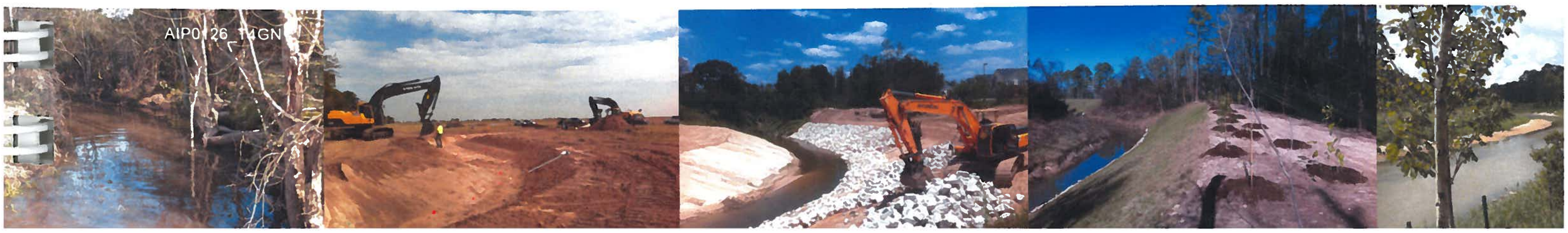
Evaluation of Natural Channel Design versus Traditional Stormwater Infrastructure in Texas

Texas Water Development Board

Prepared for the Texas Water Development Board
Contract# 1148321308
April 1, 2013

Final Report

Stantec KBR Watearth Water Resources • Green Infrastructure



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1. Executive Summary

In addition to providing alternative means for stabilizing streams, Natural Channel Design (NCD) techniques can be employed to affect environmental and ecological improvement or functional uplift. The application of these new methodologies is beginning to be considered in Texas for the management and improvement of the myriad streams, rivers, and modified channels that predominantly serve as stormwater, drainage, and flood control infrastructure in urban, urbanizing, and suburban settings. Accordingly, traditional techniques such as channelization, over-excavation, and channel bank armoring are well understood and broadly applied with respect to costs, risks and function as opposed to the application of NCD techniques. Selecting a NCD solution as part of solving a storm conveyance problem, for example, as opposed to a more conventional and efficient armored, trapezoidal channel solution may be initially understood and viewed as more costly and carry undefined risks. Increasing experience and familiarity with the application of NCD techniques is needed to demonstrate that this conventional thinking may not be correct, or at the very least the relative cost/benefit may not be completely understood.

In order to gather existing research data and to assess the applicability and benefits of NCD techniques in Texas, the Texas Water Development Board (TWDB) identified the assessment of the lifecycle cost/benefit of NCD versus traditional stormwater infrastructure as a study priority topic in fiscal year 2011. The Kellogg Brown and Root (KBR) team, comprised of KBR, Stantec, and Watearth, was awarded the research project in June 2011 and contracted by the TWDB in October 2011. The KBR team combined unique expertise in both traditional and NCD channel management methodologies, as well as water quality and sustainable stormwater management techniques.

This report presents the methodology and results of a research that evaluated the following questions:

1. Are Natural Channel Design techniques appropriate for use in Texas? What adjustments and modifications are likely needed as compared to projects that have been completed in other States within the U.S.?
2. How do Natural Channel Design and traditional stormwater practices compare with regard to ecological and water quality benefits?
3. What is the difference in costs between NCD and more traditional stormwater conveyance projects?

The priority options developed by Rosgen have been widely adopted in other regions of the country, and therefore can serve as a good basis for discussion in this report. The four priority options are organized in terms of the level of re-naturalization and the amount of functional lift that can be anticipated. Priority 1, 2 and 3 projects are also referred to as stream restoration projects or NCD projects, while Priority 4 projects apply more traditional measures of stabilization, although some minor NCD techniques may be used. Table ES-1 summarizes the four priority' objective and approaches.

Table ES-1: Four Priority Approaches to Stream Restoration Objectives

Objective	Stabilize Channel and Create Appropriate Channel Dimensions	Improve Floodplain Connectivity	Restore or Enhance Floodplain Wetlands and Aquatic Habitat
Priority 1	Excavate new, stable channel with appropriate dimensions at the original elevation	Restore connection to original floodplain	Raise streambed elevation to potentially restore wetlands in the original floodplain; restore natural streambed for aquatic habitat
Priority 2	Create new, stable channel with appropriate dimensions at the existing channel bed elevation	Create floodplain by excavating at the existing elevation	Potential for creating wetlands in the newly excavated floodplain; restore natural streambed for aquatic habitat
Priority 3	Construct a bankfull bench and use in-stream structures to reduce shear stress, may or may not address dimension/profile	Widen floodplain at existing elevation by excavating a bankfull bench	May reduce flooding potential, however typically does not affect riparian wetlands; in-stream structures may enhance habitat diversity
Priority 4	Use various stabilization techniques to armor the banks in place; do not address dimension, pattern, or profile	Typically do not improve floodplain connectivity	Typically do not enhance or create floodplain wetlands; armoring may negatively impact aquatic habitat

Source: (Doll et al., 2003)

The research methodology consisted of 1) a literature review to obtain documentation on the applicability of NCD methodologies to the various physiographic provinces in Texas, the ecological benefits of NCD and cost, benefit and economic impacts of NCD, and 2) Interviews with staff from public agencies in the four largest metropolitan areas in Texas: Houston, Dallas-Fort Worth, Austin, and San Antonio. These four metropolitan areas represent fairly diverse physiographic settings and stream systems. Of the four areas, the Houston area contained the largest number of projects with NCD components, with seven Priority 3 projects since the past 6 years. The City of Austin also implemented a pilot Priority 3 project and has a stream restoration division focused on NCD practices. All other data obtained from interviews consisted of Priority 4 projects, of which a large number contained NCD features as part of the design.

The analysis by physiographic regions provides a way to compare areas in Texas to other areas across the country with similar physiography where NCD techniques have been used more extensively and for longer periods of time. Examples of NCD projects completed in comparable physiographic regions across the country demonstrate that NCD could be used to address the specific resource issues and conditions found in Texas. Specifically, the data reviewed during this studied revealed the following conclusions:

- The Gulf Coastal Plains of Texas can be compared to other regions along the Gulf and Atlantic coasts such as Florida, North Carolina, and Maryland.
- The Basin and Range and High Plains provinces of West Texas share physiography characteristics with several southwestern states including Colorado, Utah, Nevada and New Mexico**.**

- The North Central Plains and Grand Prairie provinces of North Texas share characteristics with many Midwestern states including Oklahoma, Arkansas, Nebraska, and Missouri.

- The North Central Plains and Grand Prairie provinces of North Texas share characteristics with many Midwestern states including Oklahoma, Arkansas, Nebraska, and Missouri.

- Beyond the physiographic characteristics of the restoration site, the most important factors to consider are exiting land use and development. The problems and restoration potential differ for streams in highly urbanized areas and agricultural areas, but case studies indicate that NCD techniques can be applied in both settings by adapting the techniques to the restoration site.

- A key to a successful restoration project is proper planning, detailed identification of restoration goals, and analyzing the goals against the restoration potential of the site.

- The following factors must be assessed in order to evaluate the applicability of NCD to a particular site: degree of degradation, riparian corridor, availability of stabilization materials, existing pattern and infrastructure, belt width (width of consecutive meander bends) constraints, and flooding concerns.

- Figure ES-1 shows decision making flowchart that can assist Texas agencies in determining and applicability of NCD to their particular stream project.

Water quality performance of NCD for this study focused on nutrients, TSS, and bacteria as a larger volume of research is available and these are pollutants that commonly have established TMDLs (Total Maximum Daily Loads) in the major metropolitan areas in the State of Texas. Additionally, a number of studies were found regarding the ecological benefits and effectiveness of NCD with regard to improved habitat for wildlife, fish, and benthic macroinvertebrates. The research of the water quality and ecological benefits of NCD yielded the following conclusions:

- NCD appears to be effective at improving water quality, which is often seen as one of the primary benefits of NCD projects over traditional stormwater conveyance practices.

- Monitoring data is limited and most NCD projects are constructed on only a portion of the watershed/stream length. Watershed-wide restoration projects that include monitoring are recommended in Texas to better describe water quality benefits that may be achieved with more extensive implementation of NCD.

- Significant data is available on the water quality and pollutant-removal benefits of LID (Low Impact Development) for a number of pollutants, including: TSS (Total Suspended Solids), bacteria, nutrients, hydrocarbons, metals, pesticides, and others. A large number of LID facilities is needed to achieve a substantial impact on watershed health and water quality. Similarly, significant implementation of NCD is needed to achieve substantial impact on watershed health and water quality.

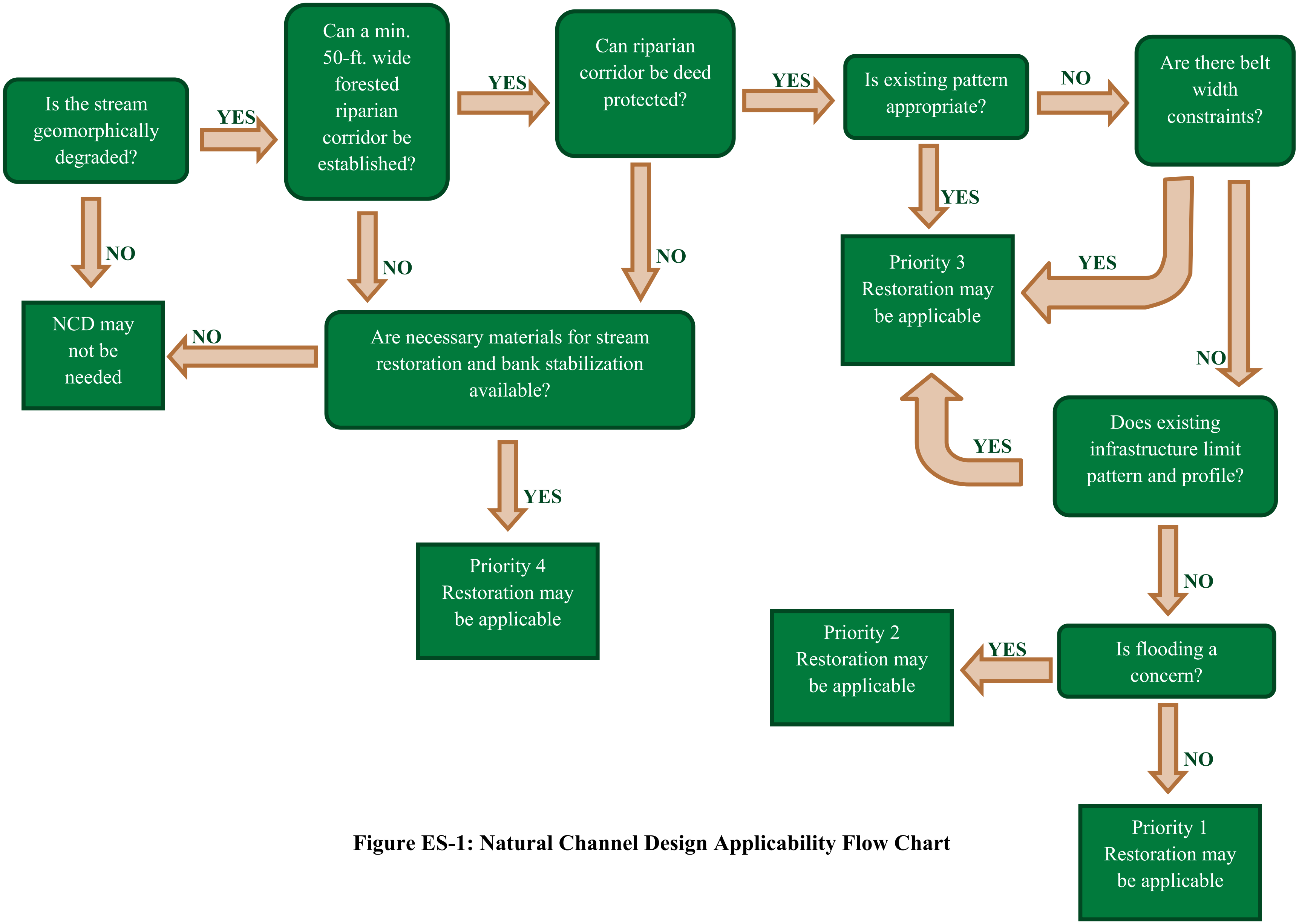

Figure ES-1: Natural Channel Design Applicability Flow Chart

- A number of studies were found regarding the ecological benefits and effectiveness of NCD with regard to improved habitat for wildlife, fish, and benthic macroinvertebrates. Benefits for wildlife (mammals, birds, reptiles, and amphibians) correlate with the quality and extent of the riparian buffer that provides food, shelter, and a wildlife corridor for travel.
- A major finding of this effort is that monitoring of NCD projects within the various physiographic provinces of Texas is critical for standardizing and optimizing future designs for water quality and pollutant removal performance.
- Table ES-2 summarizes advantages and disadvantages of NCD and traditional stormwater conveyance practices. Habitat benefits of NCD correlate to in-stream habitat for macroinvertebrates and fish as well as riparian and wildlife corridor habitat for birds, butterflies, frogs, and mammals.

Table ES-2: Comparison of NCD and Traditional Stromwater Conveyance

Type of System	Land Required[1]	O&M	Addresses Multiple Objectives	Stabilize Banks	Water Quality	Habitat	Aesthetics	Familiarity with Concepts
Natural Channel Design	High	Low	✓	✓	✓	✓	✓	
Traditional Stormwater Conveyance	Low	High		✓				✓

[1] Land requirements for full implementation, whereas partial implementation requires less land.

Cost data were obtained and analyzed on a linear footage basis for projects in the Houston, Austin, San Antonio and North Texas areas. The cost data was limited and included only Capital Improvement (design and construction) costs. Projects were grouped into categories according to the hydrologic order of the stream (Stream Order 4 or greater, and Stream Order 3 or less) and restoration priority according to the type of work performed. Most Texas projects fell within the Priority 3 or 4 categories, and several projects were categorized as Priority 4 projects with NCD Features.

A comparison of construction costs and design costs between NCD (Priority 3) and Traditional methods (Priority 4) built on streams of order 4 or greater indicated the following:

- The overall construction cost for both NCD and Traditional projects are less for projects of shorter length.
- The cost per linear foot for traditional projects was significantly higher than NCD for the larger projects and less for shorter projects. A breakpoint length was observed at approximately 1,250 lf of project length.
- In general, design costs are higher for NCD as compared to traditional methods.

A comparison of construction costs between Priority 4 projects utilizing solely traditional methods and Priority 4 projects containing NCD features built on streams of order 3 or less indicated the following:

- The cost for projects with NCD components trends higher than traditional construction. No apparent breakpoint project length was observed as noted for stream order 4 or greater projects.
- The costs/lf for stream order 3 or less projects also tend to increase as the project length decreases.
- There was not enough data with respect to design costs to support a comparison.
- There was not enough available data on Priority 3, Stream Order 3 projects to support a comparison with Priotity 4 projects of same stream order.

Based on the limited cost analysis performed, the following general conclusions can be drawn:

- The application of NCD follows the same general pattern for construction and design costs that traditional methods follow, with the possible exception of the cost per linear foot for traditional methods for the larger Priority 4 projects.
- The trends indicate that, for Stream Order 4 or greater, traditional projects are significantly higher in cost than NCD projects, at least for longer projects which involve stream lengths greater than 1,250 feet.
- For creeks classified as Stream Order 3 or less, the construction and design costs trends each gave indication that NCD is slightly more costly overall.
- The validity of these types of comparisons is based upon the ability to break the data into like groupings, such as streams of same hydrologic order and restoration priority. The development of a rich data set is imperative in order to develop cost curves that may be used to assist scientists, engineers and planners in the selection of appropriate design and construction methods.
- The cost analysis presented in this study only included Capital Improvement Costs. A supplemental analysis taking into account Operation and Maintenance costs and debt service costs is necessary for a more thorough comparison of NCD and Traditional costs.

In order to supplement the limited data available during the present study and to create a decision making tool that accounts for all aspects of NCD versus Traditional stormwater infrastructure benefits, it is recommended that the State work cooperatively with other agencies in Texas to build a more comprehensive project database of stream restoration projects. It is essential that the project dataset contain other costs such as O&M (Operation and Management) and debt service costs, as well as parameters that quantify any economic and environmental benefits of stream projects. The dataset must be grouped into the like categories, such as stream order or contributing drainage area, and restoration priorities as presented in this study. Furthermore, a monitoring program must be implemented following construction of Priority 1, 2, 3 and 4 projects to track water quality and pollutant removal performance.

2. Introduction

2.1. Background

Comparing the applicability of Natural Channel Design (NCD) techniques in Texas to more traditional storm water practices requires, as a start, that the term Natural Channel Design be defined. For the purposes of this evaluation, Natural Channel Design is the application of design means and methods that effectively evaluate and develop stream restoration improvements so that a stream may be able to maintain a natural state of "dynamic equilibrium" or stability. A stream in a natural state of stability is able to transport water and sediment over time while maintaining channel form and ecological characteristics. This understanding of stream channel stability from a flow and sediment transport perspective is succinctly stated by Rosgen (1996) as follows:

> *"is the ability of a stream, over time, in the present climate, to transport the sediment and flows produced by its watershed in such a manner that the stream maintains its dimension, pattern and profile without either aggrading nor degrading".*

NCD techniques are employed for a number of reasons including stream stability as well as ecological improvement or functional uplift. However, these new methodologies are seldom utilized in the management of the myriad streams, rivers, and modified channels that predominantly serve as stormwater, drainage, and flood control infrastructure in urban, urbanizing, and suburban settings. Accordingly, traditional techniques such as channelization, over-excavation, and channel bank armoring are well understood and broadly applied with respect to costs, risks and function as opposed to the application of NCD techniques. Selecting a NCD solution as part of solving a storm conveyance problem, for example, as opposed to a more conventional and efficient armored, trapezoidal channel solution may be initially understood and viewed as more costly and carry undefined risks. Increasing experience and familiarity with the application of NCD techniques is needed to demonstrate that this conventional thinking may not be correct, or at the very least the relative costs may be overstated while the relative benefits may be understated. Research is needed to better quantify and understand the benefits and costs associated with NCD, especially when compared to traditional channelization techniques employed in stormwater infrastructure.

Traditional applications as compared to NCD applications are based on achieving largely different goals. NCD applications target stream restoration while the traditional techniques focus on hydraulic efficiencies and detention strategies. There are common goals, however, as stated by Lave (2009), when evaluating Rosgen techniques as follows:

> *"But despite sharply differing purposes, NCD and hydraulic engineering share one key goal: stabilize the channel to prevent lateral migration or downcutting…There is clear kinship between traditional tools of hydraulic engineers …and the suite of techniques that Rosgen has developed".*

Some proponents of NCD reject the idea that a channel that is "locked in place" is actually a natural channel. Even in the case where that is true, NCD seeks to improve habitat for overall aquatic life benefit utilizing woody material and other features as well as to present a natural aesthetic. (Lave 2009). Additionally, land use history and condition of the watershed is a major consideration for the application of NCD. (NRCS Design Handbook, 2007, p. 11-20). An urbanized land use, for example, often requires the manipulation of the natural stream due to changes in upstream flows and bedload, the need for outfall depth and deepening of streams, and the need to reduce flooding. Many man-made or channelized streams have suffered significant aggradation and degradation, resulting in loss of function in areas of flood control, water quality, and ecological health.

A paradigm shift is occurring as various regulatory entities throughout the country and NCD experts apply more holistic solutions to solving drainage concerns, increase the quality and condition of regulated waters as well as improve the overall quality of life in their communities. Texas communities will increasingly look toward restoration and preservation of ecologically-enhanced natural stream forms that are both stable (low maintenance) and provide water quality treatment/benefits. Additionally, regulations may require that projects and regulatory agencies address stream hydromodifications as a result of prior, on-going, and future development within the watershed. NCD is an emerging technique that can be used in conjunction with Low Impact Development (LID) and other techniques to reach ultimate watershed restoration goals. A full cost/benefit assessment of NCD versus traditional stormwater infrastructure, looking at both the direct and indirect costs and consequences, should provide the design community and the end-user agencies information that is currently not available in making fiscal decisions on stormwater infrastructure projects.

In order to gather existing research data and to assess the applicability and benefits of NCD techniques in Texas, the Texas Water Development Board (TWDB) identified the assessment of the lifecycle cost/benefit of Natural Channel Design (NCD) versus traditional stormwater infrastructure as a study priority topic in fiscal year 2011. The Kellogg Brown and Root (KBR) team, comprised of KBR, Stantec, and Watearth, was awarded the research project in June 2011 and contracted by the TWDB in October 2011. The KBR team combined unique expertise in both traditional and NCD channel management methodologies, as well as water quality and sustainable stormwater management techniques.

2.2. Study Goals and Objectives

Complete natural restoration of impaired streams would necessarily include stream form improvement along with the restoration of floodplain function requiring substantial flexibility with respect to land use. In an urbanized setting, however, lateral constraints along a channel will limit the scope and approach taken by natural channel designers to restore a stream. In such a case, protection of property from flooding and erosion loss quickly becomes paramount. As stated earlier, however, NCD techniques may be utilized to protect against lateral stream movement and downcutting in similar fashion as traditional methods. Additionally, some of the potential benefits of NCD over traditional methods may include the following:

- NCD helps to maximize ecological function in the stream
- NCD will create a more aesthetic environment
- NCD utilizes natural materials and techniques
- NCD techniques may help satisfy regulatory requirements

Several factors are increasing the interest and application of NCD in the country, including the utilization of NCD techniques to assess sediment impacts within the regulated waters of the U.S. as well as the creation of stream mitigation banks in accordance with Section 404 of the Clean Water Act. (Lave, 2009). Regulatory agencies across the country are increasingly advocating the Natural Channel Design approach to address stream issues. These regulations have made their way to Texas, and the U.S. Army Corps of Engineers Galveston and Fort Worth Districts are currently developing new guidelines for working within Texas streams.

Considering the afore-mentioned comments in Section 2.1 and 2.2, please note that the intent of this research is to evaluate the following questions:

1. Are Natural Channel Design techniques appropriate for use in Texas? What adjustments and modifications are likely needed as compared to projects that have been completed in other States within the U.S.?
2. How do Natural Channel Design and traditional stormwater practices compare with regard to ecological and water quality benefits?
3. What is the difference in costs between NCD and more traditional stormwater conveyance projects?

This research benefits any individual, municipality, or other entity of the State of Texas charged with the use and protection of the state's water resources, including: regional water districts, water authorities, municipal water programs, regulatory agencies, and private landowners as they increasingly evaluate and make decisions on new ways to handle stormwater, stream stability issues and regulatory issues.

2.3. Channel Evolution and Erosion Processes

Evaluating the advantages and disadvantages of the channel management strategies described henceforth in this report requires an understanding of channel erosion processes. Alluvial riverine systems dominate the Texas urban/suburban landscape. These systems include alluvial floodplains, which are flat, unconsolidated deposits of sediments that have been transported to and deposited on the floodplain by the alluvial channels that flow through the valley. The alluvial channels develop a stable form within these unconsolidated sediments by actions of the flow of water and sediments through the system. A schematic of a typical optimized alluvial system is shown in Figure 1 (Simon, 1989).

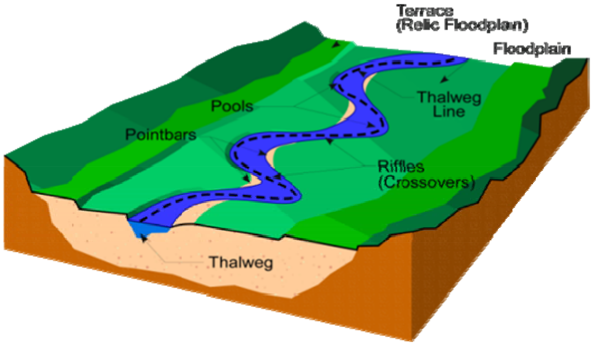

Figure 1: Typical Optimized Alluvial System Form
Source: Simon (1989), obtained from the Federal Interagency Stream Restoration Working Group [FISRWG], 1998).

Natural alluvial streams are formed and maintained by the water and sediment delivered to them by their watersheds. Changes in these loadings naturally occur over time. Streams adjust to these slowly changing conditions by altering their dimension, pattern, and profile, constantly trending toward dynamic equilibrium (stability of an open system in a steady state). (Rosgen, WARSSS, 2009, see discussion on River Stability, p 2-37). However, in the past 200 years, Texas streams have been forced to rapidly respond to anthropogenic hydromodification, defined as a change in the natural hydrologic processes and runoff characteristics (e.g., interception, infiltration, overland flow, interflow and groundwater flow) caused by urbanization that result in increased stream flows and changes in sediment transport.

In addition, direct modification of stream and river channels (including straightening, channelization, and over-excavating/oversizing to increase channel conveyance capacity) and installation of dams and water impoundments are also considered hydromodification, due to their disruption of natural watershed hydrologic processes. Direct channel modification and land development are the most significant causes of hydromodification in urban/ suburban settings. Improperly managed construction sites frequently load excessive sediments to the streams, while impervious surfaces of completed developments prevent rainfall infiltration, decrease sediment loadings, and increase the velocity and peak flow and shorten the duration of stormwater loadings from the watershed to the receiving stream. The last-mentioned effect is exacerbated by the rapid transfer of stormwaters to the stream via piped storm sewer systems and straightened/channelized small tributaries across the watershed.

Driven by the entropic tendency to re-establish dynamic equilibrium through geomorphic processes, alluvial streams respond to hydromodification through a channel evolution process documented by Simon (1989), as shown in Figure 2 (taken from the Federal Interagency Stream Restoration Working Group [FISRWG], 1998).

Simon’s model was derived by studying stable streams that were straightened, channelized, and oversized for drainage and flood control purposes. In response to this hydromodification, six process-oriented stages of morphologic adjustment were observed. Driven by the tendency to re-establish dynamic equilibrium by the geomorphic processes, the stream incises (downcuts), widens, and then builds a new stable channel with a bankfull floodplain bench at a new lower elevation.

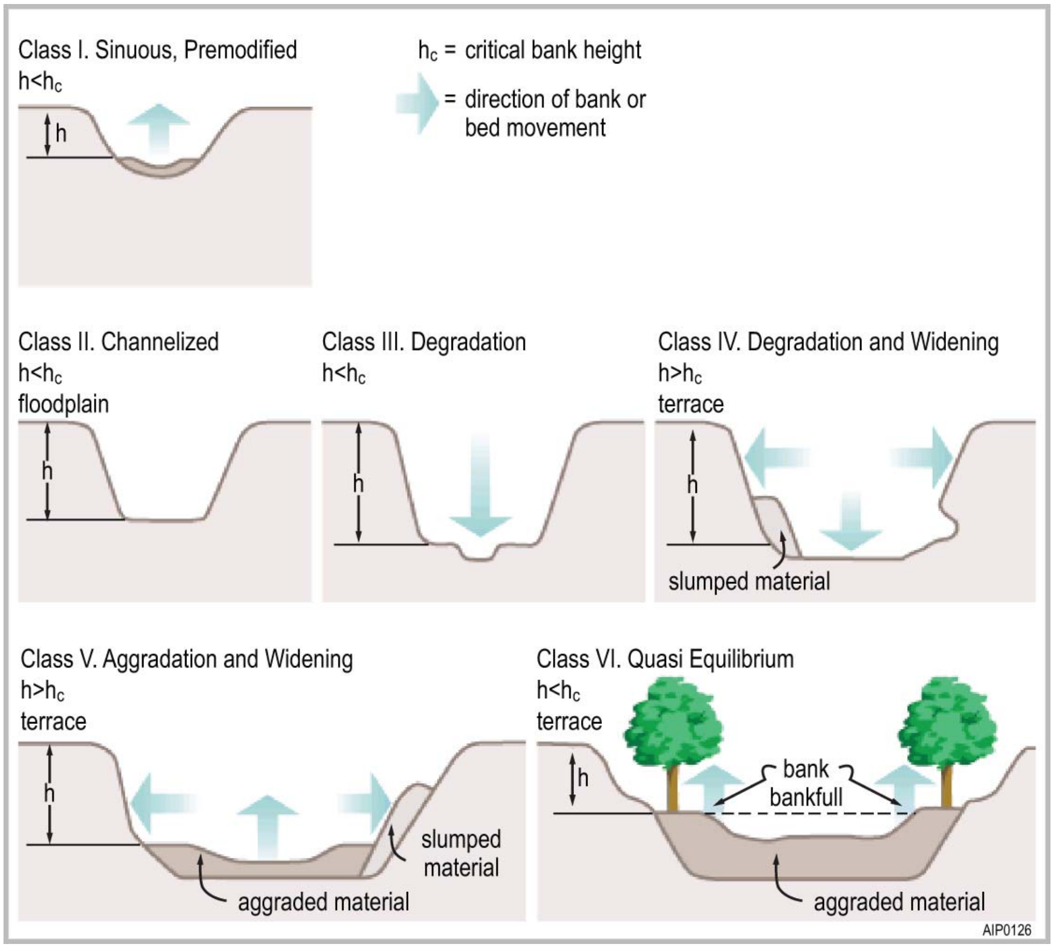

Figure 2: Simon's Model of Channel Response in Disturbed Alluvial Channels
Source: Simon (1989), obtained from the Federal Interagency Stream Restoration Working Group [FISRWG], (1998).

Once a stream has become incised within its valley, it becomes unstable. The channel loses access to a bankfull floodplain bench, which provides lateral flow relief, channel flow head, and a reduction of flow velocity. The elevation of the bankfull floodplain bench in a stable, natural system is directly related, among other factors, to the erosional resistance capacity of the channel bank materials. A stable stream maintains this head and velocity dissipating floodplain at the critical depth of the channel. This critical depth corresponds to the depth at which the shear stresses acting on the channel walls are just less than the resistive capacity of the bank materials. When a channel becomes incised, the shear stresses (a function of head, velocity and slope) on the channel bank toe will exceed the resistive capacity of the bank materials causing erosion to occur and subsequently bank failure. Note that the maximum shear stresses in channel are at the toe of the channel bank. (Simon, 1989).

Once incised, the stream seeks to build a new stable channel with a bankfull floodplain bench at a new lower elevation, as depicted in Simon's model of channel response in disturbed alluvial channels (Figure 2). However, the re-establishment of a stable channel in urban settings based on Simon's model of channel evolution would take many years even if stable hydrologic conditions could be immediately and completely imposed across the entire watershed. Consider that channel-forming flows only occur once or twice a year in snowmelt-driven systems and four to eight times a year in subtropical settings with thunderstorm-driven systems. The geologic timescale, within which these natural systems adjust their form to re-establish dynamic equilibrium, is not compatible with the human timescale for channel management.

2.4. Rosgen Classification System Guide

Rosgen (1985, 1994) developed a classification system for natural streams which is useful for describing stream systems based on quantitative morphological characteristics and is also used in NCD applications. The classification system is based on the concept that stream pattern morphology is a function of interrelated variables including channel width, depth, velocity, discharge, slope, channel materials, sediment load, and sediment size (Rosgen, 1994). These variables are interdependent in that a change to any one variable results in adjustment of the other variables, and eventually changes in the channel pattern. The Rosgen classification system uses the measureable variables as criteria to classify stream characteristics into discreet combinations.

The Rosgen classification system divides channels into seven major stream types (A, B, C, D, E, F, and G). Type D refers to multiple channel systems and all other types refer to single-thread channels. Classification into these major stream types is based on ranges of measurable morphological parameters including entrenchment ratio, width/depth ratio, and sinuosity. These stream types are further subdivided into classifications based on slope and the size of the dominant channel material. A modifier is added to the major stream type based on the size of the channel material. For example, a Type A stream with bedrock becomes A1, while a Type A stream with silt/clay material becomes A6. This level of classification is illustrated in more detail by the graphic included in Appendix E. Rosgen classification system is often referred to in NCD restoration projects, but it should be noted that the classification system itself is not a recipe for a successful NCD design. Instead, the final design objective is to replicate the appropriate natural stream type based on the specific watershed conditions, and the classification system is simply used to describe a set of morphological characteristics that are incorporated into the design.

2.5. The Spectrum of Channel Management Options

Rosgen (1997) presents four priority options for restoring incised channels, which includes the entire spectrum of channel management options, including traditional stormwater conveyance channel solutions. The priority options developed by Rosgen have been widely adopted in other regions of the country, and therefore can serve as a good basis for discussion here. The four priority options are organized in terms of the level of re-naturalization and the amount of functional lift that can be anticipated if the restoration is successful. The Priority 1 approach provides the highest level of re-naturalization and thus aims to achieve the greatest functional lift, while the Priority 4 approach provides the lowest level of re-naturalization and therefore is expected to provide less functional lift, even with complete success. Priority 1, 2 and 3 projects are also referred to as stream restoration projects or NCD projects, while Priority 4 projects apply more traditional measures of stabilization, although some minor NCD techniques may be used. The four priority options are well-documented in the NCSRI's *Stream Restoration: A Natural Channel Design Handbook* (Doll et al., 2003). Table 1 outlines several objectives of NCD stream restoration and the ways in which each priority project addresses these objectives. The priorities are described in further detail below.

Table 1: Four Priority Approaches to Stream Restoration Objectives

Objective	Stabilize Channel and Create Appropriate Channel Dimensions	Improve Floodplain Connectivity	Restore or Enhance Floodplain Wetlands and Aquatic Habitat
Priority 1	Excavate new, stable channel with appropriate dimensions at the original elevation	Restore connection to original floodplain	Raise streambed elevation to potentially restore wetlands in the original floodplain; restore natural streambed for aquatic habitat
Priority 2	Create new, stable channel with appropriate dimensions at the existing channel bed elevation	Create floodplain by excavating at the existing elevation	Potential for creating wetlands in the newly excavated floodplain; restore natural streambed for aquatic habitat
Priority 3	Construct a bankfull bench and use in-stream structures to reduce shear stress, may or may not address dimension/profile	Widen floodplain at existing elevation by excavating a bankfull bench	May reduce flooding potential, however typically does not affect riparian wetlands; in-stream structures may enhance habitat diversity
Priority 4	Use various stabilization techniques to armor the banks in place; do not address dimension, pattern, or profile	Typically do not improve floodplain connectivity	Typically do not enhance or create floodplain wetlands; armoring may negatively impact aquatic habitat

Source: (Doll et al., 2003)

2.5.1. Priority 1: Establish Bankfull Stage at the Historical Floodplain Elevation

Priority 1 projects replace an incised stream with a new, stable channel with appropriate dimensions, pattern, and profile at the historic stream elevation (Doll et al., 2003). The bankfull stage of the new channel is located at the ground surface of the original floodplain (Figure 3). Priority 1 projects usually can be constructed in dry conditions, and the water can be diverted into the new channel once it is stabilized and revegetated. The increase in streambed elevation in Priority 1 projects raises the water table and results in higher flood stages in the area surrounding the project, which may restore or enhance floodplain wetlands. However, this increase in flooding potential may be a concern in places where land use restricts the stream corridor, such as in urban environments. In addition, the Priority 1 approach requires adequate space in the existing floodplain surrounding the existing incised stream to construct a new channel with appropriate pattern and dimensions (Doll et al., 2003).

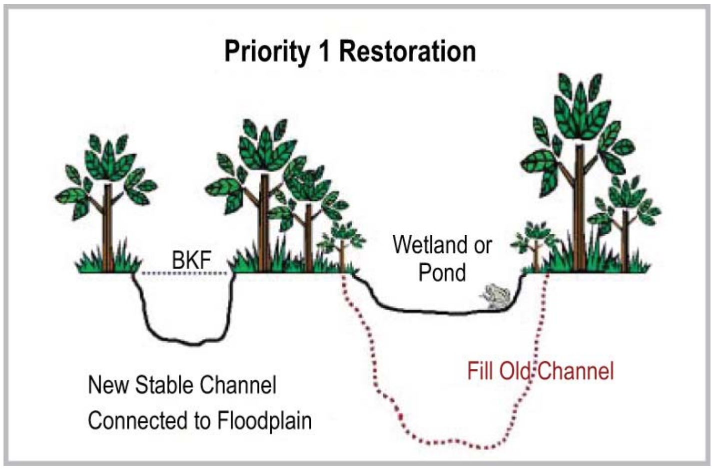

Figure 3: Cross Section of a Priority 1 Restoration Project
Source: (Doll et al., 2003)

2.5.2. Priority 2: Create a New Floodplain and Stream Pattern with the Stream Bed Remaining at the Present Elevation

The Priority 2 approach is to create a new, stable channel with appropriate dimensions, pattern, and profile at the existing channel-bed elevation (Doll et al., 2003). The channel and floodplain are excavated so that the new channel's bankfull stage is located at the elevation of the newly excavated floodplain (Figure 4). Priority 2 projects do not raise the water table as Priority 1 projects do, which diminishes the project's ability to restore or enhance wetland conditions on the larger, historic floodplain. However, the project may create or enhance riparian wetlands in the newly excavated floodplain and stream corridor. In addition, because of the lower elevation of the new floodplain, Priority 2 projects may decrease the potential for flooding as a result of additional storage and conveyance capacity. As with Priority 1 projects, the Priority 2 approach requires sufficient land area on one or both sides of the stream to widen the stream corridor and construct the new floodplain. Another concern is that Priority 2 projects typically produce a surplus of material excavated from the floodplain, and designers must consider the expense and logistics of removing it (Doll et al., 2003).

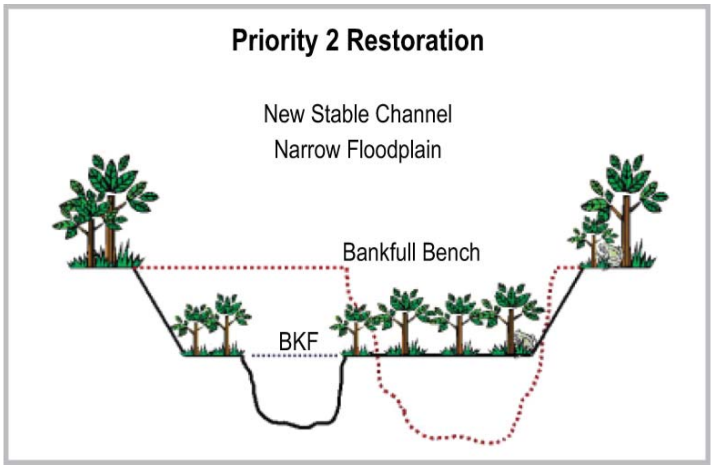

Figure 4: Cross Section of a Priority 2 Restoration Project
Source: (Doll et al., 2003)

2.5.3. Priority 3: Widen the Floodplain at the Existing Bankfull Elevation

Like Priority 2, Priority 3 projects aim to widen the floodplain at the existing channel elevation (Doll et al., 2003). Priority 3 projects accomplish this by excavating a floodplain bench or "bankfull bench" on one or both sides of the existing stream channel (Figure 5). Priority 3 approaches may be used when existing land uses restrict the area available for the floodplain. Because of the existing land constraints, Priority 3 projects may modify the existing channel to enhance its dimension and profile, but typically do not significantly increase sinuosity. Because of this, Priority 3 projects usually require more structural measures and maintenance than Priority 1 or 2 projects. In-stream structures, such as boulder or log cross-vanes and riffles, are important for grade control and bank protection in Priority 3 projects. This can add to cost and complexity, depending on structure requirements. Priority 3 projects can reduce flooding potential, however, they typically do not enhance riparian wetlands above the bankfull bench. These projects usually require minimal change to surrounding land use (Doll et al., 2003).

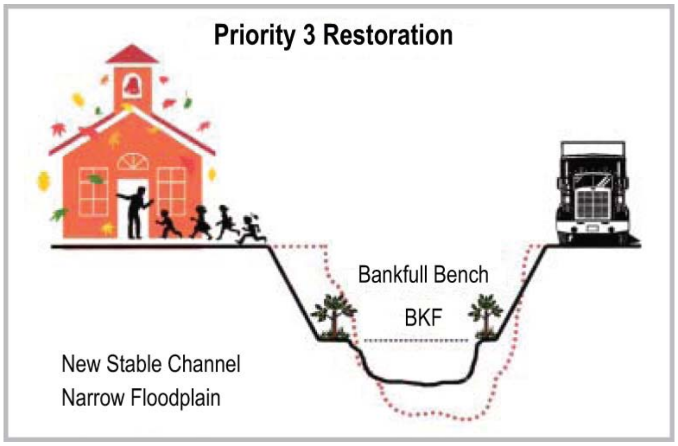

Figure 5: Cross Section of a Priority 3 Restoration Project
Source: (Doll et al., 2003)

2.5.4. Priority 4: Stabilize Existing Streambanks in Place

The Priority 4 approach uses armoring to stabilize banks in place without attempting to correct problems with dimension, pattern or profile (Doll et al., 2003). Engineering practices such as riprap, concrete, gabions, bioengineering, combinations of structures, and other traditional stormwater conveyance channel prescriptions fall under the Priority 4 approach. These projects typically do not change flooding potential or enhance or create riparian wetlands.

Priority 4 projects can reduce sediment loads by decreasing erosion. Bioengineering techniques and vegetative components may also be used to provide aquatic habitat and shade. However, in projects where the entire channel is armored, this small functional lift is offset by the negative impacts to aquatic habitat resulting from the elimination of the natural channel bed and aquatic vegetation. Monolithic concrete provides the least functional lift, because it eliminates the hydraulic connection between the stream and the adjacent groundwater table. Priority 4 projects do not address issues with dimension, pattern and profile, and therefore banks may continue to be susceptible to extreme shear stress. Because of this, Priority 4 projects require continued inspection and maintenance, and may be more expensive in the long-term (Doll et al., 2003).

2.6. Overview of Traditional Stormwater Infrastructure

Stormwater management in the United States and Texas has evolved from an emphasis on dams and reservoirs designed for large-scale flood control to the recent concept that combines flood control, water quality, habitat/ecological design, and other components that can meet a complex regulatory requirements.

In the 1950s and 60s, the U.S. Army Corps of Engineers (USACE) and local agencies began implementing conveyance improvements to convey floodwaters more rapidly downstream and to reduce the risk of structural flooding. While these channelization projects (concrete-lining and trapezoidal improvements) were effective at moving water downstream, other issues including downstream flooding, loss of habitat, and stream impairment due to in-stream erosion ensued.

Increased impervious cover associated with development, as well as closed conduit storm drain systems designed to quickly collect and discharge stormwater runoff, lead to "flashy" urban hydrology, which includes: shorter times to hydrograph peaks, higher peak flows, higher volumes of runoff, and changes in flow duration from an undeveloped site.

In the 1970s, the concept of stormwater detention began to gain ground. Although most metropolitan areas in Texas required detention mitigation for new development by the 1980s. some municipalities did not begin detention programs until the 21st century. While this centralized stormwater management strategy addressed project-level and downstream flooding, the shift in timing of releases of stormwater runoff to later in the rainfall event created additional issues with downstream impacts to peak flows as well as the duration of the peak flows. The additional volume of runoff associated with development also substantially increases in-stream erosion and is not mitigated by detention (Emerson, 2005).

Traditional construction-phase stormwater BMPs (Best Management Practices), such as erosion (i.e., fiber rolls and filter fabric fence) and sediment (i.e., sediment traps and sediment basins) controls are effective for reducing sediment loads from construction sites, but do not mitigate pollutants, such as: heavy metals, bacteria, TSS, and nutrients in post-construction stormwater runoff or address in-stream erosion and sedimentation processes. Additionally, many construction-phase BMPs are not properly installed or maintained and fail over time. Traditional post-construction BMPs, such as hydrodynamic separators, sand filters, baffle boxes, and extended detention are effective at removing TSS and trash, but do not mitigate "flashy" hydrology conditions or address in-stream processes.

Traditional surface water channel management strategies in urban/suburban settings fail to accommodate natural stream processes, water quality goals, or sustainable aquatic ecosystems. Further, they are inherently unstable and require long-term maintenance to counter the modified streams' tendencies to revert to stable, natural forms. Even recently, traditional stormwater management has emphasized flood control and economic benefits of land development, while often compartmentalizing water quality, stream degradation/restoration, and habitat loss as separate concerns.

2.7. Overview of Low Impact Development (LID)

The relatively recent strategy of Low Impact Development (LID), also referred to as Green Infrastructure, was developed in the early 1990s in Prince George's County, Maryland. The primary goal of this distributed and decentralized stormwater management approach is to regain pre-development hydrology (both peak flows and volume of runoff) through infiltration, storage, and evapotranspiration. LID techniques address water quality concerns associated with development of a site as well as hydromodification associated with watershed development.

LID includes stormwater BMPs such as bioretention, permeable pavement, green roofs, stormwater wetlands, vegetated swales, vegetated buffers, level spreaders, rainwater harvesting, infiltration trenches, and infiltration basins. These LID BMPs are shown in Figures 6 to 11. Water quality benefits and pollutant removal are achieved primarily through infiltration and evapotranspiration, which reduces the volume of runoff and associated pollutants into streams.

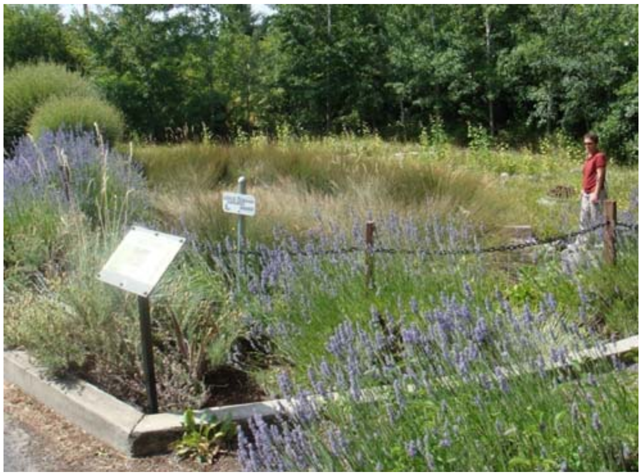

Figure 6: Example Rain Garden at Glencoe Elementary, Portland, Oregon
Source: Watearth, Inc.

Figure 7: Commercial Parking Lot Application of Bioretention, Northgate Mall, Seattle
Source: Watearth, Inc.

Figure 8: Green Roof at Kansas City, Missouri Public Library
Source: Watearth, Inc.

Figure 9: Vegetated Swale at Lake Merritt, Oakland, California
Source: Watearth, Inc.

Figure 10: Vegetated Stream Buffer, Seattle, Washington
Source: Watearth, Inc.

Figure 11: 28,000-Gallon Cisterns for Rainwater Harvesting on Brodie Lane, Austin, Texas
Source: Watearth, Inc.

Other pollutant removal processes achieved through LID include physical, chemical, and biological processes. Physical processes include filtering of sediment and pollutants, such as metals absorbed to the sediment. Degradation of fecal coliform bacteria also occurs by drying out and exposure to ultraviolet (UV) light from the sun. Biological processes include bioremediation, which uses soil microorganisms to break-down pollutants, and biodegradation, which is defined by the U.S. Geological Survey as "transformation of a substance into new compounds through biochemical reactions or the actions of microorganisms such as bacteria (USGS, 2007). For example, hydrocarbons may be broken down by biodegradation and bioremediation as documented in a study of rain gardens compared to uplands forested sites in Minnesota (LeFevre, 2010).

Phytoremediation, or pollutant removal by plants, includes pollutant uptake into and bioaccumulation within the plants, release of some pollutants from plants into the atmosphere, and breakdown of pollutants at the soil-plant root interface. For the latter process, micorrhizal fungi play an important role by attaching to the roots and extending microfilaments into the soil, which significantly increases the functional surface area of plant roots. Because native, or indigenous, plants have evolved to the unique microclimate of an area and typically have deeper roots and greater levels of mycorrhizal fungi, incorporating these elements into LID may represent an increased opportunity for carbon sequestration (i.e., the process of capture and long-term storage of atmospheric carbon dioxide) in mitigating climate change.

The water quality benefits of LID are well-documented with regards to TSS, fecal coliform bacteria, metals, hydrocarbons, and other pollutants. LID is also effective at removing nutrients, Nitrogen (N) and Phosphorus (P), provided that background levels in the native soil and growing media are not excessive. Nitrate (NO_3) removal through LID requires specific design modifications to create anaerobic conditions and an energy source (Carbon) required for denitrification. Table 2 summarizes LID pollutant removal performance from up to ten controlled studies (depending on pollutant) evaluated by Davis (2009).

Additionally, Appendix C includes a summary table developed by Watearth as part of the TWDB project entitled *Watershed Protection for Texas Reservoirs: Addressing Sedimentation and Water Quality Risk* which further summarizes pollutant removal rates for TSS as well as construction and Operations and Maintenance costs for LID and other landscape-based BMPs. See Appendix C for details of specific LID BMPs performance, including permeable pavement, bioretention, vegetated swales, and other BMPs.

Table 2: Summary of LID Removal Performance

Pollutant	Percent Removal
Bacteria	70 – 92
TSS	54 – 99
Phosphorous	28 – 99
Nitrogen	32 – 99
Heavy Metal	54 – 99
Predicated Oil & Grease	>96 – 99

Source: Davis (2009).

Because LID facilities are decentralized and distributed, stormwater must discharge into and flow through an LID facility to receive this treatment. Stormwater detention is typically required to address larger events and provide flood control for the 100-year event. NCD techniques in conjunction with LID may help provide water quality treatment for stormwater that does not discharge into an LID facility and also provides the stormwater treatment train approach where stormwater runoff travels through multiple BMPs for enhanced treatment. Furthermore, NCD techniques may help alleviate or reduce the need for stormwater detention in new developments or provide an integrated strategy to increase habitat, recreational, and quality-of-life benefits.

Stormwater that does not discharge into an LID facility is not effectively treated by LID. While upcoming regulations may mandate LID on new projects within Texas, large-scale retrofits of developed portions of watersheds with LID are not on the immediate horizon, except as isolated cases. For these areas, NCD represents an important opportunity to retrofit centralized water quality improvements that also provide flood control, habitat, economic, and aesthetic benefits.

Although LID is currently optional in the State of Texas, it is being strongly promoted by the U.S. EPA (Environmental Protection Agency) through the “Proposed National Rulemaking to Strengthen the Stormwater Program” anticipated for release in June, 2013 and action by December, 2014. Further, it is likely to be mandatory on many projects in large Texas municipalities in the near future as Green Infrastructure moves to the forefront of stormwater management. Since LID typically addresses smaller rainfall events and water quality issues, flood control elements are generally required in addition to LID and include stormwater detention and conveyance elements.

LID methods and all other traditional structural BMPs fail to address the ongoing problems of channel evolution in response to the dramatic hydromodifications of the past 200 years unless an aggressive watershed-wide green infrastructure retro-fit program is implemented.

2.8. Regulatory Drivers

Several federal and state regulatory programs are driving an increase in NCD projects in Texas. All of these programs are components of the Federal Clean Water Act (CWA), a comprehensive statute aimed at restoring and maintaining the chemical, physical and biological integrity of the nation's waters. The CWA establishes the basic structure for regulating discharges of pollutants into the waters of the United States and regulating surface water quality standards. Much of the text of the following descriptions of the relevant Sections of the CWA has been taken directly from the EPA’s website (www.epa.gov) to ensure clarity.

A cornerstone of the CWA is the requirement for states to establish Water Quality Standards (WQS). These are state-adopted and EPA-approved ambient standards for waterbodies. The standards designate the use of the waterbody and establish the water quality criteria and anti-degradation measures that must be met to protect those designated uses. The main thrust of the CWA is to develop and implement pollution reduction strategies to meet the WQS of every waterbody in every state.

If monitoring and assessment indicate that a waterbody or segment fails to meet one or more water quality standards and is therefore placed on the 303(d) list, then the relevant entity (state, territory or authorized tribe) is required to assess and allocate pollutant loads in a manner that would lead to attainment of WQS. The process of quantifying existing pollutant loads and calculating the load reductions needed to meet WQS is required under section 303 of the CWA, which describes the result as the "Total Maximum Daily Load" or TMDL.

The CWA requires development of TMDLs for those pollutant-affected waters whereby implementation of the technology-based controls, which are imposed upon point sources by the CWA and EPA regulations, would not result in achievement of WQS. At this point in the history of the CWA, most point sources have been issued NPDES (National Pollutant Discharge Elimination System) permits with technology-based discharge limits. In addition, a substantial fraction of point sources also have more stringent water quality-based permit limits. But because nonpoint sources are major contributors of pollutant loads to many waterbodies, even these more stringent limits on point sources have not resulted in attaining WQS.

Strategies that help to achieve WQS must consist of a TMDL or another comprehensive effort that includes the functional equivalent of a TMDL implementation plan. Some states have developed watershed management plans that address water bodies that are threatened or affected by pollution. The key point to remember is that TMDLs are "pollutant budgets" for a specific water body or segment that, if not exceeded, would result in attaining WQS.

The CWA established an iterative process of program implementation, monitoring, and, if the WQS is still not met, revision/improvement of pollution reduction strategies, and repeating the process until the WQS are met. After achieving WQS in a water body, anti-degradation measures are applied to ensure that acceptable water quality is maintained. This "Big Picture" of the CWA is shown below in Figure 12, which was taken from the EPA's website. All of the regulatory programs discussed below are forms of the pollution reduction strategies at the heart of the CWA. A detailed description of each program in included in Appendix A.

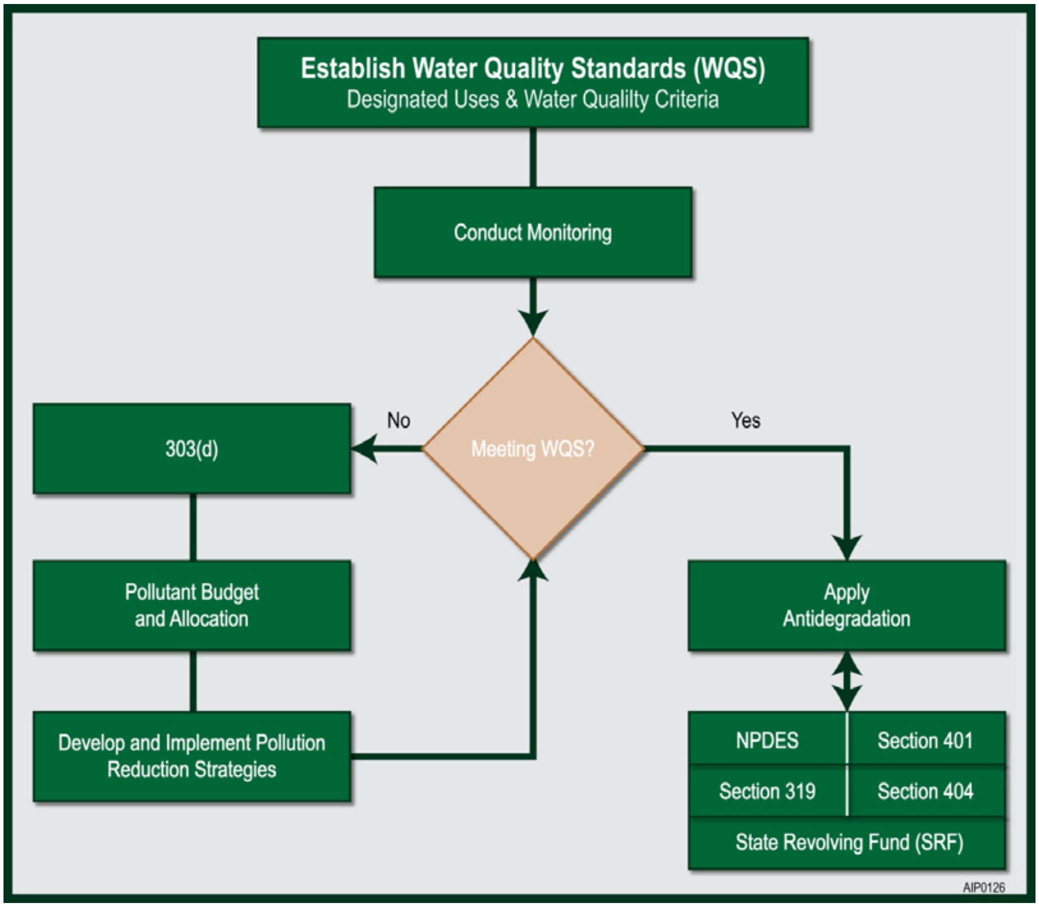

Figure 12: EPA Pollutant Reduction Regulatory Programs
Source: USEPA Watershed Academy Web – Distance Learning Modules on Watershed Management, "Introduction to the Clean Water Act", www.epa.gov/watertrain.

Section 404 of the CWA, enacted as part of the CWA in 1972, deals with one broad type of pollution—discharge of dredged or fill material into "waters of the United States" including wetlands. This law is commonly referred to as the "No Net Loss of Wetlands" law. In Texas, the 404 permit program is administered jointly by EPA and the U.S. Army Corps of Engineers.

A paradigm shift in the Section 404 permitting program began in 2001 when it was recommended that compensatory mitigation be integrated into a 'Watershed Context" whereby in-kind mitigation in the same watershed as the impacts would be preferable to out-of-kind mitigation or mitigation in a separate watershed. Stream mitigation was required to offset impacts to streams. It was no longer acceptable to use wetland mitigation to offset stream impacts. In 2008, the Corps and the EPA jointly issued the 2008 Final Compensatory Mitigation Rule.

Both the Galveston and Ft. Worth Corps Districts have subsequently developed compensatory stream mitigation tools for use in both evaluating compensatory mitigation required for stream impacts and in the development of stream mitigation credits through stream restoration activities. As a result, NCD projects are in development in both Districts. These two districts regulate most of Texas. These projects include both onsite mitigation, and more commonly, the development of large, third-party stream restoration projects for stream mitigation banks.

3. Study Methodology

3.1. Literature Review

A literature review was conducted to obtain documentation on the applicability of NCD methodologies to the various physiographic provinces in Texas, the ecological benefits of NCD and cost, benefit and economic impacts of NCD. Previous studies, technical articles, and reports were primarily obtained through 1) the use of a privately-owned literature review firm, Scitek; 2) the American Society of Civil Engineers (ASCE) Cybrary; 3) technical search services from the University of Wisconsin; and 4) articles purchased directly from Amazon.com. Articles, reports and previous studies utilized in the preparation of the present research study are cited throughout the report and listed in Section 9 – References.

3.2. Recent Experiences in Texas

Information regarding the use of NCD methods in stream and channel management was obtained from public agencies in the four largest metropolitan areas in Texas: Houston, Dallas- Fort Worth, Austin, and San Antonio. These four metropolitan areas represent fairly diverse physiographic settings and stream systems. Information was obtained through meetings with public agency staff, phone conversations and email correspondence. In some cases, the authors had been personally involved with the projects. In such cases, all information provided was presented to the public agency for review before disclosure.

Attempts were made to collect information regarding the number and types of NCD projects undertaken (i.e., what level of channel stabilization, enhancement, and/or restoration), typical project settings and objectives, NCD design approaches and methodologies, cost details, and funding mechanisms.

3.2.1. Houston Area

The city of Houston lies within the Gulf Coastal Plains physiographic region of Texas; it is located within the Coastal Prairies (BEG, 1996). A discussion on the physiographic regions of Texas is provided later in this report in Section 4.2.

The management of the majority of waterways and streams in the Houston metropolitan area is the responsibility of the Harris County Flood Control District (HCFCD), which has jurisdiction over more than 2,500 miles of channels in the county. The HCFCD has been trying various NCD methodologies on selected projects since 2002. These NCD projects include a combination CIP (Capital Improvement Program) and maintenance projects. The HCFCD is actively monitoring each project for geomorphic stability and will update design and maintenance as needed based on long-term performance. The following information was gathered via phone conversations and email correspondence with the HCFD CIP Department, and through the author’s direct experience working with the HCFCD.

A countywide fluvial geomorphological study was substantially completed in 2009 that included a representative geomorphological assessment of the channels in the 22 watersheds in Harris County and development of a set of analog and empirical fluvial geomorphological relationships and associated design tools for use in NCD stabilization, enhancement, and restoration design.

On a planning level, the HCFCD has initiated watershed-based studies on major waterways in Harris County such as Buffalo Bayou and Halls Bayou. These planning studies will assess effective flood damage reduction measures and will integrate diverse community goals for enhancing the bayous through urban design, public access, habitat conservation and restoration, water quality improvements, sediment and erosion management, and economic development. Each of the planning teams the HCFCD has developed for these watersheds includes internal staff and consultant experts in NCD and fluvial geomorphology and stream stabilization, enhancement, and/or restoration using NCD methods.

Furthermore, the HCFCD is exploring the use of various levels of NCD design county-wide in response to the Corps' new requirement for stream mitigation offsets for all stream impacts, as discussed in Section 2.6. The HCFCD has recently begun a project to develop an internal NCD design guidance document. The design guidance manual will provide specific design guidance for various levels of channel stabilization, enhancement, or restoration on all applicable HCFCD channel projects.

Since 2002, fifteen NCD projects were designed by the HCFCD, eleven of which were implemented by the Maintenance Engineering Department and two were capital projects. The design approaches varied between the projects based on site conditions, available data, and project objectives. A summary of the projects is presented in Table 3. Refer to Appendix B for details on each project.

The District's largest revenue source is derived primarily from a dedicated *ad valorem* property tax. The District's tax rate is variable, set at $0.02809 per $100 of assessed value for fiscal year 2012. This tax funds both the District's Operational/Maintenance expenses and services part of the District's Debt. Capital projects are primarily funded by both the Harris County Debt Service tax rate and the District's Debt Service tax rate.

In addition, data from two traditional erosion control projects involving bank stabilization on Buffalo Bayou were obtain for this study from the private sector. The Houston Country Club (HCC) is currently bidding a project to install a Mechanically Stabilized Earth (MSE) wall along 1,450 ft of stream bank. The River Oaks Country Club (ROCC) completed the design of gabion walls along Tee #14 on the banks of Buffalo Bayou, but has recently halted the project in lieu of the Memorial Park Demonstration Project (MPDP) which will incorporate the Tee #14 banks into the project reach. For more details on the MPDP project undertaken by the HCFCD refer to Appendix B.

Table 3: Summary of NCD Projects in the Houston Area

Project Name	Project Length (ft)	Project Description/Objective	Total Construction Cost	Construction Cost per linear foot	Design as % of Construction Cost	Project Status
HCFCD Maintenance Engineering Projects						
Cypress Creek at Meyer Park – Phase 1	1,200	Restore failing stream to a stable dimension, pattern and profile, including construction of new bankfull bench at a lower elevation	$1,500,000	$1,250/lf	16%	Construction completed in 2006
Cypress Creek at Meyer Park – Phase 2	2,200	Same as Phase 1 plus added objective to establish vertical grade control in the Phase 2 stream reach and the downstream end of the Phase 1 reach	$1,449,400	$658/lf	32%	Under construction
Tributary to Big Gulch Bayou	1,800	The core of the project will be a quasi-natural, exaggerated step-pool grade-drop channel from the upstream storm sewer outfall to the natural receiving stream. The channel will consist of short segments of "threshold" rock cascade riffles and longer reaches of meandering, zero-slope, sand-bed, three-stage channels	$1,119,750	$662/lf	19%	Design is complete but construction not yet scheduled
Buffalo Bayou at Sabine Street	1,200	Re-establishment/excavation of a bankfull floodplain bench on both banks and removal of invasive species and planting of native riparian vegetation.	$245,000	$204/lf	72%	Construction completed in 2011
Buffalo Bayou Shepherd to Sabine Street	12,144	Excavation of bankfull floodplain benches on incised sections, removal of invasive species and planting of native riparian vegetation, channel realignment and extensive bank stabilization using bioengineering prescriptions.	$5,145,000	$423/lf	17%	Under construction
Buffalo Bayou – Memorial Park Demonstration Project (MPDP)	7,880	Demonstrate a full Priority 2 restoration, water quality monitoring program to demonstrate reduction of sediment load and improvement of water quality	$5,065,400 (Engineer's estimate at 80% Design)	$643/lf	18%	Under Design
Little Vince Bayou – Witchita Street to Pasadena Blvd.	200	Installation of 3 rock cross-vanes using pre-cast concrete blocks and a base of granular fill and rip-rap. Construction of deep pools for habitat improvement to a depth of 2 feet below existing water surface. A 1,300-ft reach was stabilized. Total length of structures was 200 ft.	$14,784	$74/lf	In-house design	Construction completed in 2010
Rummel Creek – Edith L. Moore Nature Sanctuary	570	A rock cross-vane composed of square granite boulders was used to direct flows away from the repaired channel slopes. Additionally, eroded slopes were laid back and stabilized with erosion control matting, rock toe protection, and native riparian trees.	$376,418	$660/lf	In-house design	Construction completed in 2008

Project Name	Project Length (ft)	Project Description/Objective	Total Construction Cost	Construction Cost per linear foot	Design as % of Construction Cost	Project Status
Little Vince Bayou Improvement - Cherrybrook Lane to Witchita St	870	Concrete channel lining (above mitigation reach)	$499,597	$574/lf	In-house design	Construction completed in 2010
Cypress Creek Spot Repair	1,245	Slope bank at stable angle and armor side and protect toe with rock	$485,632	$390/lf	20%	Construction completed in 2011
Cypress Creek Fire Station	400	Slope bank at stable angle and armor side and protect toe with rock	$226,613	$566/ft	22%	Construction completed in 2012
HCFCD Capital Improvement Projects						
Vogel Creek – Arncliffe Drive to White Oak Bayou	8,300	The overall channel was widened to 150-165 feet and deepened 2-5 feet, with a meandering low flow pilot channel constructed in the bottom of the expanded channel corridor with riffles, pools and a bankfull bench. Native trees were planted to provide riparian habitat.	$9,000,283	$1,084/lf	14%	Construction completed in 2008
Mason Creek Extension	3,750	Channel corridor was constructed with a meandering pilot channel in the bottom and planted with native woody riparian vegetation. The project included the construction of an in-line regional stormwater detention basin with stormwater quality enhancement features	$5,097,203	$1,359/lf	3%	Construction completed in 2005
Brays Bayou Federal Flood Control Project – Ardmore to Holcombe	8,800	Channel widening, concrete lining repair, bridge re-construction	$12,021,022	$1,366/lf	6%	Construction completed in 2012
Goose Creek Channel Improvement Project – Baker Rd	4,775	Channel repair, concrete lining, detention	$8,631,050	1,808/lf	2.5%	Construction completed in 2010
Other projects in Houston Areas (Private Sector)						
HCC Holes #8 and Bank Stabilization	1,450	MSE green walls	$2,200,000	$1,517/ft	15%	Under bidding process
ROCC Hole #14 erosion repair	320	slope bank at stable angle and armor side and toe with gabions	$928,000 (Engineer's estimate)	$2,900/ft	NA	Re-designed as part of MPDP

Source: Harris County Flood Control District, River Oaks Country Club (ROCC) and Houston Country Club (HCC)

3.2.2. Dallas/Ft Worth and North Texas

Dallas and Fort Worth lie within the Gulf Coastal Plains physiographic region of Texas, within the Blackland Prairies. The city of Grand Prairie lies within the Grand Prairie physiographic region of Texas (BEG, 1996).

CITY OF FORT WORTH

The information presented here was obtained during a meeting with Mr. Steven Eubanks, P.E., Ms. Linda Young, P.E., and Mr. Ranjan Muttiah, PhD, P.E., CFM from the City of Fort Worth Public Works Department. The department staff indicated a strong interest in using NCD, although the city has not implemented any NCD projects to date. City staff expressed strong need for design guidelines, details, and specifications to encourage consideration of these techniques in conjunction with private development. According to city staff, during the last surge in development, the natural flood plain was preserved in several developments contrary to popular development practice in the city and state. This strategy streamlined the development process as there were no lengthy studies or delays related to fill in the flood plain and approval of a Conditional Letter of Map Revision (CLOMR) from the Federal Emergency Management Agency (FEMA). City staff reported that such areas with preserved flood plain “parks” are a community amenity and seem to have a long-term positive effect on property values.

CITY OF DALLAS

According to email correspondence with Mr. Steve Parker, PE, from the City of Dallas Trinity Watershed Management group, although the City of Dallas has not implemented any stream restoration or NCD projects, there are currently three stream restoration projects included in the City’s future project needs:

1. Lower Fivemile Creek with an estimated cost of approximately $28M, which is not recommended for funding at this time;
2. “Daylighting” a portion of upper Mill Creek, which is not recommended for funding at this time; Mill Creek and Peaks Branch were natural streams draining the M Streets area south of Mockingbird Lane until they were enclosed during development beginning in the 1930s.
3. Mill Creek, Phase III including a partial stream restoration to reestablish a portion of the open channel to convey low flows with a bypass for high flows.

The City staff expressed concerns about public perception of the created habitat (snakes, mosquitoes, etc.) associated with a proposed mitigation wetland to be constructed in the floodway as part of an agreement with the EPA, as well as concerns that NCD would not provide adequate conveyance to prevent flooding. The City’s typical storm drainage and flood management projects are intended primarily for flood control.

CITY OF GRAND PRAIRIE

The City of Grand Prairie has the most experience with NCD projects in the North Texas area and it began introducing NCD concepts approximately four to five years ago with the Kirby Creek project. The following information was gathered in a phone interview with Mr. Gabe Johnson, PE from the City of Grand Prairie, Public Works Department.

Initial studies to determine equilibrium slopes, design, and construction were performed on Kirby Creek, which experienced extreme erosion and falling banks. The project goal was to provide stream stabilization without hard armoring by identifying hard points in the channel to control down cutting through strategic placement of non-anchored rip-rap. The remaining portion of the stream was not modified. This project only minimally incorporated NCD techniques.

Construction costs were $580,000 (2007) and the project was funded by the City. Costs per linear foot were approximately $200 considering the entire stream segment length of approximately 3,000 linear feet. According the City staff, the largest project issue/cost was gaining access rights to private properties.

The Kirby Creek project has functioned as intended and has not required maintenance except for removal of downed trees and "as-needed" maintenance reported by residents. Water quality monitoring is performed on a monthly basis and annual basis; however, insufficient data have prevented conclusions to be drawn regarding the water quality benefits of the Kirby Creek improvements.

Since the Kirby Creek improvements were constructed, the City has performed approximately 20 to 30 linear miles of stream assessments. Associated projects are being incorporated into the Capital Improvements Program (CIP) planning process. The greatest challenge has been that the equilibrium slope requires too many drops of 2 to 3 feet. To minimize the locations, the City is looking for strategic locations to incorporate hard points in the streams (i.e., pipe crossings, etc.) where multiple benefits may be realized. Similar improvements to Cedar Creek are scheduled for construction in the next 12 months.

3.2.3. San Antonio

The city of San Antonio lies within the Gulf Coastal Plains physiographic region of Texas and is located on the border of the Blacklands Prairies and the Interior Coastal Plains (BEG, 1996). Overall, the streams within the region are highly urbanized. Many of the channels are intermittent or ephemeral and subject to flash flooding during large rainfall events. Bedrock outcropping is present in a number of the streams and helps to serve as grade control in these systems.

Within the San Antonio area, the San Antonio River Authority (SARA) has been focused on developing a stream restoration program for the region. Since the development of the program, SARA has implemented one stream restoration project, the East Salitrillo Creek Stream Restoration Project, and has plans to implement several more projects over the next couple of years. SARA is also in the process of developing tools to assist the stream restoration community including the development of regional curves. They routinely review projects from the city and county and advise other groups on the applicability of NCD and LID approaches to projects. The following information was gathered in a phone interview with Ms. LeeAnne Lutz, PE from SARA.

The East Salitrillo Creek Stream Restoration Project was completed in 2010 and consisted of the restoration of 1,288 linear feet of perennial stream at the Judson High School for the purpose of improving habitat and water quality, as well as demonstrating the use of NCD techniques.

Figure 13 shows a typical view of the erosion present at the site prior to restoration and a view of the project during construction.

The restored stream was designed as a Bc/C4 stream type according to the Rosgen Classification system. The project incorporated riffle and pool complexes as well as a number of habitat enhancement features such as constructed riffles and soil bioengineering techniques. The project included cross vanes to provide grade control as well as a plunge pool at a storm water outlet and the use of a Bioswale. The project was constructed utilizing SARA's construction crews at a cost of $321,072 ($249/lf). Design costs were 25% of the total construction costs.

Figure 13: Typical Erosion at East Salitrillo Creek Prior to Construction (left) and View of Project During Construction (right).

Source: San Antonio River Authority

3.2.4. Austin

The City of Austin lies within the Edwards Plateau physiographic region of Texas (BEG, 1996). The City of Austin has restored over 27,000 feet of urban and suburban streams since 1997 through the Watershed Protection Department's Stream Restoration Program. Project designs are fairly consistent and are driven by site conditions and constraints and guided by environmental values instilled in the Austin culture. The Program's objectives are to create a stable stream system that decreases property loss from erosion and increases the beneficial uses of the City's waterways. Projects typically address streams with eroding banks that are threatening adjacent property and infrastructure. The following information was gathered in an interview with Mr. Morgan Byars, P.E. of the Stream Restoration Program and from additional information and data provided by Mr. Byars.

Typical project site conditions in the city include alluvial ephemeral and some intermittent streams. Bedrock outcrop grade controls are common but are not dominant. Dominant riffle materials typically range from cobbles to gravels. As one of Texas' oldest cities, many of its numerous stream corridors were extensively developed.

The City of Austin has developed a fairly consistent design approach to address eroding streams in response to these typical conditions, and the goal of preserving or restoring natural functions provided by the waterways. The Stream Restoration Program's approach is to restore degraded streams by stabilizing the existing channel planform, creating pool and threshold (immobile) riffle systems to enhance habitat, armoring of the eroded banks, and re-establishment of the riparian landscape with native plants. There is usually very little lateral space to increase sinuosity in these restoration projects due to the extensive development in the stream corridors.

Most projects implemented by the City of Austin fall within the Priority 4 restoration option discussed in Section 2.4.4, where the stream beds are typically left in their existing dimension, pattern, and profile and are augmented with grade control structures. To provide vertical stability, grade control is usually accomplished with threshold (immobile) rock cascade riffles through the project reach. The rock cascades are designed such that the slopes of the pools between the riffles are at an equilibrium condition. Recognizing the limitations and reliability of engineering methods to predict a dynamic equilibrium and because clear water conditions from urban runoff are dominant, quite often the design slope between grade controls is set at zero. That is, the invert of the crest of the downstream riffle is at an elevation that imposes tailwater conditions on the downstream end of the upstream riffle. Riffle spacings are typically five to seven times the bankfull width of the stream. A typical rock cascade riffle/pool sequence is shown in Figure 14.

Figure 14: Typical City of Austin Rock Cascade Riffle/Pool Sequence
Source: City of Austin, Infrastructure Division, Watershed Protection Department, Stream Restoration Program.

The City of Austin has experimented with several bank stabilization techniques over the years, including geogrid encapsulated soil lifts and rock gabions. The preferred approach, which has become a standard of practice since around 1998, is to install stacked, limestone boulders for toe protection, with vegetated soil slopes on the upper banks. The boulder treatment usually extends below the anticipated scour elevation (e.g. below the creek bed) and up the channel bank to bankfull elevation, although they are often stacked higher depending on site conditions.

Vegetated soils lifts, which may be designed as MSE walls, when needed on steeper slopes, are placed on top of the stacked boulders. Fill is then placed at a 3H:1V slope to the existing terrace/floodplain and vegetated with grasses, forbs, and trees. The stacked boulder walls are typically installed on the outside bends of project reaches, with vegetated bank protection installed on the inside bend banks when site conditions allow. However, the stacked boulder walls are often installed on both banks on highly incised reaches with tight lateral constraints. A typical stacked boulder wall installation is shown in Figure 15 and Figure 16.

Figure 15: City of Austin Typical Stacked Boulder Wall Installation
Source: City of Austin, Infrastructure Division, Watershed Protection Department, Stream Restoration Program.

Figure 16: City of Austin Typical Stacked Boulder Wall Installation Near End of Construction (left) and After Vegetative Establishment (right)

Source: City of Austin, Infrastructure Division, Watershed Protection Department, Stream Restoration Program.

The City also applies other bank stabilization projects where site conditions permit. These bank stabilization projects range from purely vegetative protection such as using graded slopes with soil retention blankets and coir logs for toe protection to riprap armoring.

A summary of the City of Austin Priority 4 projects is presented in Table 4. On average, projects implemented by the City of Austin range between 200 and 3,500 feet in length. Construction costs for these typical projects range from $339 to $1,562 per foot of stream length with an average cost of $1,136 per linear foot. The linear cost depends on the bank height and the proportionate use of boulders and soil lifts. The City uses a value of $100 per square foot of bank face to estimate construction costs for these projects. As expected, the structural excavation and placement of stacked boulder banks and large riprap are the most expensive components of the projects, generally ranging from 50 to 60% of the total construction costs. Design costs for these projects ranged from 13% to 102% of the total construction costs, with an average of 33%. Inspection costs ranged from 1% to 24% of the total construction costs, with an average of 7.16%. Finally, the City's internal project management costs ranged from 2% to 16% of the total construction costs, with an average of 8%.

The majority of funding for the Stream Restoration Program is provided from funds generated through the City's Drainage Utility Fee. Additional funding is obtained from municipal bond issues for Capital Improvement Projects and, to a lesser extent, state and federal grants.

Table 4: Summary of Priority 4 Projects in the Austin Area

Project Name	Project Length (ft)	Project Description	Total Construction Cost	Construction Cost per linear foot	Design as % of Construction Cost	Year of Construction Completed
Shoal Creek at Ridgelea Bank Stabilization	510	MSE Bank Stabilization with boulder toe and soil lifts	$614,410	$1,205	In-house Design	2011
Williamson Creek - Pack Saddle Pass Tributary Rehabilitation	1,290	Stacked cut limestone boulders to top of bank (no soil lifts)	$461,000	$367	102%	2010
Fort Branch Reach 1 - Manor to Westminster	3,425	MSE Bank Stabilization with boulder toe and soil lifts	$3,700,00	$1,080	13%	2008
Tannehill Branch Tributary Stabilization - Victoria Dr	880	Stacked cut limestone boulders to top of bank (no soil lifts)	$683,000	$776	18.59%	2006
Fort Branch at Manor Road Emergency Project	510	MSE Bank Stabilization with boulder toe and soil lifts	$477,000	$935	In-house Design	2005
Tannehill Branch at Manor Circle Emergency Bank Stabilization	260	MSE Bank Stabilization with boulder toe and soil lifts	$406,000	$1,562	14.18%	2005
Shoal Creek at 5th Street Bridge - Erosion Stabilization	180	MSE Bank Stabilization with boulder toe and soil lifts	$276,700	$1,537	In-house Design	2003
Shoal Creek at Northwest Park	2803	Various including grade control and MSE structures	$1,518,034	$542	In-house Design	2003
Little Walnut Creek-3003 Loyola Ln Erosion Stabilization	265	MSE Bank Stabilization with boulder toe and soil lifts	$257,180	$970	In-house Design	2002
Tannehill Branch Highland Park Cemetary	300	Stacked Natural Boulders to top of bank (no soils lifts)	$243,318	$811	In-house Design	2001
Shoal Creek Bank Stabilization West Avenue to 5th St	650	MSE Bank Stabilization with boulder toe and soil lifts	$926,000	$1,425	21.06%	2000
Tannehill Branch Givens Park Streambank Stabilization	440	MSE Bank Stabilization with boulder toe and soil lifts	$279,150	$634	In-house Design	2000
Little Walnut Creek Erosion Control Ph. 3 - Bridgewater Dr	800	MSE Bank Stabilization with boulder toe and soil lifts	$777,770	$972	In-house Design	2000
Little Walnut Creek-Erosion Control Ph. 7 - Lakeside	500	MSE Bank Stabilization with boulder toe and soil lifts	$705,370	$1,411	In-house Design	2000
Shoal Creek at 26th Channel Improvements	425	Stacked Natural Boulders to top of bank (no soils lifts)	$433,075	$1,019	29.78%	1998
SRP -Waller Creek at Shipe Park Erosion Project	300	Rock toe, graded slopes	$222,000	$740	In-house Design	1999
SRP - Tannehill Branch at Lower Bartholomew Park	1300	Slope grading, boulder toes, grade control	$441,000	$339	In-house Design	2001

Source: City of Austin, Infrastructure Division, Watershed Protection Department, Stream Restoration Program.

4. Objective 1: Are NCD Techniques appropriate for use in Texas?

4.1. Methodology

Due to the expansive area and the diversity of geologic and climatic conditions across the state, water resource management strategies must be adaptable and suitable to a wide range of conditions to be applicable on a state level. The Bureau of Economic Geology (BEG) at the University of Texas at Austin divides the state into seven broad physiographic provinces based on characteristic geology, vegetation, and climate (BEG, 1996). These seven physiographic provinces break the state into more manageable regions for dealing with water resource issues. Each physiographic region was formed under a unified set of geomorphic processes, with similar geology and climate throughout each region. Therefore, the landscapes within each region share similar topography, structure, and soil types, and may vary greatly from landscapes in other regions within the state. Within each region, stream conditions are similar and can be expected to respond to degradation or restoration in similar ways.

The physiographic regions also provide a way to compare areas in Texas to other areas across the country with similar physiography where NCD techniques have been used more extensively and for longer periods of time. Examples of NCD projects completed in comparable physiographic regions across the country demonstrate how NCD could be used to address the specific resource issues and conditions found in Texas.

The following section will evaluate whether NCD techniques are appropriate for use in the various physiographic provinces of Texas, based on existing data from within the state and from other areas of the country that share similar physiography.

The following criteria should be considered when judging the applicability of NCD to Texas:

- Have NCD projects been successfully designed and implemented in a similar physiographic setting?
- Did the NCD projects implemented in that setting meet the intended objectives and success criteria? If so, would similar objectives be applicable to addressing water resource issues in Texas?

It should be noted that NCD is an evolving science and within the literature there are documented cases of failures, which often can be attributed to poor designs or misapplication of the method (Sliwinski and Niezgoda, 2009; Verdonschot, 2009). This paper is intended to provide evidence that NCD can be successfully implemented in Texas and is not meant to be an exhaustive review of the number of successful versus unsuccessful projects.

The success of NCD restoration techniques depends not only on the physiographic conditions, but also on the existing land use and the influence of human activities on the resource. Urban development can significantly change site conditions and issues, and therefore may affect the applicability of NCD at a particular site. Thus, the use of NCD within both urban and rural settings was also explored as part of this study.

4.2. Texas Physiographic Provinces and Use of NCD in Similar Physiographic Provinces of the US

Physiographic provinces within Texas include the Basin and Range, High Plains, North-Central Plains, Edwards Plateau, Central Texas Uplift, Grand Prairie, and Gulf Coastal Plains. The BEG map of the physiographic provinces is shown in Figure 17.

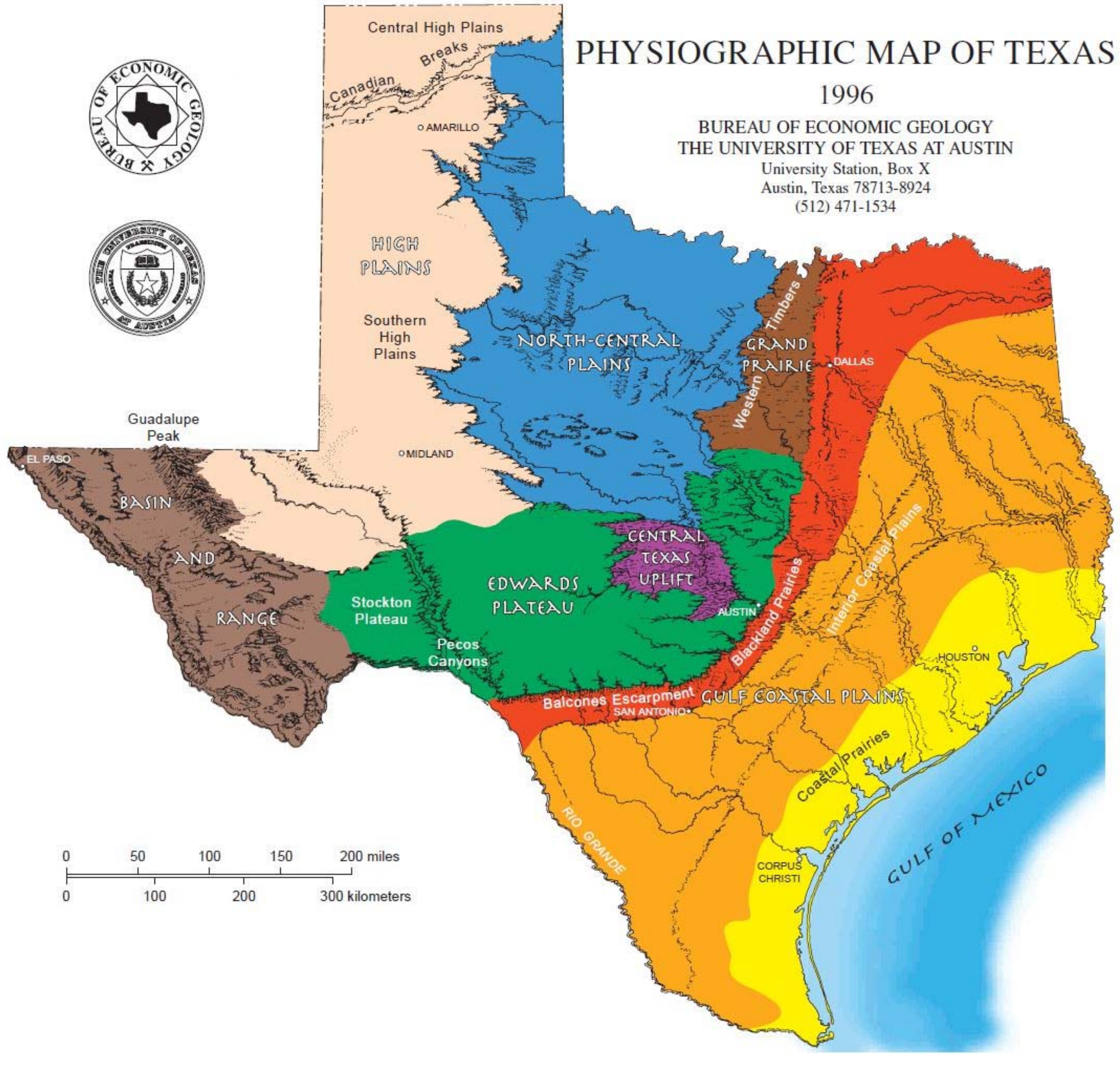

Figure 17: Physiographic Provinces of Texas (BEG, 1996)
Source: (BEG, 1996)

4.2.1. Texas Coastal Plains with Gulf and Atlantic Coast Regions

The Gulf Coastal Plains includes the Coastal Prairies, Interior Coastal Plains, and innermost Blackland Prairies. The geology is dominated by deltaic sands and silts near the coast, with belts of shales and uncemented sands towards the interior. The Interior Coastal Plains have thin, sandy and clay soils, while the innermost Blackland Prairies have deep, fertile clay soils. Slopes are gentle throughout the coastal plains. The eastern part of the region is dominated by pine and hardwood forests with numerous perennial streams. Forests transition into brush and sparse grasses to the west and south of this region (BEG, 1996). The climate ranges from subtropical-humid in the east to subtropical-subhumid in the south (OSC, 2010).

The Gulf Coastal Plains of Texas can be compared to other regions along the Gulf and Atlantic coasts, due to similar geology, coastal geomorphology, humidity, and precipitation. Florida, North Carolina, and Maryland, where the use of NCD is common, all contain coastal physiographic regions similar to the coastal plains in Texas. In addition, the cities of Houston and San Antonio are contained within this physiographic region and each of these cities already has an active stream restoration program. Examples of similar regions are detailed in the Table 5.

Representative City	USGS Physiographic Region[1]	Average Annual Precipitation [2] (inches)	Characteristic Geology[3]	Topography[4]
Houston, TX	West Gulf - Coastal Plain	49.76	Quaternary; sedimentary rocks and recent deposition; deltaic sands and muds [5]	Flat, gently sloping seaward
Orlando, FL	Floridian - Coastal Plain	50.58	Upper Tertiary to Quaternary, sandy deposits with underlying limestones [6]	Flat, gently sloping seaward
Greenville, NC	Embayed Atlantic - Coastal Plain	49.60	Upper Tertiary, sedimentary rocks and recent deposition; clay, mud, and sand [7]	Step-like terraces and gently rolling hills, gently sloping seaward
Baltimore, MD	Embayed Atlantic - Coastal Plain	41.85	Cretaceous to lower Tertiary; gravels and sands [7]	Flat, gently sloping seaward
Norfolk, VA	Embayed Atlantic - Coastal Plain	46.41	Quaternary; sand, gravel, and unconsolidated material [7]	Flat, gently sloping seaward

Table 5: Physiographic Data for the Texas Coastal Plains and Similar Regions

Table Notes: [1] USGS, 2010. [2] National Weather Service, 2012. [3] USGS, 2002. [4] USGS and National Park Service, 2000. [5] BEG, 1996. [6] Florida Geological Survey, 1994. [7] USGS, 2012.

Before comparing the Texas Coastal Plains to the Gulf and Atlantic Coastal Regions, it is worth noting that a number of stream restoration projects have already been implemented in the coastal plains region of Texas. The fact that stream restoration has already been conducted here may be the best indicator of the applicability of NCD in the Coastal Plains region. However, additional examples of successful restorations in similar regions of the US are provided in the following paragraphs to further substantiate the applicability of NCD.

A large portion of the Texas Coastal Plains physiographic region is located within the Fort Worth Corps District. Several stream and wetland mitigation banks have been constructed along the Highway 80 corridor between Longview and Dallas. Others are scattered throughout the eastern portion of the District boundary. These include projects on the Trinity River, the Sabine River, as well as several smaller streams. Additionally, the Galveston Corps District, which has jurisdiction over the southern portion of the Coastal Plains physiographic region, has developed a standard operating procedure (SOP) for compensatory stream mitigation. A number of mitigation banks have been established within the Galveston Corps District boundary. The authors were involved in the restoration and enhancement of approximately 17,800 feet of stream at the Katy Prairie Mitigation Bank located in Harris County, TX. The cities of Houston and San Antonio are contained within this physiographic region and each of these cities already has active stream restoration programs as discussed in Section 3 of this report.

North Carolina has been very active in the field of stream and wetland restoration, conducting a great deal of research and experimentation, partly driven by 404 permitting requirements. As a result, they have developed a cadre of knowledgeable professionals and very capable conservation agencies in the state. The North Carolina Ecosystem Enhancement Program (NCEEP) is one such agency that has been tasked with restoring and enhancing North Carolina streams and wetlands through in-lieu fee mitigation programs (Rheinhardt and Brinson, 2007). NCEEP has completed numerous successful stream restoration projects in the coastal plains region of NC and has also promoted research on restoration science in coastal areas, including studies by Rheinhardt and Brinson (2007) on evaluating the condition of coastal watersheds and by Rheinhardt, et al. (2005) on the use of ecological assessments in planning stream restorations in the coastal plains.

As in Texas, North Carolina features an outer coastal plain and an inner coastal plain region (North Carolina Geological Survey, 2004). Texas can capitalize on the wealth of experience and research on stream restoration in the coastal plains of North Carolina to improve the success of stream restoration projects in the Texas Coastal Plains. Resource managers planning NCD stream restorations in the Gulf Coastal Plains can utilize case studies of restorations from the North Carolina Coastal Plains to determine the design features and methodologies that have been successful in a similar area.

One such case study is the Unnamed Tributary to Pembroke Creek Restoration Project completed by NCEEP. The restoration was performed on a headwater stream in the outer coastal plains of northeastern North Carolina. Restoration planners addressed many of the same design issues that would be faced in designing a NCD restoration project in coastal Texas. The design had to incorporate the regrading of a very shallow valley and the creation of appropriate microtopography in a mostly flat, low-lying area (Morris, 2005). In the case of the UT to Pembroke Creek project, land use was historically and currently agricultural.

Restorations have also been completed in more urban areas, addressing the unique design issues of urban environments. The Pine Valley Golf Course Tributary project in Wilmington, NC demonstrated the use of NCD techniques to restore a coastal plains stream in an environment that was more constrained by existing land use and development (Jennings, 2003). The Pine Valley Golf Course project design also addressed issues that may be common in the coastal region of

Texas, including sandy soils with low cohesion, constraints due to existing infrastructure, and the need to maintain the existing stream elevation (Jennings, 2003).

Numerous other case studies of NCD restoration projects are available from coastal plains areas in the Carolinas, Florida, Maryland, and Virginia, for example. Case studies for projects in the coastal plains have been completed by government and non-government organizations, private companies, and academic sources. For example, The Center for Watershed Protection (CWP) focuses on the entire Atlantic and Gulf Coastal Plains Region and maintains case studies of restoration and watershed planning projects throughout the region (CWP, 2011). The CWP could be an excellent resource for restoration planners looking to research successful NCD techniques in the Coastal Plains region.

4.2.2. West Texas (Basin and Range and High Plains) with Southwest US

The Basin and Range is characterized by mountains rising from rocky plains. Many of the peaks are formed from volcanic rock. The High Plains consist of a nearly flat plateau with drainage dominated by small intermittent streams (BEG, 1996). Vegetation ranges from oak-pine-juniper forests in the mountains of the Basin and Range to scrub-shrub and grassland vegetation in the basins and the High Plains (BEG, 1996). Climate in the Basin and Range and High Plains provinces is typically semi-arid with areas of cooler mountain climate in the higher elevations, and desert areas forming in the rain shadows of the mountains (Office of the Texas State Climatologist, 2010).

Table 6: Physiographic Data for West Texas and Similar Regions

Representative City	USGS Physiographic Region[1]	Average Annual Precipitation (inches) [2]	Characteristic Geology[3]	Topography[4]
Amarillo, TX	High Plains - Great Plains	20.34	Tertiary, sandstones, mudstones, and clays; eolian silts and fine sands [5]	Mostly flat, lower-lying than the Basin and Range
Carlsbad, NM	Mexican Highland - Basin and Range	13.25	Quaternary eolian deposits and alluvium; Permian sandstones and carbonates [6]	Steep elongate mountains and flat valleys
Colorado Springs, CO	Colorado Piedmont - Great Plains	16.51	Cretaceous to lower Tertiary, sandstones, dune sands, silt [6]	Mostly flat, lower-lying than the Basin and Range
El Paso, TX	Mexican Highland - Basin and Range	9.69	Tertiary; Igneous, metamorphics, sediments [5]	Steep elongate mountains and flat valleys
Las Cruces, NM	Mexican Highland - Basin and Range	12.00	Tertiary and Quaternary, clastics, igneous rock, and unconsolidated materials [6]	Steep elongate mountains and flat valleys
Tucson, AZ	Sonoran Desert - Basin and Range	11.56	Tertiary to Quaternary, sand, gravel; underlying conglomerate and granite [6]	Steep elongate mountains and flat valleys
Las Vegas, NV	Great Basin - Basin and Range	5.08	Quaternary alluvium, basalt, granite, and andesite [6]	Steep elongate mountains and flat valleys

Table Notes: [1] USGS, 2010. [2] National Weather Service, 2012. [3] USGS, 2002. [4] USGS and National Park Service, 2000. [5] BEG, 1996. [6] USGS, 2012.

The Basin and Range and High Plains provinces of West Texas share physiography characteristics with several southwestern states including Colorado, Utah, Nevada and New Mexico. A comparison of these different physiographic regions is presented in Table 6 above. A number of projects have been successfully constructed in these regions including several well-documented projects in southwestern Colorado. One such project is the Lower Rio Blanco River near Pagosa Springs, Colorado. This project consisted of the conversion of an F3 and over-widened C3 channel to a low width to depth ratio C3 stream type (Rosgen, 2002). This project consisted of 1.1 miles of restoration constructed in 1999 and monitored through 2002. Results of the monitoring over this time period indicated that the channel was able to maintain its dimension, profile and pattern without significant aggradation or degradation. Since this initial project, two additional phases have been completed with Phase II encompassing 3.25 miles of restoration (completed in 2004) and Phase III encompassing 1.25 miles of restoration (completed in 2009).

Other examples of successful river restoration in southwestern Colorado include the East Fork of the San Juan River, which was constructed in 1986 and consisted of converting a braided channel into a meandering C3 stream type, and the Weminuche River restoration which restored over 3 miles of channel using NCD techniques.

Another project documented in Colorado is the restoration of the Little Snake River. Approximately 14.4 miles of the Little Snake River and its tributaries located in Northwestern Colorado were restored in 2000 (Bledsoe, 2005). This area of Colorado is located near the transition between the Basin and Range physiographic province and the Southern Rocky Mountains. After five years of monitoring the project, it was determined that in-stream structures were performing as intended despite high flows, and that the observed channel adjustments were within the range of variability observed in comparable un-impacted natural systems (Bledsoe, 2005).

A couple of stream restoration projects of note have been constructed in Utah. Several government agencies and non-profits banded together to stabilize 1,100 feet of eroding stream banks along East Canyon Creek located 20 miles east of Salt Lake City (USU Extension, 2008). The project, started in 2005, also included the construction of a cross vane to improve fish habitat within the restored reach. The Utah Division of Wildlife Resources (UDWR) has performed several stream restorations to improve trout habitat in the state. In 2010, the UDWR performed a stream restoration on Mud Creek in Carbon County (UDWR, 2011). The project included reshaping the channel and installing in-stream structures along one mile of stream. Restoration was performed to reduce sedimentation to the downstream reservoir, improve water quality, and provide habitat for cutthroat trout.

4.2.3. North Texas (North Central Plains and Grand Prairie) with Midwest

The North Central Plains are characterized by an erosional surface with shale, sandstone, and limestone bedrock and landforms including rolling plains with low ridges called questas. Drainage consists of meandering rivers in the shale-dominated prairies and highly dissected slopes in areas dominated by harder bedrock (BEG, 1996).

The Grand Prairie consists of plains in the east with low stair-step hills in the west. The area developed on limestones, forming thin, rocky soils. The prairie is dissected by many streams on flat or gently sloping land. Vegetation is dominated by grasses in the east, transitioning to post-oak forests in the west. Climate in the Grand Prairie and North Central Plains is subtropical-subhumid, tending more towards humid towards the east (OSC, 2010).

The North Central Plains and Grand Prairie provinces of North Texas share characteristics with many Midwestern states including Oklahoma, Arkansas, Nebraska, and Missouri. Within Oklahoma and Nebraska, the use of NCD is just beginning to grow in popularity and projects utilizing NCD techniques are relatively new. Both the Oklahoma State University and the University of Nebraska have created stream restoration programs. Characteristics of these regions are provided in the Table 7.

Table 7: Physiographic Data for North Texas and Similar Regions

Representative City	USGS Physiographic Region[1]	Average Annual Precipitation (inches) [2]	Characteristic Geology[3]	Topography[4]
Abilene, TX	Osage Plains - Central Lowland	24.79	Permian, sandstones, mudstones, and clays; limestones, sandstones, shales [5]	Mostly flat and low-lying
Oklahoma City, OK	Osage Plains - Central Lowland	36.66	Permian, sandstones and shales, sand, and gravel [6]	Mostly flat and low-lying
Kansas City, MO	Osage Plains - Central Lowland	38.83	Pennsylvanian, shales, limestones, silt, loess [6]	Mostly flat and low-lying
Omaha, NB	Dissected Till Plains - Central Lowland	30.93	Pennsylvanian, limestones and shales; Cretaceous sandstones and shales [6]	Mostly flat and low-lying
Fort Smith, AR	Arkansas Valley - Interior Highlands	45.40	Pennsylvanian shale and sandstone [6]	Ridges and valleys eroded on folded strata
Wichita, KS	Osage Plains - Central Lowland	32.62	Permian limestones and shales; Quaternary gravel, sand, and silt [6]	Mostly flat and low-lying

Table Notes: [1] USGS, 2010. [2] National Weather Service, 2012. [3] USGS, 2002. [4] USGS and National Park Service, 2000. [5] BEG, 1996. [6] USGS, 2012.

In Arkansas, there are more instances of documented NCD projects. One such project is the West Fork White River Restoration project, where 1,600 feet of channel was restored in 2009 using NCD techniques including using a reference reach to design more stable dimensions and installing in-stream structures to reduce near-bank stress (WCRC, 2012). Multiple bankfull flow events have occurred since the project's implementation, indicating that the structures have remained stable under typical high flows. Post-restoration monitoring indicates that the project is meeting project objectives of reducing sediment loads and preventing accelerated streambank erosion. Sediment loading to the West Fork White River from the project site was reduced by 96 percent following the restoration (WCRC, 2012).

Restoration of Niokaska Creek in Fayetteville, AR was completed in the fall of 2008, using funds from a Section 319(h) grant from the EPA. NCD restoration techniques were used with the objectives of stabilizing the stream, reducing erosion, and enhancing habitat. This project remained stable during a rain event that produced above-bankfull flow just after the completion of construction, demonstrating the improved stream stability. Habitat was also improved by revegetating the riparian area with native herbaceous and woody species (WCRC, 2012).

In Missouri, stream restoration is primarily driven by the need for compensatory mitigation as required by permits issued by the U.S. Army Corps of Engineers (USACE) to satisfy Section 404 of the Clean Water Act. Several stream and wetland mitigation banks have been constructed in the State of Missouri so that applicants of Section 404 permits can purchase credits to compensate for stream and wetland impacts incurred by their projects. Some stream banks that have been constructed include the Fox Creek Stream Mitigation Bank (St. Louis County), the Lower Missouri River Mitigation Bank (St. Louis County), and the Little Dardenne Creek Stream Mitigation Bank (St. Charles County). In addition, if a permittee would prefer to construct and monitor the required stream mitigation, the USACE St. Louis District encourages stream restoration by the issuance of the Stream Mitigation Method developed specifically for the State of Missouri.

One project independent of compensatory mitigation located in Harrisonville, Missouri is the Town Creek Riparian Restoration Demonstration. This project included the restoration of 210 feet of stream with the goal of reducing channelization, decreasing non-native vegetation, and increasing water holding capacity during storm events in order to better manage stormwater (MARC, 2006). The project designers used a bankfull bench and a meandering channel to alleviate the channelization and improve connectivity with the floodplain, and established native vegetation in the riparian area (MARC, 2006).

4.2.4. Central Texas Uplift and Edwards Plateau with Karst areas

The Edwards Plateau is capped by hard limestones and includes the Hill Country and the Stockton Plateau of central Texas. Drainage ranges from entrenched streams on the plateau, to canyons with perennial flow fed by springs, to karst networks of sinkholes and caverns. The Pecos River forms a deep canyon dividing the western Stockton Plateau from the rest of the Edwards Plateau region. Vegetation is composed of sparse brush and shrubs, and climate is subtropical with hot summers and rain decreasing from east to west (BEG, 1996).

The Central Texas Uplift region is a knobby plain with round, granite hills and questas (BEG, 1996). Climate is similar to the Edwards Plateau and the North Central Plains with subhumid conditions and hot summers and dry winters typical (OSC, 2010).

The Central Texas Uplift and the surrounding Edwards plateau can be compared to karst areas in the eastern United States such as central Kentucky, central Tennessee, and southern Missouri. The city of Austin, which already has an active stream restoration program, is contained within this physiographic region. Examples of similar physiographic regions are presented in the Table 8.

Stream restoration projects in central Kentucky and central Tennessee range from NCD projects associated with transportation related projects to stream mitigation projects utilizing in-lieu fee dollars. Stream mitigation for Section 404 permits is a major driver of stream restoration projects in both Kentucky and Tennessee. As such, several projects have been completed in areas with karst geology.

Table 8 : Physiographic Data for Central Texas and Similar Regions

Representative City	USGS Physiographic Region[1]	Average Annual Precipitation (inches) [2]	Characteristic Geology[3]	Topography[4]
Austin, TX	Central Texas - Great Plains	34.29	Cretaceous; limestones and dolomites [5]	Mostly flat and low-lying
Kerrville, TX	Edwards Plateau - Great Plains	32.01	Cretaceous; limestones and dolomites [5]	Mostly flat, higher and more relief than the lowlands
Bowling Green, KY	Highland Rim - Interior Low Plateaus	49.33	Mississippian, limestones, dolostones, and sandstones [6]	Mostly flat and low-lying
Murfreesboro, TN	Nashville Basin - Interior Low Plateaus	53.23	Ordovician limestones and shales [6]	Mostly flat and low-lying
Springfield, MO	Ozark Plateaus - Interior Highlands	45.47	Mississippian and Pennsylvanian, limestones, sandstones, siltstones [6]	High, hilly landscape

Table Notes: [1] USGS, 2010. [2] National Weather Service, 2012. [3] USGS, 2002. [4] USGS and National Park Service, 2000. [5] BEG, 1996. [6] USGS, 2012.

One example is Wallens Bend Creek and the Clinch River Restoration in Kyle's Ford, Tennessee where 4,000 feet of stream were restored. The project was constructed in 2007, and subsequent monitoring has shown that the project is successful. In addition, approximately 3,800 feet of Trammel Creek, a spring fed trout stream located in Allen County, Kentucky, were restored using in-lieu fee dollars in 2008. Similar to the agricultural land use in many areas of rural Texas, cattle had access to Trammel Creek before the restoration. Grazed banks caused the banks to be more susceptible to erosion and, in turn, the stream over-widened and formed mid-channel bars. The stream was re-established at a more appropriate width-to-depth ratio and in-stream structures were constructed to provide trout habitat and bank protection. Subsequent monitoring indicates that habitat at the project site has been significantly improved from pre-construction conditions based on EPA Rapid Bioassessment Protocol scores (Stantec, 2011).

In general the principles of natural channel design used within other regions of the United States apply to karst areas; however, within karst areas additional attention must be given to bankfull discharge determinations because flow received by the channel may originate from areas outside of the stream's contributing surface drainage area. Otherwise, NCD procedures in karst environments are very similar to techniques utilized in non-karst areas.

4.3. Applicability of NCD in Texas

4.3.1. Urban vs. Rural

Restoration projects and techniques vary greatly based on the environment in which they are implemented. Beyond the physiography of the restoration site, the existing land use and development is probably the most important factor to consider in restoration design. Streams in highly developed urban environments have very different problems and different restoration potentials than streams in agricultural or rural environments. Despite these differences, case studies have demonstrated that NCD techniques can be applied in both urban and rural environments by adapting the techniques to the particular issues of the restoration site. Studies indicate that NCD techniques can be used to improve stream stability, habitat, and water quality in both urban and rural environments (Jennings, 2003).

Stream restorations differ significantly in urban and rural environments due to differences in the causes of degradation as well as differences in the social, economic, and physical conditions of the surrounding environments (Carpenter, et al., 2004). Streams in rural environments are often impacted by agriculture and land clearing, which can lead to sedimentation, erosion, and water quality degradation from fertilizers and pesticides. On the other hand, urban streams are often impacted by increased stormwater runoff, limited floodplain connectivity, and pollution from chemicals, trash, temperature, and sewage systems. Stream restorations in rural areas are often less restricted by existing infrastructure, and designs may be more flexible than in urban stream restorations. There are often fewer landowner issues with rural stream restorations simply because land parcels are larger and there are fewer landowners with whom to coordinate (Bernhardt and Palmer, 2007). Because of this flexibility, it may be easier to implement larger projects in rural areas, and there may be a greater possibility of connecting the restorations to other less degraded areas of the watershed.

For example, the Big Harris Creek restoration project, which is located in an agricultural area of North Carolina, is NCEEP's longest project and is projected to restore approximately 7 miles of stream (Fairley, 2010). A project of this magnitude would probably not be possible in an urban environment. However, in the majority of cases, rural areas have fewer landowners invested in the land, which may mean fewer stakeholders interested in protecting and restoring the land. Rural restoration projects may also receive less attention and less opportunity for community involvement because they are not in high-profile areas.

Urban stream restoration presents different design challenges. Many urban streams are severely degraded due to modification of hydrology, water quality, sediment transport, and morphology caused by development (Carpenter, et al., 2004). Landowner cooperation is essential in both urban and rural restorations, but it is especially important in urban areas where long-term maintenance and protection of completed projects can be difficult due to higher property values, infrastructure development, and multiple landowners (Bernhardt and Palmer, 2007). In addition, urban environments typically have more existing restrictions on the plan and profile of the stream, due to existing road and utility crossings, development in the floodplain, and the importance of compatibility with existing land uses and aesthetics. These factors can lead to increased restoration costs, and decreased potential for habitat creation and ecological connectivity in urban areas.

However, despite the challenges associated with urban restoration, the results can be especially valuable to the urban environment through added benefits such as flood reduction, infrastructure protection, and the potential for educational and recreational opportunities (High, 2010). Because urban streams are highly susceptible to degradation due to the drastic changes caused by urbanization, many urban streams are in great need of restoration (Bernhardt and Palmer, 2007). In addition, urban restoration efforts can extend benefits to a large number of people by improving the immediate environment and increasing the recreational and aesthetic value of streams in densely populated areas (Bernhardt and Palmer, 2007). Typical objectives in urban restoration include stabilizing banks, adding meanders to channelized reaches, daylighting channels that have been diverted into conduits, removing dams and culverts, and improving habitat (Carpenter, et al., 2004).

In addition to the land restrictions and increased cost of land in urban areas, restoration designers also face the challenge of creating a more natural stream system without increasing the threat of flooding to existing structures. Approximately 17 percent of urban land in the United States is within the 100 year flood zone (Bernhardt and Palmer, 2007). In past decades, many urban streams were channelized and disconnected from the floodplain to allow for this development despite higher peak discharges due to increased impervious surface area. Stream morphology has been changed in the interest of transporting storm water effectively. Thus, it is not always practical or possible to achieve the ideal natural channel design in an urban setting.

Ideally, the goal of NCD restoration is to restore the channel to historic or reference conditions, but urban development necessitates consideration of the fact that hydrology of the surrounding area has been permanently altered (Bernhardt and Palmer, 2007). For example, urban streams have higher peak discharges than forested reference streams because they are connected to efficient networks of stormwater conveyances that transport water off of impervious surfaces. It may not be possible to raise channel elevation or recreate the historic floodplain connection under these altered conditions.

In order to design a successful urban stream restoration, planners must monitor current flow and sediment data and incorporate the data into the design along with reference data. While pre-construction monitoring is important in both urban and rural settings, it is especially important in an urban restoration to understand how the existing watershed conditions alter the urban stream flow in comparison to the reference reach. Byars and Kelly (2004) documented the use of sediment transport data in an urban restoration design for Fort Branch in Austin, TX. In the Fort Branch study, historical trends and field observations were used in conjunction with a sensitivity analysis of channel adjustment to sediment loads in order to calculate a stable design slope (Byars and Kelly, 2004).

Despite the challenges associated with urban stream restoration, government agencies and conservation groups in metropolitan areas throughout the country have successfully implemented urban restoration projects in recent years. The Rocky Branch restoration project in Raleigh, NC demonstrates that with careful planning, NCD techniques can be used successfully in very urban environments. Rocky Branch runs through the North Carolina State University campus, and has been degraded by urban development, resulting in channelization and severe incision (Jennings, 2003). NCD techniques have been successful in this area despite the constraints, including numerous lateral restrictions that limit the design of the floodplain and stream pattern. In some areas, existing infrastructure (including sewer lines, culverts, and parking lot spaces) were removed or relocated to facilitate the restoration. In other areas, bioengineering and in-stream structures were used to protect vulnerable banks where the planform could not be altered.

The NCD restoration techniques used in the Rocky Branch design were combined with other urban best management practices, including energy dissipaters at stormwater outfalls, to help increase the success of the restoration in an urban environment. The results of the Rocky Branch project indicate that while urban stream restoration can sometimes require additional efforts and costs, urban restorations can provide both environmental and social benefits to some of the most severely degraded watersheds (Jennings, 2003).

Within Texas, the City of Austin has completed several urban stream restoration projects over the last decade implementing various stream restoration techniques, including natural channel design features. The Tannehill Branch of Boggy Creek project, completed in 2001, included construction of pool and riffle complexes to control grade and a combination of traditional hard armoring techniques and bioengineering techniques such as live plantings and brush mattresses to stabilize banks (Carpenter, et al., 2004). The Upper Tannehill Branch Project, completed in 2006, also included constructed riffles, installation of rock toes, vegetated soil lifts, and planting of native riparian vegetation (Chin, et al., 2010). Chin, et al. studied the Upper Tannehill Branch Project and two other Austin-area restoration projects, Lower Tannehill Branch and Waller Creek, and found improvements in both habitat quality and in macroinvertebrate community metrics following restoration. In general, post-restoration monitoring results showed positive ecological responses at all three urban sites, including greater macroinvertebrate taxa richness, and improvement in many of the metrics measured by the EPA RBP (Environmental Protection Agency Rapid Bioassessment Protocols) score, including increased diversity of velocity and depth regimes, decreased sediment deposition and embeddedness, and increased epifaunal substrate (Chin, et al., 2010).

While there are pros and cons to designing restorations in either urban or rural areas, successful restorations have been demonstrated in both environments. With proper planning, both urban and rural stream restorations can provide long-term benefits. In order to have a successful restoration project in either environment, restoration planners must be able to identify the restoration goals and then match those goals with the restoration potential of each site (Beechie, et al., 2008).

It may not be possible to implement a long, continuous restoration in an urban area confined by pre-existing structures, but local projects can provide valuable habitat, reduce pollutant and sediment loading, and create recreational and aesthetic benefits for city residents. By the same idea, a rural project may not receive as much human use as an urban project, but it may be possible to design a larger restoration and protect a larger area of the watershed. In either case, a successful NCD restoration project is possible as long as resource managers carefully prioritize restoration actions to best meet their restoration goals (Beechie, et. al., 2008).

4.3.2. Flowchart (Applicability Tree)

The following flowchart presented in Figure 18 provides a general assessment of the applicability of NCD. Major geomorphic factors that influence the determination of whether or not a stream warrants the need for NCD include degree of degradation, riparian corridor, availability of stabilization materials, existing pattern and infrastructure, belt width (width of consecutive outside meander bends) constraints, and flooding concerns. By evaluating a potential project site based on these factors, we can determine what priority of NCD may be most applicable, if any. Refer to Section 2.4 for Description of Priority 1 through 4 Restoration options.

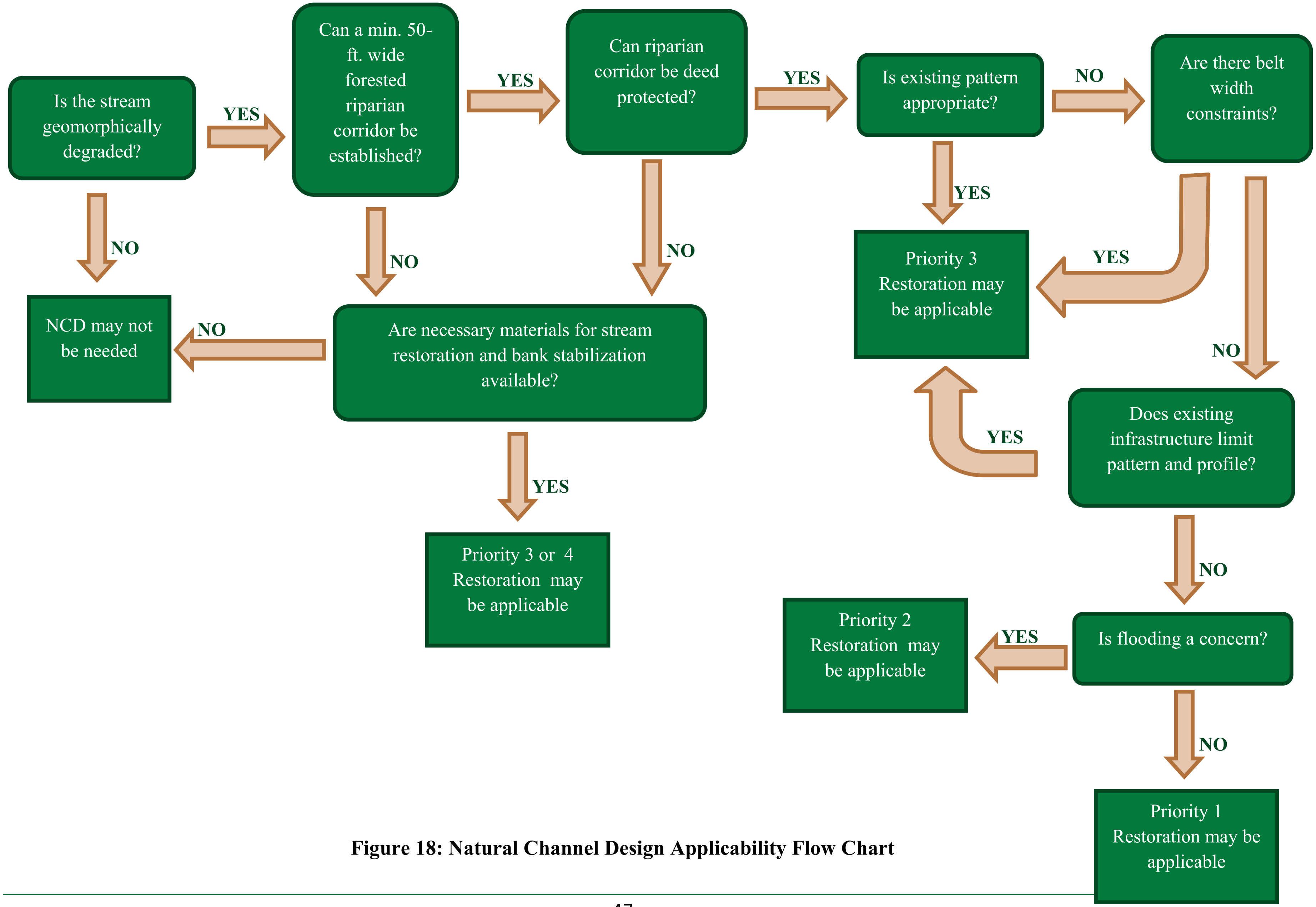

Figure 18: Natural Channel Design Applicability Flow Chart

5. Objective 2: How does NCD and traditional stormwater practices compare regarding ecological and water quality benefits?

In addition to conveying the sediment and water generated by its watershed, while maintaining dimension, pattern and profile (without aggradation or degradation), a stable stream supports healthy ecological characteristics similar to a natural stream. It is proposed that the only means to achieve effective and sustainable riverine systems in U.S. urban/suburban settings is to move towards a new design goal, one that strives for such stable, naturalistic channels that can accommodate virtually any combination of sediment and hydrologic loadings, boundary conditions, and site constraints.

As previously stated, traditional surface water channel management strategies in urban/suburban settings fail to accommodate natural stream processes, water quality goals, or sustainable aquatic ecosystems. The use of NCD methods in the management of these riverine systems as a primary BMP offers a sustainable solution that can accommodate the drainage and flood control needs of the community while also re-establishing a stable, naturalistic system towards the attainment of both water quality objectives and aquatic ecosystem restoration.

As noted by Sivirichi (2011), NCD techniques are increasingly used as a stormwater BMP to improve water quality in urbanized watersheds; however, minimal data exists to assess the effectiveness of NCD for these purposes. Browning (2008) found that less than ten-percent of NCD projects are monitored post-construction. Additionally, only minimal data on watershed-wide restoration projects is available. Instead, most studies involved restoration within only small portions of the overall watershed.

With traditional BMPs and LID (Green Infrastructure) techniques, it is expected that each structural BMP may treat only a small drainage area with regards to water quality and pollutant removal. For example, bioretention may need to be employed at a rate of four- to ten-percent of the contributing drainage area to achieve expected reduction rates. While a single bioretention cell is not expected to significantly affect water quality within the overall watershed, watershed-wide implementation of Green Infrastructure may significantly and positively impact water quality and pollutant concentrations. Similarly, a small segment of stream restored with NCD is not expected to significantly affect water quality within the overall watershed. However, watershed-scale stream restoration is expected to have a significant impact on water quality and pollutant concentrations. Additionally, it is likely that NCD may be needed to fully achieve watershed TMDLs and restoration as part of MS4 permits.

A literature review (see Section 5.3) revealed the majority of the recent and relevant research is focused on nutrients (nitrogen and phosphorous), dissolved oxygen (DO), dissolved suspended solids (DSS), and to a lesser extent total suspended solids (TSS). Many studies focused on two or more of these commonly studied pollutants. A few recent studies discussed in Section 5.3 were found on bacteria (i.e., fecal coliform), whereas minimal studies were found for metals, chloride, pesticides, and other pollutants.

Water quality performance of NCD for this study focused on nutrients, TSS, and bacteria for this study as more studies were found on these pollutants than other pollutants. Additionally, these are pollutants that commonly have established Total Maximum Daily Loads (TMDL)s in the major metropolitan areas in the State of Texas. Additionally, a number of studies were found regarding the ecological benefits of NCD with regard to improved habitat for wildlife, fish, and benthic macroinvertebrates.

5.1. TMDLs in Texas Metropolitan Areas

The most common TMDL requirements for streams in Texas' metropolitan areas (Houston, Austin, Dallas-Fort Worth, and San Antonio) are TSS and bacteria. A comprehensive list of TMDLs pending and currently in-place for streams in Texas were determined from discussions with the Texas Commission on Environmental Quality (TCEQ) and obtained from the following pages on the TCEQ's website:

- http://www.tceq.texas.gov/waterquality/tmdl/nav/tmdlcounties.html
- http://www.tceq.texas.gov/waterquality/tmdl/nav/tmdlsegments

Table 9 lists the pollutants for which there are TMDLs or pending TMDLs for each major metropolitan area. Actual TMDLs for specific counties and streams should be determined from the referenced website.

Table 9: TMDLS in Major Metropolitan Areas in Texas

Pollutant	Austin	Dallas – Fort Worth	Houston	San Antonio
Bacteria	●	●	●	●
Chlordane in fish tissue		●	●	
Chlordane, DDE, Dieldrin, and PCBs in fish tissue		●		
Chlordane, Dieldrin, DDE, DDT, Heptachlor Epoxide, and PCBs in fish tissue		●		
Chloride	●	●	●	
Dichloroethane in fish tissue			●	
Dioxin			●	
Dissolved Oxygen (DO) [1]	●	●		●
Nickel			●	
Polychlorinated biphenyls (PCBs) in fish tissue			●	
Sulfate	●			
Total Dissolved Solids (TDS)	●		●	
Trichloroethane in fish and crab tissue			●	
Zinc			●	

Table Notes: [1]Pending for Dallas-Fort Worth, but underlying study results may be questionable according to referenced TCEQ website.

5.2. Processes or Mechanisms of Removal

As with traditional structural stormwater BMPs and the newer suite of LID BMPs, pollutant removal within restored stream segments occurs via various processes including: physical, chemical, and biological. Physical processes include filtering of sediment and pollutants, such as metals, absorbed to the sediment. Degradation of fecal coliform bacteria also occurs by drying out and exposure to ultraviolet (UV) light from sun exposure. Biological processes include bioremediation and biodegradation. For example, hydrocarbons may be broken down with soil microorganisms.

Another biological process is phytoremediation, or pollutant removal by plants. This includes: pollutant uptake into and bioaccumulation within the plants, release of some pollutants from plants into the atmosphere, and breakdown of pollutants at the soil-plant root interface. For the latter process, mycorrhizal fungi play an important role by attaching to the roots and extending microfilaments into the soil, which significantly increases the functional surface area of plant roots. Because native, or indigenous, plants have evolved to the unique microclimate of an area and typically have deeper roots and greater levels of mycorrhizal fungi, incorporating these elements into NCD and other stormwater BMPs may represent an increased opportunity for carbon sequestration in mitigating climate change.

5.3. Pollutant Removal Performance

Articles and publications containing both published and unpublished data on removal of nutrients, TSS and bacteria were reviewed. Some publications contained data on removal of more than one pollutant. Findings for each pollutant removal are discussed separately under each subsection below.

5.3.1. Nutrients

A more substantial volume of research was found on the performance of NCD with regards to nutrient removal than with other common stormwater pollutants. From the literature review, NCD has been shown to remove nutrients (nitrogen [N] and phosphorous [P]). Nutrient loading and removal rates typically vary depending on the urbanization of the watershed as well as point and non-point source pollutants. Nitrate (NO_3) and N production and removal in sediments was reported by Mayer (2005) to be higher in suburban streams than forested streams due to higher NO_3 loading, which results in increased denitrification.

Kaushal (2008) reported that stream restoration projects designed to ‘‘reconnect’’ stream channels with floodplains in the Chesapeake Bay can increase denitrification rates. Additionally, there is substantial variability in the efficacy of stream restoration designs and additional study is recommended to identify designs most effective in conjunction with watershed strategies to reduce NO3-N sources to streams.

Shields (2009) found significantly higher concentrations of Total Phosphorous (TP) and Total Kjeldahl N in an incised as compared to a non-incised urbanizing stream, while NO3 was significantly higher in the non-incised urbanizing stream ($p \leq 0.02$).

Browning (2008) reported reductions in NO_3-N and Ammonia (NH_4)-N of 39-percent and 44-percent, respectively. Additionally, Filoso and Palmer (2009) reported reductions in Total N

(TN) of 20-percent and higher, although indicating that additional efforts beyond stream restoration may be required to achieve water quality goals and that monitoring is needed to advance the performance of NCD for water quality and pollutant removal.

A 2009 study by Filoso found that step-pools and in-stream wetlands are significantly more effective at reducing N loads than traditional channel design or restoration with older techniques. Additional research and guidelines to tie restoration designs to physiographic region was recommended.

Monitoring of three restored stream reaches was performed bimonthly between October, 2007 and April, 2008 during baseflow conditions (Browning, 2008). The restored reaches encompassed three design approaches to NCD: 1) "hard" structural design, 2) "soft" bioengineering design, 3) and "seepage wetland" design. The author's concluded that all restored urban streams have the potential to improve water quality, as demonstrated by statistically significant differences between upstream and downstream concentrations for NO3-N and DO in all three streams. Additionally, the "seepage wetland" design achieved a greater percent removal of NO_3-N than the other two approaches.

A 2010 study by Brown about Regenerative Stormwater Conveyance (RSC) systems in Anne Arundel County, Maryland contains unpublished data that indicates these systems perform similar to swales, infiltration, filtering, and wetlands with regards to nutrients removal. RSC systems include multiple components of NCD and consist of open channel sections with a series of shallow aquatic pools, riffle-weir grade controls, native vegetation, and an underlying carbon rich sand filter layer for groundwater infiltration. These systems are designed to meet both water quality and conveyance objectives.

Doyle (2003) reported greater variability in P retention related to biochemical uptake rates than in hydrogeomorphology and suggested that maintaining or restoring channel conditions conducive to biochemical uptake are of greater priority than restoration of hydrologic or geomorphic conditions with regards to P retention.

An integrated stream and wetlands restoration project in Upper Sandy Creek, a headwater stream for the Cape Fear River in the North Carolina Piedmont, resulted in reductions in nutrients in an impaired stream due to enhancement of the stream-wetland connection and restoration of groundwater wetland hydrology. Stormwater event nutrient budgets indicated a substantial attenuation of N and P associated with the project. The (NO_2^- and NO_3^-)-N loads were reduced by 64% and P loads were reduced by 28% (Richardson, 2011).

In a study of the Baleares Creek by Macedo (2008), in Belo Horizonte, Brazil, a significant improvement in the physical-chemical and bacteriological parameters was observed due to stream restoration. Nutrient concentrations in the stream improved as follows: TN declined from over 40 mg/L to less than 0.05 mg/L and TP declined from over 3 mg/L to less than 0.15 mg/L.

As noted in several agricultural extension publications from North Carolina State University, Yamhill County, Oregon, and Pennsylvania State (2011), riparian buffers (strips of vegetation adjacent to rivers and streams) filter stormwater runoff flowing overland through the buffers thus reducing nutrients. While the performance may vary significantly based on the design of the buffer, removal rates of up to 60% may be achieved as reported by the Potomac Conservation. Study results typically indicate N and P removal rates ranging from 50% to 80% (U.S. EPA, 1993). Additionally, diverting runoff that is high in inorganic nutrients through the riparian areas instead of directly into streams could remove a large amount of nutrients before they reached the stream.

Andrews (2011) found that stream restoration at Wilson Creek reduced NO3 and N levels in the stream. The authors believe that reconnecting the stream to its floodplain was a major factor that contributed to improved water quality and enhanced nutrient processing.

It is generally understood that anaerobic conditions and a carbon source are required for dentrificaton and removal of NO_3- N to occur. Several NCD researchers and practitioners are investigating burying woody debris within the stream bottom to serve as a carbon source to speed-up the dentrification process.

Dosskey (2010) evaluated root biomass, organic matter levels, and denitrification potential in a series of degraded, restored, and control riparian zones in Baltimore, Maryland. The author reported that establishment of organic matter–based nutrient cycling may be particularly slow in urban riparian restorations due to importing low-carbon substrates to physically stabilize the stream and/or cutting of stream banks to remediate stream incision that exposes carbon-poor subsoils. These findings appear to support the inclusion of carbon sources, such as woody debris, to enhance denitrification.

Additionally, Davis (2009) recommends incorporating wood chips as a carbon source into bioretention systems that include an elevated underdrain, which creates anaerobic conditions and improves hydrologic performance, in an effort to enhance denitrification. According to a 2010 study by Brown, unpublished data indicates a reduction in sediment load from RSC systems in Anne Arundel County, Maryland. As described previously, RSC systems incorporate multiple components of NCD and include an underlying carbon rich sand layer.

5.3.2. Total Suspended Solids (TSS)

Based on the results of the literature review, NCD has generally been shown to remove TSS. While standard values of percent removal associated with NCD were not reported, specific studies and case studies did yield reductions in sediment in the receiving streams for some systems. Based on limited research, it appears that integrating wetlands into the NCD design as well as including riparian buffers provides increased sediment removal.

In addition to the nutrient removal findings in the Browning 2008 study, a 38% reduction in TSS was demonstrated through the "seepage wetland" design, whereas the other two designs showed increased TSS for this limited monitoring period.

Richardson (2011) also reported reductions in sediment load in the impaired stream due to enhancement of the stream-wetland connection and restoration of groundwater wetland hydrology. Sediment retention in the stormwater reservoir and riparian wetlands showed accretion rates of 1.8 cm/year and 1.1 cm/year, respectively, and annual sediment retention was nearly 500 metric tons/year.

The 2010 study by Brown also contained unpublished data indicating a reduction in sediment load from RSC systems in Anne Arundel County, Maryland.

Similarly to what was reported for nutrients, riparian buffers also help reduce erosion and filtering of sediments in stormwater runoff. (North Carolina State University, Pennsylvania State [2011], and Yamhill County, Oregon).

While most sources indicate significantly lower removal rates ranging from 50% to 80% (U.S. EPA, 1993) for vegetative filter strips and riparian buffers, TSS removal rates up to 85% are reported for vegetative filter systems following design procedures outlined in the Edwards Aquifer Technical Guidance Manual.

5.3.3. Bacteria

While the body of scientific research is less substantial and results are somewhat less conclusive than for nutrients, NCD generally performs well for bacteria (i.e., fecal coliform) removal.

A 2006 study by Struck confirmed that, for the studied stream, a good predictive relationship can be made between turbidity and E. coli concentrations. Thus, the reported reductions in sediment discussed above, tend to support the idea that NCD also reduces bacterial loads. Additionally, Brown (2010) also reported a reduction in bacterial loads between upstream and downstream sections in RSC systems in Anne Arundel County, Maryland.

As reported by the Potomac Conservation, pathogenic bacteria removal rates are typically less than or may approach 30% (U.S. EPA, 1993). Additionally, riparian buffers used in conjunction with NCD are reported to deter wildlife from entering streams, which reduces fecal coliform bacteria in the water.

In his study of the Baleares Creek, Macedo (2008) reported a significant improvement in the physical-chemical and bacteriological parameters due to stream restoration. Results of this study indicated that the level of thermotolerant coliform values dropped sharply from over 24,000 MPN to nearly zero from pre-restoration to post-restoration.

In addition to nutrient and TSS reductions previously discussed above, Richardson (2011) also observed reductions in coliform bacteria in an impaired stream due to enhancement of the stream-wetland connection and restoration of groundwater wetland hydrology.

Within Texas, a recent City of Austin study (Austin, 2011) found reductions in fecal load in the Lower Bull Creek after riparian improvements were constructed. It is important to note that this study did not include controls or isolated various BMPs implemented within the watershed. While a quantitative analysis was not performed, the reduction in bacterial loading was attributed to a variety of BMPs, including: public education, supposed reduction in bacteria from dog feces due to on-leash requirements, and the constructed riparian improvements. Although point and non-point source loading was reduced through non-structural BMPs, sediment removal due to scouring during Tropical Storm Hermine was also thought to play a significant role in the reduced loading in the stream.

5.4. Ecological Considerations

As with water quality, larger-scale restoration projects that rehabilitate longer stream lengths are expected to provide increased ecological benefits due to connectivity. While historically not considered a major component of stormwater management and flood control projects, the shift in emphasis to the "Triple Bottom Line" approach that considers the economic, social, and ecological benefits and impacts of projects is anticipated to further support NCD as an important 21st Century ecological/habitat restoration tool. Some ecological considerations associated with NCD techniques are discussed below.

5.4.1. Riffle/Run/Pool/Glide and Fish Habitat

A typical natural stream system has a variety of bed forms including riffles, runs, pools and glides. Each of these bed forms are important to the overall ecological health of the stream system and serve a variety of natural functions. Riffles are important habitat for macroinvertebrates and also serve as the hydraulic control of a stream system. Riffles are the shallowest feature of a stream system and have steeper water surface slopes during low flow. The water surface slope in a riffle flattens as the stream reaches the bankfull stage. The steeper slope through a riffle at low flow also helps to promote aeration of the water.

Pools are critical habitat for fisheries. They are the deepest sections of a river and have the flattest water surface slopes during low flow. Pools have a tremendous impact on the water temperature of a stream system, and the presence of pools can significantly decrease water temperatures relative to a more monostructure stream system. Lower water temperatures in turn help to increase biological activity in a stream system.

Runs and glides serves as the transitions between riffles and pools in a natural stream system. These features help to dissipate energy in a river system and provide critical habitat for a variety of aquatic organisms. Runs are also important spawning habitat for a number of fish species.

Slaney (1997) noted that rehabilitation of off-channel fish habitat, including creation of channel-pond complexes, is one of the primary techniques to offset habitat degradation in hydrologically unstable or non-functional stream channels within logged floodplains.

Roni (2002) recommended that restoration focus on reconnecting isolated high-quality fish habitats, such as in-stream or off-channel habitats made inaccessible by culverts or other artificial obstructions. Once the connectivity of habitats within a basin has been restored, efforts should focus on restoring hydrologic, geologic (sediment delivery and routing), and riparian processes through road decommissioning and maintenance, exclusion of livestock, and restoration of riparian areas. In-stream habitat enhancement (e.g., additions of wood, boulders, or nutrients) should be employed after restoring natural processes or where short-term improvements in habitat are needed (e.g., habitat for endangered species).

Because fish depend on good aquatic habitat, a stream without a riparian buffer is not likely to support good fish populations. Lack of riparian buffers or poor quality riparian buffers can result in excess erosion and runoff. Fine sediments then damage fish populations by clogging gills and smothering spawning sites for fish and aquatic insects. As the ecological conditions of a stream declines, populations of fish that are more tolerant of poor conditions (i.e., catfish and carp) start to increase, while populations of fish that are less tolerant (i.e., trout) begin to decline and the ecological balance is disturbed.

In a 2011 study, Johnson reported on physical, chemical, and biological attributes of forested and non-forested sections of 12 streams with different levels of watershed development. As with the water quality findings, preliminary results show lower fish populations in non-forested stream reaches as compared to forested stream reaches for all levels of watershed development. No significant differences in species composition were found between forested and non-forested reaches; however, differences in occurrence of several species were noted along the urbanization gradient. While a slight increase in species variety was found in forested reaches as compared to non-forested reaches, there was no significant difference with increased watershed urbanization.

Shields (2009) found that physical aquatic habitat and fish populations in non-incised urbanizing streams were superior to those in incised streams. The non-incised streams supported almost twice as many species and yielded more than four times as much biomass per unit of effort. The authors suggest that channel incision is associated with a complex of ecological stressors that includes channel erosion, hydrologic perturbation, and water quality and physical habitat degradation. As part of the findings, the authors recommend that stream restoration equally weight managing habitat quality, mediating hydrologic perturbations, and water quality benefits.

5.4.2. Macroinvertebrates

Benthic macroinvertebrates serve as valuable indicator organisms for water quality studies. Macroinvertebrates are organisms without a backbone and benthic refers to organisms living on the bottom of a body of water or within the bottom sediment.

In a study of 12 streams with different levels of urban development within their watersheds and including forested and non-forested reaches, Johnson (2011) found that both benthic algae and benthic macroinvertebrates had higher diversity values and lower percent dominance values in forested reaches as opposed to non-forested or open reaches. Preliminary results suggest that macroinvertebrate diversity is slightly greater in forested reaches due to the greater diversity of microhabitats. Additionally, the species of macrovinvertebrates is affected by watershed urbanization.

As reported by Pennsylvania State (2011) and Yamill Country, macroinvertebretes in a stream system benefit from food source found in organic materials (leaves and woody debris) present within stream buffers.

The results of a study in Fairfax, Virginia (Selvakumar, 2010) indicated that stream restoration alone had little effect in improving the conditions of in-stream water quality and biological habitat, though it has lessened further degradation of stream banks in critical areas where the properties were at risk. Control of storm-water flows by placing BMPs throughout the watershed to reduce and delay discharge to the stream may ultimately improve habitat and water quality conditions to a greater degree. These findings seem to promote the use of riparian buffers and LID throughout the watershed in conjunction with NCD in order to improve habitat and biological activities.

Hines (2007) speculated and Dosskey (2010) found that design improvements, such as adding large boulders in the pool, could be beneficial as habitat for macroinvertebrates. Additionally, diverting runoff that is high in inorganic nutrients through the riparian areas instead of directly into streams could remove a large amount of nutrients before they reached the stream.

5.4.3. Riparian Wildlife Habitat and Corridor

As reported by several agricultural extensions (Pennsylvania, 2011, North Carolina State University, and Yamhill County), riparian buffers improve food, water, shelter, and breeding habitat for mammals (deer, rabbit, mice, etc.), birds (quail, migratory songbirds, etc.), amphibians (i.e., frogs), and reptiles (snakes). In addition to providing food and cover, riparian buffers serve as a wildlife corridor, or travel way, for a variety of wildlife.

Organic materials and debris within riparian buffers provide a food source for aquatic invertebrates, which provide food for wildlife. While the specific species in riparian habitats depends largely on the type and size of the water source (wetland, river, stream, lake, or pond), the habitat within the riparian buffer (i.e., diversity of tree species, availability of nest and perch sites, frequency of flooding, etc.) also plays a significant role (Pennsylvania, 2011).

Evans (2007) reported benefits in water quality and wildlife habitat enhancement associated with NCD practice, despite the need for two to three times more land area than traditional channel design.

After channel improvements and a drop structure were constructed on Segment 15 of the South Platte River to remove a backwater pond and provide re-aeration of flow, a previously unseen large population of tadpoles was noted in off-channel areas (Brooks, 1998). Increased DO levels were also measured as a result of the stream restoration improvements.

6. Objective 3: What is the difference in cost between NCD and more traditional stormwater conveyance projects?

6.1. Cost Comparison of Channel Management Options

A comparison of the difference in cost between NCD and more traditional stormwater conveyance projects requires a clear understanding that both approaches include the application of a broad spectrum of channel improvements, with an equally broad range of costs and benefits. All applied channel improvement options, whether using traditional or NCD methodologies, are focused on stabilization of a channel that is failing through excessive bed and/or bank erosion.

Table 10 below, summarizes general advantages and disadvantages of the four priority channel management options originally outlined by Rosgen and later included in the NCSRI's *Stream Restoration: A Natural Channel Design Handbook* (Doll et al., 2003), previously discussed in Section 2.4.

Table 10: Advantages and Disadvantages of Restoration Options for Incised Streams

Option	Advantages	Disadvantages
1	Results in long-term stable stream Restores optimal habitat values Enhances wetlands by raising water table Minimal excavation required	Increases flooding potential Requires wide stream corridor Unbalanced cut/fill May disturb existing vegetation
2	Results in long-term stable stream Improves habitat values Enhances wetlands in stream corridor. May decrease flooding potential	Requires wide stream corridor Requires extensive excavation May disturb existing vegetation Possible imbalance in cut/fill
3	Results in moderately stable stream Improves habitat values May decrease flooding potential Maintains narrow stream corridor	May disturb existing vegetation Does not enhance riparian wetlands Requires structural stabilization measures May require maintenance
4	May stabilize streambanks Maintains narrow stream corridor May not disturb existing vegetation	Does not reduce shear stress May not improve habitat values May require costly structural measures May require maintenance

Table 11 below presents the spectrum of priority options and sub-options, organized to show that Priority 1 improvements will generally be anticipated to provide a higher level of overall stream function than the other options.

Table 11: Overall Stream Function Improvement by Restoration Options

Decreasing Functional Lift → → → → → → → → → → → → → →				
Priority 1	**Priority 2**	**Priority 3**		
Restore Dimension, Pattern & Profile at Historical Floodplain Elevation	Restore Dimension, Pattern & Profile Excavate Bankfull Bench at Present Elevation	Bankfull Bench Excavation, Grade Controls, Bank Stabilization & Dimension **AND** Profile Restoration	Bankfull Bench Excavation, Grade Controls, Bank Stabilization & Dimension **OR** Profile Restoration	Bankfull Bench Excavation, Grade Controls & Bank Stabilization
Decreasing Functional Lift → → → → → → → → → → → → → →				
Priority 4				
Bioengineering Stabilization of One or Both Banks	Riprap Stabilization of One or Both Banks	Monolithic Concrete Stabilization of One or Both Banks	Riprap Stabilization of Entire Channel	Monolithic Concrete Stabilization of Entire Channel

Priority 1 and Priority 2 projects are fairly consistent, respectively, in their applicability and costs as they both include complete restoration of dimension, pattern, and profile with a new stream channel. Priority 3 and 4 projects, however, include a broad range of prescriptions and costs. Priority 3 projects may or may not include restoration of dimension and/or profile, both of which involve additional earthwork and in-stream structures and both of which provide additional functional lift. As described in Section 2.4, Priority 4 projects can range from stabilization/armoring of a single bank, both banks, or both banks and the channel bed. Also, the stabilization prescriptions can range from bioengineering methods, riprap, or monolithic concrete, which vary significantly in price and in the level of functional lift achieved.

Stream restoration projects, whether Priority 1, 2, 3, or 4, are linear projects and cost comparisons between projects are typically presented as costs per linear foot (lf) of channel restored. This convention is helpful in evaluating the different cost factors between two or more projects. Such per foot costs, however, can be deceiving, because they do not take into account the scale of a project from the perspective of channel size. A more appropriate cost convention for stream restoration projects would be to present costs in terms of the linear footage of the project and the capacity of the channel, which is best represented, especially for natural channels, by the drainage area of the project reach in square miles or acres. Drainage areas of channel projects are typically known, since they are required to perform the hydrologic and hydraulic analysis necessary to develop channel restoration designs.

The smallest intermittent and perennial streams in a typical watershed reviewed during this study are 2nd and 3rd order streams, where stream order is qualitatively related to drainage area. In the authors' collective experience, the majority of Priority 1 and 2 projects have been implemented on 2nd and 3rd order streams. Most CWA Section 404 stream mitigation guidelines give preference to restoration of intermittent and perennial streams and seldom do these guidelines allow additional credit for the capacity of the stream. Since larger capacity streams cost more to restore, most CWA Section 404 stream mitigation projects focus on the smallest intermittent and perennial streams within a given watershed. As such, this study will attempt to present restoration costs for 2nd and 3rd order channels for comparison purposes, wherever possible.

The primary cost factors of implementing a stream restoration project are the same for projects using NCD methods or traditional stormwater conveyance methods. These include costs associated with acquisition of right-of-way (ROW)/easement for construction, design, permitting, construction, and maintenance. Where stream restoration is implemented to generate ecosystem impact offset mitigation credits, such as CWA Section 404 projects, as discussed in Section 2.7, additional costs are incurred for a period of monitoring and perpetual stewardship. However, the focus of this study is a comparison of the use of NCD methods as an alternative to traditional stormwater conveyance prescriptions, where no such monitoring or perpetual stewardship would be required. Monitoring and perpetual stewardship, therefore, are not included as cost factors here. Likewise, the level of effort and associated costs to obtain environmental and construction permits do not vary across the spectrum of channel restoration prescriptions, and, as such, are not included as cost factors in this study.

6.1.1. Right-of-Way/Easement Acquisition

The literature review did not identify any papers where quantitative values of ROW/easement costs of NCD projects were evaluated in comparison to traditional stormwater conveyance projects, as is the focus here. Templeton et al. (2009) documented the total costs for such acquisition by North Carolina's Department of the Environment and Natural Resources (NC DENR) through their Ecosystem Enhancement Program (EEP) and its predecessor, the Wetlands Restoration Program. The EEP is responsible for CWA Section 404 stream mitigation in North Carolina through a state-wide in-lieu-fee program. The study examined costs for stream restoration projects implemented by the program from its inception, in 1997, through 2006, during which time the EEP had spent or committed to spend $46.34 million for 45 design-build or design-bid-build projects to restore or enhance 191,374 ft of streams. Although the study presented mean, maximum, and minimum costs per project for ROW/easement acquisition, it did not relate these costs to the footage of stream length restored. Such costs could likely be developed using the acquisition cost data available at the State Property Office in the North Carolina Department of Administration (Templeton et al., 2009) and the EEP's annual reports. However, for reasons described here, the results of such analysis would not be relevant to this study. As described by Templeton et al. (2009), EEP usually does not purchase land or conservation easements in urban and suburban areas, which is the focus of this TWDB study. Most of the ROW/easements acquired for EEP projects are on rural farmland with a small stream. In addition, the land or easements are often owned by another government agency and acquired through a non-financial agreement.

We can, however, qualitatively evaluate ROW/easement costs by looking at what additional lands would be required for typical Priority 1, 2, 3, and 4 projects on a hypothetical project reach (Table 12). Let us assume that a ROW or easement already exists on the hypothetical project reach, that it runs parallel to the existing stream channel, and that its width includes the channel width plus a setback on both banks that will likewise be required for the restored channel. Under these conditions, the following can be concluded:

- A Priority 1 project would require a relatively large acquisition of additional ROW/easement because the new ROW or easement would generally have to accommodate the existing channel, which will be converted to a series of oxbow wetlands, the new channel, and land between the two channels (Figure 4).
- A Priority 2 project typically would require slightly more additional ROW/easement than a Priority 1 project because it would have the same need to accommodate the abandoned channel, the new channel, and land between them, but, because the new floodplain is established at a new lower elevation, additional ROW or easement will be required to accommodate the new, sloped valley walls (Figure 5).
- A typical Priority 3 project would require significantly less ROW or easement. The only additional easement required would be additional width to excavate small bankfull floodplain benches at a new, lower elevation plus additional ROW or easement to accommodate the new, sloped valley walls (Figure 6).
- A Priority 4 project would require the least, and in many cases, no additional ROW or easement since it involves only stabilization of the banks in their current location.

6.1.2. Design and Total Construction Costs

Design and total construction costs for stream restoration projects are available in the literature. Texas-specific costs for Houston, San Antonio and the Austin markets were obtained, respectively, from the Harris County Flood Control District, the San Antonio River Authority, and the City of Austin Watershed Protection Department's Stream Restoration Program (refer to Section 3.2).

Templeton et al. (2009) reported that the EEP had spent or committed to spend $46.34 million for 4 design-build and 41 design-bid-build projects from 1997 through 2006. These projects resulted in the restoration or enhancement 191,374 ft of streams, ranging from 1,400 to 13,000 lf, with an average length of 4,253 feet. The projects had the following characteristics:

- Priority 1 and 2 projects constituted 166,053 ft of streams (87%)
- Priority 3 projects that included restoration of both dimension and profile constituted 16,623 ft of streams (8.5%). Priority 3 projects that did not restore both dimension and profile constituted 8,698 ft of streams (4.5%).
- Twenty projects in this study totaling 64,347 ft were in urban settings and the other 25, totaling 127,027 ft, were in rural settings. Fifteen of the 25 urban projects were in parks or golf courses and one of the rural projects was at a golf course.
- The total costs per linear foot (including project administration, property rights acquisition, pre-construction engineering, construction management, monitoring, maintenance, and perpetual stewardship) in 2006 dollars were $242 for all projects, $285 for urban projects, and $220 for rural ones.
- The average design cost for all projects was 14.3% of total costs.

Assuming the design costs for 13% of the projects that were Priority 3 did not significantly skew this number and that design costs for Priority 1 and 2 projects are not significantly different from one another, based on the extensive personal design experience of the investigators of this TWDB study, we can estimate the EEP average design costs, in 2006 dollars, for both Priority 1 and 2 projects. Applying the average design percentage of costs to the average total costs for all 45 projects ($242/lf), an average design cost of $34.60/ft is estimated for Priority 1 and 2 projects.

Although neither Templeton et al. (2009) nor the EEP itself, in its 2004 - 2005 Annual Report (2005) used for the study, distinguish costs between Priority 1 and Priority 2 projects, we can make an assumption that urban projects were Priority 2 and rural projects were Priority 1. Rural projects typically do not have flood zone restrictions/concerns, allowing for the preferred and less expensive Priority 1 options. Urban projects are more likely to be Priority 2 because they can be completed without raising regulatory flood elevations.

The average design cost for all projects was 14.3% of total costs. Applying the average design percentage of costs to the average total costs for urban projects results in an average design cost of $40.64/ft for Priority 2 projects. Similarly, applying the average design percentage of costs to the average total costs for rural projects results in an average design cost of $31.46/ft for Priority 1 projects.

Bonham and Stephenson (2004) looked at the costs of 14 completed or nearly completed projects in North Carolina (9), Virginia (4) and Kentucky (1) prior to 2003. Twelve of the projects are considered in-kind projects centered on stream restoration and enhancement. Two of the Virginia projects were representative of out-of-kind mitigation involving the amelioration of acid mine drainage from abandoned mine land, and are not included in the data presented here. The study broke the costs out by the lengths of the project (less than 3,001 lf, 3,001 to 10,000 lf, and greater than 10,000 lf) and found that all cost factors decreased on a per foot basis as the projects got larger. The authors posted that per foot costs may be affected by project size because each project contains fixed costs imbedded in each expense component for which economies of scale can be realized. Actual design costs were only available for the North Carolina projects, design costs for the Virginia and Kentucky projects were estimated by agency personnel as a percentage of construction costs. As such, the actual design costs used in this study would have been captured in the Templeton et al. study (2009).

The design costs reported by Bonham and Stephenson (2004) were, in 2002 dollars, $26.14/lf (< 3,001 lf), $21.25/lf (3,001 to 10,000 lf), and $13.04/lf (>10,000 lf). The study did not provide the restoration priority option implemented in the projects, but it is assumed that those were Priority 1 and 2 projects, since these projects are preferred and dominate in compensatory mitigation projects and because 9 of the 12 in-kind projects evaluated were North Carolina projects, which Templeton et al. (2009) documented included 87% Priority 1 and 2 projects.

As presented in Section 3, the SARA provided cost data on the East Salitrillo Priority 3 project. The total construction cost was $249/lf and design costs were $62/lf. The City of Austin has implemented several stream restoration projects which may be categorized as Priority 4 with application of bioengineering or NCD features. Their projects averaged $1,136/ linear foot in construction costs and $246/lf in design costs. The City of Grand Prairie project was Priority 4 with NCD features and the total construction cost was approximately $200/lf.

For the Houston area, the HCFCD provided cost data for various stream restoration projects implemented since 2002 and data was also obtained from private sector projects implemented by the Houston Country Club and River Oaks Country Club. Houston Priority 3 projects averaged $703/lf in total construction costs and $146/lf in design costs. Some of the Priority 3 projects included work completed on major, stream order 4 or greater streams such as Cypress Creek and Buffalo Bayou in highly urbanized areas of Houston. Construction cost for Houston Priority 4 projects averaged 1,121/lf and design costs averaged $226/lf.

Table 12 provides a spectrum of costs by category for the stream restoration projects evaluated during this study. It also breaks down individual cost factors, where available.

Table 12: Costs for the Spectrum of Stream Restoration Options

COST FACTOR/ SOURCE	AVERAGE COSTS			
	Priority 1	Priority 2	Priority 3	Priority 4
Right-of-Way/ Easement Acquisition	High	High to Very High	Low	Very Low to None
Design (D) and/or Total Construction (TC)				
NC EEP (Templeton et al., 2009)	D: $34.60/lf (estimated, 2006 dollars) TC: $242/lf		NA	
NC DENR (Bonham and Stephenson, 2004)	D: $26.14/lf (< 3,001 lf) D: $21.25/lf (3,001 to 10,000 lf) D: $13.04/lf (>10,000 lf) (2002 dollars)		NA	
East Salitrillo Project (SARA)	NA		D: $62/lf TC: $249/lf	
City of Austin Projects	NA			D: $241/lf TC: $1,136/lf
HCFCD Projects	NA	NA	D: $146/lf TC: $703/lf	D: $226/lf TC: $1,121/lf
City of Grand Prairie	NA		NA	D: NA TC: $200/lf

Note: Average of Design and Total Construction costs for the Priority 3 HCFCD projects include work completed on major, greater than 2nd or 3rd order streams.

6.2. Direct Comparison of Costs

Applying a direct comparison of costs between traditional and NCD methods requires that the data be sorted in accordance with stream order and priority improvements. Accordingly, the project data itemized within Section 3 and summarized in Table 12 above have been sorted for comparison and presented in Table 13 below. Summary charts showing cost comparison by project groups are further discussed below. Trend analysis charts for the available data collected during this study are included in Appendix D.

Table 13: Comparison Projects Sorted by Stream Order, Priority Improvement, and NCD or Traditional Designation and Features

Project Description	Location	Stream Order	Priority Type	NCD(1) or Traditional (2)	NCD Features? Yes(1) No(2)
Brays Bayou Federal Flood Control Project - Ardmore to Holcombe	Houston	4 or greater	4	2	2
Cypress Creek Spot Repair (x043)	Houston	4 or greater	4	2	2
Cypress Creek Spot Repair (x042) Fire Station	Houston	4 or greater	4	2	2
Buffalo Bayou @ Houston Country Club	Houston	4 or greater	4	2	2
Buffalo Bayou @ River Oaks Country Club	Houston	4 or greater	4	2	2
Cypress Creek - Myer Park-Phase 1	Houston	4 or greater	3	1	1
Cypress Creek - Myer Park-Phase 2	Houston	4 or greater	3	1	1
Buffalo Bayou - Sabine Street	Houston	4 or greater	3	1	1
Buffalo Bayou - Shepherd to Sabine	Houston	4 or greater	3	1	1
Buffalo Bayou - Memorial Park Demonstration Project	Houston	4 or greater	3	1	1
Rummel Creek - Edith L. Moore Nature Sanctuary	Houston	3 or less	4	2	1
Little Vince Bayou Channel Improvement - Cherrybrook Lane to Witchita St.	Houston	3 or less	4	2	2
Williamson Creek - Pack Saddle Pass Tributary	Austin	3 or less	4	2	2
Tannehill Branch Tributary Stabilization - Victoria	Austin	3 or less	4	2	2
Tannehill Branch Highland Park Cemetary	Austin	3 or less	4	2	2
Shoal Creek - 26th Channel Improvements	Austin	3 or less	4	2	2
SRP - Waller Creek Shipe Park Erosion Project	Austin	3 or less	4	2	2
SRP - Tannehill Branch Lower Bartholomew Park	Austin	3 or less	4	2	2
Goose Creek Channel Improvement Project - Baker Rd.	Houston	3 or less	4	2	2

Project Description	Location	Stream Order	Priority Type	NCD(1) or Traditional (2)	NCD Features? Yes(1) No(2)
Little Vince Bayou - Witchita Street to Pasadena Blvd.	Houston	3 or less	4	1	1
Mason Creek Extension	Houston	3 or less	4	1	1
Shoal Creek - Redgelea Bank Stabilization	Austin	3 or less	4	1	1
Fort Branch Reach 1 - Manor to Westminster	Austin	3 or less	4	1	1
Fort Branch - Manor Road Emergency Project	Austin	3 or less	4	1	1
Tannehill Branch - Manor Circle Emergency Bank Stabilization	Austin	3 or less	4	1	1
Shoal Creek - 5th Street Bridge Erosion Stabilization	Austin	3 or less	4	1	1
Shoal Creek - Northwest Park	Austin	3 or less	4	1	1
Little Walnut Creek - Loyola Lane Erosion Stabilization	Austin	3 or less	4	1	1
Shoal Creek Bank - West Ave. to 5th Street Stabilization	Austin	3 or less	4	1	1
Tannehill Branch Givens Park Streambank Stabilization	Austin	3 or less	4	1	1
Little Walnut Creek - Erosion Control Ph. 3 - Bridgewater Dr.	Austin	3 or less	4	1	1
Little Walnut Creek - Erosion Control Ph. 7 - Lakeside	Austin	3 or less	4	1	1
Kirby Creek	Grand Prairie	3 or less	4	1	1
Tributary to Big Gulch Bayou	Houston	3 or less	3	1	1
Vogel Creek- Arncliffe Dr. to White Oak Bayou	Houston	3 or less	3	1	1
East Salitrillo Creek	San Antonio	3 or less	3	1	1
Warren Creek Ph.I	Houston	1	1	1	1

6.2.1. NCD vs Traditional Costs for Stream Order 4 or Greater

A comparison was made with respect to construction costs and design costs between NCD (Priority 3) and Traditional methods (Priority 4). The trends indicated that the overall construction cost for both NCD and Traditional projects are less for shorter projects. As shown in Figure 19, the cost per linear foot however, for traditional projects was significantly higher than NCD for the longer projects, but less for shorter projects. The break point length was at approximately 1,250 lf. This trend for traditional projects was not consistent with the other categories compared. As shown in Figure 20, design as a percentage of construction trends higher for NCD and Traditional as the project length and corresponding construction costs decrease. Design percentage trends higher for NCD as compared to traditional methods.

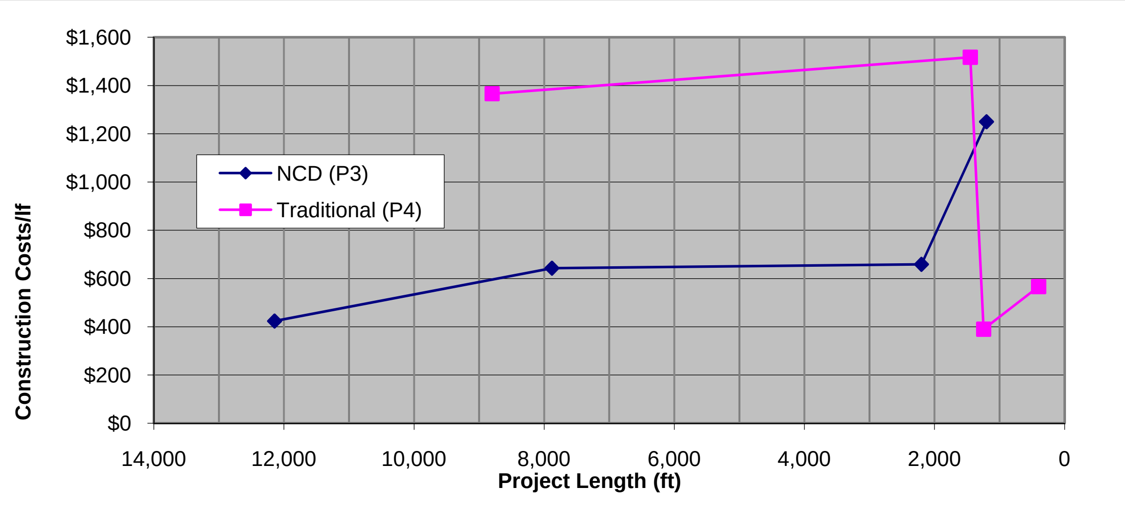

Figure 19: Construction Costs/lf NCD vs Traditional for Stream Order 4 or Greater

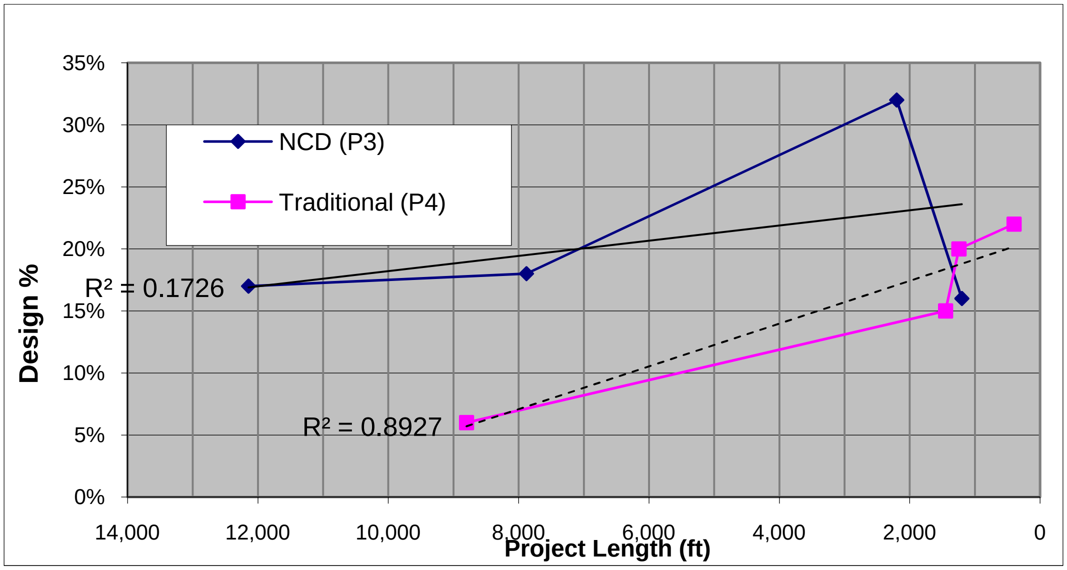

Figure 20: Design as % of Construction Costs NCD vs Traditional for Stream Order 4 or Greater

6.2.2. NCD Versus Traditional Cost for Stream Order 3 or Less

Under the category of Stream Order 3 or less, a cost comparison was made between Priority 4 projects utilizing solely traditional methods and Priority 4 projects containing NCD features. There was not enough data on Priority 3, Stream Order 3 projects to support comparison. As observed in analysis of Stream Order 4 Projects, the costs/lf for Stream Order 3 projects also tend to increase as the project length decreases. Figure 21 shows that cost for projects with NCD components trends higher than traditional construction with no apparent break point as observed previously. With respect to design percentage, there was not enough data to observe any trend.

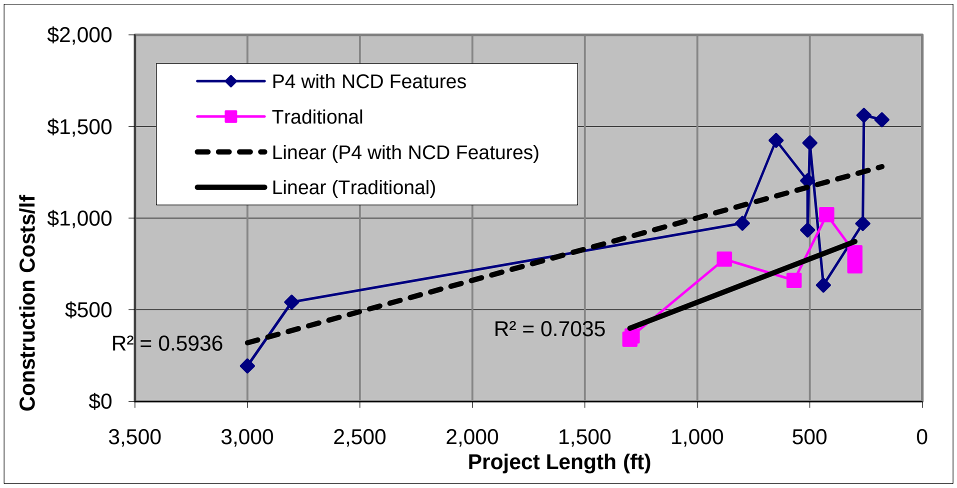

Figure 21: Construction Costs/lf NCD vs Traditional for Stream Order 3 or Less

6.2.3. NCD versus Traditional Methods Comparative Conclusions

It is apparent that the application of NCD follows the same general pattern for construction and design costs that traditional methods follow, with the possible exception of the cost per linear foot for traditional methods for the larger Priority 4 projects. The construction and design costs trends each gave indication that NCD is slightly more costly overall. The validity of these types of comparisons is based upon the ability to break the data into like groupings. Methodology utilized for this exercise is based upon stream order and priority. The development of a rich data set is imperative in order to develop cost curves that may be used to assist scientists, engineers and planners in the selection of appropriate design and construction methods.

Other parameters that may influence cost, additionally, need to be evaluated and considered. Life cycle cost as well as monetized environmental and quality of life factors can be considered as factors in determining the appropriate stream improvement technique. Some of the economic benefits as well as methods of quantifying some of these considerations are discussed in the subsequent sections.

6.3. Economic Benefits of NCD Projects

6.3.1. Economic Framework for Stream Restoration

Hurd (2009) describes that “within the economic framework of the United States, healthy watersheds are a public good. Everything else builds on this foundation.” Public goods have two defining characteristics. First, nobody can exclude others from their benefits. Second, additional people utilizing public goods cannot diminish the utility of others (Callan and Thomas 2004). A healthy watershed qualifies on both counts. These two characteristics make it difficult for public goods to be bought and sold on the open market. This is both an asset and a liability to watershed restoration. The benefits of restoration accrue to all people inhabiting a watershed.

However, little incentive exists for individuals to restore watersheds on their own, because no single person reaps all the rewards, though they could bear all the costs creating what may be considered "market failure". Market failures prevent the goods and services arising from watershed restoration from being bought and sold in traditional economic markets and cause people to misunderstand watershed restoration as an activity with no product. It is not that watershed restoration has no product. Healthy watersheds produce clear streams (and associated clean drinking water), healthy aquatic and terrestrial wildlife, and thriving forests (that among other things sequester carbon). Rather, few traditional markets exist for the products that watershed restoration produces. This usually forces collective action—such as government intervention—to provide for the societal demands for the public good (Ostrom 1991).

Public goods and market failures exist in many other public realms as well. For example, governments intervene in the provision of fire protection and street lighting, both of which are public goods. Fire protection provides important services to communities, as people value firefighting and the availability of that service. However, individuals do not provide fire protection on their own; no market for it exists—thus a market failure. Because of this, people come together, usually through government, to form fire protection services.

The same holds true for watershed restoration. However, the public does not always recognize the importance of the environmental goods and services provided by healthy watersheds (Cowling et al. 2007). Without this recognition, collective action and government mobilization become much more difficult.

6.3.2. Methods of Quantification of Economic Benefits of Stream Restoration Projects

As discussed in Section 6.1, the costs of NCD or stream restoration projects (Priority 1, 2, and 3) are typically higher than traditional stormwater conveyance projects (Priority 4). Such projects, therefore, typically require economic justification in order to gain support. The literature includes studies which provide enumeration of the economic benefits of such projects, often within the larger context of ecosystem restoration. However, restoration advocates face hurdles in justifying restoration on economic grounds due to the vague nature of nonmarket valuation of many of the benefits, long timescales required for achieving a positive return on investment in certain restoration projects, and unknown incremental benefits of watershed restoration in increasing the natural amenity qualities of communities (Hurd, 2009).

Most NCD projects include restoration of the adjacent riparian buffer corridor. These restored riparian corridors provide significant economic benefits through their air and water quality pollution reductions, improved aesthetics and quality of life benefits, increased home prices, and increased recreational values. Recreational values are especially increased where greenway trails are installed within the riparian corridor, which is very common on Priority 1, 2, and 3 projects. As such, for the purposes of this study, the economic benefits of riparian corridor restoration are included in the discussion.

There are methods to quantify the direct market-based benefits of NCD projects. They involve the quantification of direct return on investments (ROI) from the restoration project. These direct returns include: avoidance of government or private sector costs for services provided by the restored ecosystem; increases in economic activities, and associated sales and employment taxes as a result of the restoration; and, real increases in property values and their associated property taxes. Hurd (2008) noted that "large returns on investment from restoration in these areas do exist, but the cumulative benefits do not always outweigh the costs." Further, these direct market-based valuations do not capture all of the economic benefits of such projects.

There are also methods to quantify the indirect market-based benefits of NCD projects. The most significant indirect market-based benefits include long-term benefits like population growth and business creation in affected communities. Finally, methods have been developed to quantify the benefits of such projects that are not associated with direct market factors. Loomis (2006) provides an excellent description of the various methods used by economists to value the nonmarket benefits of stream and other ecosystem restoration projects. As described by Loomis (2006), "the Total Economic Value (TEV) associated with restoration is made up of the on-site use value, as well as the off-site passive use values. On-site use values of stream restoration projects include ecosystem services such as recreation, fish habitat, water quality, stormwater management and aesthetics. However, restoration also provides benefits to the broader community through knowledge that the natural aquatic ecosystem has been restored (i.e., existence value) and through the knowledge that restoration today will provide the restored aquatic ecosystem to future generations (i.e. a bequest value)." These existence and bequest values are known as off-site passive use values.

To estimate use values of river restoration, economists often rely upon actual market behavior to detect how visitors or homeowners value river restoration. Visitors reveal their greater demand and benefits for improved rivers by the increased number of trips they take to restored streams and rivers as compared to degraded ones. The Travel Cost Method (Loomis and Walsh 1997) can be used to estimate the demand curve for restored rivers and allows for the calculation of the visitor's additional net willingness to pay (WTP) to visit these restored rivers, as compared to degraded ones. For rivers running through residential areas, the Hedonic Property Method is used to value homeowners' WTP for house price differentials for living by a restored or natural stream as compared to a degraded one Loomis (2006).

Again, as described by Loomis (2006), economists develop constructed or simulated markets to allow survey respondents to state what they would pay to obtain these passive use values. Two methods are used to value these stated preference approaches, the Contingent Valuation Method (CVM) (Mitchell and Carson 1989) and conjoint/choice experiments (Louviere et al. 2000). Both methods involve providing households with a comparison of existing river conditions and improved river conditions and then ask whether they would pay a given increase in cost that varies across households. The varying costs and the response to them allow for tracing out a demand-like relationship for restoration (i.e., the higher the cost, the fewer people would pay). CVM estimates a value for the entire restoration improvement program (Loomis 1996), while the conjoint method allows for the valuation of each individual ecosystem service component Loomis (2006).

Loomis (2006) discovered that previous studies have shown that existence values make up at least half the benefits of improving water resources (Fisher and Raucher 1984, Sanders et al. 1990) and therefore these passive use or non-use benefit approaches would seem to be the most comprehensive when calculating the benefits of stream restoration. Results from use and passive use valuation studies are expressed in terms of the fees the average household is willing to pay for the improved stream conditions. This WTP is typically presented in terms of fees paid per household per year, or per month.

The direct and indirect market-based methods described above are very expensive to implement in direct support of a proposed stream restoration project or program because they require the collection of real market values that are often difficult to obtain. Use and passive use value studies, collectively referred to as willingness to pay (WTP) studies hereafter, do require surveys of the affected community, but they are usually much simpler to implement in that they only require the investigator to provide the survey respondents with an overview of the proposed restoration activity and querying the dollar value the respondents would be willing to pay to achieve the resulting restoration.

WTP studies are often used to capture the specific economic benefit of components that are difficult to capture through real market data, as part of larger studies that also include direct and indirect market-based benefit valuation components. However, WTP studies are often used as the sole economic benefit valuation method in studies for ecosystem restoration projects. In such studies, it is implied that the WTP evaluation captures the comprehensive benefits of the project in that the stakeholder respondents would theoretically be paying for the projects through some tax mechanism (i.e., utility fee) and therefore would intrinsically include the total perceived value in their WTP responses. Obviously, such studies do not account for the direct and indirect market-based economic impacts to the community, such as increased tourism revenues and property and sales taxes. But, in the simplest context, they do capture the perceived value of the projects to the stakeholder community.

Use and passive use studies are also helpful in the context of this study because the WTP fees are analogous to a utility fee, that is, what would the respondent be willing to pay to receive the utility of the restored stream. Further, such studies could be used by Texas municipalities to evaluate potential new or additional fees that the community might be willing to accept as part of a flood control, drainage, or stormwater utility fee to implement the proposed restoration project or program.

6.3.3. Case Studies of the Evaluation of the Economic Benefits of NCD

Two major municipalities have recently implemented economic impact studies in support of proposed or existing major natural resource restoration programs that include stream and riparian corridor restoration as significant components. These two studies used various combinations of direct and indirect market-based valuation methods and nonmarket WTP methods.

A study for the Philadelphia Water Department, Office of Watersheds (Stratus Consulting Inc. 2009), examined the economic benefits of the implementation of a comprehensive program of LID (e.g., tree planting, permeable pavement, green roofs) and riparian and stream restoration projects. The study used both direct market-based (economic ROI) and nonmarket WTP methods to estimate the cumulative economic benefits from the project. ROI methods were used only to estimate the benefits from avoidance of government or private sector costs for services provided by the restored ecosystem. WTP methods were used to estimate recreation, home value, and water quality benefits. Because the project encompasses many components in addition to stream and riparian corridor restoration, many of the benefits would not be significantly affected by the stream and riparian corridor restoration components. Table 14 summarizes the estimated benefits that were significantly affected by the restoration of streams and riparian corridors.

Table 14: Summary of Philadelphia Project Benefits that are Significantly Affected by Sream and Riparian Corridor Restoration Components

Benefit and Basis	Benefit Valuation Method	Benefit Value (2009 million USD)
Reduction in heat stress mortality: Increase in vegetation and associated water vapor emissions and reduction in heat absorbing materials.	Direct ROI by avoidance of costs	$1,057.6
Social costs avoided by green collar jobs: Green infrastructure projects, in contrast to traditional stormwater management solutions, create the opportunity to hire unskilled – and otherwise unemployed – laborers for landscaping and restoration activities. Avoided costs for social services that the City would provide on behalf of the same people if they remained unemployed.	Direct ROI by avoidance of costs	$124.9
Reduction in healthcare costs from air quality pollutant removal: Trees and vegetation improve air quality by filtering some airborne pollutants (particulate matter and ozone). Likewise, reduced energy consumption results in decreased emissions (SO2 and NOx) from power generation facilities. These air quality improvements can reduce the incidence and severity of respiratory illness and associated health care lost work day costs.	Direct ROI by avoidance of costs	$131.0
Reduction in water quality treatment costs provided by wetlands: Watershed restoration and related efforts create or enhance wetlands in the relevant watersheds. Monetized using a benefits transfer approach based on relevant published literature of wetland values .	Direct ROI by avoidance of costs	$1.6
Increased recreational opportunities: Stream restoration and riparian buffer improvements will result in increase in creek side recreational opportunities (jogging, biking, walking, picnicking) in green areas along and adjacent to the impacted waters. Little or no increases expected in in-stream recreation. Also includes increase in non-creekside recreational opportunities.	WTP	$524.5
Property value increases: Trees and plants improve urban aesthetics and community livability, and several empirical studies show that property values are higher when trees and other vegetation are present in urban neighborhoods.	WTP	$574.4
Water quality/aquatic habitat enhancement: LID options, in conjunction with the stream and riparian corridor restoration efforts, are expected to generate improvements to riparian and aquatic ecosystems and habitat areas.	WTP	$113.16

Source: Philadelphia Water Department, Office of Watersheds (Stratus Consulting Inc. 2009)

Cambell and Munroe (2004) studied the economic benefits of the completion of the 153-mile Catawba Regional Trail in the three counties that comprise the core of the Charlotte, North Carolina metropolitan area. Like many greenway trail systems being developed across the country, the majority of the trail system will occupy preserved or restored riparian corridors, including extensive stream restoration projects. The study used both direct (economic ROI) and indirect market-based methods to estimate the cumulative economic benefits from the project. ROI methods were used only to estimate benefits from increases in economic activities (projected recreational activities) and their associated sales taxes as a result of the restoration; and, real increases in property values and their associated property taxes. Indirect market-based methods were used to estimate community growth benefits, which included increased residential development near the greenway and associated sales taxes.

The Cambell and Munroe (2004) study did not include the economic benefits from avoidance of government or private sector costs for services provided by the restored ecosystem (i.e., decreased health care costs due to increased recreational opportunities; or the impact of the trail in slowing or halting erosion), or the many non-pecuniary factors that are part of any public good, such as overall quality of life. The authors acknowledged that, as such, the economic benefits presented in the report represented only a portion of the total value of the project. This project primarily consisted of development of greenway trails through riparian corridors. The economic benefit analysis was specific to the greenway trails, not stream restoration. However, many of the streams within these corridors have been restored or are planned for restoration, and, as mentioned above, most stream restoration project in metropolitan areas include riparian corridor restoration and/or preservation and the establishment of greenway trails. As such, the level of economic benefits obtained should be similar to projects developed in Texas metropolitan areas which include stream restoration, riparian corridor preservation and/or restoration, and the development of greenway trails. Table 15 summarizes all of the estimated benefits of the project.

Table 15: Summary of Catawba Regional Trail Project Benefits

Benefit and Basis	Benefit Valuation Method	Benefit Value (2004 million USD)
Property value increases on existing, developed residential and commercial properties: Other things being equal, home buyers are willing to pay more for a house that is closer to a greenway than one that is more distant. Used real, local data from real estate transactions over the 2000-2003 period to estimate the impact on residential and commercial sales prices due to existing greenway and open space proximity while controlling for all other significant factors (location, size, age, number of bedroom, etc.)	Direct ROI from real increases in property values	$112.3/year
Property tax increases on existing, developed properties: Increase in real property values results in real increase in associated property taxes.	Direct ROI from real increases in property taxes from increases in property values	$1.5/year
Investment in new residential development: Rising land values are indications of increasing demand. As demand for housing near the greenway increases, new housing will be developed and sold at a new, higher prices.	Indirect benefit ROI from community growth	$153.0 (over total project life)
Property taxes from new residential development: Increase in residential development results in increase in associated property taxes.	Indirect benefit ROI from community growth	$0.9/year (once completely developed)
Increased tourism revenue and sales taxes: Greenways will attract daily visitors seeking recreation. Visitorsfrom outside the area will use the greenway and purchase goods and services while utilizing this amenity and some will stay overnight generating hotel occupancy impacts. Increased purchases of goods, services, and occupancy will also generate increased sales taxes.	Direct ROI from increases in economic activities (projected recreational activities) and their associated sales taxes	$2.1/year (upon completion)

Source: Cambell and Munroe (2004)

Studies were identified in the literature that solely used WTP methods, as discussed above, to estimate the economic benefit of stream and riparian corridor restoration projects. These studies include both CVM and conjoint/choice experiment methods. Hurd (2009) identified nine such studies related to stream and riparian buffer restoration. A summary of the restoration project details and the results of each of these studies are included as the first nine studies summarized in Table 15 (taken from Hurd, 2009).

Holmes et al. (2004) performed CVM analysis on the Little Tennessee River (LTR) in western North Carolina. The restoration option presented to the respondents was based on 54 projects already completed on the river and included riparian buffer restoration, fencing out of cattle, bank stabilization with log revetments plus 0, 2, 4 or 6 miles of stream restoration. Although stated as a CVM analysis, the study resembles a conjoint/choice experiment. The study concluded that respondents were willing to pay a premium for total restoration of the LTR ecosystem relative to modest restoration levels, and the benefits of ecosystem restoration were super-additive in the sense that the value was greater than the sum of benefits measured for partial restoration programs.

The mean household annual WTP of the 11 studies analyzed and listed in Table 16 was $80 per household per year, with a range of $1.1 to $328.

Table 16: Summary of Contingent Valuation Method Studies on Stream Restoration

Authors	USDYear	Who	What	WTP Method	Amount *	Measurement
Crandall (1991)	2008	Visitors of Hassayampa River Preserve, Arizona	Non-consumptive benefits of restoration of the streamside area of HRP to higher streamflow	CVM	$104.95	WTP for restoration project
Crandall et al. (1992)	2008	Arizona residents visiting Hassayampa River Preserve in Arizona	Value of instream flow and recreation in riparian area	CVM	$100.34	WTP for improvement in instream flow from inadequate to adequate
De Zoysa (1995)	2008	Households within Maumee River and Western Lake Erie basins, Ohio	Improve surface water and groundwater quality and preserve wetlands	CVM	$111.38	WTP for improved water quality
Loomis and White (1996)	2008	Residents of Clallam County, Washington State	Non-market economic value for restoring Elwha River and its fisheries	CVM	$91.10	WTP for restoration
Loomis et al. (1999)	2008	Homeowners along Platte River, Colorado	Restoration of 45 mile section of Platte River	CVM	$327.60	WTP for river restoration

Authors	USDYear	Who	What	WTP Method	Amount *	Measurement
Lindsey and Knapp (1999)	2008	Property owners, renters, and county residents in Indianapolis, Indiana	Projects to improve quality of creek within city greenway	CVM	$8.55	WTP for improved creek quality
Farber and Griner (2000)	2008	Homeowners in Western Pennsylvania	Restoration of two creeks	CVM	$113.16	WTP for restoration of creeks
Georgiou et al. (2000)	2008	Local residents in Birmingham, UK	Water quality improvements in the river with both biodiversity and recreational opportunities on River Tame	CVM	$25.88	WTP for proposed water quality improvements
Collins et al. (2005)	2008	Homeowners around Deckers Creek, West Virginia	Restoration of Deckers Creek	CVM	$186.24	WTP for creek restoration
Holmes et al. (2004)	2004	Homeowners around Little Tennessee River, North Carolina	Riparian buffer restoration, cattle fence-out, and log revetment bank stabilization of Little Tennessee River plus 0, 2, 4 or 6 miles of stream restoration	Stated as CVM, but resembles conjoint/ choice experiment	$5.66 $1.09(plus 2 miles) $2.30 (plus 4 miles) $53.76 (plus 6 miles)	WTP for riparian buffer restoration and bioengineering bank stabilization plus the 4 levels of restoration
Bae (2004)	2004	Homeowners in a metropolitan area of Korea	Increased natural and recreational value of transforming an urban concrete-enclosed channel into a natural stream	Cojoint Analysis	$50 (natural) $25 (recreational)	WTP for increased natural and recreational attributes

Source: Hurd, 2009. *WTP values are per household per year

7. Potential Funding Mechanisms for NCD

As discussed in detail in Section 6.2, the economic benefits associated with stream improvements are important aspects and must be considered when analyzing funding opportunities for stream restoration projects or NCD projects. Return of investment, willingness to pay, and municipal growth and business opportunities are all factors that can play a role in the decision making process. According to data published by the Wildlands CPR in 2010, erosion costs the US about $63B per year. Funding stream restoration projects will not only minimize or eliminate the effects of erosion within a watershed but also create benefits such as flood reduction, water quality, riparian, aquatic and habitat improvements, recreational opportunities and support for economic development.

Securing funds for NCD projects often requires an understanding of the project baseline conditions, defining the full potential of the resource, alternative or feasibility analysis, and cost benefits analysis. This research study is a good example of setting overall baseline conditions for funding NCD projects since it describes the applicability, ecological benefits, and cost benefits of NCD techniques. Another important factor is early engagement of stakeholders to strengthen local support in the community. Joint collaboration among agencies to seek project funding also proves to be beneficial in many situations. For example, converting an eroded sewer crossing channel section to a riffle can improve river stability, aesthetics and protect municipal infrastructure.

Funding sources for stream restoration include Federal, State, and local programs, non-government organizations, Parks and Recreation fees, utility fees, property owners, flood insurance, and mitigation demand. Many times the biggest challenge is lining up local match. Federal initiatives are usually funded through existing programs such as the USACE Section 206, Ecosystem Restoration Program, the US EPA Center for Environmental Finance and the US Fish and Wildlife Service. Local funding focuses more on WTP and municipal growth and includes bonds, infrastructure maintenance funds, recreation funds, and economic development. Market-driven funding opportunities also exist through wetland and stream mitigation, natural resource damage, conservation banking and clean water credits. Non-government entities such as the Nature Conservancy, the Trust for Public Land, local foundations, etc. can be a good source of project funding both monetarily and through in-kind services.

8. Conclusions and Recommendations

8.1. Applicability for Use of NCD Techniques in Texas

A comparison of the Texas physiographic provinces and similar physiographic provinces in the remainder US where NCD projects have been widely implemented resulted in the following conclusions:

- The Gulf Coastal Plains of Texas can be compared to other regions along the Gulf and Atlantic coasts, due to similar geology, coastal geomorphology, humidity, and precipitation. Florida, North Carolina, and Maryland, where the use of NCD is common, all contain coastal physiographic regions similar to the coastal plains in Texas. A number of stream restoration projects have already been implemented in the coastal plains region of Texas, both within the Fort Worth and Galveston Corps District boundaries. The cities of Houston and San Antonio are contained within this physiographic region and each of these cities already has an active stream restoration program.
- The Basin and Range and High Plains provinces of West Texas share physiography characteristics with several southwestern states including Colorado, Utah, Nevada and New Mexico, where numerous successful and well-documented stream restoration projects have been implemented as cited throughout this report.
- The North Central Plains and Grand Prairie provinces of North Texas share characteristics with many Midwestern states including Oklahoma, Arkansas, Nebraska, and Missouri. Within Oklahoma and Nebraska, the use of NCD is just beginning to grow in popularity and projects utilizing NCD techniques are relatively new. Both the Oklahoma State University and the University of Nebraska have created stream restoration programs.
- The North Central Plains and Grand Prairie provinces of North Texas share characteristics with many Midwestern states including Oklahoma, Arkansas, Nebraska, and Missouri. The city of Austin, which already has an active stream restoration program, is contained within this physiographic region.

Restoration projects and techniques vary greatly based on the environment in which they are implemented. Beyond the physiography of the restoration site, the existing land use and development is probably the most important factor to consider in restoration design. Streams in highly developed urban environments have very different problems and different restoration potentials than streams in agricultural or rural environments. Despite these differences, case studies have demonstrated that NCD techniques can be applied in both urban and rural environments by adapting the techniques to the particular issues of the restoration site.

While there are pros and cons to designing restorations in either urban or rural areas, successful restorations have been demonstrated in both environments. With proper planning, both urban and rural stream restorations can provide long-term benefits. In order to have a successful restoration project in either environment, restoration planners must be able to identify the restoration goals and then match those goals with the restoration potential of each site.

In order to determine whether or not a stream warrants the need for NCD, one must assess factors such as degree of degradation, riparian corridor, availability of stabilization materials, existing pattern and infrastructure, belt width (width of consecutive outside meander bends) constraints, and flooding concerns. By evaluating a potential project site based on these factors, we can determine what priority of NCD may be most applicable, if any. Figure 18 provides a decision making flow chart for Texas agencies to evaluate the applicability NCD to their particular stream projects.

8.2. Ecological and Water Quality Benefits of NCD Techniques over Traditional Stormwater Practices

A significant finding of this study is that monitoring data is limited and most NCD projects are constructed on only a portion of the watershed/stream length. Watershed-wide restoration projects that include monitoring are recommended in Texas to better describe water quality benefits that may be achieved with more extensive implementation of NCD.

At present, significant data is available on the water quality and pollutant-removal benefits of LID for a number of pollutants, including: TSS, bacteria, nutrients, hydrocarbons, metals, pesticides, and others. While LID is a decentralized and distributed approach to stormwater management, significant implementation of a large number of LID facilities is needed to achieve a substantial impact on watershed health and water quality. Similarly, the authors suggest that significant implementation of NCD is needed to achieve substantial impact on watershed health and water quality.

Based on the results of this literature review and interviews with public agencies, NCD appears to be effective at improving water quality, which is often seen as one of the primary benefits of NCD projects over traditional stormwater conveyance practices. Water quality performance of NCD for this study focused on nutrients, TSS, and bacteria as a larger volume of research is available and these are pollutants that commonly have established TMDLs in the major metropolitan areas in the State of Texas.

A number of studies were found regarding the ecological benefits and effectiveness of NCD with regard to improved habitat for wildlife, fish, and benthic macroinvertebrates. Benefits for wildlife (mammals, birds, reptiles, and amphibians) correlate with the quality and extent of the riparian buffer that provides food, shelter, and a wildlife corridor for travel. NCD within the stream itself may also increase the type and availability of food sources for some of the wildlife found within the riparian corridor (Pennsylvania State, 2011). One study by Selvakumar (2010), recommended NCD in conjunction with stormwater BMPs or LID throughout the watershed as well as point-source and non-point source pollutant controls. Two of the reviewed literature, Dosskey (2010) and Hines (2007), reported that macroinverebrates habitat in NCD streams may be improved by adding large boulders in pool sections. With regards to fish, the riparian buffer also is critical for cooling stream temperatures, increasing dissolved oxygen levels, and decreasing fine sediments that may otherwise clog gills (Pennsylvania State, 2011). Specific in-stream NCD techniques are also identified in several studies regarding designs to improve fish habitat.

A major finding of this effort is that monitoring of NCD projects within the various physiographic provinces of Texas is critical for standardizing and optimizing future designs for water quality and pollutant removal performance. Filoso (2009). Many studies also recommend additional research in NCD in the fields of water quality improvement and pollutant removal. Kaushal (2008) recommended additional study to identify designs most effective in conjunction with watershed strategies to reduce nitrate-N sources to streams. Additionally, Andrews (2011) noted that stream restoration projects should consider the importance of riparian vegetation and recommended additional research on vegetation types (i.e., forested vs. cane) within the riparian zone to enhance pollutant removal.

Table 17 summarizes advantages and disadvantages of NCD and traditional stormwater conveyance practices. Habitat benefits of NCD correlate to in-stream habitat for macroinvertebrates and fish as well as riparian and wildlife corridor habitat for birds, butterflies, frogs, and mammals.

Table 17: Comparison of NCD and Traditional Stromwater Conveyance

Type of System	Land Required[1]	O&M	Addresses Multiple Objectives	Stabilize Banks	Water Quality	Habitat	Aesthetics	Familiarity with Concepts
Natural Channel Design	High	Low	✓	✓	✓	✓	✓	
Traditional Stormwater Conveyance	Low	High		✓				✓

[1] Land requirements for full implementation, whereas partial implementation requires less land.

8.3. Cost Difference between NCD and Traditional Stormwater Projects

All applied channel improvement options, whether using traditional or NCD methodologies, are focused on stabilization of a channel that is failing through excessive bed and/or bank erosion. The spectrum of restoration priorities presented in this report included four levels of restoration: Priorities 1 through 4, with Priority 1 restoration reaching the maximum level of uplift. Priority 4 projects include the various traditional stabilization techniques to armor river banks in place and do not address dimension, pattern and profile, like the other 3 Priorities.

Cost data were obtained from projects in the Houston, Austin, San Antonio and Grand Prairie area and included Capital Improvement (design and construction) costs only. The cost data was evaluated on a linear footage basis and the projects were grouped into categories according to the hydrologic order of the stream. Two categories were assigned: Stream Order 4 or Greater, and Stream Order 3 or Less. In addition, all projects were assigned a restoration priority according to the type of work performed. Most Texas projects fell within the Priority 3 or 4 categories. Some of the Priority 4 projects contained certain NCD features such as a bankfull bench, grade control, and riffles, and were categorized as Priority 4 projects with NCD Features.

A comparison of construction costs and design costs between NCD (Priority 3) and Traditional methods (Priority 4) built on streams of order 4 or greater indicated the following:

- The overall construction cost for both NCD and Traditional projects are less for projects of shorter length.
- The cost per linear foot for traditional projects was significantly higher than NCD for the

larger projects and less for shorter projects. A breakpoint length was observed at approximately 1,250 lf of project length.

- In general, design costs are higher for NCD as compared to traditional methods

A comparison of construction costs between Priority 4 projects utilizing solely traditional methods and Priority 4 projects containing NCD features built on streams of order 3 or less indicated the following:

- The cost for projects with NCD components trends higher than traditional construction. No apparent breakpoint project length was observed as noted for stream order 4 or greater projects.
- The costs/lf for stream order 3 or less projects also tend to increase as the project length decreases.
- There was not enough data with respect to design costs to support a comparison.
- There was not enough available data on Priority 3, Stream Order 3 projects to support a comparison with Priotity 4 projects of same stream order.

Based on the limited cost analysis performed, it is apparent that the application of NCD follows the same general pattern for construction and design costs that traditional methods follow, with the possible exception of the cost per linear foot for traditional methods for the larger Priority 4 projects. The trends indicate that, for Stream Order 4 or greater, traditional projects are significantly higher in cost than NCD projects, at least for longer projects which involve stream lengths greater than 1,250 feet. For creeks classified as Stream Order 3 or less, the construction and design costs trends each gave indication that NCD is slightly more costly overall. The validity of these types of comparisons is based upon the ability to break the data into like groupings, such as streams of same hydrologic order and restoration priority. The development of a rich data set is imperative in order to develop cost curves that may be used to assist scientists, engineers and planners in the selection of appropriate design and construction methods.

It is important to note that the cost analysis presented in this study only included Capital Improvement Costs. A supplemental analysis taking into account Operation and Maintenance costs and debt service costs is necessary for a more thorough comparison of NCD and Traditional costs. In addition, the available project data collected from agencies in the Houston, San Antonio, Austin and north Texas areas did not incorporate any cost factor for environmental, quality of life, or other economic benefits as discussed in Section 6.3 of this report.

8.4. Recommendations

Figure 18 presented a decision making flow chart for Texas agencies to evaluate the applicability of NCD for site specific conditions. Once the technical applicability is warranted, the agencies will need to evaluate project costs in order to determine viability of a Priority 3 project against a Priority 4 project with NCD features, for example. Therefore, in order to supplement the limited data available during the present study and to create a decision making tool that accounts for all aspects of NCD versus Traditional stormwater infrastructure benefits, it is recommended that the

State work cooperatively with other agencies in Texas to build a more comprehensive project database of stream restoration projects as follows:

- Projects must be grouped into the categories of same like, such as stream order or contributing drainage area, and restoration priorities as presented in this study. This will allow for a fair comparison taking into account stream size.
- The project dataset must contain other costs such as O&M and debt service, as applicable, as well as parameters to value economic and environmental benefits of stream projects. This will allow for a complete life cycle analysis of projects.
- A monitoring program must be implemented following construction of Priority 1, 2, 3 and 4 projects to track water quality and pollutant removal performance in Texas.

8.5. Webinar

A technical webinar will be sponsored by the TWDB to present the results of this research to a broad range of agencies that are likely to benefit from and implement the results of this study. All agencies that participated during the course of this study and provided data from local implementation of stream restoration projects will also be invited to the webinar. All agencies will be notified soon as to specific details on the webinar and instructions for participation.

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Appendix A

EPA Regulatory Programs

Appendix A – EPA Regulatory Programs

1. CWA Section 402

The CWA makes it illegal to discharge pollutants from a point source (i.e., a manmade conveyance, such as a pipe, ditch, tank, vehicle, etc.) to the waters of the United States except in accordance with a permit. Section 402 of the act created the National Pollutant Discharge Elimination System (NPDES) regulatory and permitting program. In Texas, point sources must obtain a discharge permit from the Texas Commission on Environmental Quality (TCEQ), which assumed authority from the EPA to administer the NPDES program in Texas in 1998, after which it became known as the Texas Pollutant Discharge Elimination System (TPDES). A TPDES permit sets specific discharge limits for point sources discharging pollutants into waters of the United States and establishes monitoring and reporting requirements, as well as special conditions.

Streams are affected by CWA Section 402 via the NPDES Stormwater Program, which includes regulation of stormwater discharges from municipal separate storm sewer systems (MS4s), which are considered point sources. These MS4s include discharges to the myriad creeks, streams, bayous, and drainage channels that are part of the storm sewer systems. Phase I of the NPDES Stormwater Program, promulgated in 1990, addressed large and medium MS4s, which are an incorporated place or county with a population of 100,000 or greater. Phase II of the Program was promulgated in 1999 and added small MS4s to the NPDES regulated communities. Small MS4s primarily include “urbanized areas” as defined by the 2010 U.S. Census, which were not already regulated under the Phase I Program. There are currently 305 regulated Phase I and II MS4s in Texas.

These Phase I MS4 permits require MS4s to reduce the discharge of pollutants to the maximum extent practicable and prohibit illicit discharges to the MS4. The storm water Phase II program requires Phase II MS4s to include “measurable goals” in their program for each BMP. Phase I storm water MS4 permits are beginning to include these measurable goals allowing the permitting authority to assess whether each permitttee is in compliance.

In 2009, the U.S. EPA proposed a new regulation to make regulatory improvements to strengthen its storm water program. Of interest here, the EPA has proposed to:

- Expand the physical area subject to federal storm water regulations;
- Develop a single set of consistent storm water requirements for all MS4s (i.e., Phase I and Phase II); and,
- Require MS4s to address storm water discharges in areas of existing development through retrofitting the sewer system or drainage area with improved storm water control measures.

The TCEQ intends to incorporate elements into the TPDES permitting program as required following adoption of any new rules.

The EPA maintains the National Menu of Stormwater Best Management Practices online (http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm). These BMPs include structural, non-structural, and institutional controls to reduce pollution discharges from MS4s. Neither stream restoration nor general channel stabilization are included in the BMPs. At present in the U.S., stormwater BMPs stop at the site boundaries, prior to discharge to the receiving stream. This is a short-sighted approach, as discussed further in later sections, and assumes that if all pollutant loads and altered hydrology are mitigated on the site, then the water in the streams will be pollutant free. This fails to recognize that most of the natural channels that comprise MS4 storm sewer networks are suffering from channel degradation and aggradation in response to hydromodifications of the last 150 years. Again, this subject will be addressed in greater detail in later sections.

Regardless, the latest, most advanced structural BMPs in the EPA's National Menu are focused on Low Impact Development (LID) methodologies, which strive to manage stormwater and pollutants onsite and recreate pre-development hydrology. In large developments, LID practices include protection/preservation of existing, natural onsite streams and the use of naturalized drainage channels (e.g., vegetated swales) for onsite stormwater conveyance. It is reasonable to expect that LID practices will ultimately expand to include stream restoration of onsite drainage systems. In fact, several large, master-planned communities in Texas in the last few years have employed these practices in their developments, touting the environmental benefits as well as the increased natural amenities and property values achieved from such practices.

2. CWA Section 404

Section 404 of the CWA, enacted as part of the CWA in 1972 deals with one broad type of pollution—discharge of dredged or fill material into "waters of the United States", including wetlands. This law is commonly referred to as the “No Net Loss of Wetlands” law. The 404 permit program is administered jointly by EPA and the U.S. Army Corps of Engineers in Texas. The Corps handles the actual issuance of permits, individual and general. The Corps has primary responsibility for ensuring compliance with permit conditions, while EPA typically takes the enforcement lead for unpermitted discharges.

Activities in waters of the United States regulated under this program include fill for development, water resource projects (such as dams and levees), infrastructure development (such as highways and airports) and mining projects. Section 404 requires a permit before dredged or fill material may be discharged into waters of the United States, unless the activity is exempt from Section 404 regulation (e.g. certain farming and forestry activities). The basic premise of the program is that no discharge of dredged or fill material may be permitted if: (1) a practicable alternative exists that is less damaging to the aquatic environment or (2) the nation's waters would be significantly degraded. In other words, when you apply for a permit, you must show that you have, to the extent practicable:

- Taken steps to avoid wetland impacts;
- Minimized potential impacts on wetlands; and
- Provided compensation for any remaining unavoidable impacts.

Proposed activities are regulated through a permit review process. An individual permit is required for potentially significant impacts. However, for most discharges that will have only minimal adverse effects, a general permit may be suitable. General permits are issued on a nationwide, regional, or State basis for particular categories of activities.

In 2001 the National Academies of Sciences' National Research Council and the General Accounting Office concurrently issued reports that provided a critical evaluation of the effectiveness of compensatory mitigation for authorized losses of wetlands and other waters of the United States under Section 404. In response, a federal, multi-agency task force developed the "Wetland Mitigation Action Plan." The Plan recommended 17 changes to the program. Relative to streams, it was recommended that compensatory mitigation be integrated into a 'Watershed Context," whereby in-kind mitigation (e.g., stream mitigation required for stream impacts) in the same watershed as the impacts would be preferable to out-of-kind mitigation (e.g., wetland mitigation required for stream impacts), or mitigation in a separate watershed. Previously impacts to streams were mitigated with wetland mitigation. In 2008, the Corps and the EPA jointly issued the 2008 Final Compensatory Mitigation Rule, which incorporated the goals and objectives of the National Mitigation Action Plan.

Both the Galveston and Ft. Worth Corps Districts have subsequently developed compensatory stream mitigation tools for use in both evaluating compensatory mitigation required for stream impacts and in the development of stream mitigation credits through stream restoration activities. As a result, NCD projects have begun to be developed across the two Districts, which regulate most of Texas. These projects include both onsite mitigation by impactors, and more commonly, the development of large, third-party stream restoration projects at stream mitigation banks. These banks then sell stream mitigation credits to impactors for whom onsite mitigation is either infeasible or not preferable.

3. CWA Section 401

Under Section 401 of the CWA, States and Tribes can review and approve, condition, or deny all Federal permits or licenses that might result in a discharge to State or Tribal waters, including wetlands. The major Federal licenses and permits subject to Section 401 certification in Texas are CWA Section 402 (NPDES) and 404 permits, Federal Energy Regulatory Commission (FERC) hydropower licenses, and Rivers and Harbors Act (RHA) Section 9 and 10 permits. The TCEQ administers the 401 program in Texas related to CWA Sections 402 and 404, FERC permits, and RHA Section 9 and 10 permits. The majority of these activities pertain to the CWA Section 404 and RHA Section 10 permits administered by the Corps. The Texas Railroad Commission (TRC) administers the 401 certification program for oil and gas drilling permits. States and Tribes make their decisions to deny, certify, or condition permits or licenses primarily by ensuring the activity will comply with State water quality standards. This authority gives the State broad power to impose additional requirements on permitted projects toward attainment of

WQS. In the future, as the State strives to attain WQS through more robust pollutant reduction strategies, and stream restoration gains acceptance as a water quality BMP, this regulatory authority may result in the imposition of stream restoration BMPs on appropriate, federally permitted projects.

4. CWA Section 319

Nonpoint source pollution (NPS) represents the most significant source of pollution overall in the country. The most recent set of 303(d) reports (from 2002-2010) indicated that more than 40 percent of all impaired waters were affected solely by nonpoint sources, while less than 10 percent of water quality criteria exceedances were caused by point source discharges alone. The CWA does not provide a detailed definition of nonpoint sources. Rather, they are defined by exclusion— they include all sources of pollution caused by runoff of precipitation (rain and/or snow) over or through the ground and not considered a “point source” according to the act and EPA regulations.

While Congress chose to address “point” sources with a regulatory approach, it chose a different path with regard to “nonpoint” sources. When it added Section 319 to the CWA in 1987, it created a federal grant program that provides money to states, tribes, and territories for developing and implementing NPS management programs. Under the Clean Water Act section 319, states, territories, and delegated tribes are required to develop nonpoint source pollution management programs (if they wish to receive 319 funds). Once it has approved a state’s nonpoint source program, EPA provides grants to these entities to implement NPS management programs under section 319(h). Recipients of CWA section 319 grant funds must provide a 40 percent match, either in dollars or in-kind services.

Section 319 funds can be used to conduct activities to ensure the use of BMPs, develop strategies for collaborating with other agencies and draft monitoring and evaluation plans. Section 319 funds also can be used for developing and implementing TMDLs in watersheds where nonpoint sources are a substantial contributor of loadings of the pollutant(s) causing impairment. A state, tribe, or territory receiving section 319 funds must complete and update an NPS management plan every five years. The development of the Texas Nonpoint Source Management Program and administration of Section 319 grants are handled jointly by the TCEQ and the Texas Soil and Water Conservation Board (TSWCB). The TSWCB administers grants related to runoff pollution from agricultural and forestry practices.

Relative to streams, CWA Section 319 includes degrading stream beds and banks as NPSs. This includes both rural streams and urban and suburban streams that are not regulated MS4 components, which includes the majority of larger receiving natural streams in these settings. The TCEQ has developed a BMP Finder for NPS BMPs in Texas. This tool includes many stream restoration and NCD prescriptions, including bed and bank stabilization. To date, however, there have been only a few stream stabilization projects implemented in Texas through the Section 319 grant program. The majority of 319 grants in Texas have been directed toward the development of watershed protection plans (WPPs) and implementation of LID practices. Other states (e.g. Ohio, North Carolina, New Jersey, Colorado, Montana, Georgia, Oklahoma, Pennsylvania, California, New Hampshire) have directed 319 grants to stream restoration projects on a much more extensive basis and it should be expected that communities in Texas will eventually move in this direction, as their WPPs are completed, the use of NCD and stream restoration becomes more known and acceptable, and they struggle to meet their WQS.

5. Clean Water State Revolving Fund

In 1987, Congress voted to phase out the old construction grants program for funding of municipal sewer and wastewater treatment plant upgrades, replacing it with the Clean Water State Revolving Fund (CWSRF). Under the CWSRF, EPA provides annual capitalization grants to states, that in turn provide low interest loans for a wide variety of water quality projects. States must match the federal funds with $1 for every $5 (a 20-percent match). Although most loans have gone to local governments, they also can go to businesses or nonprofit organizations. Payback periods for loans extend to 20 years.

The Texas Water Development Board administers the CWSRF in Texas. Most of the CWSRF dollars loaned to date have gone for construction expansion, repair, or upgrading of municipal sewage collection and treatment systems. Relative to streams, however, CWSRF loans can also be made for the following: (1) stormwater pollution control; (2) NPS control projects consistent with a state Section 319 program; or (3) implementing a management plan developed under the National Estuary Program.

There are two overarching components of both programs that are pertinent to streams and stream restoration.

1. Both programs, at their core are part of the pollution-reduction strategies whose overall objective is to achieve WQS; and,

2. Both programs include requirements to assess and improve the programs periodically toward attainment of their regulatory goals.

Appendix B

NCD and Traditional Projects in the Houston Area

Appendix B – NCD in the Houston Area

The following information was obtained through the authors' direct involvement in most of the past NCD projects implemented by the Harris County Flood Control District and from the District's Natural Stable Channel Design Team.

Overview of Harris County Fluvial Geomorphology

The 22 watersheds of Harris County are quite limited in geomorphological variety due to the predominance and consistency of their coastal plains setting. Generally, both valleys and streams are relatively flat. Of the 45 stable or quasi-stable stream reaches surveyed in the countywide fluvial geomorphological study, 37% were E5 or E6 streams, 30% were C5, C6, or C5c- streams, and 33% were B5c streams, where the stream types are taken from the Rosgen Stream Classification System (Rosgen, 1996). Unstable stream types observed during the study but not surveyed were limited to F5, F6, G5c, G6c, D5, and D5c stream types. Dominant channel materials, as defined by the median grain size, D50, in county streams are limited to sand and silt-clay and, as such, sediment transport in the systems is strictly mono-modal (i.e., suspended load transport with very little bed load transport). Gravels exist in small amounts in a few streams, however, nowhere are they the dominant channel material. The lack of any dominant quantities of channel materials larger than sand has significant implications on the fluvial geomorphology of Harris County streams. In stream systems where the dominant channel materials are gravel or larger, riffles are armored and quasi-fixed from a stability standpoint by the larger, dominant channel materials. The armored riffles of such systems, although not fixed, provide a great deal of vertical and, to a lesser extent, lateral stability to the stream system. From a sediment transport perspective, these systems are bi-modal. That is, the larger rock particles are moved only during bankfull or higher discharge conditions and travel along the bottom of the channel by saltation, rolling, or sliding (referred to as bed load transport). Alternatively, sand and silt-clay particles in these bi-modal systems are put into suspension much more easily and are transported downstream through the entire vertical water column, though not uniformly, once they are suspended (referred to as suspended load transport). These mono-modal systems are very unstable, since the dominant channel materials are frequently lifted from the channel bottom and transported as suspended sediments at channel velocities well below bankfull discharge conditions. As a result, the streams are far more mobile, dynamic, and unstable than those with more stable grave/cobble/boulder covered riffles. Stream stability for such sand/silt-clay systems is much more dependent on the ability of the stream to lower the channel slope through sinuosity, to access broad floodplains, and bank protection provided by dense, well-rooted vegetation.

Consolidated marine clay outcrops were observed as dominant features in streams throughout the 22 Harris County watersheds. These outcrops have created fairly unique fluvial geomorphological conditions in the stream channels where they occur. The outcrops are typically exposed by down-cutting streams and usually exhibit as perpendicular, or slightly askew riffles in the range of 20 to 50 ft in length within the stream longitudinal profile. These clay riffles are moderately plastic. As such, the riffles are very cohesive in their wetted conditions and are acting as slowly melting bedrock grade controls in the affected streams.

Streams that are being influenced by the clay outcrop riffles were designated as 5/6 stream types in the study, relative to dominant channel material. This designation implies that the dominant channel materials transported through the system are sand, but that these clay riffle features are preventing the stream from functioning as a purely alluvial system.

The streams in Harris County exist in both natural and man-made valley settings. Using the Valley Classification System developed by Rosgen (Rosgen, 1996), natural stream/valley systems include:

- Smaller streams, including most headwater tributaries, at the upstream boundaries of watersheds that have access to the surface soils of the coastal plains (Valley Type X).
- Streams within terraced valleys (Type VIII) near their coastal outfalls, which have formed as the streams incised slowly in response to the gradual uplift which occurred across Texas during the last 1 million years.
- Some larger streams in the middle portions of watersheds, where the valleys are transitioning to the well-developed Type VIII valleys at the lower end of the watersheds. These systems are highly incised into the coastal plain terrace and are often in an unstable, transitional phase. In strict accordance with the Rosgen classification system, they would be classified as incised Type X valleys. However, to provide a more meaningful classification in relation to valley types in Harris County, they were classified as Type X/VIII valleys in the study.
- Small- to medium-sized streams that drop their elevations relatively rapidly from coastal plains headwaters to the larger, incised, and well-developed Type VIII terraced valleys and the transitioning Type X/VIII valley systems formed by the larger streams, as described above. The valleys of these streams are very similar to Rosgen Type II valleys. Again, in strict accordance with the Rosgen classification system, they would be classified as Type X valleys with incised/entrenched streams. However, to provide a more meaningful classification in relation to valley types in Harris County, they were classified as Type X/II valleys in the study.

Numerous channels in Harris County were excavated as straightened, deepened trapezoidal channels in the last century to improve drainage and flood control capacities. Where these channels were left unarmored, they are acting as manmade valleys for the re-naturalizing streams within. These “stream within a ditch” systems present some of the primary reaches the District has identified for potential stabilization or enhancement using NCD methodologies. As such, an assessment of these manmade valleys was included in the study. Man-Made stream/valley systems in Harris County include:

- Streams within excavated, trapezoidal channels that are sufficiently large in comparison to the drainage area of the channel, such that quasi-stable E, C, and Bc streams have formed or are forming in the bottom of the over-excavated channel, including re-meandering. These “stream within a ditch” systems have access to a new, accessible terraced floodplain forming or formed in the bottom of the larger flood control channel. These valleys have the same characteristics as the natural Type X/VIII valleys described above and they were classified as Type X/VIII(M) (M for manmade) valleys in the study.
- Streams within excavated, manmade channels that are not sufficiently large in comparison to the drainage area of the channel, such that the streams are too large to

develop a new, terraced floodplain in the bottom of the channel. Instead, their primary lateral reworking actions, meandering, typically results in undercutting of the manmade valley walls and massive bank sloughing that usually requires significant channel maintenance projects. As such, they have the same characteristics as the natural Type X/II valleys described above and were classified as Type X/II (M) valleys in the study.

Maintenance Engineering Projects

Eight NCD projects have been designed by the Maintenance Engineering Department since 2006. These projects have all been on natural or naturalized streams. The design approaches varied between the projects based on site conditions, available data, and project objectives. Details of these projects are provided below.

CYPRESS CREEK AT MEYER PARK – PHASE 1

Cypress Creek is a large stream at the project location with a drainage area of approximately 248 square miles and a bankfull discharge of 1,853 cubic feet per second (cfs). At the time of the design, the stream resided in a generally unstable Type X/VIII valley as a G5c stream. Like most natural or naturalized streams in Harris County, the stream was responding to significant hydromodification (primarily development and channelization of tributaries) in its watershed. It did not have sufficient access to a bankfull floodplain (incised and entrenched), resulting in massive bank erosion. This bank erosion located along an outer bend of Cypress Creek, was threatening the adjacent Elizabeth Kaiser Meyer Park infrastructure, as shown in Figures B1 and B2.

The project objectives were to restore approximately 1,400 feet of the failing stream to a stable dimension, pattern and profile and to construct a new bankfull floodplain bench at a new, lower elevation, thereby reducing the erosional forces on the outer valley walls. The channel design consisted of single trapezoidal cross-section for a single, very long (but appropriate) meander bend pool. At the time of design, no regional hydraulic geometry curves were available. A quasi-suitable reference reach was identified and used to develop the channel dimensions. The design discharge was estimated using recurrence interval analysis of peak annual discharge as the surrogate for channel-forming discharge. Threshold (immobile) riprap toe protection was prescribed for both channel banks to ensure channel stability. Constructed wetlands were designed on the new bankfull floodplain bench to capture and provide water quality treatment for stormwater runoff from the upper terrace. Extensive vegetation in form of broadcasted Bermuda grass, buffalo grass sod, shrubs, and trees completed the project.

Figure B1: Cypress Creek at Meyer Park – Phase 1, North Bank, Pre-Construction

Figure B2: Cypress Creek at Meyer Park – Phase 1, South Bank, Pre-Construction

Since construction was completed in 2006, the project has performed very successfully. The restored reach has experienced numerous channel-forming or higher flows without any channel or valley wall erosion. Figures B3 and B4 show before and after photos of the project and were taken from the same location and perspective.

Construction costs were approximately $1,500,000, or $1,250 per foot. Design costs for the project were approximately $241,000 or 16% of the construction costs.

Figure B3: Cypress Creek at Meyer Park – Phase 1, Before Restoration

Figure B4: Cypress Creek at Meyer Park – Phase 1, After Restoration

CYPRESS CREEK AT MEYER PARK – PHASE 2

This project is approximately 2,200 feet in length and is located directly downstream of the Cypress Creek at Meyer Park – Phase 1 project described above. The project setting and objectives were identical to the Phase 1 project, with the added objective to establish vertical grade control in the Phase 2 stream reach and the downstream end of the Phase 1 reach. The U.S. Army Corps of Engineers' (the Corps') effective discharge analysis (Biedenharn et al., 2000) was performed to approximate the channel-forming discharge for design. Suspended sediment rating curves for the analysis were developed using suspended sediment data the Corps had collected over many years at a USGS gage station located on Cypress Creek downstream of the project reach. Rosgen's Flowsed/Powersed Prediction Models for Suspended and Bedload Transport (Rosgen, 2006) were utilized for hydraulic geometry design, using the Phase 1 pool cross-section design as the first iteration. A natural marine clay outcrop in an upstream reach provided the model for threshold rock cascade riffle/grade control structures through the project reach for channel stabilization in conjunction with excavation of a bankfull floodplain bench. Threshold riprap toe protection for Phase 2 was reduced to only the outside banks of meander bends.

The project is under construction at the time of this writing. Construction costs for the 2,200 foot project are $1,449,400, or $658 per foot. Design costs for the project were approximately $470,000, or 32% of the total construction costs.

TRIBUTARY TO BIG GULCH BAYOU

The project reach, approximately 1,800 feet in length, is a small, highly degraded urban drainage channel located between a County Nature Park and two schools. Flash loading from the tributary's watershed, a completely suburbanized headwater system totally confined in a stormsewer system and equipped with no storm water detention capacity, has resulted in the dramatic downcutting of the channel into the landscape (up to 45 feet deep), resulting in dangerous sheer slopes and soil erosion, as shown in Figures B5 and B6, which threatened both the park and the schools. Additionally, the stream has eroded very old deposits of early 20th century rubble heap/burns containing large amounts of glass and ceramic containers (the rubble heaps were deposited before the age of plastics). The stream had worked these massive amounts of glass/ceramics as though they were gravel and has created glass/ceramic shard-coated point bars and stream riffles for over 2,000 linear feet, even into the Big Gulch Bayou, an incredibly unique situation. The restoration of such urban streams is always challenging because of the negatively-affected hydrology of the urbanized watershed and the lack of space to accommodate improvements. The exposed rubble heaps and extensive amount of glass/ceramic shards being worked through the stream system only exacerbate the problem.

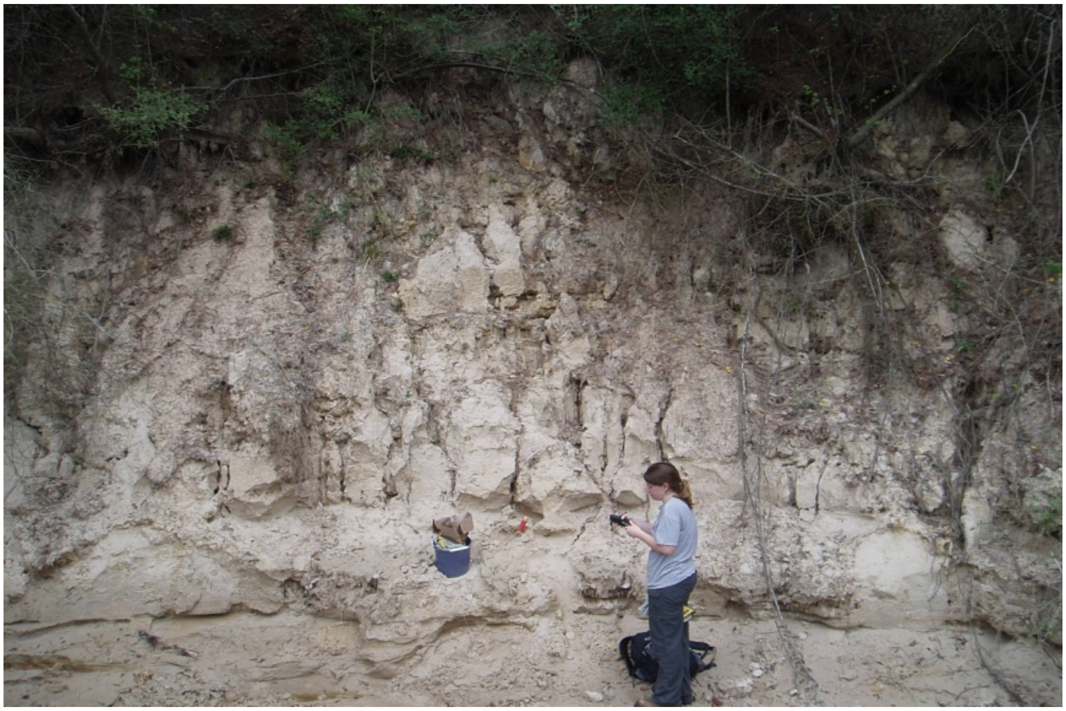


Figure B5: Tributary to Big Gulch Bayou, Failing Channel Banks

Figure B6: Tributary to Big Gulch Bayou, Sheer Slopes

The design for this project has been completed, but the project has not been scheduled for construction to date. The core of the project will be a quasi-natural, exaggerated step-pool grade-drop channel from the upstream storm sewer outfall to the natural receiving stream. The channel will consist of short segments of “threshold” rock cascade riffles (Rosgen Type B) and longer reaches of meandering, zero-slope, sand-bed, three-stage channels (Rosgen Type E). Geomorphological assessment of nearby stable, and quasi-stable reference reaches, in conjunction with synthetic rainfall/runoff hydrologic simulations in SWMM, were used to develop the dimensionless hydraulic (cross-sectional) and planform geometries and channel-forming design discharge, respectively, necessary for channel design. Sediment transport analysis of the predicted stability of the project reach was based on a “clear water” design, assuming no net sediment input to, or conveyance out of, the system. The project includes the installation of an end-of-pipe floatables and trash screening system on the culverts that outfall to the upstream end of the project.

The Engineer’s Estimate of construction costs for the 1,800 foot project, excluding right-of-way acquisition costs, is $1,119,750, or $622 per foot. If the costs for the floatables/trash trap system are excluded, the Engineer’s Estimate of construction costs reduces to approximately $943,125, or $523 per foot or 32% of the total construction costs. Design costs for the project, including the floatables/trash trap system, were approximately $215,000, or 19% of the total construction costs.

BUFFALO BAYOU AT SABINE STREET

This project is located just upstream of downtown Houston within Eleanor Tinsley Park. The 1,200-foot project reach is subjected to frequent overbank sedimentation due to excessive sediment loads from massive bank failures on upstream reaches of Buffalo Bayou, its location in a tidal influence zone, and backwater conditions from the downstream confluence with White Oak Bayou during storm events. The buildup of sediments had removed good floodplain access and resulted in some band erosion, as shown in Figure B7. The project reach has a drainage area of approximately 180 square miles and a channel-forming discharge of approximately 1,950 cfs. The project consisted of re-establishment/excavation of a bankfull floodplain bench on both banks and removal of invasive species and planting of native riparian vegetation. Bankfull elevations were established using gage calibration methods and data from a USGS gage station upstream of the project. Figure B8 shows the project after construction.

Construction costs for the 1,200 foot project were approximately $245,000, or $204 per foot. Design costs for the project were approximately $177,000, or 72% of the total construction costs.

Figure B7: Bank Erosion on Buffalo Bayou at Sabine Street

Figure B8: Buffalo Bayou at Sabine Street – Just After Construction, Prior to Planting

BUFFALO BAYOU – SHEPHERD DRIVE TO SABINE STREET

This project is continued and expanded the restoration of Buffalo Bayou from just upstream of the Sabine Street project to Shepherd Drive, a length of approximately 12,144 feet. This project reach is incised and entrenched and, unlike the Sabine Street reach, has numerous sections with eroding, failing channel banks. The project not only includes excavation of bankfull floodplain benches on incised sections and removal of invasive species and planting of native riparian vegetation, but also some channel realignment and extensive bank stabilization using bioengineering prescriptions. The design of this project occurred after the completion of the countywide fluvial geomorphological study described above. As such, the design team was able to use the regional hydraulic geometry curves developed in the study to develop first design iterations for realigned and reshaped channel sections. Channel-forming discharges developed in the Sabine Street project were checked using effective discharge analysis, where the suspended sediment rating curves developed on the Cypress Creek at Meyer Park - Phase 2 project described above.

The project is under construction at the time of this writing. Construction costs for the 12,144 foot project are $5,145,000, or $423 per foot. Design costs for the project were approximately $900,000, or 17% of the total construction costs.

BUFFALO BAYOU – MEMORIAL PARK DEMONSTRATION PROJECT

This 7,880-foot (175 square mile drainage area) project is located upstream of Shepherd Drive and is largely located between Memorial Park and the River Oaks Country Club. The project is unique in that the objectives are to demonstrate a full Priority 2 restoration (i.e., restore dimension, pattern, and profile with a new, lower bankfull floodplain bench within the larger Type X/VIII valley). Further, a water quality monitoring program will be used to document improvements to water quality as a result of the project. Massive bank erosion/failure throughout the project reach (refer to Figure B9) is threatening both the park and the River Oaks Country Club, as well as several private residences and the Hogg Bird Sanctuary, which are located downstream of the country club and the park. The project is being funded as a public/private partnership between the HCFCD, the City of Houston, and the River Oaks Country Club. The project design utilized the latest NCD methods and included lowering the width/depth ratio of the stream to a more efficient channel, constructed log riffles, bankfull floodplain benches, and the widespread use of toe wood installation on channel banks. Reference reaches identified and surveyed in the countywide fluvial geomorphological study, as well as the regional hydraulic geometry curves, were used to facilitate a modified analog design. Channel geometries and sediment transport competency and capacity were verified using Rosgen's Flowsed/Powersed Prediction Models for Suspended and Bedload Transport (Rosgen, 2006).

Figure B9: Bank Erosion/Failure on Buffalo Bayou at Memorial Park

This project is in the final design stage and is scheduled to go to construction within the next six to 12 months. The 80% design Engineer's Estimate for construction costs for the 7,880 foot project are $5,065,400, or $643 per foot. Design costs for the project were approximately $900,000, or 18% of the total construction costs.

LITTLE VINCE BAYOU – WITCHITA STREET TO PASADENA BLVD.

Little Vince Bayou is a natural stream channel that has been historically channelized and straightened to improve conveyance (Figure B10). Little Vince Bayou is located in Pasadena, Texas and is a tributary to Vince Bayou. Little Vince Bayou between Cherry Brook Lane and Wichita Street was experiencing heavy erosion and slope instability. Due to constrained right-of-way and other factors, it was determined that 870 feet of low flow channel would be need to be concrete-lined to stabilize the eroding channel. As mitigation for this impact to the stream channel, the reach downstream of Wichita Street to Pasadena Boulevard was enhanced with rock cross-vanes and deep pools to improve channel stability and habitat (Figure B11). The enhancement reach is a grass-lined, channelized stream.

The enhancement project was designed by District engineers in the Maintenance Engineering Department. Approximately 1,300 feet of channel enhancement was constructed from Wichita Street to Pasadena Boulevard. A total of three rock cross-vanes were installed using pre-cast concrete blocks and a base of granular fill and rip-rap. Deep pools were constructed for habitat to a depth of 2 feet below existing water surface. Pool length ranged from 20-25 feet long. Construction cost for the rock vanes and pools was $14,784. Construction was completed in 2010, and initially some flow was going around the outside end of the cross-vanes arms.

However, the vanes are performing well now by directing flows into the center of the channel and building up deposits around the outside ends of the vanes.

Figure B10: Little Vince Bayou (before)

Figure B11: Little Vince Bayou (after)

RUMMEL CREEK – EDITH L. MOORE NATURE SANCTUARY

Rummel Creek is a tributary to Buffalo Bayou in west-central Harris County. Rummel Creek in the Edith L. Moore Nature Sanctuary was experiencing significant bank erosion and instability (Figure B12). NCD alternatives were considered at the project outset to maintain the natural setting of the nature sanctuary, which included a mature riparian corridor with trails and a footbridge. Construction access to the project site was difficult due to the forested corridor along both sides of the channel and steep slopes.

Approximately 570 feet of channel were restored in several segments to repair erosion and stabilize banks. A rock cross-vane composed of square granite boulders was used to direct flows away from the repaired channel slopes along the approach to the nature sanctuary footbridge (Figure B13). Throughout the reach, eroded slopes were laid back and stabilized with erosion control matting, rock toe protection, and native riparian trees. Construction costs totaled $376,418 or $660 per linear foot. Project construction was completed in 2008 and the site has performed well since that time. The restored banks are stabilized with riparian vegetation and the cross-vane is functioning as designed.

Figure B12: Rummel Creek, eroded bank

Figure B13: Rummel Creek after stabilization (2012)

Capital Improvement Projects

Two NCD projects have been implemented by the District as capital projects. The Vogel Creek project expanded channel capacity for flood control conveyance and provided NCD for improved stability and long-term sustainability. The Mason Creek Extension Project created a new channel for improved drainage and used available right-of-way for a NCD corridor. Details of the projects are provided below.

VOGEL CREEK – ARNCLIFFE DRIVE TO WHITE OAK BAYOU

Vogel Creek is a principal tributary to White Oak Bayou located in north central Harris County, partially within the corporate limits of the City of Houston. The contributing drainage area to the channel is 8.49 square miles. The project limits include Vogel Creek from the downstream confluence with White Oak Bayou to Arncliffe Drive, a distance of approximately 8,300 feet.

Between 1958 and 1966, portions of Vogel Creek have been cleared, straightened, and enlarged by the District. A 1976 USACE Report identified the need for additional conveyance improvements to Vogel Creek, which included the recommendation for partial concrete lining. Frequent overbank flooding events in the 1980s – 2000s, including Tropical Storm Allison in June, 2001, resulted in a FEMA funded voluntary buyout program with many adjacent property owners electing to participate. As a result of the additional property acquired through the buyout program, a larger grass-lined corridor with low flow pilot channel was identified as an alternative. The grass-lined channel alternative was determined to be cost effective and more favorable to the Texas Commission on Environmental Quality (TCEQ) for permitting.

The overall channel was widened to 150-165 feet and deepened 2-5 feet. Side slopes were constructed at 4(H):1(V). A meandering low flow pilot channel was constructed in the bottom of the expanded channel corridor with riffles and pools. Geomorphic benches provide a location for sediment deposition and reduce erosion by providing a new floodplain. Native trees were planted to provide riparian habitat. The final phase of construction was completed in 2008 with a total construction cost of $9,000,283 or $1084 per foot. Design costs were $1,223,823 or 14% of the total construction costs. To date, the project has performed well. Some minor natural adjustments by the meandering low flow channel have been observed through monitoring, and establishment and growth by the planted trees has been very successful.

MASON CREEK EXTENSION

The Mason Creek Extension Project lengthened Mason Creek from its original end near Trotter Drive to the Katy Hockley Cutoff Road near Katy Park. The project included the construction of an in-line regional stormwater detention basin with stormwater quality enhancement features. The Mason Creek extension upstream of Porter Road included 3,750 feet of NCD.

The channel corridor was constructed with a meandering pilot channel in the bottom and planted with native woody riparian vegetation (Figures B14 and B15). The pilot channel layout was not designed in detail, instead, a general design was conducted and space was provided for the pilot channel to adjust to current and future flow and watershed conditions. The corridor was constructed with varying side slopes and a curvilinear top of bank. Construction began in 2002 and was completed in 2005 for a total cost of $5,097,203, including construction of the 95-acre detention basin. Design costs were $161,745 or 3% of total construction cost. The project has performed well with some minor natural adjustments by the meandering low flow channel observed through monitoring. The riparian vegetation has been very successful with some minor maintenance of nuisance and invasive species required.

Figure B14: Mason Creek Extension

Figure B15: Mason Creek Riparian Corridor

Appendix C

Landscape-Based BMP Summary Table

SOURCE: WATERSHED PROTECTION FOR TEXAS RESERVOIRS: ADDRESSING SEDIMENTATION AND WATER QUALITY RISKS (TWDB CONTRACT #:1004831120)

APPENDIX C: LANDSCAPE-BASED BMP SUMMARY TABLE FROM Watershed Protection for Texas Reservoirs: Addressing Sedimentation and Water Quality Risks
(TWDB contract #:1004831120)

Landscape-Based BMP	Type of BMP	Total Suspended Solids (TSS) Removal	Watershed/Regional Characteristics										Planning-Level Costs						Level of O&M	O&M Comments
			Soil Types			Depth to SH Water Table	Land Use			Land Slope (%)			New Dvlpt. ($/impervious ac)	Retrofit ($/impervious ac)	Volume-Based $/CY Storage	Area-Based $/Acre of Facility	O&M[3] ($/impervious ac)	O&M[4] ($/5-acre facility)		
			Ideal	Acceptable	Allowable		Ideal	Acceptable	Allowable	Ideal	Acceptable	Allowable								
Extended Detention	Centralized	75[EA]	ABCD			>5	com/res	ag/os/ugrs	ind/trans/bs	0-3	3-7	7-10	---	---	5 - 10	---	---	2,020	low - med	shallow detention basin mowing w/ structural components
Retention-Irrigation	Centralized	100[EA]	AB	C	D	>5	com/res	ag/os/ugrs	ind/trans/bs	0-3	3-7	7-10	---	---	5 - 10	---	---	2,020	high	irrigation system, vegetation maintenance, detention/retention basin
Stormwater Wetlands	Centralized	68[CPR]	D	C	AB	0-2	os/ag/ugrs	res/com/trans	f/ind/bs	0-2	2-5	5-8	---	---	---	26,000 - 55,000	---	2,630	med - high	vegetation maintenance, periodic sediment removal
Wet Ponds	Centralized	65[CPR]	D	C	AB	>5	os/ugrs/ag	res/comm/trans	f/ind/bs	0-3	3-7	7-10	---	---	5 - 10	---	---	3,090	med - high	periodic sediment removal, vegetation
Bioretention	Distributed/De-Centralized	85[CPR]	AB	C	D	>5	res/com/trans	os/ugrs	f/ag/ind/bs	0-3	3-7	7-12	110,000	160,000	---	---	3,100	---	med - high	similar to high-end vegetation w/ structural components
Green Roofs	Distributed/De-Centralized	Preventative BMP	ABCD			0+	com/ind	res		0+			250,000	500,000	---	---	4,000	---	med	vegetation maintenance, irrigation, inspections
Infiltration Trenches/Dry Wells	Distributed/De-Centralized	95[CPR]	A	B	C	>4	com/res	trans	ind/bs	0-5	5-10	10-15	110,000	160,000	---	---	2,900	---	med	sediment removal
Permeable Pavement	Distributed/De-Centralized	93[EA]	AB	C	D	>3	com/trans	res	ind/bs	0-2	2-3	3-5	110,000	160,000	---	---	2,400	---	med	requires vaccuum sweeping equipment twice per year
Vegetated Swales	Distributed/De-Centralized	70[EA]	ABCD			>5	res/os/ugrs/ag/trans	com	f/ind/bs	0-5	5-10	10-15	110,000	160,000	---	---	3,100	---	low - med	similar to vegetation
Soil Amendments/Conservation Tillage	Site-Wide	Preventative BMP	ABCD			0+	ag/bs/os/ugrs	res	trans/comm/ind	0-5	5-10	10-15	50,000	50,000	---	---	3,100	---	low	mowing, vegetation maintenance, aeration, amending/deep tilling for clogging
Sediment/Erosion Control (Vegetative/Cover Options)	Site-Wide	80 - 99[NC]	ABCD			0+	ag/bs	os/ugrs/res	trans/comm/ind	0+			---	---	---	0 - 8,000 (Construction + O&M/ac)		---	high	inspection and modify to continue functioning, monitoring, operating active treatment systems
Trees/Native Grasses/Conservation (Vegetated) Buffers	Site-Wide	80 - 94[NC]	ABCD			0+	ag/bs/os/ugrs	res/trans	comm/ind/f	0+			15,000	18,000	---	---	1,800	---	low	pruning, mulching, irrigation

Notes:
1. Land Use Categories refer to:
   - Agriculture = ag
   - Bare Soil = bs (may also include construction sites)
   - Commercial/Industrial/Transportation = com/ind/trans (Brownfields excluded for these purposes)
   - Forested = f
   - Low and High Intensity Residential = res
   - Open Space/Grasslands = os
   - Urban/Recreational Grasses = ugrs
2. TSS Removal rates based on the National Pollutant Removal Database/Other Sources Summarized by *Cost and Pollutant Removal of Storm-water Treatment Practices* (CPR) and the *Edwards Aquifer Authority Technical Guidance Manual* (EA). EA rates based on sizing methodology in Manual.
3. Construction and O&M costs per impervious acre treated are in 2009 dollars from *Planning-Level Cost Estimates for Green Stormwater Infrastructure in Urban Watersheds* .
   Bioretention construction costs used for Vegetated Swales.
4. Stormwater wetlands construction costsin 1999 dollars from *EPA Storm Water Technology Fact Sheet Storm Water Wetlands.*
5. Volume-based construction costs in $/cubic yard based in approximately 2006 dollars from *Costs of Urban Stormwater Practices* by Narayanan and Pitt, University of Alabama.
6. O&M costs per five-acre facility are in 2011 dollars from North Carolina State University's *Determining Inspection and Maintenance Costs for Structural BMPs in North Carolina* .
   Dry detention basin costs for 0.8 to 2.0-acre facilities listed for Retention-Irrigation and Extended Detention basins.
   Bioretention O&M costs used for Vegetated Swales and Soil Amendments/Conservation Tillage, although actual costs may be lower due to lack of structural components.
7. Level of O&M includes consideration for specialized and/or heavy equipment as a higher level of O&M. *Edwards Aquifer Authority Technical Guidance Manual* considered as starting point for consistency for those BMPs included in the Manual.
8. Depth to Seasonally High Groundwater Table (SHWT) based on minimum clearance of two feet below bottom of stormwater facility and SHWT as well as typical stormwater facility depths.
9. Construction costs for Soil Amendments/Conservation Tillage in 2005 dollars from *Fairfax County LID BMP Fact Sheet* .
10. Sediment/Erosion Control BMP includes Vegetative/Cover options only, such as: Preserve Natural Vegetation, Wood Fiber, Straw, Seed + Mulch, Permanent Vegetation, and Degradable Blankets. Costs do not encompass Sod or Blankets/Mats or include Sediment Basins, Filter Fabric, or Other Structural Measures associated with Construction-Phase BMPs.
11. Sediment/Erosion Control BMP cost includes construction and O&M from *Modeling Cost-effectiveness of Standard and Alternative Sediment and Turbidity Control Systems on Construction Sites: a Case Study from NC (NC)* by North Carolina State University.

Appendix D

Cost Trend Analysis of NCD versus Traditional Projects

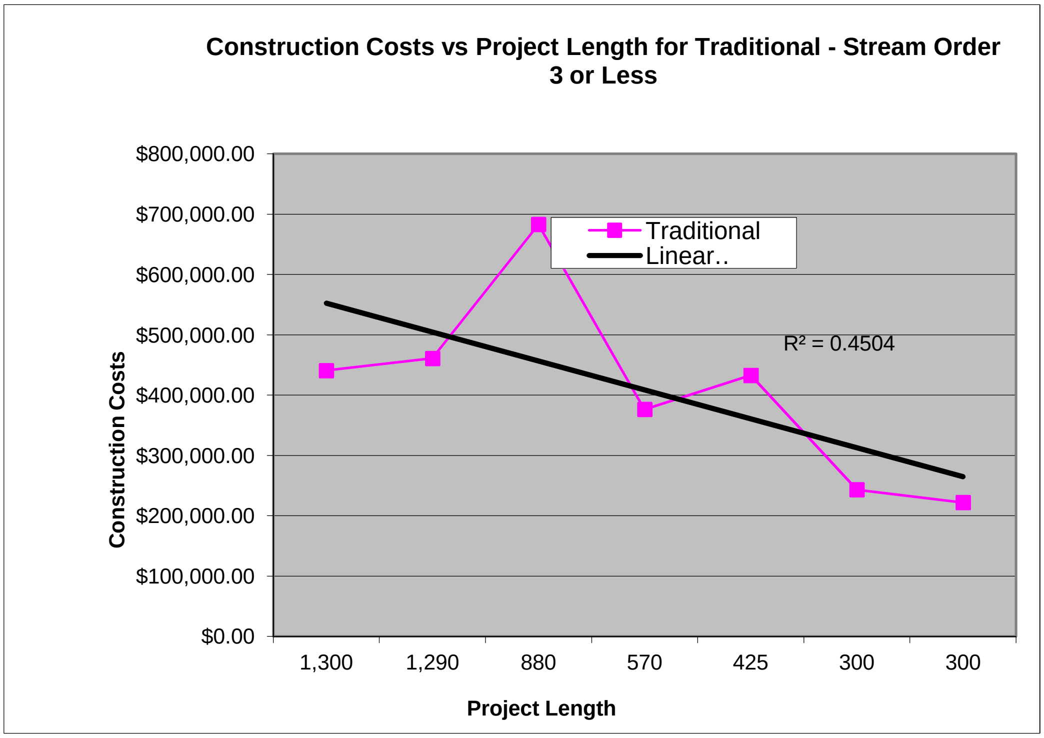
Appendix D - Cost Trend Analysis of NCD Versus

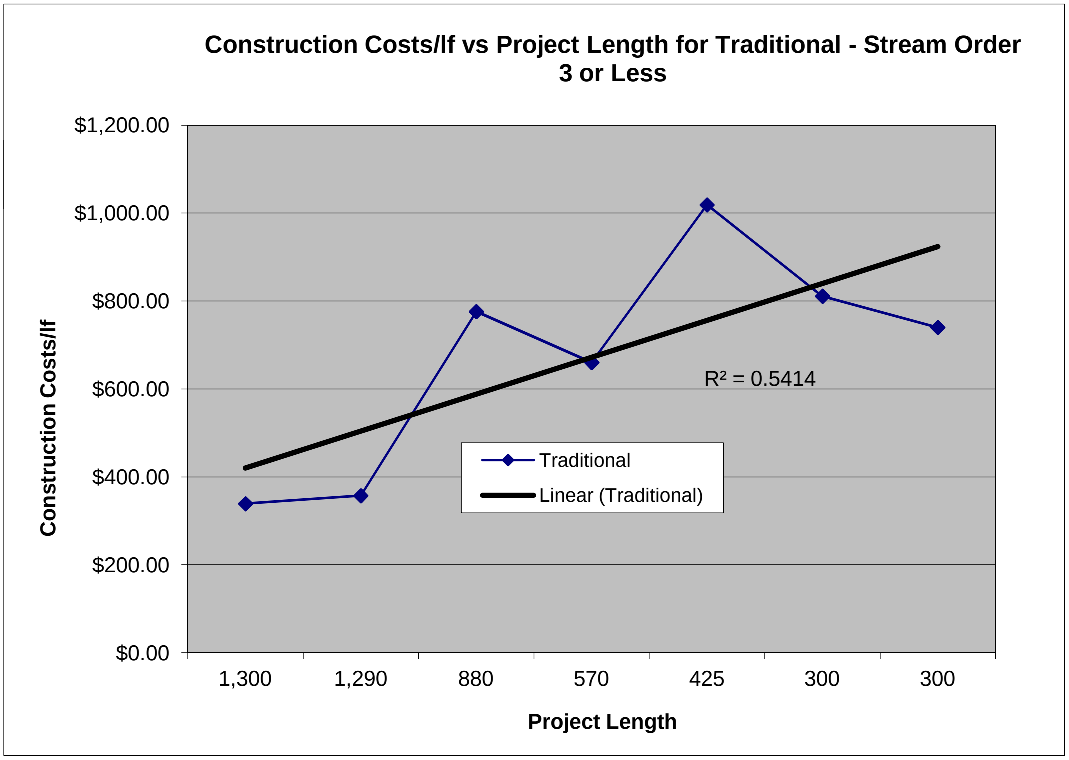
Harris County
Grand Prairie
San Antonio
Austin

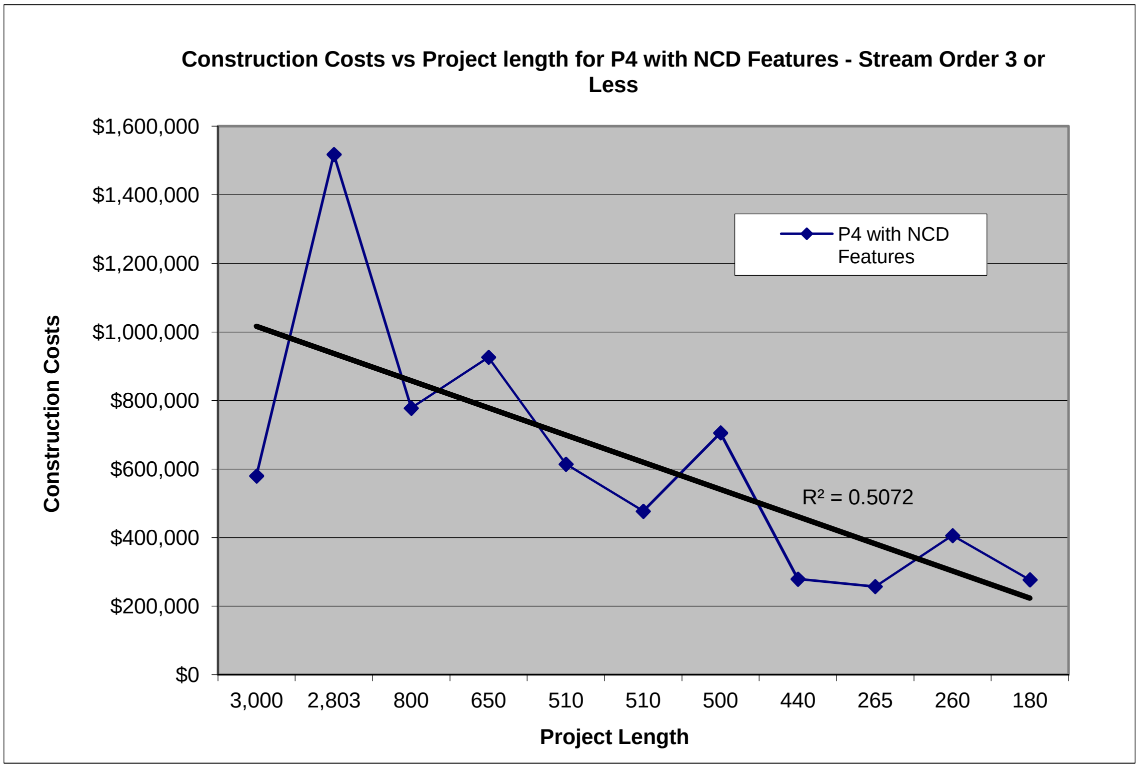
Comparison of NCD versus Traditional Project Costs for Stream Order No. 4 or Greater Projects

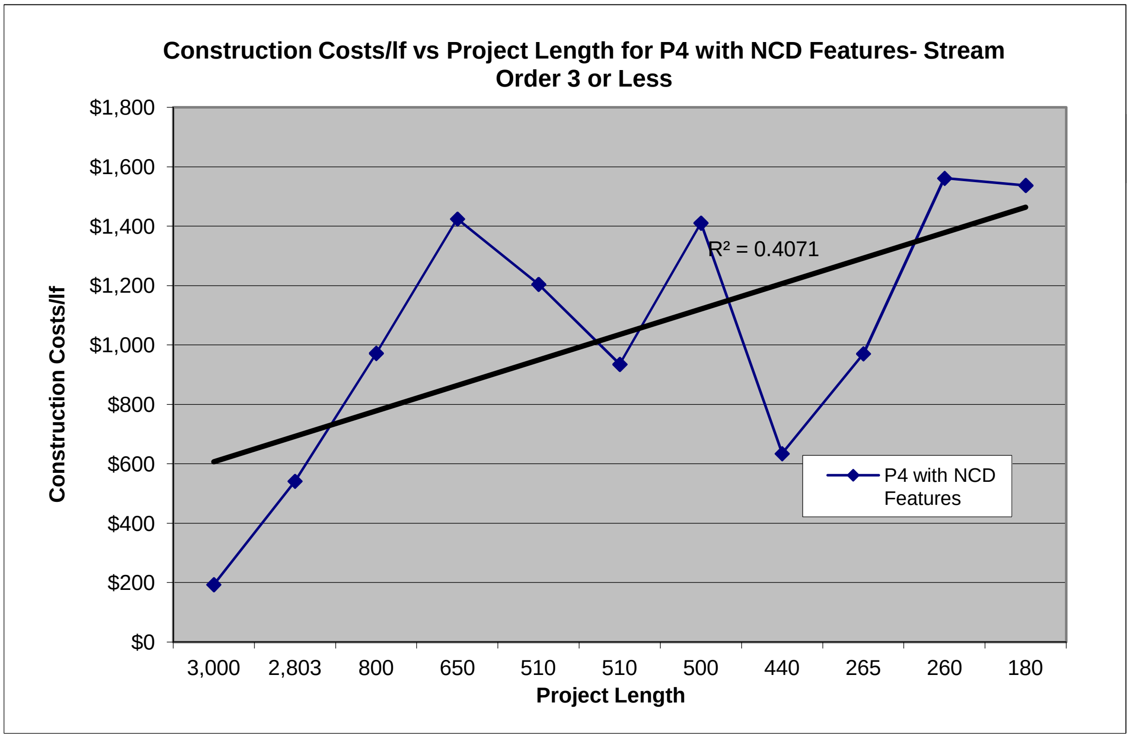
NCD - Stream Order 4 or greater	Priority Improvement	Project Length	Construction Costs	Construction Costs/lf	Design as % of Construction Costs	Design Cost	Design Costs/lf
Buffalo Bayou - Shepherd to Sabine	3	12,144.00	$5,145,000.00	$423.67	17.00%	$874,650.00	$72.02
Buffalo Bayou - Memorial Park Demonstration Project	3*	7,880.00	$5,065,400.00	$642.82	18.00%	$911,772.00	$115.71
Cypress Creek - Myer Park-Phase 2	3	2,200.00	$1,449,400.00	$658.82	32.00%	$463,808.00	$210.82
Cypress Creek - Myer Park-Phase 1	3	1,200.00	$1,500,000.00	$1,250.00	16.00%	$240,000.00	$200.00

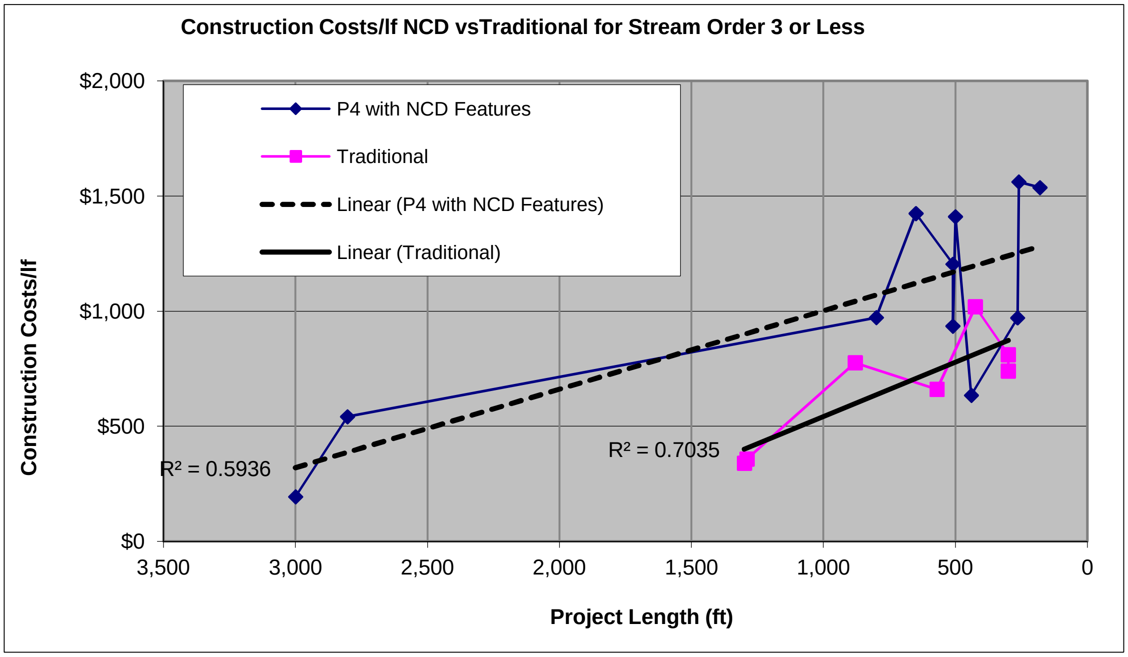
Traditional - Stream Order No.4	Priority Improvement	Project Length	Construction Costs	Construction Costs/lf	Design as % of Construction Costs	Design Cost	Design Costs/lf
Brays Bayou Federal Flood Control Project - Ardmore to Holcombe	4	8,800.00	$12,021,022.00	$1,366.03	6.00%	$721,261.32	$81.96
Buffalo Bayou @ Houston Country Club	4	1,450.00	$2,200,000.00	$1,517.24	15.00%	$330,000.00	$227.59
Cypress Creek Spot Repair (x043)	4	1,245.00	$485,632.00	$390.07	20.00%	$97,126.40	$78.01
Cypress Creek Spot Repair (x042) Fire Station	4	400.00	$226,613.00	$566.53	22.00%	$49,854.86	$124.64

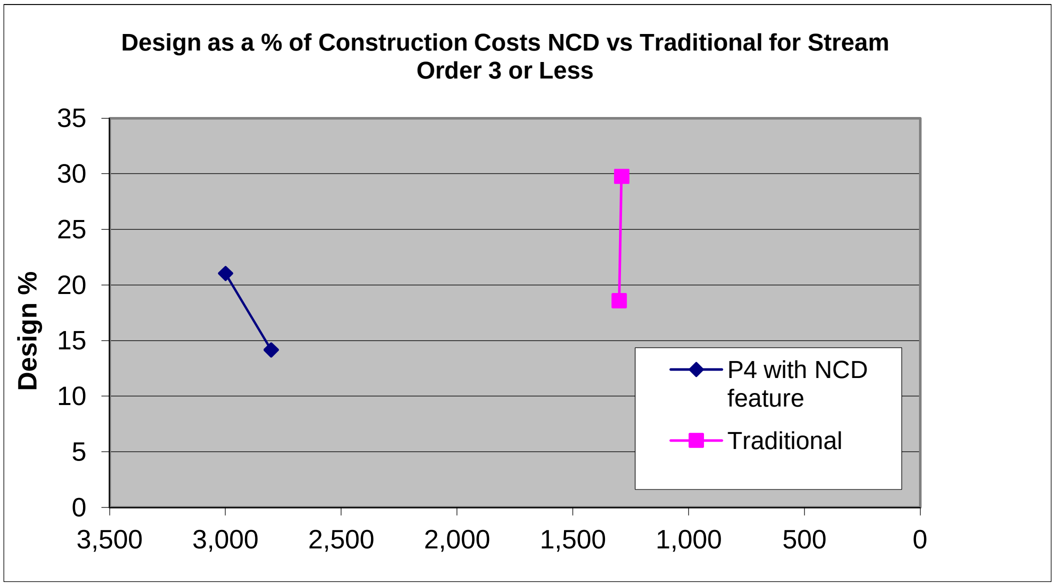

Construction Costs vs Project Length for Traditional - Stream Order 3 or Less
$800,000.00
$700,000.00
$600,000.00
$500,000.00
$400,000.00
$300,000.00
$200,000.00
$100,000.00
$0.00
Construction Costs
Traditional
Linear..
R² = 0.4504
1,300
1,290
880
570
425
300
300
Project Length

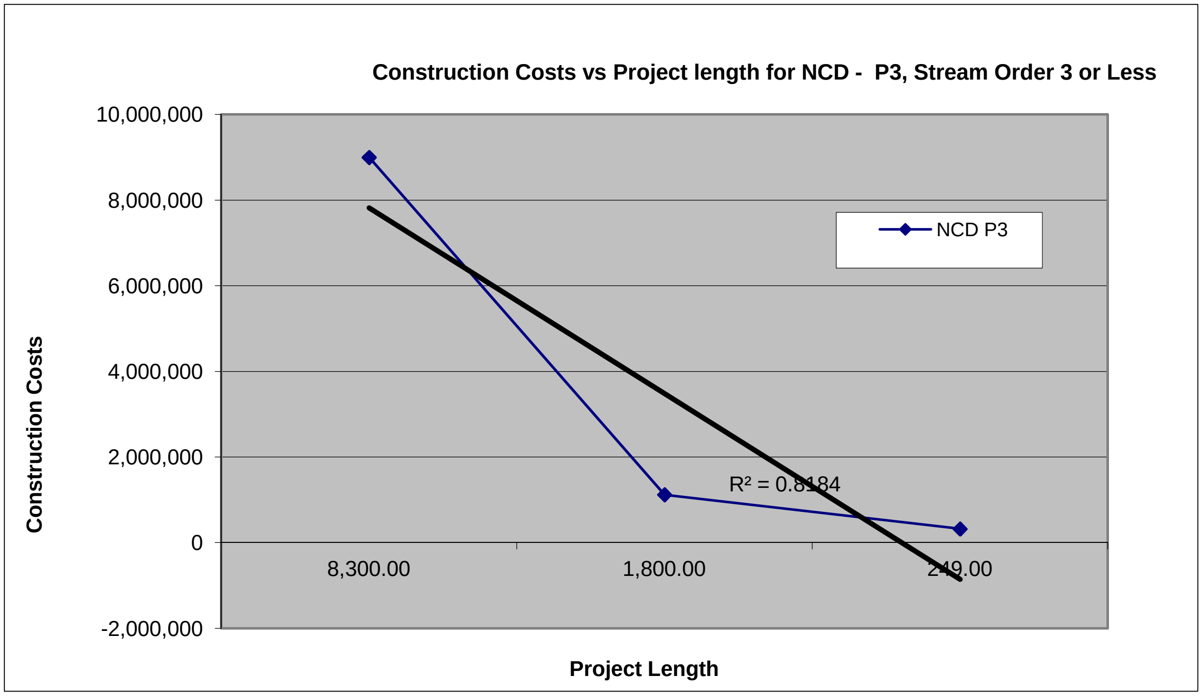

Construction Costs/lf vs Project Length for Traditional - Stream Order 3 or Less
$1,200.00
$1,000.00
$800.00
$600.00
$400.00
$200.00
$0.00
Construction Costs/lf
R² = 0.5414
Traditional
Linear (Traditional)
1,300
1,290
880
570
425
300
300
Project Length

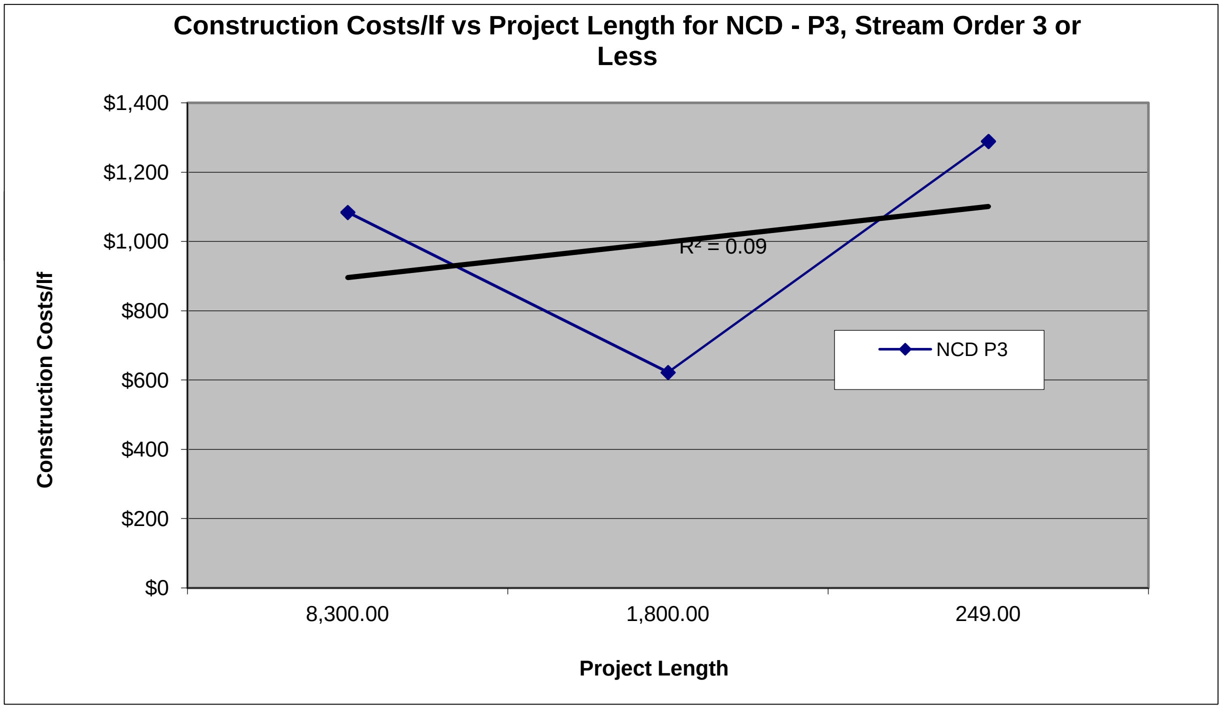

Construction Costs vs Project length for P4 with NCD Features - Stream Order 3 or Less

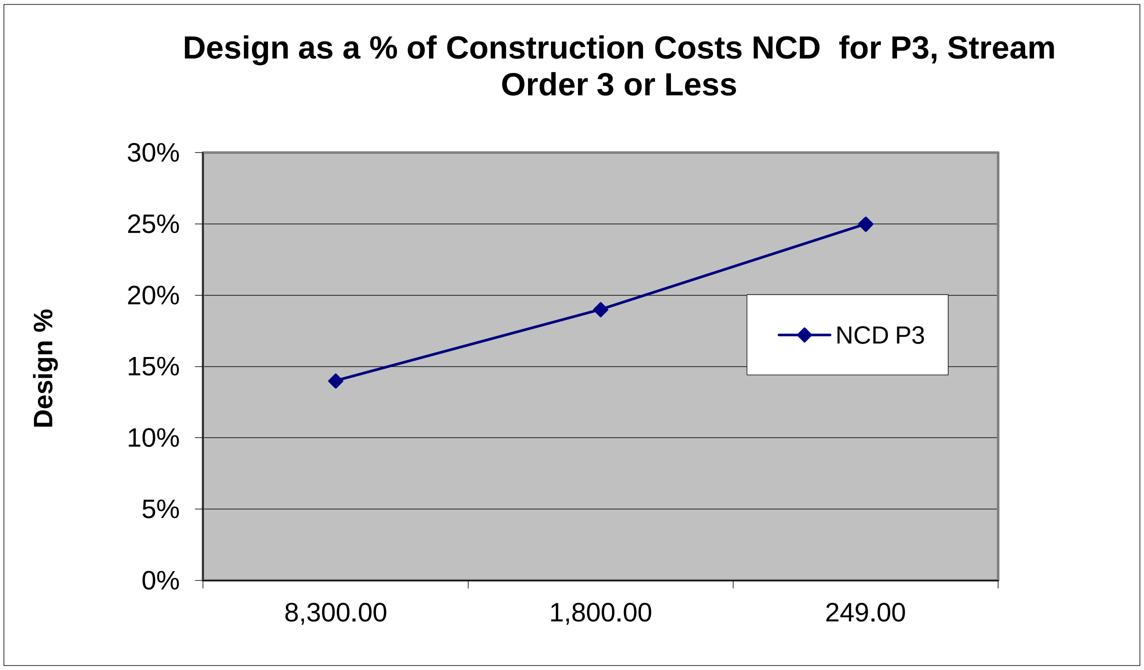

Construction Costs/lf vs Project Length for P4 with NCD Features- Stream Order 3 or Less


Construction Costs/lf NCD vsTraditional for Stream Order 3 or Less
P4 with NCD Features
Traditional
Linear (P4 with NCD Features)
Linear (Traditional)
Construction Costs/lf
$2,000
$1,500
$1,000
$500
$0
R² = 0.5936
R² = 0.7035
3,500
3,000
2,500
2,000
1,500
1,000
500
0
Project Length (ft)


Design as a % of Construction Costs NCD vs Traditional for Stream Order 3 or Less
Design %
35
30
25
20
15
10
5
0
3,500
3,000
2,500
2,000
1,500
1,000
500
0
P4 with NCD feature
Traditional


Construction Costs vs Project length for NCD - P3, Stream Order 3 or Less
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
-2,000,000
Construction Costs
NCD P3
R² = 0.8184
8,300.00
1,800.00
249.00
Project Length


Construction Costs/lf vs Project Length for NCD - P3, Stream Order 3 or Less
$1,400
$1,200
$1,000
$800
$600
$400
$200
$0
Construction Costs/lf
R² = 0.09
NCD P3
8,300.00
1,800.00
249.00
Project Length


Design as a % of Construction Costs NCD for P3, Stream Order 3 or Less
Design %
30%
25%
20%
15%
10%
5%
0%
8,300.00
1,800.00
249.00
NCD P3

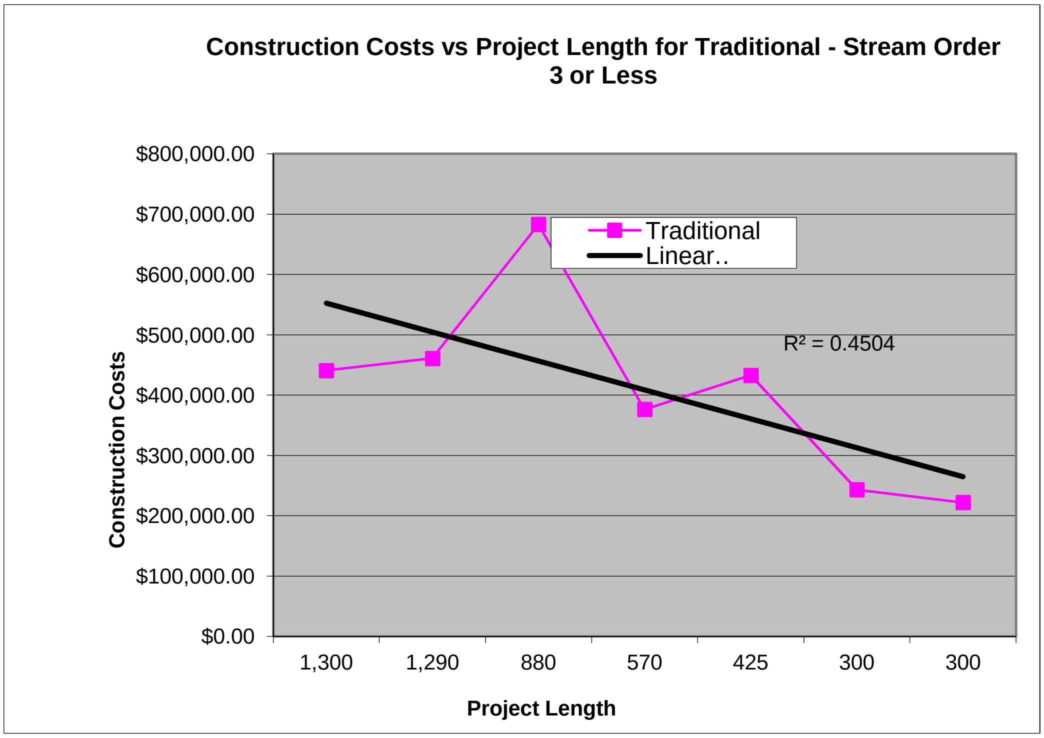
Harris County
Grand Prairie
San Antonio
Austin

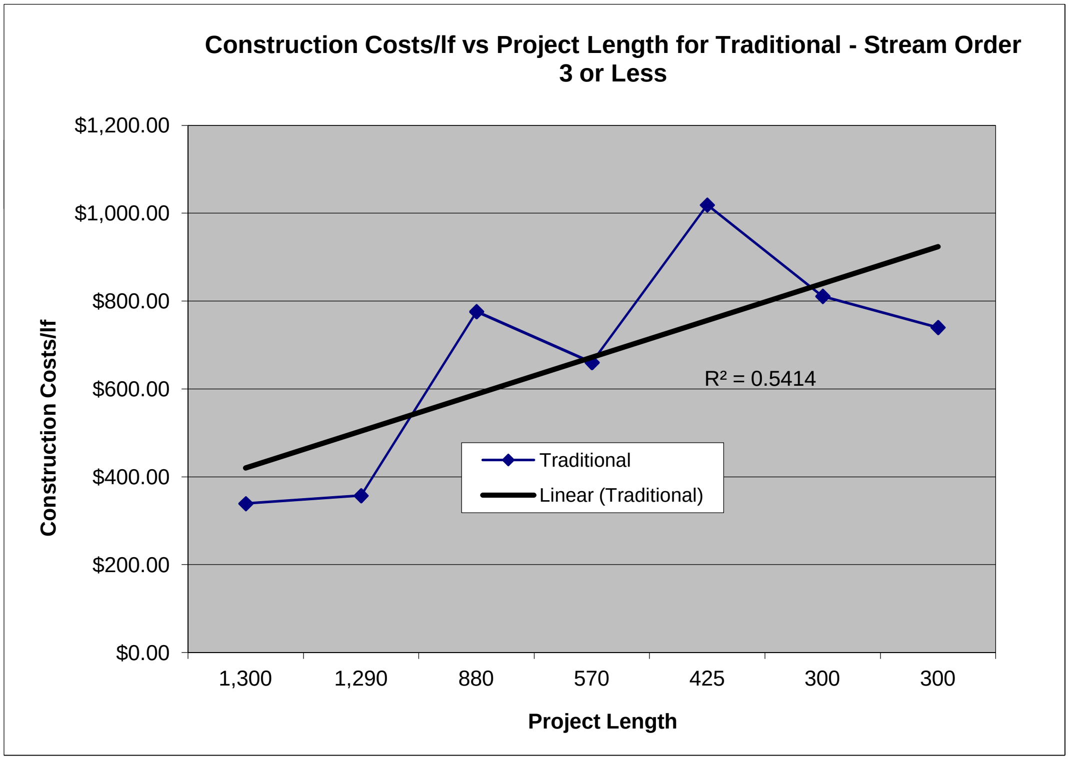
Comparison of NCD versus Traditional Project Costs for Stream Order No. 3 or Less Projects

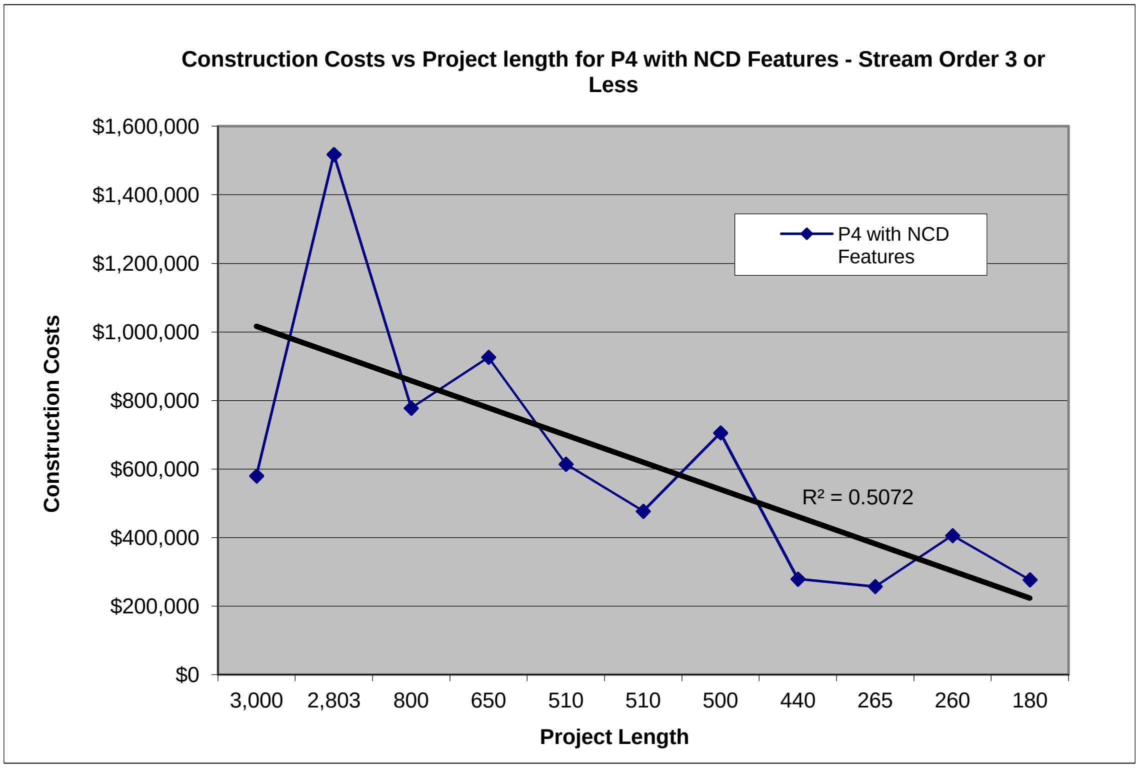
NCD Features - Stream Order 3 or Less	Priority Improvement	Project Length	Construction Costs	Construction Costs/lf	Design as % of Construction Costs	Design Cost	Design Costs/lf
Kirby Creek	4	3,000.00	$580,000.00	$193.33	na	na	na
Shoal Creek - Northwest Park	4	2,803.00	$1,518,034.00	$541.57	in house	na	na
Little Walnut Creek - Erosion Control Ph. 3 - Bridgewater Dr.	4	800.00	$777,770.00	$972.21	in house	na	na
Shoal Creek Bank - West Ave. to 5th Street Stabilization	4	650.00	$926,000.00	$1,424.62	21.06%	$195,015.60	$300.02
Shoal Creek - Redgelea Bank Stabilization	4	510.00	$614,410.00	$1,204.73	in house	na	na
Fort Branch - Manor Road Emergency Project	4	510.00	$477,000.00	$935.29	in house	na	na
Little Walnut Creek - Erosion Control Ph. 7 - Lakeside	4	500.00	$705,370.00	$1,410.74	in house	na	na
Tannehill Branch Givens Park Streambank Stabilization	4	440.00	$279,150.00	$634.43	in house	na	na
Little Walnut Creek - Loyola Lane Erosion Stabilization	4	265.00	$257,180.00	$970.49	in house	na	na
Tannehill Branch - Manor Circle Emergency Bank Stabilization	4	260.00	$406,000.00	$1,561.54	14.18%	$57,570.80	$221.43
Shoal Creek - 5th Street Bridge Erosion Stabilization	4	180.00	$276,700.00	$1,537.22	in house	na	na

Traditional - Stream Order 3 or Less	Priority Improvement	Project Length	Construction Costs	Construction Costs/lf	Design as % of Construction Costs	Design Cost	Design Costs/lf
SRP - Tannehill Branch Lower Bartholomew Park	4	1,300.00	$441,000.00	$339.23	in house	na	na
Williamson Creek - Pack Saddle Pass Tributary	4	1,290.00	$461,000.00	$357.36	na	na	na
Tannehill Branch Tributary Stabilization - Victoria	4	880.00	$683,000.00	$776.14	18.59%	$126,969.70	$144.28
Rummel Creek - Edith L. Moore Nature Sanctuary	4	570.00	$376,418.00	$660.38	in house	na	na
Shoal Creek - 26th Channel Improvements	4	425.00	$433,075.00	$1,019.00	29.78%	$128,969.74	$303.46
Tannehill Branch Highland Park Cemetary	4	300.00	$243,318.00	$811.06	in house	na	na
SRP - Waller Creek Shipe Park Erosion Project	4	300.00	$222,000.00	$740.00	in house	na	na

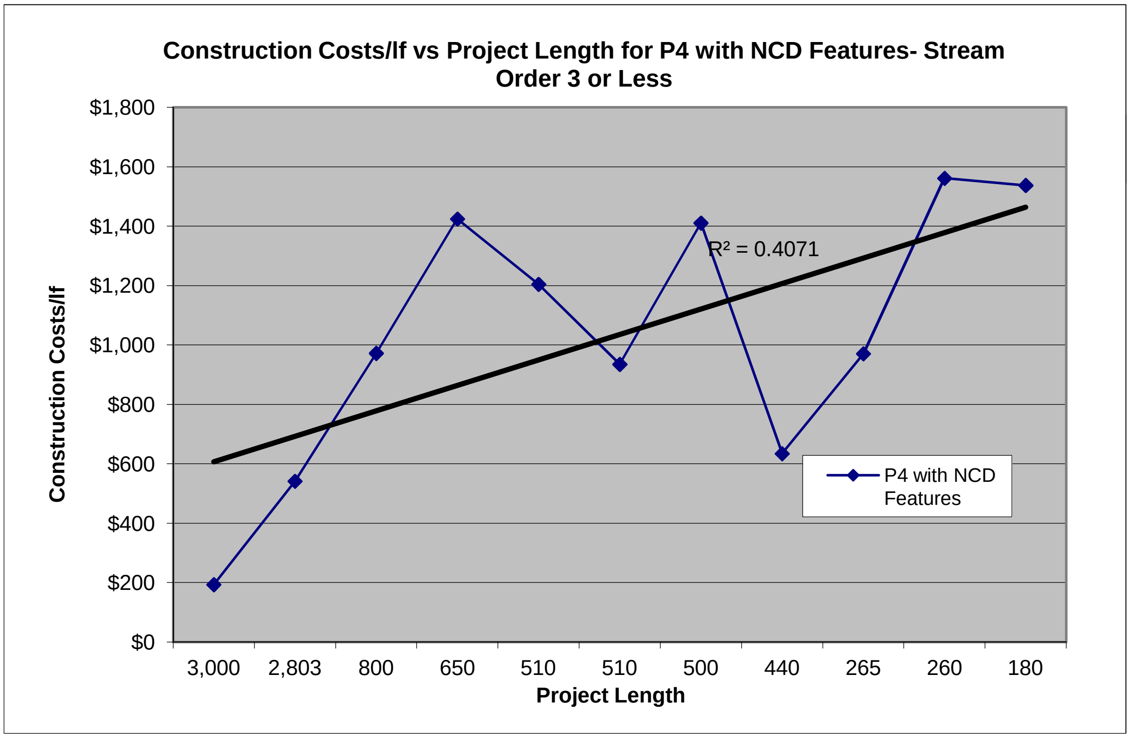
NCD - Stream Order 3 or Less	Priority Improvement	Project Length	Construction Costs	Construction Costs/lf	Design as % of Construction Costs	Design Cost	Design Costs/lf
Vogel Creek- Arncliffe Dr. to White Oak Bayou	3	8,300.00	$9,000,283.00	$1,084.37	14.00%	$1,260,039.62	$151.81
Tributary to Big Gulch Bayou	3	1,800.00	$1,119,750.00	$622.08	19.00%	$212,752.50	$118.20
East Salitrillo Creek	3	249.00	$321,072.00	$1,289.45	25.00%	$80,268.00	$322.36


Construction Costs vs Project Length for Traditional - Stream Order 3 or Less

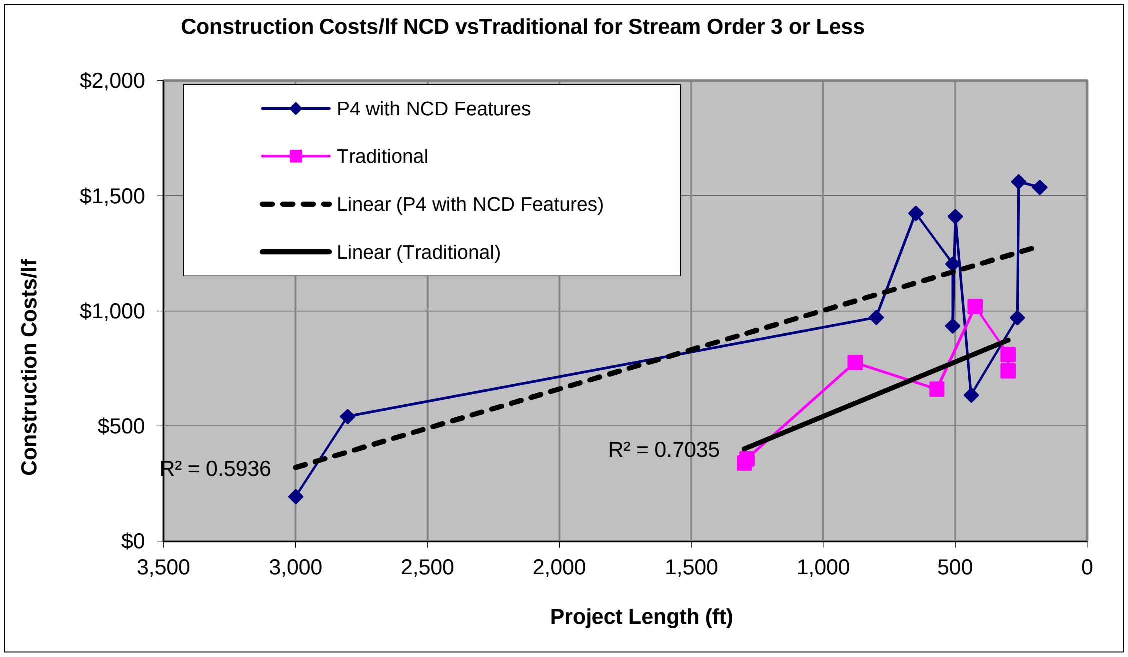

Construction Costs/lf vs Project Length for Traditional - Stream Order 3 or Less

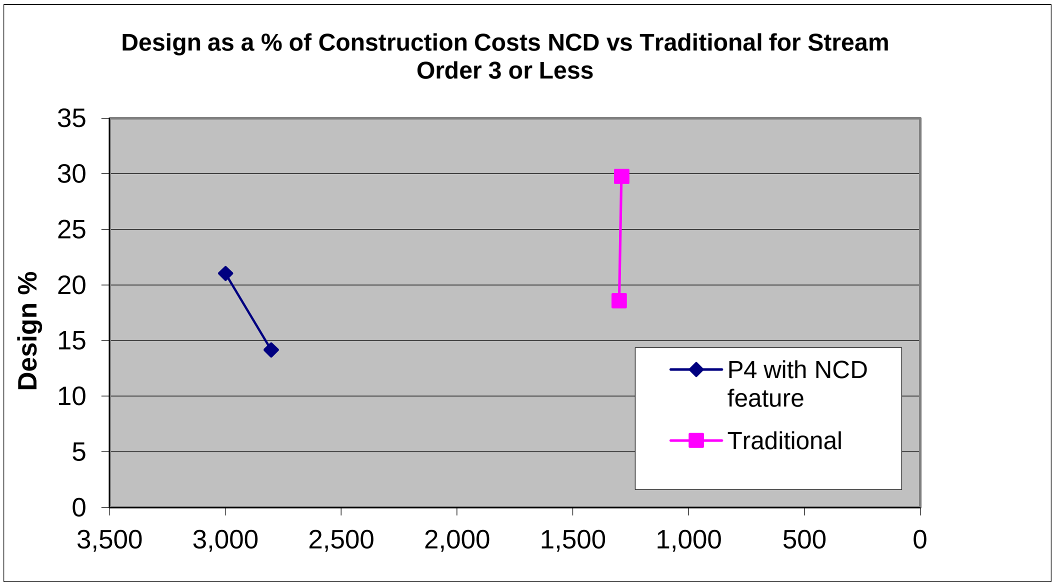


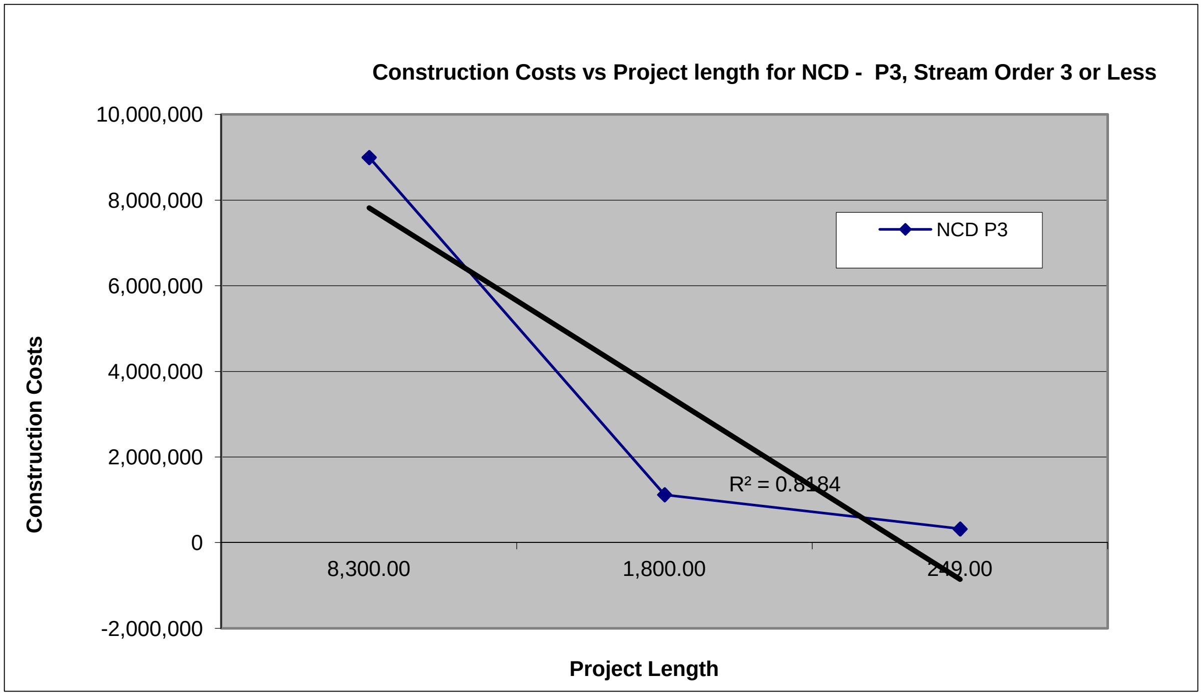
Construction Costs vs Project length for P4 with NCD Features - Stream Order 3 or Less

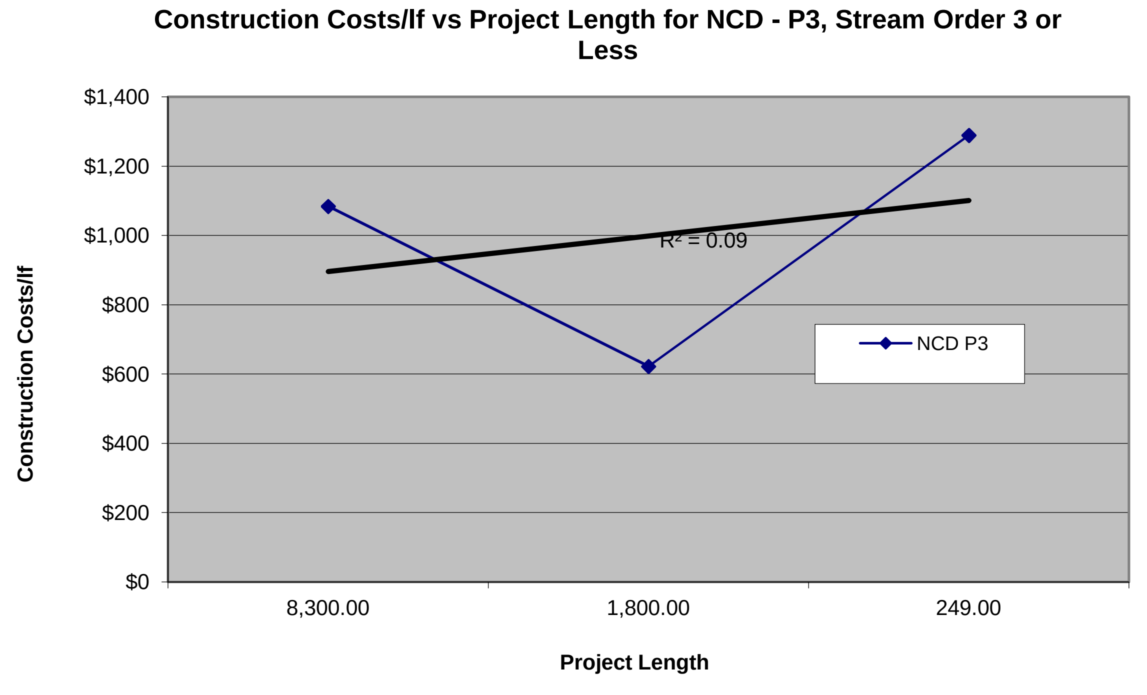


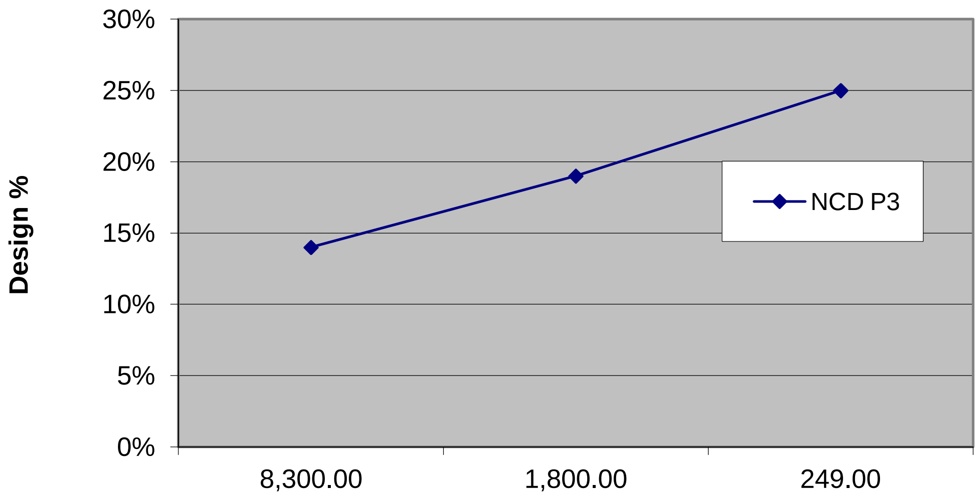
Construction Costs/lf vs Project Length for P4 with NCD Features- Stream Order 3 or Less


Construction Costs/lf NCD vsTraditional for Stream Order 3 or Less
P4 with NCD Features
Traditional
Linear (P4 with NCD Features)
Linear (Traditional)
Construction Costs/lf
$2,000
$1,500
$1,000
$500
$0
R² = 0.5936
R² = 0.7035
3,500
3,000
2,500
2,000
1,500
1,000
500
0
Project Length (ft)


Design as a % of Construction Costs NCD vs Traditional for Stream Order 3 or Less
Design %
35
30
25
20
15
10
5
0
3,500
3,000
2,500
2,000
1,500
1,000
500
0
P4 with NCD feature
Traditional


Construction Costs vs Project length for NCD - P3, Stream Order 3 or Less
10,000,000
8,000,000
6,000,000
4,000,000
2,000,000
0
-2,000,000
Construction Costs
NCD P3
R² = 0.8184
8,300.00
1,800.00
249.00
Project Length


Construction Costs/lf vs Project Length for NCD - P3, Stream Order 3 or Less
$1,400
$1,200
$1,000
$800
$600
$400
$200
$0
Construction Costs/lf
R² = 0.09
NCD P3
8,300.00
1,800.00
249.00
Project Length



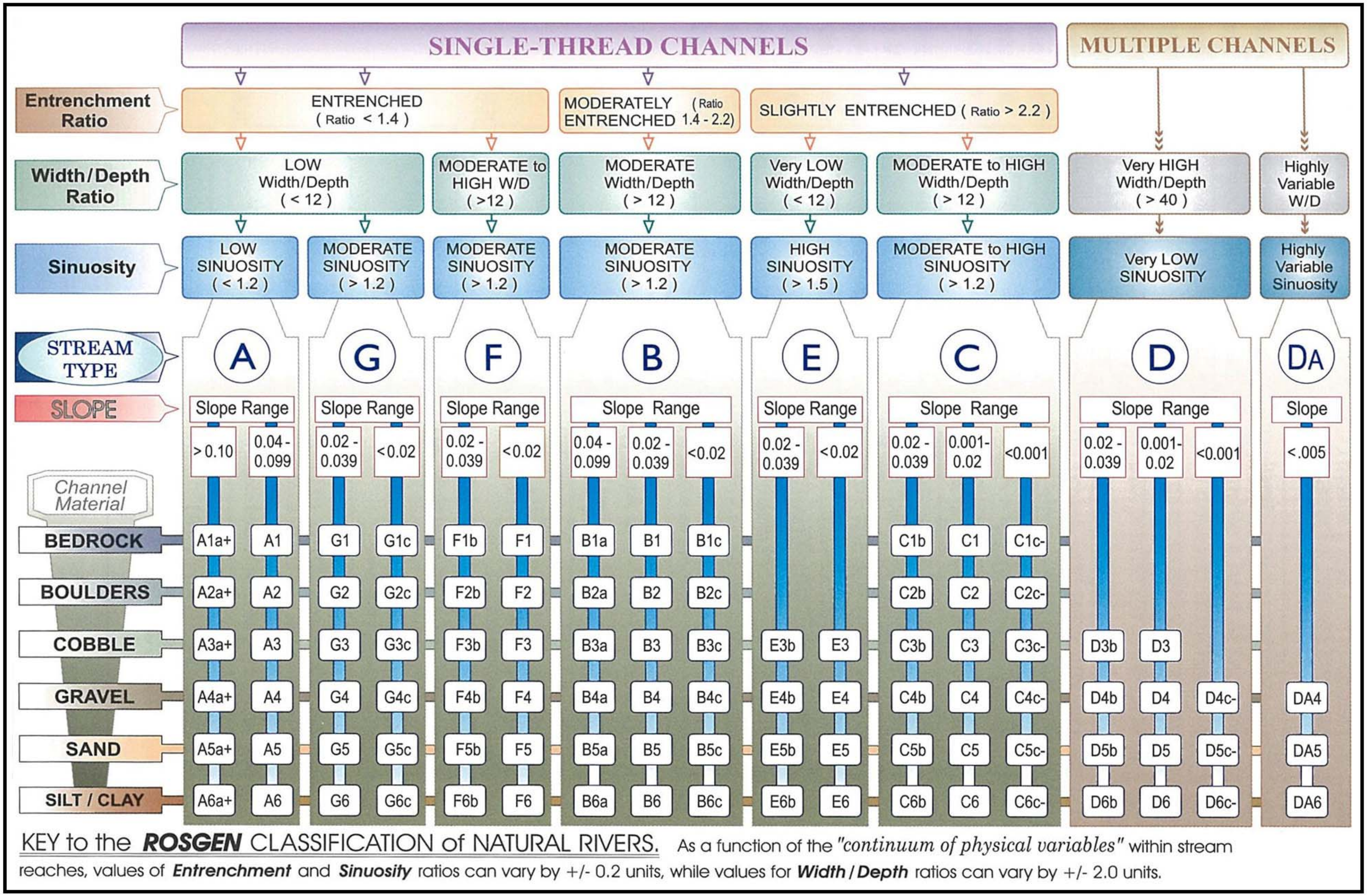
Design as a % of Construction Costs NCD for P3, Stream Order 3 or Less

Appendix E

Rosgen Classification System

SOURCE: WILDLAND HYDROLOGY

Appendix E – Rosgen Classification System



KEY to the **ROSGEN** CLASSIFICATION of NATURAL RIVERS. As a function of the *"continuum of physical variables"* within stream reaches, values of ***Entrenchment*** and ***Sinuosity*** ratios can vary by +/- 0.2 units, while values for ***Width / Depth*** ratios can vary by +/- 2.0 units.

Source: Wildland Hydrology

Appendix F

Draft Report Comments and Responses

Texas Water
Development Board

P.O. Box 13231, 1700 N. Congress Ave.
Austin, TX 78711-3231, www.twdb.texas.gov
Phone (512) 463-7847, Fax (512) 475-2053

February 26, 2012

Betty Leite
Project Manager
KBR Infrastructure Americas
601 Jefferson, JE-1604
Houston, Texas 77002-7900

RE: Research Contract between the Texas Water Development Board (TWDB) and Kellogg Brown and Root (KBR); TWDB Contract No. 1148321308, Draft Report Comments

Dear Ms. Leite:

Staff members of the TWDB have completed a review of the draft report prepared under the above-referenced contract. ATTACHMENT I provides the comments resulting from this review. As stated in the TWDB contract, KBR will consider incorporating draft report comments from the Executive Administrator as well as other reviewers into the final report. In addition, KBR will include a copy of the Executive Administrator's draft report comments in the Final Report.

The TWDB looks forward to receiving one (1) electronic copy of the entire Final Report in Portable Document Format (PDF) and six (6) bound double-sided copies. **Please further note, that in compliance with Texas Administrative Code Chapters 206 and 213 (related to Accessibility and Usability of State Web Sites), the digital copy of the final report must comply with the requirements and standards specified in statute. For more information, visit http://www.sos.state.tx.us/tac/index.shtml.** If you have any questions on accessibility, please contact David Carter with the Contract Administration Division at (512) 936-6079 or David.Carter@twdb.texas.gov

KBR shall also submit one (1) electronic copy of any computer programs or models, and, if applicable, an operations manual developed under the terms of this Contract.

If you have any questions concerning the contract, please contact Gilbert Ward, the TWDB's designated Contract Manager for this project at (512) 463-6418.

Sincerely,

Carolyn L. Brittin
Deputy Executive Administrator
Water Resources Planning and Information

Enclosures

c: Gilbert Ward, TWDB

Attachment 1

TWDB Comments on Evaluation of Natural Channel Design versus Traditional Stormwater Infrastructure in Texas

TWDB Contract #1148321308

1.0 Please perform a final edit for typos, grammar, and inconsistent usage of acronyms and abbreviations, and that all references are properly cited and included in Section 10 (References) of the report.

2.0 The Executive Summary should be considered as a "stand alone" document and, as such, all acronyms must be properly defined. Please amend as necessary.

3.0 Executive Summary, page 3 states that construction and design cost trends gave indications that Natural Channel Design (NCD) techniques are more costly than Traditional Stormwater Infrastructure. The Executive Summary should state that this is the case for creeks classified as Stream Order 3 or less, as described in Section 6.2.2. However Section 6.2.1 states that for Stream Order 4 or greater, Traditional projects are significantly higher in cost than NCD projects (at least for longer projects which involve stream lengths greater than 1,250 feet). Please make the necessary edits to the Executive Summary to reflect this information or provide additional discussion as necessary to clarify.

4.0 The Executive Summary should provide a summary of the findings and conclusions, particularly as they pertain to the three study objectives. Please include in the final report.

5.0 Chapter 4; discussions on page 38 include stream classifications by type which is not defined within this section or elsewhere in the report. Stream classifications are also used in Appendix B of the report, but not defined. Please include additional detail as necessary to define stream classifications as used within the study report.

6.0 Chapter 6; page 57, last paragraph has a statement that the smallest perennial streams in a typical watershed are 2nd and 3rd order streams. However 1st order streams are the smallest perennial streams in a watershed. Please amend and include the necessary discussion specific to the study's evaluation of streams relative to stream order.

7.0 Chapter 6; Section 6.3 contains considerable and complex discussions related to development of economic benefits associated with NCD projects, including various methodologies which could be employed in quantifying benefits. However, it does not appear that any of the methodologies described were actually used by the study. Please consider the value of such a discussion within the context of this study if not to be used, and amend as necessary.

8.0 Please consider inclusion of a discussion of the Webinar which will be conducted following KBR's receipt of draft report comments. This discussion could possibly be included as part of Chapter 8 in the final report.

KBR RESPONSES

February 27, 2013

Priority Water Research Topic – FY2011

Evaluation of Natural Channel Design versus Traditional Stormwater Infrastructure in Texas

(Contract # 1148321308)

1.0 Please perform a final edit for typos, grammar, and inconsistent usage of acronyms and abbreviations, and that all references are properly cited and included in Section 10 (References) of the report.

Response: A final edit was conducted to correct all editorial and technical issues described above.

2.0 The Executive Summary should be considered as a "stand alone" document and, as such, all acronyms must be properly defined. Please amend as necessary.

Response: All acronyms have been properly defined in the Executive Summary.

3.0 Executive Summary, page 3 states that construction and design cost trends gave indications that Natural Channel Design (NCD) techniques are more costly than Traditional Stormwater Infrastructure. The Executive Summary should state that this is the case for creeks classified as Stream Order 3 or less, as described in Section 6.2.2. However Section 6.2.1 states that for Stream Order 4 or greater, Traditional projects are significantly higher in cost than NCD projects (at least for longer projects which involve stream lengths greater than 1,250 feet). Please make the necessary edits to the Executive Summary to reflect this information or provide additional discussion as necessary to clarify.

Response: Changes were made to the Executive Summary to reflect the cost comparison discussions and findings of Sections 6.2.1 and 6.2.2.

4.0 The Executive Summary should provide a summary of the findings and conclusions, particularly as they pertain to the three study objectives. Please include in the final report.

Response: The executive summary has been revised to include a summary of conclusions pertaining to each study objective, as well as main findings and constraints. Summary tables and figures discussed in detailed within the body of the report were also added to the Executive Summary for completeness.

5.0 Chapter 4; discussions on page 38 include stream classifications by type which is not defined within this section or elsewhere in the report. Stream classifications are also used in Appendix B of the report, but not defined. Please include additional detail as necessary to define stream classifications as used within the study report.

Response: Although this comment refers to Chapter 4, this explanation probably belongs earlier in Chapter 2 where the Rosgen methodology is first mentioned when discussing Channel Evolution and Channel Mgmt Options. Therefore, it would be more appropriate to add the "Rosgen Classification System Guide" section to Chapter 2. Also, Chapter 2 is where we lay out all the introductions to NCD. A new subsection, "Section 2.4 – Rosgen Classification System Guide" was added to the final report and section numbers were updated accordingly to reflect the change.

6.0 Chapter 6; page 57, last paragraph has a statement that the smallest perennial streams in a typical watershed are 2nd and 3rd order streams. However 1st order streams are the smallest perennial streams in a watershed. Please amend and include the necessary discussion specific to the study's evaluation of streams relative to stream order.

Response: The referenced paragraph has been revised to add the following underlined clarification: "The smallest intermittent and perennial streams in a typical watershed reviewed during this study are 2nd and 3rd order streams."

7.0 Chapter 6; Section 6.3 contains considerable and complex discussions related to development of economic benefits associated with NCD projects, including various methodologies which could be employed in quantifying benefits. However, it does not appear that any of the methodologies described were actually used by the study. Please consider the value of such a discussion within the context of this study if not to be used, and amend as necessary.

Response: The discussion presented in Section 6 provides the basis for conclusions drawn later in the report regarding the overall benefit of NCD over traditional methods. As discussed in the report, the data collected from Texas Agencies did not incorporate important factors such as environmental, quality of life and other economic benefits associated with NCD applications. It is one of the recommendations of the present study that further research be conducted to gather and document O&M and debt service, economical, environmental and quality of like parameters to allow for a complete life cycle analysis of the projects.

8.0 Please consider inclusion of a discussion of the Webinar which will be conducted following KBR's receipt of draft report comments. This discussion could possibly be included as part of Chapter 8 in the final report.

Response: A discussion of the webinar has been included as Section 8.5.

AIP0126_T4GN

Texas Water Development Board

Stantec

KBR

Watearth
Water Resources + Green Infrastructure