Wetland Treatment Study

Lake Thunderbird Watershed Implementation Project, Phase II

FY 2011/2012 §319(h) Task 5.4e
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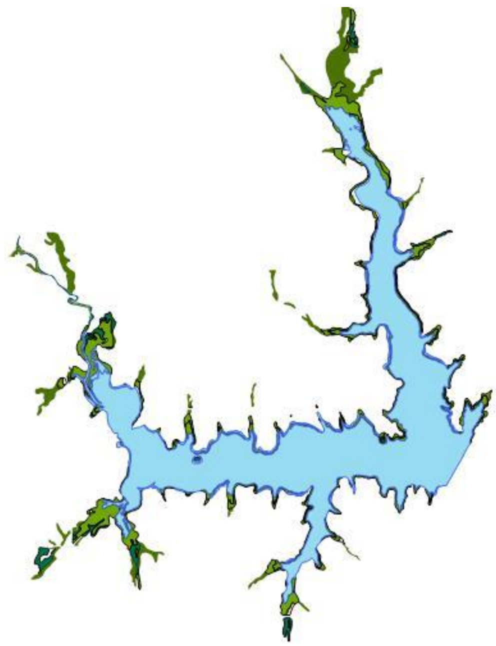

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Executive Summary

Lake Thunderbird in central Oklahoma is not supporting its Fish and Wildlife Propagation (Warm Water Aquatic Community) designated use. Excessive nutrient loading in the watershed, specifically from rapidly urbanizing areas, and resulting eutrophication are impacting the ability of the lake to supply drinking water and recreation. This report addresses the feasibility of wetlands as an option for storm water treatment. Four sub-tasks were addressed: i) a general analysis of existing wetland types in the watershed, ii) an evaluation of large-scale wetland creation and restoration, iii) an assessment of targeted, small-scale storm water treatment wetlands and iv) development of a comparative decision matrix for these two types of structural best management practices (BMPs) in the Lake Thunderbird watershed. Historic wetland ecosystems in the watershed were found to be restricted to narrow, linear corridors along streams, occurring in high densities and representing a relatively large portion of the local landscape. Existing wetlands are prevalent on reservoir feeder streams adjacent to Lake Thunderbird. Several large-scale created/restored wetlands, established primarily for water quality improvement in other regions of the United States, were evaluated. These systems, ranging in size from five to over 50,000 acres, effectively retain phosphorus, sediment and other storm water constituents. It is estimated that approximately 1,250 acres of wetlands could be created in Lake Thunderbird arms with little impact to surrounding uplands, representing between 13 and 76% of the necessary surface area for storm water abatement. Several types of small-scale (0.1 to 10 acres) treatment wetlands exist, employing more ways to improve water quality than any other structural BMP. Performance data were summarized for numerous treatment wetlands worldwide; they were found to effectively retain sediment and all forms of phosphorus and nitrogen. Design guidance for these systems is readily available from several sources. A mathematical design approach treating these systems as steady-state, plug-flow reactors provides for use of first order rate constants, detention times, hydraulic loading rates and expected concentration changes to develop areal and volumetric removal rates. Small-scale treatment wetlands may be implemented as new construction or as retrofits for existing storm water detention/retention ponds. The results of these analyses were used to develop a decision matrix addressing the ability of generic large-scale created wetlands

and small-scale treatment wetlands to meet several technical (e.g., water quality improvement performance, peak flow reduction, flood storage) and non-technical (e.g., social acceptance, recreational benefits, capital and operation/maintenance costs) objectives in the Lake Thunderbird watershed. Both types of wetlands were found to be technically feasible and appropriate storm water BMPs that would effectively address storm water quality while providing ancillary benefits. Implementation of a combination of both targeted small-scale treatment wetlands in specific upstream source areas and large-scale created systems adjacent to Lake Thunderbird would result in improvement of reservoir water quality and overall environmental benefit.

1.0 Introduction

Wetlands provide certain ecosystem services on which society places great value, e.g., storm water abatement, flood mitigation, water quality improvement (e.g., Mitsch and Gosselink 2007; Smith et al, 2011; Wardrop et al. 2011; Mitsch et al. 2012; McLaughlin and Cohen 2013). However, in many regions the great majority of natural wetlands have been converted to other uses and these ecosystem services have been subsequently lost (e.g., Mitsch and Gosselink 2007; Moreno-Mateos et al. 2012; Tweel and Turner 2012). Therefore, in recent years, created and restored wetlands (typically built to replace lost function and provide wildlife habitat) and treatment wetlands (designed and constructed specifically for water quality improvement) have become popular best management practices (BMPs) incorporated into watershed planning (e.g., Tilley and Brown 1998; Brabec 2002, 2009; Cohen and Brown 2007; OCC 2010; Bulkley 2011; Lawrence 2011; Tomer et al. 2013). This designation between created/restored and treatment wetlands is important not only from an intended functional perspective but also from an engineering design viewpoint. Design of created/restored systems often focuses on establishment (or reestablishment) of wetland hydrology, which, if properly introduced, is naturally followed by other wetland functions, including water quality enhancement. Design of treatment wetlands explicitly includes project variables to address specific water quality improvement goals, and include hydrologic control structures, substrates which promote beneficial biogeochemical processes, and biological factors like particular vegetation plantings and/or microbial habitats. Treatment wetlands have been used to address a wide variety of waste streams to remove nutrients, problematic organic constituents, trace metals, pathogens and even antibiotics (e.g., EPA 1998; Nairn and Mitsch 2000; Kadlec and Wallace 2009; Nairn et al. 2010; Hijosa-Valsero et al. 2011; Walker and Kadlec 2011; Malaviya and Singh 2012; Adhikari et al. 2013; Langergraber 2013).

Because of the water quality improvement benefits that both of these kinds of wetlands provide, incorporation of some type of wetland ecosystems has been discussed in Lake Thunderbird watershed planning (OCC 2010). For this task of the larger project *Lake Thunderbird Watershed Implementation Project, Phase II*, the viability of wetlands as storm water BMPs was evaluated. Furthermore, additional low impact development (LID) BMPs, not restricted to "wetlands", may provide water quality benefits. LID is the concept of strategically mitigating the adverse effects of urban storm water runoff, while maintaining pre-development levels of storage, infiltration, runoff and groundwater recharge (Bedan and Clausen 2009). Urban storm water BMPs are the tools used to sustain a low level of impact during and after development, and include a suite of techniques including rain gardens, permeable concrete, grass swales, rain barrels, bioretention systems, public education efforts, and others. Some of these LID BMPs have been implemented at the Trailwoods site, a separate task included in the Lake Thunderbird Watershed Implementation project. Several have a certain wetland character, but they were not explicitly evaluated in this task report. In this document, the benefits of using a few downstream large-scale created/restored wetland systems versus many upstream small-scale treatment wetlands are evaluated. However, it must be noted that these designations are somewhat arbitrary; a large created system could be considered a treatment wetland depending on project objectives and a small treatment wetland may provide additional functions beyond water quality improvement. For purposes of this study, large-scale created/restored systems are assumed to be those situated low in the watershed directly adjacent to or in Lake Thunderbird feed streams. The surface areas of these systems would be in the 10s to 100s of acres. Small-scale treatment wetlands are assumed to be those situated high in the watershed near sources of urban storm water runoff (either in residential neighborhoods and commercial districts or on lower order tributaries). These systems would have surface areas of <1 to perhaps 10 acres.

Four sub-tasks were addressed. First, a general analysis of existing wetland types in the Lake Thunderbird watershed was conducted. Based upon available data for land use/land cover, topography and hydrology, the viability of wetland implementation as a storm water BMP was made.

Second, large-scale wetland creation and restoration was evaluated. Although these types of ecosystems are not explicitly considered treatment systems, they do provide water quality benefits, especially in disturbed or rapidly developing watersheds. This evaluation focused on wetland development on the main stem of Lake Thunderbird feeder streams, specifically the Little River arm north of Alameda Street and the Hog Creek arm north of Hickory Road, both in Norman. The viability of large-scale wetland creation and restoration was evaluated from multiple perspectives including technical, social and economic feasibility. The water quality benefits provided by these systems are often only one consideration of many when evaluating these types of large land area transformations.

Third, the possible wide-scale implementation of targeted, small-scale storm water treatment wetlands was evaluated. These on-site systems, in residential or commercial areas or at particular lower-order tributary locations, are designed specifically to address particular constituents in storm water. They are designed with a focus on water quality, so other ancillary benefits (e.g., habitat provision) are not a primary consideration in the design and evaluation process.

Lastly, the information and data collected in sub-tasks 1-3 was combined and collated into a decision matrix for the Lake Thunderbird watershed. A rubric for evaluating the relative benefits of a small number of large created or restored wetlands lower in the watershed compared to installation of a large number of small targeted treatment wetlands higher in the watershed was developed.

2.0 Existing Wetlands in the Lake Thunderbird Watershed

Wetland ecosystems are unique features of the landscape, and their structure and function is quite variable depending on location, climate, and other related factors (e.g., OCC 2000; EPA 2001; Mitsch and Gosselink 2007; Mitsch et al. 2009). Diagnostic features of almost all wetlands include appropriate hydrology, hydric soils and hydrophytic vegetation. Given the ecological diversity of Oklahoma (e.g., 12 U.S. EPA Level III ecoregion designations), natural wetland types in the state reflect a wide range of ecological structure. Oklahoma wetlands include playas, marshes, bottomland hardwood forests, swamps, oxbows, riparian corridors, and peat-building fens.

As described by OCC (2010), the Lake Thunderbird watershed (Figure 1) lies in the Central Great Plains and Cross Timbers ecoregions (Woods et al. 2005) of Cleveland and Oklahoma Counties. The Central Great Plains is a transition area between western mixed grass prairies and eastern forested mountains, and the Cross Timbers is a complex landscape of rolling hills and narrow valleys. Historically, natural wetlands were not a predominant land feature in either of these ecoregions nor the Lake Thunderbird watershed. Riparian corridors, demonstrating some wetland features, were likely present. Small areas of marsh and bottomland hardwood forest may also have existed before settlement and landscape conversion. Soil types, indicative of previous wetland condition, allow examination of the historical probability of wetland features.

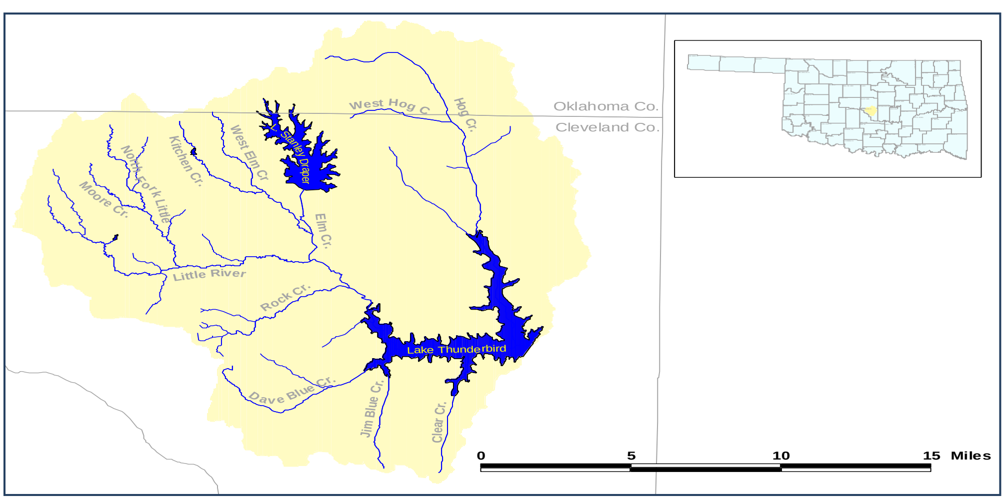


Figure 1. Lake Thunderbird watershed showing location in the State of Oklahoma, major tributary streams and county boundaries (from OCC 2010).

The National List of Hydric Soils of the United States (NRCS 2012) was created through the National Soil Information System database to identify potentially hydric soils based on selected soil properties, as determined by the National Technical Committee for Hydric Soils. An area that meets the hydric soil definition must also meet the hydrophytic vegetation and wetland hydrology definitions to be classified as a jurisdictional wetland for regulatory purposes. For Cleveland and Oklahoma Counties, no soil map unit components meeting the hydric soil criteria are included in the National List, supporting the determination of the paucity of areas of large historic wetlands extent in this region.

The Natural Resources Conservation Service Web Soil Survey (NRCS 2013) identifies a "hydric rating" for soil map units, essentially indicating the proportion of a given map unit that likely meets the hydric soil criteria. A map unit rated as "hydric" indicates that all components in that map unit are rated as hydric and that unit would thus be found on the National List of Hydric Soils of the United States (none exist in Cleveland and Oklahoma Counties). "Predominately hydric" indicates that components comprising 66 to 99 percent of the unit are rated as hydric, while "partially hydric" indicates that 33 to 66 percent of the components of the unit are rated as hydric. "Predominately nonhydric" means that components that comprise up to 33 percent of the map unit are rated as hydric and "nonhydric" indicates that none of the components (zero percent) of a given map unit are rated as hydric.

For Cleveland County, data from the Web Soil Survey (Table 1) found 15 map units identified as "predominately nonhydric" (but likely having some hydric component) with hydric ratings ranging from 1 to 10%. Based upon the areal coverage of these map units in the county, an estimated 882 acres of hydric soils may exist in Cleveland County as a whole, representing 0.25% of the total area. For Oklahoma County, a single map unit was identified as "predominately hydric" with a hydric rating of 81%. Based upon the areal coverage of this map unit in the county, an estimated 397 acres of hydric soils may exist in Oklahoma County as a whole, representing 0.09% of the total area.

It is important to note that these data are presented by county and were not generated solely for the Lake Thunderbird watershed. They include soils found in the greater Canadian River watershed. However, they do indicate that hydric soils, and thus historic wetlands, represent a minor portion of the soils in the area of study.

Table 1. Soil series in Cleveland and Oklahoma Counties, Oklahoma with hydric ratings greater than zero. Data from NRCS Web Soil Survey (2013).

	Hydric rating (%)	Estimated hydric soils (acres)
Cleveland County		
Gracemore-Gaddy complex, 0 to 1 percent slopes, occasionally flooded	10	213
Goodnight loamy fine sand, 5 to 20 percent slopes	5	46
Brewless silty clay loam, 0 to 1 percent slopes, rarely flooded	3	83
Norge-Ashport complex, 0 to 8 percent slopes	2	95
Asher-Urban land complex, 0 to 1 percent slopes, rarely flooded	1	1
Asher silt loam, 0 to 1 percent slopes, clayey substratum, rarely flooded	2	33
Asher silty clay loam, 0 to 1 percent slopes, clayey substratum, rarely flooded	1	17
Asher silty clay loam, saline, 0 to 1 percent slopes, occasionally flooded	1	6
Kirkland-Pawhuska complex, 0 to 3 percent slopes	1	46
Slaughterville fine sandy loam, 1 to 3 percent slopes	2	36
Keokuk very fine sandy loam, 0 to 1 percent slopes, rarely flooded	2	52
Port fine sandy loam, 0 to 1 percent slopes, occasionally flooded	2	61
Port silt loam, 0 to 1 percent slopes, occasionally flooded	2	70
Ashport silt loam, 0 to 1 percent slopes, occasionally flooded	2	111
Canadian fine sandy loam, 1 to 3 percent slopes, rarely flooded	2	13
Oklahoma County		
Hibsaw-Lomill complex, 0 to 1 percent slopes, occasionally flooded	81	397

Historic wetland ecosystems, if present, were likely restricted to narrow, linear corridors along streams, occurring in high densities and representing a relatively large portion of the local landscape. Wetlands are represented as being “widespread along the Little River and its tributaries” in the *Watershed Based Plan for the Lake Thunderbird Watershed* (OCC 2010), but bottomland hardwood forests and riparian wetlands were likely never an extensive or dominant part of the larger landscape, as indicated by soil types. This fact is not surprising, given that evapotranspiration exceeds precipitation in most of the southern Great Plains (Cleveland County receives slightly more than 37 inches of annual precipitation on average, but lake evaporation is estimated at more than 55 inches) and extensive areas of wetland ecosystems are typically found in areas of a net positive water balance.

A spatial representation of current wetland coverage in the Lake Thunderbird watershed was generated from the U.S. Fish and Wildlife Service National Wetland Inventory (NWI, USFWS 2013). NWI data, available through the online USFWS Wetland Mapper, were developed for wetland and deep water habitat classification and inventory, with classification based on the Cowardin et al. (1979) scheme. The inventory was developed from high altitude aerial photography and does not include ground trouthing. The Lake Thunderbird watershed was mapped from 1981 imagery so current landscape conditions may not be fully represented.

Data were downloaded from the Wetland Mapper into ArcGIS software (ESRI 2013) for purposes of this watershed analysis. Other than wetlands located along Lake Thunderbird feeder streams (e.g., Little River, Hog Creek, Dave Blue Creek, Jim Blue Creek and Clear Creek) and the lakeshore itself, all mapped wetlands consisted of diked/impounded man-made structures (Figure 2). These bodies of water represent stock or farm ponds in rural areas, and storm water retention/detention ponds in urban areas (and in some cases stock ponds converted to storm water ponds). Some of these small (all < 15 acres) systems include fringe freshwater emergent wetlands in the zone of water level fluctuation.

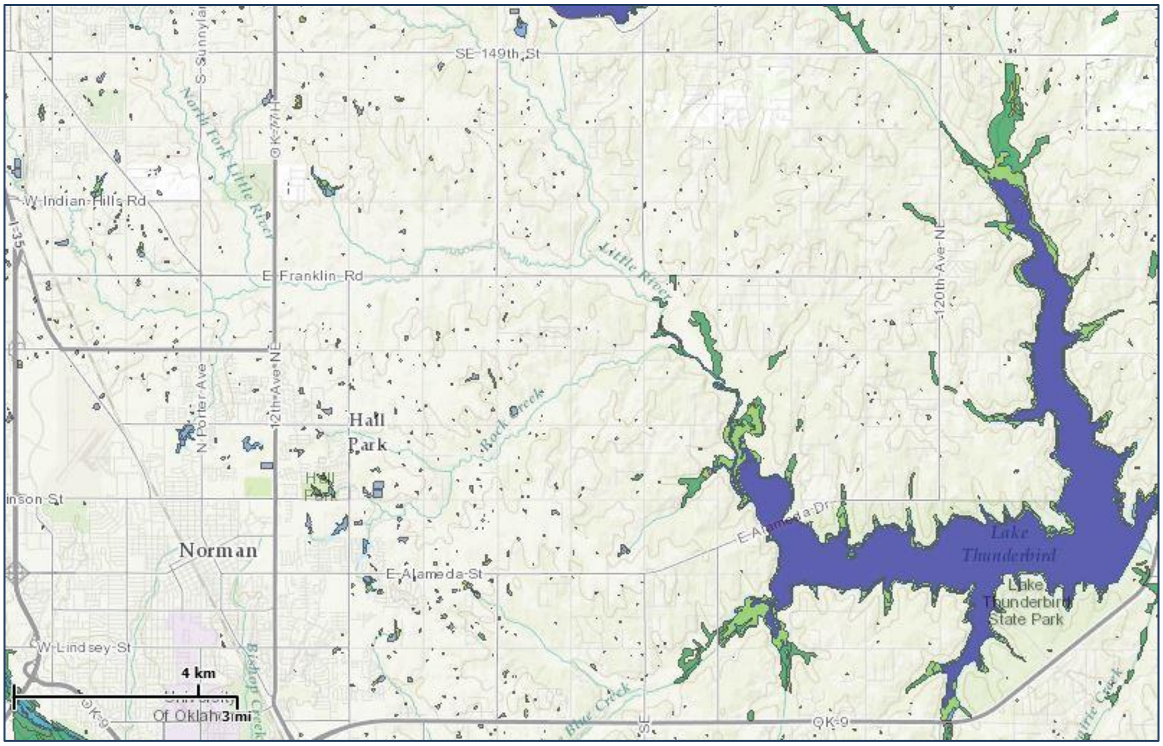


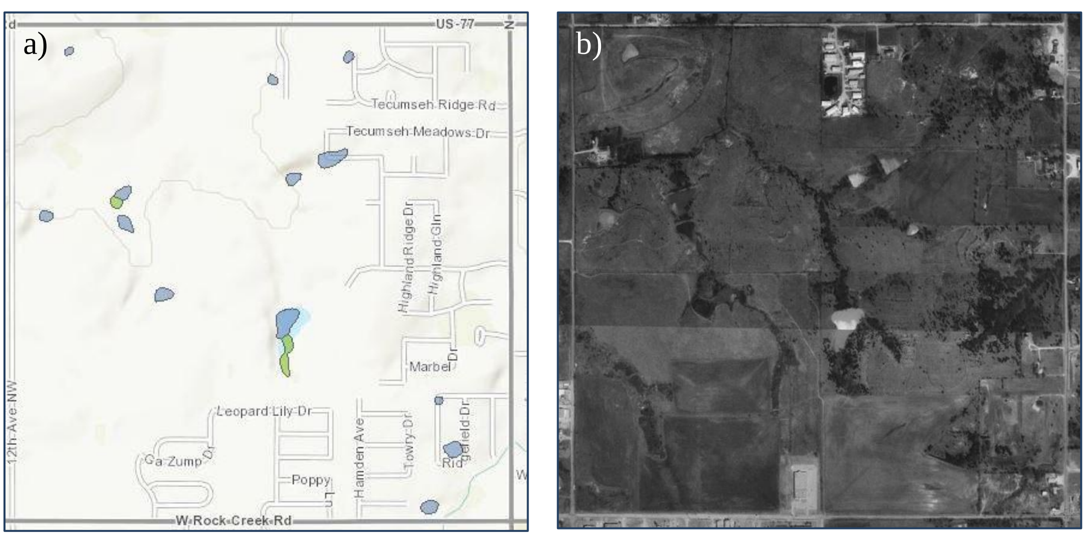
Figure 2. Portion of the Lake Thunderbird watershed showing National Wetland Inventory coverage; note the large number of small impoundments in the urbanized area of Norman to the west of Lake Thunderbird between Highway 9 and SE 149th Street and the lack of mapped wetlands in the riparian areas on the Little River, North Fork Little River and Elm Creek. Image from USFWS (2013).

As a specific example, the one square mile section which includes the Trailwoods neighborhood, bordered by Tecumseh Road on the north, Rock Creek Road on the south, Porter Avenue on the east and 12th Avenue NW on the west (Figure 3), includes 15 mapped water bodies ranging from 0.12 to 1.18 acres in surface area (mean 0.46 ± 0.29 acres). Thirteen of the 15 mapped water bodies are freshwater ponds and two are pond fringe-associated freshwater emergent wetlands. Fourteen of the 15 water bodies are diked/impounded systems, and the other one is an excavated pond. All are man-made. This section is a typical example of the rapidly urbanizing portion of the City of Norman and the Lake Thunderbird watershed.

Figure 4 displays the wetland coverage adjacent to Lake Thunderbird. Freshwater emergent and forested/shrub wetlands account for 1,171 and 737 acres, respectively, for a total of 1,908 acres. Table 2 displays a detailed classification of these wetlands using the

Cowardin et al. (1979) classification scheme. It is important to note that only 499 acres of mapped wetlands (26%) were not determined to be explicitly created due to the diking and impounding of water behind Norman Dam, e.g., due to Lake Thunderbird, although the continued presence of these wetlands without Lake Thunderbird is questionable. Approximately 88% (438 acres) of the non-diked/impounded wetlands are classified as “Palustrine Forested Broad-Leaved Deciduous Temporary Flooded” and may be indicative of historic bottomland hardwood forest habitat. Relatively large areas of these specific types of wetlands are located on the lower lake-associated reaches of Hog Creek, Little River, Dave Blue Creek and Jim Blue Creek. In any case, the great majority of extant mapped wetlands adjacent to Lake Thunderbird exist due to creation of the reservoir. These data are in concurrence with the soils data, indicating that wetlands were likely never an extensive or dominant part of the landscape in this watershed, with the exception of riparian areas.

These mapped wetland data are helpful for determination of possible wetland implementation sites, as appropriate hydrology for wetland development will need to be created. Given the paucity of hydric soils and lack of historic wetlands in the watershed, all wetland development, whether small- or large-scale systems, will most likely be



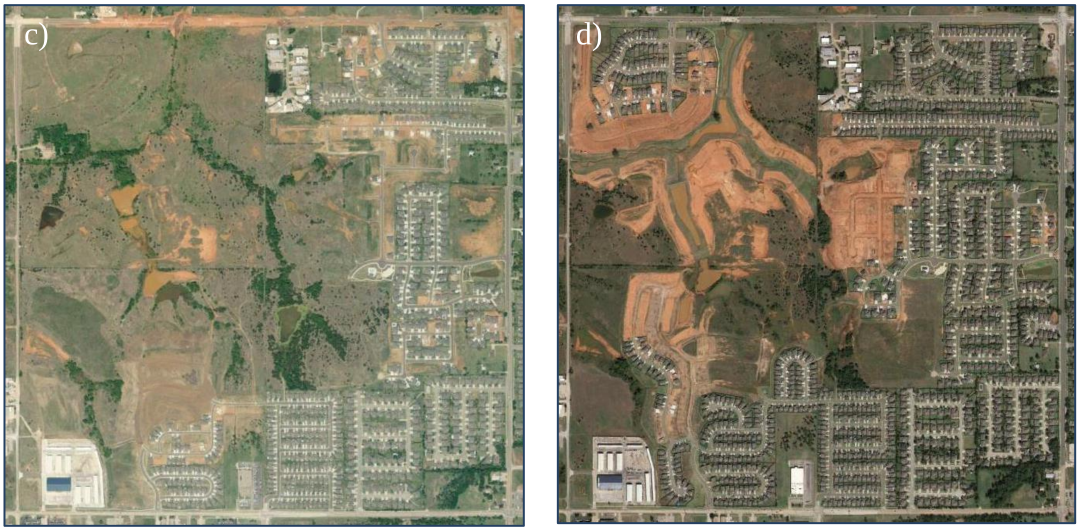


Figure 3. Section of Norman which includes the Trailwoods neighborhood (bottom center in all images): a) NWI map showing 15 water bodies < 1.2 acres in surface area, b) February 1995 aerial photo showing existing ponds and urban development limited to eastern (right) half of section, c) May 2008 aerial photo showing urban development (eastern and southern halves of section) and existing ponds and d) October 2013 aerial photo showing additional ongoing urban development throughout the entire section and establishment of new storm water ponds. Base images are USFWS (2013) and GoogleEarth (2014).

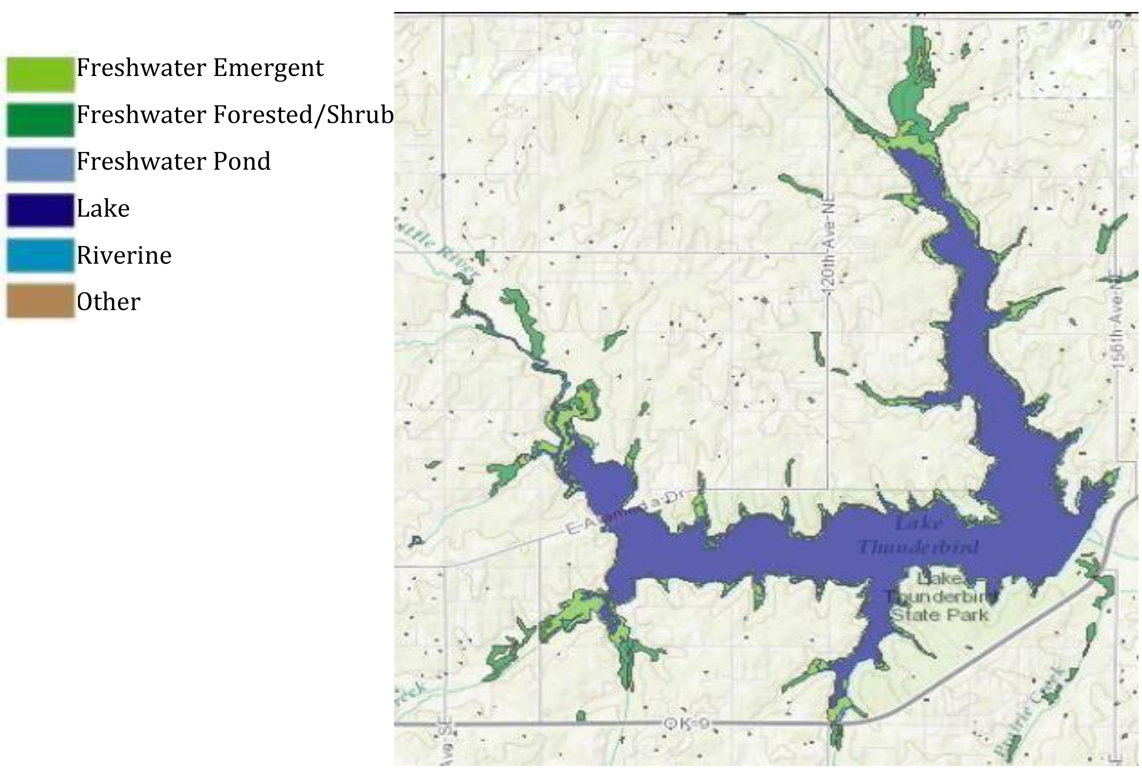


Figure 4. National Wetland Inventory coverage of Lake Thunderbird (USFWS 2013).

Table 2. Classification of wetland types adjacent to Lake Thunderbird (USFWS 2013).

	Diked (acres)	Not diked (acres)	Total (acres)
Freshwater Emergent Wetlands			
Palustrine Emergent Persistent Seasonally Flooded	685	14	
Palustrine Emergent Persistent Semipermanently Flooded	472	0	
Total Freshwater Emergent Wetland	1157	14	1171
Freshwater Forested/Shrub Wetlands			
Palustrine Forested Broad-Leaved Deciduous Temporary Flooded	126	438	
Palustrine Forested Broad-Leaved Deciduous Seasonally Flooded	16	0	
Palustrine Scrub-Shrub Broad-Leaved Deciduous Temporary Flooded	2	30	
Palustrine Scrub-Shrub Broad-Leaved Deciduous Seasonally Flooded	108	15	
Palustrine Scrub-Shrub Temporary Flooded	0	3	
Total Freshwater Forested/Shrub Wetlands	252	486	737
Total Wetlands	1409	499	1908

creations and not restorations. Although some wetlands adjacent to Lake Thunderbird are not classified as diked and impounded, their location in the landscape suggests their continued presence is due to the dam and reservoir creation and landscape position on a perennial Lake Thunderbird feeder stream. It must be noted that the available data sets from which these conclusions were drawn are not infallible, and some soils and historic wetlands information is no doubt lacking. However, these data do provide a foundation when evaluating possibilities for implementation of man-made wetlands in the landscape.

Successful wetland creation on non-hydric soils has been well-documented (e.g., Confer and Niering 1992; Nairn 1996; Anderson et al. 2005; Mitsch et al. 2005; Besasie and Buckley 2012; Mitsch et al. 2012; Drohan and Brooks 2013; Stapanian et al. 2013), but typically requires substantial hydrologic manipulation and control. On the small-scale (e.g., neighborhood storm water management), wetland-type BMP creation may require limited earthwork, but successful wetland development would likely be limited by availability of excess water in the hotter, drier times of the year. Other non-wetland LID BMPs, perhaps not as dependent on excess water availability, may be more appropriate for small-scale, site-specific storm water management. Large-scale wetland creation, assumedly near Lake Thunderbird, would require greater amounts of earthwork but water availability would likely not be as much of a problem given the larger contributing watershed area.

3.0 Large-Scale Created Wetlands

For purposes of this analysis, large-scale created wetlands represent systems that could be implemented as single, downstream, non-point source water quality improvement projects. These systems would be located on main stem feeder streams adjacent to the receiving water body, Lake Thunderbird in this case, and be designed to provide suitable conditions for nutrient and sediment retention prior to waters entering the main body of the lake. They would likely provide wetland-related benefits in addition to water quality improvement, e.g., wildlife habitat, public recreation, esthetics and others.

As with any size wetland creation, designs would require appropriate hydrologic controls to ensure that desired functions and services are provided, given that hydrology is the major forcing function of wetland service provision (Mitsch and Gosselink 2007). A positive water balance for the system is required, e.g., water inputs must exceed water outputs on an annual basis. Since the rate of evapotranspiration substantially exceeds the rate of precipitation in central Oklahoma, adequate runoff from the contributing watershed area is a critical design factor in creation of these systems.

The contributing watershed area needs to be large enough to maintain a permanent pool of water. EPA (2005) notes that 25 acres is a sufficient minimum watershed area for wetland creation in humid regions, but that in areas of lesser precipitation larger watershed areas may be required. Norman falls within the temperate humid subtropical climate region (Koppen climate classification Cfa; OCS 2014), and given sufficient watershed runoff, large-scale wetland creation is likely a viable alternative. Substantial and variable water level control and/or upstream bypass development would be required to not only maintain minimum water levels in those times of excessive heat and evapotranspiration, but to allow extreme flood flows to pass with minimal retention time.

Required contributing watershed areas for successful wetland creation are typically noted as being between 2 and 5 percent of the total watershed, depending on land use and cover (EPA 2005; Vieux 2007). The Lake Thunderbird drainage basin covers 163,840 acres and therefore between 3,277 to 8,192 acres of wetlands could be created throughout the watershed based on this criterion, assuming no significant upstream storage. The current existing wetland acreage adjacent to Lake Thunderbird is 1,908 acres so these values represent a potential increase of two to four times in wetland area.

OCC (2010) identifies two proposed wetland development sites in the *Watershed Based Plan for the Lake Thunderbird Watershed*: the Upper Little River and Hog Creek arms of the lake (Figure 5). Based on existing topography and assuming establishment of water level control structures at the Alameda Drive bridge for Little River and in a line due east of Hickory Road for Hog Creek, approximately 500 and 750 acres of wetlands could be established on the Little River and Hog Creek arms of the lake, respectively. The establishment of approximately 1,250 acres of created wetlands would represent 15 - 38 percent of the potential wetlands coverage, based on the watershed size. These two created wetlands would occupy an additional 0.8% of the watershed area. These large systems would provide ancillary benefits (e.g., wildlife habitat and public recreation) and would have a positive impact on water quality, especially with regard to sediment loads. Wetland construction would represent a large public works-type project with the associated significant costs.

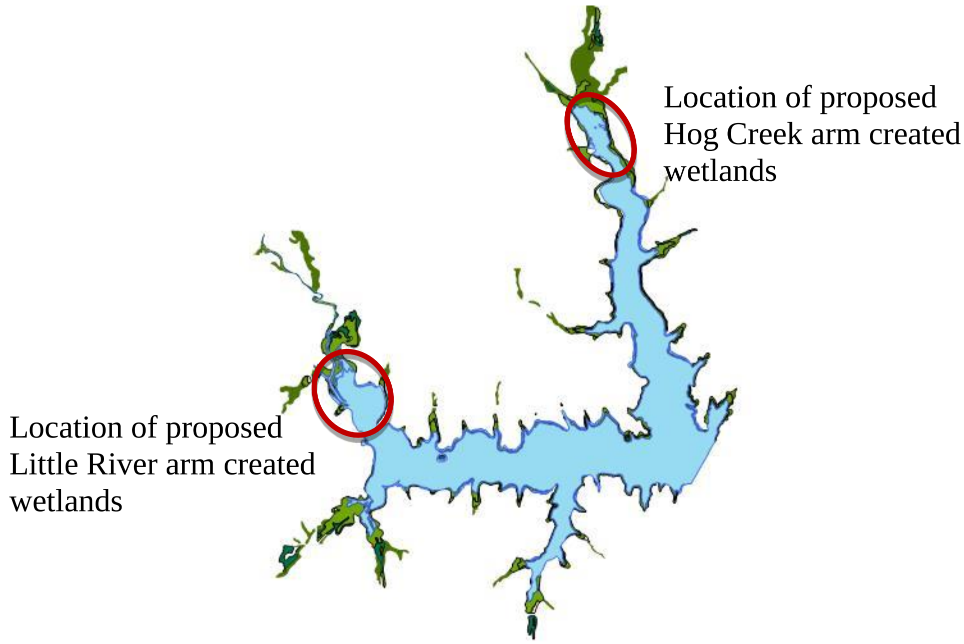


Figure 5. Previously identified (OCC 2010) areas for proposed wetlands creation on the Hog Creek and Little River arms of Lake Thunderbird.

Several excellent publications provide technical guidance for designing and implementing created and/or treatment wetlands for storm water quality improvement (e.g., ODEQ 2003; NJDEP 2004; Hunt et al. 2007; PADEP 2008; IDNR 2009; Burchell et al. 2010; VADCR 2011). Many states, including Oregon, New Jersey, Pennsylvania, Iowa and Virginia, have developed specific design guidance for storm water wetlands. The great majority of the guidance, however, focuses on smaller scale wetlands as on-site BMPs. Design specifications developed by the State of Virginia (VADCR 2011) unequivocally state that:

> *"Constructed wetlands are the final element in the roof-to-stream runoff reduction sequence. They should only be considered for use after all other upland runoff reduction opportunities have been exhausted and there is still a remaining water quality or channel protection volume to manage."* (VADCR 2011)

However, several notable large-scale wetlands have been established primarily for water quality improvement. Grenoble (2009) cites several proposed and existing wetland projects developed specifically to improve water quality for eventual human use (e.g., indirect potable reuse projects), although many more wetlands have been designed and constructed to address water quality concerns related to general environmental improvement. Four such systems of variable sizes will be discussed herein (Table 3).

Table 3. Four examples of large-scale wetland creation/restoration projects for water quality improvement showing wetted surface areas and overall percent decreases for sediment (sed.), phosphorus (P) and nitrogen (N).

	Surface area (acres)	Percent decrease Sed.	P	N
Everglades Stormwater Treatment Areas (FL)[1]	57,000	ND	73	ND
East Fork Raw Water Supply Project, TX[2]	1,840	95	65	80
Shannon Wetlands Water Reuse Project (TX)[3]	252	96	45	77
Olentangy River Wetlands Research Park (OH) – Year 1[4]	5	Sink	60	35
Olentangy River Wetlands Research Park (OH) – Year 15[4]	5	Source	10	25

[1] Data from Pietro (2012), [2] Data from NTMWD (2014), [3] Data from Kadlec et al. (2010), [4] Data from Mitsch et al. (2012). ND indicates no data available. Sink indicates lesser concentration in effluent than influent waters; source indicates greater concentration in effluent than influent waters.

The Everglades Stormwater Treatment Areas (STAs) are part of a much larger effort to restore the Florida Everglades ecosystem (SFWMD 2014). Eight STAs totaling 57,000 acres have been designed and constructed specifically to remove excess phosphorus from surface waters before those waters enter the Everglades Protection Area (Pietro 2012). Initial STAs began operation in 1996 and have reduced inflow phosphorus loads by 73% on average (decreasing annual flow-weighted mean total phosphorus concentrations from 140 to 37 μg/L) with annual retention ranging from 50 to 90%. The STAs are highly managed systems and operation requires a significant team of personnel to maintain pumps, gates, structures and vegetation. These systems are part of what has been described as “the world’s largest ecosystem restoration project” (U.S. House of Representatives 2008) and represent an extreme case of wetland creation for storm water management.

The East Fork Raw Water Supply project, developed and managed by the North Texas Municipal Water District (NTMWD), created 1,840 acres of wetland habitat fed by pumped river water from the East Fork of the Trinity River, an effluent-dominated water source (NTMWD 2014). The project was designed to provide 102,000 acre-feet of water to augment surface water supply sources. After flow through the wetland units, water is pumped 44 miles to Lake Lavon where it is blended with the water from three other reservoirs before entering a NTMWD water treatment facility. The system is an example of indirect water reuse. The wetlands are estimated to remove 95, 80 and 65% of the sediment, nitrogen and phosphorus loads, respectively, from the river water (NTMWD, 2008).

The Tarrant County Regional Water District's George W. Shannon Wetlands Water Reuse Project was also designed as a water supply alternative for a rapidly growing customer base (Machingambi and Mjelde 2012) and is another example of indirect water reuse. A pilot scale project began in 1992, the field-scale system now occupies 450 acres and a final estimated 3,000 acres of wetlands are planned. In the first five years of operation of the field scale system which received pumped river water that at times was predominately treated wastewater, removal rates of 96, 77 and 45% for sediment, nitrate-nitrogen and total phosphorus were realized (Kadlec et al. 2010).

The Olentangy River Wetland Research Park (ORWRP) is a 50-acre complex of created and natural riverine wetlands on the campus of The Ohio State University. Two 2.5-acre experimental wetlands, first flooded by pumped river water in 1994, have been the subject of extensive study for over 20 years (e.g., Nairn and Mitsch 2000, Weihe and Mitsch 2000; Harter and Mitsch 2003; Zhang and Mitsch 2005; Hernandez and Mitsch 2006; Altor and Mitsch 2008; Nahlik and Mitsch 2008; Song et al. 2010; Nahlik and Mitsch 2010; Batson et al. 2012; Mitsch et al. 2012). Although much smaller than the other systems described above and those proposed for the Little River watershed, the ORWRP wetlands are perhaps some of the most studied wetlands in the world. Water quality changes have been tracked continually since 1994. Initially, the systems acted as effective sinks for sediment, nitrogen and phosphorus. In the early stages of operation, these wetlands retained 60, 80 and 35% of the total phosphorus, soluble reactive phosphorus and nitrate-nitrogen, respectively. By the 10th year, the systems had changed from sediment sinks to sources. By the 15th year, removals for total phosphorus, soluble reactive phosphorus and nitrate-nitrogen had decreased to 10, 30 and 25%, respectively. These data point to the importance of long-term monitoring, evaluation and maintenance for continued water quality improvement in these natural treatment systems.

Large-scale wetland creation also provides ancillary benefits beyond water quality improvement. These ecosystems provide recreational opportunities ranging from hunting and fishing to wildlife watching. According to USFWS (2012), hunting and fishing enthusiasts spend $90 billion (with a total economic impact greater than $200 billion) and wildlife watchers spend another $55 billion nationwide each year. A properly developed and managed wetland can have direct economic benefits to local communities. The water quality improvement benefits provided by the wetland ecosystems are often only one consideration of many when evaluating large land area transformations.

For the Lake Thunderbird watershed, properly designed, constructed, operated and maintained large-scale created wetlands on the Little River and Hog Creek arms of the reservoir would improve water quality in the lake proper. Approximately 1,250 acres of wetland could be created in the lake arms with little impact to surrounding uplands, provided proper hydrologic controls are instituted. According to Wossink and Hunt (2003), the necessary surface area of required storm water wetlands is approximately one to six percent of the contributing watershed area. For the Lake Thunderbird watershed, approximately 1,640 to 9,830 acres would be necessary using these criteria. These systems would not address all water quality concerns in other portions of the watershed (e.g., urban streams in the City of Norman) or on other Lake Thunderbird feeder streams (e.g., Dave Blue, Jim Blue and Clear Creeks).

As essentially large civil works projects, design, construction, operation and maintenance costs for large -scale created wetlands are not trivial. According to Anderson and Lohof (1997) in a USEPA-funded study, constructions costs were estimated at between $10,000 and $50,000 per acre. The Charles River Watershed Association (CRWA 2008) provides more recent estimates of $39,000 to $82,000 per acre for treatment wetlands addressing storm water pollution.

Construction cost data were available for two of the four large-scale systems previously described: the East Fork Raw Water Supply Project and the Everglades STAs. Overall capital costs for the East Fork project (1,840 acres) was over $210M, however that cumulative cost includes $31M for pump stations, $151M for pipelines and $2M for an on-site nature center (NTMWD 2008). The wetlands construction costs were $26M or $14,130 per acre. For the Everglades STAs (57,000 acres), cumulative construction costs for the systems were greater than $700M with mean per acre costs of $12,140 (Sano et al. 2011). Both of these examples point to the economies of scale in large-scale wetland creation.

4.0 Targeted Small-Scale Treatment Wetlands

Small-scale wetlands constitute only one type of structural BMP for on-site or lower order tributary storm water control. Because of smaller contributing drainage areas, successful establishment of wetlands of this type is constrained by water balance issues, e.g., inadequate water availability under prolonged dry conditions would likely result in loss of wetland structural and functional attributes and lead to potential conversion to upland habitat. However, properly designed, constructed and maintained storm water treatment wetlands are a viable BMP (e.g., Hunt et al 2007; Burchell et al. 2010; Barbosa et al. 2012; Maleviya and Singh 2012; Moore and Hunt 2012).

The wetland environment in these systems provides ideal conditions for water quality improvement via gravitational settling, biological uptake, and beneficial microbial activity. Typically, these wetlands are designed to maximize contact time with soil, vegetation and microorganisms, thus requiring relatively long retention times (Weiss et al. 2007). In general, five types of small-scale storm water wetlands may be described: shallow marsh systems, basin/wetland systems, extended detention/retention wetlands, pocket wetlands, and floating wetlands (CRWA 2008; Winston et al. 2013), although many combinations are possible.

Shallow marsh systems often consist of long pools (water depth less than 18”) that meander through a series of elevated, vegetated marsh ridges (water depth less than 6”), thus alternating low marsh and high marsh conditions depending on water availability (CRWA 2008). Shallow marsh systems are typically designed to have little interaction with ground water and require relatively large drainage areas (CRWA 2008).

Basin/wetland systems consist of alternating wet retention ponds and high marshes, and are generally more efficient than shallow marshes in the terms of pollutant removal rates for a given required area (CRWA 2008). They may be designed to convey small storms though the wetland portion, while diverting or overflowing larger storm runoff into wet retention ponds (VADCR 2011). The wet pond may be sized to capture and retain heavy sediment loads and trash, provide for extended water flow supporting wetland conditions between storms and provide storage volume for larger storms.

Extended detention/retention may be accomplished in wetlands and/or ponds. Extended detention wetlands are also composed of the alternating low and high marshes, however the systems have a greater overall depth than the shallow marsh systems, to allow for detention of greater volumes of storm water. A major function of the extended detention wetlands is to rapidly fill with water during a storm event and slowly release the water collected over the following days (CRWA 2008). Dry extended detention basins are excavated basins for the purpose of diverting and collecting storm water runoff, ultimately reducing flood risk. Dry extended basins do not typically contain a permanent pool, and thus only large sediment particles can be removed from the system since there is not enough time for settling of all solids or for adsorption of contaminants onto solids (Weiss et al. 2007). This is a low cost method that may be helpful in removing certain fractions of the pollutant load (Weis et al. 2007). The establishment of wetland conditions in dry extended detention basins is limited by water availability. Wet retention basins collect and store water until the next precipitation event, which displaces the previous water retained. Similar to dry extended basins, the main treatment method in these systems is sedimentation, however the system is designed to sustain a permanent pool in which more and smaller particles are able to settle. A drawback to wet retention basins is the variability of the retention time for contaminants and the high probability for contaminants to short-circuit through the system (Weiss et al. 2007).

Pocket wetlands are excavations to intercept the water table, thus allowing for groundwater to be retained in the system. This method allows for smaller contributing drainage basins since the system does not rely on runoff for all of its moisture (CRWA 2008). This method may be an appropriate option for drier climates similar to Oklahoma that are subject to drought during the warmer months, if shallow groundwater is available.

Floating treatment wetlands may represent a possible retrofit option for existing storm water detention ponds (a common storm water quantity management practice) that might also provide a fair amount of ecological and water quality value within smaller drainage basins. Floating treatment wetlands consist of a hydroponic growing system, where the pond provides a growing medium for hydrophytic vegetation that is able to obtain nutrients from the storm water (Winston et al. 2013).

All storm water wetlands share certain common attributes indicative of the wetland condition: appropriate hydrology, soils/growing media and vegetation. Designs typically include forebays, deep pools, shallow water zones, transition zones temporarily inundated areas, banks, and outlet structures (Table 4). They employ perhaps more ways to improve water quality than any other structural BMP (Hunt and Doll 2000) including sedimentation, filtration, adsorption, microbial processing and plant uptake. Hunt et al. (2007) describe the importance of internal wetland zones, essentially zones of transitional elevation that allow for periodic water level fluctuations from dry to submerged to deep water conditions. Incorporation of these zones allows for the dissipation of storm water flow energy, provides for multiple and unique pollutant removal areas and diverse habitats, and delivers an esthetically pleasing landscape feature. Figure 6 provides a plan view of storm water treatment wetland incorporating these features.

Table 4. Typical design components of storm water treatment wetlands, adapted from Hunt et al. (2007).

Component	Description	Primary Functions	% area
Forebay	At least 2.5 ft deep, where runoff enters system, designed for maintenance	Initial energy dispersion, sedimentation, litter retention, wildlife refugia	10-15
Deep pools	At least 2.5 ft deep, retain water during droughts, may include floating aquatic vegetation, within wetland proper and preceding outlet	Sedimentation, adsorption, plant uptake, denitrification, water storage, wildlife refugia	5-10
Deep to shallow water transition	0.5 to 0.75 ft, ranging from 0.2 to 2.5 ft on a 1.5H:1V elevation change	Adsorption, plant uptake, nitrification and denitrification	5
Shallow water	0.2-0.3 ft deep before storm, deeper during event, emergent wetland vegetation	Filtration, adsorption, plant uptake microbial activity	40
Temporary inundation	0-1 ft deep, periodically submerged internal floodplain, diverse vegetation	Filtration, adsorption, plant uptake microbial activity, drying (pathogen elimination)	30-40
Upper bank	Never flooded, upland transition at <3H:1V slope, provides for observation	---	---
Outlet	Following deep pool, primary spillway slowly releases water but passes large storm events	Water level control	---

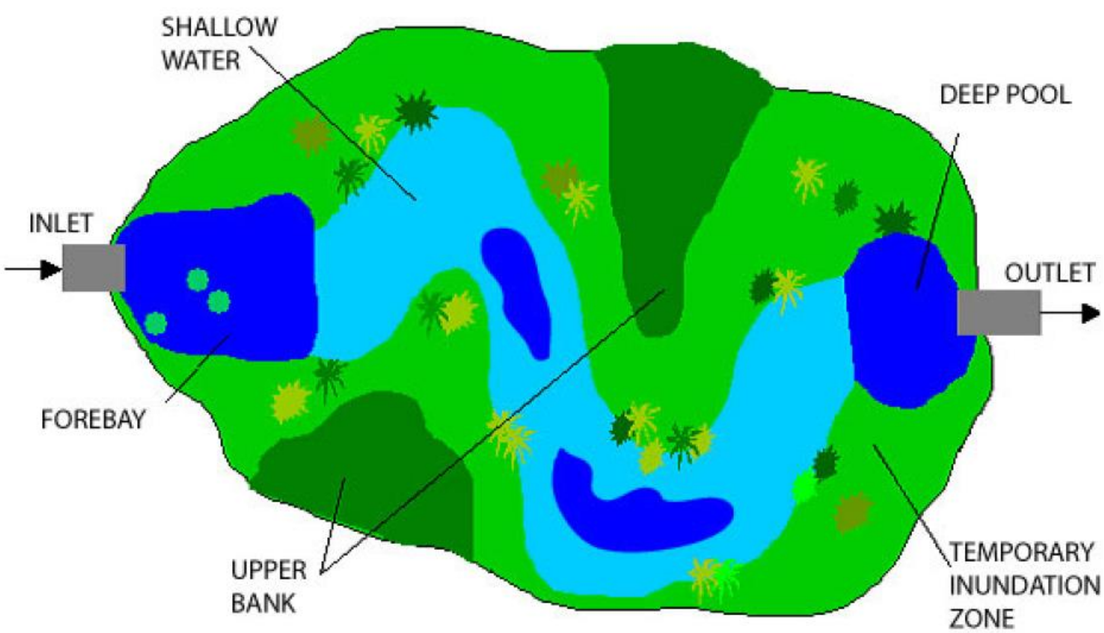


Figure 6. Plan view of a typical storm water treatment wetland, from Hunt et al. (2007).

Several states provide design guidance for storm water wetlands (e.g., ODEQ 2003; NJDEP 2004; PADEP 2008; IDNR 2009; VADCR 2011). Although state regulations differ, several common themes were evident in the review of the literature:

- Identification of site constraints, e.g., adequate water balance, available area, hydraulic head, minimum contributing drainage area, slope, and setbacks (from septic systems, property lines, private wells, etc.), depth to water table, soils, proximity to natural wetlands and other regulatory issues, was deemed crucial to success.
- A range of anticipated water quality improvement was found to be expected. As dynamic ecosystems, storm water treatment wetland performance should be expected to vary seasonally, geographically and climatically.
- The need for maintenance was emphasized, and ranged from sediment dredging to vegetation and animal control.

The Virginia Department of Conservation and Recreation (Design Specification No. 13, Constructed Wetlands; VADCR 2011) provides guidance based on three major factors: desired plant community, contributing hydrology and landscape position. Sizing is based on the ability "*to capture and treat the remaining treatment volume and channel protection volume discharged from upstream runoff reduction measures*". Details are provided for calculating the water balance, conducting appropriate geotechnical testing, and designing the forebay, conveyance and overflow structures, internal design geometry, microtopographic features, maintenance reduction features, and landscaping.

The New Jersey Stormwater BMP Manual (Standard for Constructed Stormwater Wetlands; NJDEP 2004) states that while provision of esthetics and habitat may occur, storm water wetlands are "*designed primarily for pollutant removal and erosion and flood control*". Three wetland zones are described, pool, marsh and semi-wet, for which the total volume must equal the design runoff volume. The guidance allows for both online (systems receiving runoff from all storms, providing treatment for the design storm and conveying excess water through overflow or outlet) and offline (systems treating the design storm but allowing most or all runoff from larger storms to bypass through an upstream diversion). The guidance is hydrologically-based on design storm runoff volumes and does not mention specific water quality improvement goals.

The Iowa Stormwater Management Manual (2H-1 General Information for Stormwater Wetlands; IDNR 2009) describes storm water wetlands as constructed systems "*explicitly designed to incorporate functions… to aid in pollutant removal*". Depending on site specific conditions, they are described as having high effectiveness (65-100% removal) for suspended solids, metals, bacteria and hydrocarbons, medium effectiveness (30-65% removal) for nitrogen, phosphorus, metals and bacteria and low effectiveness (<30% removal) for phosphorus. Properly designed, sized, constructed and maintained wetlands are noted to be able to remove 80% of the total suspended solids load, while nitrogen and phosphorus removal is expected to be more variable. Four design variants are identified: shallow wetlands, extended detention shallow wetlands, pond/wetland systems and pocket wetlands. Step by step design procedures are provided and include i) computation of runoff control volumes, ii) determination of site-specific feasibility, iii) identification of jurisdictional design criteria and applicability standards, iv) determination of pre-treatment volume, v) allocation of water quality volumes to specific zones, vi) determination of location and preliminary geometry, vii) computation of extended detention orifice release rates, viii) calculation of the 25-year storm release rate and water level elevation, ix) design of embankments and spillways, x) investigation of pond/wetland hazard classifications, xi) design of inlets, forebays, outlets, maintenance access and safety features and xii) preparation of a vegetation and landscaping plan.

As biologically-driven ecosystems, the performance of storm water wetlands is variable and dependent on climatic and other environmental conditions. Hunt and Doll (2000) cite data from a Brown and Schueler (1997) study in the Mid-Atlantic region showing considerable performance variability for storm water wetlands (Table 5). Negative pollutant removal percentages indicate that the systems were acting as sediment or nutrient sources on at least some occasions. The long retention times in these systems and the complexities of sample matching (for any given sampling event, influent water quality is not necessarily indicative of the quality of effluent waters when they entered the system) make these analyses difficult. Overall, median removal rates were all positive (78, 51 and 21% for total suspended sediment, phosphorus and nitrogen, respectively).

Table 5. Summary data for storm water treatment wetland performance from Hunt and Doll (2000).

		Pollutant removal (%)		
	Sample size	Median	Maximum	Minimum
Total suspended sediment	35	78	99.5	-29
Phosphorus				
Total P	35	51	99.5	-9
Soluble P	15	40	75	-35
Nitrogen				
Total N	22	21	83	-25
Ammonia as NH4	19	43	72	-56
Nitrate-N	30	67	90	-100
Organic N	12	1	43	-31
Total Khedjahl N	10	15	81	-10

In perhaps the most comprehensive study to date of the performance of storm water wetlands, Carleton et al. (2001) examined data from 49 treatment wetland systems in an effort to aid development of more effective designs. The study included wetlands of various volumes and surface areas, and thus hydraulic loading rates and retention times. Ten of the studied systems received pumped inflow waters. Contributing drainage basins for the other systems ranged over six orders of magnitude. Summary statistics for the studied wetland systems may be found in (Table 6).

Water quality improvement performance for the wetlands included in the Carleton et al. (2001) study demonstrated substantial variability (Table 7), similar to those included in the Hunt and Doll (2000) data set. For example, total phosphorus percent removals ranged from -55 to 89 %, with a mean of 39±5% and a median of 40%.

Table 6. Descriptive information summary of the 49 storm water treatment wetlands included in the Carleton et al. (2001) study. "St. dev" is the standard deviation, "std. error" is standard error, and "max." and "min." refer to maximum and minimum values.

	Number of wetlands	Mean	Median	Std. dev.	Std. error	Max.	Min.
Wetland volume	33	346	10	1509	263	8675	0.11

(acre-feet)							
Wetland surface area (acres)	49	323	13	1090	156	4917	0.11
Contributing drainage basin (acres)	38	$2.26x10^5$	539	$1.36x10^6$	$2.21x10^5$	$8.40x10^6$	1.58
Wetland/watershed area ratio	37	0.046	0.023	0.058	0.010	0.289	0.001

Table 7. Summary data for storm water treatment wetland performance from Carleton et al. (2001).

		Pollutant removal (%)					
	Number of wetlands	Mean	Median	Std. dev.	Std. error	Max.	Min.
Total suspended sediment	35	49	68	78	13	100	-300
Total phosphorus	48	39	40	33	5	89	-55
Orthophosphorus	16	23	40	57	14	77	-109
Total nitrogen	20	14	21	24	5	46	-49
Nitrate-N	26	43	52	56	11	99	-193

In terms of performance evaluation, Carleton et al. (2001) utilized the mathematical approach of Kadlec and Knight (1996) which treats the wetland systems as steady-state, plug-flow reactors, ignoring the mechanistic complexities of removal processes (in what is often referred to as the "k-C*" approach). First order rate constants were developed and were found to be remarkably consistent with values reported for wastewater treatment wetlands. These design equations employ mean detention time and hydraulic loading rates along with concentration changes. Areal and volumetric removal rate constants developed in the wastewater treatment wetlands literature appear to be applicable to storm water treatment wetlands and may be used to estimate an area necessary to achieve a given level of treatment.

In addition, Carleton et al. (2001) found that storm water treatment wetland performance could be predicted based on the wetland surface area to contributing watershed area ratio. This ratio varied from 0.001 to 0.289 with a median of 0.023. For total phosphorus, the resulting regression equation:

$$TP\ (\%\ removal) = 100-77.3e^{(-5.21\ x\ wetland\ area/watershed\ area)}\ ;\ r^2 = 0.32;\ p = 0.0001$$

should be used cautiously, but does provide an effective approach for preliminary design and sizing calculations. Similar regression equations were developed for total suspended sediment, total nitrogen, ammonia, nitrate, lead, cadmium, zinc, and copper.

In a more recent comprehensive review of treatment wetlands for urban storm water management, Malaviya and Singh (2012), examine the role of these systems in nutrient, metal, organic and particulate matter, herbicide, bacteria and polycyclic aromatic hydrocarbon removal. They provide a thorough review of storm water constituents, a variety of structural BMPs, detailed wetland pollutant removal mechanisms (volatilization and phytovolatilization, plant uptake and phytoaccumulation, sorption and sedimentation, phytodegradation, and microbial degradation), wetland plant species, and wetland types. They provide a thorough literature review but only general pollutant removal data for 13 systems in North America, Australia, Europe, and Asia. Sediment, total nitrogen, and total phosphorus percent removals range from 9-94%, 16-84% and 12-90%, respectively, once again showing wide variability in performance.

Moore and Hunt (2012) provide a more holistic means of evaluation of storm water treatment wetlands by examining ecosystem service provision. Ecosystem services are defined as societal benefits obtained from ecosystems (Costanza et al. 1997). Moore and Hunt (2012) evaluated three specific ecosystem services provided by 20 storm water ponds and 20 storm water wetlands in North Carolina. Carbon sequestration, biodiversity and cultural services were evaluated. Emergent wetland vegetation, whether in wetlands or littoral zones of ponds, was found to be crucial to carbon sequestration. Better tracking of carbon sources and methane emissions were noted as being important future work. Vegetative diversity was found to be higher in wetland ecosystems, but macroinvertebrate diversity was similar in both wetlands and ponds. A greater abundance of predatory insects likely contributed to lower mosquito larvae numbers in wetlands as opposed to ponds. Cultural amenities were found to be provided by both ponds and wetlands. However, wetlands were typically designed *a priori* to provide such services more so than ponds. Survey-based assessment techniques were noted as being necessary for further evaluation of cultural services. Overall, wetlands provided a greater range of ecosystem services, but ponds with vegetated fringes diminished any differences.

Overall, properly designed, constructed, operated and maintained small-scale treatment wetlands are a viable structural BMP for targeted storm water quality improvement. As noted by several authors (e.g., Barbosa et al. 2012; EPA 2012; CSN 2014; CWP 2014), they are one tool in a tool box of many structural BMPs and should not be considered a stand-alone solution. For the Lake Thunderbird watershed, implementation of targeted storm water treatment wetlands, whether in new urban neighborhood developments or as retrofits and/or replacements for existing structural BMPs, would have a positive impact on storm runoff, receiving stream and Lake Thunderbird water quality. Implementation of storm water treatment wetlands in the City of Norman would likely take both of these two approaches.

First, treatment wetlands could be implemented as part of new construction efforts, instead of the typical installation of wet or dry detention/retention ponds. It is anticipated that new treatment wetland construction costs would fall in the $39,000 to $82,000 per acre range (CWRA 2008). These costs are comparable to the typical construction costs of $41,600 for a one acre-foot pond cited by Obropta and Bergstrom (2010), based on controlling the 10-year storm volume. Second, treatment wetlands could be implemented as retrofits for existing structural BMPs. Costs would vary considerably depending on the magnitude of the retrofit. CWP (2014) provides both new construction and retrofit costs data per acre of impervious area treated. For pond retrofits, costs range from $3,600 to $37,000 for a mean contributing watershed area of 0.58 acres. This same document provides new construction of treatment wetlands costs per acre of impervious area treated of $2,000 to $9,600.

In any case, targeted small-scale treatment wetlands appear to be a cost-effective urban storm water management tool. Implementation at the neighborhood and/or small watershed scale would require close coordination with developers, homeowners associations, non-profit organizations, as well as city and state staff. For a rapidly urbanizing city like Norman, incorporating treatment wetlands into both new construction and retrofitting of existing traditional peak-flow reducing structural BMPs would be necessary for effective water quality improvement in Lake Thunderbird.

5.0 Decision Matrix

As stated in the original scope of work, this task addresses the general viability of wetlands as a BMP for the Lake Thunderbird watershed. The relative benefits of a small number of large created wetlands lower in the watershed versus a large number of small targeted treatment wetlands higher in the watershed was qualitatively evaluated.

A relatively simple, comparative decision matrix was developed, incorporating technical, social and economic factors. This initial qualitative effort was developed as a starting point to be used to help formulate a future quantitative scoring rubric for effective decision-making. Input from various watershed stakeholders would inform the quantitative scoring rubric and perhaps change the matrix inputs. Weighting factors were not generated in this initial analysis, but would be an effective method to assist in scoring of alternatives in a full analysis.

It is anticipated that the quantitative tool could be incorporated into a more complex multi-criteria decision analysis (MCDA), which is beyond the scope of the present task. MCDA is a discipline supporting decision makers making numerous and conflicting evaluations (Stewart 2012). It creates a structured process to identify objectives, examine alternatives and compare them from different perspectives and improves the quality of decisions by making them more explicit, rational and efficient. A logical next step would be development of a simple decision tree to help guide the BMP selection process and to be used as an input to the MCDA. Like the matrix, the decision tree would represent an initial effort to identify key points in the selection process. It would be modified by stakeholder input and could be incorporated into the more comprehensive MCDA process that would likely include a full suite of wetland- and non-wetland BMPs.

Based on the likelihood of reaching an overall goal of adequate and sustainable treatment of storm water runoff leading to improved Lake Thunderbird water quality, the qualitative decision matrix included both technical and non-technical factors and considered only the two alternatives covered by this task report (Table 8).

For this initial qualitative effort, the alternatives were scored from High (great likelihood of achieving objective) to Medium (likelihood of achieving objective) to Low (lesser likelihood of achieving objective) by the project team. For several stated objectives (e.g., those dealing with construction costs), determination of scores was based on an arbitrarily-defined level of "acceptance". Without site-specific data, it was determined that this approach was helpful in this "first cut" analysis. Each objective and the justifications for initial scoring are summarized below.

Technical objectives were based on water quality, water quantity and land use topics. The ability of the BMP alternative to intercept targeted pollutants prior to entering any receiving water body was considered. Although downstream created wetlands near Lake Thunderbird would likely improve water quality in the lake proper, they would not address water quality in smaller receiving streams near the runoff sources and these systems were therefore rated lower than targeted treatment wetlands.

Table 8. Decision matrix for evaluating few downstream large-scale created/restored wetlands and many upstream small-scale treatment wetlands. H, M and L refer to High, Medium and Low probabilities, respectively, of the alternative meeting objectives.

Objective \ Alternative	Large created wetlands	Small treatment wetlands
Technical objectives		
Ability to intercept target pollutants at source	L	H
Acceptable land area commitment	M	H
Justification of documented previous success	M	H
Overall water quality improvement effectiveness	M	H
Sediment retention	H	M
Nutrient removal	M	H

Trace metal removal	M	M
Oxygen demanding substances removal	L	M
Bacteria removal	H	H
Herbicide and organic removal	M	M
Small event peak flow reduction	H	M
Large event peak flow reduction	H	L
Small event flood storage	H	M
Large event flood storage	M	L
Acceptable operational commitments	H	H
Acceptable maintenance commitments	H	M
Non-technical objectives		
Social acceptance	H	M
Provision of recreational benefits	H	L
Acceptable capital construction costs	L	H
Acceptable short-term O&M costs	H	H
Acceptable long-term O&M costs	M	M
Provision of economic return	H	L

Available land area is often one of the most important and potentially contentious issues when considering storm water BMPs (CWP 2007). For large-scale created wetlands, land acquisition may be more costly than system construction costs. On the Lake Thunderbird arms considered in this study, adequate land area may be able to be made available through cooperative efforts of the City, State and the Central Oklahoma Master Conservancy District. However, given the difficulty of obtaining sufficient acreage for successful large-scale wetland creation, this objective was rated lower for these systems. It was anticipated that land areas necessary for targeted treatment wetland implementation would be readily available at new construction sites (as part of meeting existing storm water peak flow reduction requirements) or at pond retrofit locations. However, some modifications of existing ordinances may be required.

A great deal of literature justifies the water quality improvement capabilities of targeted, small-scale treatment wetlands (e.g., Carleton et al. 2001; Hunt et al. 2007; Kadlec and Wallace 2008; Maleviya and Singh 2012). Although a similar wealth of literature supports this function for large created wetlands (Kadlec and Wallace 2008; NTWMD 2008; Kadlec et al. 2010; Pietro 2012), the reliance on utilizing these systems as a stand-alone method to meet in-lake water quality improvements may not be as easily justified. Similar reasoning influenced the overall water quality improvement effectiveness ratings. Although large-scale created wetlands are more effective at sediment retention, small-scale treatment wetlands appear to be equally if not more effective for trace metal, oxygen demanding substance, bacteria, herbicide and organic removals.

In terms of hydrologic performance, large-scale created wetlands are more effective at small and large peak flow reduction and flood water storage than small-scale treatment wetlands. Many small systems are not designed for flood storage and simply allow exceedingly large flows to bypass. Although larger system designs may also incorporate a bypass for extreme events, the overall likelihood of positively addressing flood flows and storm peaks is much greater for these systems.

Operational and maintenance commitments (e.g., labor and time) for both large created and small treatment wetlands are expected to be lower than for other more intensive storm water management options. If designed and constructed properly, operation is relatively straightforward and may be considered relatively negligible from a labor and time perspective. However, given sediment loads in storm water, maintenance can be a substantial undertaking, although perhaps not on a day to day basis. It is likely that smaller treatment wetlands would require sediment removal, replanting and reconstruction on a more frequent basis than the large created wetlands, albeit at lower costs.

In terms of non-technical objectives, social acceptability was rated higher for large downstream created wetlands than for smaller upstream treatment wetlands. This rating was justified somewhat by the "not in my backyard" perception often cited in environmental decision making. By placing the BMP downstream, outside of any residential neighborhoods and commercial developments, environmental benefit may be provided with little impact on day to day economic and social activity. However, properly designed and landscaped small-scale treatment wetlands can provide environmental amenities beyond water quality improvement (Machingambi and Mjelde 2012; Moore and Hunt 2012). In other words, treatment wetlands can provide both form and function.

It is unlikely that small treatment wetlands would provide recreational benefits beyond the surrounding local neighborhood or commercial district and they were therefore rated lower for this objective. Large created wetlands lower in the watershed would potentially provide regional benefits to outdoor recreational enthusiasts. Many large created and restored wetlands in Oklahoma, e.g., Red Slough, Grassy Slough, Hackberry Flat, Drummond Flats, have been developed into Wildlife Management Areas that draw visitors (and dollars) from throughout the southern Great Plains.

Construction costs for large created wetlands would be substantial and therefore, for this initial analysis, this objective was rated lower for these systems. Innovative funding scenarios may be brought to bear to address these costs, but the overall cost would be large enough to likely need to be shared by all impacted parties. Construction costs for smaller treatment wetlands would likely fall to developers or homeowners associations, which would then pass them on to individual residents or tenants. The actual cost for a local fix such as this would be lower but would still be shared by the appropriate parties. Similar to operation and maintenance commitments, associated costs would be lower for either large created or small treatment wetlands compared to other management options. In either case, these systems can be considered low maintenance (but not no maintenance) options.

Provision of economic return was rated based on external benefits provided by the systems and not on a thorough analysis of the benefits provided by improved water quality. For example, the greater recreational benefits provided by the large created wetlands compared to small treatment wetlands would provide greater direct input into local economies.

6.0 Conclusions

Although wetlands were not a spatially dominant component of the pre-development landscape of the Lake Thunderbird watershed, riparian zones and associated bottomland hardwood forests were likely found along streams and rivers. Today, substantial wetland coverage exists adjacent to Lake Thunderbird.

Proper design and construction of both i) a few large-scale created wetlands low in the watershed and ii) many small-scale treatment wetlands higher in the watershed would likely have a positive and marked effect on Lake Thunderbird water quality. They may both be considered sustainable, economical, and energy efficient means of treating storm water runoff (e.g., Kadlec et al. 2000). Both systems rely on a complex and interactive suite of hydrologic, biogeochemical and ecological processes to improve water quality. The surface area and volume of wetlands plays an important part in the water quality improvement and pollutant removal capabilities of the systems (Malaviya et al. 2011). In recent years, improved designs of small-scale treatment wetlands have resulted in greater pollutant removal efficiencies (Hunt et al. 2007).

Perhaps the largest difference between the two strategies may be the hydraulic residence time of water in the systems. Small treatment wetlands will most likely have water residence times of between one hour and a few days, whereas large-scale wetlands may have residence times of a few weeks. Some studies have shown that as the residence time is increased from a few hours to a few days, total phosphorous removal efficiency improves from less than 10% to nearly 60% (Rushton et al. 1995, Reinelt and Horner, 1995). Furthermore, Reinelt and Horner (1995) state that if the residence time is greater than two weeks then total phosphorous removal efficiency can improve to 90%. These studies show the synergistic effect of large-scale wetlands acting as viable ecosystems. In addition, larger scale systems lower in the watershed would intercept storm water runoff from up-gradient communities who may not be currently invested in Lake Thunderbird as a drinking water source, e.g., Oklahoma City and Moore.

Small-scale, targeted treatment wetlands would control storm water runoff at the source, this providing local environmental benefit to lower order streams and tributaries, and thus residential communities. These technologies have advanced considerably in recent years and properly designed, sized, operated, and maintained systems are considered effective and efficient BMPs for improving storm water quality. Demonstration projects, both at new construction sites and as retrofits for existing storm water ponds, would help quantify the potential contribution of these systems to overall downstream water quality, and could influence longer-term decision making.

With additional critical assessment and subsequent modification, the decision matrix developed as part of this study provides a foundation for informed and critical decision-making. Input from all watershed stakeholders is necessary. With the further development of a storm water BMP decision tree specific to the Lake Thunderbird drainage basin, a multi-criteria decision analysis could be developed to address the complex water quality problems facing this watershed.

Based upon the available performance data for these systems, both large-scale created wetlands and small-scale treatment wetlands would likely have a positive influence on Lake Thunderbird water quality, if the systems are designed, constructed and maintained properly. Local (near the sources of impairment) water quality improvement would be realized by implementation of targeted treatment wetlands, perhaps as part of comprehensive residential and commercial development planning. These positive local influences would result in improved downstream water quality in the basin as a whole. Large-scale wetlands would not have distributed impacts on local water quality, but would address impairment prior to release of storm-influenced waters into the reservoir. Given the relatively large required land areas and associated acquisition and construction costs, they would need to be part of larger watershed-scale or regional planning efforts. A combination of both types of wetland systems - targeted treatment wetlands in specific upstream source areas and created systems adjacent to the downstream reservoir - would result in improvement of Lake Thunderbird water quality.

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