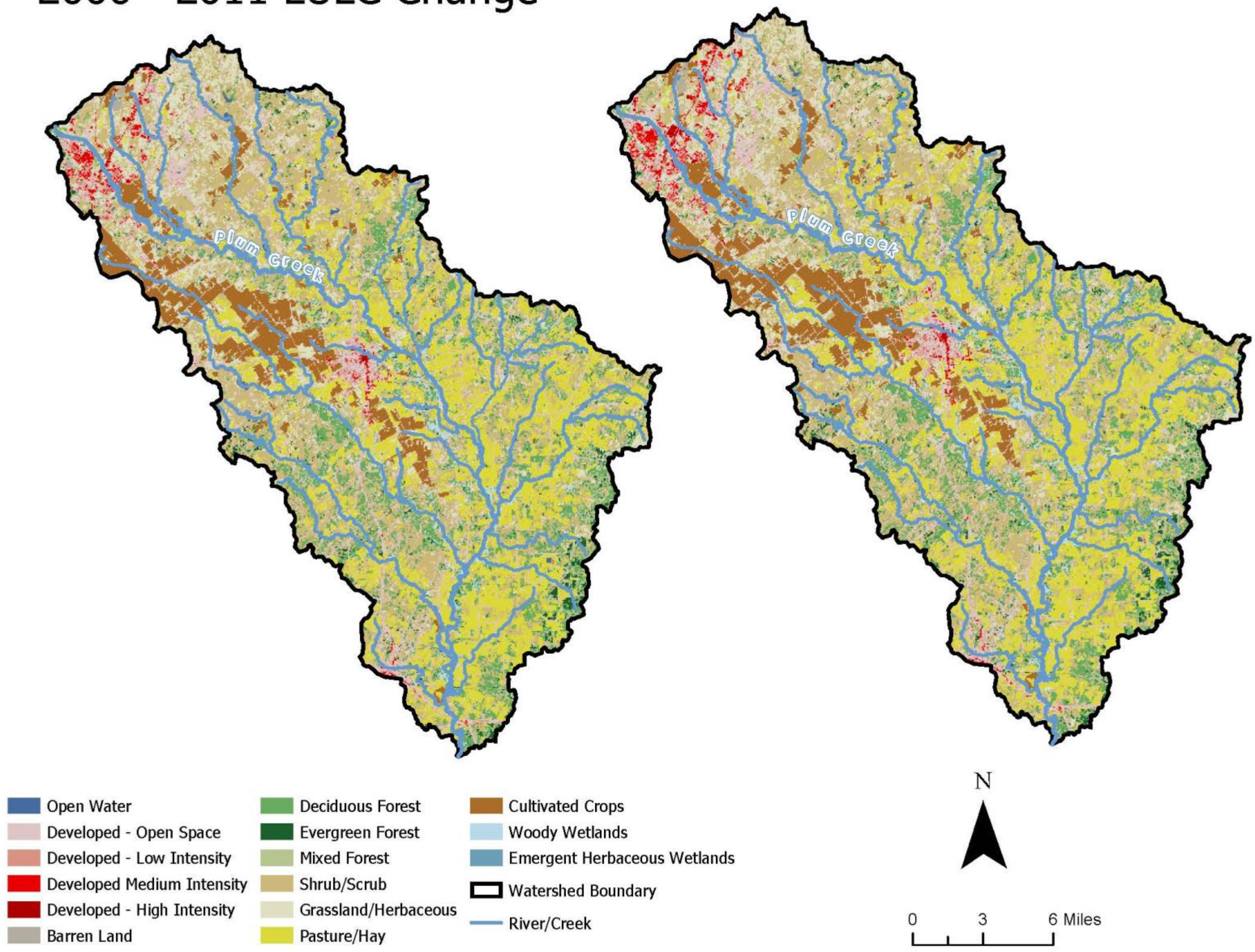
Appendix C – Land use/Land Cover Change for all Year Ranges



2001 - 2006 LULC Change



2006 - 2011 LULC Change



2011 - 2016 LULC Change