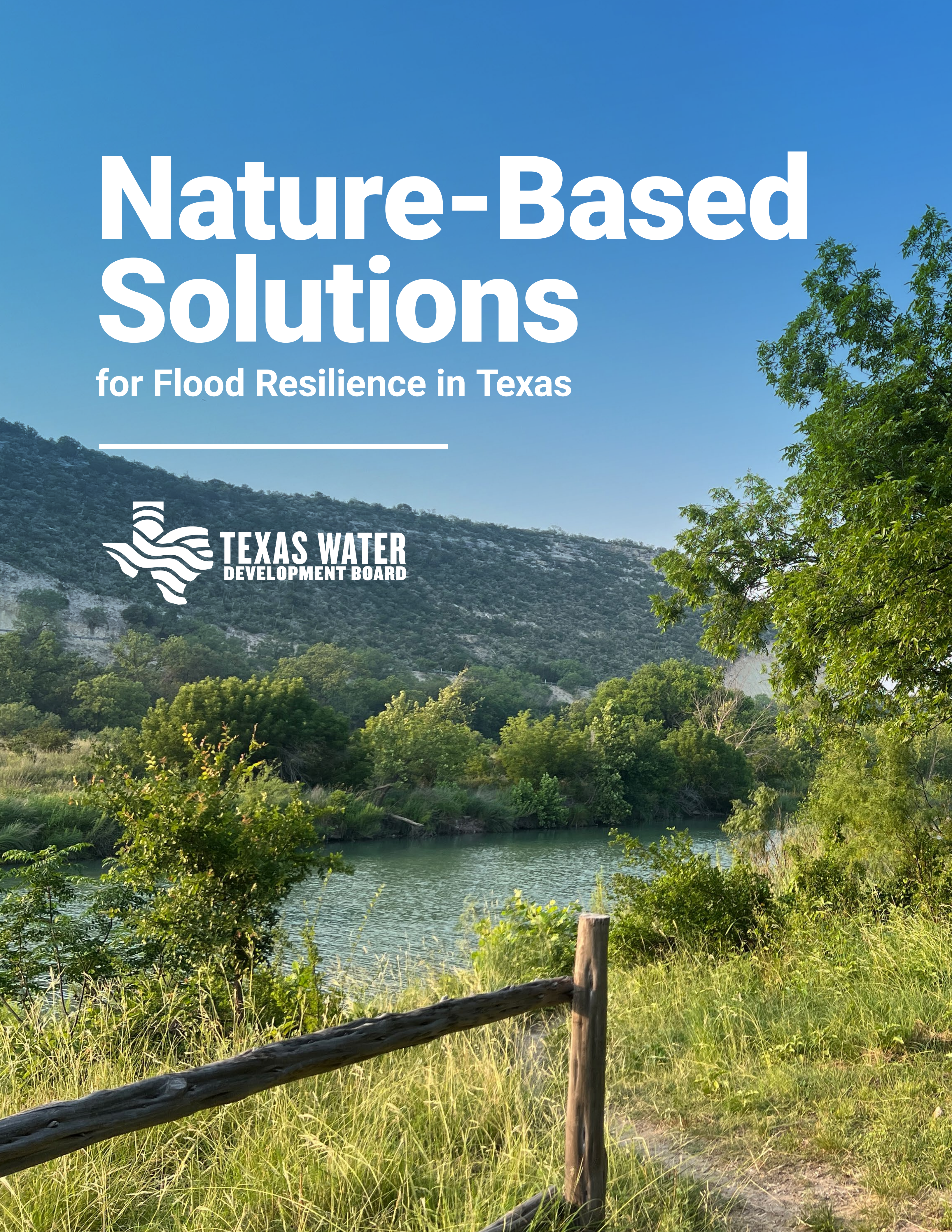


Nature-Based Solutions

for Flood Resilience in Texas

TEXAS WATER
DEVELOPMENT BOARD

Contents

Executive summary 1

Initiating Nature-Based Solutions 4

1. Laying the groundwork for NBS 6
1.1 Defining Nature-Based Solutions for flood resilience 8
1.2 What is sustainable flood resilience? 10
1.3 Purpose of this document 12
1.4 Intended audience 13
1.5 Framework for NBS 13

2. Introducing NBS for flood resilience 18
2.1 Flooding in Texas 20
2.2 Types of flood risk 22
2.3 Why NBS? 24
2.4 The spectrum of flood resilience infrastructure 27
2.5 Types and practices of NBS for flood resilience 29
2.6 Watershed NBS overview and applicability 30
2.7 Neighborhood NBS overview and applicability 32
2.8 Coastal NBS overview and applicability 34
2.9 Overcoming barriers to NBS implementation in Texas 38

3. Embracing guiding principles for NBS 46
3.1 Engage and include 50
3.2 Apply systems thinking 52
3.3 Work across boundaries 54
3.4 Learn and adapt continuously 58

4. Assessing ordinances, incentives, and regulations 62
4.1 Resolutions 67
4.2 Ordinances and regulations 68
4.3 Incentive programs 74

5. Establishing funding strategies 80
5.1 Local funding 84
5.2 State funding 89
5.3 Federal funding 92

Planning Nature-Based Solutions 98

6. Integrating NBS into planning processes 100
6.1 Recognizing the role of planning 104
6.2 Leveraging existing planning processes 108
6.3 Defining goals 112

7. Understanding flood risk and identifying NBS opportunities 128
7.1 Understanding flood risk 132
7.2 Performing opportunity assessment 136
7.3 Identifying the range of NBS options 144

Implementing Nature-Based Solutions 152

8. Evaluating NBS feasibility and alternatives 154
8.1 Evaluating project site 158
8.2 Assessing regulations and permitting 166
8.3 Performing benefit-cost analysis 174
8.4 Performing triple bottom line analysis 182
8.5 Prioritizing NBS alternatives 182

9. Designing and building NBS 186
9.1 NBS design best practices 190
9.2 NBS bidding best practices 194
9.3 NBS construction best practices 195

10. Applying watershed NBS design and construction considerations 200
10.1 General considerations 204
10.2 Stream restoration and stabilization 208
10.3 Floodplain connection and stabilization 218
10.4 Wetland restoration and creation 222
10.5 Land conservation 226

11. Applying neighborhood NBS design and construction considerations 230
11.1 General considerations 234
11.2 Bioretention basins and rain gardens 242
11.3 Bioswales 246
11.4 Vegetative filter strips 248
11.5 Wet ponds 250
11.6 Constructed wetlands 252
11.7 Rainwater harvesting 256
11.8 Stormwater parks 258

12. Applying coastal NBS design and construction considerations 262
12.1 General considerations 266
12.2 Beach nourishment and dune restoration 268
12.3 Coastal marsh restoration 271
12.4 Natural breakwaters, oyster reefs, and living shorelines 276
12.5 Waterfront parks 280
12.6 Coastal conservation 281

13. Maintaining and adaptively managing NBS 286
13.1 Monitoring, maintaining, and adapting 290
13.2 Providing access and safety 298
13.3 Maintaining vegetation 302
13.4 Sustaining watershed NBS performance 305
13.5 Sustaining neighborhood NBS performance 307
13.6 Sustaining coastal NBS performance 310

DRAFT

Figures

Figure 1-1. Defining Nature-Based Solutions for flood resilience ... 11
Figure 2-1. Increase in developed areas in Texas from 1997 to 2022 ... 20
Figure 2-2. Comparing discharge from urbanized and undeveloped watersheds. ... 21
Figure 2-3. Flash Flood Alley ... 22
Figure 2-4. Natural functions of floodplains ... 24
Figure 2-5. Ecosystem Services ... 26
Figure 2-6. Spectrum of flood resilience infrastructure ... 28
Figure 2-7. Watershed NBS ... 30
Figure 2-8. Neighborhood NBS ... 32
Figure 2-9. Coastal NBS ... 34
Figure 2-10. Multiple lines of defense on the Texas Coast ... 36
Figure 2-11. Native wetland habitat and recreational paths at Exploration Green ... 42
Figure 3-1. Watershed management cycle ... 57
Figure 4-1. Riparian buffer ... 70
Figure 4-2. Smartweed (Persicaria spp) along playa lake edge ... 72
Figure 4-3. City of Austin monthly drainage charge equation ... 77
Figure 6-1. Integrated NBS Planning ... 104
Figure 6-2. Projected subsidence patterns. ... 106
Figure 6-3. Natural Regions of Texas ... 113
Figure 6-4. Stakeholder engagement tool ... 118
Figure 6-5. Downtown Plan Meeting in Brownwood, Texas ... 118
Figure 7-1. The comments of flood risk: hazard, exposure, and vulnerability ... 132
Figure 7-2. Flood risk hot spot analysis process ... 135
Figure 7-3. Flood risk hot spot analysis results sample ... 135
Figure 7-4. Bioretention basin area analyzed near adjacent parking lot ... 143
Figure 8-1. Hydrologic soils map of Bexar County ... 161
Figure 8-2. Restoration of Dollar Bay ... 171
Figure 8-3. Jollyville Plateau salamanders found near Old Lampasas Dam. ... 173
Figure 8-4. Photo of rock outcrop at Old Lampasas Dam. ... 173
Figure 8-5. The value of ecosystem services in Texas compared to national average ... 176
Figure 8-6. Discounting Equation ... 178
Figure 9-1. Adaptive management process ... 193
Figure 9-2. Riparian vegetation establishment ... 197
Figure 10-1. Channel evolution model diagram ... 207
Figure 10-2. Turtle Creek in Austin, Texas ... 209
Figure 10-3. A channel in dynamic equilibrium with its floodplain ... 211
Figure 10-4. Natural Channel Design of Kee Branch ... 214
Figure 10-5. San Pedro Creek Stream Restoration in San Antonio, Texas ... 219
Figure 10-6. Multi-stage channel ... 221
Figure 10-7. Resaca system restoration in Brownsville, Texas ... 223
Figure 10-8. Wetland zones ... 225
Figure 10-9. Playa lake conservation ... 227
Figure 10-10. Root systems of common prairie plants ... 229
Figure 11-1. Typical contributing drainage areas of neighborhood NBS practices ... 236
Figure 11-2. Sod-planted bioretention basins. City of Austin's Todd Lane Improvement Project ... 238
Figure 11-3. Bioretention cross section. ... 239
Figure 11-4. Stormwater overflow structure with domed debris grate ... 240
Figure 11-5. Green Streets. ... 242
Figure 11-6. Green street example. ... 243
Figure 11-7. Infiltration Trench in Bee Cave, TX ... 245
Figure 11-8. Example of bioretention media cross section ... 246
Figure 11-9. Example of bioswale media cross section ... 248
Figure 11-10. Wet Pond in Leander, Texas ... 253
Figure 11-11. Wetland design cross-section ... 257
Figure 11-12. Rainwater harvesting conceptualization ... 258
Figure 12-1. Illustration of Compounding Flooding ... 268
Figure 12-2. Example vegetation placement for dune restoration ... 271
Figure 12-3. Beach and Dune Restoration at McFaddin National Wildlife Refuge. ... 272
Figure 12-4. Evolution of restored coastal wetlands. ... 274
Figure 12-5. Invasive common water hyacinth in Rio Grande near Brownsville, Texas. ... 276
Figure 12-6. Living Breakwater Site Conditions ... 279
Figure 12-7. Coastal Texas Study area ... 285
Figure 13-1. Native grassland restoration signage, Memorial Park, Houston. ... 301

Tables

Table 2-1. Additional co-benefits of NBS for flood resilience ... 27
Table 2-2. Watershed NBS ... 31
Table 2-3. Neighborhood NBS ... 33
Table 2-4. Coastal NBS ... 35
Table 3-1. Regional flood planning group members ... 53
Table 4-1. How policies, codes, ordinances, and criteria work together ... 66
Table 6-1. Flooding or water management focused planning processes ... 109
Table 6-2. Leveraging community planning processes to incorporate NBS ... 110
Table 6-3 Natural regions planning context for flood resilience ... 114
Table 6-4. Approach to developing a stakeholder engagement strategy ... 119
Table 6-5. Stakeholder roles and responsibilities ... 122
Table 7-1. NBS type by potential implementation benefits matrix ... 140
Table 8-1. Suitable NBS types for common projects ... 163
Table 8-2. NBS site suitability matrix ... 165
Table 8-3. Benefit-cost analysis definitions ... 174
Table 8-4. Expected annual damage from multiple recurrence intervals ... 175
Table 8-4. Conceptual BCA input values ... 181
Table 8-5. Conceptual BCA results ... 181
Table 8-6. Example of project evaluation table to differentiate between NBS alternatives ... 183
Table 10-1. Stream Restoration and Stabilization Design Definitions ... 210
Table 12-2. Common invasive species in Texas coastal marshes ... 275
Table 13-1. Example training framework for NBS maintenance staff ... 296
Table 13-2. Typical post-storm inspection and response checklist ... 301

Mustang Island near Corpus Christi, Texas
Photo courtesy of the Texas Water Development Board

DRAFT

Executive summary

Flooding remains one of the most costly and persistent hazards facing Texas communities. Homes, roadways, utilities, businesses, and public infrastructure are repeatedly impacted by flood events across every region of the state. As communities grow and land use patterns change, runoff increases, drainage systems are strained, and the consequences of flooding can become more severe.

Traditional flood mitigation tools—detention basins, levees, floodwalls, and storm drain systems—are essential components of community infrastructure. However, these systems are often single-purpose, expensive to expand, and difficult to adapt as conditions change.

Nature-Based Solutions (NBS) use or imitate natural features and/or processes to increase resilience while providing sustainable benefits to people and the environment. NBS store runoff, slow flows, increase infiltration, reconnect floodplains, stabilize shorelines, and reduce erosion. When applied appropriately, NBS can lower peak flood elevations, expand storage capacity, and reduce sedimentation.

NBS could be an opportunity for communities across Texas to reduce flood risk while also strengthening long-term infrastructure performance and delivering broader community value. **This manual seeks to equip local officials, engineers, community planners, and flood-related professionals with a clear framework for planning, implementing, and maintaining NBS as part of comprehensive flood resilience strategies.**

Watershed-scale approaches, such as stream restoration and floodplain connection, can attenuate downstream flood peaks. Neighborhood-scale solutions, including bioretention basins, bioswales, and vegetative filter strips can help reduce localized flooding and manage runoff at its source. In coastal areas, dune restoration, marsh restoration, and living shorelines help reduce wave energy and shoreline erosion while buffering inland communities. In many cases, the most effective approach is hybrid—integrating gray infrastructure and nature into a coordinated system that improves performance and flexibility over time.

A structured framework for action

This manual provides a practical, step-by-step framework organized around three phases: initiating, planning, and implementing NBS.

The initiating phase focuses on establishing the foundation necessary for success. Communities are encouraged to formalize flood resilience goals that incorporate NBS, review and update ordinances and development criteria, and identify sustainable funding mechanisms. This stage emphasizes internal coordination across departments and early engagement with stakeholders and decision-makers to build institutional support.

The planning phase integrates NBS into existing flood risk reduction processes. Rather than creating new parallel systems, the guidance speaks to the importance of embedding NBS into drainage master plans, hazard mitigation plans, capital improvement programs, comprehensive community plans, and regional flood planning efforts. Communities are guided through understanding flood risk conditions, identifying priority areas, conducting opportunity assessments, and aligning projects with regional strategies.

The implementation phase translates concepts into action. It addresses site feasibility, benefit-cost analysis, permitting pathways, detailed design considerations, construction best practices, and long-term maintenance and adaptive management. By providing design and construction considerations across watershed, neighborhood, and coastal contexts, the manual provides guidance that enables the implementation of projects and strategies that are technically feasible and operationally sustainable. This structured approach gives communities a clear pathway from concept to adoption.

Executive summary continued ▸

Designed for all regions of Texas

Texas is hydrologically and geographically diverse. Flood risk manifests differently in each region—from flash flooding in steep terrain, riverine flooding along major basins, and urban drainage challenges in metropolitan areas to compound flooding along the coast. Flood resilience solutions must be tailored to local conditions. Strategies appropriate for large, wide riverine systems differ from those suitable for steep terrain in the Hill Country.

By acknowledging Texas' natural regions and their varying soil types, topography, rainfall patterns, and land use pressures, the guidance ensures statewide applicability. It is equally relevant for small rural communities, rapidly growing suburban jurisdictions, large urban centers, and coastal counties. The emphasis is on context-sensitive design rather than one-size-fits-all prescriptions.

Addressing common barriers to adoption

Stakeholder engagement across Texas identified several recurring challenges that have limited broader adoption of NBS. These include limited familiarity with performance data, uncertainty about regulatory requirements, concerns about long-term maintenance, funding constraints, and institutional silos between departments.

This manual directly addresses those barriers by

- providing model ordinance language to help communities institutionalize NBS within development standards;
- outlining clear permitting considerations for federal and state agencies;
- detailing funding strategies at the local, state, and federal levels;
- including guidance for establishing drainage utility fees and bond programs; and
- highlighting benefit-cost analysis approaches that quantify both flood reduction benefits and additional economic value.

By providing clarity, examples, and structured processes, the manual reduces uncertainty and increases confidence in implementation.

Strengthening the financial case

NBS can improve the financial competitiveness of flood mitigation projects. Incorporating NBS elements can enhance the scoring potential for such programs as the Flood Infrastructure Fund and Clean Water State Revolving Fund. They can also support compliance with stormwater permits and increase Community Rating System credit under the National Flood Insurance Program.

The guidance emphasizes life-cycle cost considerations rather than solely factoring initial capital expenses. In many cases, NBS can reduce long-term maintenance burdens on traditional infrastructure, extend asset life, and provide additional economic value through ecosystem services and recreational enhancements.

Communities are guided through developing diversified funding strategies that combine local revenue mechanisms—such as drainage utility fees or bond programs—with state and federal funding sources. By aligning NBS projects with broader community goals, local governments can unlock multiple funding pathways and improve project feasibility.

Long-term performance through adaptive management

Unlike static infrastructure, NBS are dynamic systems. They evolve as vegetation matures and landscapes adjust. When properly maintained, many NBS grow stronger over time, increasing stability and resilience. The manual provides detailed guidance on monitoring, maintenance, and adaptive management. It emphasizes establishing performance benchmarks, conducting post-storm inspections, maintaining vegetation health, and documenting outcomes. Adaptive management ensures that projects continue delivering flood risk reduction benefits while responding to changing conditions. This approach transforms maintenance from a reactive obligation into a proactive strategy for sustaining resilience.

From guidance to adoption

NBS are not theoretical concepts—they are being successfully implemented across Texas. Examples include floodplain buyouts in North Texas, stormwater parks in Houston, regional watershed planning in Bexar County, and living shoreline projects along the coast. This manual builds upon those examples and provides the structure to scale them statewide, showing that NBS can be integrated into day-to-day operations, project development, and long-term capital planning.

By adopting the framework, guiding principles, and recommendations presented in this manual, Texas communities can move toward integrated, resilient flood management that protects people, infrastructure, and long-term community vitality.

Wet Pond in Leander, Texas
Photo courtesy of Freese and Nichols, Inc.

INITIATING NBS **PLANNING** NBS **IMPLEMENTING** NBS

Initiating Nature-Based Solutions

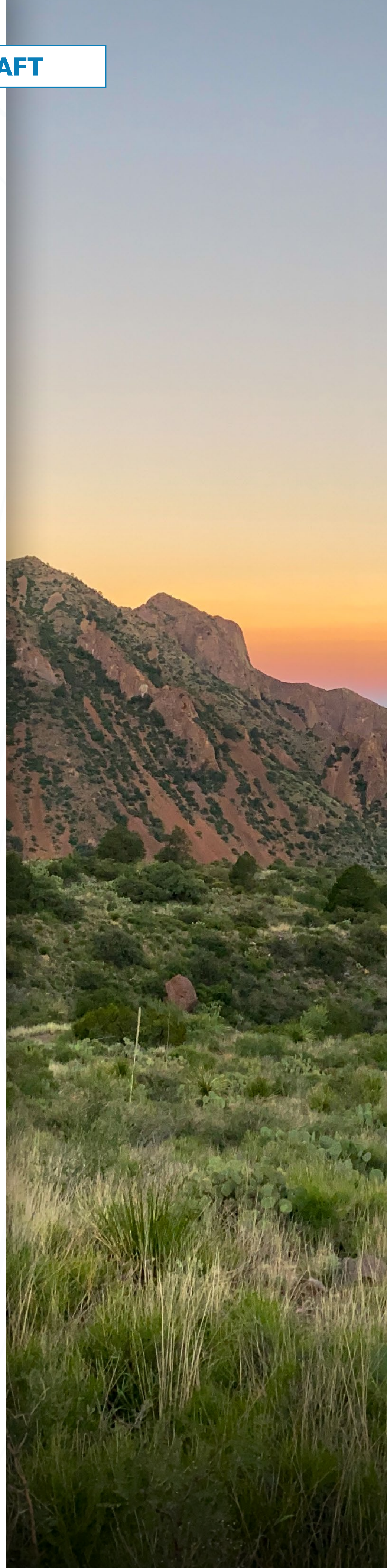
The chapters on initiating Nature-Based Solutions (NBS) form the basis for successful planning and implementation. This section explores different types of NBS and how they can achieve flood resilience goals, introduces guiding principles for local officials and practitioners, identifies funding sources and mechanisms, and examines how local regulations, ordinances, and incentives can help increase NBS adoption.

CHAPTERS 1-5

Chapter 1 Laying the groundwork for NBS
Chapter 2 Introducing NBS for flood resilience
Chapter 3 Embracing guiding principles for NBS
Chapter 4 Assessing ordinances, incentives and regulations
Chapter 5 Establishing funding strategies

Outcomes

- Commit to planning and implementing NBS to achieve flood resilience objectives
- Update local ordinances and criteria to overcome barriers and/or incentivize NBS adoption
- Establish an NBS funding strategy for program and/or project implementation



1

Laying the groundwork for NBS

This chapter defines NBS for flood resilience, discusses the purpose and intended audience of the manual, and introduces the framework of the manual.

Key takeaways

- NBS use or imitate natural features and/or processes to increase resilience while providing benefits to people and the environment.
- The purpose of this manual is to help local government officials and staff who plan, build, and manage community infrastructure to successfully implement NBS to address flood risk and build community resilience.
- The concepts of initiating, planning, and implementing are presented as a framework for NBS users.

Santa Elena Canyon on the Rio Grande
Photo courtesy of the Texas Water Development Board

Introduction

Texas' flood risk challenges are complex and multi-faceted. Traditional solutions for managing or reducing flood risk tend to favor engineered systems, such as pipes, detention basins, levees, and floodwalls. These are often referred to as gray infrastructure due to the prevalence of concrete, steel, and/or rock. These solutions form the basis of understanding for many engineers and while these solutions can be effective at reducing flood risk, they can be costly to construct and maintain and are difficult to adapt to changing conditions. Furthermore, many of these solutions do not provide additional benefits to people or the environment as they are designed for a single flood reduction purpose.

A growing body of practice and research supports the use and potential for using natural processes and materials to solve flood risk reduction challenges. These strategies can work as standalone solutions or in concert with traditional gray infrastructure to meet flood risk reduction objectives while also benefiting people and the environment. For example, if a community needs to increase flood storage to reduce flood risk exposure, one gray infrastructure approach would be to construct a detention pond. Alternatively, constructed wetlands or a wet pond could be designed to provide the same flood storage function as a detention pond while also improving water quality and providing wetland and riparian habitat.

This guidance manual was informed by a combination of coordination with industry experts, stakeholder interviews, a statewide survey on NBS practices and perceptions, and a review of current literature and case studies across Texas and nationally. These inputs helped identify common challenges, local priorities, and opportunities for integrating NBS into flood risk reduction efforts statewide.

The goal of this guidance manual is to provide guidance to communities on the use of NBS for flood resilience and flood planning efforts. This includes identifying strategies, tools, and processes that address common barriers and challenges for planning and implementing NBS as well as outlining how to integrate NBS concepts and best practices into all phases of NBS project development, from initial community-driven planning processes to their design and implementation with specific consideration of local context.

1.1 Defining Nature-Based Solutions for flood resilience

NBS is an umbrella term that encompasses a wide range of concepts across multiple disciplines—depending on the professional or departmental perspective. Many of these concepts may already be familiar: green infrastructure (GI), green stormwater infrastructure (GSI), low impact development (LID), stormwater best management practices (BMP), complete/green streets, natural and nature-based features, and Engineering With Nature®, to name a few. A common thread through all these concepts is a focus on using nature and natural processes, where possible, to solve problems and benefit people and the ecosystems in which we live.

NBS for flood resilience can be hybrid structural (constructed), such as dunes or reconnected floodplains, or nonstructural, such as conservation easements, building and development codes, policies, and regulations that protect natural spaces.

In short, NBS:

- are actions that protect, sustainably manage, or restore a natural or modified ecosystem;
- address a socioeconomic challenge (e.g., flooding, water quality);
- are expected to benefit nature; and
- are expected to benefit people or communities[1]

Definition

Nature-Based Solutions

The recognition and use of nature and natural processes as infrastructure that provides community benefits is commonly referred to as Nature-Based Solutions (NBS). **NBS use or imitate natural features and/or processes to increase resilience while providing sustainable benefits to people and the environment.** This definition was influenced by the Federal Emergency Management Agency (FEMA), United States Army Corps of Engineers (USACE), Engineering with Nature®, the International Guidelines on Natural and Nature-based Features for Flood Risk Management[2], and the International Union for the Conservation of Nature.

Frio River in Texas
Photo courtesy of the Texas Water Development Board

1.2 What is sustainable flood resilience?

Sustainable flood resilience includes the following:

- Reducing flood risk to people and infrastructure, while minimizing impacts to the environment
- Addressing a wide variety of flood risks (e.g., riverine, flash, coastal, urban, pluvial, etc.)
- Implementing adaptable flood risk reduction solutions
- Reducing the effect of processes that can lead to increased flood risk (erosion, land cover/land use change)
- Minimizing the impacts of flood risk reduction strategies and infrastructure on communities (health and well-being), the environment, and the economy
- Promoting sustainable development practices that prioritize natural flood management and preserve undeveloped land
- Adopting and enforcing sound policies and regulations, including zoning, building codes, and floodplain management standards higher than required minimums

Definition

Sustainable

The ability to meet the needs of the present without compromising the ability of future generations to meet their own needs.[3]

Resilience

The ability to prepare for threats and hazards, adapt to changing conditions, and withstand and recover rapidly from adverse conditions and/or disruptions.[4]

Heron Flats at Aransas National Wildlife Refuge
Photo courtesy of U.S. Fish and Wildlife Service

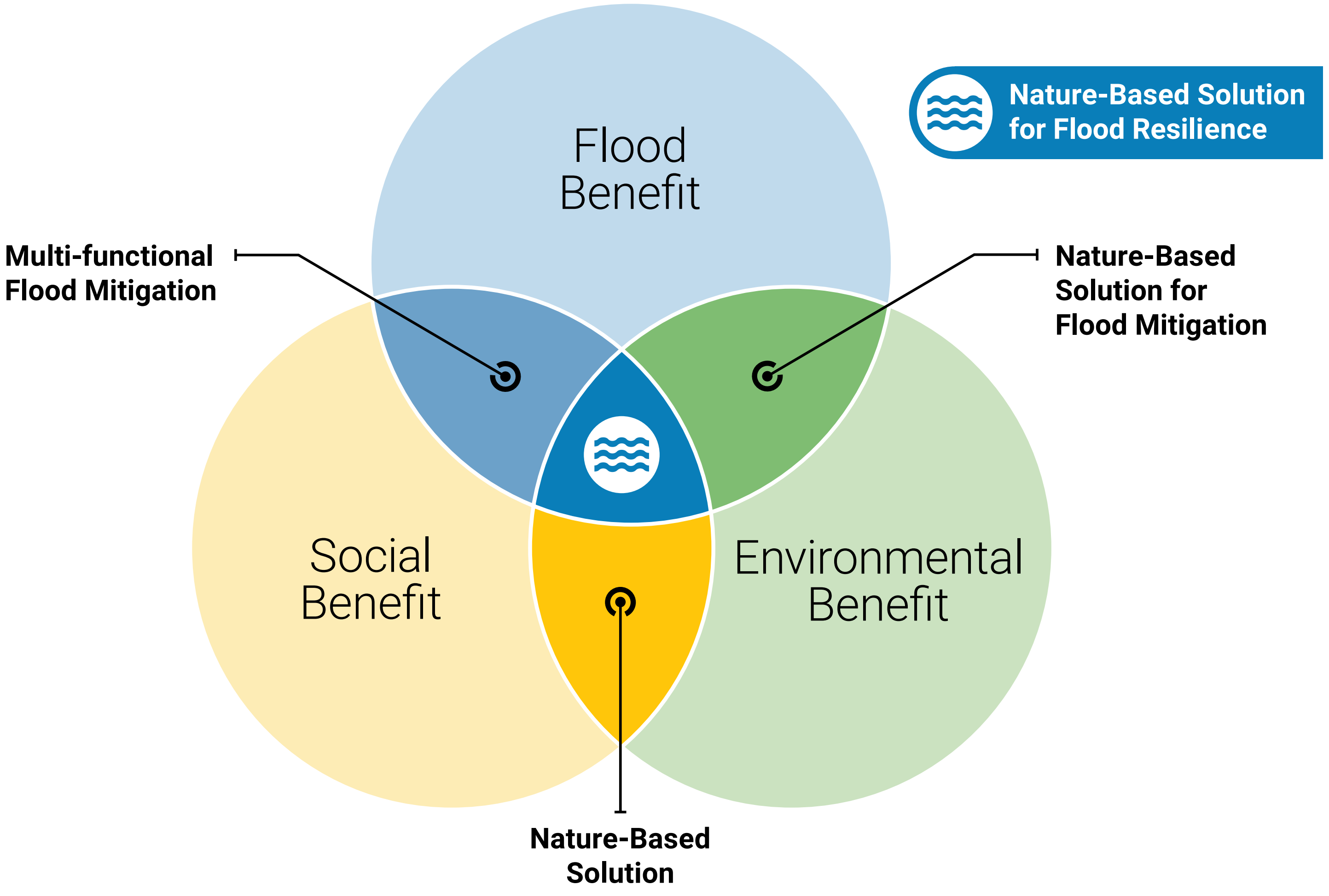


Figure 1-1. Defining Nature-Based Solutions for Flood Resilience

The Venn diagram shown in Figure 1-1 illustrates the intersection of flood benefits, social benefits (benefits to people), and environmental benefits in the context of flood resilience. Each circle represents one category of benefit, and their overlaps highlight combined advantages. While reducing flood risk is a benefit to society, for the purpose of this manual, flood benefit is highlighted as a separate category. The overlap between flood and social benefits represents multifunctional flood mitigation without the adaptivity and resilience provided by natural infrastructure (e.g., multi-use stormwater detention facility with park or recreation space), while the overlap between flood and environmental benefits reflects NBS for flood mitigation with less direct community benefits. The overlap between social and environmental benefits indicates broader NBS that might have a lower or no flood mitigation benefit (e.g., building techniques to reduce carbon emission). **At the center—where all three benefits intersect—is the concept of NBS for flood resilience, integrating social, environmental, and flood-related benefits into a unified approach.**

1.3 Purpose of this document

The purpose of this guidance manual is to help local Texas officials plan for and implement NBS to address flood risk and build community resilience. The intent of the guidance manual is to help communities institutionalize the use of NBS for flood resilience in day-to-day operations and decisions, project development, and long-term planning. This guidance manual can inform a range of use cases, including flood mitigation project development, regional flood plans, local drainage plans or studies, capital improvement planning (especially for identifying project alternatives), county hazard mitigation plans, floodplain regulation, and consideration of land use and development policies and incentives for more flood resilient communities. This document provides usable information on the form and function of NBS for flood resilience and funding their implementation, and it offers insights through research and case studies to help reduce the barriers and challenges to implement NBS in Texas. Additionally, **this document is intended to help planners and practitioners realize the many benefits NBS can provide that traditional gray infrastructure cannot.**

This guidance manual addresses the identification of appropriate NBS strategies and locations; guidance for evaluating feasibility; and considerations for design, construction, operations, maintenance, and adaptive management. Importantly, the framework encourages iteration. Many solutions will need to be evaluated, refined, and tested over time. As implementation progresses, practitioners can expect to encounter and learn from technical, regulatory, and funding challenges. Sharing these lessons can help other communities overcome barriers and advance the use of NBS across Texas.

While there are other documents promoting and providing guidance on NBS[2], they are often more general in context, not specific to a single natural hazard, and often do not focus on a specific geography. This guidance manual is developed specifically for addressing flood risk in Texas. It includes consideration of specific geographic features (e.g., playa lakes, resacas) and Texas-specific case studies and takes a comprehensive approach—from policy and rulemaking to planning to project implementation and maintenance. The development of the guidance manual was informed by extensive desktop research, interviews with subject matter experts across academia, private industry, and federal, state, and local governments, and a statewide survey.

The *National Mitigation Investment Strategy* ↗ identifies nature-based solutions as a cost-effective approach to keep natural hazards from becoming costly disasters.

1.4 Intended audience

The target audiences for this guidance manual are local government officials and representatives who may be charged with planning, developing, and managing community infrastructure or assets (e.g., city engineers, floodplain managers, planners), regional flood planning groups (RFPGs), practitioners, and stakeholders interested in advocating for NBS in their communities. While this guidance manual informs and guides readers on the use of NBS for flood resilience, including planning, funding, conceptualizing, implementing, and maintaining NBS, it is not intended to be a technical resource for the design of NBS. Many examples and technical resources are linked throughout the document.

This document is structured to take planners and practitioners through the full process of applying NBS for flood resilience, from initial planning and stakeholder engagement through design, construction, and long-term maintenance. Successful NBS efforts begin well before design and implementation. Upfront planning is required to lay the groundwork for success, including understanding regulatory requirements, setting goals, identifying funding strategies, and engaging stakeholders early.

1.5 Framework for NBS

To help communities implement NBS, the framework is comprised of three phases: **Initiating NBS, Planning NBS,** and **Implementing NBS**. These components represent the progression from high-level visioning and strategy development to design, construction, and maintenance. While this process is often presented linearly, it is intended to be iterative—allowing practitioners to revisit earlier steps as new information, input, or performance data become available.

John Bunker Sands Wetland Center in Kaufman County, Texas
Photo courtesy of the Texas Water Development Board

DRAFT

NBS GUIDANCE MANUAL
FRAMEWORK

INITIATING NBS

CHAPTERS 1-3

Defining NBS, types of NBS, and overcoming challenges and barriers

- 1 Laying the groundwork for NBS
- 2 Introducing NBS for flood resilience
- 3 Embracing guiding principles for NBS

CHAPTERS 4-5

Reviewing regulations, incentives and funding opportunities

- 4 Assessing ordinances, incentives, and regulations
- 5 Establishing funding strategies

PLANNING NBS

CHAPTER 6

Integrating NBS into planning processes

- 6.1 Recognizing the role of planning
- 6.2 Leveraging existing planning processes
- 6.3 Defining goals

CHAPTER 7

Understanding flood risk and identifying NBS opportunities

- 7.1 Performing opportunity assessment
- 7.2 Performing an opportunity assessment
- 7.3 Identifying the range of NBS options

IMPLEMENTING NBS

CHAPTER 8

Evaluating NBS feasibility

- 8.1 Evaluating project site
- 8.2 Assessing regulations and permitting
- 8.3 Performing benefit-cost analysis
- 8.4 Performing triple bottom line analysis
- 8.5 Prioritizing NBS alternatives

CHAPTERS 9-12

Designing and building NBS across different contexts

- 9 Designing and building NBS
- 10 Applying watershed NBS design and construction considerations
- 11 Applying neighborhood NBS design and construction considerations
- 12 Applying coastal NBS design and construction considerations

CHAPTER 13

Maintaining and adaptively managing NBS

- 13.1 Monitoring, maintaining, and adapting
- 13.2 Providing access and safety
- 13.3 Maintaining vegetation
- 13.4 Sustaining watershed NBS performance
- 13.5 Sustaining neighborhood NBS performance
- 13.6 Sustaining coastal NBS performance

The feedback loop represents the embodiment of learning and adapting, one of our four guiding principles presented in Chapter 2. It also acknowledges that planning and implementing are not linear processes and may require refinement and iteration before a project can be built.

Laying the groundwork for NBS **citations**

Palmetto State Park in Gonzales, Texas
Photo courtesy of the Texas Water Development Board

[1] Warnell, K., Mason, S., Siegle, A., Merritt, M., and Olander, L., 2023, Department of the Interior nature-based solutions roadmap: Durham, North Carolina, Nicholas Institute for Energy, Environment and Sustainability, Duke University, NI R 23-06, https://hdl.handle.net/10161/31687, accessed June 2026.

[2] Bridges, T.S., King, J.K., Simm, J.D., Beck, M.W., Collins, G., Lodder, Q., and Mohan, R.K., eds., 2021, Overview—International guidelines on natural and nature-based features for flood risk management: Vicksburg, Mississippi, U.S. Army Engineer Research and Development Center

[3] United Nations General Assembly, 1987, Report of the World Commission on Environment and Development—Our common future: Development and International Co-operation: Environment, p. 43, www.un.org/en/academic-impact/sustainability, accessed February 2026.

[4] Federal Emergency Management Agency, 2024, National resilience guidance, Washington, D.C., U.S. Department of Homeland Security, August 2024, www.fema.gov/sites/default/files/documents/fema_national-resilience-guidance_august2024.pdf, accessed February 2026.

2

Introducing NBS for flood resilience

This chapter defines the types of NBS and how they achieve flood resilience objectives in different contexts: watershed, neighborhood, and coastal.

Key takeaways

- The population of Texas is estimated to increase to 51.5 million by 2070—increasing land use changes that exacerbate existing flood risk and impact aging infrastructure[1].
- Natural functions (e.g., flood storage, velocity dissipation) and natural features (e.g., floodplains, wetlands) can reduce flood risk while enhancing quality of life.
- NBS types span watershed, neighborhood, and coastal contexts, are either nonstructural or structural practices, and can be used in combination with, or in addition to, existing gray infrastructure.

Gilleland Creek in Pflugerville, Texas
Photo courtesy of the Texas Water Development Board

2.1 Flooding in Texas

In Texas, flooding is an important and increasing problem that is both costly and impactful to people's everyday lives. Flood-related disasters have resulted in more than $300 billion in damages in Texas since 1980. In the same time period, Texans have made over 290,000 claims to the National Flood Insurance Program (NFIP) totaling $16.8 billion in payouts. This figure does not include flood damage covered by private insurance or not covered by insurance at all. Almost every year, Texas is in the top three states for flood-related damage. According to the 2024 State Flood Plan produced by the Texas Water Development Board (TWDB), approximately 21 percent of Texas's land area, 69,000 roadway crossings, and over 43,000 miles of roadways have a 1 percent (100-year) annual chance of flooding. Texas' existing flood challenges are significant, and according to the Office of the Texas State Climatologist, flooding in our cities is estimated to become up to 50 percent more frequent by 2036.

At the same time, Texas' population is booming. Between 1997 and 2022, its population grew from 19 million to 30 million residents and is expected to increase to 51.5 million by 2070. While this increase in population is beneficial to the state's economy, it brings significant land use changes through rapid urbanization, which increases flood risk when existing and aging drainage infrastructure is insufficient. According to a 2025 study by Texas A&M Natural Resources Institute, nearly 3.7 million acres of working lands (privately owned farms, ranches, and forests that are actively managed for agriculture production and natural resource management) converted to non-agricultural use over the last 25 years. The rate of working land use loss has accelerated since 2017, with the loss of over 1.8 million acres, as shown in **Figure 2-1**.

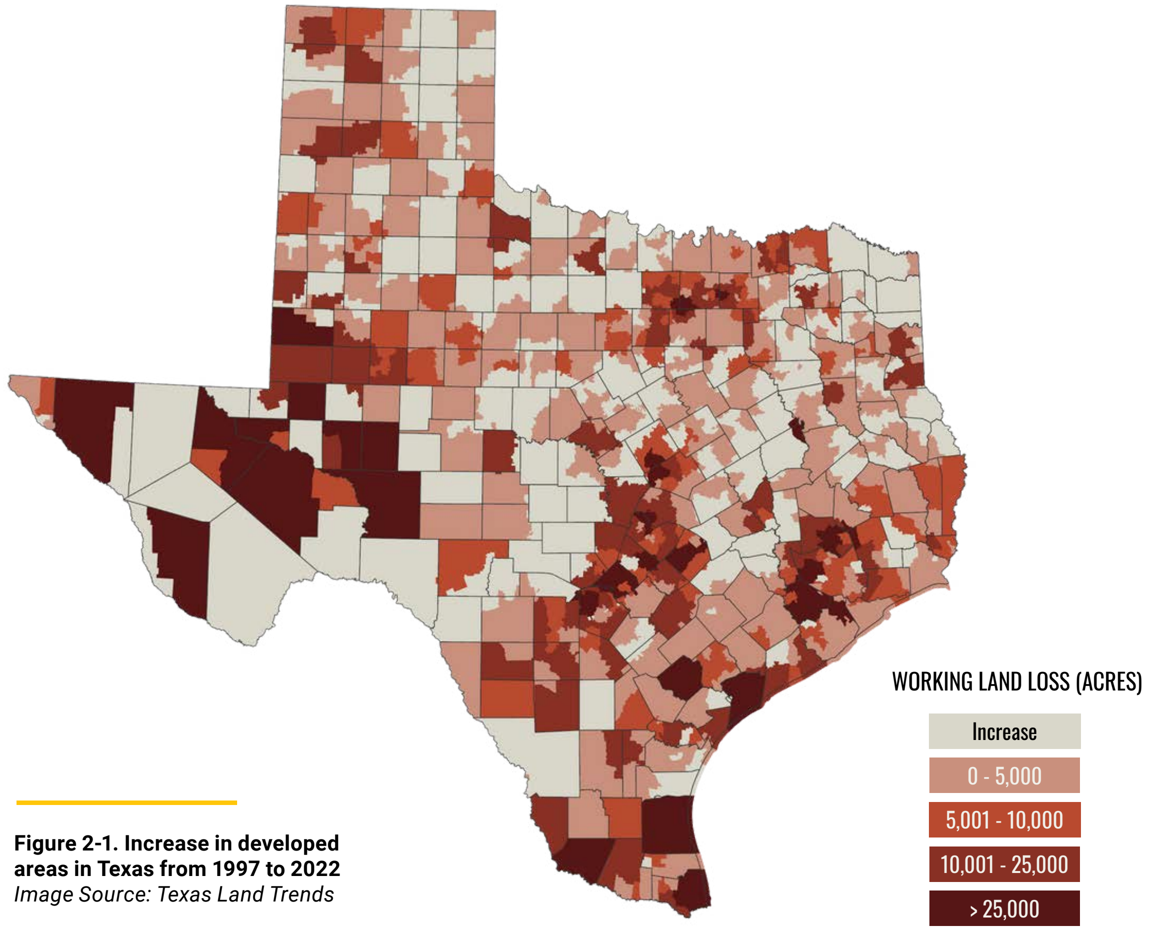


Figure 2-1. Increase in developed areas in Texas from 1997 to 2022
Image Source: Texas Land Trends

Land use changes alter the relationship between rainfall volume and rainfall runoff volume. As forests and grasslands are converted to impervious surfaces (e.g., concrete) rainfall volume increases, infiltration decreases and sediments and nutrient loads are sent to receiving channels. A 1982 study by the United States Geological Survey (USGS) of the White Rock Creek watershed in Dallas, Texas showed that converting a rural or natural watershed to a fully urbanized one can more than double the peak discharge[8], as shown in **Figure 2-2**.

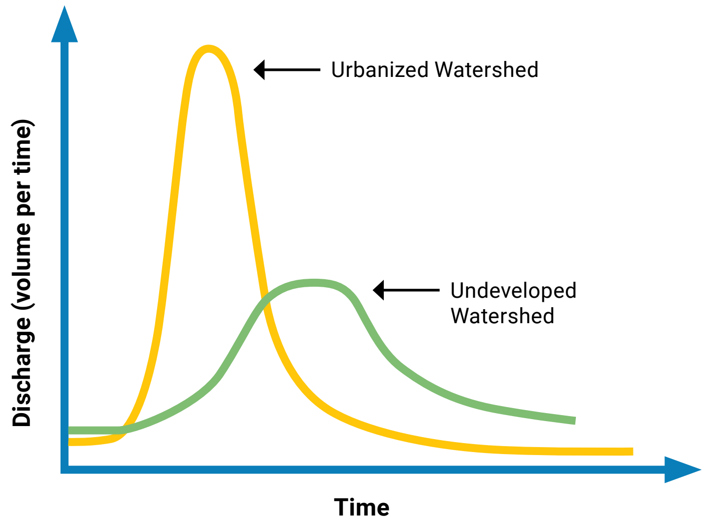


Figure 2-2. Comparing discharge from urbanized and undeveloped watersheds. A study by the USGS in Dallas, TX showed that urbanization can more than double the peak discharge.

What if flood risk reduction solutions in Texas could meet additional community and environmental needs? There is a growing body of research on the use and potential for using natural features and processes to solve flood risk reduction challenges. These strategies can work as standalone solutions or in concert with traditional gray infrastructure to meet flood risk reduction objectives while also benefiting people and the environment. The ***2024 State Flood Plan*** ↗ recognizes this opportunity through recommendations for nature-based flood resilience solutions.

This guidance manual focuses on the intentional use of NBS for flood resilience. While natural features and landscapes have always contributed to flood resilience, **NBS represent a deliberate strategy to recognize social and environmental benefits in community planning and include the beneficial functions of nature in sustainable flood risk reduction solutions.**

Communities are not separate from the environment—they are part of it. Human systems and natural systems are deeply interconnected. When natural hydrologic processes are degraded—through channelization, impervious cover, wetland loss, or disconnection from floodplains—the resulting impacts are felt by communities in the form of increased flood risk, water quality degradation, habitat loss, and economic cost.

Although this manual may distinguish between social, flooding, and environmental considerations for clarity, these elements are inseparable in practice. Flood resilience is community resilience. By intentionally incorporating the beneficial functions of nature, communities can advance sustainable, integrated approaches to flood risk reduction that support both people and the ecosystems on which they depend.

Tools and resources

- Association of State Floodplain Managers ***No Adverse Impact Legal Guide for Flood Risk Management*** ↗
- USGS ***Effects of Urbanization on Flood in the Dallas, Texas Metropolitan Area*** ↗

2.2 Types of flood risk

Riverine flooding: Abundant rainfall can result in more runoff entering a river channel than can be contained within its banks. When runoff volume exceeds the capacity of a channel, the river overflows onto adjacent lands called the floodplain. On steep, narrow floodplains, sometimes a lesser volume of runoff is needed in the streams to create excess overflows. In areas where the land is flat and floodplains are more expansive, greater volumes of runoff are required to cause flooding, the impacts of which may take hours or days to reach locations downstream.

Flash flooding: Flash floods are usually characterized by heavy rainfall that flow swiftly through riverbeds, urban streets, or mountain canyons. They can occur within minutes or a few hours of excessive rainfall. They can also occur even if no rain has fallen, for instance after a levee or dam has failed or after a sudden release of water by a debris jam.

Pluvial (Urban) flooding: Localized flooding occurs when rainfall overwhelms the capacity of engineered drainage systems to carry away rapidly accumulating volumes of water. It typically dissipates quickly, except in situations when pumping equipment fails due to loss of power, inflows exceed pumping or conveyance capacity, or debris blocks the passage of water. The solid surfaces of buildings and streets (also called impervious cover) prevent rainfall from soaking into the ground, resulting in runoff.

Coastal flooding: Low-pressure systems may gain strength as they travel across the warm waters offshore, sometimes developing into tropical storms or hurricanes. As these systems approach the Texas coast, stronger winds combined with changes in water-surface elevation can produce a storm surge that drives ocean water inland across the flat coastal plain. In addition to tropical storms or hurricanes, high-tide events also may cause frequent, localized flooding of low-lying coastal lands.

Compound flooding: Occurs when two sources of flooding, such as storm surge and riverine flooding, coincide to produce inundation extents greater than either source would generate independently.

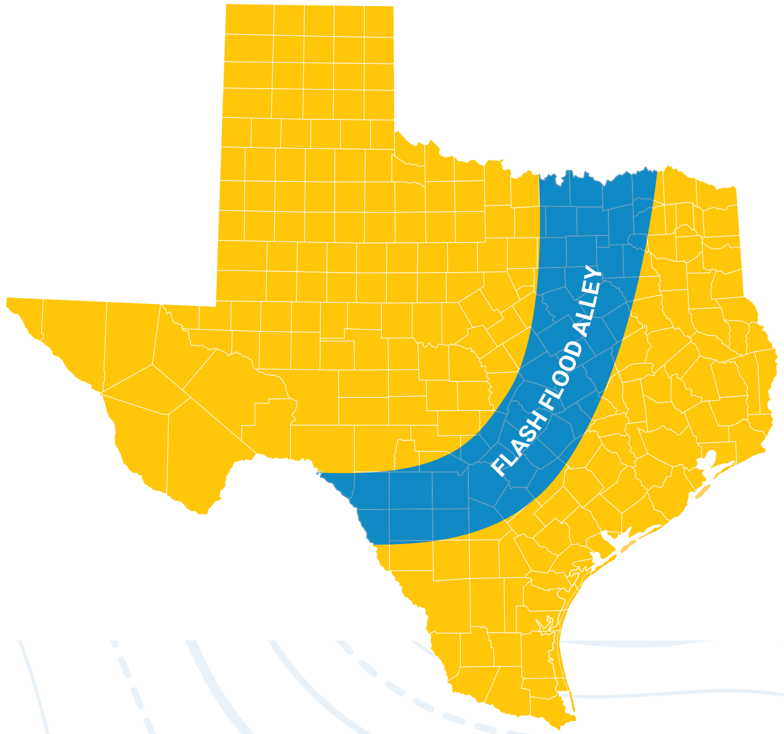


Figure 2-3. Flash Flood Alley. This flash flood is defined by a unique combination of geography and climate—where intense rainfall, steep terrain, and shallow, rocky soils limit infiltration, causing water to rapidly run off into narrow channels and produce sudden, high-velocity flash floods.

In 2025 TWDB identified provisional flash flood risk areas ↗ in the state.

Road and bridge damage on the Blanco River near Blanco, Texas, from the Memorial Day 2015 Flood.
Photo courtesy of USGS

2.3 Why NBS?

Nature is infrastructure

Natural spaces have many functions that provide benefits to society, such as improved air quality, improved water quality, and reduced flood risk that are often discounted or overlooked in planning, development, and policy decisions. The result can be an overreliance on gray infrastructure that misses the opportunity for society to take advantage of the additional benefits offered by nature. When recognized and leveraged appropriately, natural functions (e.g., flood storage, velocity dissipation) and natural features (e.g., floodplains, wetlands) can reduce flood risk and increase resilience while enhancing quality of life. In short, **nature is infrastructure** and should be accounted for as such. **Figure 2-4** shows some of the functions nature provides. Through the strategic conservation and preservation of undeveloped land, the restoration of natural spaces and functions, and the incorporation of natural features and processes in the design of existing and new infrastructure and development, NBS offer a commonsense approach to addressing many of Texas' flood risk challenges.

NBS for flood resilience function in several ways to help reduce flooding: they store, slow, and/or infiltrate floodwater across landscapes and scales. NBS can also be used to avoid future increases in flood risk by protecting existing flood infrastructure from sedimentation that can reduce flood storage space (e.g., detention basins) and erosion that can undermine stream bank stability and existing gray infrastructure (e.g., flood walls and levees). The natural functions of flood storage, infiltration, and attenuation can be replicated in NBS in developed landscapes where impervious surfaces have replaced natural systems. A few examples of how natural features function to reduce flood risk include:

- Natural areas, such as floodplains and wetlands, **provide important storage space for periodic floodwaters** in river systems that help **delay and/or reduce peak flow.**[9]
- Soil and vegetation work together to **slow surface runoff** by increasing surface and channel roughness and **increasing infiltration** by maintaining soil pore space. Vegetation also helps **manage sedimentation** by reducing erosion.[10]
- Coastal habitats like coastal marshes, beach and dune systems, oyster reefs, and mangroves **attenuate wave energy, reduce coastal erosion**, and in some cases can **reduce effects of coastal flooding by buffering against storm surge.**[11]

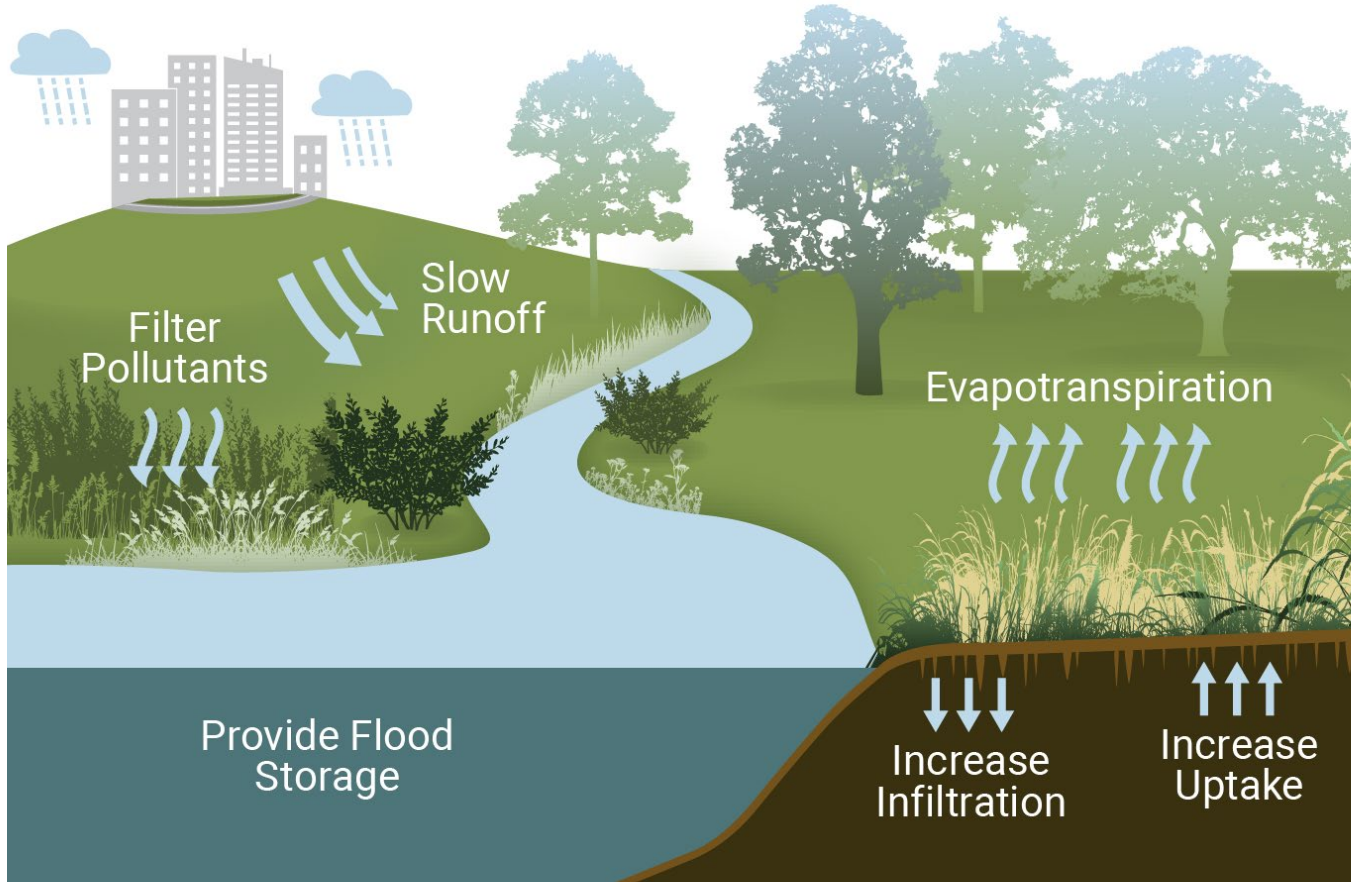


Figure 2-4. Natural functions of floodplains

NBS for flood resilience can include the deliberate protection and restoration of such natural ecosystems as wetlands and floodplains. In developed areas, NBS can restore, replicate, and integrate the functions of natural systems that have been lost, thereby enhancing flood resilience. In many cases, NBS for flood resilience will complement or enhance existing gray infrastructure, such as municipal storm drain systems, detention basins, floodwalls, and levees.

Both the conservation of existing natural areas that provide flood resilience benefits and the intentional use of NBS for flood risk reduction projects allow communities to alleviate pressure on existing infrastructure, bolster infrastructure function and value, increase quality of life, and provide for a more sustainable future.

Nature is adaptable

Flood infrastructure designs consider discrete, theoretical storm events often called design storms. The scale and intensity of these design storms are based on historical patterns and trends. As land use, climate, and weather patterns change over time, gray infrastructure has limited adaptability and can be expensive to expand or replace in response to changing conditions. **Because NBS use or imitate natural systems and processes, they are inherently adaptable.**

Over time, NBS can change and adapt with weather variability and sea level rise, and they can be added to or altered with less capital investment when compared to traditional infrastructure. For example, coastal marshes and dunes can adjust their elevation and shape with sea-level rise, if given the space to do so. Additionally, the use of native vegetation makes solutions more resilient to drought conditions, which can reduce maintenance costs associated with replanting vegetation.

Because some NBS inputs are supplied by nature, ongoing natural processes can be a source of supply or repair itself. Floodplain forests may be damaged by extreme floods, but they can naturally regenerate. It is important to note that **capitalizing on the adaptability of NBS to continue delivering flood mitigation and other benefits is not a foregone conclusion and requires long-term planning and varying levels of commitment to maintenance and adaptive management (monitoring, learning, and adjusting) depending on the NBS.**

Benefits of NBS for flood resilience

NBS are promoted as a viable and preferred approach to flood risk reduction by many state and federal agencies. Flood resilience solutions that incorporate or preserve nature and/or natural functions provide many economic, environmental, and social benefits to our communities. These direct and indirect benefits that people derive from nature are referred to as **ecosystem services** as shown in **Figure 2-5**. These benefits are often assigned a monetary value when evaluating cost-effectiveness of projects. See **Chapter 8.3** for additional discussion on benefit-cost analysis and the monetary value of ecosystem services.

By providing multiple benefits in addition to flood mitigation in a single solution, NBS can support community resilience more broadly than monofunctional gray infrastructure alone (**Table 2-1**). For example, a concrete drainage canal provides the single benefit of moving stormwater quickly downstream, whereas a more natural stream corridor that includes connected floodplain areas can store runoff while also providing green space, wildlife habitat, recreational opportunities, improved air and water quality, increased groundwater recharge, reduced downstream erosion, and pollution reduction, among other benefits.

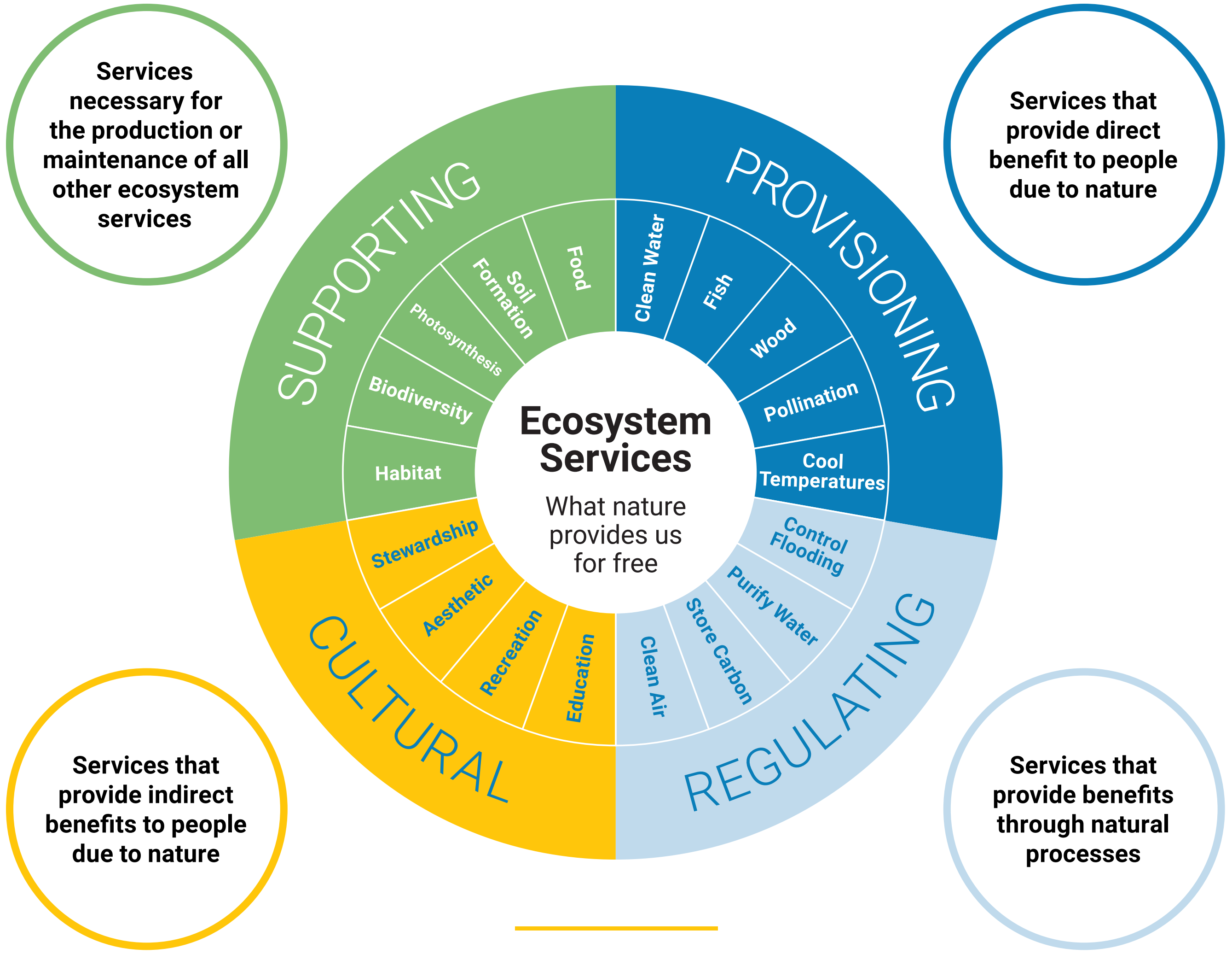


Figure 2-5. Ecosystem Services. These are defined as the direct and indirect benefits people receive from nature.
Adapted from United Nations The Economics of Ecosystem and Biodiveristy (TEEB)

Table 2-1. Additional co-benefits of NBS for flood resilience

Co-benefit	Description
Water quality	Pollution loads can be reduced by plants and soil taking up excess nutrients and sediment dropping out of the water column. The result is reduced sediment loading in downstream reservoirs and lower water treatment costs for water utilities.
Water supply and drought mitigation	Existing and restored wetlands absorb excess floodwater slowly and release that water into local streams over time. For perennial streams, the increased infiltration provided by NBS can contribute to streamflow.
Urban heat and air quality	Natural areas and vegetation used in NBS for flood resilience absorb less heat than concrete and help reduce urban heat island effect. Additionally, plants, especially trees, directly remove pollutants such as ozone, carbon monoxide, nitrogen dioxide, and sulfur dioxide from the air.
Recreation	NBS create community assets, not only for managing floodwater but also for recreation. The benefits of NBS can range from walking and biking to other outdoor activities like bird watching and hunting, and many of these benefits also contribute to economic development.
Habitat restoration	NBS projects often restore degraded ecosystems, such as wetlands, floodplains, and riparian corridors, providing essential habitat for fish, birds, pollinators, and other wildlife. Restored habitats support biodiversity, enhance ecological resilience, and contribute to the recovery of threatened and endangered species while maintaining healthy ecosystem services.
Public health and quality of life	NBS are considered a promising intervention for public health and improved quality of life. The improved air and water quality, reduced heat island effect, and availability of green space have been correlated with lower rates of hypertension, anxiety and depression, reduced inflammation, improved well-being, and an increase in social connectedness.[12]

2.4 The spectrum of flood resilience infrastructure

Flood infrastructure is often defined as either structural or nonstructural. Structural projects are practices that require physical construction to reduce or avoid the impacts of hazards, or the application of engineering techniques or technology to achieve hazard resistance and resilience in structures or systems. FEMA defines structural projects as physical constructions such as levees, floodwalls, and dams that control or divert floodwater to prevent flooding in an area.[12] In a nature-based context, these structural projects can be designed to incorporate stream and floodplain reconnection, constructed or restored wetlands, stormwater parks, living shorelines, and dune restoration, thus making them a hybrid approach.

Nonstructural projects are practices that rely on planning or policy measures to reduce disaster risks and impacts without major physical construction. FEMA defines nonstructural projects as actions that reduce flood risk through management or regulatory approaches—such as building codes, land-use ordinances (buffers and setbacks), or conservation easements that preserve the beneficial functions of floodplains and other natural areas—rather than through engineered structures.[13] In a nature-based context, these may include land conservation, floodplain and wetland preservation, property buyouts and relocations that help restore natural flood storage, flood warning and preparedness programs, and land use ordinances or setbacks that protect natural hydrologic and ecological functions.

Flood infrastructure runs the spectrum from traditional gray infrastructure (e.g., concrete channels, sea walls) to entirely natural (e.g., floodplain conservation, coastal wetland preservation), as shown in **Figure 2-6**. Often, the best solutions to address flood risk issues fall between these two extremes. This is referred to as hybrid or structural NBS.

For example:

- Stormwater parks provide natural areas to store stormwater but may still require gray infrastructure like pumps to protect surrounding areas.
- Floodplain restoration often requires engineering inlets and outlets to manage flood flows.
- Oyster reef habitat and living shorelines in front of concrete sea walls reduce wear and tear on the sea wall and add habitat and other environmental benefits that would otherwise be absent.

Integrating natural features or processes with traditional gray infrastructure can be used to add value by providing additional benefits without compromising the performance of the gray infrastructure. For example, the traditional approach for coastal flooding may be a seawall, but natural elements can be added that improve water quality and provide aquatic habitat that improves the co-benefit of recreational fishing.[27] Adding bioretention within neighborhoods can hold water on the landscape and reduce runoff into the storm drain system, while improving water quality and providing native habitat.

NBS can also be used to alleviate the burden on traditional gray infrastructure and reduce long-term maintenance costs. For example, The Texas Coastal Study[28] found that sediment placement along West Galveston Island and Bolivar Peninsula restores sediment to a critical coastal feature and supports the function of complementary coastal storm risk management measures. These examples illustrate how NBS applications can be part of a systems approach where traditional gray infrastructure is used in some parts of a system and NBS in others.

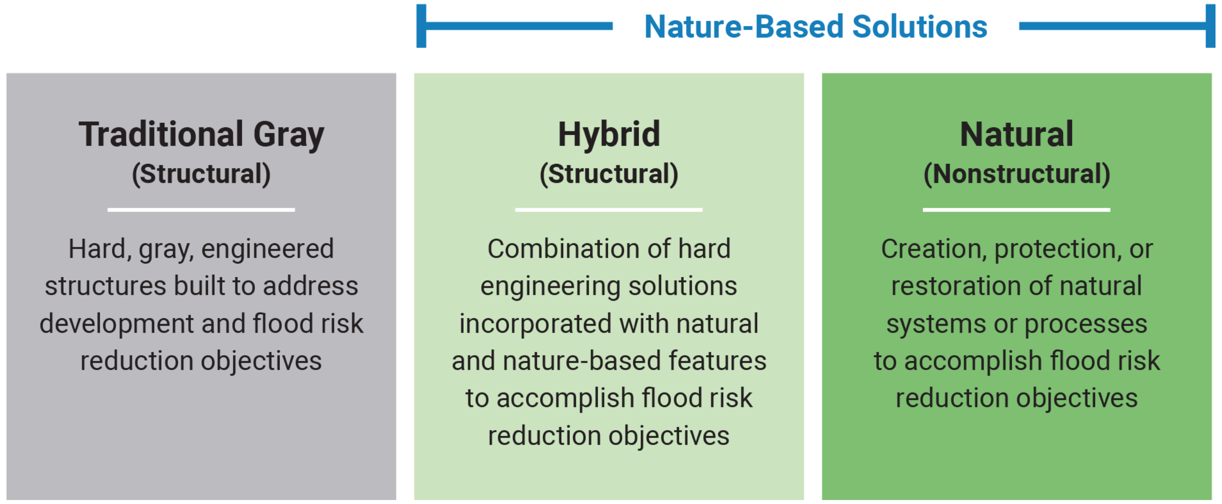


Figure 2-6. Spectrum of flood resilience infrastructure. This spectrum spans traditional gray, structural solutions, hybrid solutions and natural (nonstructural) solutions.
Adapted from the International Guidelines on Natural and Nature Based Features for Flood Risk Management

2.5 Types and practices of NBS for flood resilience

While NBS for flood resilience can be implemented across a range of contexts and scales, this manual, in alignment with FEMA[12], discusses three types of NBS: watershed, neighborhood, and coastal.

- **Watershed NBS**: Interconnected systems of natural areas and open space. These are large-scale practices that may require long-term planning and coordination. In general, these are upstream actions that have downstream benefits. **These are sometimes referred to as landscape NBS in the literature.**
- **Neighborhood NBS**: Distributed stormwater management practices that manage rainwater where it falls, thereby reducing or eliminating negative downstream impacts. These practices can often be built into a site, corridor, or neighborhood without requiring additional space. **These are sometimes referred to as site-scale NBS or urban NBS in the literature.**
- **Coastal NBS**: Features that stabilize shorelines, reduce erosion, and buffer against coastal storms. While watershed and neighborhood practices also work in coastal areas, the practices discussed in this category are focused on reducing coastal flood risk.

Case Study

Rush Creek flood mitigation and park improvements


Photo courtesy of City of Arlington

Location: Arlington

Opportunity: Properties at risk of flooding along Rush Creek

Lessons learned: Property buyouts can be an effective non structural NBS that effectively reduces flood risk while creating multi-benefit public spaces.

Following Tropical Storm Hermine in 2010, the Rush Creek watershed experienced historic flooding, with water depths reaching up to 4 feet in nearby homes. More than 50 single-family residences and a 100-unit condominium complex sustained verified damage. Since many homeowners and renters lacked flood insurance, residents faced significant recovery challenges and remained vulnerable to repeated losses.

To address the ongoing flood risk, the City of Arlington pursued a nonstructural solution focused on restoring natural floodplain functions. Through a voluntary property buyout program funded by stormwater utility bonds, the city acquired and removed 49 of the 50 flood-prone homes and the 100-unit condominium complex located within the 1 percent annual chance floodplain. Demolition of these properties re-established valley storage capacity, allowing Rush Creek to spread naturally during future storm events. The reclaimed land was integrated into an expanded park network connecting Clarence Foster Park, Kelley Park, and Rush Creek Linear Park—transforming a neighborhood that was once flood prone into a resilient public green space.

2.6 Watershed NBS overview and applicability

Watershed NBS practices are generally large in scale and function best as interconnected systems of natural areas and open space that store large volumes of floodwater across a watershed. Recognizing the flood attenuating value or potential value of existing natural areas and open spaces—and preserving or restoring that function—is a necessary step in connecting land-use decisions and long-term flood management costs. Because of the space needs and required interconnectedness of watershed NBS, long-term planning and multi-jurisdictional coordination may be required throughout a watershed to identify where opportunities exist to link NBS across multiple parcels upstream of areas with flooding challenges. The concepts discussed within this section can be applied within an urban setting, though projects must be adapted based on constructed features or available space.

Floodplains are land areas susceptible to inundation by floodwaters from any source. Functionally, floodplains allow rivers or streams to spread out flow, thereby reducing velocity, storing excess water and ultimately reducing damage to people, property, and the stream channel. Placing fill material within the floodplain reduces the natural function of the floodplain to store runoff.

In addition to their ability to slow and store large volumes of floodwater, floodplains provide essential ecosystem services that have beneficial physical, biological, economic, water quality, and societal impacts. For example, restoring or protecting a floodplain's ability to store floodwater allows water to infiltrate through the soil into the groundwater table. This removes pollutants, can recharge groundwater aquifers, and provides a higher base flow of water in the channel during dry times—a benefit for society as well as aquatic, riparian, and terrestrial biological communities.

Watershed NBS can be entirely natural, such as land conservation, or a combination of nature, natural processes, and engineered solutions. Examples of watershed NBS are shown in **Table 2-2** and **Figure 2-7**.

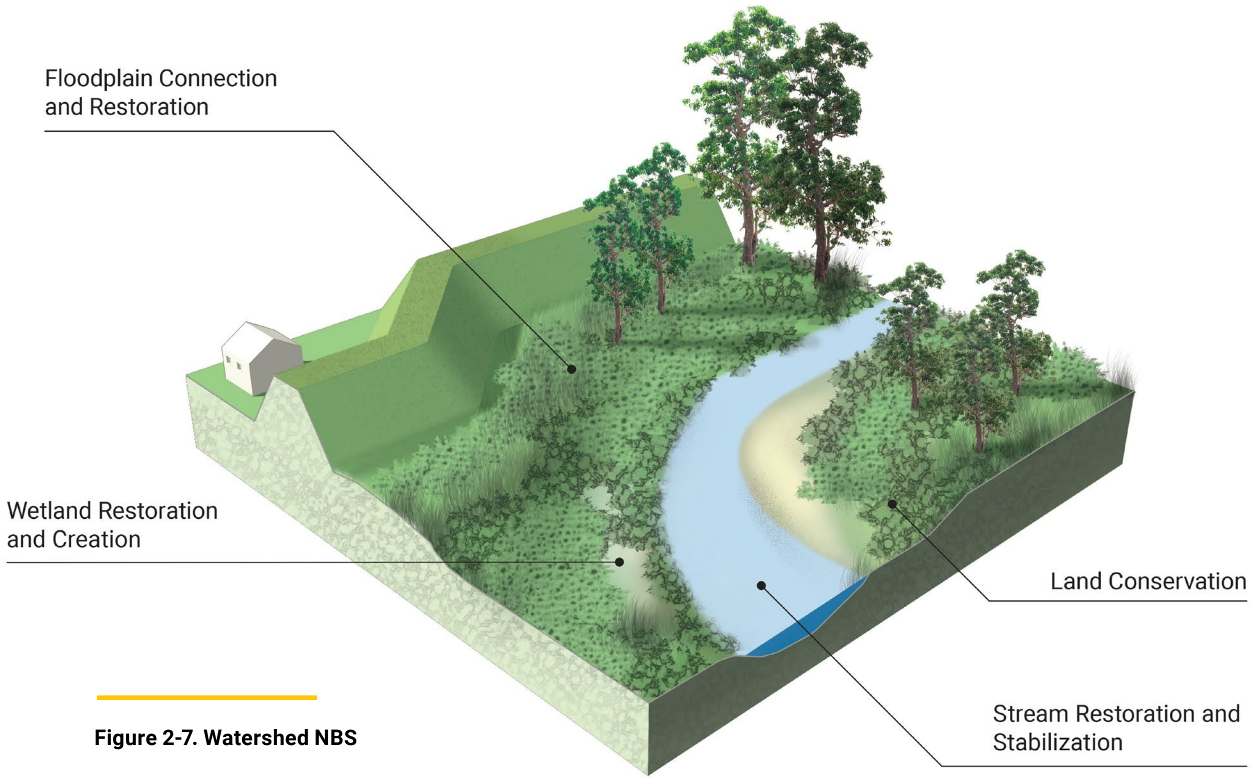


Figure 2-7. Watershed NBS

Table 2-2. Watershed NBS

Watershed NBS practice	Description and flood resilience benefit	Potential to replace gray infrastructure
Stream restoration and stabilization	Stream restoration and stabilization emulate or re-establish natural hydrologic, geomorphic, and ecological functions. Through the reconnection of the channel to its floodplain, restoring sediment and flow regimes, and rebuilding riparian and in-stream habitat complexity, stream stabilization and restoration is able to: increase floodplain storage and groundwater recharge, reduce erosion and pollutant loads, improve habitat and biodiversity, while reducing downstream flood risk. Stabilization and restoration techniques (e.g., grading and bioengineering) can be applied across localized reaches of channel corridors or incorporated into larger-scale flood control channels.	Concrete-lined or graded flood control channels
Floodplain connection and restoration	Floodplain connection rebuilds natural functions by reconnecting the floodplain to its waterway, providing flood storage, reducing erosion, filtering pollutants, providing habitat, and reducing flood impacts to downstream areas. Floodplain connection can include constructing multi-stage channels or the reconnection of a channel or river to the natural floodplain by realigning or removing an obstruction, such as a levee.	Detention ponds, concrete-lined or graded flood control channels, raising levees, dams/ reservoirs
Wetland restoration and creation	Restoring and creating wetlands and playa lakes can reduce flooding by holding water on the landscape and reducing runoff to streams. Wetlands can also recharge groundwater and provide habitat for fish and wildlife.	Detention ponds
Land conservation	The deliberate protection of land in a natural or open state through acquisition, easement, or other means by slowing and storing stormwater. This practice can include upland habitats like forests and prairies, bottomland forests and floodplains, and wetlands of all types.	Dams/reservoirs, levees, detention ponds

2.7 Neighborhood NBS overview and applicability

Neighborhood NBS practices are implemented in developed areas to manage stormwater locally and/or onsite. They include a wide set of practices adapted to the local context (geography and land use) and climate that mimic natural processes to retain and use stormwater. Because of the smaller size of developed commercial and residential lots, neighborhood NBS are often, but not always, smaller features on the landscape. They are often referred to as green infrastructure and include features such as rain gardens, bioswales, and green roofs. However, where opportunities exist, neighborhood NBS can also be larger and include features like stormwater parks, wet ponds, and constructed wetlands (**Table 2-3** and **Figure 2-8**).

Though a single neighborhood NBS practice may provide marginal flood mitigation benefits for the larger drainage area, when systematically incorporated throughout a drainage area, these practices can provide significant benefits.[14] Consider that a driveway, parking lot, or rooftop creates a marginal increase in runoff; however, the cumulative impact of thousands of driveways, parking lots, and rooftops creates a significant increase in runoff that can result in downstream flooding. For neighborhood NBS, a single feature may produce a marginal flood resilience benefit; however, many distributed NBS practices aligned in series can achieve a significant benefit in flood resilience—with additional community benefits.

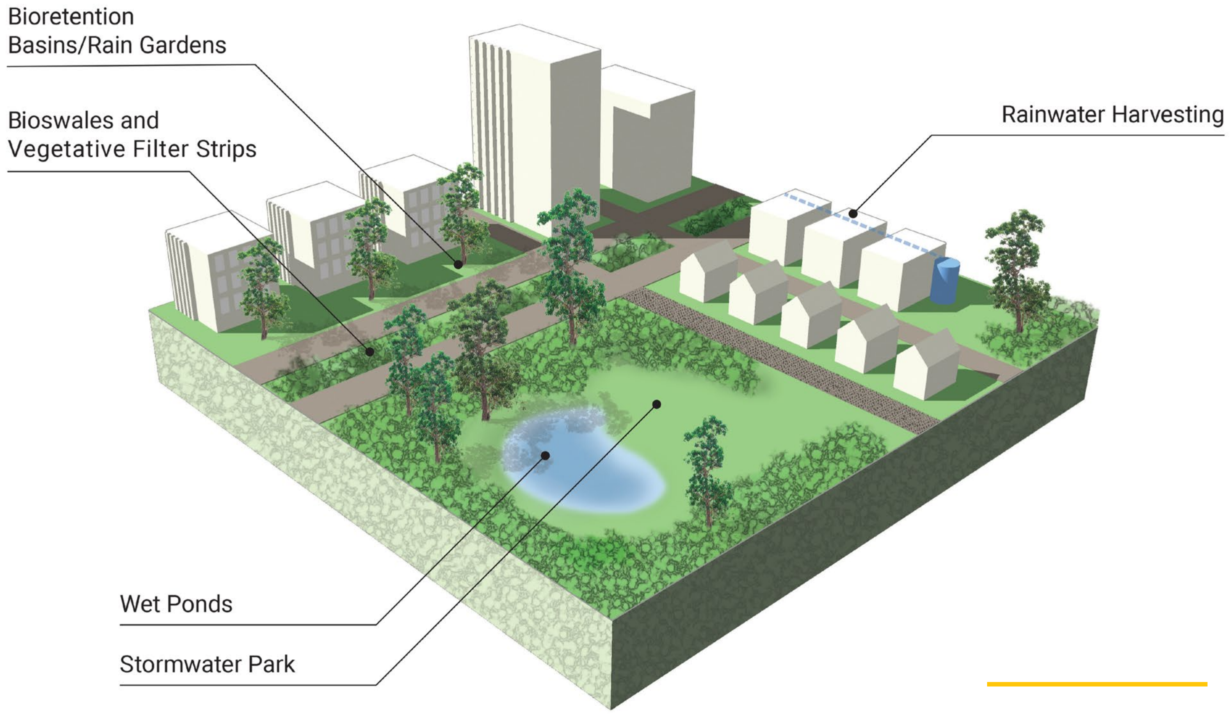


Figure 2-8. Neigborhood NBS

Table 2-3. Neighborhood NBS

Neighborhood NBS practice	Description and flood resilience benefit	Potential to replace gray infrastructure
Bioretention basins/rain gardens	Bioretention basins are landscaped depressions that capture and temporarily store runoff and utilize engineered or well-draining native soils and vegetation to filter pollutants and infiltrate runoff. This can include stormwater trees, stormwater tree trenches and infiltration basins.	Pipes, drains, catch basins
Bioswales	Bioswales are shallow, open channels that convey stormwater runoff while removing some pollutants through deposition and filtration within the vegetation itself. These swales are particularly effective as a pretreatment for concentrated stormwater flows.	Pipes, drains, catch basins
Vegetative filter strips	Vegetated filter strips are areas of dense, permanent vegetation with a consistent slope, typically designed to treat sheet flow runoff from impervious surfaces via infiltration, which aids in reducing stormwater runoff volumes.	Pipes, drains, catch basins
Wet ponds	Wet ponds, characterized by a permanent pool of water, detain and treat runoff in the pool through gravitational settling and biological uptake, particularly nutrients. Wet ponds differ from detention/retention ponds in the use of features intentionally designed to uplift and maintain aquatic ecosystems.	Detention ponds
Constructed wetlands	Constructed wetlands are areas intentionally graded and vegetated to mimic natural wetlands zones with varying wetness that filter pollutants in runoff through wetland vegetation and soils.	Detention ponds
Rainwater harvesting	Rainwater harvesting is the collection and storage of precipitation that consists of storage tanks that capture debris and sediment and store runoff from rooftops or other impervious areas, which slows runoff downstream. Local government may provide incentives to promote adoption by homeowners.	Pipes, drains, catch basins
Stormwater parks	A stormwater park, oftentimes referred to as a floodable park, is a multifunctional green space that is designed to temporarily store and manage stormwater runoff. Stormwater parks can be designed to handle large contributing drainage areas and typically feature multiple NBS practices.	Detention ponds

2.8 Coastal NBS overview and applicability

There are both small- and large-scale coastal NBS practices, from small natural breakwaters and oyster reefs to large coastal marsh, beach, and dune restoration and protection efforts (**Table 2-4** and **Figure 2-9**). Coastal NBS function to stabilize shorelines, reduce wave energy, and reduce the exposure of people and property to storm surge. Coastal NBS are popular for their flood mitigation benefits as well as their aesthetics, recreational opportunities, and fish and wildlife benefits.

Coastal NBS are most effective as part of a system of features that creates a tiered buffer against storm surge and wave energy. This is known as the multiple lines of defense strategy.[15] It includes several approaches, including NBS that combine to create a more resilient and sustainable coastline. The NBS in the multiple lines of defense strategy can include, but are not limited to, barrier island protection and restoration, beach and dune restoration, marsh and coastal wetland protection and restoration, and oyster reefs. Because most of these features are dynamic, accumulating sediment and growing with changing conditions, coastal NBS can be considered more resilient to sea level rise than their structural counterparts (e.g., levees, bulkheads, seawalls) if they are designed appropriately.

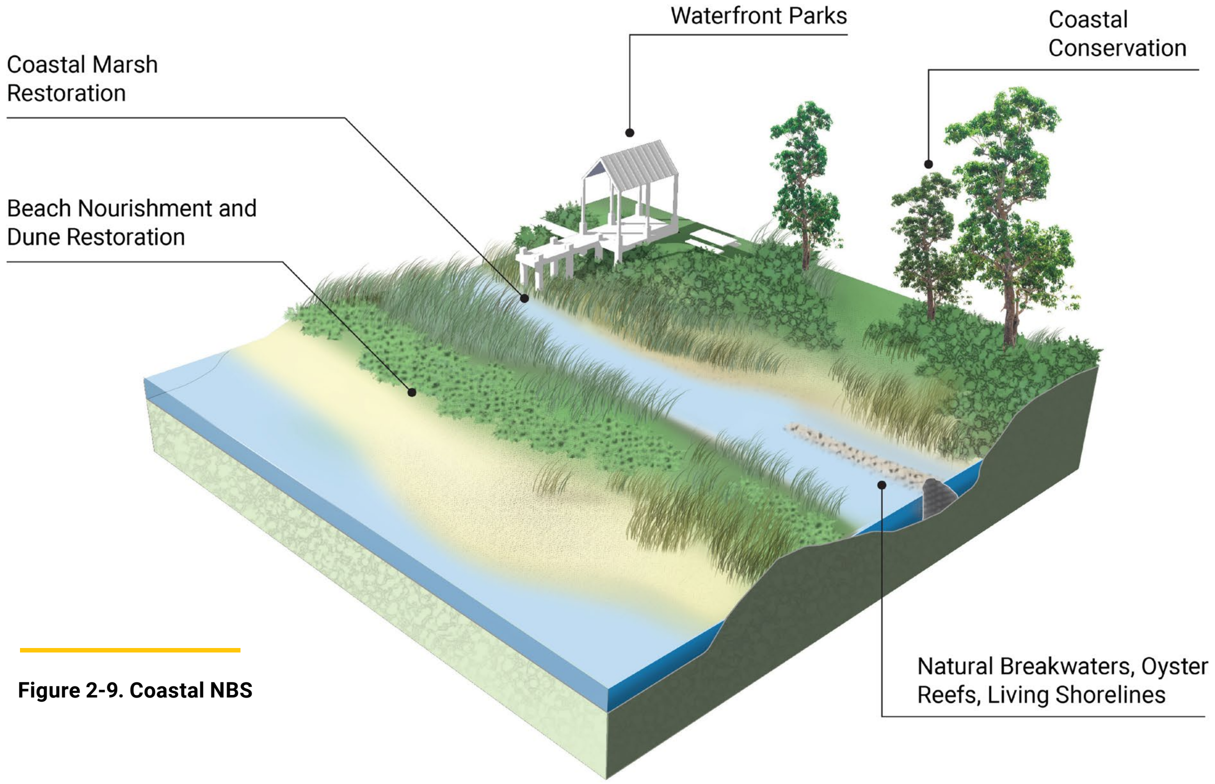


Figure 2-9. Coastal NBS

Table 2-4. Coastal NBS

Coastal NBS practice	Description and flood resilience benefit	Potential to replace gray infrastructure
Beach nourishment and dune restoration	This restoration involves the planned placement of sand landward of the beach face and restoration of dune habitat to rebuild and enhance beach and dune systems. Robust beach and dune systems can limit shoreline erosion, dampen waves, and protect from storm surge.	Seawalls, levees, floodgates
Coastal marsh, restoration	The restoration or enhancement of such coastal habitats as wetlands, marshes, and coastal prairies helps buffer storm surge, reduce wave energy, and stabilize shorelines.	Seawalls, levees, floodgates
Natural breakwaters, oyster reefs, living shorelines	The creation of natural breakwaters, such as reef habitats like oyster reefs, can absorb wave energy and buffer shorelines from currents, waves, and storms.	Riprap, revetment, breakwaters, bulkheads
Waterfront parks	Multifunctional parks located along the edges of bodies of water, such as rivers, lakes, or coastal areas that are designed to flood and buffer communities from coastal flooding.	Seawalls, levees, floodgates
Coastal conservation	Coastal conservation entails strategic protection of coastal habitats through acquisition, easement, or other means to preserve their ability to attenuate wave energy, reduce erosion, and slow and store storm surge. This practice includes offshore habitats like reefs and seagrass, intertidal habitats like mangroves, and onshore habitats like coastal marshes, prairies, and beach/dune complexes. Special consideration should be given to habitat migration space due to sea level rise.	Seawalls, levees, floodgates, breakwaters

Definition

Living shorelines

A “living shoreline” is a common description of coastal NBS practices in Texas. Often, living shorelines embody the multiple lines of defense strategy in a single project. They typically include multiple natural or nature-based features combined with hard structural components to provide shoreline protection and stabilization while maintaining shoreline ecosystem functions. They use natural or recycled materials, along with the strategic placement of plants and/or other organic materials, to reduce erosion, protect property, create habitat, and enhance resiliency. The Texas General Land Office (GLO) identifies living shorelines as an effective, natural solution that, in contrast to conventional hardened shorelines, offers many benefits to the environment and increased community resilience.[16]

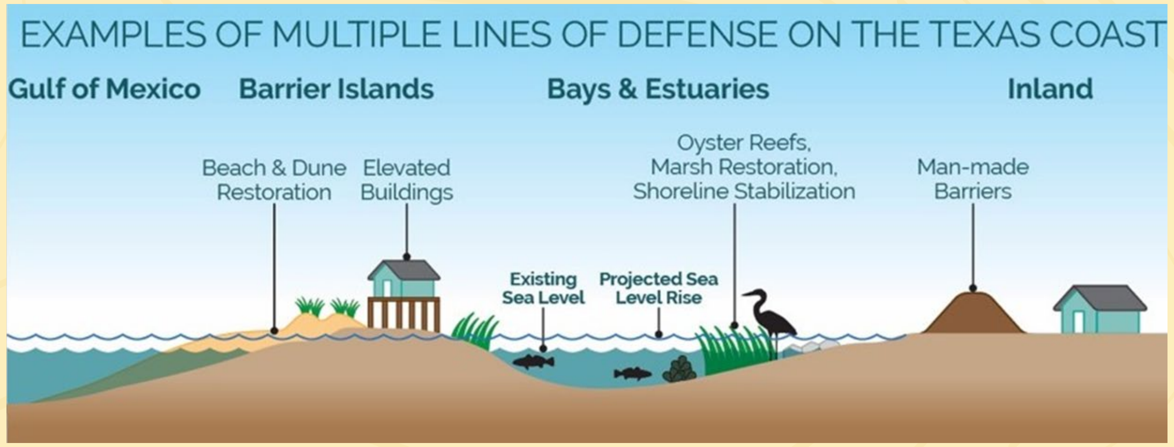


Figure 2-10. Multiple lines of defense on the Texas Coast
Source: The General Land Office

Shicke Point natural breakwater seward of marsh protecting residential area with multiple lines of appraoch.
Photo courtesy of Freese and Nichols, Inc.

2.9 Overcoming barriers to NBS implementation in Texas

In the development of this manual, stakeholder outreach helped identify common barriers to NBS implementation in Texas. The following section expands on these challenges and offers guidance on navigating them so that those seeking to implement NBS in their community can proactively work to avoid common challenges and address potential barriers.

Increase understanding of NBS and their benefits

Experience and buy-in with NBS varies widely among different agencies. Practitioners, decisionmakers, and the public would benefit from increased awareness and understanding of the potential for NBS as a tool for flood mitigation and the multiple benefits of NBS. The greatest opportunity for impact is with agencies and departments involved with design and permitting. Furthermore, government staff and decisionmakers would benefit from clear, specific, and accessible information about the multiple benefits and costs of NBS and their performance. One way of increasing awareness and understanding of the potential value of NBS is by assessing them in the same terms as traditional gray infrastructure. ***Reguero et al. (2018)*** ↗ compared the costs and benefits of various coastal adaptation measures across the Gulf Coast and showed how the cost-benefit ratio of many coastal adaptation measures such as wetland restoration, oyster reef restoration and barrier island restoration were much higher than other types of measures such as local levees, shoreline levees and structural elevation. Additional studies and examples that feature details on the performance, costs (including maintenance), and benefits across all NBS types are needed so that decision-makers will opt for an NBS approach.

The barriers discussed here are informed by research conducted specifically for this manual to identify common issues that impact the implementation of NBS projects in Texas. The research effort included interviews with stakeholders in Texas with NBS expertise, a statewide survey of experiences and knowledge of NBS practices across Texas, and a review of available NBS literature with a particular focus on the Texas context.

Ranking NBS implementation barriers from 246 survey responses

1. **Lack of technical understanding or expertise among decision-makers**
2. **Lack of general awarness**
3. **Resistance to change**
4. **Lack of technical expertise among practitioners**
5. **Difficulty incorporating NBS into existing planning processes**

Train professionals in NBS planning, design, and construction

A workforce trained in NBS is crucial for properly designed, constructed, and maintained NBS systems, which is necessary for increasing public and professional understanding and acceptance that NBS are important tools for flood resilience. The Clean Water Alliance published ***Barriers and Gateways to Green Infrastructure*** ↗[17] which discusses a lack of training among local utility staff, development, and consulting industries and how this results in an industry culture that is “skeptical” of NBS despite successful examples across Texas. There is a need for technical training in NBS among new and existing engineers, contractors, operation and maintenance professionals, and government agency staff. Additionally, involving a contractor with NBS experience in the design process, even in an advisory role, can improve project outcomes.

Train operations and maintenance personnel

The proper training of operations and maintenance personnel responsible for NBS can have many benefits. Their inclusion in the planning and design of NBS is crucial, as it can help ensure adequate planning and budgeting for long-term O&M and contribute to the buildup of a trained workforce in the private and public sector for maintaining NBS. Oftentimes, there can be a lack of communication across different disciplines such as coordination between designers and O&M staff on proper maintenance measures. For example, if maintenance professionals are not properly trained, they may mow vegetation that was intended to stay tall to help slow runoff, thus reducing the effectiveness of the design.

Adequately assigning responsibility and costs for O&M of NBS is a critical task. A review of nearly 100 research papers on green infrastructure noted that a persistent challenge was a lack of clear guidelines for maintenance.[18] Once vegetation is established, NBS projects can require maintenance to perform as intended, as with traditional infrastructure systems; however, NBS projects often have lower costs for maintenance over the life of a project when compared to typical gray infrastructure projects due to their adaptability and self-maintaining natural features.[19, 20]

Adopt a multifunctional planning approach

One of the most important benefits of NBS is the general multifunctional paradigm, in which one intervention can address multiple challenges a community may face (e.g., water and air quality, lack of access to green space and recreation, urban heat island). Unfortunately, many traditional, siloed approaches to planning and implementing flood and stormwater infrastructure tend to have a “monofunctional” approach, in which solutions only address the flooding problem (e.g., concrete-lined channels, levees). Project teams should include the multiple disciplinary skillsets required for multifunctional project designs. Another facet of the monofunctional mindset that can be a challenge to NBS implementation is a lack of understanding of how NBS can supplement or complement traditional infrastructure with nature-based components. Finally, current systems for planning and permitting may not be designed for multifunctional NBS so engaging multidisciplinary teams with a range of experience to draw from can help overcome the status quo of monofunctional approaches to project planning and development.

Tools and resources

- Texas A&M University
  Coastal Engineering & Nature-Based Solutions Short Course ↗
  Introduction to Green Infrastructure ↗
- Arid LID Coalition
  Middle Rio Grande Green Stormwater Infrastructure Maintenance Manual ↗

Physical space requirements and regional variability

Improved understanding of physical characteristics such as depth to groundwater, soil type, topography, and rainfall regimes can reveal opportunities for NBS. Like gray infrastructure, for any given site there can also be challenges associated with existing utilities, rights-of-way, and property boundary limitations. Practitioners should also develop an understanding of the cumulative performance of multiple NBS systems within a watershed (across scales). The availability of space to store floodwater is frequently a challenge for flood risk reduction; however, there are common misperceptions about NBS, including that they always require more space than traditional infrastructure or that space is not available, especially in developed areas. NBS can present opportunities to overcome physical space constraints. Chapter 6 further discusses planning for NBS across the various natural regions of Texas.

Adoption by private development community

Development techniques that preserve natural features and functions and reduce long-term costs can benefit communities. Inconsistent regulation of development in the floodplain and the lack of incentives or requirements for private land developers to maintain natural features or incorporate NBS into projects results in status quo development practices that can miss the opportunity for long-term community benefits. NBS for flood resilience can make beautiful, natural space for people to gather and live.

Adoption by the private development community could be influenced by a growing body of research from developments that implemented NBS practices and realized cost savings and financial advantages. The biggest cost savings were gained through reduced civil work required for site development, reduced paving, and reduced need for stormwater management controls and associated construction costs.[22, 23]

Funding and financing NBS

Identifying and accessing funding and financing mechanisms is “crucial yet challenging”[24] for communities wishing to implement NBS projects. While a big part of the challenge involves the general lack of awareness of potential funding sources, the lack of familiarity with the financial “math” of NBS projects that is integral to garnering support for NBS and moving projects forward also limits their implementation. This includes both the capital costs of a project and the necessary staff time and investment in figuring out something new. Further, when facing project budget constraints, the perception of NBS as a “nice-to-have” and not as a valuable community asset often results in NBS being excluded from projects. Small communities, where staff routinely wear multiple hats, may be particularly challenged by capacity issues for building the financial case for NBS.[25]

Case Study

Queenston Manor

Location: Harris County

Opportunity: NBS implemented as a multi-functional, space-saving approach to manage runoff.

Lessons learned: Bioretention can provide detention volume throughout a site which can create opportunities for site configurations.

The Queenston Manor apartment complex illustrates the value of NBS to transform stormwater management to create a multifunctional site assets. The original conventional design for the 7.2-acre development relied on a single, detention pond to meet regulatory stormwater requirements.[21] The design team pivoted to a low impact development (LID) approach that distributed stormwater management across the site using n neighborhood NBS. Permeable pavers and bioswales were integrated throughout the development to capture, filter, and manage stormwater runoff at the source. This distributed approach replaced the need for a centralized detention facility, allowing stormwater to be treated as it moves across the site rather than being collected and held in a single location. The result was a design that not only met Harris County's regulatory requirements, matching pre- and post-development hydrographs, but also fundamentally changed how land on the site could be utilized.

The shift to an NBS design unlocked significant space savings across the Queenston Manor site. By eliminating the large footprint of the traditional detention pond and replacing it with distributed NBS elements, the design freed up enough land to accommodate two additional apartment buildings, adding 48 residential units to the development.[21] This space efficiency directly translated into increased revenue potential and improved project economics, demonstrating that NBS is not simply an environmental amenity but a financially strategic design choice. The greenspace created by the bioswales and permeable paver systems also enhanced the aesthetic quality of the site, creating appealing courtyard and landscaped areas for residents.

The Queenston Manor project serves as a compelling example of how NBS can deliver multifunctional outcomes above what conventional stormwater infrastructure can provide. A single detention pond addresses only one function whereas the integrated system of permeable pavers and bioswales simultaneously manages stormwater quantity, improves water quality through filtration, creates usable green amenity spaces, and supports land use efficiency. The system was designed to drain common areas and courtyards within 24 hours of a rain event, ensuring that the NBS elements remain functional and accessible to residents between storm events.[21] This project demonstrates that when NBS is applied thoughtfully in an urban development context, it can outperform traditional approaches across multiple dimensions while maximizing the value of every square foot of the site.

Photo courtesy of Freese and Nichols, Inc.

Case Study

Creative ways to fund NBS

Location: Clear Lake City

Opportunity: Land previously used as a golf course was converted to multifunctional wet pond.

Lessons learned: NBS reduce flooding while creating civic amenities.

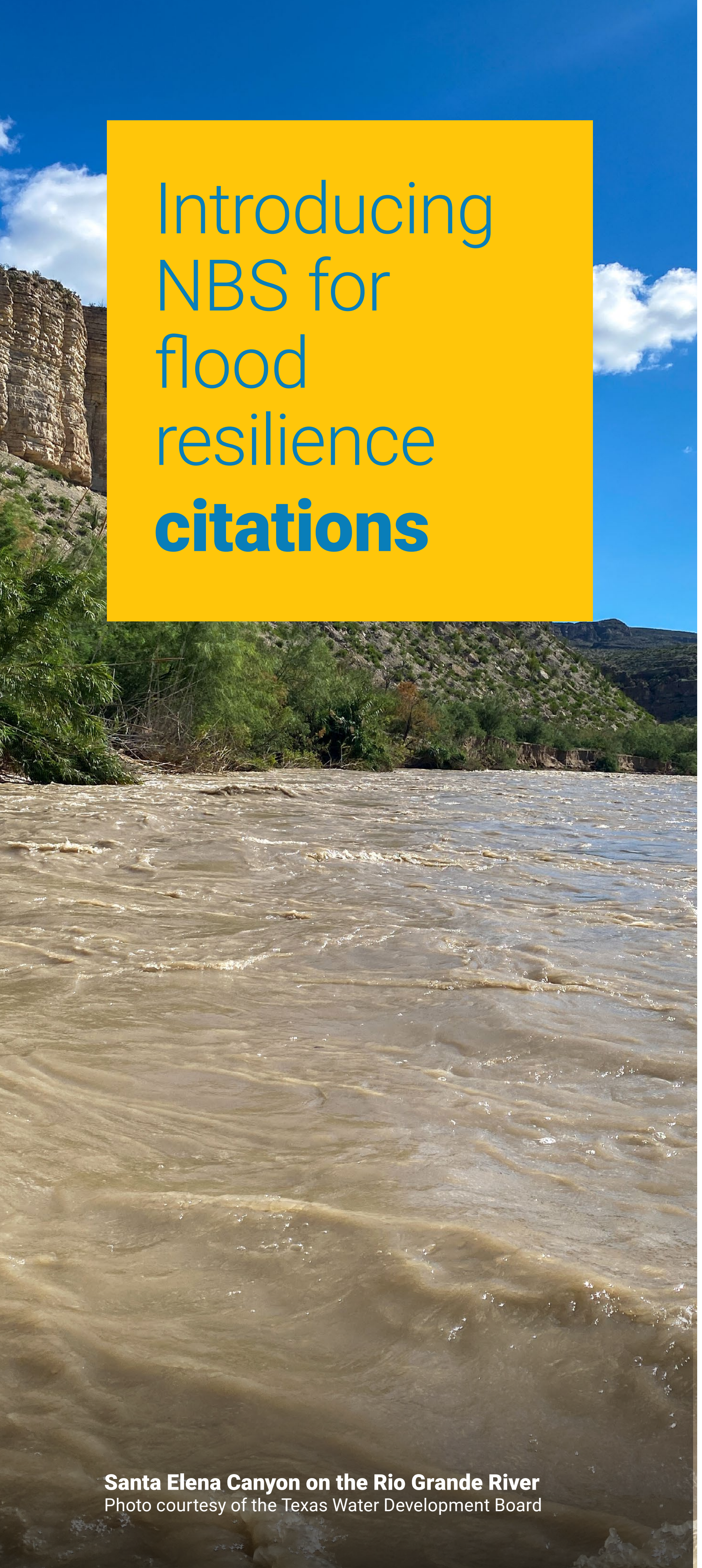
Exploration Green is located in Clear Lake City, on the southeast edge of Houston. Clear Lake City has a long history of flooding. In 2004, the corporate owners of Clear Lake City's public golf course announced their plans to sell the property for commercial development. Concerned about the impact of additional development on the area's already high flood risk, the Clear Lake City Civic League approached the Clear Lake City Water Authority with the goal of finding an alternative solution. Exploration Green retrofitted the 200-acre golf course into a public park with five large wet ponds with wetland features that provide flood storage, improve water quality, and provide recreational opportunities.

The project was planned over a 15-year time horizon and was implemented in multiple phases with extensive stakeholder engagement. The success of the stakeholder engagement is reflected in the variety of funding sources and in-kind contributions that support the project, which has an estimated implementation cost of $48 million–$50 million. The largest portion of funding comes from $45 million in local bond appropriations, demonstrating local support. Exploration Green was awarded $2.8 million in grants, primarily from the Texas Parks and Wildlife Department and the Texas Coastal Management Program. In addition, $300,000 was donated by a plethora of local civic groups, corporations, and individuals. Another $3.2 million in in-kind contributions came in the form of native trees and wetland plants donated by Trees for Houston and the Texas A&M AgriLife Extension Service.[26]

Figure 2-11. Native wetland habitat and recreational paths at Exploration Green

Bull Creek in Austin, Texas
Photo courtesy of the Texas Water Development Board

Introducing NBS for flood resilience **citations**



Santa Elena Canyon on the Rio Grande River
Photo courtesy of the Texas Water Development Board

[1] Texas Water Development Board, 2021, 2022 state water plan—Chapter 4, *Future population and water demand:* Austin, Texas Water Development Board, www.twdb.texas.gov/waterplanning/swp/2022/docs/SWP22-Water-For-Texas.pdf, accessed June 2026.

[2] Federal Emergency Management Agency, n.d., *Historical NFIP claims information and trends,*] www.floodsmart.gov/historical-nfip-claims-information-and-trends, accessed February 2026.

[3] Texas Water Development Board, 2024, *2024 state flood plan—Volume I:* Austin, Texas Water Development Board, www.twdb.texas.gov/flood/planning/sfp/doc/2024_State_Flood_Plan_Volume_I.pdf, accessed February 2026.

[4] Texas A&M University, Office of the Texas State Climatologist, n.d., *Assessment of historic and future trends of extreme weather in Texas, 1900–2036:* College Station, Texas A&M University.

[5] Texas Water Development Board, 2024, *2024 state flood plan (Vol. I)*, https://www.twdb.texas.gov/flood/planning/sfp/doc/2024_State_Flood_Plan_Volume_I.pdf, accessed June 2026.

[6] Texas Land Trends, n.d., *Texas land trends,* https://txlandtrends.org/, accessed February 2026.

[7] Bridges, T.S., King, J.K., Simm, J.D., Beck, M.W., Collins, G., Lodder, Q., Mohan, R.K., eds., 2021, *Overview—International guidelines on natural and nature-based features for flood risk management:* Vicksburg, Mississippi, U.S. Army Engineer Research and Development Center.

[8] U.S. Geological Survey, 1973, *Effects of Urbanization on Floods in the Dallas, Texas, Metropolitan Area,* pubs.usgs.gov/wri/1973/0060/report.pdf, accessed February 2026.

[9] CCurran, J.C., McKay, S.K., Beagle, J.R., Brauer, E.J., Haring, C.P., Thomas, J., Lange, J., Buhr, D., VanBuecken, N., Rose, C., Bishop, D., Jenson, S., 2025, Engineering Practice Guide for Floodplain Benching: A Natural Infrastructure Approach for Riverine Systems, ERDC TR-25-15, US Army Engineer Research and Development Center.

[10] U.S. Environmental Protection Agency, 2015, Enhancing sustainable communities with green infrastructure: A guide to help communities better manage stormwater while achieving other environmental, public health, social, and economic benefits: Washington, D.C., U.S. Environmental Protection Agency, EPA 100-R-14-006, 156 p., www.epa.gov/sites/default/files/2014-10/documents/green-infrastructure.pdf, accessed June 2026.

[11] National Oceanic and Atmospheric Administration, 2015, Conceptual guidance for considering the use of living shorelines: Silver Spring, Md., National Oceanic and Atmospheric Administration, coast.noaa.gov/data/digitalcoast/elearning/living_shorelines_webinar/story_content/external_files/Conceptual%20Guidance%20for%20Considering%20the%20Use%20of%20Living%20Shorelines%202015.pdf, accessed June 2026.

[12] Nieuwenhuijsen, M.J., 2021, Green infrastructure and health: *Annual Review of Public Health,* v. 42, no. 1, p. 317–328.

[13] Federal Emergency Management Agency, 2021, *Building community resilience with nature-based solutions—A guide for local communities:* Washington, D.C., Federal Emergency Management Agency.

[14] Jack, K., Jaber, F., Heidari, B., Prideaux, V., 2021, *Green stormwater infrastructure for urban flood resilience—Opportunity analysis for Dallas, Texas:* The Nature Conservancy.

[15] Texas General Land Office, 2023, Texas coastal resiliency master plan: Austin, Texas General Land Office, glo.texas.gov/sites/default/files/resources/glo/coast/coastal-management/coastal-resiliency/resources/files/2023-tcrmp-book.pdf, accessed February 2026.

[16] Texas General Land Office, n.d., Living shorelines www.glo.texas.gov/coastal/living-shorelines, accessed February 2026

[17] Clean Water America Alliance, 2011, *Barriers and gateways to green infrastructure:* Washington, D.C., U.S. Water Alliance, September 13, 2011, https://uswateralliance.org/sites/uswateralliance.org/files/publications/Barriers-and-Gateways-to-Green-Infrastructure.pdf, accessed February 2026.

[18] Heidari, B., Randle, S., Minchillo, D., Jaber, F.H., 2023, Green stormwater infrastructure—A critical review of the barriers and solutions to widespread implementation: *WIREs Water*, v. 10, no. 2, e1625.

[19] Houle, J.J., Roseen, R.M., Ballestero, T.P., Puls, T.A., Sherrard, J., Jr., 2013, Comparison of maintenance cost, labor demands, and system performance for LID and conventional stormwater management: *Journal of Environmental Engineering*, v. 139, no. 7, p. 932–938.

[20] Warnell, K., Mason, S., Siegle, A., Merritt, M., Olander, L., 2023, *Department of the Interior nature-based solutions roadmap:* Durham, North Carolina, Nicholas Institute for Energy, Environment & Sustainability, Duke University, NI R 23-06, https://nicholasinstitute.duke.edu/publications/department-interior-nature-based-solutions-roadmap, accessed February 2026.

[21] Convergent Water Technologies, 2025, Queenston Manor Apartments Implements LID, https://convergentwater.com/wp-content/uploads/2025/04/Queenston-Case-Study-v1.pdf, accessed June 2026. .

[22] American Rivers, 2017, Banking on green—*A look at how green infrastructure can save municipalities money and provide economic benefits community-wide:* Washington, D.C., American Rivers, https://www.americanrivers.org/wp-content/uploads/2017/03/banking-on-green-report.pdf, accessed February 2026.

[23] American Society of Civil Engineers, n.d., https://ascelibrary.org/doi/10.1061/40763(178)69, accessed February 2026.

[24] Pathak, A., Glick, P., Hansen, L.J., Hilberg, L.E., Ritter, J., Stein, B.A., 2022, *Incorporating nature-based solutions in community climate adaptation planning*.

[25] Georgetown Climate Center, n.d., *Green infrastructure toolkit—Introduction,* https://www.georgetownclimate.org/adaptation/toolkits/green-infrastructure-toolkit/introduction.html, accessed November 2025.

[26] U.S. Army Corps of Engineers, 2022, *Financing natural infrastructure—Exploration Green*, Texas: ERDC/TN EWN-22-7, Vicksburg, Mississippi, U.S. Army Engineer Research and Development Center.

[27] Suedel, B.C., Naylor, L.A., Meckley, T., Cairns, C., Bernier, J., Morgereth, E., Mears, W., Piercy, C.D., ter Hofstede, R., 2021, Chapter 14—Enhancing structural measures for environmental, social, and engineering benefits, in Bridges, T.S., King, J.K., Simm, J.D., Beck, M.W., Collins, G., Lodder, Q., Mohan, R.K., eds., *International guidelines on natural and nature-based features for flood risk management:* Vicksburg, Mississippi, U.S. Army Engineer Research and Development Center.

[28] U.S. Army Corps of Engineers, 2021, *Coastal Texas protection and restoration feasibility report*, www.swg.usace.army.mil/Portals/26/Coastal%20TX%20Protection%20and%20Restoration%20FINAL%20Feasibility%20Report_20210827.pdf, accessed February 2026.

3

Embracing guiding principles for NBS

This chapter provides guiding principles designed to address common barriers and challenges and implement NBS effectively.

Key takeaways

- These guiding principles are essential to successful NBS implementation throughout all phases of project development: engage and include, apply systems thinking, work across boundaries, and learn and adapt continuously.
- To be effective, NBS require consideration of the scale and context of flood risk vulnerability and the social, economic, and environmental systems at play.
- To be sustainable, NBS should be planned and implemented with consideration of long-term community goals versus short-term benefits.
- To be successful, NBS projects must be responsive to the shared goals of a community.

Pedernales Falls State Park near Johnson City, Texas
Photo courtesy of the Texas Water Development Board

Introduction

To be effective, NBS projects for flood resilience require careful consideration of the scale and context of flood risk and vulnerability, the specific site conditions in which they are being implemented, and the social, economic, and environmental systems at play. To be sustainable, NBS should be planned, developed, and implemented with consideration of long-term community goals, not just short-term benefits. To be successful, NBS projects must be responsive to the needs and shared goals of a community, developed through collaboration with a variety of stakeholders, and flexible in considering various aspects of flood risk reduction.

By proactively addressing institutional and perceptual barriers at the outset, communities create the conditions necessary for NBS to move from concept to implementation—directly responding to many of the common challenges outlined in the previous section that detailed the barriers to NBS.

Definition

American Society of Civil Engineers Policy Statement 418

The Role of the Civil Engineer in Sustainable Development[1]

Civil Engineers shall be committed to the following Principles of Sustainable Development:

Principle 1 *Do the right project*

A proposed project's economic, environmental, and social effects on each of the communities served and affected must be assessed and understood by all stakeholders before there is a decision to proceed with a project. Consider nonstructural as well as structural (built) solutions to the needs being addressed.

Principle 2 *Do the project right*

The civil engineer shall actively engage stakeholders and secure public understanding and acceptance of a project's environmental, social, and economic costs, risks, and benefits. To move toward the conditions of sustainability, engineers must design and deliver projects that address sustainability holistically from concept to demolition or reuse.

Guadalupe River in New Braunfels, Texas
Photo courtesy of the Texas Water Development Board

3.1 Engage and include

Successful NBS implementation depends on inclusive and transparent communication, intentional community engagement throughout the development and implementation of a project, and collaboration with a variety of stakeholders to align community needs and project goals. Engagement strategies should intentionally consider who may be missing from the conversation and proactively remove barriers to participation, ensuring that all community members have meaningful opportunities to shape project outcomes. Stakeholder engagement is a critical path to appropriate NBS design that maximizes multiple benefits and can create community support through effective communication and learning. Because of the multiple benefits of NBS, communities have a different relationship with NBS projects than traditional gray infrastructure. NBS projects become part of a community, frequently with direct community interactions, so stakeholder engagement is required to ensure the right suite of benefits is being provided. Moreover, stakeholder engagement is essential to overcome many common challenges and barriers to successful NBS implementation.

Stakeholder engagement

Stakeholder engagement helps ensure that NBS projects provide appropriate benefits and that their design and function are compatible with community wants and needs to the maximum extent possible. Additionally, stakeholder engagement throughout the planning and design of an NBS project helps promote support and ownership for NBS projects amongst local stakeholders that can be an important complement to long-term operations and maintenance.

Consider two alternatives for a project to increase conveyance capacity in a channel: one option is a grass-lined mowed channel, and the other option is a floodplain restoration project that includes native vegetation. Will the community be supportive of the proposed aesthetics of native taller vegetation, or will they consider the channel to be unmaintained?

Furthermore, if an NBS project is to address multiple challenges or provide multiple benefits, then relevant interest groups and stakeholders from a variety of backgrounds need to be involved in the planning and design process. Each neighborhood in a community has different needs that must be understood to ensure an NBS project provides the appropriate benefits. Importantly, the local community may draw attention to issues beyond a project boundary that can limit the success of the project. For example, a project may feature assets and amenities desired by the community, but if access to the site is insufficient or unsafe, the success of the project will be limited. A project champion, from any of the broad stakeholder groups, can be the best advocate to fight for a sustainable solution that addresses the community's needs. Learn more about developing a stakeholder engagement strategy in **Chapter 6**.

Stakeholders engaging in land use planning in Lockhart, Texas
Photo courtesy of Freese and Nichols, Inc.

Broad stakeholder engagement is essential for developing a variety of NBS strategies throughout a watershed.

Some examples of important stakeholders include:

- Members of the public, who may be the most impacted but are often not effectively engaged in flood planning
- Local community groups, who are trusted voices that have a wealth of local knowledge that may not otherwise be available to the project team
- Texas' federally recognized tribes—Alabama-Coushatta (Polk County), Kickapoo Traditional (Maverick County), and Ysleta del Sur Pueblo (El Paso County)–whose sovereign status, cultural resources, land interests, and environmental priorities should be respectfully considered within their respective regions
- Developers, especially those with large land use impact, as they can be critical to adopting (or blocking) effective flood risk reduction ordinances and on-the-ground practices
- Public drainage entities or municipalities, who set ordinances and regulations and issue permits that influence flood risk and manage stormwater infrastructure
- Other departments like Parks and Recreation, Roads and Bridges, or Public Works
- Nonprofit or private organizations, who may assist with long-term maintenance and community events through public-private partnerships
- Researchers, who can help demonstrate and monitor solutions and access current research

3.2 Apply systems thinking

Effective implementation of NBS for flood resilience requires consideration of physical, chemical, biological, and social systems and their interactions when evaluating flood risk reduction strategies. Flood infrastructure projects are often approached as monofunctional without considering additional functions the projects could serve. Transitioning to a multifunctional approach to flood infrastructure allows projects to provide more benefits on a single piece of land.

Applying systems thinking to NBS project planning and implementation promotes the development of multifunctional, sustainable solutions with short- and long-term effectiveness. The premise of systems thinking is that the best way to improve a system is not to work on each part separately but to improve the relationship among its parts. Understanding NBS as infrastructure can impact multiple systems in a community (e.g., drainage, water supply, recreation, environmental quality), which lays the foundation for a multidisciplinary approach to planning, funding, designing, implementing, and maintaining NBS for flood resilience throughout a watershed.

Systems thinking can enhance value across multiple systems by revealing connections amongst them. Stormwater drainage, water supply and wastewater treatment, transportation, parks and recreation, and natural areas are often seen as different public infrastructure systems within separate departments. A systems thinking approach to public infrastructure reveals the connections between these systems. For example, NBS for flood resilience, such as green infrastructure, can also help address water quality and community health challenges. A stormwater park can provide significant storage of flood waters during a storm event while otherwise serving as a recreational asset and source of social cohesion. By recognizing that multiple challenges and community needs can be addressed together, there is a greater potential for cost efficiency and the ability to create opportunities to access a wider variety of local, state, and federal funding sources to plan for and implement multi-benefit projects.

By helping make connections across systems, systems thinking can improve the quality and consistency of communication across departments and disciplines, thereby creating a working environment conducive to conceptualizing and pursuing multifunctional and multi-objective projects. The ability of NBS to address multiple challenges is key to its value proposition, and methods to incorporate these benefits into planning and budgeting across numerous systems are essential. The multi-benefit quality of NBS—a noted distinction from traditional gray infrastructure—is one of the biggest drivers for why NBS are promoted by the TWDB, FEMA, and USACE as a preferred mitigation strategy and ultimately why they are implemented.

> *Systems thinking means considering physical, biological, and social processes, and their interactions, in evaluating flood risk problems and solutions, and identifying ways to reduce conflict and maximize synergies to produce sustainable solutions*
>
> - International Guidelines on Natural and Nature-Based Features for Flood Risk Management

Finally, systems thinking supports common understanding and a common vision. A systematic view of the many factors impacting a particular location and the challenges facing local communities includes consideration of all stakeholders that could be impacted or stand to benefit from a project. The best practice for stakeholder engagement is to use a bottom-up approach. A good embodiment of this principle is the multi-jurisdictional regional flood planning process facilitated by the TWDB, which seeks to align data, stakeholders, and planning groups along major riverine watersheds to identify flood resilience strategies and projects that avoid upstream and downstream impacts. Regional flood planning groups maintain representation from a variety of interests, including state and federal agencies (**Table 3-1**).

Systems connected to flood infrastructure

- Natural areas and ecosystems
- Water supply
- Wastewater treatment
- Transportation
- Parks and recreational areas
- Private development

Table 3-1. Regional flood planning group members

Voting members	Non-Voting members
The public	Texas Water Development Board
Small businesses	Texas Commission of Environmental Quality
Municipalities	General land Office
Counties	Texas Parks Wildlife Department
Environmental interests	Texas Department of Agriculture
Agricultural interests	State Soil and Water Conservation Board
River authorities	Texas Division of Emergency Management
Water utilities	Texas Department of Transportation
Electric generating utilities	Other Agencies or Interest Groups Selected by RFPG
	State Soil and Water Conservation Board

3.3 Work across boundaries

NBS also require working across boundaries. Political and jurisdictional boundaries can limit the ability to address the full scope of a flooding issue. Departmental boundaries can also limit the ability to apply NBS to address multiple community issues in plans and projects--or worse, it can result in conflict with other community objectives. Professional and disciplinary boundaries across public and private sectors can limit consideration of an array of project alternatives and limit project design concepts.

Political and jurisdictional boundaries, with some exceptions like river authorities and drainage districts, are rarely aligned with the watershed boundaries that need to be considered to best address a community's flood risk. Therefore, it is often necessary to work across jurisdictional boundaries to find solutions to watershed-scale challenges. In most cases, this will include coordination among municipalities, counties, river authorities, and other legal entities like drainage districts. While the extra coordination is additional work on the front end, it can pay dividends over time by increasing the decision space to pursue effective and cost-effective projects and by filling gaps in expertise and capacity that may exist for individual entities.

NBS cross boundaries

- Private property and easements
- Political jurisdictions
- Internal departments
- State or federal agencies
- Professional disciplines

Further, it provides a way for leveraging resources and funding across jurisdictions.

Departmental boundaries within government also need to be considered for successful NBS implementation; however, this can be a challenge. Historically, government departments have been siloed in their operations. This is understandable given that departments exist to address a specific challenge or provide a specific service and are structured around that objective. Too rigid a structure can lead to a narrow focus that fails to leverage skills and expertise, limit opportunities for systems thinking, and could lead to unintended conflict. Occasionally, a community's economic development plan identifies opportunities for growth in the same area that its hazard mitigation plan identifies as high risk. Modern challenges are multi-faceted and have multiple drivers that may not fit neatly into departmental boundaries; for example, the interrelated issues of development patterns and economic mobility, public health, and flood risk. NBS are multifunctional and can address these multi-faceted challenges.

These challenges require a level of flexibility and adaptability to effectively and efficiently be addressed, especially for the coordination of long-term plans, and this can be facilitated through interdepartmental collaboration. For example, the City of Austin's Watershed Protection and Development Review Department Mission Integrated Project Team seeks to maximize the opportunities to reduce structure flooding, enhance the drainage system, maintain or improve channel stability, and maintain or improve the factors that affect water quality through all projects regardless of their primary purpose. This includes minimizing negative impacts on all departmental missions (flooding, erosion, and water quality) and looking for opportunities to improve conditions, including benefits beyond the driving mission's needs.

Working across professional and disciplinary boundaries can develop NBS projects that effectively provide a suite of benefits. The benefits of NBS projects span multiple disciplines (e.g., public health, recreation, stormwater, and air quality). Identifying opportunities for multiple benefits and then designing and implementing projects that deliver those benefits requires tapping into multiple disciplines throughout the planning and implementation of a project. It is not often, for example, that personnel with flood risk reduction expertise are also experts on accessible recreation or public health. Bridging multiple disciplines and sectors can be achieved through intentional representation on such project development groups as steering committees, working groups, planning groups, and project teams.

Case Study

Bexar Regional Watershed Management Partnership

Location: Bexar County

Opportunity: A quickly growing community with significant flood risk shows that regional cooperation across jurisdictions can pave the way for innovative solutions.

Lessons learned: Coordination across political jurisdictions leads to multifunctional flood resilience solutions.

The *Bexar Regional Watershed Management* ↗ (BRWM) program represents a cooperative effort among Bexar County, the City of San Antonio, the San Antonio River Authority, and twenty suburban municipalities to address watershed-scale flooding, water quality, and environmental challenges across jurisdictional boundaries. The program was created to ensure consistent stormwater management standards and to promote regional solutions that are more effective and efficient than piecemeal local efforts. BRWM emphasizes integrated flood control and water quality improvements, encouraging nature-based solutions such as green infrastructure, low-impact development, and stream corridor preservation. By recognizing the value of natural systems, the program helps reduce infrastructure costs, enhance community resilience to flooding, and sustain the long-term ecological health of the San Antonio River watershed.

Mission Reach in San Antonio, Texas
Photo courtesy of U.S. Fish and Wildlife Service

Systems thinking

The BRWM partnership uses a watershed-based approach to create holistic watershed master plans by individual sub-watershed within the San Antonio River Watershed. This allows for recognizing differences in land characteristics while working towards common goals. This watershed system level approach manages and reduces flood risk throughout Bexar County by coordinating planning and capital improvement programs across the watershed and enabling the effective and efficient allocation of manpower and resources among its partners.

Work across boundaries

Bexar County's Flood Control Capital Improvement Program funds watershed management and flood control capital improvement projects on a regional, rather than jurisdictional, basis. By working at the watershed level, the BRWM partnership strengthens each partner's ability to address their local flood risk and reduces wasteful duplicated efforts. It has also increased the region's capacity to comply with state and federal requirements and to seek state and federal funding.

Engage and include

Through partners and various committees, BRWM provides the public with information and education opportunities to raise awareness about flood risks and water quality projects and programs. The fifteen-member public participation group, the Watershed Improvement Advisory Committee, has representation from each of the five Bexar County watersheds and works collaboratively, rather than individually, to shape long-term flood risk management throughout the region.

Learn and adapt

The BRWM watershed management approach is an ongoing cycle that allows learning and adapting over time. The **Planning** phase establishes functional watershed units, identifies issues to be assessed, and identifies the needed stakeholders to be engaged. The **Data Collection** phase quantifies water related issues across the watershed. The **Assessment and Targeting** phase assesses current conditions and establishes desired future conditions. The **Strategy Development** phase develops goals and strategies to achieve the desired future conditions. Finally, the **Implementation** phase uses public policy, best BMPs and education to meet established goals. Through this process data is collected and used to make watershed management decisions, measure progress, and ensure implementation continues to be results oriented.

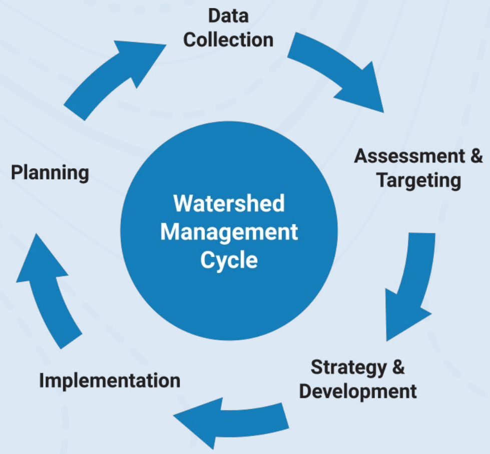


Figure 3-1. Watershed management cycle
Adapted from Bexar Regional Watershed Management

3.4 Learn and adapt continuously

Learning and adapting continuously is critical for incorporating NBS for flood resilience into mainstream practice. It requires building capacity and capability among key stakeholder groups, particularly among local government staff, designers, contractors, and maintenance professionals. To scale up NBS practice, education and training, workforce development, community education and outreach, planning support (data, tools, and templates), and funding resources may all be necessary. While this list of needs for learning and adapting over time may seem daunting, employing the guiding principles of engaging and including stakeholders, applying systems thinking, and working across boundaries throughout all stages of NBS planning and implementation provides a means to learn and adapt continuously, one plan and one project at a time.

NBS are innately dynamic. Using adaptive management practices in all stages of an NBS project will lead to more cost effective and more successful NBS projects over the long-term. Part of this learning involves the need for clear, specific, accessible information on the benefits, costs, and cost savings of NBS to generate buy-in and promote understanding. If key groups are not familiar with NBS, they will continue to rely wholly on gray infrastructure practices—even in situations when an NBS would add value or produce better results. Therefore, education and training, particularly for government agencies and practitioners, is essential to building institutional knowledge and capacity for widespread deployment and maintenance of NBS.

One way in which institutional knowledge and capacity can be increased and NBS practice be improved is by monitoring and measuring project performance. Not only is it important that a project works, but it is also important to understand how and why a project was effective. By documenting performance and maintenance successes or issues, including adaptations to initial designs, institutional knowledge can be improved over time and shared across peer networks (e.g., through conferences, workshops, and professional societies).

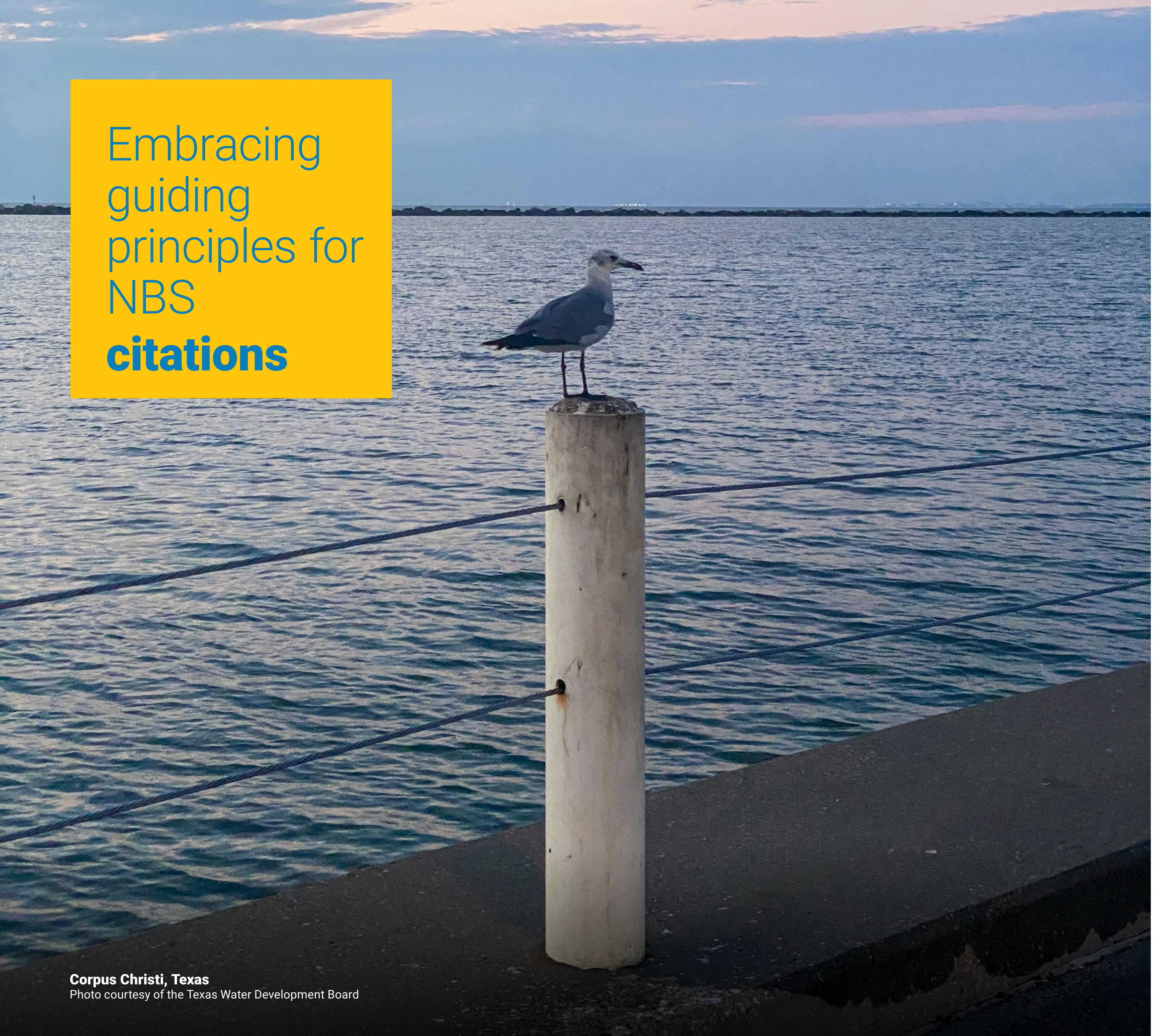
In addition to relevant, accessible information on NBS, training and workforce development for engineers, operations and maintenance professionals, contractors, and agency staff may be necessary for practitioners to become proficient in NBS and include them in their day-to-day work. While gray infrastructure is maintained to function in a specific way, maintenance of NBS requires flexibility and adaptability, as significant events can alter the components (e.g., sediment, plantings) of the system. As such, workflows and maintenance schedules may be fundamentally different for NBS. A knowledgeable workforce ensures consistently well-designed, constructed, and maintained NBS projects. Learn more about NBS maintenance in **Chapter 13.**

Tools and resources

- Engineering With Nature®
  International Guidelines on Nature and Nature-Based Features on Flood Risk Management, Chapter 7 ↗
- Institutional Foundations of Adaptive Planning
  Exploration of Flood Planning in the Lower Rio Grande Valley, Texas, USA ↗
- Texas A&M University
  An Adaptive Toolkit for Projecting the Impact of Green Infrastructure Provisions on Stormwater Runoff and Pollutant Load —A Case Study on the City of Galena Park, Texas, US ↗

Embracing guiding principles for NBS

citations



Corpus Christi, Texas
Photo courtesy of the Texas Water Development Board

---

[1] American Society of Civil Engineers, [n.d.], *Policy statement 418--The role of the civil engineer in sustainable development*, https://www.asce.org/advocacy/policy-statements/ps418---the-role-of-the-civil-engineer-in-sustainable-development/, accessed February 2026.

4

Assessing ordinances, incentives, and regulations

This chapter discusses opportunities at the local level to facilitate NBS and outlines existing state and federal policies and regulations that can enable or even incentivize the use of NBS for flood resilience.

Key takeaways

- Identifying potential conflicts early with local, state, or federal regulations or permitting requirements increases the likelihood of success.
- Incentives can increase the application of NBS for flood resilience by practitioners.
- Aligning project goals with state and federal programs can unlock additional financial and technical support.
- Integrating NBS into local ordinances and development codes can streamline local adoption of NBS practices

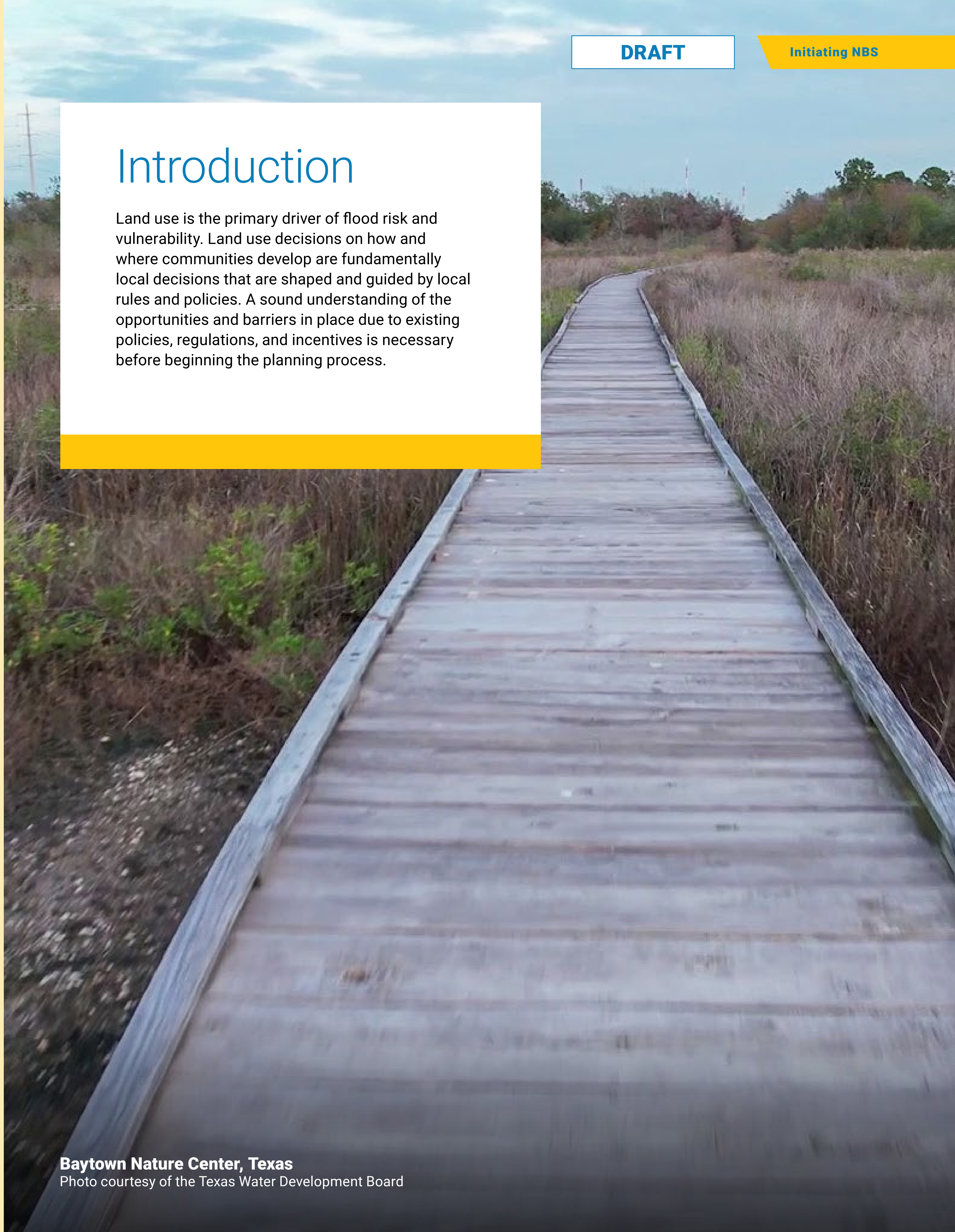
Balmorhea State Park
Photo courtesy of the
Texas Water Development Board

How the guiding principles apply to this chapter

Engage and include	Engagement in the development and adoption of regulations and policies that enable NBS can improve quality, compliance, and understanding.
Apply systems thinking	Auditing local regulations as a whole system can help remove conflicts that act as barriers or cause confusion when pursuing NBS projects.
Work across boundaries	Consider incentive programs that offer benefits across department boundaries for implementing NBS for flood resilience.
Learn and adapt continuously	Coordinate with those submitting NBS projects under local regulations for opportunities to improve.

Introduction

Land use is the primary driver of flood risk and vulnerability. Land use decisions on how and where communities develop are fundamentally local decisions that are shaped and guided by local rules and policies. A sound understanding of the opportunities and barriers in place due to existing policies, regulations, and incentives is necessary before beginning the planning process.



Baytown Nature Center, Texas
Photo courtesy of the Texas Water Development Board

Any individual NBS project can be subject to a number of regulations, ordinances, and criteria. Local policies can encourage and prioritize NBS in development and other land use decisions. Further, interagency collaboration on NBS plans and projects should be encouraged and facilitated. Often, these regulations necessitate additional agency coordination based on specific site characteristics. This chapter also discusses opportunities at the local level to facilitate and incentivize the use of NBS for flood resilience. The topics presented in this chapter should be considered prior to and during the planning, design, and construction of NBS, as design criteria and permit requirements (**Section 8.2**) will impact feasibility, final design, and successful implementation. **Table 4-1** distinguishes several components of the policy context for NBS.

Table 4-1. How policies, codes, ordinances, and criteria work together

Category	Description	Examples
Policy decisions	High-level priorities set by elected officials or agencies. They guide decision-making, ordinances, codes, and criteria by defining what outcomes the community values and how community leaders plan to support those values.	“Reduce flood risk,” “Increase public access to open space”
Statutes	Overarching rules or benchmarks established at the state or federal levels that establish the framework for requirements and standards.	Americans with Disabilities Act, Clean Water Act
Regulations	Legally adopted rules/standards at local, state, national, or federal levels used to enforce legislation.	U.S. Code of Federal Regulations, Texas Administrative Code
Ordinances and court orders	Local laws adopted by cities or counties. They enforce community-specific requirements and reflect local priorities such as land use, flood control, or environmental protection.	City stormwater ordinance, county flood damage prevention order
Design criteria	Technical manuals or guidelines for engineers that specify how to design infrastructure, buildings, or sites. They ensure consistency and practical application of ordinances and codes in projects.	Design criteria manual

4.1 Resolutions

Resolutions can be an effective way for local governments to establish policies. For example, a resolution by a local government entity can establish a policy that prioritizes NBS for capital projects. Such a resolution raises awareness of NBS as a potential infrastructure solution, encourages contractors and designers to incorporate NBS into their business portfolios, and can lead to increased education across departments and the public. A good example is the Travis County Resolution Support for Nature Based Solutions in the Implementation of Travis County Projects.[1]

The resolution prioritizes: ***“The effective use of NBS in all Travis County-funded public works, construction, reconstruction, renovation, and maintenance projects (including parks, urban infrastructure, streets, drainage, flood control infrastructure, and public buildings)” and directs county staff to include a preference for the “effective use of NBS in the design standards of all future construction projects by including the solicitation of designs utilizing NBS in the county’s Requests for Proposals and in the county’s evaluation and scoring criteria for such proposals.”***

Local government officials have many opportunities to engage across departments and review existing barriers and conflicts that would prevent or discourage NBS. While organizational structure and titles vary widely across communities, local departments that should be involved in a comprehensive review of local regulations[2] include:

Floodplain Administrator

- Engineering, Public Works, and Roads and Bridges
- Planning and Zoning and Economic Development
- Watershed Protection or Environmental Planning
- Parks and Recreation
- Emergency Management
- Utility Districts or Cooperatives

Additionally, local government officials can assess the overarching planning documents for their community. For example, the approach to land use is a foundational component of a city’s comprehensive plan. Establishing guiding principles or flood resilience goals and reflecting the approach to land use in a comprehensive plan[3] includes a policy to “Embrace environmental sustainability.”

The City of Dallas sees land use as crucial to achieving its ForwardDallas 2.0 vision and includes a policy on embracing environmental sustainability. Implementation measures include:

- Establish areas of conservation including floodplains, wetlands, stream corridors, steep slopes, and the escarpment.
- Prioritize resources to develop recreational opportunities.
- Coordinate growth projections with the Parks Department’s planning to ensure the future need for parks and open space is met.
- Consider the opportunity for permanent conservation and encourage the use of other environmentally sensitive building practices.

Tools and resources

- EPA
  Water Quality Scorecard ↗
- University of Florida
  Enabling Low Impact Development and Green Stormwater Infrastructure: A Code Audit Tool for Florida Counties and Municipalities ↗
- Association of State Floodplain Managers
  The 2015 National Flood Programs and Policies in Review ↗
- FEMA
  Higher Standards Reference Guide for Local Floodplain Management Regulations: A Guide for Local Officials ↗

Regulations and ordinances enforce policies and, as they endure beyond a single administration, can address future as well as current flood risk. They can also apply to large areas, helping to support regional scale approaches to flood resilience. This makes them effective nonstructural NBS. In the absence of NBS-friendly local regulations, extensive and time-consuming variances may be required to implement NBS, resulting in traditional gray infrastructure in lieu of NBS to avoid delays and associated costs. Working across boundaries is key to updating regulations and ordinances to best encourage NBS.

Enforcing regulations is essential to safeguard both people and the environment from flooding and reduces the potential for increases in future flood risk.

Building and development codes and thoughtful land-use planning ensure developments are placed outside of flood-prone areas, directly protecting human lives by minimizing exposure to flood risks. By maintaining compliance with these rules, communities also decrease the economic losses associated with flood damage to infrastructure and property. The enforcement of regulations serves to preserve natural landscapes, such as wetlands, forests, and floodplains, which act as natural barriers by absorbing excess water and slowing runoff. Maintaining these critical ecosystems not only reduces flood severity but also safeguards biodiversity and ecological balance.

4.2 Ordinances and regulations

The following sections describe potential applications of land use ordinances that can work at the local level to enable or promote the use of NBS for flood resilience.

National Flood Insurance Program

Administered by FEMA, the National Flood Insurance Program (NFIP) provides flood insurance to property owners in communities that adopt and enforce minimum floodplain management standards in the regulatory floodplain. The NFIP requires community land-use and building code standards for floodplain development, provides a mechanism for communities to rebuild after floods, and offers grants and incentive programs for community-level investments in flood risk reduction. The NFIP does not prevent development in the regulatory floodplain; it guides how to develop in the regulatory floodplain in a way that reduces, but does not eliminate, flood risk for floodplain development. Implicitly, the NFIP recognizes that maintaining the beneficial functions of the floodplain, a nonstructural NBS, is sound floodplain management policy.

Texas Water Code (TWC § 16.315) delegates the responsibility of local governmental units to adopt regulations designed to minimize flood losses. Participation in the NFIP improves community resilience, creates the opportunity for federally backed individual flood insurance policies and post-disaster federal relief funding.

FEMA estimates that buildings constructed to NFIP standards suffer about 80 percent less damage annually than those not built in compliance.[4]

Clean Water Act

Administered by the U.S. Environmental Protection Agency (EPA) and delegated in Texas to the Texas Commission on Environmental Quality (TCEQ), the Clean Water Act (CWA) established the regulatory framework for protecting and restoring the nation's water quality.[5] The act prohibits the discharge of pollutants to waters of the United States except in compliance with a permit and requires that discharges meet state and federal water quality standards designed to protect human health and aquatic ecosystems.[5] Although the Clean Water Act is a federal statute, its implementation directly affects local governments, utilities, and developers. Through delegated authority and permit requirements, cities and counties play a central role in protecting water quality by regulating discharges, managing stormwater systems, and enforcing development standards.

Under the Clean Water Act, the National Pollutant Discharge Elimination System permit program regulates point-source discharges of pollutants to surface waters. In Texas, this program is implemented through the Texas Pollutant Discharge Elimination System, authorized by the EPA in 1998.[6,7] The Texas Pollutant Discharge Elimination System program includes the regulation of publicly owned systems designed to convey stormwater,[8] or municipal separate storm sewer systems.

Municipal separate storm sewer systems permittees are required to develop and implement a stormwater management program that reduces the discharge of pollutants in stormwater runoff to the maximum extent practicable and protects water quality. Participation in the municipal separate storm sewer systems program provides a mechanism for communities to manage stormwater comprehensively, protect local water resources, and maintain compliance with federal and state mandates. Although the CWA and its implementing regulations do not explicitly require NBS, the municipal separate storm sewer systems framework offers significant opportunities for communities to integrate these practices into local ordinances, stormwater design manuals, and development review processes.

By emphasizing nonstructural controls, such as preserving open space, protecting riparian buffers, and restoring wetlands, and implementing green infrastructure techniques like bioretention, rain gardens, bioswales, and permeable pavements, communities can meet pollutant reduction goals while improving flood resilience, groundwater recharge, and habitat connectivity. The EPA recognizes these practices within the ***Integrated Planning and Green Infrastructure Framework ↗***.[9] The TCEQ also supports the use of green infrastructure and low impact development to achieve stormwater quality and volume reduction goals within the general permit for small municipal separate storm sewer systems.[10]

Floodplain preservation ordinance

Floodplain conservation and restoration are important watershed NBS. Many communities have regulations or ordinances that address issues related to excessive flooding such as loss of life and property, health and safety hazards, disruption of commerce and governmental services, and extraordinary public expenditures when flooding occurs. Bastrop County[11] acknowledges that obstructions in the floodplain can increase flood heights and velocities. Many such floodplain regulations seek to limit alteration of natural floodplains so they can continue to accommodate floodwater, which is the primary purpose of floodplain conservation NBS.

Floodplain buffer zone and riparian buffer ordinance

Riparian and floodplain buffer zones provide similar hydrologic, hydraulic, and ecological benefits as floodplain preservation areas. They simply differ in how the buffer is established. A floodplain buffer zone establishes a protected area of the floodplain based on the inundation area of a specific design storm event (e.g., 1 percent annual chance storm). A riparian buffer zone is a set width from the stream centerline and can vary in width based on stream size, with larger streams having larger buffers. A community may choose to use either one or both regulations based on the topography, flood risk, and community goals.

Vegetated riparian and floodplain buffers slow down water traveling to channels due to the higher hydraulic roughness when compared to barren ground or pavement. Slowing the water allows increased opportunities for sediment and debris to settle, as well as ponding, infiltration, and percolation of stormwater. These riparian and floodplain buffer functions allow for a reduced peak discharge to the channel, which reduces downstream flooding impacts.[12] Preserving these buffer areas is a form of land conservation NBS.

Distancing developments and infrastructure from stream channels establishes a buffer to allow room for channel migration. Erosion associated with channel migration can expose buried utilities or undermine the structural foundations of roads, bridges, and buildings. Like other NBS, buffer space can also be used to add value—for example, by including aquatic and terrestrial recreational trail systems and providing access to recreational opportunities, like fishing and birding.

When development disturbs riparian areas, it can take away the benefits and co-benefits riparian and floodplain areas provide. Local communities can implement ordinances to prevent new construction from building or disturbing them within a certain distance of a stream.[13] Riparian and floodplain buffer ordinances require buffers on either side of the stream depending on the natural terrain and vegetation, the amount of area draining to a given point of a channel, and the goals of the community. The flood risk reduction benefits of these buffers can contribute to an overall watershed approach to NBS for a community.

Buffers may be difficult to achieve in already developed areas, and ordinance modifications may be considered. For example, the City of San Antonio allows some activities with specific stipulations in riparian buffer zones—such as street crossings, utilities, public and private parks and open space, and water quality and flood control systems (City of San Antonio Ordinance § 34-912).[14]

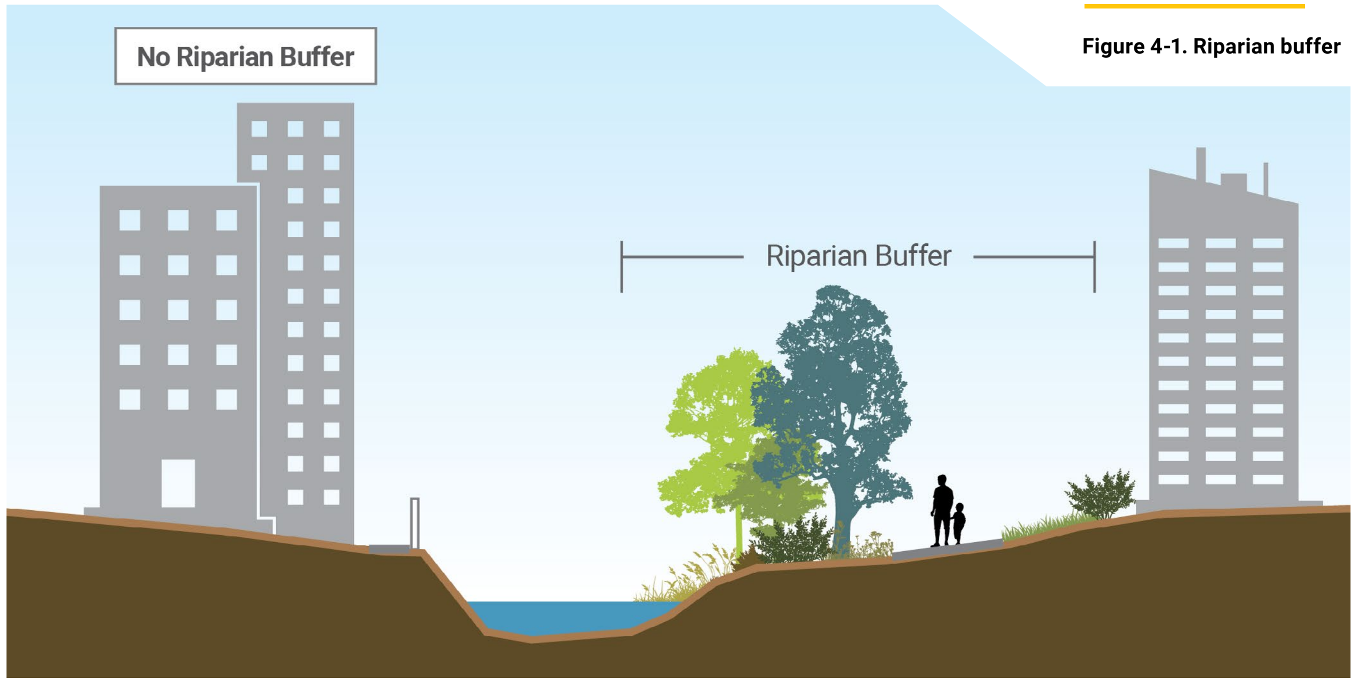


Figure 4-1. Riparian buffer

Floodplain and riparian buffer orindances

City of San Antonio ↗ ordinances include the establishment of floodplain buffer zones.

City of Bulverde ↗ and ***City of Denton*** ↗, consider riparian buffer conservation.

City of San Marcos ↗ development code requires buffer zones for all waterway development.

City of Laredo ↗ establishes preservation and design standards for buffers.

North Central Texas Council of Governments ↗ collected best practices for flood prevention in development codes.

White Oak Bayou in Jersey Village, Texas
Photo courtesy of the Texas Water Development Board

Native plant use ordinance

Native plants have a higher probability of survival compared to foreign plants since native plants are adapted to have more resiliency to their native climate and require less irrigation to maintain once established. Native plants are more resilient to pests and disease and provide well-suited habitat for local wildlife. When native plants are used in NBS, there is a higher probability of longevity and success.

Native plants are encouraged for NBS like riparian buffers, stormwater planters, bioretention, rain gardens, and constructed wetlands. Conversely, non-native plants can require additional irrigation and have a higher likelihood of failure.

Development codes for native plants must first define which plants are considered native or invasive. Tailoring local ordinances for plants native to each community is critical in a state as vast and diverse as Texas. The U.S. Department of Agriculture (USDA) hosts the ***PLANTS database*** ↗ that can be referenced for creating a list of native or invasive species for a particular community.

Once native species are adopted for a community, ordinances may require the use of native plants in new stormwater infrastructure across a range of development types. For example, the City of San Antonio's ***Stormwater Design Criteria Manual*** ↗ includes information on methods and recommendations for plant materials to be used for the vegetation or revegetation of drainage facilities within the San Antonio area.

Figure 4-2. Smartweed (*Persicaria spp*) along playa lake edge. Its dense roots stabilize soil, slow floodwaters, and provide vital habitat and food for wildlife. This native plant flourishes in seasonally-flooded areas, helping sustain healthy wetland ecosystems.

Photo courtesy of the Texas Water Development Board

Rainwater harvesting ordinance

Rainwater harvesting can be an effective tool to reduce stormwater runoff and address water supply issues. Rainwater harvesting can be designed for a site of any size or land use. Harvested rainwater is typically used for landscaping irrigation in place of potable water, which lowers the potable water bill for property owners and reduces the demand on a community's water supply. Repurposing rainwater can be especially important for water supply in Texas areas that experience periods of drought. If rainwater harvesting is intended for gray water use, the design should include precautions for public safety. TCEQ has outlined beneficial reuse of gray water.

Local regulations for harvesting rainwater can provide guidelines to ensure that harvesting systems are conducted safely and effectively, and that adequate storage is available to capture rainwater. The TWDB published ***The Texas Manual on Rainwater Harvesting*** ↗ to provide technical guidance and considerations to Texas communities. Topics in this manual include basic components and design, water quality, BMPs, cost estimates, and incentives. Note that some of the specific design topics may be more appropriate in a design criteria manual rather than an ordinance.

Tools and resources

- Native Plant Society of Texas ***Native Plant Database*** ↗
- USDA ***PLANTS Database*** ↗
- TWDB ***Rainwater Harvesting Resources*** ↗
- Texas A&M AgriLife Extension ***Rainwater Harvesting*** ↗

Photo courtesy of the Texas Water Development Board

Design criteria and guidelines

Beyond ordinances, local governments can utilize design criteria manuals to promote or require NBS for flood resilience. Design criteria manuals can also be a barrier to incorporating NBS, if time consuming variances are required to implement NBS. These manuals can serve as comprehensive guides that outline the standards and practices for infrastructure projects and should be written to encourage multifunctional solutions.

Design criteria can outline the benefits and performance standards for NBS practices to satisfy local detention requirements. Detailed and prescriptive criteria can better guide practitioners as compared to vague criteria. However, criteria that is too stringent may become burdensome to enforce.

Tools and resources

- San Antonio River Authority
  Low Impact Development Technical Design Guidance Manual ↗
- Lower Colorado River Authority
  Highland Lakes Watershed Ordinance Technical Manual and Construction Standard Details ↗
- Harris County Flood Control District
  Design Guidelines for HCFCD Wet Bottom Detention Basins with Water Quality Features ↗

4.3 Incentive programs

Local governments can incentivize the use of NBS in their local community using a number of mechanisms or programs. The nature of the incentives varies as well as the beneficiaries, and there are many examples across Texas already that directly or indirectly promote the use of NBS. Some examples include:

Community rating system

The FEMA Community Rating System (CRS) is a voluntary incentive program that recognizes and encourages community floodplain management practices and rewards their use with lower flood insurance premiums. It credits community efforts beyond minimum National Flood Insurance Program standards by providing discounts on flood insurance premiums for the community's property owners. CRS discounts on flood insurance premiums range from 5 to 45 percent depending on the types of activities a community implements. Open space preservation, associated with many NBS, is one of the categories in which communities can gain credit, as is planning to protect natural functions within the community's floodplain. **As of 2022, over 65 Texas communities participated in CRS with several receiving discounts of 20 percent or more on their flood insurance.**

Tax incentives

Landowners may receive a reduction in income tax liability through enhanced deductions or tax credits related to the costs or expenses incurred in the installation of land management practices that implement NBS. Placing a qualified conservation easement on land may provide the landowner with federal tax benefits, as well as possible property tax benefits. Qualifying conservation easement donations are considered charitable contributions under IRS regulations. Under the enhanced conservation easement tax incentive, and if the conservation easement meets all IRS criteria, the landowner may deduct the full value of the conservation easement donation from his or her adjusted gross income—up to 50 percent of the landowner's income for the year of the gift.[15]

The Texas Legislature has the authority to allow cities, counties, or special districts to grant property tax exemptions to properties with water conservation initiatives (Texas Constitution, Article 8, § 1-m).[16] Taxing units can also exempt all or part of the assessed property value of taxes for water conservation initiatives (Texas Tax Code § 11.32)[17] which can include certain types of NBS.

Tax or drainage fee reduction

NBS can be encouraged through property tax exemptions, reductions, or rebates for properties where NBS practices have been installed. Another approach is to provide discounts on stormwater utility fees to private-property owners who manage stormwater onsite or make other kinds of NBS installations. Learn more about developing a drainage utility fee in **Chapter 5**.

Facilitating the acquisition of property

Communities could provide low-cost capital or provide an exemption from capital gains tax liability where the purpose of the land being acquired is for NBS management-related purposes or installations.

Encouraging NBS in development or redevelopment

Expedited permitting, decreased fees, zoning upgrades, reduced stormwater requirements, and other benefits can incentives private developers who plan to implement NBS.

Award programs

Communities can utilize award programs to recognize new ideas, provide an opportunity for communication to a broader audience about NBS, and incentivize further applications. For example, the Austin Green Award seeks to recognize and reward innovative and sustainable design, which could include NBS for flood resilience—the Waterloo Greenway Park Project was recognized in 2022.

Voluntary certification and rating systems

Voluntary certification and rating systems can also function as incentives by providing recognition, benchmarking, and competitive advantages for projects and communities that incorporate NBS.

The ***Envision*** ↗ framework, developed by the Institute for Sustainable Infrastructure, is used to evaluate the sustainability and resilience of infrastructure projects across multiple categories including quality of life, natural world, and climate and resilience. NBS strategies can contribute directly to achieving higher Envision scores and certification levels, which may improve a project's competitiveness for funding and public support.

Similarly, ***LEED for Cities and Communities*** ↗, administered by the U.S. Green Building Council, provides a framework for measuring and certifying sustainability and resilience at a community level. This system includes credits related to natural systems, stormwater management, and climate adaptation–all of which can be supported through NBS implementation. Participation in LEED can help local governments track progress toward sustainability goals, attract financial investments, and signal leadership in resilience and environmentally responsible development.

Tools and resources

- City of San Antonio
  Low Impact Development and Natural Channel Design Protocol ↗
- TWDB
  Texas Rainwater Harvesting Tax Exemption Form Information ↗

Lady Bird Lake in Austin, Texas
Photo courtesy Freese and Nichols, Inc.

Case Study

City of Austin drainage fee NBS incentive

Location: Austin

Opportunity: Drainage fees provide a reliable funding source for flood infrastructure.

Lessons learned: The reduction of drainage fees can be used to incentivize the voluntary implementation of NBS.

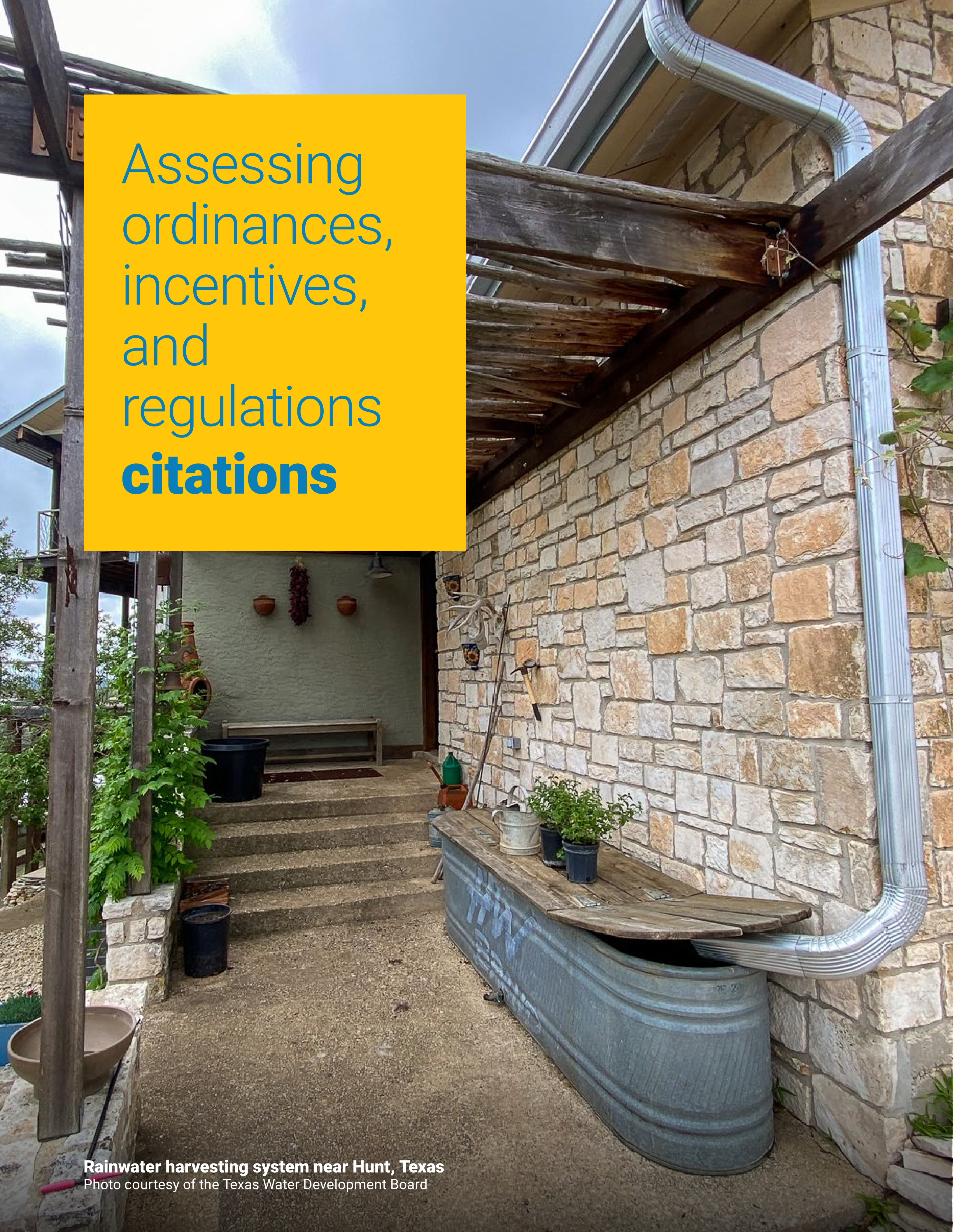
The City of Austin has a drainage charge for all properties to fund flood mitigation projects and programs to offset the negative impacts of impervious cover. The drainage charge is calculated individually for each property based on the amount and percentage of impervious cover. A Stormwater Management Discount[18] has been implemented to incentivize the voluntary efforts (on top of the minimum requirements for development) of Austin's residents and businesses to reduce the impact of their impervious cover through the use of rainwater harvesting, rain gardens, and certain ponds that capture, detain, and slowly release stormwater.

The drainage charge for a property is calculated based on the quantity and percentage of impervious cover on the lot. The equation for the monthly drainage charge can be found in **Figure 4-3**. This formula incentivizes developments to use less impervious cover.

Monthly drainage charge	Lower adjustment factor due to added stormwater control measure	Discounted monthly drainage charge
Monthly base rate x Amount of impervious cover x Adjustment factor	*Discounted impervious cover = Volume of stormwater control measure x Conversion ratio *Adjusted impervious cover = Amount of impervious cover – Discounted impervious cover *Adjustment factor= (1.5425 x Percent of impervious cover) + 0.1933	Monthly base rate x Adjusted impervious cover x Discounted adjustment factor

Figure 4-3. City of Austin monthly drainage charge equation

Assessing ordinances, incentives, and regulations **citations**



Rainwater harvesting system near Hunt, Texas
Photo courtesy of the Texas Water Development Board

[1] Travis County Commissioners' Court, 2024, June 25, Resolution recommending the implementation of nature-based solutions in Travis County projects [Resolution], Travis County, TX.

[2] Federal Emergency Management Agency, (2021), Building Community Resilience with Nature-based Solutions: A guide for local communities, Federal Emergency Management Agency.

[3] City of Dallas, 2024, *Forward Dallas! Policy Plan — Land Use Element*, City of Dallas Planning & Urban Design (Strategic Planning Division), dallascityhall.com/departments/pnv/Strategic%20Planning%20Division%20Documents/Land%20Use.pdf, accessed June 2026.

[4] Federal Emergency Management Agency, 2023, Answers to questions about the National Flood Insurance Program (NFIP), https://agents.floodsmart.gov/resource-library/en/answers-questions-about-nfip, accessed June 2026.

[5] United States Code, 1972, Federal Water Pollution Control Act, 33 U.S.C. § 1251 et seq. https://www.epa.gov/sites/default/files/2017-08/documents/federal-water-pollution-control-act-508full.pdf [epa.gov] 33 U.S.C. § 1251 et seq., Federal Water Pollution Control Act (Clean Water Act).

[6] Texas Water Code § 26.027, ,n.d., Water Quality Control, Texas Statutes, statutes.capitol.texas.gov/Docs/WA/htm/WA.26.htm Texas Water Code § 26.027, Texas Pollutant Discharge Elimination System.

[7] Texas Commission on Environmental Quality, n.d., 30 Texas Administrative Code Chapter 205: General permits for waste discharges, Texas Secretary of State, www.sos.texas.gov/tac/index.shtml 30 Texas Administrative Code (TAC) Chapter 205, General Permits for Waste Discharges.

[8] Environmental Protection Agency, 2025, 40 C.F.R. Part 122 – EPA administered permit programs: The National Pollutant Discharge Elimination System, Electronic Code of Federal Regulations, www.ecfr.gov/current/title-40/chapter-I/subchapter-D/part-122, accessed June 2026.

[9] U.S. Environmental Protection Agency, 2019, Integrated municipal stormwater and wastewater planning approach framework, Office of Water, www.epa.gov/npdes/integrated-planning-municipal-stormwater-and-wastewater, accessed June 2026.

[10] Texas Commission on Environmental Quality, 2024, Texas Pollutant Discharge Elimination System (TPDES) Small MS4 General Permit No. TXR040000, https://www.tceq.texas.gov/downloads/permitting/stormwater/general/ms4/2024-txr040000-general-permit-signed.pdf, accessed June 2026.

[11] Bastrop County, Texas, 2025, Flood Damage Prevention Order. Bastrop County Commissioners Court, Bastrop County, TX. www.bastropcounty.gov/upload/page/0145/docs/FLOOD%20DAMAGE%20PREVENTION%20ORDER%20-%20ADOPTED%207.14.2025.pdf.

[12] Bridges, T. S., J. K. King, J. D. Simm, M. W. Beck, G. Collins, Q. Lodder, R. K. Mohan, eds. 2021, International Guidelines on Natural and Nature Based Features for Flood Risk Management, Vicksburg, MS: U.S. Army Engineer Research and Development Center.

[13] City of Austin Watershed Protection Department, 2013, Criteria for establishing an erosion hazard zone: Austin, Texas, City of Austin Watershed Protection Department, https://data.austintexas.gov/api/assets/AC9B91CB-54B7-4A9A-9C50-FA02F609C9C3?download=true, accessed February 2026.

[14] City of San Antonio, n.d., Ordinance No. 34-912, San Antonio City Code, https://library.municode.com/tx/san_antonio/codes/code_of_ordinances?nodeId=PTIICO_CH34WASE_ARTVIWAQUCOPOPR_DIV6AQREZOWAPR_SDDPOPRCR_S34-912FLPRAR, accessed June 2026.

[15] Texas Land Trust Council, 2018, Conservation Easements: A Guide for Texas Landowners, https://texaslandtrustcouncil.org/wp-content/uploads/2019/01/CEguidebook_2018_small.pdf, accessed June 2026.

[16] Texas Constitution, n.d., Article 8, §1-m: Taxation and Revenue, Texas Statutes, statutes.capitol.texas.gov/Docs/CN/htm/CN.8.htm Texas Constitution, Article 8, § 1-m.

[17] Texas Tax Code § 11.32., n.d., Taxable Property and Exemptions, Texas Statutes, statutes.capitol.texas.gov/Docs/TX/htm/TX.11.htm, accessed June 2026.

[18] City of Austin Watershed Protection Department, n.d., Codes and regulations: Austin, Texas, City of Austin Watershed Protection Department, https://www.austintexas.gov/watershed-protection/codes-and-regulations, accessed February 2026.

5

Establishing funding strategies

Identify viable local, state and federal funding sources for successful programmatic and project-specific NBS implementation.

Key takeaways

- A successful funding strategy often requires a combination of funding sources and mechanisms.
- Funding strategies require substantial lead time, cross-agency coordination and stakeholder engagement.

Inks Lake State Park near Burnet, Texas
Photo courtesy of the Texas Water Development Board

How the guiding principles apply to this chapter

Engage and include	Funding strategies for NBS should actively engage a diverse range of stakeholders. Inclusive engagement strengthens grant competitiveness, builds public support, and helps identify co-benefits that can unlock multiple funding sources.
Apply systems thinking	Effective funding strategies recognize that NBS deliver benefits across interconnected systems. In addition to flood focused funding, communities can braid and stack funding sources, improve cost-effectiveness, and demonstrate multiple returns on investment.
Work across boundaries	Developing strong funding strategies requires collaboration across disciplines, departments, and jurisdictions. Cross-sector partnerships can expand eligibility for funding programs, strengthen applications, and position projects for funding.
Learn and adapt continuously	Funding landscapes evolve, as do regulatory requirements and community needs. Continuous learning improves grant readiness, strengthens long-term capital planning, and ensures that investments in nature-based solutions remain responsive, resilient, and sustainable.

Introduction

Public finance is a critical aspect of government operations, involving the collection, management, and allocation of funds to meet public needs and promote economic stability. The primary sources of public finance include taxes and fees, direct appropriations, and public borrowing through bonds. Each of these funding mechanisms can be strategically tied to NBS for flood resilience purposes. Funding was cited as one of the most significant barriers to implementing NBS and other resilient infrastructure measures. Therefore, identifying viable funding sources, developing strategic approaches, and cultivating an understanding of available financial mechanisms should be prioritized during the initial phases of planning. Importantly, many funding strategies require substantial lead time, cross-agency coordination, and stakeholder engagement. By proactively establishing funding pathways early in the process, communities are better positioned to overcome implementation hurdles and move from planning to action with greater efficiency and impact.

Many communities do not have a dedicated and sustained funding mechanism for flood mitigation solutions. Unless there is a dedicated funding source from, for example, a drainage utility fee, these projects are often funded by state or federal grants or loans or a combination thereof. Incorporating nature and/or natural features into these projects can unlock additional funding opportunities. The purpose of this chapter is to explore the mechanisms available to local communities to fund NBS for flood resilience.

> *“Funding is our #1 challenge. There are endless missed opportunities due to funding.”*
>
> - Survey Respondent

McKinney Falls in Austin, Texas
Photo courtesy of the
Texas Water Development Board

5.1 Local funding

NBS projects can sometimes be funded using mechanisms available within a city or county. Local funding can include taxes, drainage utility fees or stormwater utility fees, bonds, or public-private partnerships. Many federal and state funding programs require a local match and local funding mechanisms that can be leveraged to match state or federal funding—in which case only a percentage of the total project cost is necessary to fund locally.

However, using local funding alone to fund NBS for flood resilience has limitations as local governments often have constrained budgets and many competing priorities for resource allocation. This is especially true for many smaller communities who may need support for meeting match requirements or preparing funding applications, and may benefit from regional partnerships, county assistance, or technical help through RFPGs, non-governmental organizations (NGOs), or universities. This section will explore the mechanisms available to local communities to fund NBS for flood resilience.

Drainage utility fee

Many infrastructure projects are paid for with local funding designated for infrastructure improvements. Unlike toll roads or water treatment systems, flood infrastructure and drainage projects do not directly generate revenue for the community, instead these projects prevent or reduce damage to community assets. In Texas, drainage utility fees are a valuable funding source for flood mitigation projects. Typically levied by municipalities, these drainage fees are specifically allocated for stormwater-related activities.

The funds collected from drainage utility fees are used for a variety of purposes, all aimed at mitigating flood risks and improving stormwater management. Stakeholder outreach conducted during development of this manual identified gaps in understanding and training related to NBS maintenance as a barrier to implementation in some communities. With dedicated funding for NBS maintenance, a drainage utility fee can allow a community to invest in training maintenance staff to properly maintain NBS. In Texas, municipalities are specifically authorized under Texas Legal Government Code, Chapter 552, Subchapter C[1] to develop and implement a stormwater utility fee. The law includes specific allowances and constraints that cities are required to follow.

Tax Increment Reinvestment Zones (TIRZ)

Tax Increment Reinvestment Zones (TIRZ) allow cities in Texas to attract investment into a specific zone or area within the city under ***Texas Tax Code § 311.004*** ↗. At the time of creating a TIRZ, all taxable property value within the area is calculated and designated as that zone's tax increment base. As development occurs within the area and property values increase, the taxes collected past the initial tax increment base are put in the area's Tax Increment Fund (TIF). Money collected into the TIF can only be used on projects and development within the TIRZ boundary. TIRZ have set durations, so after the time period is complete, all taxes levied within the area will go to the city's general fund again.

To implement a TIRZ, the governing body must get approval through the local taxing unit by presenting a financing and project plan for the zone, detailing the zone boundary, planned projects that will be funded by the TIRZ, and the zone termination date. After the TIRZ is approved, other funding opportunities can be solicited from overlapping taxing units like counties or school districts. The participation from supplementary taxing units is completely voluntary and does not have to last the duration of the TIRZ. The taxes collected from the TIRZ can then be used to implement projects within the zone. Every fiscal year, the TIRZ must submit an annual report to the taxing units that the zone is a part of detailing the revenue, projects, and compliance with the adopted project and financing plans.

Throughout Texas, TIRZ have been utilized to implement NBS projects and mitigate flooding. TIRZ funding has contributed to the Waller Creek District in Austin, TX (https://www.austintexas.gov/watershed-protection/programs/waller-creek-district-and-tunnel), which added 37 acres of parks and green space within the city. Additionally, TIRZ funding helped contribute to the construction of rain gardens in the Midtown neighborhood in Houston, TX.

Learn more: ***Implementing a TIRZ*** ↗

How To

Develop a drainage utility fee

By following these steps, a Texas municipality can develop and implement a stormwater utility fee that provides a recurring funding source for essential stormwater management and flood mitigation efforts. This structured approach ensures that the fee is fair, transparent, and capable of supporting the long-term sustainability of the municipality's stormwater infrastructure.

1. Conduct feasibility study

A feasibility study involves evaluating the current stormwater management system, identifying funding gaps, and estimating the costs of necessary compliance, maintenance, and improvements. The study also considers the legal, technical, and financial feasibility of implementing the fee.

2. Compile parcel, land, and customer data

Texas state law requires the fee to be "reasonable, equitable, and non-discriminatory" and based on drainage costs. Impervious area is the most common basis for estimating properties' use of the storm system. Accurate data collection is crucial for determining the fee structure and rates. The municipality should compile detailed information on all parcels of land within its jurisdiction, including the size, type of land use, and the amount of impervious surface area.

3. Perform rate study analyses and develop rate structure

A comprehensive rate study is conducted to analyze different rate structures and determine an equitable way to distribute the costs of stormwater management. This involves calculating the total revenue needed to cover the costs of stormwater services and determining how to allocate these costs among property owners. Various rate models, such as flat or tiered residential rates, certain allowable exemptions, and fee credits for impact minimizing property features are evaluated to find an appropriate structure for the community.

4. Adopt stormwater utility ordinance

Once the rate structure is developed, the municipality drafts a stormwater utility ordinance that outlines the legal framework for the fee. A fee schedule specifying the specific rates must also be developed. This ordinance includes details on how the fee will be calculated, billed, and used, as well as provisions for appeals and exemptions. The ordinance is then presented to the city council or governing body for approval. Public notices and public hearings are required by state law, and additional community engagement is often part of this process to ensure transparency and gather feedback.

5. Implement billing and data administration systems

With the ordinance in place, the municipality sets up the necessary billing and data administration systems. This includes integrating the stormwater utility fee into existing billing systems, such as utility or property tax bills, and ensuring that data management systems can handle the new information. Business processes are also developed for the municipality to maintain up-to-date stormwater utility billing information to account for property development, rate adjustments, and other changes.

6. Implement stormwater utility fee

Property owners begin receiving bills that include the new fee, and the municipality starts collecting revenue. Ongoing monitoring and evaluation ensure that the fee enhances effective stormwater management, and adjustments are made as needed.

Stormwater bonds

Public borrowing involves raising funds through the issuance of bonds. Bonds are debt securities that governments sell to investors, promising to repay the principal amount along with interest. This method allows governments to finance large-scale projects without immediately depleting their financial reserves. Local governments can issue green bonds specifically designated for environmental projects, including NBS. Green bonds provide a way to attract investment in sustainable infrastructure, such as the creation of urban green spaces that can absorb excess rainwater and reduce flood risks. Additionally, revenue bonds, which are repaid through the income generated by the funded projects, can be used to finance flood resilience initiatives. For example, a city might issue revenue bonds to fund the construction of a new stormwater management system, with the bond repayments coming from stormwater utility fees.

A bond referendum can help raise local funds for stormwater infrastructure, including NBS for flood resilience. Bonds would be sold on the open public bond market based on the authorization of the local entity. Bond funds can only be used for the purpose approved by the voters.

A stormwater or flood bond is a type of municipal bond specifically issued to raise funds for stormwater management and flood mitigation projects. These bonds are typically approved by voters and are repaid over time through property taxes or other municipal revenue sources. The money raised from these bonds can be used for the purposes specified by voters, such as the design, construction and maintenance of stormwater infrastructure, NBS, and other related initiatives. The funds generated from stormwater bonds must be used strictly for the purposes outlined in the bond proposal that voters approved. Communities often develop a list of proposed projects prior to the bond proposition election to ensure transparency and accountability, so taxpayers can see that their money is being used as intended.

The purpose of a stormwater bond can be tailored to meet the specific needs of a community. For example, a bond might be issued to fund the construction of new detention basins, upgrade existing drainage systems, or implement green infrastructure projects. Customizing the bond purpose allows municipalities to address their unique stormwater and flood management challenges effectively.

Green bonds are a bond instrument that use proceeds to finance or refinance environmental, water, or clean energy projects. Green bonds help governments finance new projects while enabling investors to reach sustainability targets.

Public-private partnerships

Public-private partnerships (PPPs) are collaborative agreements between government entities and private sector companies that leverage the strengths and resources of both to achieve common goals. Local communities can also partner with river authorities to implement and fund flood mitigation projects. In the context of flood mitigation, PPPs can be particularly effective in funding and implementing NBS. PPPs can tap into a variety of funding sources, combining public funds with private investments to finance large-scale flood mitigation projects.

Public funds might come from federal, state, or local government budgets, grants, or bonds, while private investments can include contributions from businesses, nonprofits, and philanthropic organizations. This diversified funding approach can significantly increase the financial resources available for NBS projects. By sharing costs and risks, PPPs make it more feasible to undertake innovative flood mitigation projects. PPPs can foster greater community involvement in flood mitigation projects. Private partners, especially those with strong local ties, can help engage residents, businesses, and other stakeholders in the planning and implementation processes. This collaborative approach ensures that NBS projects are tailored to the specific needs and preferences of the community, increasing their acceptance and long-term sustainability.

How To

Develop a stormwater/flood bond program

Developing a stormwater or flood bond program involves several key steps to ensure the bond is well-planned, effectively communicated to the public, and successfully implemented.

1. Identify specific purpose for bond funds

The first step is to clearly define the specific purpose for the bond funds. This involves identifying the stormwater or flood mitigation needs of the community and determining how the bond funds will address these needs. This could include projects like constructing or enhancing stormwater infrastructure.

2. Identify potential projects and preliminary costs

Next, the municipality identifies potential projects that the bond funds could support. This includes conducting preliminary cost estimates for each project to ensure that the bond amount requested is sufficient to cover the anticipated expenses. Detailed project descriptions and cost estimates help build a strong case for the bond proposal.

3. Prioritize potential projects

Once potential projects are identified, they need to be prioritized based on several criteria. Prioritization criteria should be developed based on stakeholder engagement and should reflect the needs and values of the community.

4. Develop ballot language

The final step is to develop clear and concise ballot language that accurately describes the bond proposal. This language should outline the specific projects and purposes for which the bond funds will be used, the total amount of the bond, and how the bond will be repaid. Clear ballot language helps voters understand the importance of the bond and how it will benefit their community.

Examples

Kendall County Prop A ↗

Harris County 2018 Bond Program ↗

City of Austin Proposition D: Flood Mitigation, Open Space, and Water Quality Protection ↗

Case Study

Memorial Park public-private partnership for flood resilience

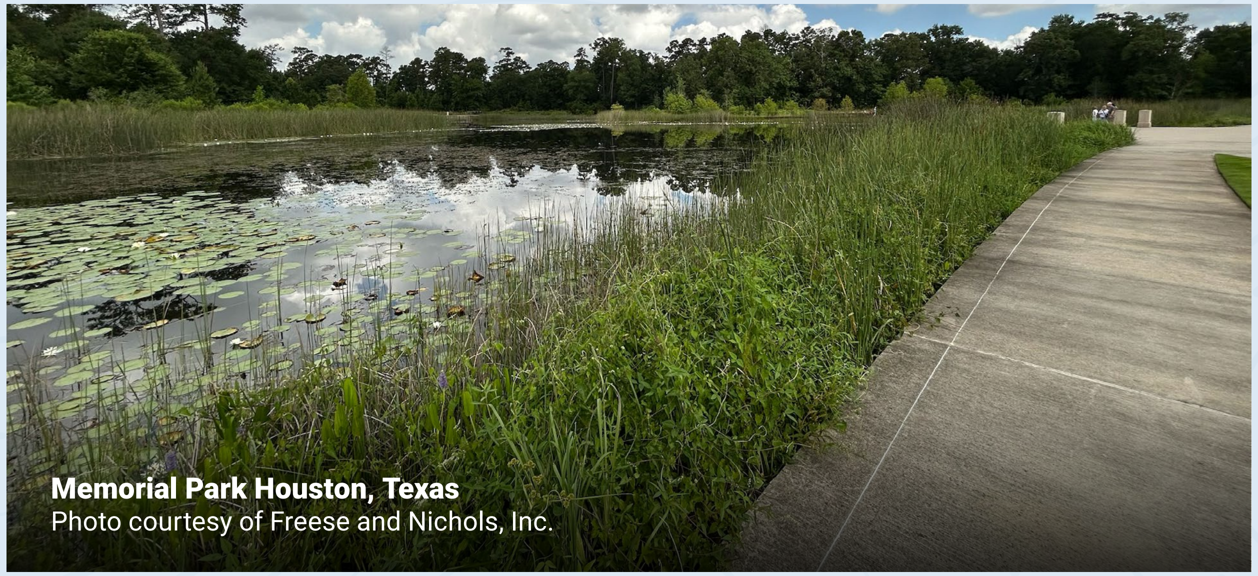
Location: Houston

Opportunity: Private donors help support at city park and provide funding for coastal prairie restoration and flood risk reduction.

Lessons learned: Incorporating NBS into flood resilience actions creates opportunity for additional funding sources.

Memorial Park, one of the largest urban parks in the United States, spanning over 1,500 acres, is a vital green space for Houston, providing recreational opportunities and serving as a natural buffer against flooding from Buffalo Bayou. The park has been the focus of significant restoration and enhancement efforts. The Memorial Park Conservancy, a nonprofit organization that works in partnership with the City of Houston, Harris County Flood Control District, and private donors, most notably the Kinder Foundation, undertook the Memorial Park Master Plan. In 2015, Memorial Park Conservancy entered a formal public-private partnership with the Houston Parks and Recreation Department to oversee the regular operations and maintenance of the park on behalf of the city. This diversified approach extended the city's capacity and ensures that sufficient resources are available to implement flood resilience NBS projects, such as the restoration of 45 acres of native Gulf Coast prairie and 135 acre-feet of detention to enhance stormwater management and reduce flood risks.[2]

Memorial Park demonstrates how public-private partnerships can effectively fund and implement NBS for flood mitigation. By combining public resources with private sector expertise and innovation, public-private partnerships can enhance the resilience of urban areas to flooding while providing multiple co-benefits, such as improved water quality, enhanced biodiversity, and increased recreational opportunities. This collaborative approach ensures that projects are well-funded, efficiently managed, and widely supported by the community.



Memorial Park Houston, Texas
Photo courtesy of Freese and Nichols, Inc.

5.2 State funding

Flooding is a significant and recurring challenge in Texas that impacts communities, infrastructure, and the economy. The implementation of infrastructure projects can often exceed the capacity of local funding sources, especially for small and rural communities, but funding programs from state and federal agencies can support the implementation of flood mitigation projects. **NBS projects are uniquely positioned to access additional funding related to the co-benefits they provide.**

To address these flooding challenges, Texas has established several funding programs aimed at enhancing flood control, mitigation, and resilience. These programs provide crucial financial assistance for planning, acquisition, design, and construction of infrastructure projects that reduce flood risk and improve water quality. By leveraging these resources, Texas communities can develop and maintain critical infrastructure, ensuring a safer and more resilient future for all residents. Additionally, the ***Flood Information Clearinghouse*** ↗ is a great resource for flood infrastructure funding opportunities in Texas.

State and federal funding for NBS projects can come in the form of loans or grants. Both funding mechanisms play a role in supporting projects that enhance flood resilience, but they have distinct characteristics and implications for recipients.

Loans are financial instruments that must be repaid over time. State and federal loans for flood resilience projects are often provided at favorable terms, including lower interest rates and longer repayment periods, to make them more accessible to local governments and organizations. While loan programs create a sustainable and revolving fund that can be reused as repayments are made, the requirement to repay loans, even on favorable terms, can be challenging for projects that do not generate direct revenue or savings. Local governments must identify a sustainable mechanism to fund loan payments.

Grants are funds to support specific projects or initiatives without the repayment requirement. Grants do not need to be repaid, making them an attractive option for recipients who may not have the capacity to take on additional debt. Some grants have a match requirement where the local government would pay a percentage of the total cost. Grants for NBS for flood resilience are typically awarded based on competitive applications that demonstrate the project's potential impact and alignment with funding priorities. Grant funding is often limited and highly competitive, making it difficult for all deserving projects to receive support.

Communities should understand and plan for all prerequisites and repayment terms under any potential program. The choice between loan or grant funds depends on the specific needs, capacities, and goals of the recipients. By strategically utilizing both funding mechanisms along with local funding, federal programs can effectively support a wide range of flood resilience projects, enhancing the ability of communities to withstand and recover from flood events. It is important to note that federal funding is available for projects, but not for maintenance of a project over time.

Flood Infrastructure Fund

The Texas Flood Infrastructure Fund (FIF) is a program established to provide financial assistance for flood control, flood mitigation, and drainage projects across Texas. This initiative, passed by the Texas Legislature and approved by voters through a constitutional amendment, provides loans and grants for flood activities and projects. The TWDB collaborates with regional RFPGs who recommend flood management evaluations (FME), flood mitigation projects (FMP), and flood management strategies (FMS). The TWDB gathers recommendations from the regional flood plans and develops a combined state flood plan. Inclusion in the most recently adopted State Flood Plan is a requirement to be eligible for FIF funds.

The application process involves submitting an abridged application to provide necessary information for project prioritization. FMPs, FMSs, and FMEs that rank within the program's capacity are invited to submit full applications for detailed review and funding consideration. The prioritization of FMPs in the 2024 State Flood Plan included additional points for projects with nature-based components. The FIF is a crucial resource for Texas communities to enhance their resilience against flooding and ensure the safety and well-being of residents.

The overarching goal of the regional and state flood plans is to protect against the loss of life and property. The ranking criteria for FMP within the state flood plan balanced areas with the greatest risk of flooding with solutions with the greatest overall reduction in flood risk. The prioritization process involved developing criteria and assigning each criteria a weighted value. Notably, the ranking criteria included 5 percent of total project score if the percentage of project cost is related to NBS; 5 percent if the project provides water supply benefits; 2.5 percent if the project provides multiple co-benefits, in addition to flood risk reduction; and 2.5 percent if the project provides environmental benefits. Depending on the NBS type and benefits, a total of 15 percent of the total project score could be unlocked by incorporating the guiding principles of NBS for flood resilience.

Learn more: www.twdb.texas.gov/financial/programs/FIF ↗

Texas Water Development Fund

The Texas Water Development Fund (DFund) is the TWDB base funding program designed to provide flexibility and loan capacity while still providing competitive loan rates.[3] The DFund can fund water, wastewater, and both structural and nonstructural flood control projects in a single loan. Interest rates are based on the Texas AAA bond rating, so rates may be lower than applicants can access directly through the open bond market. As with the other TWDB programs, eligible project phases include planning, acquisition, design, and construction, and alternative delivery methods may be utilized.

The DFund was granted an ongoing, rolling-loan capacity of $6 billion and currently does not have a project size limit. While applications may be submitted year-round, only those applications received by December 31 in any given year will be considered for funding the following summer. As such, the DFund is truly the most flexible TWDB financial assistance program.

Learn more: www.twdb.texas.gov/financial/programs/TWDF ↗

Clean Water State Revolving Fund

The Texas Clean Water State Revolving Fund (CWSRF) is a program designed to provide low-cost financial assistance for the planning, acquisition, design, and construction of wastewater, reuse, and stormwater infrastructure. Authorized by the Clean Water Act, the CWSRF aims to support projects that improve water quality and protect public health. Principal forgiveness may be available for projects “with green components”.

Information on appropriations for the latest state fiscal year is available on TWDB CWSRF website. The solicitation for state revolving fund programs opens in December and closes in March of the following year. Entities must submit a completed project information form by the deadline to be considered for funding. The CWSRF is a tool for Texas communities to develop and maintain critical water infrastructure, ensuring clean and safe water for all residents.[4]

Learn more: www.twdb.texas.gov/financial/programs/CWSRF

Section 319 Nonpoint Source Management Program

The Section 319 Nonpoint Source (NPS) Management Program is authorized under Section 319 of the Clean Water Act and provides grant funding to states to reduce water pollution from nonpoint sources. In Texas, the program is administered by the TCEQ. Section 319 funds support watershed-based planning and implementation projects that improve water quality. Projects must align with an approved watershed protection plan or total maximum daily load (TMDL) implementation plan.

Funding is competitive at the state level. Eligible applicants typically include local governments, river authorities, soil and water conservation districts, and nonprofit organizations. Projects are evaluated based on expected pollutant load reductions, stakeholder involvement, and consistency with watershed priorities.

Learn more: www.tceq.texas.gov/waterquality/nonpoint-source ↗

Additional funding opportunities

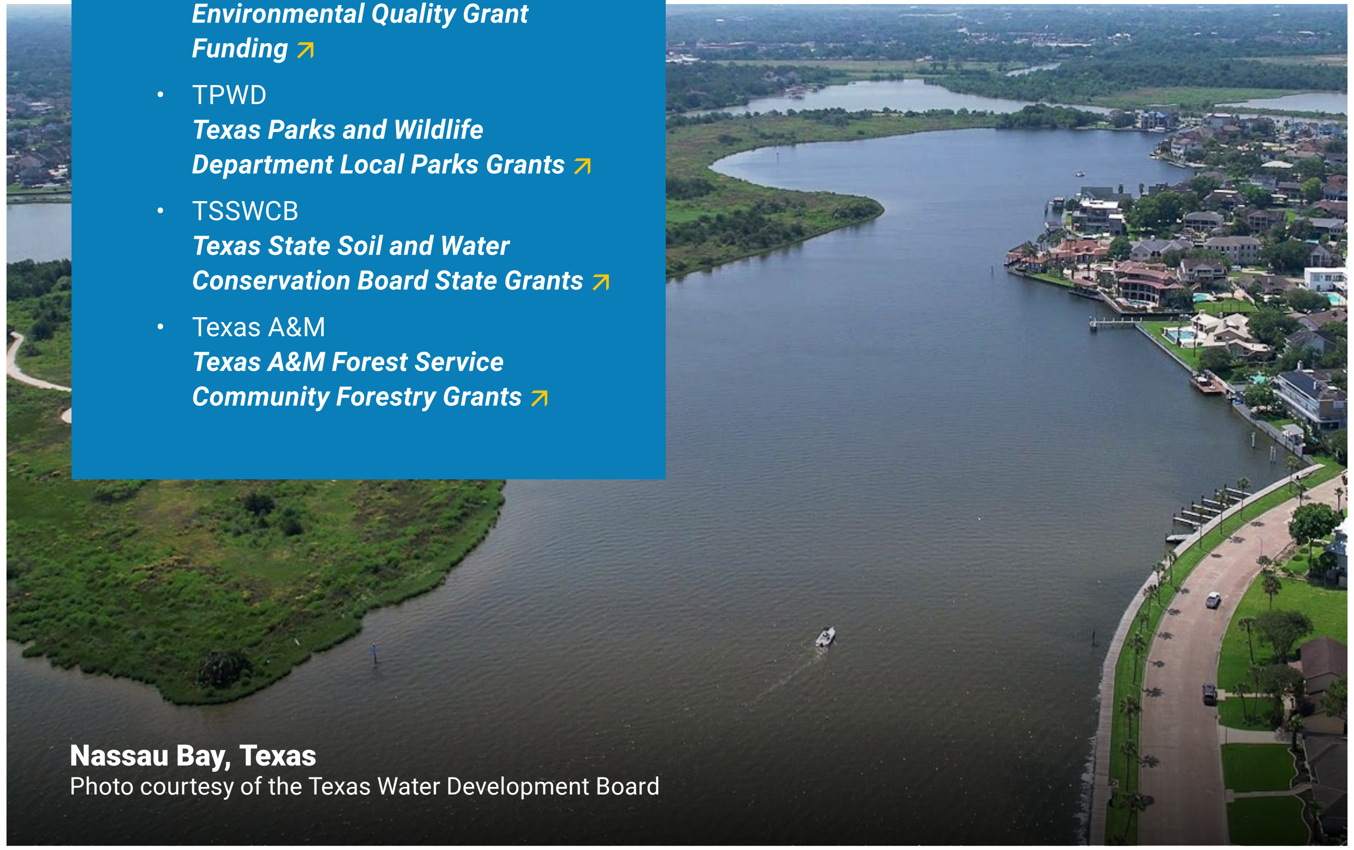
NBS can open new pathways for project funding. Flood mitigation projects that apply systems thinking and include co-benefits, such as recreation and conservation in project goals, expand their funding eligibility. Many state agencies offer programs to fund projects that provide co-benefits possible with NBS for flood resilience. For example, the Texas Parks and Wildlife Department (TPWD) and the Texas State Soil and Water Conservation Board offer several grant programs aimed at supporting conservation, recreational trails, and NBS for flood mitigation projects. The TPWD offers grants that can assist with recreational amenities and habitat conservation elements of an NBS project. These grants are opportunities for communities to enhance their natural resources, provide recreational opportunities, and improve resilience against flooding.

Texas A&M Forest Service developed a tool to connect landowners with financial assistance for land stewardship. Using this online map tool, landowners can visually see and learn more about programs available in their geography.

Funding Connector - Financial Assistance for Land Stewardship in Texas ↗

Tools and resources

- TCEQ
  Texas Commission on Environmental Quality Grant Funding ↗
- TPWD
  Texas Parks and Wildlife Department Local Parks Grants ↗
- TSSWCB
  Texas State Soil and Water Conservation Board State Grants ↗
- Texas A&M
  Texas A&M Forest Service Community Forestry Grants ↗



Nassau Bay, Texas
Photo courtesy of the Texas Water Development Board

5.3 Federal funding

In addition to state and local funding, federal funding for NBS for flood resilience plays an essential role in enhancing community resilience to flooding. As with state funding programs, communities should understand the prerequisites for funding under potential programs. For example, a community must have a hazard mitigation action plan approved by FEMA to be eligible for funding from the Hazard Mitigation Grant Program (HMGP). The Section 319 Nonpoint Source Management Program administered by the EPA offers funding that can be leveraged for NBS for areas located within an approved watershed protection plan. Some federal programs target grant funding to underserved or vulnerable communities that may lack the resources to implement flood resilience measures on their own.

The following sections highlight examples of federal programs available to communities to fund NBS for flood resilience.

Hazard Mitigation Grant Program

The Hazard Mitigation Grant Program (HMGP) provides post-disaster mitigation funding to reduce future disaster losses. Authorized under Section 404 of the Stafford Act, HMGP funding becomes available following a presidentially-declared disaster. Eligible activities include floodplain restoration, property acquisition and demolition, drainage improvements, and other mitigation measures that reduce long-term flood risk. NBS for flood resilience solutions are eligible if they demonstrate measurable hazard reduction.

Projects must be consistent with the jurisdiction's FEMA-approved Hazard Mitigation Plan and meet FEMA BCA requirements. Funding is allocated to the state based on a percentage of total disaster assistance, and the state administers project selection. The HMGP can be a valuable opportunity to advance flood mitigation projects that were previously identified in planning documents but lacked funding prior to a disaster event.

Learn more: www.fema.gov/grants/mitigation ↗

Community Development Block Grant

The Community Development Block Grant-Mitigation (CDBG-MIT) and Disaster Recovery (CDBG-DR) programs provide federal funding to state and local governments to address disaster recovery and long-term risk reduction needs. These programs are administered by the U.S. Department of Housing and Urban Development (HUD) and are allocated following major disaster declarations. Eligible activities include drainage improvements, flood control projects, property acquisition, and resilience planning.

Projects that incorporate floodplain restoration, green infrastructure, and recreational amenities may qualify when tied directly to mitigation objectives. States develop action plans that establish priorities and application procedures. Projects must meet HUD national objectives and comply with federal environmental review requirements. CDBG-MIT and CDBG-DR can fund large-scale, multi-benefit projects that combine flood mitigation, environmental restoration, and community amenities.

Learn more: www.hudexchange.info ↗

Emergency Watershed Protection Program

The Emergency Watershed Protection (EWP) Program, administered by the U.S. Department of Agriculture – Natural Resources Conservation Service (USDA NRCS), provides assistance to local sponsors following natural disasters to address watershed impairments that pose an imminent threat to life or property. Eligible measures include debris removal, streambank stabilization, and emergency protective works. In some cases, the EWP may support floodplain easements that permanently remove structures from high-risk areas. Local governments or conservation districts serve as project sponsors and request assistance through NRCS after a qualifying disaster event. The EWP can serve as an early recovery funding source that stabilizes damaged waterways and creates opportunities for longer-term floodplain restoration and wetland conservation.

Learn more: www.nrcs.usda.gov/programs-initiatives/emergency-watershed-protection ↗

Wetland Program Development Grants

Through Wetland Program Development Grants (WPDGs), the EPA helps recipients build capacity for wetland monitoring, assessment, planning, and restoration. Funds may support watershed-based wetland restoration, mapping, and regulatory program improvements that enhance flood storage, water quality, and habitat functions. While the program does not typically fund large-scale construction directly, it provides technical assistance and grant funding to states, tribes, and local partners to strengthen wetland programs and implement restoration activities.

Projects are administered at the state level and must align with Clean Water Act objectives and approved work plans. Emphasis is placed on measurable ecological outcomes, watershed-based approaches, and long-term sustainability. For flood mitigation projects, EPA wetlands funding can support planning, assessment, and restoration activities that complement structural measures and enhance the natural flood storage capacity of wetlands.

Learn more: www.epa.gov/wetlands ↗

Urban Waters Federal Partnership

The Urban Waters Program supports community-led efforts to restore and revitalize urban waterways while improving public access, environmental quality, and neighborhood resilience. The program focuses on reconnecting communities with their local water resources through partnerships and coordinated investment. While the Urban Waters Program does not function as a traditional infrastructure grant program, it provides technical assistance, interagency coordination, and strategic support to help communities advance waterway restoration, green infrastructure, wetland enhancement, and recreational access projects.

Learn more: www.epa.gov/urbanwaters ↗

National Coastal Resilience Fund

The National Coastal Resilience Fund (NCRF), administered by the National Oceanic and Atmospheric Administration (NOAA) in partnership with the National Fish and Wildlife Foundation, supports projects that restore or enhance natural infrastructure to reduce coastal flood risk while improving habitat and community resilience. Eligible activities include wetland restoration, living shorelines, floodplain reconnection, and hybrid gray-green infrastructure. Projects are evaluated based on risk reduction benefits, habitat improvement, community engagement, and implementation readiness.

Cost share requirements vary by funding round. Competitive proposals typically demonstrate strong partnerships, measurable ecological benefits, and quantifiable flood risk reduction outcomes. The NCRF is particularly well-suited for projects that integrate wetland conservation with recreational access and ecological enhancement in coastal or tidally influenced areas.

Learn more: www.coast.noaa.gov/funding ↗

Additional funding opportunities

The programs highlighted in this section are a non-exhaustive list of opportunities for funding NBS for flood resilience.

Additional examples federal funding programs and partnerships include:

- ***Beneficial Uses of Dredged Sediment* ↗**
- ***Brownfields Revolving Loan Fund Grant Program* ↗**
- ***Flood and Coastal Storm Risk Management* ↗**
- ***Flood Mitigation Assistance Grant Program* ↗**

The ***Green Infrastructure Federal Collaborative* ↗** has cataloged dozens of federal programs that can fund planning, design, construction, maintenance, and/or monitoring of NBS. The ***National Wildlife Federation Funding Database* ↗** also hosts an interactive database on federal funding and technical assistance programs for NBS.

Local communities can effectively collaborate with federal agencies to access funding opportunities for flood mitigation and NBS by

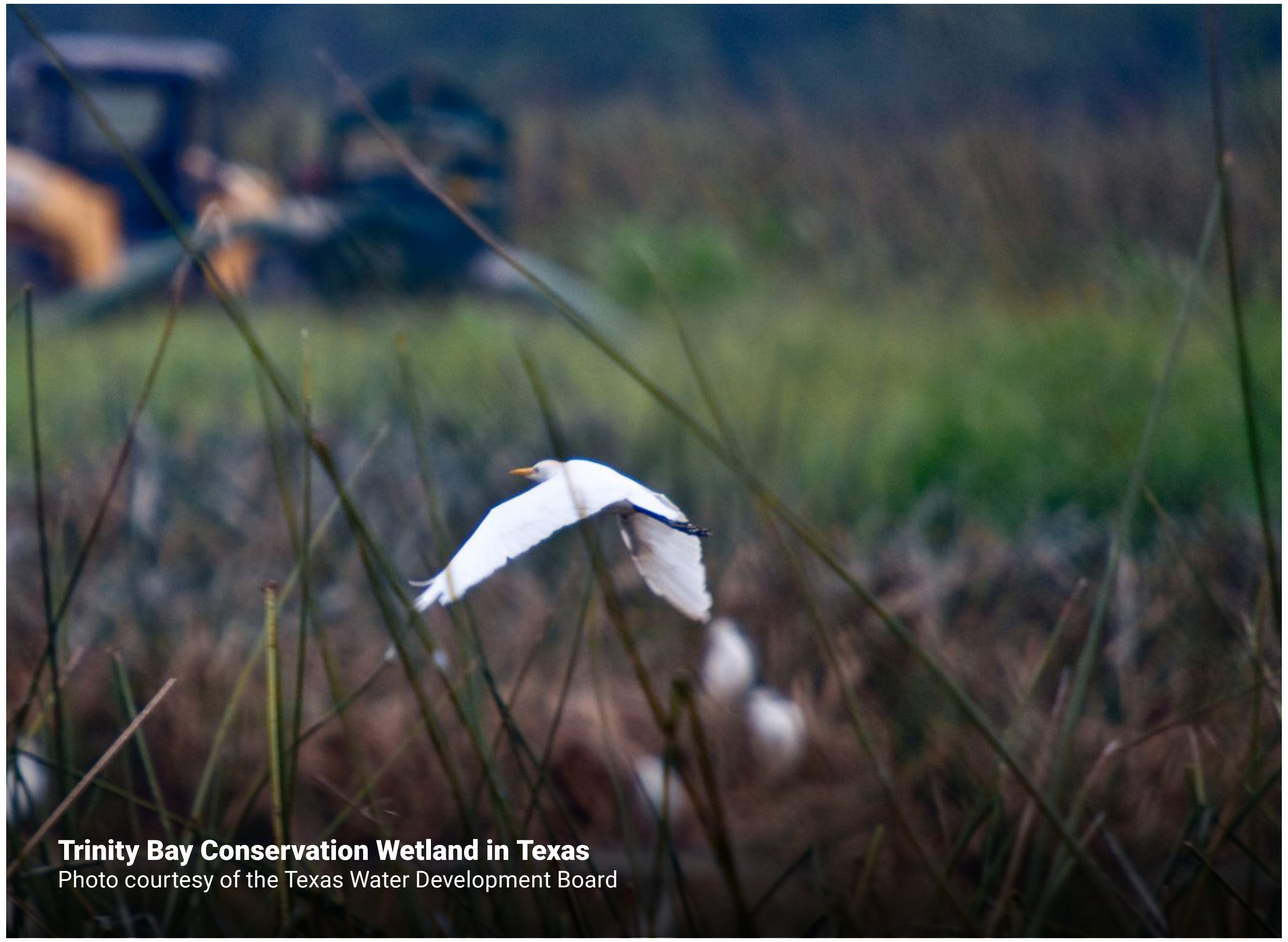
- enhancing local mitigation planning,
- leveraging FEMA technical assistance,
- aligning project with program's goals and eligibility requirements,
- building relationships and partnerships,
- using data to conduct risk assessments, and
- engaging a wide range of stakeholders.

Procurement considerations

The primary tool communities have for soliciting expert input are requests for qualifications (RFQs). Traditional RFQs are inherently narrow in their language and implementation, which can limit responses and not provide the community with the opportunity to consider all available options. Ensuring RFQs are inclusive of NBS may increase the quality and variety of the resulting proposals in favor of those that use nature-based or other innovative solutions that increase resiliency and provide additional public benefits.

The Nature Conservancy's ***A Procurement Guide to Nature-Based Solutions*** ↗ is a resource communities can use to assess their RFP language and ensure it is not limiting potential responses. The guidance is organized into two parts to help communities consider the advantages of NBS and develop RFQ language that encourages proposals with strategic, innovative approaches to conceptualize, design, and implement water infrastructure projects.[5]

The Institute for Sustainable Infrastructure's ***Guide to Procuring Sustainable Infrastructure Services*** ↗ is a resource that outlines best practices for approaching projects using different procurement models.[6]



Trinity Bay Conservation Wetland in Texas
Photo courtesy of the Texas Water Development Board

How To

Develop a funding strategy for flood resilience

1. Research eligibility requirements:

Understand procedural requirements of potential funding sources. By being prepared, a city or county can enhance its chances of securing state or federal funding for flood mitigation construction projects, ultimately leading to improved community resilience and reduced flood risks.

2. Engage in community and stakeholder outreach:

Gather input and build support for the proposed projects. Outreach could include hosting public meetings, surveys, and collaboration with local organizations, or developing partnerships with local businesses, nonprofits, and other entities to strengthen the application and demonstrate broad-based support. Evidence of stakeholder engagement is a requirement for eligibility for some funding programs.

ⓘ **Learn more in Chapter 6**

3. Identify projects:

Applications should point to specific flood mitigation projects that address a need or reduce flood risk. Communities should estimate preliminary costs to fully implement the projects, including planning, design, construction, and maintenance. If the full scope of the project is not yet determined, communities could apply for funding to further develop the plan for a project.

ⓘ **Learn more in Chapter 6**

4. Conduct a benefit-cost analysis (BCA):

Some programs include cost-effectiveness as a requirement for eligibility. Benefits in the analysis should include co-benefits also provided by the solution.

ⓘ **Learn more in Chapter 8**

5. Secure matching funds:

Identify and secure the required non-federal matching funds. Many federal grant programs require a cost share, which can come from state, local, or private sources or in-kind services. NBS have additional funding opportunities connected to the co-benefits created by the project, so consider partnerships or grant programs connected to these co-benefits to unlock funding.

6. Prepare detailed project proposals:

Develop detailed project proposals that include technical descriptions, cost estimates, timelines, and expected outcomes. Expected flood risk reduction values should be signed and sealed by a licensed professional engineer. Review environmental and historic preservation requirements.

7. Coordinate with state and federal agencies:

Contact the appropriate point of contact to understand the specific guidelines and requirements of the intended funding program. Hold pre-application meetings as required or recommended by agencies.

Establishing funding strategies **citations**

Guadalupe River near Hunt, Texas
Photo courtesy of the Texas Water Development Board

[1] Texas Local Government Code, n.d., Chapter 552, *Subchapter C—Municipal utilities:* Texas Statutes, statutes.capitol.texas.gov/Docs/LG/pdf/LG.552.pdf, accessed February 2026.

[2] Memorial Park Conservancy, 2026, Memorial Park Houston | 1,500 Acres of Nature, Trails & Recreation: Memorial Park Conservancy, https://www.memorialparkconservancy.org/, accessed June 2026.

[3] Texas Water Development Board, n.d., *Texas Water Development Fund (DFund)*, www.twdb.texas.gov/financial/programs/TWDF, accessed June 2026.

[4] Texas Water Development Board, n.d., *Clean Water State Revolving Fund (CWSRF)*, www.twdb.texas.gov/financial/programs/CWSRF, accessed June 2026.

[5] Leung, V.A., Woiwode, N., Smith, M.P., 2018, *Nature-based solutions procurement guide:* Naturally Resilient Communities, nrcsolutions.org/wp-content/uploads/2018/02/NBS_Procurement_Guide.pdf, accessed June 2026.

[6] Institute for Sustainable Infrastructure, 2024, *Guide to procuring sustainable infrastructure services*, sustainableinfrastructure.org/new-procurement-guide/, accessed June 2026.

INITIATING NBS

PLANNING NBS

IMPLEMENTING NBS

Planning Nature-Based Solutions

Planning NBS includes the core preparatory work necessary for implementation. This involves integrating NBS into current planning processes, assessing flood risk, establishing project goals, developing a stakeholder engagement plan, and evaluating opportunities for NBS within your community or watershed.

CHAPTERS 6-7

Chapter 6 Integrating NBS into Planning Processes

Chapter 7 Understanding Flood Risk and Identifying NBS Opportunities

Outcomes

- Embed NBS principles into planning processes
- Secure stakeholder buy-in via effective engagement
- Determine multi-beneficial goals
- Identify structural and nonstructural NBS

6

Integrating NBS into planning processes

Proactive planning, versus reactive action, is essential to achieving multifunctional and sustainable flood resilience objectives.

Key takeaways

- Integrating flood resilience into land use planning helps communities proactively prevent future flood loss.
- Flood planning processes are the most effective way to integrate NBS into a community's flood resilience strategy.
- Effective stakeholder engagement requires understanding roles and responsibilities, and consistent, intentional outreach.

Rio Grande River near Big Bend National Park
Photo courtesy of the Texas Water Development Board

How the guiding principles apply to this chapter

Engage and include	Planning processes provide opportunities to engage and include a variety of stakeholders to provide a holistic view of the flooding problems, and to consider other issues and co-benefits that communities would like to see addressed.
Apply systems thinking	The benefits and co-benefits of NBS for flood resilience give the opportunity to connect potentially siloed planning processes.
Work across boundaries	Using multidisciplinary teams (planners, engineers, landscape architects, environmental scientists, etc.) to develop plans allows for various perspectives and expertise to be included when potential projects are considered.
Learn and adapt continuously	Planning cycles and plan updates are opportunities to learn from and adapt flood resilience strategies, take stock of what worked and what didn't, and confirm community needs are being met.

Introduction

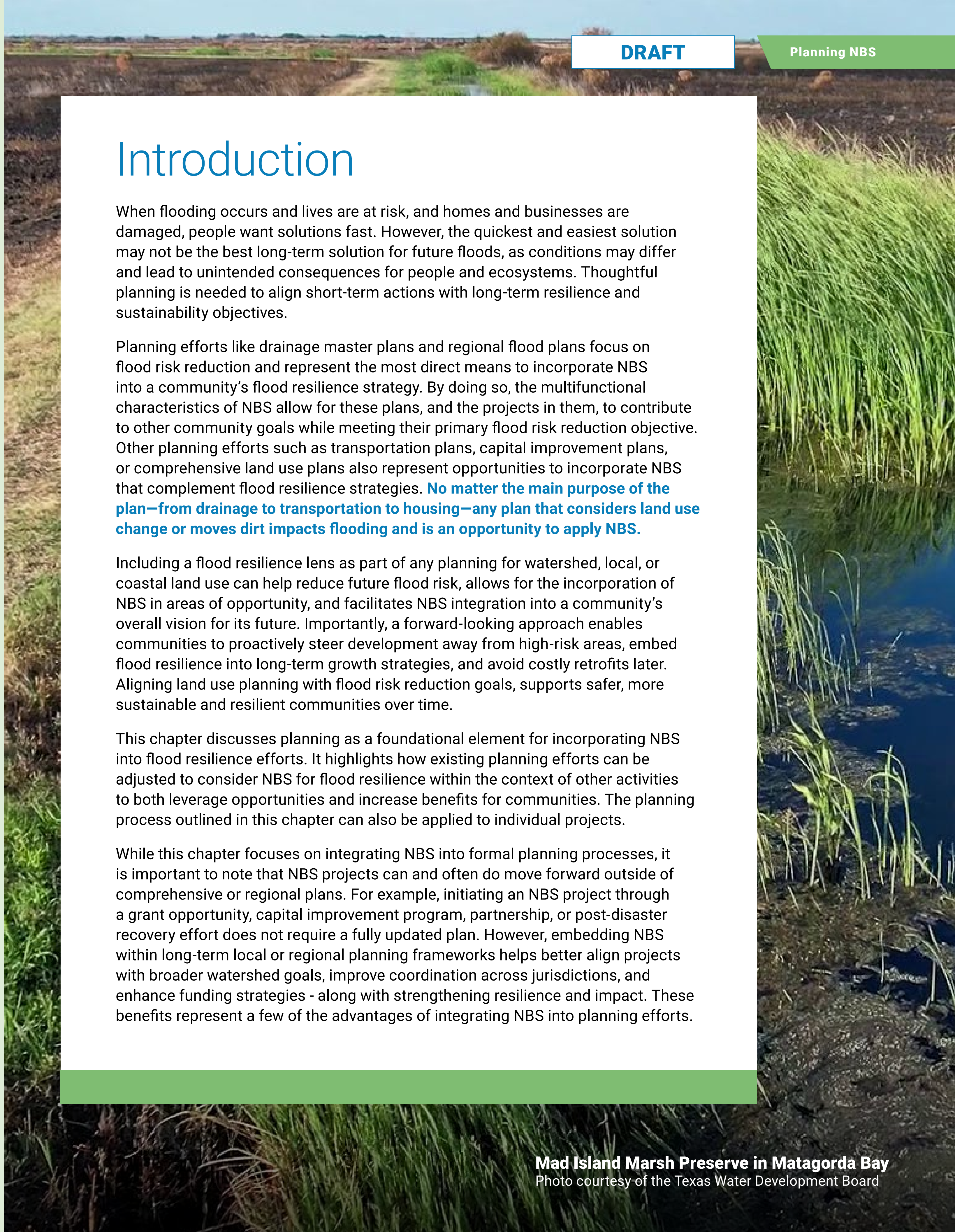
When flooding occurs and lives are at risk, and homes and businesses are damaged, people want solutions fast. However, the quickest and easiest solution may not be the best long-term solution for future floods, as conditions may differ and lead to unintended consequences for people and ecosystems. Thoughtful planning is needed to align short-term actions with long-term resilience and sustainability objectives.

Planning efforts like drainage master plans and regional flood plans focus on flood risk reduction and represent the most direct means to incorporate NBS into a community's flood resilience strategy. By doing so, the multifunctional characteristics of NBS allow for these plans, and the projects in them, to contribute to other community goals while meeting their primary flood risk reduction objective. Other planning efforts such as transportation plans, capital improvement plans, or comprehensive land use plans also represent opportunities to incorporate NBS that complement flood resilience strategies. **No matter the main purpose of the plan—from drainage to transportation to housing—any plan that considers land use change or moves dirt impacts flooding and is an opportunity to apply NBS.**

Including a flood resilience lens as part of any planning for watershed, local, or coastal land use can help reduce future flood risk, allows for the incorporation of NBS in areas of opportunity, and facilitates NBS integration into a community's overall vision for its future. Importantly, a forward-looking approach enables communities to proactively steer development away from high-risk areas, embed flood resilience into long-term growth strategies, and avoid costly retrofits later. Aligning land use planning with flood risk reduction goals, supports safer, more sustainable and resilient communities over time.

This chapter discusses planning as a foundational element for incorporating NBS into flood resilience efforts. It highlights how existing planning efforts can be adjusted to consider NBS for flood resilience within the context of other activities to both leverage opportunities and increase benefits for communities. The planning process outlined in this chapter can also be applied to individual projects.

While this chapter focuses on integrating NBS into formal planning processes, it is important to note that NBS projects can and often do move forward outside of comprehensive or regional plans. For example, initiating an NBS project through a grant opportunity, capital improvement program, partnership, or post-disaster recovery effort does not require a fully updated plan. However, embedding NBS within long-term local or regional planning frameworks helps better align projects with broader watershed goals, improve coordination across jurisdictions, and enhance funding strategies - along with strengthening resilience and impact. These benefits represent a few of the advantages of integrating NBS into planning efforts.



Mad Island Marsh Preserve in Matagorda Bay
Photo courtesy of the Texas Water Development Board

6.1 Recognizing the role of planning

Planning for flood resilience can be conducted at a variety of scales and for many purposes. It is considered best practice for communities to develop their own flood risk reduction plan. Participating in regional planning efforts helps provide a broader understanding and deeper appreciation of how flood risk in your community both influences and is influenced by upstream and downstream conditions in the watershed.

Some community plans are prompted by requirements of state and federal funding programs. For example, FEMA requires local applicants to have an approved hazard mitigation action plan (updated in five-year cycles) when applying for certain funding programs.

Plans may also be developed in response to community concerns. These planning efforts allow for a deliberative process that considers many plausible options to address a problem. Planning compares and evaluates those options and their multiple consequences, such as how well they address the problem at hand. They also engage a wide array of interests in deciding an appropriate path to pursue. In many cases, this process begins with recognizing recurring flooding or drainage issues, using available data to better understand the extent and causes of the problem, and securing funding to support a more formal assessment and planning effort—often with technical support to evaluate existing infrastructure and system performance.

Planning for NBS for flood resilience will look different in each community. The FEMA ***National Resilience Guidance: A Collaborative Approach to Building Resilience*** ↗ can help communities think about trade-offs and decide how to plan for resilience whether as a standalone plan, as a core component of an existing plan, or as integration into all community planning efforts.

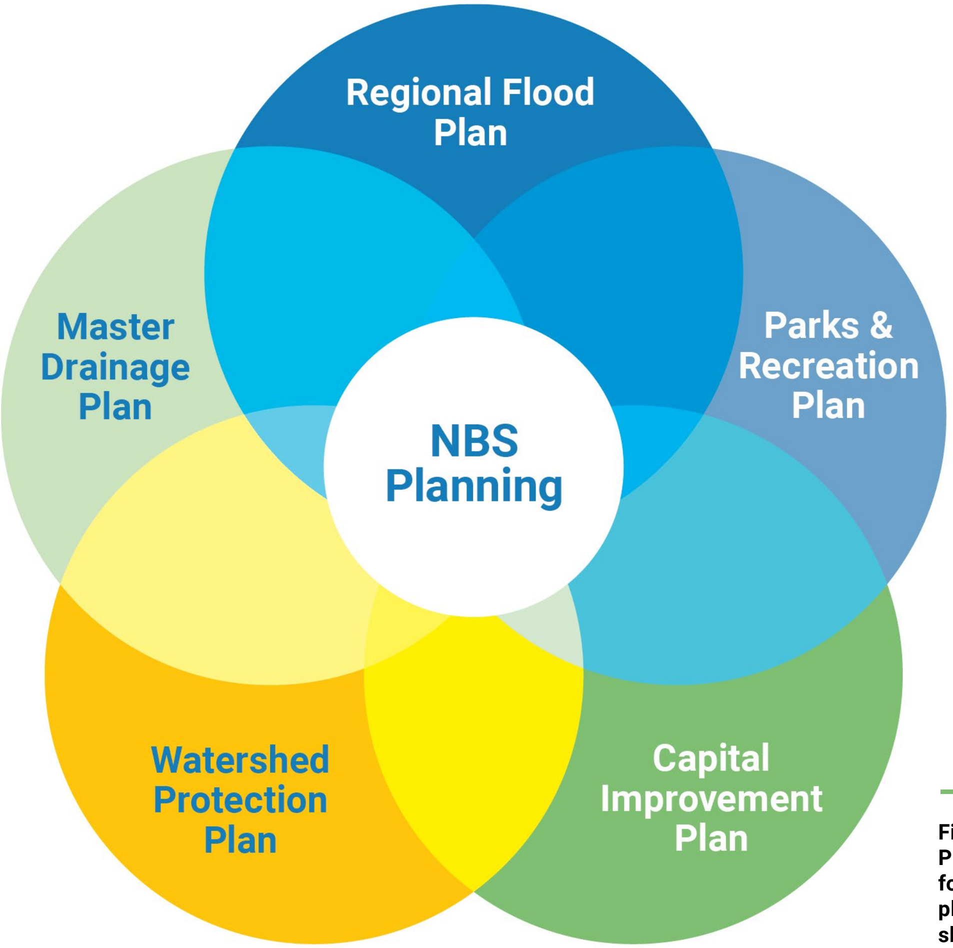


Figure 6-1. Integrated NBS Planning. Integrating NBS for flood resilience into planning processes is a shared responsibility.

> *The strategic value of considering [NBS] is that it often triggers planning-level ideas on long-term solutions that align well with natural behavior. For example, on an eroding coastline, the long-term solution may be spatial adaptation (in most cases)—all other measures, whether hard or soft, are often short-term measures. The overarching objectives for informing the design of such integrated systems will be to produce sustainable outcomes that promote the resilience of our communities and environment, while creating long-lasting, diversified value. There are many planning efforts that offer opportunities to increase flood resilience.*
>
> - International Guidelines on Natural and Nature-Based Features for Flood Risk Management.[1]

Long-term planning considerations

Historically, flood planning has largely assumed that future conditions will resemble current conditions. But the variables that drive flood risk- land use, subsidence, land cover, climate, and weather, change over time. As a result, the context for flood resilience planning changes over time. The study, "Year 2060 Floodplain Maps for Texas - Final Report" (July 2025) recommended regional flood planning groups use Scenario 3 (significant future climate forcing with future subsidence and land use change) as a worst-case scenario for long-term planning when considering future conditions. Under Scenario 3 widespread expansion of pluvial, fluvial, and coastal flood inundation occurs across most of the state primarily driven by climate forcing. Land use change has a minimal overall impact on floodplain extent, though it can influence localized conditions. In contrast, subsidence plays a more significant role (vs. land use) in increasing coastal flood inundation.

Climate and weather patterns also impact the flood threat. A 2021 study found that one third of flood damages in the U.S. since 1988 were due to changing precipitation patterns.[2] Increases in precipitation may stress existing riverine and urban flood storage. Planning for flood resilience, therefore, must be periodically revisited to confirm that current and predicted risks are still being addressed. NBS practices can be incorporated into existing flood management systems to provide increased flood storage capacity.

A study across the Gulf Coast showed that strategic land conservation of natural open space can more effectively reduce observed flood damage at the watershed level as opposed to multiple small and fragmented patches,[3] while an analysis of the Dallas, San Antonio, Austin, and Houston metropolitan statistical areas showed that the size, fragmentation, and connectivity of landscape affect peak runoff.[4] Considering these factors in long-term regional plans can allow for strategic conservation (e.g., protection of critical areas). It also allows for the incorporation of land management strategies like floodplain easements, updating development codes, and adjustment to land use plans. These solutions can better enable landscape features to contribute to flood resilience.

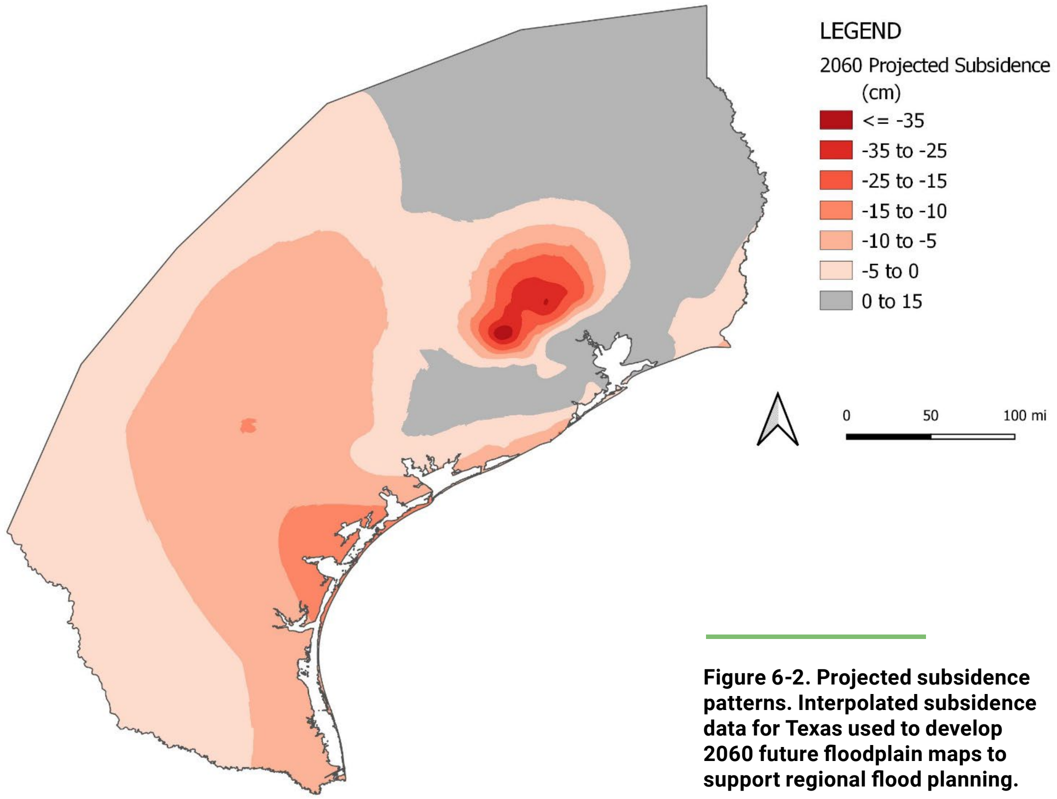


Figure 6-2. Projected subsidence patterns. Interpolated subsidence data for Texas used to develop 2060 future floodplain maps to support regional flood planning.

Case Study

Upper Langham Creek Frontier Program

Location: Harris County

Opportunity: Private development anticipated in flood prone area that would require significant drainage infrastructure that could incorporate NBS.

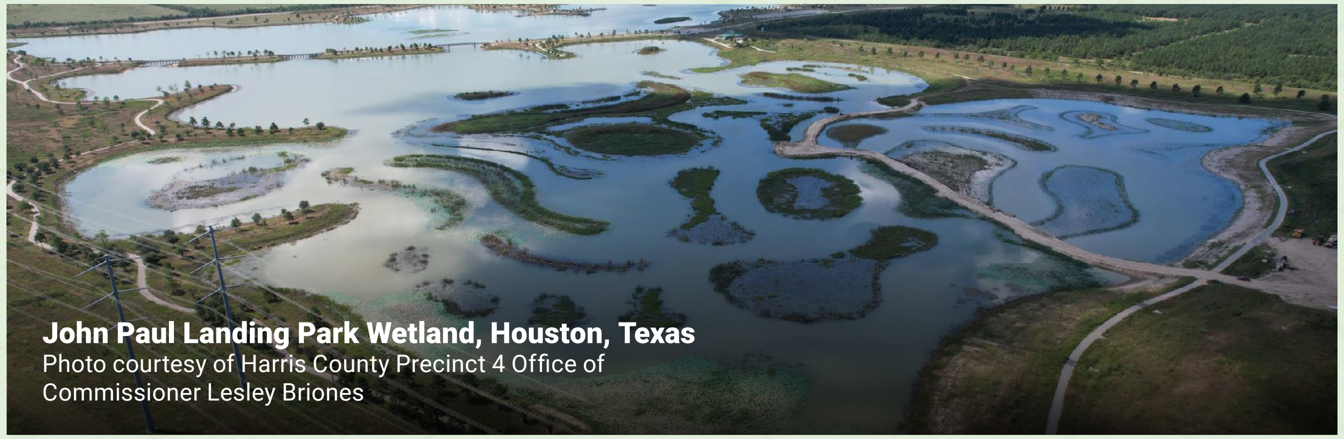
Lessons Learned: Plan first. Early, regional planning creates space—physically and institutionally—to integrate nature-based features with multiple benefits in mind, such as flood control, habitat creation, and community amenities.

Typical development practices rely on individual landowners to design and construct drainage infrastructure to mitigate adverse impacts. The Harris County Flood Control District (HCFCD) launched its Frontier Program to shift from this fragmented model to proactive stormwater planning before development occurs. Upper Langham Creek became a showcase for integrating NBS into regional flood control planning. By planning regionally, HCFCD was able to anticipate community needs, conserve open green space, provide public recreation opportunities, and deliver cost-effective flood mitigation and water quality improvements.

Floodplain preservation is a central component of the approach, exemplified by the John Paul Landing Detention Basin, which is shaped and landscaped to provide both flood storage and public recreation. Rather than relying on straightened channels, alignments are designed to meander naturally, restoring more resilient flow patterns and creating diverse habitats. Stormwater treatment wetlands are incorporated into the geomorphic floodplain to filter runoff, improve water quality, and protect downstream communities.

Community partnerships further strengthen the success of these efforts. Master-planned developments have integrated detention corridors as greenways and trails, transforming necessary flood infrastructure into community amenities. These multi-benefit assets promote flood safety, expand recreational access, and enhance property values, demonstrating how collaborative planning can align environmental stewardship with community growth.

The outcomes are significant: reduced downstream flood risk through regional mitigation, improved quality of life with parks and trails along stormwater corridors, and more cost-effective growth by avoiding fragmented or duplicative detention systems. Environmental co-benefits include healthier habitats, cleaner water, and greater climate adaptability. Larger drainage corridors also provide long-term resilience, allowing for expansion and adaptation without the costly and disruptive acquisition of existing homes or businesses.



John Paul Landing Park Wetland, Houston, Texas
Photo courtesy of Harris County Precinct 4 Office of Commissioner Lesley Briones

6.2 Leveraging existing planning processes

State and federal governments, counties, municipalities, and regional bodies develop plans for many purposes. Not all plans address flood resilience directly; however, any land use related plan has the opportunity to incorporate NBS for flood resilience that can benefit a community. Successful integration of NBS into flood resilience plans is enabled if the planning process explicitly allows NBS and their multiple benefits to be considered alongside gray solutions.

In Texas, communities have a growing number of opportunities to incorporate NBS and flood resilience strategies into existing planning frameworks, rather than starting from scratch. One of the most significant efforts is the ***Regional Flood Planning Program*** ↗. These plans are developed across 15 flood planning regions and are intended to identify flood risks, evaluate mitigation strategies, and recommend projects that address both structural and nonstructural needs. Communities participating in these plans are well-positioned to align local projects with regional priorities and access future funding for implementation. NBS can be integrated throughout the planning process by identifying natural flood infrastructure, studying feasibility through flood management evaluations, and recommending nonstructural flood management strategies and structural flood mitigation projects.

Beyond regional flood plans, other common existing planning tools like hazard mitigation action plans, capital improvement plans, comprehensive plans, and parks and open space master plans can be leveraged to advance NBS. Comprehensive plans can integrate NBS as part of future land use goals, guiding growth away from flood-prone areas while promoting multifunctional green spaces. Local watershed protection plans, often developed with support from state and local stakeholders, are also an opportunity to identify co-benefits of NBS for both water quality and flood mitigation.

Coordinating these planning efforts helps reinforce that flood risk reduction is not addressed in isolation—instead it is embedded within broader community development goals. Doing so promotes efficient use of public resources, reduces duplication of effort, and helps communities meet the multiple demands of urban growth, climate resilience, and environmental protection. As data and conditions evolve, particularly with population growth, land use change, and shifting rainfall patterns, these existing planning processes provide valuable checkpoints for reassessing local risk and adapting strategies over time. **Tables 6-1** and **6-2** highlight a variety of plans both for flood resilience and other land use considerations that can incorporate NBS and contribute to a community's flood resilience.

Definition

Flood management evaluation

A proposed study to identify, assess, and quantify flood risk or identify, evaluate, and recommend flood risk reduction solutions.

Flood mitigation project

A proposed structural or nonstructural flood project that has a non-zero capital cost or other non-recurring cost and, when implemented, will reduce flood risk.

Flood management strategy

Ideas and strategies that do not belong in the flood management evaluation or flood mitigation project categories. Examples may include regulatory enhancements, development of entity-wide buyout programs, and public outreach and education.

Table 6-1. Flooding or water management focused planning processes

Type of Plan	Purpose of Plan	Example Use of NBS
Regional flood plan	Assesses flood risk and presents opportunities for coordination and strategic action.	The ***Region 7 Upper Brazos 2023 Regional Flood Plan***[5] includes the Bovina Buyout Program which will lead to the creation of open space adjacent to an existing playa lake.
Hazard mitigation plan	Identifies risk from natural disasters and develops strategies for protecting people and property.	The ***Travis County Hazard Mitigation Action Plan***[6] includes prioritization and design of floodplain restoration projects to mitigate flood risk and reduce the urban heat island effect in eastern Travis County.
Watershed protection plan	Identifies potential sources of water body impairment and provides a framework to reduce pollution and improve overall water quality.	The ***La Nana Bayou Watershed Protection Plan***[7] includes best management practices designed to reduce for E. coli, other bacteria and pollutants while also enhancing inflow, infiltration, and overall flood resilience through features such as rain gardens, rain barrels/ cisterns, permeable pavements, bioswales, and detention ponds.
Integrated water management plan	Improves public health and environmental quality by linking water supply, wastewater and stormwater management.	***One Water in the Texas Hill Country***[8] includes a strategy to utilize green infrastructure to manage flooding and revitalize neighborhoods.
Water conservation plan	Provides recommendations for optimum levels of water use efficiency and conservation.	The ***North Texas Municipal Water District 2023 Water Conservation Plan***[9] recommends that member cities and customers use water efficient landscapes that limit irrigation and adverse runoff and use water on site, consistent with many neighborhood NBS practices.
Drainage/ stormwater master plan	Analyzes drainage and stormwater infrastructure to help cities manage water quality and reduce flood risk.	The ***Denton Stormwater Management Plan***[10] calls for environmentally sensitive areas, such as undeveloped floodplain habitats, to be protected for use as flood control features that provide erosion prevention and pollutant removal from stormwater, mitigate downstream impacts of development and redevelopment, and maintain the natural resources of the City of Denton.

Table 6-2. Leveraging community planning processes to incorporate NBS

Type of Plan	Purpose of Plan	Example Use of NBS
Public works plan	Plans for public infrastructure at the local level.	The ***City of Farmers Branch Sustainability Plan***[11] considers identifying opportunities to install green infrastructure and other low impact development features alongside capital improvement projects.
Capital improvement plan	Strategic plans that identify and prioritize capital projects for a city, school district, or other local government entity.	The ***San Antonio Capital Improvements Program*** allocates funds for parkland acquisition along creek corridors and creekbank stabilization, recognizing that integrating greenway restoration into infrastructure planning strengthens flood resilience.
Transportation plan	Policies, goals, and projects for moving people and goods.	***Austin's Complete Streets Policy***[12] recognizes that Complete Streets may include stormwater management, tree canopy, landscaping, accessible and integrated parks, and natural areas which can contribute to flood resilience.
Comprehensive land use plan	Plan created by a local government that outlines their vision for future development, including goals, policies, and strategies to guide how land should be used within their jurisdiction.	The ***Tyler Tomorrow Comprehensive Plan***[13] includes strategies to incentivize green infrastructure and tree preservation and to mandate stormwater systems that combine engineered solutions with natural systems to reduce runoff and enhance resilience.
Conservation plan	Plan that outlines how to manage natural resources on a property.	The ***Texas Hill Country Conservation Network's Land, Water, Sky and Natural Infrastructure*** highlights important places where natural infrastructure investments can help address flooding in more urban areas.
Open space/ parks plan	A strategic framework that outlines a community's vision for preserving, enhancing, and managing natural areas and public recreational spaces.	***Houston Multi-Use Park Facilities: A Guide to Applying Mitigation in Parks***[14] identifies the stormwater potential provided by park amenities (e.g., stormwater parks that include soccer fields). The ***El Paso Open Space Master Plan: A Green Infrastructure Plan for El Paso***[15] seeks to preserve a significant fringe "bosque" area along the Rio Grande to address the needs for open space as well as the need for areas that can act as safety valves for flood events.

Case Study

Harris County Precinct 3 parks and trails master plan

Location: Harris County

Opportunity: County owned land with potential to be used for flood resilience and recreation.

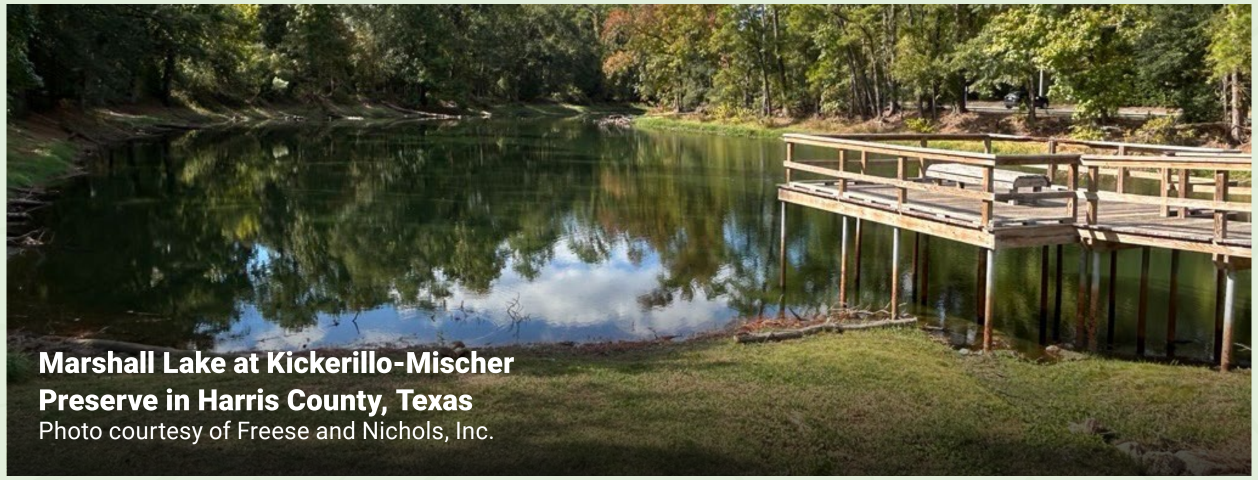
Lessons learned: Aligning parks and recreation planning with flood infrastructure can maximize park space and recreational opportunities, while improving flood resilience.

The Harris County Precinct 3 Parks and Trails Master Plan takes a strategic approach to integrating flood-prone areas, greenways, and stormwater infrastructure into its park system. With limited space given much of Precinct 3's land lies along creeks, bayous, and natural drainage corridors, the plan considers these areas as opportunities rather than limitations.

By developing a continuous network of linear parks and trails along major waterways, the precinct aims to create greenways that both enhance recreation and support flood mitigation. This dual-purpose use of land allows areas that are periodically inundated to serve as valuable open spaces for residents during dry periods, while maintaining their essential hydrological functions during heavy rain events.

A key feature of the plan is its coordination with the Harris County Flood Control District (HCFCD). The document emphasizes that new parks and trails will be planned in conjunction with flood mitigation projects, ensuring alignment between recreational goals and flood control objectives. This collaboration allows infrastructure such as detention basins, drainage channels, and wetlands to be designed with compatible public access, such as walking trails and naturalized landscaping. In doing so, the plan transforms what might otherwise be purely functional flood control sites into community amenities that educate and connect residents to the region's natural systems.

By turning flood-prone zones into accessible greenways and coordinating closely with HCFCD, Precinct 3 sets an example for how urban park planning can harmonize recreation, ecology, and flood management to create safer, more livable communities.



Marshall Lake at Kickerillo-Mischer Preserve in Harris County, Texas
Photo courtesy of Freese and Nichols, Inc.

6.3 Defining goals

A critical component of any planning process is establishing goals and objectives. These components help to measure the success of the plan or solution. Goals and objectives should be aspirational, achievable, and should not assume specific solutions. Additionally, goals should not be singularly focused on flood resilience—rather they should also consider the social and environmental systems that exist within the planning area.

Planning processes should consider the following when identifying goals:

Flood risk reduction is a central objective, with clear goals to mitigate the frequency, severity, and impacts of flooding. Projects should prioritize and deliver measurable outcomes, such as lowering flood levels, improving drainage, or managing stormwater more effectively, all while integrating these benefits within the larger watershed context.

Sustainability and resilience should be at the forefront, so that projects are designed to adapt to changing conditions such as climate variability, increasing flood risks, and evolving community priorities. These solutions must enhance the ability of both natural and built environments to withstand disturbances while promoting ecological health and longevity.

Economic viability across the project's life cycle is equally critical. Goals should account for all phases—planning, design, implementation, maintenance, and long-term adaptation to meet changing needs—while maintaining cost efficiency and maximizing long-term benefits. By leveraging natural processes, NBS often reduce ongoing maintenance costs compared to gray infrastructure, making them a more cost-effective investment over time.

NBS projects also offer unique opportunities to deliver **environmental and social benefits**. Goals should emphasize restoring ecosystems, enhancing biodiversity, and improving natural hydrological functions. Simultaneously, projects should prioritize social outcomes, such as creating inclusive and accessible green spaces, improving public health, and addressing equity by delivering benefits to vulnerable and underserved communities disproportionately impacted by flood risks.

Stakeholder support is a cornerstone of successful NBS implementation, and project goals should focus on fostering collaboration with diverse stakeholders—including local communities, landowners, government agencies, the private sector, and nonprofits. Transparency and inclusivity are essential, allowing stakeholder perspectives and needs to shape the project throughout its life cycle.

Plan development is the first step in making sure action happens on the ground. Planning uses high-level information and rarely includes the onsite data collection necessary to understand local conditions that influence project performance. But if NBS are not included in the plan, they are unlikely to be implemented on the ground. Plans need to be updated periodically to enable flood resilience approaches to evolve alongside changing conditions such as population growth, land-use changes, and climate impacts. Updates to plans allow communities to integrate new data, refine strategies based on lessons learned and new or altered funding sources, and address emerging challenges. It also provides an opportunity to better integrate NBS where appropriate.

Understand the characteristics of your region

Texas' diverse natural regions—ranging from the coastal marshes of the Gulf Coast to the arid landscapes of Big Bend—present different flood challenges, ecological systems, and community needs. These differences directly influence the NBS planning approach. The section below provides an overview of potential co-benefits that communities across Texas may choose to prioritize alongside flood resilience when implementing NBS. **Understanding the ecological and hydrological characteristics of your region helps achieve contextually-sensitive solutions**.

NBS designs that require a permanent pool of water, such as wet ponds and constructed wetlands, are not recommended in arid and semi-arid regions where water conservation should be prioritized. For examples and resources for alternative practices, refer to EPA ***Low-Impact Development and Green Infrastructure in the Semi-Arid West*** ↗.

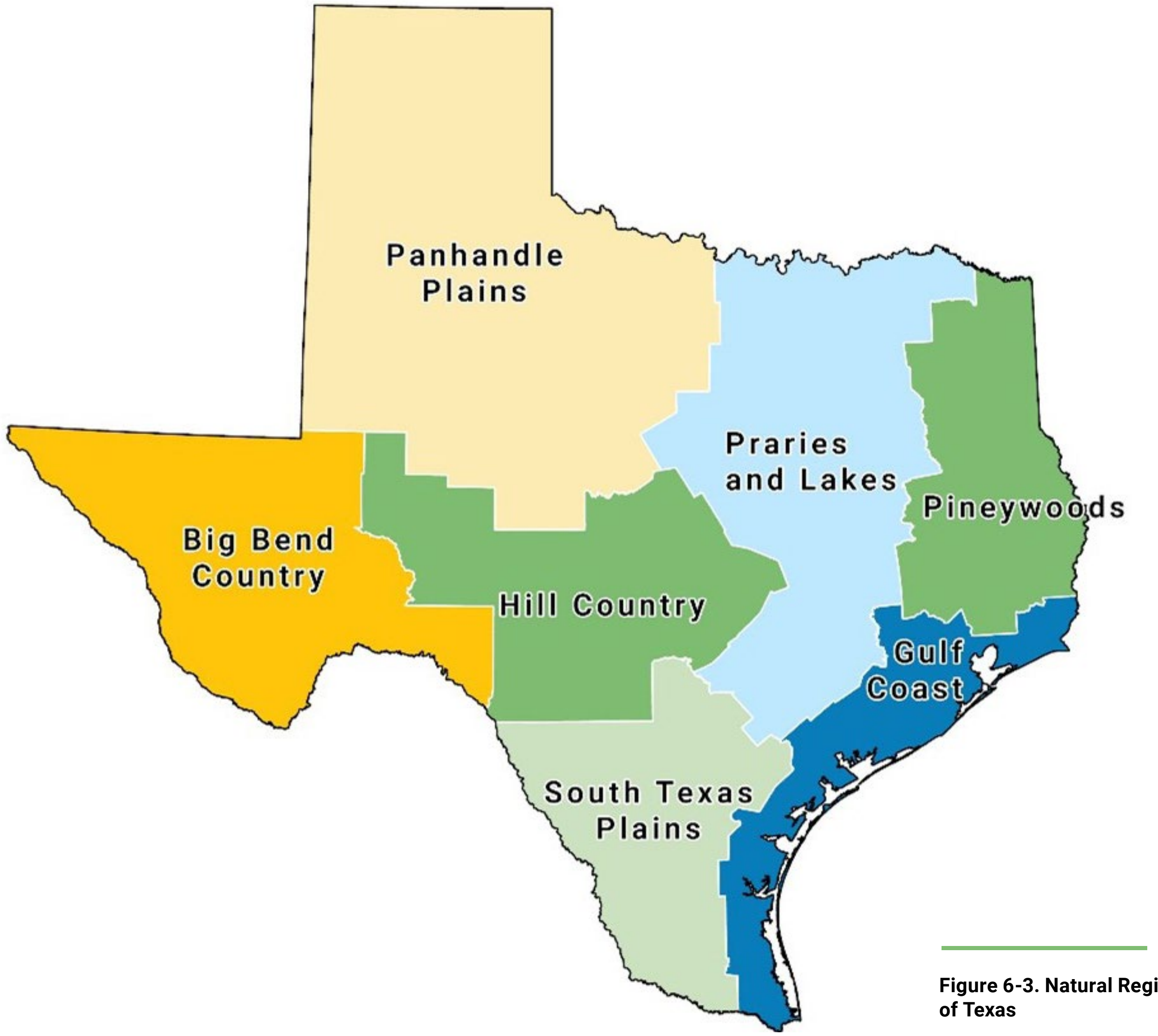


Figure 6-3. Natural Regions of Texas

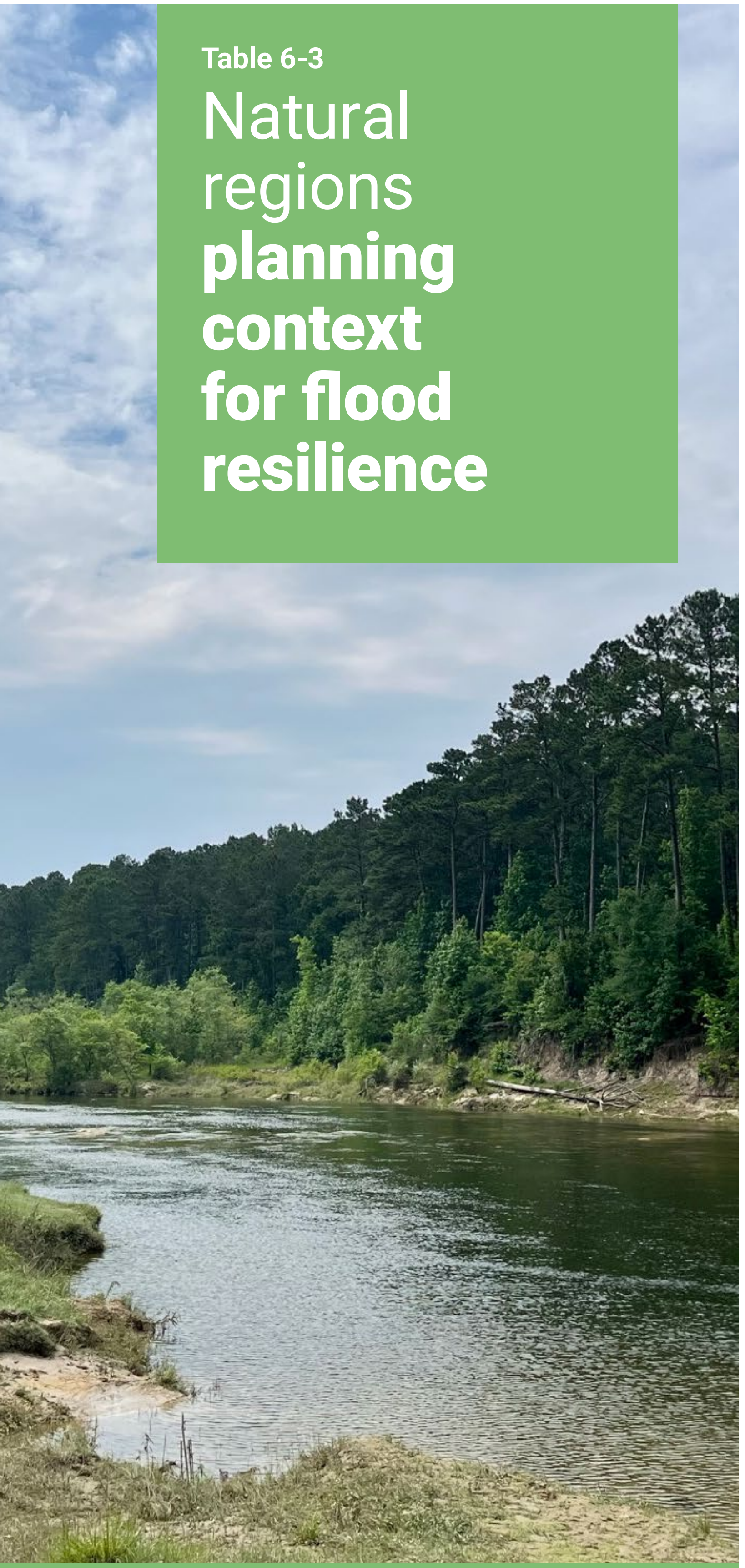
In Texas, ecoregions and natural regions both describe patterns in the state's landscape, but they differ in focus and classification. Ecoregions are scientifically defined areas based on ecological factors such as climate, soil, vegetation, and wildlife communities. Natural regions, on the other hand, are more broadly geographic and often used in education and general reference. **Figure 6-3** shows the natural regions of Texas.

Texas's seven natural regions differ significantly in rainfall patterns, topography, and hydrologic behavior. These landscape characteristics shape how flood risk manifests across the state and influence the role natural systems can play in reducing that risk. **Table 6-3** summarizes key regional flood risk drivers and highlights example nature-based planning emphases tailored to each natural region's context. While core flood resilience principles apply statewide, NBS strategies may vary and should reflect regional conditions, watershed dynamics, and population growth patterns.

For additional information on natural region-specific vegetation, wildlife, rare or endangered species, and habitat characteristics, refer to the ***Texas Parks and Wildlife Department (TPWD) Natural Regions*** ↗.

Table 6-3

Natural regions **planning context for flood resilience**



Sabine River near Burkeville, Texas
Photo courtesy of Freese and Nichols, Inc.

Natural Region	Rainfall (inches/year)	Flood Risk Drivers	Regional Flood Planning Notes	Example NBS Planning Emphasis
Panhandle Plains	15–28	• Flash floods due to flat terrain and deep canyons. • Heavy rainfall drives erosion and sedimentation. • Inadequate or aging municipal drainage infrastructure contributes to localized roadway flooding.	**Canadian Upper Red** identifies many communities with deficient or non-functional flood mitigation infrastructure.	• Prioritize protection of playa lakes and natural depressional storage. • Maintain native grasslands and drainage corridors to reduce erosion and support distributed stormwater retention.
Big Bend Country	8–20	• Steep terrain and desert basins generate rapid runoff. • Significant sedimentation from arroyos, particularly in El Paso near Franklin Mountain, contributes to flash floods and mudslides.	**Upper Rio Grande** highlights sedimentation issues impacting culverts, roads, agriculture, and irrigation infrastructure.	• Preserve natural arroyos (dry drainage channel) and canyon systems as primary conveyance features. • Integrate land conservation and erosion control strategies to maintain natural sediment and flow processes.
Hill Country	15–34	• Steep slopes, exposed rock, and thin topsoil contribute to flash floods, erosion, and sedimentation. • Numerous springs and canyons accelerate downstream flows. • Rapid population growth and development.	**Guadalupe and San Antonio** predict population increase of 40–60%, highlighting the need for improved flood control systems due to changing land use and development patterns.	• Protect recharge zones, spring systems, and riparian corridors. • Use land conservation and natural drainage preservation to moderate rapid runoff and downstream impacts in karst terrain.
South Texas Plains	20–32	• Flat terrain, sparse vegetation, and clayey soils limit infiltration. • Tropical storms from the Gulf result in intense wind, rain, and widespread flooding.	**Lower Rio Grande** identifies tropical storms as the primary cause of flooding.	• Preserve resacas (oxbow lakes), wetlands, and shallow depressions as natural storage features. • Maintain floodplain connectivity and integrate conservation-based drainage planning.
Prairies and Lakes	26–40	• Intense rainfall combined with extensive urban development overwhelms drainage systems, particularly in the Dallas-Fort Worth metroplex. • Low-lying areas and river corridors, including areas along the Trinity River and Dallas Levee System, face flood and erosion pressures.	**Trinity** notes severe flood risk: a 1% annual chance storm event could displace 1.32 million residents and cause over $636 billion in building damages.	• Incorporate distributed green infrastructure, floodplain restoration, and regional detention to offset low-infiltration soils and to help increase impervious cover.
Pineywoods	36–50	• High and prolonged annual rainfall. • Expansive river basins (Neches and Sabine) and low-lying wetlands and swamps drive riverine flooding with some of Texas' highest flood volumes and present significant erosion concerns during heavy rainfall events.	**Neches and Sabine** highlight the high flood volumes in the river basins as significant regional concerns.	• Protect and restore wetlands and broad floodplains to enhance natural storage and attenuation during high flows.
Gulf Coast	32–60	• Low-lying coastal terrain, tropical systems, and storm surge create high vulnerability to compound flooding. • Altering natural drainage patterns and gray infrastructure intensify flash flooding and sedimentation, with flood events posing risks to critical energy facilities.	**San Jacinto** anticipates significant population growth by 2050—requiring expanded flood control infrastructure and strategies to manage land-use changes and flooding risks.	• Preserve and restore coastal marshes, prairies, and river floodplains to improve surge buffering, natural storage, and resilience to compound flooding.

Sources: Texas Parks and Wildlife, 2024 State Flood Plan

Case Study

Defining goals by working across boundaries

Location: Austin

Opportunity: Stakeholders identified a degraded channel as having potential for ecological and social improvement.

Lessons learned: Collaborative, cross-departmental planning and early community engagement can transform stormwater infrastructure into multifunctional green spaces that deliver ecological, social, and mobility benefits.

The JJ Seabrook Greenbelt Stream Restoration, Rain Garden, and Urban Trail Project is an example of engaging and including local stakeholders and working across boundaries to establish goals and objectives for an NBS project. The project was guided by neighborhood stakeholder input and implemented by a multi-department team that included the Watershed Protection, Public Works, Parks and Recreation, and Transportation departments. The project goals and objectives included: (1) restoring a stable, functional, and ecologically sustainable creek system by creating a complex riparian landscape and reconnecting the creek by replacing a culvert with a pedestrian bridge; (2) reducing pollution and slowing runoff by providing rain gardens and vegetative swales within the contributing watershed and removing unnecessary impervious cover; (3) creating bicycle and pedestrian connectivity and calming vehicular traffic by reusing a vehicular roadway as an urban trail and replacing a culvert system with a pedestrian bridge; (4) providing a park trail system for the community to better utilize the greenbelt; and (5) creating an aesthetically pleasing place for the local community to enjoy in a natural setting. The project restored 900 feet of stream, added 1,200 feet of urban trail, and created 2,250 feet of park loop trail, while treating 1,800 pounds of water pollution per year. The result is reduced stormwater runoff velocity and volume and improved water quality and stream function while creating a unique sense of place for the local community.

Photos courtesy of City of Austin Watershed Protection Department

Stakeholder engagement

Stakeholder engagement plays a functional and strategic role across all stages of planning and through design and implementation. Its purpose extends beyond consensus-building; it is an essential mechanism for integrating diverse expertise, identifying constraints, and aligning projects with both regulatory frameworks and community priorities.

Early engagement guides the development of flood management strategies with an understanding of local conditions, infrastructure limitations, environmental sensitivities, and socio-political dynamics. For drainage and flood mitigation planning specifically, **stakeholders help define key objectives** such as prioritizing vulnerable populations, integrating open space preservation, and designing with natural features. Stakeholders can also contribute to evaluating the trade-offs of structural and nonstructural alternatives. Stakeholder-informed evaluation criteria improve transparency and help decision-makers justify project selection.

During project development and implementation, stakeholder engagement becomes more targeted and procedural. Community input helps ground design decisions in each site's context where competing land uses, access constraints, and maintenance responsibilities must be balanced. Regulatory stakeholders are engaged to achieve compliance and streamline permitting, while funding partners assess whether proposals align with grant requirements or funding cycles. Technical teams coordinate across disciplines to integrate hydrologic modeling, ecological restoration, and engineering feasibility into the design process.

Moreover, the effectiveness of stakeholder engagement depends not only on who is involved, but when and how. Engaging stakeholders too late can result in design delays, overlooked constraints, or missed funding windows. A proactive engagement strategy that is integrated from the beginning and sustained through adaptive management allows NBS projects to evolve in response to feedback, performance data, and changing conditions.

In Texas, where hydrologic regimes, regulatory structures, and development pressures vary widely across the state, stakeholder engagement is essential to advancing context-sensitive solutions. Planning and project teams that engage stakeholders deliberately and consistently are better equipped to deliver NBS that are implementable, cost-effective, and aligned with long-term community resilience goals.

Engaging the community in the planning and design process fosters local support and helps tailor the NBS to meet residents' needs. Educational signage can raise awareness about stormwater management, and the ecological benefits of green infrastructure and public amenities like playgrounds, recreational paths, parkland, and shaded street corridors encourage community use while integrating flood management features and making the space vibrant and multifunctional. It is also important for walkways, bridges, and other spaces to be universally accessible to all community members, including those with mobility challenges. Transparent communication and engagement create opportunities for stakeholder input, allowing the NBS design to align with community expectations and urban design goals while fostering a sense of ownership and belonging.

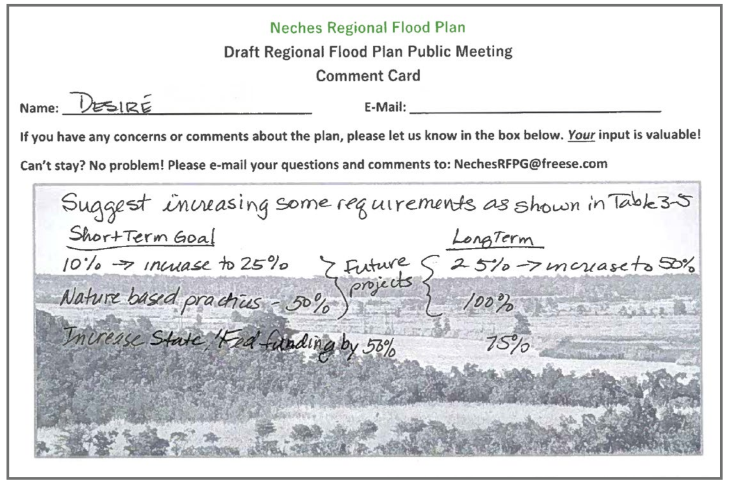
Beyond informing design decisions, meaningful engagement can help cultivate long-term ownership of NBS projects. When stakeholders are involved throughout planning and implementation, they are more likely to support community-led maintenance, shared responsibility, and ongoing stewardship activities. This sense of ownership strengthens accountability, reinforces trust, and increases the likelihood that NBS projects will perform as intended over time.

An often-overlooked component of stakeholder engagement is the inclusion of those responsible for long-term maintenance and adaptive management of NBS. This includes non-profits, neighborhood associations, parks and public works crews, and other local partners who sustain project performance over time. These stakeholders provide practical insight into maintenance capabilities, constraints, and resources that influence design decisions, plant selection, access, and life-cycle costs. Engaging them early helps guide planning and implementation, while also supporting ongoing monitoring and education.

Developing a stakeholder engagement strategy

Developing a stakeholder engagement strategy involves defining a clear, intentional approach for how stakeholders will be meaningfully involved throughout each stage of an NBS project. Rather than listing discrete actions, the strategy establishes a framework for organizing engagement so that it is purposeful, sequenced, and aligned with project milestones - explaining why engagement is needed, who should be involved, when it should occur, and how it integrates into the overall project life cycle.

Table 6-4 illustrates a proactive, step-by-step approach to developing a stakeholder engagement strategy. Each step outlines the strategic focus, example methods, and intended outcomes that collectively support inclusive, transparent, and sustained engagement throughout the project life cycle.



Neches Regional Flood Plan
Draft Regional Flood Plan Public Meeting
Comment Card

Name: Desiré
E-Mail:

If you have any concerns or comments about the plan, please let us know in the box below. *Your* input is valuable!

Can't stay? No problem! Please e-mail your questions and comments to: NechesRFPG@freese.com

Suggest increasing some requirements as shown in Table 3-5

Short Term Goal		Long Term
10% → increase to 25%	Future projects	25% → increase to 50%
Nature based practices - 50%		100%
Increase State/Fed funding by 50%		75%

Figure 6-4. Stakeholder engagement tool. A comment card used to collected stakeholder input during the development of Neches Regional Flood Plan.

Figure 6-5. Downtown Plan Meeting in Brownwood, Texas
Source: Freese and Nichols, Inc.

Table 6-4. Approach to developing a stakeholder engagement strategy

Step	Strategic Focus	Example Engagement Methods	Intended Outcomes
1. Define purpose and objectives	Clarify why stakeholder engagement is critical and how it supports overall project goals, such as building trust, incorporating local knowledge, advancing equity, and fostering long-term stewardship.	Goal-setting workshops, community visioning or listening sessions, coordination meetings with agencies and partners.	Shared understanding of the purpose of engagement and alignment between community, agency, and project objectives.
2. Identify stakeholders and define roles	Identify and analyze individuals, organizations, and communities that influence or are affected by the project. Determine their interests, influence, and roles in decision-making to tailor engagement effectively.	Stakeholder mapping exercises, interviews, stakeholder roundtables, advisory or working group formation.	Comprehensive understanding of key stakeholders (e.g. who, when, how), clear definition of engagement responsibilities, improved coordination and inclusivity.
3. Align engagement with project phases and decision points	Integrate engagement activities into key project milestones so that feedback is received when it can meaningfully influence decisions.	Engagement timelines linked to planning phases, milestone-specific meetings, interagency coordination sessions.	Engagement that is timely, coordinated, and aligned with decision-making processes.
4. Select methods and tools for engagement	Choose formats and tools that fit the purpose and audience by balancing accessibility, inclusivity, and technical needs.	Listening sessions, surveys, community design workshops, virtual meetings, interactive dashboards.	Broad, representative participation and equitable access to engagement opportunities.
5. Facilitate transparent and responsive communication	Establish clear processes for documenting and sharing how stakeholder input informs project decisions. Communicate trade-offs and constraints openly to maintain trust and credibility.	"You Said, We Did" summaries, comment-response matrices, decision memos, public FAQs.	Increased transparency, trust, and accountability throughout the project life cycle.

Roles and responsibilities of stakeholders

Across each phase of NBS projects—from identifying opportunities to adaptive management—stakeholder roles evolve in ways that reflect their knowledge, responsibilities, and connection to the community. The following overview highlights how stakeholder involvement shifts to help ensure flood mitigation strategies remain grounded in local needs, are environmentally responsive, and are feasible over time.

It is important to understand that NBS practices vary not only by project stage, but also by spatial scale. Different types of NBS operate effectively at watershed, neighborhood, and coastal scales—and understanding these distinctions early on helps inform stakeholder roles, planning decisions, and project priorities.

Aligning specific NBS practices with their expected benefits across these scales allows stakeholders to more clearly see where and how their input can be most effective—whether it is helping to guide local site selection, influencing regional planning priorities, or supporting long-term funding and maintenance strategies. This framing also helps ensure that flood mitigation efforts are both technically sound and socially meaningful to the communities they serve.

Comal River in New Braunfels, Texas
Photo courtesy of Freese and Nichols, Inc.

Table 6-5. Stakeholder roles and responsibilities

Example Stakeholder Group	Example Stakeholder	Initiating	Planning	Implementing (Feasibility)	Implementing (Design and Build)	Implementing (Maintain and Adaptively Manage)
Local community	• Residents • Community leaders • Small business owners • Advocacy groups • Media communications and channels	Share lived experiences, highlight environmental justice concerns, and express cultural values related to flood risk, green space access, and neighborhood priorities.	Help prioritize values like equity, aesthetics, or long-term resilience. Voice preferences between alternatives and flag potential impacts.	Offer detailed feedback on specific sites, share concerns about access or property impacts, and assist in outreach to underrepresented populations.	Monitor progress, provide input during final design reviews, and confirm designs still align with their priorities. Help promote transparency.	Provide feedback on how the project performs and impacts daily life. Assist with stewardship or community-based monitoring.
Government (local/state/federal)	• Elected officials • City engineer • County engineer • Public works department • Local planning and zoning departments	Ensure early alignment with local development plans, zoning regulations, and floodplain policies. Identify inter-agency coordination needs.	Evaluate alternatives for policy and regulatory compliance; support permitting pathways; assess land use compatibility. Identify maintenance constraints.	Provide permits, review compliance, and guide risk assessments. Align site selection/choices with public land use or infrastructure plans. Begin detailed budgeting for site acquisition, capital costs, and maintenance needs.	Approve construction documents, manage contracts, and maintain adherence to safety, environmental, and permitting requirements.	Oversee safety, maintenance standards, and regulatory compliance. Review and approve management changes as needed.
Environmental	• Regulatory agencies • Nongovernmental organizations • Academic institutions • Research centers	Establish ecological context and identify areas with potential for habitat restoration or co-benefits.	Assess ecological trade-offs and co-benefits; prioritize biodiversity and watershed health.	Conduct site-based ecological evaluations and recommend habitat enhancement or mitigation measures.	Monitor environmental compliance during construction; offer on-site recommendations to minimize ecological disturbances.	Track ecological health and help identify necessary management adjustments to preserve co-benefits.
Technical experts	• Engineers • Hydrologists • Landscape architects • Urban planners • Environmental scientists • Academic institutions	Begin assessing feasibility and data availability to support later modeling and analysis.	Lead alternatives analysis using H&H models, cost-benefit frameworks, and life cycle performance assessments.	Lead multidisciplinary site studies and refine concepts to reflect on-the-ground constraints. Provide analysis and data to support decision-making.	Incorporate lessons learned though adaptive management and finalize engineering and landscape architecture plans, manage contractors, and provide QA/QC throughout implementation.	Implement monitoring protocols, analyze performance data, and recommend adaptive changes.
Funding partners	• Government funding agencies • Nonprofit organizations • Private investors • Corporate sponsors	Evaluate general budget constraints, future funding availability, and program alignment for resilience-focused investments.	Compare funding scenarios and develop intended use plans to encourage multifunctionality of NBS project(s).	Evaluate funding cycles and eligibility, assess long-term affordability, and evaluate return on investment based on proposed alternatives.	Release construction funds, track expenditures, and verify that contingency plans are in place for budget overruns.	Allocate funding for maintenance and performance upgrades. Evaluate the cost-effectiveness of adaptive actions over time.

Developing a stakeholder engagement plan

A stakeholder engagement plan defines how stakeholders will be identified, engaged, involved, and communicated with throughout the planning and implementation phases of a project. It provides a proactive, structured approach that keeps engagement inclusive, transparent, and aligned with project goals, timelines, and regulatory expectations. The stakeholder engagement plan outlines when, how, and with whom engagement will take place—from early outreach during project scoping, through planning and design, to implementation and long-term responsible stewardship. A well-designed engagement plan creates a process that is responsive, equitable, and integrated—and allows stakeholder input to meaningfully shape decisions and outcomes.

Key components of a proactive stakeholder engagement plan typically include:

- **early engagement** to incorporate local knowledge, identify constraints, and shape project objectives before key decisions are made;
- **structured communication across project phases** to align engagement with project milestones and provide multiple opportunities and formats (e.g., in-person, virtual, etc.) for input;
- **inclusive and accessible outreach** to promote meaningful participation by underrepresented and vulnerable communities;
- **transparency and responsiveness** to build trust by documenting how feedback is used and clearly communicating tradeoffs;
- **integration with planning and design** so that stakeholder insights help to inform criteria development, alternatives analysis, and final recommendations; and
- **sustained involvement through implementation and adaptive management** to support long-term responsible stewardship and performance monitoring.

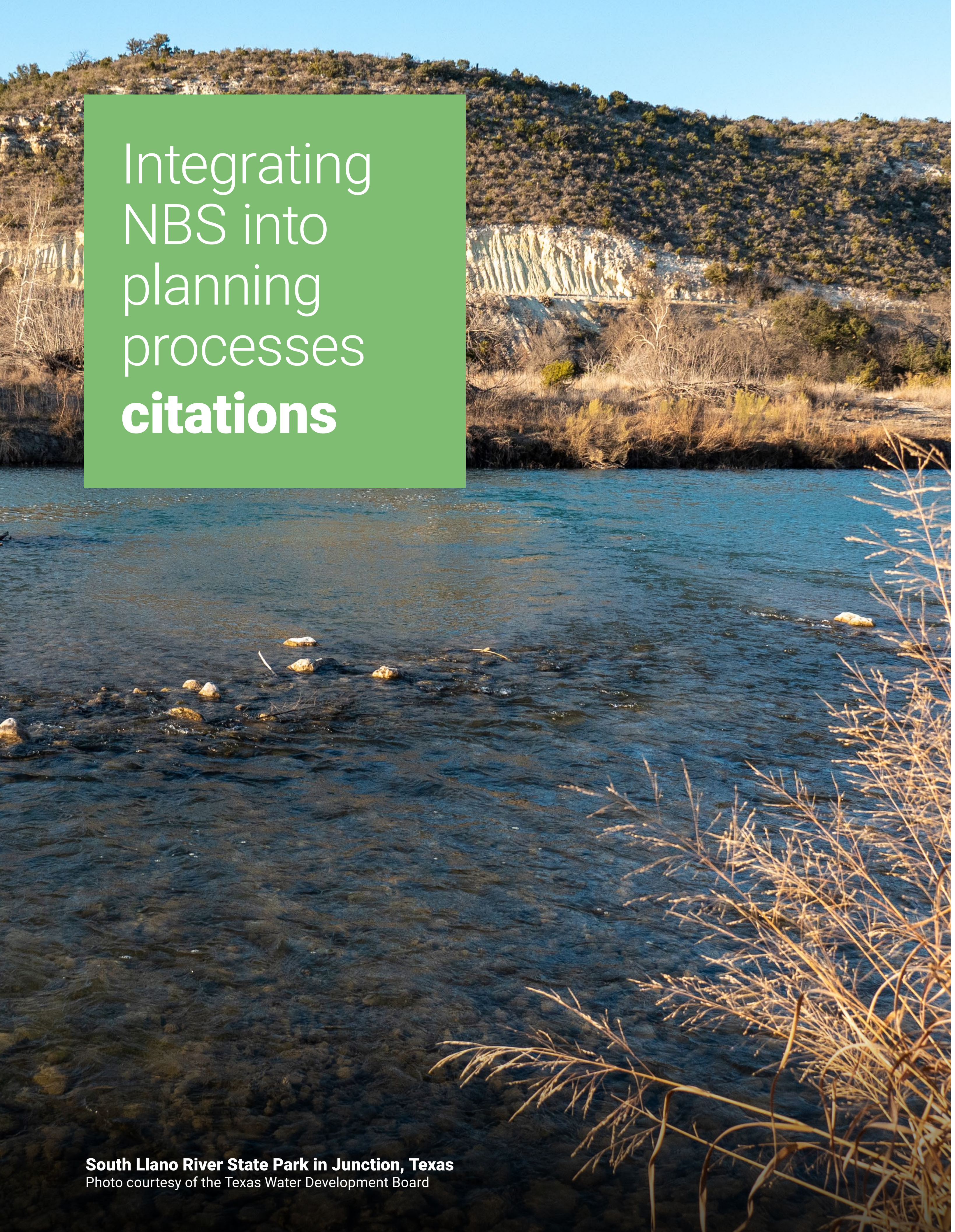
When done effectively, a stakeholder engagement plan serves as both a roadmap and feedback loop, so that NBS are context-sensitive, implementable, equitable, and supported by the communities they are designed to serve.

Tools and resources

- City of Fort Worth
  City of Fort Worth Stormwater Management Program Master Plan ↗
- North Central Texas Council of Governments
  Stakeholder Engagement Plan for Integrating Transportation and Stormwater Infrastructure ↗
- FEMA
  Guidance for Stakeholder Engagement: Project Planning and Discovery Process ↗
- Port of Houston Community and Stakeholder Engagement Policy
  Community and Stakeholder Engagement Framework ↗
- City of Corpus Christi Parks and Recreation
  City of Corpus Christi Parks and Recreation Public Engagement Plan ↗

Stakeholder engagement meeting in Lubbock, Texas
Photo courtesy of Freese and Nichols, Inc.

Integrating NBS into planning processes **citations**



South Llano River State Park in Junction, Texas
Photo courtesy of the Texas Water Development Board

[1] U.S. Army Corps of Engineers, ,2022, International Guidelines on Natural and Nature-Based Features for Flood Risk Management, https://ewn.erdc.dren.mil/international-guidelines-on-natural-and-nature-based-features-for-flood-risk-management/, accessed June 2026.

[2] Davenport, F.V., Burke, M., Diffenbaugh, N.S., 2021, Contribution of historical precipitation change to U.S. flood damages: *Proceedings of the National Academy of Sciences*, v. 118, no. 4, e2017524118, www.pnas.org/content/118/4/e2017524118, accessed June 2026.

[3] Brody, S.D., Highfield, W.E., Blessing, R., Makino, T., Shepard, C.C., 2017, Evaluating the effects of open space configurations in reducing flood damage along the Gulf of Mexico coast: *Landscape and Urban Planning*, v. 167, p. 225–231.

[4] Kim, H.W., Park, Y., 2016, Urban green infrastructure and local flooding—The impact of landscape patterns on peak runoff in four Texas MSAs: *Applied Geography*, v. 77, p. 72–81.

[5] Upper Brazos Regional Flood Planning Group, 2023, *2023 Upper Brazos Regional Flood Plan—Region 7 (Upper Brazos)* (amended November 20, 2023): Lubbock, Texas, South Plains Association of Governments, November 2023.

[6] Travis County, Texas, *Travis County hazard mitigation action plan www.traviscountytx.gov/images/emergency_services/docs/Travis_County_HMAP.pdf*, accessed June 2026.

[7] Trinity River Authority of Texas, L*a Nana Bayou watershed protection plan* https://twri.tamu.edu/wp-content/uploads/2024/04/tr-547.pdf, accessed June 2026.

[8] Hill Country Alliance, 2021, *One water report*, hillcountryalliance.org/wp-content/uploads/2021/09/HCA_NWF_One_Water_Report_FINAL_SinglePage.pdf accessed June 2026.

[9] North Texas Municipal Water District, 2024, *2024 water conservation plan*, www.ntmwd.com/DocumentCenter/View/2163/2024-NTMWD-Water-Conservation-Plan-PDF, accessed June 2026.

[10] City of Denton, Texas, *Stormwater management plan*, www.cityofdenton.com/DocumentCenter/View/598/Stormwater-Management-Plan-PDF, accessed June 2026.

[11] City of Farmers Branch, Texas, *Sustainability plan*, content.civicplus.com/api/assets/180f5cb1-8580-4206-89ac-3ea3ff393c49, accessed June 2026.

[12] City of Austin, Texas, *Complete streets policy (adopted)*, Microsoft Word - Complete Streets Policy Ex A 6-10-14, accessed June 2026. (3).docx.

[13] City of Tyler, Texas, *Land Use & Development*, https://www.cityoftyler.org/home/showpublisheddocument/16748/639106311772800000, accessed June 2026.

[14] City of Houston, Houston Public Works, Stormwater operations, https://www.houstonpublicworks.org/stormwater-operationswww.houstonpublicworks.org/stormwater-operations, accessed June 2026.

[15] City of El Paso, Texas, *Towards a Bright Future A Green Infrastructure Plan for El Paso, Texas*, Microsoft Word - 2_01-23-07_InsideCover.DOC, accessed June 2026.

7

Understanding flood risk and identifying NBS opportunities

This chapter shifts the focus to project-specific planning and implementation. It provides guidance on how to translate strategic goals and priority areas into actionable NBS projects—moving from conceptual planning toward design and implementation.

Key takeaways

- Understanding flood risk and community vulnerability is necessary when identifying NBS opportunities.
- An opportunity assessment helps determine where and how NBS can be effectively used to address flood risk and achieve broader community goals.
- NBS for flood resilience spans a range of solutions from hybrid to natural, structural and nonstructural.

Flooding in Hereford, Texas
Photo courtesy of National Weather Service Amarillo

How the guiding principles apply to this chapter

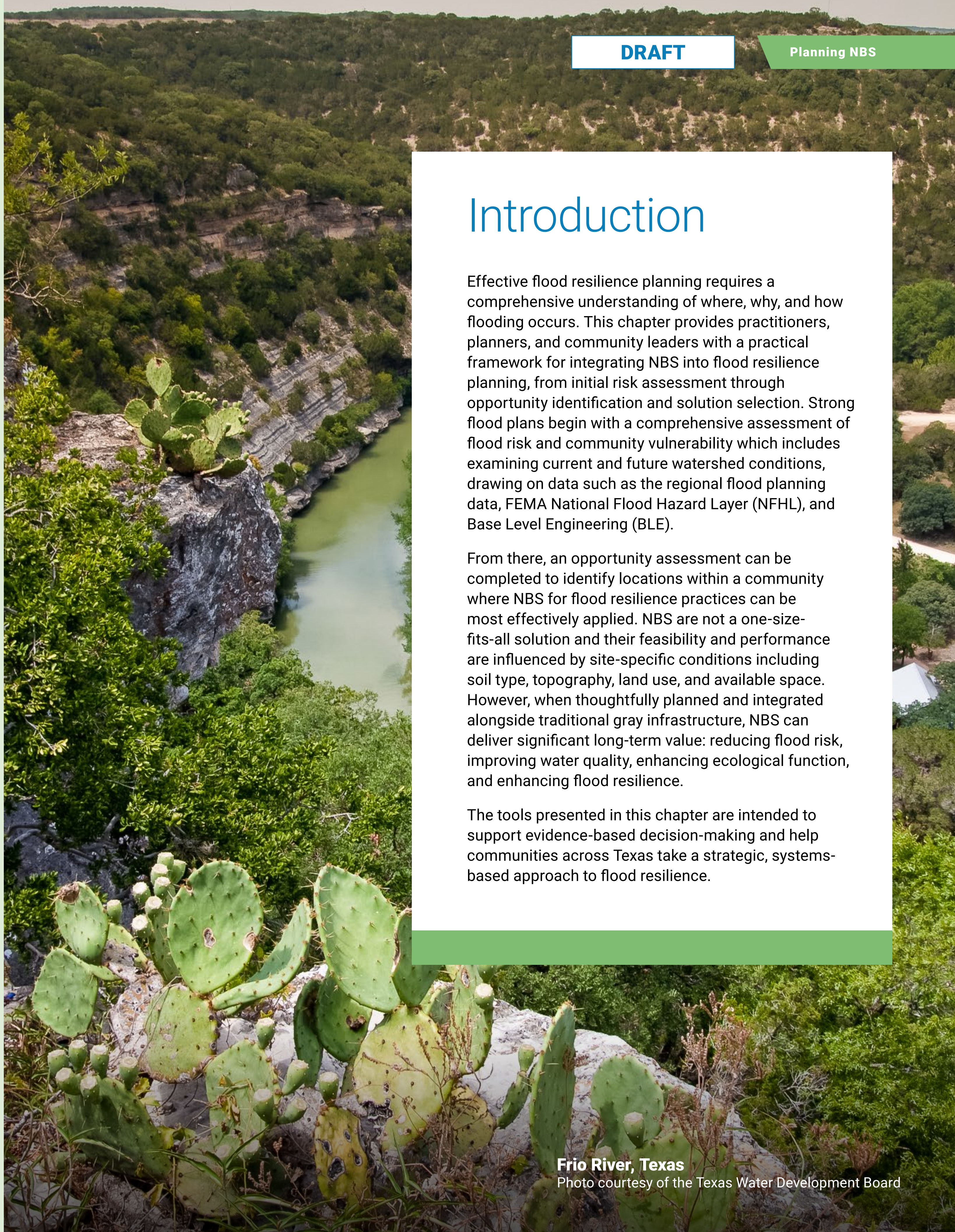
Engage and include	Involve diverse stakeholders to shape project-level NBS opportunities. Focus on solutions that reduce flood risk, enhance public spaces, and advance equity for vulnerable communities.
Apply systems thinking	Evaluate NBS opportunities within the broader watershed context to support site-scale projects with larger system goals and functions.
Work across boundaries	Coordinate across departments and disciplines—such as engineering, planning, and parks—to design projects that deliver multiple community and environmental benefits.
Learn and adapt continuously	Apply lessons from past projects and adjust designs as conditions and data evolve to improve performance and resilience over time.

Introduction

Effective flood resilience planning requires a comprehensive understanding of where, why, and how flooding occurs. This chapter provides practitioners, planners, and community leaders with a practical framework for integrating NBS into flood resilience planning, from initial risk assessment through opportunity identification and solution selection. Strong flood plans begin with a comprehensive assessment of flood risk and community vulnerability which includes examining current and future watershed conditions, drawing on data such as the regional flood planning data, FEMA National Flood Hazard Layer (NFHL), and Base Level Engineering (BLE).

From there, an opportunity assessment can be completed to identify locations within a community where NBS for flood resilience practices can be most effectively applied. NBS are not a one-size-fits-all solution and their feasibility and performance are influenced by site-specific conditions including soil type, topography, land use, and available space. However, when thoughtfully planned and integrated alongside traditional gray infrastructure, NBS can deliver significant long-term value: reducing flood risk, improving water quality, enhancing ecological function, and enhancing flood resilience.

The tools presented in this chapter are intended to support evidence-based decision-making and help communities across Texas take a strategic, systems-based approach to flood resilience.



Frio River, Texas
Photo courtesy of the Texas Water Development Board

7.1 Understanding flood risk

Understanding where, what kind, and to how much a community is at risk of flooding is key to planning for flood resilience. Flood risk is a function of three factors: the specific flood hazard (where is it going to flood), the potential exposure of people and property to that hazard (who and what might flood), and the vulnerability of the people and property exposed to that flood hazard (the degree to which a community and/or critical facilities are affected and how quickly and easily they may recover after a flood event).[1] Figure 7.1 depicts hazard, exposure, and vulnerability as components of flood risk.

Identifying flood hazard areas

Identifying flood hazard areas requires hydrologic and hydraulic analyses. Hydrology is the study of how water is captured, conveyed, or stored across a watershed. The primary goal of a hydrologic analysis is to understand the rainfall intensity and frequency, and peak discharge in the watershed. NOAA publishes ***Point Precipitation Frequency Estimates*** ↗ that report rainfall intensity for communities across Texas. Point precipitation estimates relate the probability of rainfall (in inches) over various durations (e.g. 60 minutes, 24 hours, or three days).

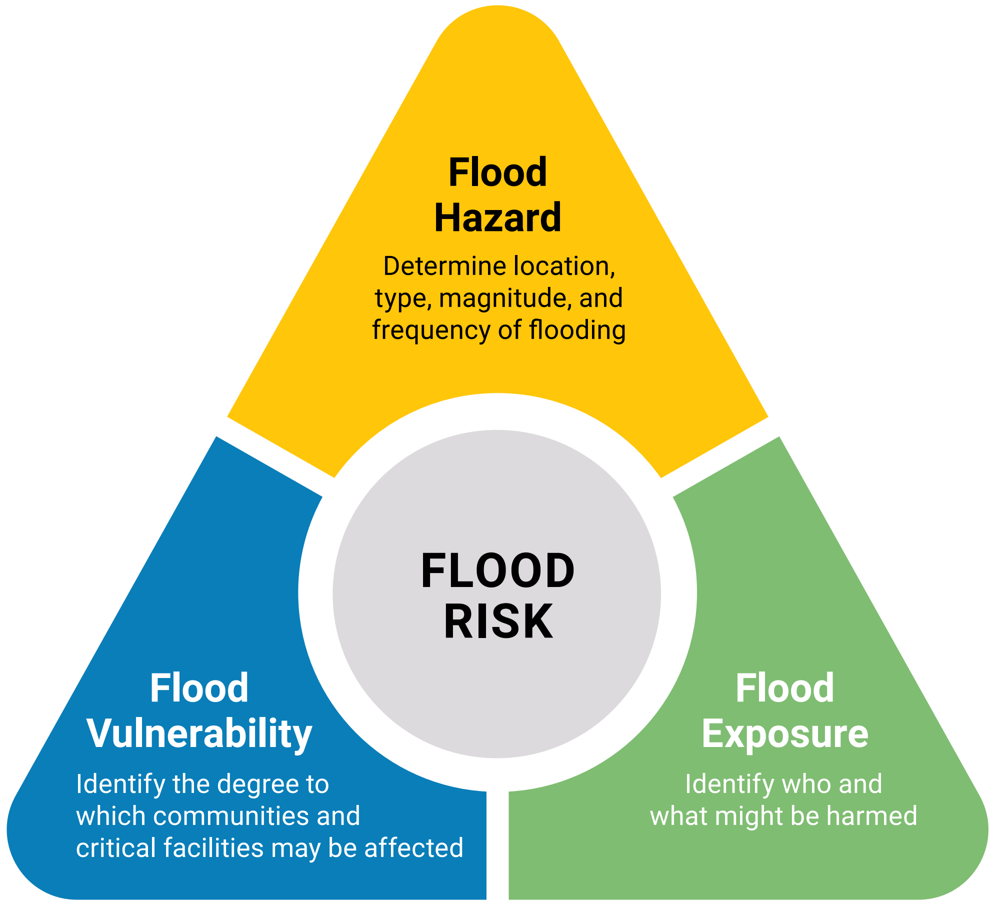


Figure 7-1. The components of flood risk: hazard, exposure, and vulnerability
Adapted from 2024 State Flood Plan

Hydraulics is the study of how water moves and informs flow rates, water depth, and pressure. At the watershed scale, hydraulic analyses consider land cover data, channel cross section, obstructions to flow such as bridges or culverts, and drainage infrastructure. In developed areas, hydraulic analyses can also consider the capacity of drainage systems to convey runoff.

Hydrologic and hydraulic modeling produce water surface elevations for selected storm events. The 1 percent annual chance event (commonly referred to at the 100-year event) represents the event that has a 1 percent probability of occurring in any given year. This and the 0.2 percent annual chance event (the event that has a 0.2 percent probability of occurring in any given year) are modeled and mapped to identify flood prone areas. The 1 percent annual chance floodplain, also referred to as the Special Flood Hazard Area (SFHA), is the regulatory floodplain shown on FEMA's flood insurance rate maps (FIRMs). It defines the minimum federal floodplain management standards. ***FEMA's National Flood Hazard Layer (NFHL)*** ↗ provides the regulatory data subject to FEMA's minimum standards. Regional flood planning flood hazard areas, accessible on the ***Interactive State Flood Plan Viewer*** ↗ and Base Level Engineering (BLE), accessible on FEMA's ***Estimated Base Flood Elevation (BFE) Viewer*** ↗ and are also valuable sources of flood hazard mapping that can be used in flood resilience planning.

When modeling coastal flood inundation, it is important to distinguish between elevated water levels and wave-driven processes, as both contribute to flood hazards. Coastal inundation is primarily driven by stillwater elevations (SWELs), which represent the baseline water level and include storm surge and astronomical tides. Storm surge, the abnormal rise in water level caused by storm-driven winds and pressure, is the dominant contributor to SWEL and controls the regional extent of flooding.

In addition to elevated stillwater levels, wave processes can significantly increase localized flood hazards. As waves propagate toward and interact with the shoreline, they contribute to wave setup (an increase in the mean water level due to breaking waves) and wave runup, which is the uprush of water above the stillwater elevation on beaches, dunes, shorelines, or structures. Wave runup can result in overtopping, erosion, and damage to coastal infrastructure, particularly in exposed or steep coastal settings. Nature-based solutions (NBS) can help mitigate these wave-driven processes by reducing wave energy and limiting runup and erosion.

Definition

What is Base Level Engineering?

Base Level Engineering (BLE) is a standardized flood hazard modeling approach designed to give communities across Texas a better understanding of their flood risk, including areas where traditional flood studies are outdated or don't exist at all. BLE fills gaps in flood hazard information by leveraging modern elevation data and updated rainfall statistics, establishing a baseline for flood risk assessment across large geographic areas such as entire watersheds and river systems.

The data products generated through BLE typically include floodplain boundaries, estimated water surface elevations, and flood depths for significant events like the 1 percent annual chance (100-year) flood. Importantly, these outputs are intended to support planning decisions rather than replace detailed, site-specific engineering studies. BLE data and models are accessible on FEMA's ***Estimated Base Flood Elevation (BFE) Viewer*** ↗ and BLE improves the accessibility of flood modeling tools and data for local and state officials. In practice, BLE serves as a reliable starting point for identifying areas that may need more in-depth analysis, making it especially valuable in regions with inadequate or aging flood maps. **For more information on BLE visit: www.twdb.texas.gov/flood/science/ble.asp**

FEMA's Wave Height Analysis for Flood Insurance Studies (WHAFIS) modeling software is typically used to evaluate coastal wave hazards along transects extending inland from the shoreline. The WHAFIS model uses stillwater elevations (including storm surge and tides) as the baseline water level and accounts for wave setup, wave propagation, starting wave conditions, ground elevations, shoreline profile, and shoreline obstructions. Because wave transformation and runup are sensitive to physical conditions, accurate characterization of bathymetry, coastal topography, vegetation, and built structures is critical for reliable modeling results.

Rainfall patterns and land-use are changing across Texas. Older hydrologic and hydraulic analyses may under-identify areas that will face flood risk in the future. Communities can consider future flood risk informed by updated rainfall frequency estimates, future land use scenarios, and sea-level rise projections. As a part of the statewide regional flood planning program, existing and future flood hazard areas were developed that could be used for planning purposes. **For more information on regional flood planning visit: www.twdb.texas.gov/flood/planning/regions**.

Identifying flood exposure and vulnerability

Flood exposure refers to the people, property, and infrastructure that may be directly affected by a flood hazard. Identifying exposure begins with overlaying flood hazard data with information about existing structures, critical facilities, utilities, and transportation networks. This analysis reveals to what degree people or property may be affected by storms of varying frequency and severity. Historical flood claims and local knowledge can further refine this picture by capturing areas of recurring inundation that may not be fully reflected in modeled results. TWDB compiled publicly available datasets useful for identifying flood exposure on the ***Flood Planning Data Hub*** ↗.

Vulnerability assessments go a step further by assessing the degree to which exposed communities and facilities would be harmed by a flood event and how quickly and easily they could recover. Vulnerability is shaped by a range of physical, social, and economic factors that make recovery more difficult, such as limited financial resources, language barriers, lack of access to transportation, the availability of emergency resources.

Tools such as the ***Texas Flood Social Vulnerability Index (SVI)*** ↗ can help identify communities that face compounding challenges that make flood recovery more difficult. Understanding vulnerability alongside hazard and exposure helps flood resilience planning be not only technically grounded but also equitable, directing resources across planning area.

Identifying flood risk hot spots

Once the people and property are at a risk of flooding are identified, further analysis can be done to determine "hot spots". Hot spots are spatially concentrated areas where the combination of hazard, exposure, and vulnerability is greatest and where intervention is likely to have the most impact.

The hot spot analysis can, and should, be tailored to the intended planning process. For example, if the goal of the planning process is to reduce roadway flooding, hot spots should focus roadways exposed to flooding. Layering exposure data with social vulnerability indicators further sharpen the analysis by highlighting areas where flood impacts are compounded by limited capacity to prepare, respond, and recover. The result is a spatially prioritized picture of where risk is highest and where targeted flood mitigation, NBS strategies, infrastructure improvements, or community resilience investments can deliver the greatest benefit.

As part of the Texas General Land Office's ***River Basin Flood Study*** ↗, a flood risk hot spot analysis was conducted to aggregate flood hazard, exposure, and vulnerability data, Figure 7-2 conceptually depicts the process the analysis followed. A sample of the results of this process are shown in Figure 7-2 where darker shades represent higher confidence of flood risk. The flood risk hot spot analysis informed where the study prioritized efforts to develop flood mitigation projects.

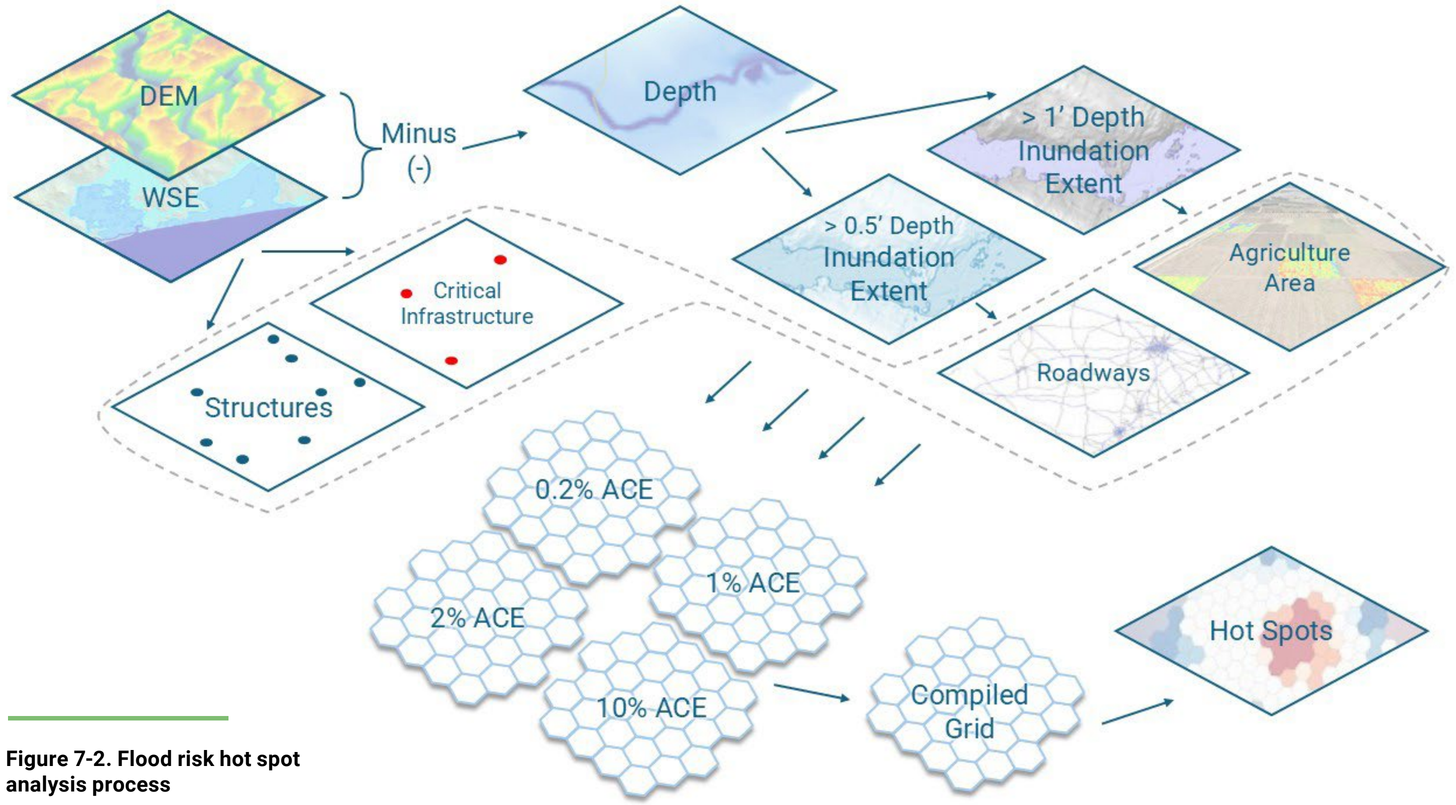


Figure 7-2. Flood risk hot spot analysis process

Source: GLO River Basin Flood Study

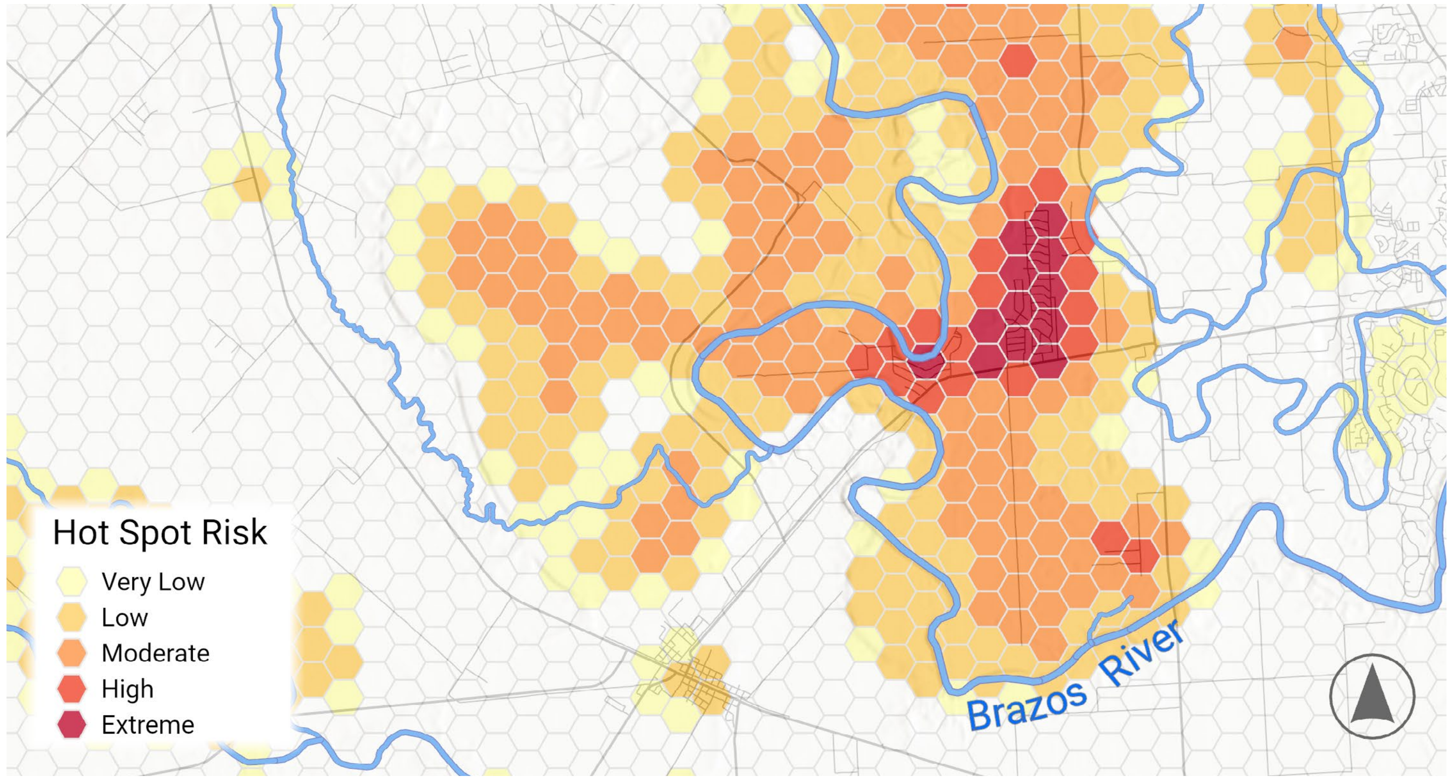


Figure 7-3. Flood risk hot spot analysis results sample

Adapted from GLO River Basin Flood Study

7.2 Performing opportunity assessment

An opportunity assessment is a phase of project planning that focuses on identifying and investigating possible opportunities or ideal locations for implementing NBS. This is beneficial if you have not identified a project site or are seeking regional solutions to reduce flood risk, which is common when undertaking a master drainage plan. The opportunity assessment begins once a community's current and future flood risks are understood, and high-risk areas, or hot spots, are identified.

An opportunity assessment evaluates available data and seeks to identify locations within a community or watershed to implement projects that have the greatest potential to achieve multiple benefits. It begins with collecting available data:

- Existing Infrastructure (e.g., structures, critical facilities, stormwater or drainage infrastructure, utilities)
- Natural assets (e.g., riparian corridors, wetlands, prairies, dunes, tree canopy, undeveloped floodplains, and other ecological features providing existing protective benefits)
- Site conditions (e.g., terrain, groundwater table and recharge capacity, infiltration capacity of soil)
- Flood risk and vulnerability (e.g., National Flood Hazard Layer, Base Level Engineering, Social Vulnerability Index)
- Environmental data (e.g., water quality, threatened or endangered species)

Once collected, this information can be overlain with flood risk hot spots to identify potential project locations for more detailed analysis of NBS feasibility. **NBS for flood resilience function primarily to increase infiltration, slow down flood flows, and/or increase flood storage. If the cause of flooding would be addressed by these functions, NBS should be considered.** An opportunity assessment helps determine where and how NBS can be effectively applied to address flood risk and achieve broader project goals. By assessing the environmental, social, and economic conditions, the opportunity assessment supports high-level evaluation of the feasibility and potential benefits of NBS within the specific project context.

A thorough exploration of potential solutions during planning allows NBS opportunities to be fully considered, both as standalone projects and to add function and value to new or existing gray infrastructure projects. This can include examining solutions that have been applied successfully in other communities. A range of options could include those that are easy to implement with near-term effects but with limited impact, as well as larger-scale efforts that may be more challenging to realize but which address the problem on a scale for the long term. Local entities can increase NBS implementation in their communities by encouraging or requiring NBS implementation on private property through regulations, policies, and incentives (**Chapter 4**).

The ***Trinity River Floodplain Tool (FPPT)*** ↗ helps to identify and prioritize key opportunities for floodplain protection and restoration in the Trinity River Basin. Users can specify criteria related to current and future flood risk, current and projected land use characteristics, water quality, wildlife habitat, and development pressure. The map changes to help identify the geographies where floodplain conservation is likely to have the greatest positive impact for the conservation and community priorities selected.

Developing a multidisciplinary team during this phase helps to build a comprehensive understanding of the opportunities and challenges that an NBS project can address. Including diverse perspectives by working across boundaries helps evaluate a wide range of factors that will affect the overall success of the project, from environmental impacts and technical feasibility to social equity and economic viability.

As part of the opportunity assessment, it is important to consider the full range of benefits each potential NBS can offer—not just flood risk reduction, but also environmental, economic, and social co-benefits. Prioritizing options that align with community goals and deliver multiple benefits can lead to projects that are more feasible, fundable, and broadly supported.

Table 7-1 presents a range of NBS types, organized by context and scale, along with the general benefits each is likely to provide. It serves as a practical tool to help project teams match identified opportunities with NBS strategies that best reflect the needs, values, and priorities of the community. By using this table during the opportunity assessment, planners and stakeholders can take a strategic, systems-based approach to selecting NBS—ensuring that proposed solutions deliver the desired beneficial impacts.

Tools and resources

- World Bank
  Nature-Based Solutions Opportunity Scan ↗
- U.S. Climate Resilience Toolkit
  Risk Mapping, Assessment, and Planning (Risk MAP) Program ↗
- NOAA Digital Coast
  Coastal Resilience Evaluation and Siting Too ↗

Clear Fork Trinity River, Fort Worth, Texas
Photo courtesy of Freese and Nichols, Inc.

How To

Using the opportunity matrix tool

1. Refer to the project's goals and needs identified.

Consider the community's top priorities — such as flood mitigation, improved water quality, biodiversity, recreational space, economic revitalization, etc.

2. Identify the context of the project area.

Determine whether the opportunity is located at the watershed, urban, or coastal scale. This helps narrow down the NBS types that are typically most appropriate for the physical and planning context.

3. Scan the table to explore applicable NBS types.

Review the NBS options listed under their corresponding scale or context. For each NBS type, note the categories of benefits it may provide. **Use the descriptions on the following page** to better understand what each benefit and its corresponding subcategories include and how it supports broader flood resilience and community goals.

4. Match NBS types to your project's objectives.

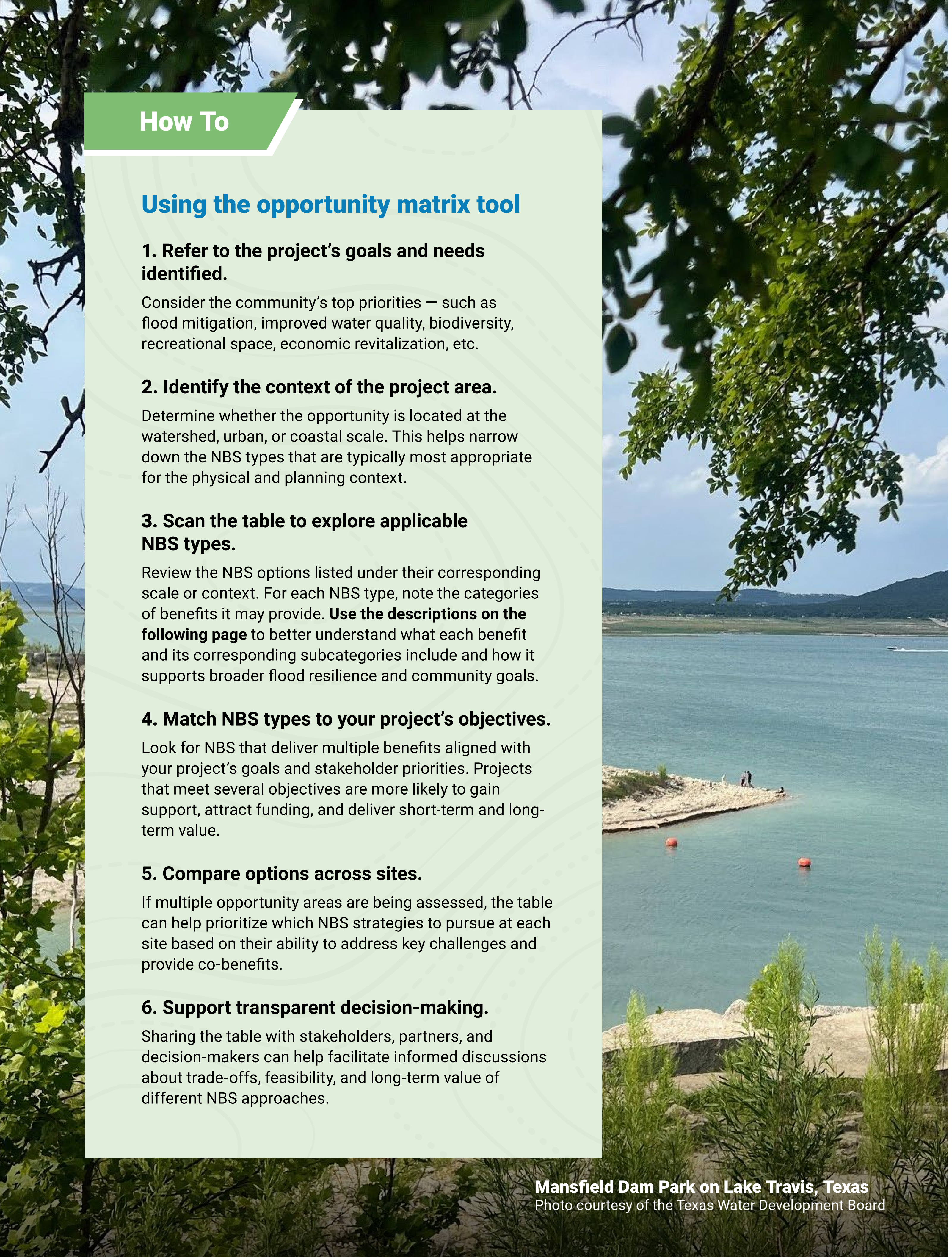
Look for NBS that deliver multiple benefits aligned with your project's goals and stakeholder priorities. Projects that meet several objectives are more likely to gain support, attract funding, and deliver short-term and long-term value.

5. Compare options across sites.

If multiple opportunity areas are being assessed, the table can help prioritize which NBS strategies to pursue at each site based on their ability to address key challenges and provide co-benefits.

6. Support transparent decision-making.

Sharing the table with stakeholders, partners, and decision-makers can help facilitate informed discussions about trade-offs, feasibility, and long-term value of different NBS approaches.



Mansfield Dam Park on Lake Travis, Texas
Photo courtesy of the Texas Water Development Board

Table 7-1 Key

The following symbols reflect the relative contribution of each NBS to flood risk reduction, including how performance varies by context and storm magnitude*.

● **Primary Benefit** – This symbol indicates that the NBS provides a **primary flood mitigation function**. The practice plays a direct and significant role in reducing flood-related impacts at the appropriate scale and is expected to influence conditions during moderate to larger storm events (e.g., events approaching or exceeding the 4 percent annual chance storm), depending on site conditions and design.

◐ **Moderate Benefit** – This symbol indicates that the NBS provides a **moderate flood mitigation benefit**. The practice can reduce runoff, increase infiltration, provide storage, attenuate flows, or lessen coastal or erosive forces under certain conditions, and is typically most effective during smaller to moderate storm events. Performance is often dependent on size, placement, design, and cumulative implementation across a system.

○ **Incremental Benefit** – This symbol indicates that the NBS provides an **incremental flood mitigation benefit**. The practice primarily reduces localized impacts such as runoff volume, peak flow timing, wave energy, or erosion, and is generally most effective during frequent, lower-intensity storm events (e.g., storms more frequent than the 10 percent annual chance storm). On its own, it is not expected to significantly influence larger storm events.

Flood mitigation benefits category definitions:

- **Reduced runoff and increased infiltration** refers to practices that slow, capture, infiltrate, or reduce surface runoff near its source.
- **Increased storage and flow attenuation** refers to practices that temporarily store floodwater, reduce flow velocities, or delay peak flow timing.
- **Sea level rise adaptation and resilience** refers to the long-term ability of an NBS to maintain or adapt its function under changing coastal conditions.
- **Wave and surge attenuation** refers to reducing wave energy and storm surge impacts during coastal storm events.
- **Reduced erosion** refers to stabilizing soils, shorelines, streambanks, or channels to minimize sediment transport. By preventing excessive sediment loading, this practice helps preserve natural channel capacity, providing storage for flood conveyance.

Environmental and **social benefit** categories are shown as general indicators of potential co-benefits and are not intended to reflect relative magnitude or performance.

■ **Environmental or Social Benefit** – This symbol indicates that the NBS may provide the identified environmental or social co-benefit.

**Note: Many NBS provide incremental benefits during extreme storm events (e.g., 1 percent (100-year) annual chance storms). Even when they do not prevent flooding or coastal impacts, these practices can reduce flood depth, delay peak timing, and lessen strain on downstream infrastructure. The greatest flood mitigation benefits are typically achieved when multiple NBS are implemented together across a watershed or system.*

Table 7-1. NBS type by potential implementation benefits matrix

Context	NBS type	Flood mitigation benefits					Environmental benefits											Social benefits								
		Reduced runoff and increased infiltration	Increased storage and flow attenuation	Sea level rise adaptation and resilience	Wave and surge attenuation	Reduced erosion	Improved water quality and pollutant removal	Improved air quality	Reduced pollutant runoff	Supports native plants	Habitat creation	Increased biodiversity	Habitat connectivity	Increased tree canopy	Carbon storage	Pollinator plantings	Reduced heat island effect	Reduced maintenance cost	Job creation	Increased property value	Recreational opportunities	Community health	Enhanced aesthetics	Volunteering	Social gatherings	Educational opportunities and signage
Watershed	Stream restoration and stablization	◐	◐			●	🟩		🟩	🟩	🟩	🟩	🟩			🟩	🟩	■	■	■	■	■	■	■	■	■
	Floodplain connection and restoration	◐	●	○		●	🟩		🟩	🟩	🟩	🟩	🟩			🟩	🟩		■	■	■	■	■	■		■
	Wetland restoration and creation	◐	●	◐		◐	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩	🟩	■	■	■	■	■	■	■		■
	Land conservation	●	◐	●		●	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	■	■	■	■	■	■	■	■	■
Neighborhood	Bioretention	◐	◐			◐	🟩	🟩	🟩	🟩	🟩	🟩			🟩		🟩	■	■	■	■	■	■	■	■	■
	Constructed wetlands	◐	●			◐	🟩		🟩	🟩	🟩	🟩	🟩		🟩	🟩	🟩	■	■	■		■	■	■		■
	Vegetated filter strips	◐	○			○	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩		🟩	■	■	■		■	■	■		■
	Bioswales	◐	◐			○	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩		🟩	■	■	■		■	■	■		■
	Rainwater harvesting	◐	○			○			🟩									■	■							■
	Stormwater trees and stormwater tree trenches	◐	◐			◐	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	■	■	■	■	■	■	■	■	■
	Stormwater parks	◐	●		◐	●	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	■	■	■	■	■	■	■	■	■
	Wet ponds		●			●									🟩			■	■			■	■	■		■
Coastal	Beach nourishment and dune restoration		◐	●	●	●				🟩	🟩	🟩	🟩			🟩		■	■	■	■	■	■	■	■	■
	Coastal marsh, seagrass, and prairie restoration		●	●	●	●	🟩			🟩	🟩	🟩	🟩		🟩	🟩		■	■			■		■		■
	Living shorelines		◐	●	●	●	🟩			🟩	🟩		🟩		🟩			■	■			■		■		■
	Waterfront parks	◐	◐	◐	◐	○	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	■	■	■	■	■	■	■	■	■
	Coastal habitat conservation	●	◐	●	●	●	🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩		🟩	■	■	■	■	■	■	■	■	■

Case Study

Green stormwater infrastructure for urban flood resilience

Location: Dallas

Opportunity: Neighborhood NBS can be implemented within residential, commercial, or industrial sites.

Lessons learned: NBS provide substantial, measurable flood resilience benefits.

The Nature Conservancy and Texas A&M AgriLife completed the **Green Stormwater Infrastructure for Urban Flood Resilience: Opportunity Analysis for Dallas, Texas**[2] to identify priority areas in Dallas where green infrastructure can most effectively enhance urban flood management considering capacity, costs, and the future impacts of changing weather patterns. The focus was on evaluating opportunities to enhance flood management where the existing drainage network may be limited.

Part 1: Identify flooding hot spots and flood-prone subwatersheds.

The EPA Storm Water Management Model (EPA SWMM v. 5 .1) was used to identify and evaluate potential stormwater system hot spots where the drainage network is undersized and likely to contribute to inlet overflows and areal flooding during various storm events. Models were run for the 50 percent (2-year), 10 percent (10-year), and 1 percent (100-year) annual chance flood event for existing conditions and forecasted climate scenarios for 2045. The flooding hot spots identified in the model were "ground-truthed" using observational data from the City of Dallas.

Part 2: Identify potential locations to place green infrastructure[3,4]

The subwatersheds draining to system hot spots were spatially evaluated for potential sites to deploy three types of green infrastructure: bioretention, rain gardens, and rainwater harvesting. The three green infrastructure practices were selected for their cost efficiency and their ability to improve infiltration and store water when distributed throughout developed watersheds.

- **Bioretention** basin areas were assigned as a portion of parking lots, road medians, planting strips, parks, and commercial sidewalks, following guidelines from the City of Dallas' Code of Ordinances. As a result, bioretention areas were placed as 10 percent of parking lots, 35 percent of vegetated road medians, 35 percent of nonresidential sidewalks that are greater than 8 feet wide, 35 percent of planting strips in residential neighborhoods, and 10 percent of parks.
- **Rain gardens** with an area of 200 square feet were applied to all residential and commercial sites to estimate the potential area for rain garden installations.
- **Rainwater harvesting** cisterns (1,000-gallon) were applied to all residential and commercial structures.

Part 3: Model comparative volume capture and costs for maximum green infrastructure deployment compared to upgrading gray infrastructure.

For the selected existing conditions storm events, the capacity and costs were estimated for managing stormwater with the maximum implementation scenario of these green infrastructure practices and compared to gray infrastructure for the 1 percent (100-year) annual chance flood event design storm. This included a desktop analysis, before and after implementing NBS to determine the potential flood mitigation benefits.

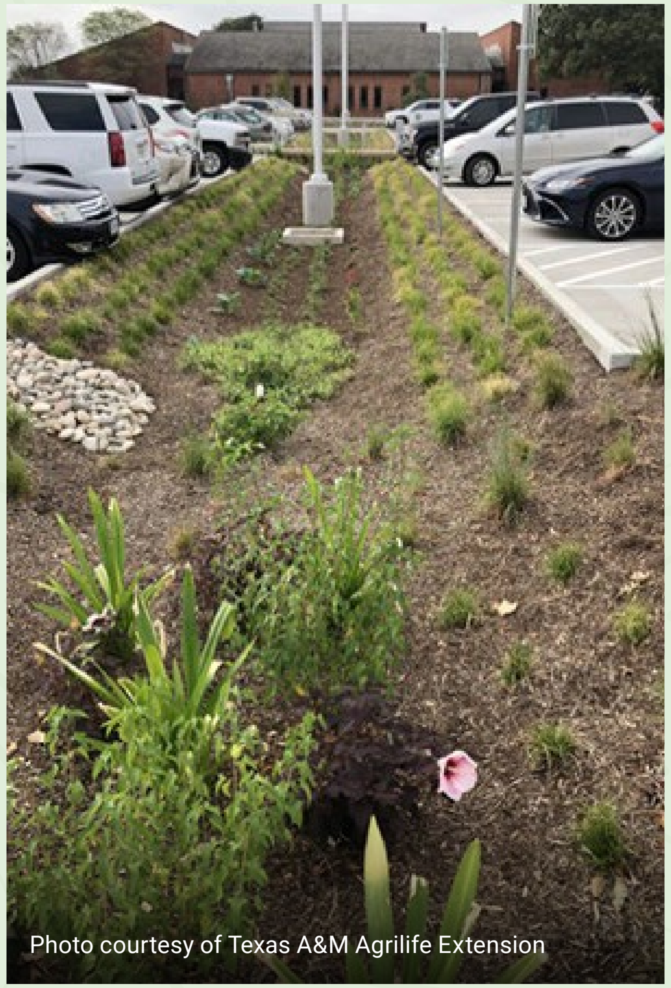


Photo courtesy of Texas A&M Agrilife Extension

Figure 7-4. Bioretention basin area analyzed near adjacent parking lot

Key findings of this opportunity assessment:

1. Substantial cost-effective opportunities exist to improve stormwater management in Dallas with green infrastructure.
2. Green infrastructure reduced modeled overflows for all storms (17–31 percent reduction) and delayed peak flows, which can reduce area flooding, creek flows, and overbank flooding.
3. Under the modeled maximum implementation scenario, green infrastructure was found to be 77 percent less costly to meet modeled overflows than upgrading gray infrastructure alone, and a combination of green and gray infrastructure provides the most cost-effective pathway*.
4. Bioretention areas—particularly in parking lots—represent the "biggest bang for the buck," with the most widely available siting opportunities.
5. When integrated into the fabric of our cities, green infrastructure can provide substantial flood management benefits, improve water quality, reduce urban heat island impacts, and improve ecological function of city landscapes.

** This analysis reflects modeled capacity and cost estimates under standardized siting assumptions and does not include land acquisition or programmatic implementation costs.*

7.3 Identifying the range of NBS options

When considering NBS to address flood risk it is important to remember the range of available approaches or the spectrum of NBS as discussed in **Chapter 2**. NBS can include both structural and nonstructural strategies that function across a spectrum from gray infrastructure that integrates nature or nature-based features (hybrid or structural NBS) to natural (nonstructural NBS), such as floodplain protection and conservation.

Hybrid (structural NBS)

Hybrid (structural NBS) involve some form of physical construction or engineered intervention to manage floodwater and reduce flood risk within a target area. Structural approaches can range from restoration-based practices, such as floodplain or wetland restoration, to hybrid solutions that combine engineered infrastructure with nature-based components. Examples include stormwater parks, constructed wetlands, living shorelines, and floodplain reconnection projects that work alongside traditional drainage, conveyance, or coastal protection infrastructure.

Selecting the right NBS for a site begins with understanding how physical, environmental, and contextual characteristics influence feasibility and long-term performance. Not all NBS are suitable for all locations—factors such as soil type, topography, available space, and surrounding land use can significantly affect both the design and function of a given solution. The design of most NBS types can be altered for any ecoregion in Texas, though a rain garden in Austin, Amarillo, and Houston may look very different. (Learn more about Texas Natural Regions in **Chapter 6**.)

NBS encompass a wide range of physical interventions designed to reduce flood risk by mimicking or restoring natural hydrologic and ecological processes. These solutions can be implemented across multiple spatial scales, from green streets and bioretention systems at the neighborhood scale, to stream and floodplain restoration at the watershed scale, and dune restoration along coastal zones. Regardless of setting, NBS are intentionally designed to incorporate natural functions (e.g., conveyance, storage, infiltration, protection), while also generating co-benefits (e.g. improved water quality, habitat restoration, and public space enhancements).

To support effective identification and application of structural NBS, the site suitability matrix (**Table 8-3**) outlines key characteristics that influence the feasibility, design, and long-term performance of different NBS strategies. These include physical, environmental, and contextual factors that help guide project teams toward appropriate interventions aligned with the site-specific conditions and project goals. This tool can support early screening of site conditions, guide design considerations, and support alignment between selected interventions, project goals, and local constraints.

Hybrid (structural NBS) versus traditional gray infrastructure

Examples of conditions where a hybrid strategy should be considered over gray infrastructure include:

- when there is sufficient land available to construct a new NBS project or to adapt existing infrastructure to include nature or nature-based features;
- when the community values co-benefits like green space, habitat, or aesthetics;
- when maintenance responsibilities and site access are well defined; and
- when the project area is expected to experience future changes (e.g., urban growth, climate variability) that require flexible, adaptive systems.

For all hybrid solutions, performance is sensitive to site-specific variables. For neighborhood NBS—which generally operate at a smaller footprint than watershed NBS—soil infiltration rates, subsurface utility conflicts, slope, and the location of existing stormwater infrastructure (e.g., curb cuts or catch basins) can influence both feasibility and effectiveness. Field reconnaissance, such as confirming soil conditions, identifying buried infrastructure, or observing ponding after rainfall events, is often necessary to verify constraints and opportunities identified through desktop screening.

When carefully sited, co-designed with community input, and integrated into the existing built environment, NBS can serve as reliable infrastructure that builds long-term resilience, enhances public spaces, and delivers sustained value across multiple dimensions.

Tradeoffs, limitations and opportunities

As with any infrastructure approach, selecting and implementing NBS involves weighing both benefits and limitations. While these solutions often offer a wider array of co-benefits when compared to traditional gray infrastructure, they also come with specific design, maintenance, and regulatory considerations that should be carefully evaluated during the planning phase. In dense or highly urbanized areas, available land may be limited, which can restrict opportunities to implement certain types of NBS that require a larger footprint, such as wetlands or regional wet ponds. Even in less developed areas, land ownership, competing land uses, or environmental sensitivities may present additional constraints. Practitioners must also assess site-specific conditions—such as soil permeability, drainage patterns, topography, and existing vegetation—which can significantly influence feasibility, design requirements, and cost.

Maintenance is another important consideration (see **Chapter 13**). Although NBS can be designed to function with minimal inputs, some practices (especially those located in high-use or urban environments) may require regular upkeep to maintain long-term performance. This could include sediment and debris removal, vegetation management, or structural inspections. Compared to gray infrastructure, maintenance tasks for NBS may be more distributed or seasonal in nature, which calls for a clear understanding of roles, responsibilities, and available resources over time.

Regulatory requirements and permitting can also pose challenges, particularly when working across jurisdictional boundaries or integrating multiple benefit objectives. Multifunctional designs may require coordination between public works departments, environmental regulators, parks and recreation agencies, and community groups. While this can add time to the process, early and inclusive engagement with key stakeholders often leads to stronger project support and more durable outcomes.

Despite these considerations, when incorporated with gray infrastructure as a hybrid approach, NBS can unlock significant opportunities. When thoughtfully planned, they can reduce long-term operational costs, enhance local ecosystems, improve public health, and contribute to climate resilience. These systems are inherently adaptable and regenerative, which makes them especially valuable in areas facing future growth, climate variability, or shifting community needs. To help maximize the benefits and minimize potential trade-offs, practitioners are encouraged to use tools like the site suitability matrix (**Table 8-3**) alongside benefit-cost assessments (see **Chapter 8.3**) and community engagement strategies. These approaches support transparent decision-making and align selected NBS with technical feasibility and community support.

Natural (nonstructural NBS)

Creating, protecting, or restoring natural systems or processes (nonstructural NBS) rely on knowledge, planning, policy, and land management approaches to reduce flood risk by preserving or enhancing the beneficial hydrologic functions of floodplains, wetlands, and other natural areas. Examples include strategic land conservation, floodplain preservation, conservation easements, and regulatory approaches that limit development in flood-prone areas. These strategies help absorb, store, and slow floodwaters while also providing ecological and community benefits.

Updates to local ordinances and regulations

Updating local ordinances to support nonstructural, nature-based flood resilience involves revising existing regulatory frameworks and creating new standards to guide development toward more sustainable and flood-resilient practices. Communities can learn from neighboring communities and existing, published model ordinances to begin the update process. Chapter 4 provides additional guidance and examples of adopted ordinances. In addition, communities can take the following actions:

- **Review and evaluate current ordinances:** Communities can begin by assessing existing zoning, subdivision, floodplain management, and stormwater ordinances to identify opportunities to incorporate NBS.
- **Incorporate NBS:** Ordinances can be amended to include requirements or incentives for low-impact development practices—such as rain gardens, bioswales, green roofs, and permeable pavement—aimed at reducing runoff and increasing infiltration.
- **Strengthen floodplain protections:** Communities can establish or enhance buffer zones around rivers, streams, and wetlands, prohibit development in high-risk flood areas, and adopt higher floodplain management standards than those required by federal guidelines.
- **Engage with public and stakeholders:** Ordinance revisions should involve extensive public input, stakeholder engagement, and collaboration with local planning boards, conservation commissions, residents, and developers to build broad support and compliance.
- **Formally adopt and enforce:** Following public hearings and stakeholder reviews, the updated ordinances are formally adopted by the local legislative body (e.g., town council or city council), integrated into comprehensive plans, and enforced through permitting and inspection processes.
- **Educate with outreach:** After updates are implemented, communities can provide educational resources, training, and outreach to residents, developers, and municipal officials to foster understanding and compliance with new requirements.

Tools and resources

- **TWDB Flood Community Assistance Program ↗**
- **Coastal Texas Model Ordinance ↗**
- **TCEQ Model Ordinance MS4 Model Ordinance - Texas Commission on Environmental Quality ↗**
- **NCTCOG GI Maintenance Ordinance – Model NCTCOG ↗**
- **EPA GI Maintenance Ordinance Model Post-Construction Stormwater Runoff Control Ordinance ↗**
- **Texas Land Conservation Assistance Network ↗**
- **Texas Land Trust Council Conservation Easements: A Guide for Texas Landowners ↗**
- **Center for Large Landscape Conservation - Integrating Wildlife Habitat Connectivity Into Local Government Planning ↗**

How To

Model ordinance language for Nature-Based Solutions for flood resilience

A model ordinance to support NBS is provided as an attachment to this manual. The purpose of the model ordinance is to increase the resilience of people and property to flooding, while providing sustainable benefits to people and the environment within a municipality, district, or jurisdiction responsible for flood risk management. It is designed to support development practices and flood risk reduction projects that incorporate NBS and conservation practices that reduce the impact of current and future flood risk. It is written to be included in an existing zoning ordinance.

Language that is variable is indicated by red text.

The language developed in the Model Ordinance Language to Support Nature Based Solutions is for educational purposes only and is not inclusive nor a substitute for any existing regulations. It is also not a substitute for legal advice. Those wishing to incorporate the ideas presented in this document should consult an attorney.

Access the model ordinance language at: *https://www.twdb.texas.gov/flood/research/Nature-based-Solutions-2022/*

Strategic land conservation

Land conservation is the practice of protecting natural landscapes to support the sustainability of ecosystems, biodiversity, and natural resources. Effective land conservation for flood risk management preserves flood mitigation benefits and can also protect water resources, promote water quality and quantity, foster biological diversity, and enhance the resilience of communities while maintaining an ecosystem necessary for the survival of numerous species. Priority areas for land conservation for flood resilience are outlined below.

Natural habitats in uplands (i.e., forests and grasslands), wetlands, and floodplains act as natural sponges, absorbing and slowing down surface runoff before it reaches streams and rivers. Additionally, the root systems of these natural areas stabilize soil, thereby reducing erosion and sediment transport that can reshape channels, undermine existing flood infrastructure, exacerbate flooding, and reduce reservoir storage capacity.

Conserving riparian and floodplain areas is particularly important to allow for maintaining the natural meandering, storage, and flow attenuation functions of rivers and streams. These areas act as natural buffers that dissipate flow energy during flood events, reduce erosion, and provide space for floodwaters to spread and slow. Integrating the conservation of riparian corridors and floodplains into flood mitigation strategies can provide long-term, low-maintenance flood resilience benefits while helping protect downstream infrastructure and channel stability.

A study that was part of the Cypress Creek Overflow Management Plan found that the restoration of 1 acre of prairie would offset the volume impact of about 2 acres of a single-family subdivision, or about 1 acre of commercial or retail development.[5]

In addition to flood mitigation benefits, riparian and floodplain conservation can improve water quality by filtering pollutants, support biodiversity and habitat connectivity, and provide recreational opportunities that enhance community value, ecosystem stability, and recovery after floods. The Natural Resource Conservation Service (NRCS) recommends various widths for vegetated riparian areas based on the function to be protected. For example, NRCS recommends a buffer of 150–250 feet, or the width of the 1 percent (100-year) annual chance floodplain, to protect riparian habitat areas, and buffers ranging from 20–200 feet for urban streams.[6]

Sandy or loamy soils are better at absorbing and storing water compared to clay-based soils due to their larger grain size and the ease with which water can infiltrate. Additionally, nutrient rich soils found in wetlands and within riparian zones support diverse vegetation with dense, fibrous root systems capable of retaining substrate during storm events, reducing runoff and erosion and further mitigating flood risk. Conserving these areas helps maintain the long-term function and resilience of streams, wetlands, and floodplains. The ***NRCS Web Soil Survey*** ↗ provides geospatial soil data.

Conserving undeveloped areas can provide a buffer against flooding. Minimizing development in these areas helps maintain their natural flood mitigation functions. These green spaces with well-established native flora and fauna can absorb excess water, decrease runoff velocity, and capture associated debris. This reduces the burden on drainage systems and lowers the risk of flooding. The ***National Land Cover Dataset*** ↗ provides geospatial land use data that practitioners can access for planning and design

Case Study

Fort Worth Open Space Conservation Program

Location: Fort Worth

Opportunity: As significant population growth and development is expected, community leaders value protecting open spaces and natural areas for current and future residents.

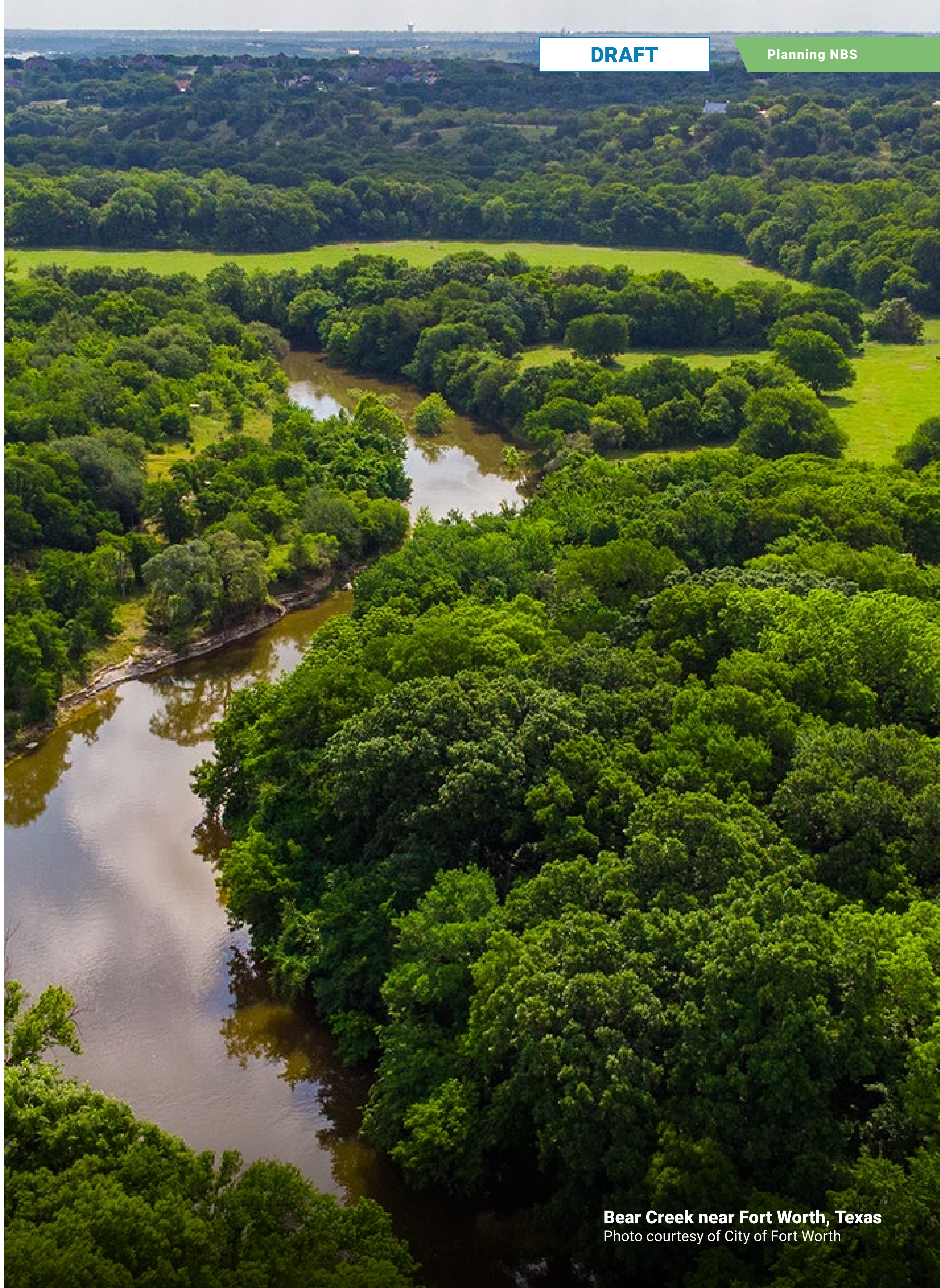
Lessons learned: Locally issued bonds can create funding for NBS implementation.

The Fort Worth Open Space Conservation Program is a prime example of how bond funding can be effectively utilized to preserve natural areas, increase flood resilience, and enhance environmental quality. These efforts are part of a broader strategy to create a network of green spaces that provide environmental, recreational, and flood mitigation benefits. This program, supported by a voter-approved bond measure, aims to protect and improve green spaces throughout Fort Worth. The City of Fort Worth partnered with the Trust for Public Land to identify and prioritize areas for open space conservation. Areas across the city were evaluated for ecosystem preservation, water quality, community health, recreation, flood control, equitable access to open space, and economic development.

In May 2021, Fort Worth residents voted to approve a $15 million bond measure specifically for the city's Natural Area and Open Space program. This bond was part of a broader effort to enhance air and water quality, preserve natural habitats, and provide recreational opportunities for the community. The bond measure received overwhelming support, reflecting the community's commitment to environmental conservation.

Since the approval of the bond measure, Fort Worth has made significant progress in acquiring and improving natural areas. For example, the city has purchased land along Lake Arlington to protect it from development and enhance its ecological value. The bond-funded projects have also contributed to enhancing community resilience against flooding. By preserving natural areas and developing green infrastructure, Fort Worth is better equipped to manage stormwater and reduce flood risks. This not only protects property and lives but also enhances the overall quality of life for residents.

Learn more: https://www.fortworthtexas.gov/departments/tpw/stormwater/open-space



Bear Creek near Fort Worth, Texas
Photo courtesy of City of Fort Worth

Understanding flood risk and identifying NBS opportunities citations

Barton Creek Greenbelt in Austin, Texas
Photo courtesy of the Texas Water Development Board

---

[1] National Oceanic and Atmospheric Administration (NOAA), 2026, *Hazard Mitigation Value*, Office for Coastal Management, NOAA, https://coast.noaa.gov/states/fast-facts/hazard-mitigation-value.html, accessed June 2026.

[2] The Nature Conservancy, 2020, *Green Stormwater Infrastructure Analysis*, The Nature Conservancy, www.nature.org/content/dam/tnc/nature/en/documents/GSIanalysisREVFINAL.pdf, accessed June 2026.

[3] GIS data provided by The Trust for Public Land

[4] GIS data from City of Dallas GIS Services (City of Dallas, 2020a)

[5] Harris County Flood Control District, (2019), Cyprus Creek overflow management plan [PDF report], https://www.hcfcd.org/Portals/62/Watershed/Cy-Creek/cypruscreekoverflowreport_fin2.pdf?ver=2019-10-23-112853-617, accessed June 2026.

[6] U.S. Department of Agriculture, Natural Resources Conservation Service, 2007, Technical supplement 14S: Sizing stream setbacks to help maintain stream stability (National Engineering Handbook, Part 654, Stream Restoration Design), U.S. Department of Agriculture, directives.nrcs.usda.gov/sites/default/files2/1712931172/7377.pdf, accessed June 2026.

INITIATING NBS

PLANNING NBS

IMPLEMENTING NBS

Implementing Nature-Based Solutions

Implementing NBS focuses on turning plans into action. Key implementation activities include evaluating site-specific suitability, selecting and refining design alternatives to achieve multi-objective benefits, navigating applicable permitting requirements, overseeing construction activities, and establishing protocols for long-term maintenance and adaptive management. Throughout the implementation phase, meaningful stakeholder engagement remains essential, particularly in design review, construction monitoring, and long-term stewardship of the completed NBS.

CHAPTERS 8-13

Chapter 8 Evaluating NBS feasibility and alternatives

Chapter 9 Designing and building NBS

Chapter 10 Applying watershed NBS design and construction considerations

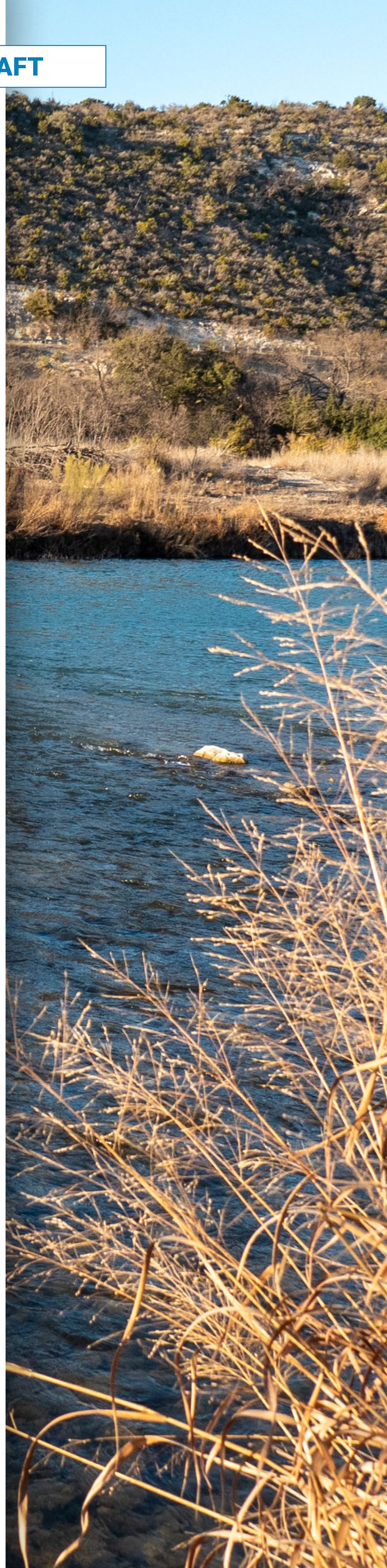
Chapter 11 Applying neighborhood NBS design and construction considerations

Chapter 12 Applying coastal NBS design and construction considerations

Chapter 13 Maintaining and adaptively managing NBS

Outcomes

- Assess suitability of NBS based on project type and site characteristics
- Calculate benefits of NBS to support decision-making
- Incorporate design and construction best practices
- Provide safe access to monitor, maintain, and adapt NBS to sustain long-term performance



8

Evaluating NBS feasibility and alternatives

This chapter presents an approach to evaluating the feasibility of NBS for flood resilience, guiding practitioners through site evaluation, regulatory assessment, alternatives analysis, and cost-effectiveness evaluation to support informed decision-making and the identification of implementable, community-aligned NBS strategies.

Key takeaways

- Understanding site characteristics and NBS suitability enables tailored solutions and early identification of potential challenges.
- Early engagement with state and federal regulatory agencies can streamline the permitting process and avoid costly delays.
- Balancing life cycle costs, benefits, co-benefits, and stakeholder input helps decision-makers determine which projects to implement.

Padre Island near Flour Bluff, Texas
Photo courtesy of the Texas Water Development Board

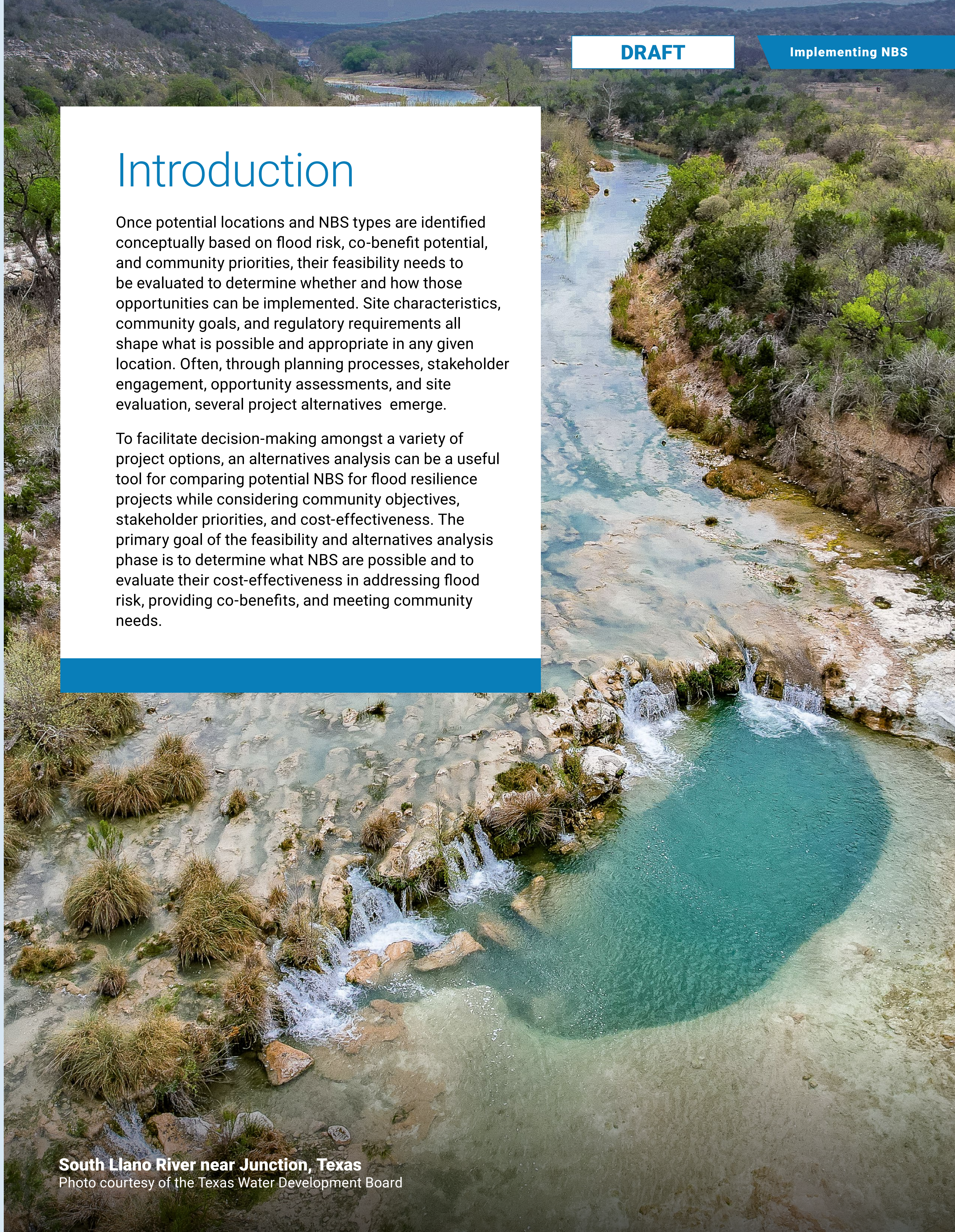
How the guiding principles apply to this chapter

Engage and include	Collaborate with stakeholders, including community members and technical experts, to assess feasibility tradeoffs, identify site constraints, and align preferred project alternatives that reflect shared priorities.
Apply systems thinking	Evaluate how the proposed NBS project will interact with physical, social, and ecological systems including existing storm drainage networks, land use plans, and community infrastructure to create multi-benefit outcomes.
Work across boundaries	Coordinate feasibility assessments across jurisdictional, departmental, and disciplinary boundaries to consider relevant data, expertise, and permitting pathways.
Learn and adapt continuously	Use feasibility evaluations as an opportunity to pilot new approaches, document lessons learned, and improve decision-making for future NBS planning and implementation.

Introduction

Once potential locations and NBS types are identified conceptually based on flood risk, co-benefit potential, and community priorities, their feasibility needs to be evaluated to determine whether and how those opportunities can be implemented. Site characteristics, community goals, and regulatory requirements all shape what is possible and appropriate in any given location. Often, through planning processes, stakeholder engagement, opportunity assessments, and site evaluation, several project alternatives emerge.

To facilitate decision-making amongst a variety of project options, an alternatives analysis can be a useful tool for comparing potential NBS for flood resilience projects while considering community objectives, stakeholder priorities, and cost-effectiveness. The primary goal of the feasibility and alternatives analysis phase is to determine what NBS are possible and to evaluate their cost-effectiveness in addressing flood risk, providing co-benefits, and meeting community needs.



South Llano River near Junction, Texas
Photo courtesy of the Texas Water Development Board

8.1 Evaluating project site

When planning and designing NBS, practitioners should consider

- characteristics of your site such as soils, groundwater table, and topography;
- existing infrastructure and historical site conditions;
- the presence of ecologically significant or sensitive resources (such as sand dunes, wetlands and estuaries, oyster reefs, endangered species and archaeological resources).

Feasibility depends on factors such as utilities, trees, soils, hydrology, sensitive features, local land use regulations, and community guidelines. Additionally, high-value sites, such as those near schools, transportation infrastructure, or community hubs, may require design adaptations to maximize benefits and optimize technical performance.

During this phase, various forms of data and analyses, supplemental material, and potential outcomes are explored, communicated, and adjusted as needed to inform and guide decision-making.

Engagement with stakeholders, local communities, and regulatory agencies at this phase creates alignment with cultural, social, and economic priorities. Information obtained from site evaluation helps tailor NBS implementation to local conditions, resulting in context-specific solutions that optimize flood mitigation and ecological and societal benefits.

Data collection and analysis

Data collected directly from the project site provides critical insight into the local conditions that influence the design and performance of nature-based solutions (NBS).[1] A desktop analysis of available information can determine the scope and level of field surveys and measurements required in watershed, neighborhood, or coastal setting. Example datasets for this initial screening include previous hydrologic and hydraulic studies, as-built plans, utility locations, topographic data (e.g., LiDAR or digital elevation models), soil surveys, property boundaries, easements, and applicable local design criteria. For coastal NBS, desktop analysis should also include shoreline change data, historical aerial imagery, wave, tide and current data, sea level change projections, sediment type mapping, bathymetry, wind data, salinity gradients, sediment transport pathways, habitat mapping, and regulatory designations (e.g., wetlands, critical habitat areas, or protected coastal zones).

While existing datasets support preliminary evaluation, site-specific field surveys provide the most reliable information for design. Property boundaries and easements play a key role in defining feasible design limits, siting, and construction access. Accurate topographic data is particularly important, as many NBS rely on precise grading to function effectively. Field surveys should collect detailed ground elevations, utility locations, drainage infrastructure, tree location and size, property and easement boundaries, and other relevant site features to fully characterize existing conditions.

In coastal environments, bathymetric surveys may also be required to assess nearshore conditions, including erosion and subsidence, and to guide project design and placement. Surveys should document shoreline position (e.g., mean higher high water), beach profiles, dune elevations and geometry (to comply with the Texas Dune Protection Act, **See Section 8.2**), submerged or buried features (e.g., utilities or pipelines), and habitat boundaries such as oyster reefs, marsh edges, or seagrass beds. Additionally, Texas law requires landowners planning coastal erosion response projects, including living shorelines, to obtain a coastal boundary survey (CBS). The CBS is a special survey to determine the boundary between private and state-owned submerged land. The CBS must be performed by a licensed state land surveyor and approved by the GLO or the county surveyor of the county in which the land is located. GLO authorization is required for the use of state-owned submerged lands.

Geotechnical and specialty data are essential for evaluating subsurface conditions and system dynamics. Data collected as part of a geotechnical analyses (e.g., soil borings and water table measurements), bank erodibility measurements, and sediment characteristics (size, type, and bed material) are essential for evaluating infiltration capacity, water table constraints, bank stability, sediment transport dynamics, and geomorphic processes. These factors are especially important for NBS applications such as stream restoration, stabilization, and floodplain reconnection. For coastal NBS, additional specialty data collection may include gage deployment for in-situ measurement of wave climate (height, period, and direction), tidal datums and variability, and current patterns all of which influence NBS performance and longevity.

Special consideration should be given to ecologically significant and sensitive resources, such as sand dunes, wetlands and estuaries, oyster reefs, and archaeological or cultural resources. Field surveys and analyses should document the presence, condition, and spatial extent of these resources, as they may constrain project design, require avoidance or mitigation, and influence permitting requirements.

Together, these site-specific datasets provide the foundation for tailoring NBS to the unique physical and ecological conditions of each location, supporting effective design and long-term function and resilience.

Threatened and endangered species

NBS, in contrast to gray infrastructure, offer a unique opportunity to deliver environmental benefits alongside flood risk reduction. These solutions can support habitat creation, improve water quality, and enhance biodiversity. Many of these environmental benefits, like habitat for threatened or endangered species, are difficult to quantify in economic terms but still contribute to the overall value of a project. Recognizing these co-benefits early in the design process can help shape project goals so that ecological integrity is prioritized alongside engineering performance. The recognition of co-benefits can also unlock additional funding opportunities (**See Chapter 5**).

To integrate these considerations effectively, project teams should evaluate whether species of interest, particularly those that are threatened or endangered, are within the vicinity of the site. Tools like the ***U.S. Fish and Wildlife Service's Information for Planning and Consultation*** ↗ platform can assist with preliminary mapping and inventory. Additionally, collaboration with nonprofit organizations (e.g., American Rivers, The Nature Conservancy, Ducks Unlimited), state agencies like Texas Parks and Wildlife, and academic institutions across Texas can provide valuable insights and data. Texas Parks and Wildlife Department (TPWD) hosts the ***Rare, Threatened, and Endangered Species of Texas*** ↗ database. Engineers and planners can download geospatial data of critical habitats. The U.S. Fish and Wildlife Service hosts various classes through the ***National Conservation Training Center*** ↗ focusing on various conservation topics and other focal areas. This information may influence where and how NBS are implemented, helping avoid sensitive habitats or enhancing areas critical for species recovery, ultimately leading to more sustainable and ecologically beneficial outcomes.

Existing infrastructure and natural processes

NBS must be designed to accommodate existing site constraints and infrastructure — often complex in developed areas. These constraints may include proximity to existing utilities, roadways, buildings, critical infrastructure and/or sensitive environmental features.

Many NBS practices are integrated into existing drainage systems. This requires practitioners to understand how water is conveyed on-site, how it is conveyed after it leaves the site and how the project interacts with downstream storm drain networks, channels, culverts, floodplains, or other infrastructure. Similar considerations can also arise in watershed or coastal NBS projects, where placement should account for natural processes, sensitive habitats, or large-scale infrastructure.

NBS should complement or enhance existing infrastructure and natural processes without negative impacts. Considering future land use, zoning, drainage connectivity, environmentally sensitive areas (e.g., aquifer recharge zones) and development can help the project function effectively within the larger system. For example, neighborhood NBS are well-suited for smaller or constrained spaces such as sidewalks, community spaces, and parking lots to help maximize available space. At the watershed scale, placement may focus on reconnecting streams to their floodplains or restoring wetlands and playa lakes. In coastal settings, design and constructability should account for tides, waves, and shoreline dynamics.

Changes in land use

Historic data and aerial imagery further enhance site understanding by documenting changes in stream alignment, floodplain extent, land use, shoreline position, and dune migration. Changes in land use or terrain modifications in the watershed can significantly influence watershed processes and the success of a solution. Historical maps and aerial imagery also help illustrate how deforestation, agriculture, and urbanization have altered sedimentation patterns and terrain. By examining past conditions in the watershed before major development, designers can make informed decisions about NBS design and vegetation selection that align with the site's natural characteristics.

Current and historical imagery, along with topographic and LiDAR data, are important tools in determining how the landscape has evolved. LiDAR is especially useful for detecting abandoned or relic channels that may not be visible in aerial photos but reflect past geomorphic conditions. Evaluating imagery across time helps to identify stable reaches and support the placement of solutions where they are most likely to succeed. LiDAR can also be used to build a relative elevation model (REM) map. A REM map shows the vertical relationship between a channel and its floodplain.

The ***Texas Geographic Information Office*** ↗ has an online repository for LiDAR and imagery. Libraries, historic societies, and private businesses are also sources of historic aerial images.

Soil and groundwater table characteristics

Understanding the geologic setting, both past and present, is important for effective NBS design. The geology beneath a site includes both the solid bedrock deep underground and the loose sediments, like sand, gravel, and silt, that sit on top of it. These materials influence groundwater movement, surface hydrology, and sediment transport processes that shape the landscape.

Soil characteristics—including stability, infiltration capacity, compaction, nutrient content, organic composition, pH, and depth to bedrock (as identified through geotechnical analysis)—are fundamental inputs to design. These properties directly influence both hydrologic performance and vegetation success. Because many NBS rely on healthy, functioning vegetation, understanding native soil conditions is essential to support plant establishment, long-term health, and overall system performance.

Soil investigations and an understanding of geological history can also shed light on future design challenges— such as erodible soils, instability, shallow bedrock, or contamination—that influence the long-term success of the project. For instance, shallow bedrock may limit excavation depth, footprint, and configuration, while contaminated soils may require removal and proper disposal. Although contamination assessments are not always a state or federal requirement for a project, evaluating potential risks early in the project is a best practice to avoid lengthy and costly delays during construction.

Soils are classified according to their rate of infiltration and are assigned to four groups (A, B, C, and D) and three dual classes (A/D, B/D, and C/D).

- **Group A** consists of well-drained to excessively-drained sands or gravelly sands with a high infiltration rate.
- **Group B** consists of soils with a moderate infiltration rate.
- **Group C** typically consists of soils with moderately fine texture and a slow infiltration rate.
- **Group D** most commonly consists of clay soils or where the water table is high and has a very slow infiltration rate.
- **Group A/D** consists of soils that have drained areas that apply to Group A but also have undrained areas that apply to Group D.
- **Group B/D** consists of soils that have drained areas that apply to Group B but also have undrained areas that apply to Group D.
- **Group C/D** consists of soils that have drained areas that apply to Group C but also have undrained areas that apply to Group D.

Where feasible, NBS design should prioritize preserving or utilizing soils with higher infiltration rates such as hydrologic soil groups A or B.[2]

Many neighborhood NBS practices rely on engineered soils to meet performance goals. These soils are designed to support both infiltration and plant health and typically consist of a balanced mix of sand (for porosity and drainage), compost (for organic matter and nutrient retention), and topsoil (to support plant growth). The composition is designed to achieve a target infiltration rate that allows for effective stormwater management while maintaining conditions suitable for long-term plant growth.

In addition to infiltration rates, other soil characteristics should be evaluated to support successful vegetative growth and long-term ecosystem health. Seasonal groundwater fluctuations can influence root zone saturation and plant viability, especially for deep-rooted native species. Soil texture, organic matter content, compaction levels, and nutrient availability also help designers select appropriate plant species, determine necessary soil amendments, and predict how the site will respond to varying hydrologic conditions.

Designs should also account for drainage and soil structure. Features such as perforated underdrains may be needed to prevent prolonged waterlogging that can harm root systems and reduce functionality during heavy storm events. Soil amendments (i.e., adjustments to soil structure via aeration or blending) may be necessary in areas where clay-heavy or compacted soils may limit infiltration. Proper grading and soil preparation promotes tree vitality and optimal stormwater performance across a range of NBS practices—from floodplain restoration, to bioretention and tree trenches, to shoreline stabilization.

In areas where increasing groundwater recharge is a goal, NBS projects can be designed to enhance infiltration using highly porous soil mixtures, omitting underdrains, or increasing storage capacity to capture and infiltrate more stormwater. These designs should incorporate pretreatment to remove pollutants and avoid placement in areas with known or suspected contamination risks, such as industrial sites or hot spots.

Tools and resources

- **TWDB**
  Groundwater Data Viewer ↗
- **NRCS**
  Web Soil Survey ↗

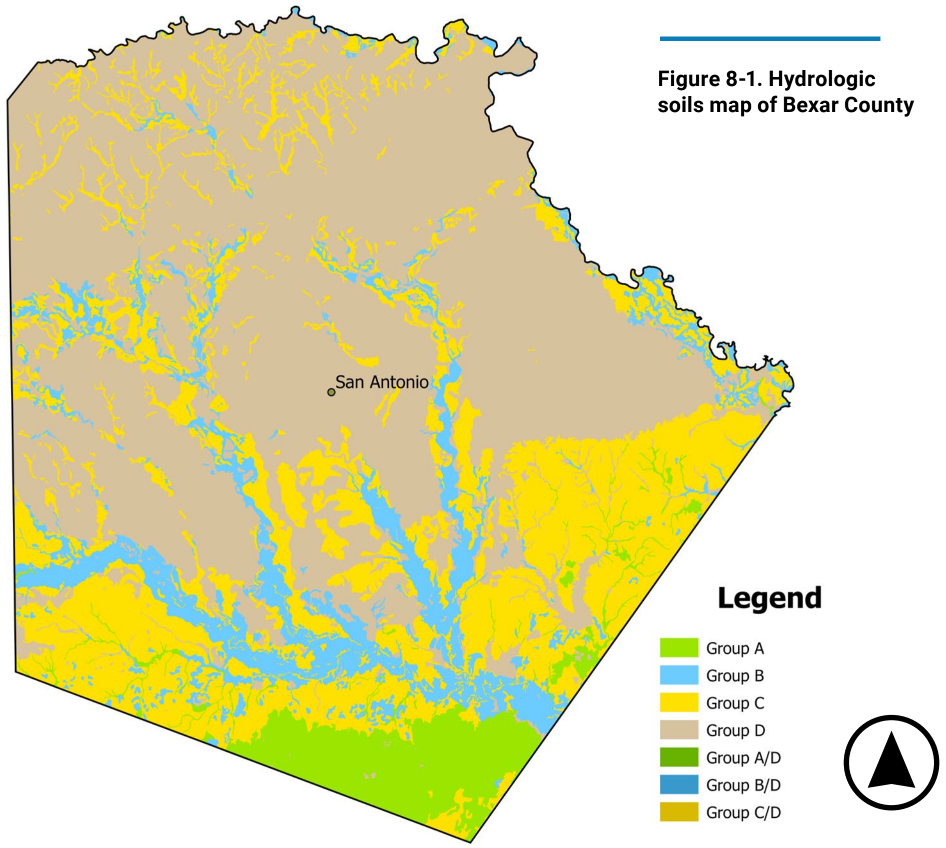


Figure 8-1. Hydrologic soils map of Bexar County

Project type

Project type refers to the broader development or infrastructure context in which NBS could be applied. Understanding the type of project underway—whether it is a new subdivision, roadway improvement, or coastal protection effort—helps identify which NBS practices can be integrated most effectively. Each project type presents opportunities to implement NBS.

- **Preservation & Parks:** Areas that are undeveloped or minimally developed, such as parks, nature preserves, or vacant land are often ideal for conservation, restoration, nonstructural NBS, or conversion to parks that function to reduce flood risk such as stormwater and waterfront parks.
- **Medium/High Density Development:** New or redeveloped residential neighborhoods, retail centers, or business parks often offer opportunities for integrating bioretention, rainwater harvesting, stormwater parks, and infiltration basins within parking lots, roadways (i.e., green streets), landscaping, and corridors.
- **Roadways:** Projects focused on upgrading or building roads, highways, or improved streetscapes can incorporate vegetated filter strips, bioswales, and stormwater tree trenches within the corridors to manage runoff and enhance aesthetics.
- **Detention:** Projects that involve managing stormwater through temporary storage to reduce downstream flooding can be made more multifunctional and beneficial by converting traditional basins into constructed wetlands, wet ponds, or stormwater parks.
- **Conveyance:** Efforts to improve or modify water channels (e.g., creeks, drainage ditches, stormwater channels) for better water movement might include stream restoration or floodplain connection.
- **Channel Stability:** Projects addressing erosion problems along streambanks or channels can stabilize banks, restore vegetation, and reduce sediment transport with bioengineering and/or regrading.

Rain Garden, Stella Hotel
College Station, Texas
Photo courtesy of Freese and Nichols, Inc.

Table 8-1. Suitable NBS types for common projects

Context	NBS Type	Project Type					
		Preservation/Parks	Medium/High Density Development	Roadways	Detention	Conveyance	Channel Stability
Watershed	Stream restoration and stabilization	●	●	●	●	●	●
	Floodplain connection and restoration	●	●	●	●	○	●
	Wetland restoration and creation	●	●		●		
	Land conservation	●	●	●	●	●	●
Neighborhood	Bioretention basins/rain gardens	●	●	●	●		
	Bioswales	●	●	●	●	●	
	Vegetative filter strips	●	●	●	●	●	●
	Wet ponds	●	●		●		
	Constructed wetlands	●	●		●		
	Rainwater harvesting	●	●		●		
	Stormwater parks	●	●		●	●	●
Coastal	Beach nourishment and dune restoration	●	●				●
	Coastal marsh restoration	●	●		●		●
	Natural breakwaters, oyster reefs, and living shorelines	●	●	●			●
	Coastal conservation	●	●	●	●		●

Table 8-1 Key

The symbols in Table 8-1 indicate the general applicability of each NBS type to common project types and implementation contexts.

● **Applicable** – This symbol indicates that the NBS type is commonly applied and generally well-suited for the identified project type or implementation context.

○ **Conditionally applicable** – This symbol indicates that the NBS type may be suitable for the identified project type under certain conditions, but implementation may require design modifications, additional space, site-specific adaptations, or coordination with other infrastructure or project objectives.

Note: Applicability may vary depending on site conditions, design objectives, available space, regulatory requirements, and project scale.

NBS suitability

The site suitability matrix (Table 8-2) is designed to help project teams evaluate how well different NBS practices fit specific site conditions. Each factor includes categories that reflect common conditions and how they relate to the feasibility and performance of various NBS. Practitioners can use this table to screen sites for NBS compatibility, inform design considerations and sizing, and prioritize interventions that align with project goals and resource constraints. The definitions of each factor and their respective conditions are outlined below:

Slope describes the steepness or grade of a site or channel and affects construction feasibility. The slope of an area also affects whether planting vegetation is possible or if a more bioengineered design approach is necessary. Some NBS practices do not depend on the slope of the site and therefore, any slope is feasible for the design. Slope is commonly expressed as a percentage:

- **Flat (0–1%):** Ideal for most NBS practices.
- **Gently sloped (1-4%):** Suitable for some NBS with appropriate design considerations.
- **Steep (>4%):** Can present challenges for stability and erosion; typically requires additional engineered support or slope-adapted practices. Incorporating check dams into designs of bioretention or stream restoration NBS solutions may be necessary under these conditions.

Tree canopy* indicates the proximity and extent of tree coverage on or near the site that would need to be protected, preserved, or incorporated into the proposed NBS design. Categories are defined as:

- **Within:** Existing trees or canopy occur within the footprint of the proposed NBS.
- **Near:** Existing trees or canopy occur within approximately 25-50 feet of the proposed NBS footprint and may influence grading, utilities, infiltration, or design.
- **Distant:** Existing trees or canopy are located more than 50 feet from the proposed NBS footprint; supplemental vegetation or tree planting may be needed to support tree-based NBS functions.

Infiltration rate is a measure of how quickly water moves into the soil, typically expressed in inches per hour. It reflects actual field conditions and affects suitability of various NBS types. If natural soils do not have enough infiltration for the desired NBS practice, engineered soil media can be incorporated into the design. Infiltration rates are categorized as:

- **High:** Ideal for infiltration-based NBS.
- **Not infiltration dependent:** Suitable for practices that do not rely on soil infiltration.

Impervious cover (IC) represents the percentage of the land surface covered by materials that prevent water infiltration, such as pavement or rooftops. Higher imperviousness increases runoff volume and affects NBS selection:

- **Low IC:** Allows for more natural infiltration and preservation-focused strategies.
- **Moderate IC:** Supports a balance of infiltration and detention practices.
- **High IC:** Requires systems capable of managing large runoff volumes, often in constrained urban settings.

Maintenance needs describe the anticipated level of effort and frequency required to keep the NBS functioning as intended after establishment. These are typically categorized as:

- **Low:** Minimal intervention, passive systems like conserved or restored natural habitat.
- **Moderate:** Periodic upkeep such as vegetation management or debris removal.
- **High:** Regular inspections, cleaning, or specialized maintenance—common in urban, engineered systems.

**Please note that tree canopy distance categories are intended for planning-level screening and are not substitutes for site-specific arborist evaluation.*[3]

Table 8-2. NBS site suitability matrix

Context	NBS Type	Slope (%)			Tree Canopy			Infiltration Rates		Maintenance Needs		
		0-1	1-4	>4	Within	Near	Distant	None	High	Low	Moderate	High
Watershed	**Stream restoration and stabilization**	●	●	●	●	●	●	●	●	●		
	Floodplain connection and restoration	●	●		●	●	●	●	●	●		
	Wetland restoration and creation	●	○		●	●	●	●		●		
	Land conservation	●	●	●	●	●	●	●	●	●		
Neighborhood	**Bioretention basins/rain gardens**	●	●		○	●	●	○	●		●	○
	Bioswales	●	●	○	●	●	●	○	●		●	○
	Vegetated filter strips	●	●	○	●	●	●	●	●	●		
	Wet ponds	●					●	●	○			●
	Constructed wetlands	●	○				●	●			●	
	Rainwater harvesting	●	●	●		●	●	●	●		●	○
	Stormwater parks	●	●	●	●	●	●	●	●		●	○
Coastal	**Beach nourishment and dune restoration**	●	●	●			●		●	●	●	
	Coastal marsh restoration	●					●		●	●	●	
	Natural breakwaters, oyster reefs, and living shorelines	●	●	●	○	●	●	○	●	●	●	○
	Coastal conservation	●	●	●	○	●	●	●	●	●	●	○

Table 8-2 Key

The symbols in Table 8-2 indicate the general suitability of each NBS type relative to selected site characteristics and operational considerations. Suitability may vary depending on local environmental conditions, project design, maintenance capacity, and implementation scale.

- ● **Suitable** – This symbol indicates that the site characteristic or condition is generally compatible with the NBS type and is commonly associated with successful implementation.
- ○ **Conditionally suitable** – This symbol indicates that the NBS type may be suitable under the identified condition, but successful implementation may depend on site-specific factors, design modifications, adaptive management, or additional maintenance considerations.

Note: Site suitability should be evaluated alongside hydrologic, hydraulic, ecological, regulatory, and community considerations. Many NBS can be adapted to function under a broader range of site conditions through modified design approaches or integration with complementary practices.

8.2 Assessing regulations and permitting

For any infrastructure project to be implementable, it must comply with all applicable permits. Given the variety in local permitting requirements across Texas communities, this section will focus on state and federal permitting requirements.

Many NBS projects—especially those involving regulated habitats or watercourses—require permitting and approval from state and federal agencies. Because federal roles, responsibilities, and permitting requirements can evolve over time, practitioners should verify current requirements early in the project and coordinate with the appropriate agencies to ensure compliance.

Engaging regulatory agencies during early planning helps identify required permits, clarify timelines, and understand any limitations or mitigation requirements. This proactive coordination can streamline the approval process, improve project outcomes, and reduce the risk of costly delays or unexpected challenges during design and construction.

Designing NBS projects to qualify for streamlined permitting processes, such as the USACE Nationwide Permits, can result in more efficient permitting reviews. Potential permitting requirements should be outlined before the design phases begin.

Federal Emergency Management Agency (FEMA)

Local governments that participate in the National Flood Insurance Program (NFIP) must adopt floodplain management ordinances that meet FEMA minimum standards. For participating communities, development within the Special Flood Hazard Area (SFHA) is subject to federal NFIP requirements. As a result, when property owners apply for construction permits in the SFHA, local permitting authorities are required to confirm that proposed projects comply with these regulations. This often includes requirements such as elevating structures above the base flood elevation, using flood-resistant materials, and avoiding activities that could increase flood risks to surrounding properties. Local governments may also impose higher standards than NFIP minimums.

When projects receive federal funding through FEMA, they must undergo an environmental and historic preservation review. While not a formal permit, this process is intended to check that proposed activities comply with federal environmental and cultural resource laws such as the National Environmental Policy Act (NEPA), Endangered Species Act, and National Historic Preservation Act. The review helps identify potential impacts on natural resources, historic properties, and communities before work begins.

U.S. Army Corps of Engineers

U.S. Army Corps of Engineers (USACE) has the authority under multiple statutes to regulate construction activities within waters of the United States. Communities with flooding concerns potentially related to waters of the United States will need to coordinate with the USACE to ensure proposed construction and/or mitigation measures are compliant with current permitting requirements.

Section 404 of the Clean Water Act is one of the primary regulatory mechanisms through which USACE exercises this authority. Section 404 establishes a permit program that regulates the discharge of dredged or fill material into waters of the United States, including wetlands, streams, rivers, and other aquatic resources. Any project that involves grading, filling, or placing material within jurisdictional waters may require a Section 404 permit prior to construction. Section 404 permits are issued in two primary forms: individual permits, which are project-specific and require a more detailed review process, and nationwide permits, which provide streamlined authorization for activities that have minimal adverse effects on the aquatic environment.

Individual permits are typically required for larger or more complex projects with the potential for significant environmental impacts, and they involve a public notice and comment period, interagency coordination, and a more comprehensive environmental review. For projects that do not qualify for a nationwide permit, early coordination with the appropriate USACE district office is strongly recommended to help determine the appropriate permit pathway and avoid delays during project delivery. Section 404 permits require that the least environmentally damaging practical alternative for a project is used and any environmental impacts are either avoided or mitigated if necessary. The U.S. Army Corps of Engineers issues the Section 404 permits, but the EPA develops the guidelines and has the authority to veto permits.

Incorporating NBS elements into a construction or mitigation project can aid in compliance with water quality and aquatic ecosystem health standards. The use of USACE nationwide permits can help to streamline authorization on projects that have minimal adverse effects on the environment. To utilize a nationwide permit, practitioners should submit a pre-construction notification to the appropriate USACE district office and ensure that the project meets all terms of the associated nationwide permit. Texas is served by the Fort Worth, Galveston, Albuquerque, and Tulsa Districts. Pre-construction notifications are documents that provide a detailed description of the proposed project and its effects on the surrounding environment. Pre-construction notifications document compliance with the nationwide permit. There are various types of nationwide permits, three common types are:

Nationwide Permit 13 – Bank Stabilization authorizes small discharges of dredged or fill material for bank stabilization activities necessary for erosion control or prevention, which could include NBS approaches such as soft stabilization techniques (e.g., vegetative bank stabilization and bioengineering using appropriate native plants).

Nationwide Permit 27 – Aquatic Habitat Restoration, Enhancement, and Establishment Activities authorize aquatic habitat restoration, enhancement, and establishment that is "planned, designed, and implemented so that it results in aquatic habitat that resembles an ecological reference." For example, wet ponds and constructed wetlands are NBS practices that can help improve water quality and habitat and reduce flooding impacts to downstream areas by providing storage space for floodwaters.

Nationwide Permit 54 – Living Shorelines authorizes the discharge of dredged or fill material in coastal waters of the United States for construction and maintenance of living shorelines, marsh habitat restoration, and barrier island construction and rehabilitation. Each of these NBS help attenuate wave energy and stabilize banks and shores.

U.S. Fish and Wildlife Service

The Endangered Species Act (ESA) establishes protections for fish, wildlife, and plants that are listed as threatened or endangered. U.S. Fish and Wildlife Service (USFWS) is tasked with implementing and enforcing the ESA. Impacts to threatened or endangered species or their habitats may occur through the implementation of a project, either temporarily during construction or permanently. The permitting process is intended to align actions that are consistent with the conservation and recovery of the species.

If NBS activities may result in the taking of endangered or threatened animal species, it can be necessary to obtain an incidental take permit. For non-federal entities, this entails the development of a habitat conservation plan that adequately minimizes and mitigates impacts of the authorized incidental take. Given the flexibility of many NBS approaches, take can often be avoided.

However, coastal or watershed NBS projects can often help restore or protect important habitats for federally listed threatened and endangered species. For example, the USFWS has implemented multiple projects on its National Wildlife Refuges with the objective of restoring habitat for federally listed species, such as the eastern black rail (*Laterallus jamaicensis jamaicensis*). This species typically occupies areas that can act as NBS by providing wetland buffers for waves and small storms in coastal areas.

National Marine Fisheries Service

The Gulf of Mexico Fishery Management Council established by the Magnuson-Stevenson Sustainable Fisheries Act identifies Essential Fish Habitat (EFH) for each federally managed species. It defines the waters and substrate needed for fish to spawn, breed, feed, or grow to maturity and may include migratory routes, open waters, wetlands, estuarine habitats, artificial reefs, shipwrecks, mangroves, mussel beds, and coral reefs. Federal agencies are required to consult with the National Marine Fisheries Service (NOAA Fisheries) before taking actions that might harm EFH, which may be a consideration for coastal NBS and watershed NBS activities in riverine systems for anadromous species.

While coastal NBS may change the character of fish habitat in an estuary or coastal bay, for example by replacing open water bottom with vegetated marsh, NOAA Fisheries often consider the long-term and net effects at a larger scale than individual project features. For example, in their general assessment of essential fish habitats for the Gulf of Mexico, the Gulf of Mexico Fisheries Management Council recognized that many of the federally managed species use estuarine and gulf habitat during some portion of their life for spawning, food, development, and/or protection.[4]

In their evaluation of the Coastal Texas Study, NOAA Fisheries noted that “the proposed actionable measures of the recommended plan would provide an overall positive benefit to the ecosystem by increasing EFH quality and quantity, while also protecting existing EFH from storm surge, tidal energies, and relative sea level rise.” This connection between EFH and NBS often means that EFH consultations for NBS should not be seen as a major barrier to implementation.

Texas Commission on Environmental Quality

Some federal regulations are administered by state agencies. For example, the Texas Commission on Environmental Quality (TCEQ) administers aspects of federal statutes such as the Clean Water Act, the Clean Air Act, and the Safe Drinking Water Act. Water quality is a key component in building resilient ecosystems and promotes the overall health of NBS. Water quality measures can be embedded into NBS intended for flood resilience or gray infrastructure improvements to enhance the overall benefits to a watershed. The TCEQ is charged with protecting the state's public health and natural resources consistent with sustainable economic development and regulates the design, construction, maintenance, or modifications to dams under Title 30, Part 1, Chapter 299 of the Texas Administrative Code (TAC).

In Texas, most communities have separate systems for stormwater and wastewater so that their water quality measures can be modified to the pollutant type and quantity in each. Municipal Separate Storm Sewer Systems (MS4) are publicly owned systems designed to manage stormwater by controlling the volume and velocity of runoff entering water bodies—thus also reducing flood risk—and are designed and maintained to minimize pollutants. These systems are regulated by the National Pollutant Discharge Elimination System (NPDES) Program established under the Clean Water Act.

The NPDES program aims to reduce water pollution by regulating point sources that discharge pollutants into waters of the United States. TCEQ administers NPDES permits in Texas. Communities subject to MS4 permitting requirements should consider NBS to achieve permit obligations. The EPA has published the *Compendium of MS4 Permitting Approaches Part 6: Green Infrastructure*[5] which provides examples of approved permit approaches that use green infrastructure making this a streamlined opportunity for NBS.

MS4 permits require municipalities to develop and implement a stormwater management program to reduce the contamination of stormwater runoff. By managing both water quality and water quantity, NBS create opportunities to implement projects with multiple benefits. The stormwater management program is required to include a number of “minimum control measures” that address issues such as construction site stormwater runoff control, illicit discharge detection and elimination, and pollution prevention. Although the focus of these measures is stormwater pollution prevention, if NBS are used, there can be flood risk reduction benefits to these measures. For example, runoff control from construction sites can not only reduce sediment delivery to waterbodies but also reduce flood peaks by using NBS that promote water retention and infiltration.

A stormwater pollution prevention plan (SWP3) is a major construction component that outlines construction plans and BMPs to control pollutants that may be discharged in stormwater runoff. The TCEQ requires developments greater than one acre to create a SWP3 and receive approval to proceed with construction.[6] Local governmental bodies may require a SWP3 for smaller developments as well. A SWP3 that incorporates NBS can create positive impacts to downstream sites and waterbodies. Regardless of SWP3 requirements, erosion and sediment controls must be regularly monitored and maintained to control pollutant discharges as their uses may evolve throughout construction. Erosion and sediment control measures should be checked frequently, especially before and after storm events.

For communities located within the Edwards Aquifer Recharge, Transition, and Contributing Zones—as designated by the TCEQ in Title 30, Part 1, Chapter 21—any development, construction, or land-disturbing activities within these zones must comply with the Edwards Aquifer rules. The *Edwards Aquifer Protection RG-348*[7] is a technical guidance manual issued by the TCEQ that explains how to comply with the Edwards Aquifer Protection Program rules Title 30, Part 1, Chapter 213, requiring developments in sensitive aquifer zones to use BMPs that provide permanent water quality protection. RG-348 also provides formulas for calculating pollutant load reductions, optional enhanced measures for sensitive habitats, and helps achieve long-term accountability through certification and record-keeping, making it the cornerstone for balancing development with aquifer protection.

Beyond regulatory requirements, communities can also take proactive steps to protect drinking water sources through voluntary programs such as the Source Water Protection Program (SWPP)."***The Source Water Protection Program (SWPP)*** ↗ is designed to protect public water systems used for drinking water sources from contaminants. SWPP helps to identify potential contaminant risks and provides tools and data to the public water systems that opt in. The SWPP helps identify potential contaminant risks within source water protection areas and provides tools, data, and technical assistance to public water systems that opt in to the program. Source water protection areas are delineated zones around drinking water sources including rivers and reservoirs where land use and activities are evaluated for their potential to introduce pollutants into the water supply.

NBS can play a meaningful role in supporting source water protection objectives. Practices such as riparian buffers, wetland restoration, and vegetated filter strips can reduce sediment, nutrient, and pollutant loading within source water protection areas, helping to maintain the quality of drinking water sources. Communities that incorporate NBS into their stormwater and land management strategies may find that these practices align well with SWPP goals, creating opportunities to address both flood resilience and drinking water protection through a coordinated approach. Public water systems and communities located within or adjacent to designated source water protection areas are encouraged to consider NBS as part of their broader water resource management planning.

Texas Parks and Wildlife Department

The Texas Parks and Wildlife Department (TPWD) is charged with management and conservation of the natural and cultural resources of Texas and providing hunting, fishing, and outdoor recreation opportunities for the use and enjoyment of present and future generations. As such, it regulates activities in some Texas land and water bodies, and permits must be obtained for some activities.

The TPWD has a responsibility to manage, control, and protect marl and sand of commercial value and all gravel, shell, and mudshell located within tidewater limits of the state and within the freshwater areas of the state that are not privately owned. Permits may be required for activities which disturb stream beds. Permits may be more readily obtained for NBS that preserve the natural channel than traditional gray infrastructure that may seek to line or straighten channels to increase the conveyance of floodwaters.

Aquatic Introduction permits are also required to introduce and/or relocate fish, shellfish, or aquatic plants into public waters. NBS that include vegetation should be sure to use native vegetation to avoid any issues with the introduction of non-native, potentially invasive plants. If aquatic plants will be transplanted from another site, as opposed to purchasing from an approved Texas aquatic plant nursery, an Aquatic Resource Relocation Plan may be required by the TPWD.

Texas General Land Office and the Texas Coastal Management Program

The Texas Coastal Management Program (CMP), within the Texas General Land Office (GLO), is a federally approved member of the federal Coastal Zone Management Program which was established by the Coastal Zone Management Act of 1972. The Texas CMP links together the existing regulations, programs, and local, state, and federal entities that manage various aspects of coastal resource uses.

The Texas Dune Protection Act emphasizes the necessity of protecting dunes because stabilized, "vegetated dunes offer the best natural defense against storms and are areas of significant biological diversity". Through this statute, local governments define the Texas dune protection line. Any construction activities seaward of this line are heavily regulated to prevent damage to the dunes. Developers must obtain permits and adhere to strict guidelines that support the preservation of dune vegetation and stability. This includes measures such as using dune walkovers instead of pathways that cut through dunes and implementing dune restoration projects when necessary. These regulations help maintain the integrity of the dunes, which in turn protects inland areas from storm surges and erosion. GLO assists local governments to review applications for Beachfront Construction Certificates and Dune Protection Permits.

Many NBS in the coastal zone, such as dune or marsh restoration, or living shorelines, can take advantage of free coastal permitting assistance through GLO Permit Service Centers. These are "one-stop shops" for projects that fall within the Texas coastal boundary. Learn more at ***Coastal Boundary Survey*** ↗.

Texas Historic Commission

The mission of the Texas Historic Commission (THC) is to protect and preserve the state's historic and prehistoric resources for the use, education, economic benefit, and enjoyment of present and future generations.

Throughout history, humans have used floodplains and other lowland Texas landscapes for various purposes, and during project site assessments it is important to identify any potential historical, cultural, or tribal uses of these areas. Special consideration should be given when tribal resources are present on or near the project site, and in consultation with indigenous nations and tribal governments, portions of the project area may be preserved for cultural significance by avoiding excavation in those areas. Historical structures cannot be removed during construction without proper approval, documentation, or mitigation.

Coordination with state and local historic preservation offices, including the THC, throughout the design process is beneficial. Federal and state laws protecting historic properties and archeological sites require consultation with the THC. An archeological review may be needed to evaluate subsurface disturbances within a project footprint that may impact archeological sites. Proposed project areas are assessed for known archeological sites, whether previous archeological investigations have been conducted there, and whether there is potential for buried archeological sites. This is a requirement for the USACE permitting.

Figure 8-2. Restoration of Dollar Bay. The image of the top is an degraded area of Dollar Bay in Texas City, Texas. The image on the bottom shows the same bay after a marsh terraces and conservation efforts were completed to preserve the viability of Dollar Bay as a functional estuarine system.

Photos courtesy of Texas General Land Office

Case Study

Flood control dam modernization within critical habitat

Location: Austin

Opportunity: Aging infrastructure located within critical habitat needed modernization.

Lessons learned: Multidisciplinary team and continuous coordination with permitting agencies creates more resilient infrastructure while protecting critical habitat.

Old Lampasas Dam was built in 1984 to provide regional flood detention for nearby neighborhoods. The City of Austin later annexed the area, inheriting the high-hazard dam that had deteriorated due to maintenance access problems, was later damaged by Tropical Storm Hermine and required updating to comply with city and state dam safety criteria.

During the preliminary engineering phase, there was no observed presence of critical habitat because of the drought conditions, therefore the project was planned to be federally permitted using a USACE Nationwide Permit. However, during the dam modernization design phase, Jollyville Plateau salamanders (Eurycea tonkawae) were found in the vicinity of the embankment and upstream and downstream of the dam. By the time the project reached 60% design, the salamanders became listed as threatened by USFWS. Due to the salamander's status as a threatened species, additional local, state and federal permits were required.

During the on-site pre-application meeting, the USACE determined that a Letter of Permission would be required, an option that lies between the Nationwide and Individual Permits. The Letter of Permission was greatly informed by the biological assessment necessitating design changes to preserve critical habitat. Changes included a subsurface drain within the embankment to connect the subsurface habitat to a new surface outlet downstream of the dam embankment. To design the drain, the design team used geophysical exploration to estimate the location of the source spring to understand the origin of the subsurface habitat within the embankment.

During the on-site pre-application meeting, the USACE determined that a Letter of Permission would be required, an option that lies between the Nationwide and Individual Permits. The Letter of Permission was greatly informed by the biological assessment necessitating design changes to preserve critical habitat. Changes included a subsurface drain within the embankment to connect the subsurface habitat to a new surface outlet downstream of the dam embankment. To design the drain, the design team used geophysical exploration to estimate the location of the source spring to understand the origin of the subsurface habitat within the embankment.

The Letter of Permission included specifications for construction to minimize impacts to critical habitat. Most notably, construction activities were to be stopped when the groundwater table was high, which causes the salamanders to exit underground caves and travel to nearby springs. A groundwater well was installed during the design phase to estimate potential shut down days to include in the contract.

Figure 8-3. Jollyville Plateau salamanders found near Old Lampasas Dam.

Photos courtesy of Freese and Nichols, Inc.

Figure 8-4. Photo of rock outcrop at Old Lampasas Dam.

Photos courtesy of Freese and Nichols, Inc.

Once construction started, the groundwater table stayed higher than projected, causing excessive delays. USFWS, and the USACE agreed to modify the permitting constraints if City biologists would commit to monitoring and relocating any salamanders so construction could continue.

Multidisciplinary teamwork between engineers, landscape architects, geologists, biologists, and federal, state, and local officials helped achieve the city's goals, which in addition to preserving salamander habitat, include reducing flood risk downstream, modernizing the dam to reduce risk of erosion or failure, and improve water quality.

For updates on construction and to learn more visit: https://www.austintexas.gov/watershed-protection/projects/old-lampasas-dam-modernization

8.3 Performing benefit-cost analysis

A benefit-cost analysis (BCA) evaluates the economic feasibility of a project by comparing its benefits to its costs over the life span of the project. BCAs aid practitioners in developing effective and sustainable flood mitigation strategies by balancing benefit costs over the life cycle of the project. How an NBS alternative is evaluated depends on who the final decision-makers are and what information they need to make decisions regarding the implementation of feasible solutions. If a BCA is needed, the methodology, calculations, and inputs used in a BCA should align with requirements of the intended source of funding and/or program. If the feasible solutions are submitted to state or federal agencies for funding, those agencies may have technical standards for completing a BCA. Note, not all funding sources require a BCA. See **Chapter 5** for more information on NBS funding.

Table 8-3. Benefit-cost analysis definitions

Term	Definition
Benefit Cost Analysis	A comparison of project benefits with project costs using a defined methodology to convert benefits and costs to equivalent units
Benefit Cost Ratio	The ratio calculated by dividing the benefits of a project by the costs
Present Value (PV)	The discounted value of future revenue or future costs which is based upon a defined discount rate and the future revenue/costs per year
Discount Rate	An interest rate used to discount future revenues or costs for a project; typically defined by the project sponsor before performing a benefit cost analysis
Recurrence Interval	The average number of years between floods of a certain size
Expected Annual Damage (EAD)	The average economic loss expected from flood events in a given year, calculated by integrating the probability and severity of various flood events with their corresponding damages.
Losses Avoided	The economic benefits of a flood risk management project quantified as the difference in damages that would occur without the project versus damages that occur with the project in place.
Project useful life (PUL)	The period of time over which the project is expected to be effective and provide its intended benefits

Calculating flood damage reduction benefits

Flood damage benefits are the economic losses avoided due to the project. Losses avoided are determined by calculating the difference between the expected flood damages before mitigation (without the project) and after mitigation (with the project).

Flood risk reduction benefits can include reduced flood damage to structures, roadways, utilities, or critical facilities. Historical flood damage records and results from a hydrologic and hydraulic (H&H) study can be used to establish and justify expected flood damages. Hydrology and hydraulics modeling results, such as those developed in **Chapter 7**, provide water surface elevations across a range of recurrence intervals that are needed to quantify expected damages.

The data required to quantify flood damages varies by asset type. For structures, the key inputs are the type and size of the structure, the finished floor elevation, and the depth of flooding within the structure, which is determined by comparing the water surface elevation from hydrology and hydraulics modeling to the finished floor elevation. For roadways, the daily traffic volume and the additional time and distance of the detour caused by road closure are needed to estimate economic losses from flood-related disruptions.

Once the depth of flooding is established for each asset and recurrence interval, depth-damage functions are used to monetize expected flood damages.

Depth-damage functions relate the depth of flooding above the finished floor elevation to a percent of the structure's value that is expected to be damaged. These functions are available for a range of structure types and are incorporated into standard BCA tools such as the FEMA BCA Toolkit or the TWDB Flood BCA Calculator.

Expected flood damages should be calculated for each recurrence interval both before mitigation (without the project) and after mitigation (with the project) to establish the damage reduction attributable to the NBS alternative.

Once expected flood damages are calculated, the expected annual damage (EAD) is calculated. Annual damages calculations consider the damage-frequency curve across all flood events and weight potential damages by their annual exceedance probability. **Table 8-4** shows an example calculation of expected annual damage from multiple recurrence intervals. The difference in EAD before and after mitigation represents the annual avoided damage.

It is not recommended that most practitioners conduct this calculation themselves. The Professional Expected Damages module within the FEMA BCA Toolkit is a good tool to use to calculate the present value of benefits based on damages from multiple recurrence intervals.[8]

Table 8-4. Expected annual damage from multiple recurrence intervals

Recurrence Interval	Probability	Event Damages	Annual Damages
10-year storm	10%	$20,000	$2,683
25-year storm	4%	$100,000	$9,487
100-year storm	1%	$1,000,000	$25,298
500-year storm	0.2%	$10,000,000	$19,999
Total (Expected Annual Damage)			**$57,467**

Adapted from TWDB Benefit-Cost Analysis Guidance

Quantifying additional benefits

Co-benefits such as ecosystem services and increased recreational opportunities can also be included in a BCA. As the science of valuing ecosystem services has matured through the large body of work of scientists, engineers, and practitioners, ecosystem service values have been incorporated into FEMA programs and policies.

FEMA has developed monetary values per acre for habitats that could be protected or enhanced as part of an NBS. To include the economic benefit of habitats, the "project must demonstrate a significant level of ecosystem restoration, creation, enhancement, or protection of the relevant land cover category".[9] A significant level of restoration would increase the health or functionality of an ecosystem. The annual ecosystem service value is multiplied by the area of habitat affected and then discounted to present value using the same discount rate and project useful life applied to flood damage benefits, as described above. In 2022, FEMA published a list of ecosystem services values ***FEMA Ecosystem Service Value Updates*** ↗.

For recreational benefits, the TWDB Benefit-Costs Analysis Guidance provides unit values and methodology for estimating the economic value of recreational opportunities associated with NBS features.

Not all co-benefits can be represented as a monetary value. However qualitative or quantitative descriptions of these co-benefits can be used in funding applications and stakeholder engagement.

Where appropriate, future climate conditions, such as projected sea level rise can be considered in a BCA. The TWDB ***Benefit Cost Analysis Guidance*** ↗ includes a case study comparing results for current climate and future climate scenarios.

Texas A&M AgriLife reviewed the national ecosystem services values published by FEMA, and after additional research and focused attention on Texas, published ***Ecosystem Services Values for Texas*** ↗. This study developed ecosystems services values specific to Texas. **Figure 8-5** compares the values determined for wetlands and urban green open spaces. For both ecosystems, the values determined by Texas A&M AgriLife were higher than published FEMA values. Using these Texas-specific values will result in higher benefit cost ratios.[10] These values have been accepted and used by Texas state agencies including TWDB and GLO.

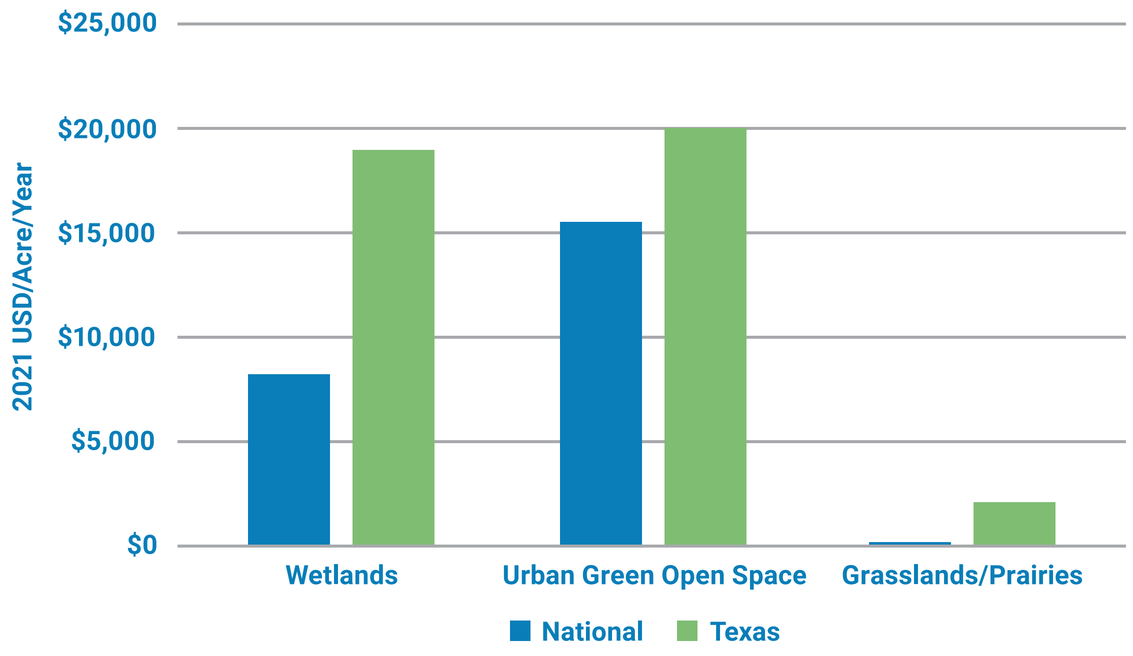


Figure 8-5. The value of ecosystem services in Texas compared to national average

Calculating costs

The costs associated with designing, permitting, and constructing NBS should be developed considering recent, local estimates. Link to resources have been provided to published datasets of construction costs for items included in NBS implementation. Maintenance costs should be estimated considering material, equipment, and wages needed to sustain the designed function of the NBS. **Chapter 13** provides considerations and common actions for maintaining NBS.

Life cycle costs include initial costs such as construction, materials, and labor, as well as future costs such as annual maintenance. The project useful life (PUL) is the period over which the project is expected to be effective and provide its intended benefits. The useful life of a project is the analysis period for economic calculations within the BCA.

FEMA has developed recommended project useful life (PUL) durations for elements commonly incorporated in NBS. For example, bioretention systems have a recommended PUL of 35 years, floodplain and stream restoration projects have a recommended PUL of 30 years, and land acquisition with a conservation easement has a recommended PUL of 100 years.

Definition

Ecosystem services

Benefits that natural systems provide to people, including flood attenuation, water quality improvement, habitat provision, carbon sequestration, and recreational opportunities. See Chapter 2 for a full discussion of ecosystem services associated with NBS.

Sandhill cranes in Muleshoe National Wildlife Refuge
Photo courtesy of USFWS

Calculating present value of costs and benefits

Future costs and benefits are discounted to present value using a discount rate that reflects the time value of money. That is, a dollar of benefit received in the future is worth less than a dollar of benefit received today. The discounted value, also referred to as the present value, of a future expected benefit is calculated as shown in **Figure 8-6**, where the difference between calendar year and discount year represents how far in the future the benefits are expected. The same formula can be used for future costs, such as annual maintenance. The appropriate discount rate should be confirmed with the intended funding agency prior to conducting the BCA, as different programs may apply different rates. Summing the discounted benefits across all years of the project useful life produces the total present value of benefits, which is then compared to the present value of project costs to calculate the BCR.

$$\text{Discounted Benefits} = \frac{\text{Benefits}}{(1 + \text{Discount Rate})^{(\text{Calendar Year - Discount Year})}}$$

Figure 8-6. Discounting Equation

Adapted from TWDB Benefit-Cost Analysis Guidance

Interpreting the results

A benefit-cost ratio (BCR) divides the benefits by the costs of a project. A BCR greater than 1.0 indicates that the project's measured benefits outweigh its costs, making it a cost-effective investment. This ratio can be used to determine which alternative provides the greatest net benefits to the community. However, BCR alone may not capture the full value of a project. Benefits that cannot be easily monetized, such as habitat quality, community resilience, or social equity, should be documented qualitatively and presented alongside the BCR to provide decision-makers with a complete picture of project value. Where multiple alternatives are being compared, net benefits (total benefits minus total costs) can be considered, as BCR and net benefits can produce different project rankings.

TWDB developed the BCA Guidance Document and associated BCA calculation software tool (TWDB Flood BCA Calculator) to support flood planning and funding activities. The guidance document discusses basic BCA concepts, levels of analysis, limitations, available computer programs, benefits, vulnerability, sensitivity, and costs. See TWDB's Benefit Cost website for more information. ***https://www.twdb.texas.gov/financial/programs/fif/bca.asp***

Tools and resources

- **FEMA**
  Benefit Cost Analysis ↗
- **TWDB**
  Benefit Cost Analysis Guidance Document ↗
- **RS Means**
  RSMeans Online ↗
- **Texas Department of Transportation (TxDOT)**
  Bid Items and Index ↗
- **Coastal Protection and Restoration Authority**
  Project Costing Tool Documentation ↗
- **Journal of Environmental Engineering**
  Comparison of Maintenance Cost, Labor Demands, and System Performance for Low Impact Development and Conventional Stormwater Management ↗

Lake Tyler near Whitehouse, Texas
Photo courtesy of the Texas Water Development Board

How To

Conceptual benefit-cost analysis for NBS for flood resilience

The purpose of this example is to walk through the process of incorporating NBS into a BCA for flood resilience projects. This hypothetical scenario involves a channel that runs through a residential area with homes on both sides of a channel and residential structures at risk of riverine flooding. A floodplain restoration project has been proposed to reduce flood risk and a voluntary property acquisition is proposed for repetitive loss properties. In this example, the owner does not anticipate applying for federal funding. As such, the values in this example were developed using the TWDB Flood BCA Calculator, which is a spreadsheet-based tool designed to support BCA calculations. Inputs and outputs from the calculator are referenced throughout this example.

Step 1. Data collection

Table 8-4 summarizes the key inputs used in this example. These inputs are required by the TWDB Flood BCA Calculator and should be collected and documented prior to beginning the BCA. The flood depths presented are hypothetical values used for illustrative purposes only. In practice, flood depths used in a BCA should be supported by historical damage records or results from a calibrated H&H model, as discussed in Chapter 7 and previously here in Chapter 8.

Step 2. Determine total project cost

The total project cost should include all costs required for the completion of the project, such as design, permitting, construction and annual maintenance cost. FEMA's standard value project useful life for floodplain restoration project is 30 years. For this example, the project cost is $1,000,000 with $1,000 in annual maintenance costs. Future annual maintenance costs are discounted to present value using the formula previously discussed. The total present value of project costs is calculated as the total of the discounted annual maintenance costs across all 30 years, in the TWDB Flood BCA Calculator this is $20,188. Therefore, the present value (PV) of the total cost over the project's useful life is:

PV Total Project Cost: $1,000,000 (project cost) + $20,188 (total discounted annual maintenance cost) = $1,020,188

Step 3. Calculate flood damage reduction benefits

In this example, 20 average sized houses are at risk of riverine flooding. After the floodplain restoration project is completed the depth of flooding at the structures is reduced. The expected depth of flooding at the structures before and after mitigation for the 2-percent (50-year), 1 percent (100-year), and 0.2 percent (500-year) annual chance flood events are shown in Table 8-4.

Depth-damage functions are then applied to convert flood depths to estimated dollar damages for each recurrence interval, as shown in Table 8-5. The reduction in flood depth at each recurrence interval reflects the hydraulic benefit of the floodplain restoration project and directly drives the reduction in expected damages. The difference in damages before and after mitigation at each recurrence interval are used to calculate the expected annualized damage avoided, as described in Step 5.

Flood damage reduction benefits are quantified as the expected annualized damage (EAD) avoided by the project. EAD is calculated by weighing the damages at each recurrence interval by the corresponding annual exceedance probability and integrating across the damage-frequency curve. As shown in Table 8-5, the EAD of $87,703 before mitigation and $60,850 after mitigation are calculated using the TWDB Flood BCA Calculator. The difference between the two, $26,853, represents the annual benefit provided by the reduction in flood risk. The total flood damage reduction benefit as a present value is calculated as sum of the annual benefits in each year of the project's useful life discounted to consider the time value of money. In this example the **PV flood damage reduction benefit is $542,121.**

Step 4. Incorporate ecosystem services

Ecosystem service benefits accrue when land use is changed or enhanced by a mitigation activity to provide a higher level of natural benefits. FEMA assigned a value for riparian habitat of $37,199 per acre per year in 2021.[9] In this example, 2 acres will be restored riparian habitat. The annual ecosystem service value is calculated by multiplying the per-acre annual value by the number of qualifying acres: $37,199 x 2 acres = $74,398 per year. This annual value is then discounted to present value over the 30-year project useful life using the same discount rate applied to flood damage benefits. The present discounted value of ecosystem services calculated using the Flood BCA Calculator is $1,723,637, as shown in Table 8-5.

Step 5. Calculate total benefits

The total benefits of the project, $2,265,757, are calculated as the sum of flood damage reduction benefits and ecosystem service benefits.

PV Total Benefits: $542,121 (flood damage reduction benefit) + $1,723,637 (ecosystem services) = $2,265,757

Step 6. Calculate the BCR

When comparing only the flood damage reduction benefits versus the cost, the BCA is 0.5 which is not cost-effective.

Final BCR (with ecosystem services) = $2,265,757 (PV Total Benefits) / $1,020,188 (PV Total Costs) = 2.2

Accounting for ecosystem services benefits in this example resulted in a cost-effective project.

Table 8-4. Conceptual BCA input values

Input	Value
Number of structures at risk	20
Structure type	Single-family residential
Average structure size	2,500 square feet
Depth of flooding 50-year event	12 inches (before mitigation) 0 inches (after mitigation)
Depth of flooding 100-year event	24 inches (before mitigation) 12 inches (after mitigation)
Depth of flooding 500-year event	36 inches (before mitigation) 24 inches (after mitigation)
Project cost	$1,000,000
Annual maintenance cost	$1,000
Project useful life (PUL)	30 years
Area of riparian habitat restored	2 acres

Table 8-5. Conceptual BCA results

Even Damages	Before Mitigation	After Mitigation
50-year storm	$3,086,160	$1,657,065
100-year storm	$4,391,843	$3,086,160
500-year storm	$5,602,387	$4,391,843
Expected annualized damages (EAD)	$87,703	$60,850
PV flood damage reduction benefit		$542,121
PV ecosystem services benefit		$1,723,637
PV total benefits		$2,265,757
PV total project cost		$1,020,188
Final BCR		**2.2**

8.4 Performing triple bottom line analysis

While a traditional BCA focuses primarily on economic costs and benefits, a triple bottom line analysis provides a more comprehensive framework for evaluating NBS by considering three interconnected dimensions of value: economic, social, and environmental. This approach recognizes that the full value of NBS extends beyond direct financial returns and flood damage reduction, encompassing broader community and ecological outcomes that are often difficult to capture in a standard BCA.

The economic dimension of this analysis aligns closely with traditional BCA metrics, including flood damage reduction, infrastructure cost savings, and property value impacts. However, triple bottom line also accounts for longer-term economic considerations such as reduced emergency response costs, avoided costs associated with water quality degradation, and the economic value of ecosystem services such as carbon sequestration, groundwater recharge, and water supply protection.

The social dimension evaluates how a project affects community well-being, equity, and quality of life. For NBS projects, social benefits may include improved access to green space and recreational opportunities, enhanced community resilience and preparedness, health benefits associated with improved air and water quality, and equitable distribution of flood risk reduction across diverse or historically underserved communities. Engaging stakeholders throughout the planning process is a key component of understanding and documenting social value.

The environmental dimension captures ecological outcomes that are often treated as co-benefits in a traditional BCA but are central to the value proposition of NBS. These include improvements to water quality, habitat restoration, biodiversity support, urban heat island reduction, and the long-term health of aquatic and riparian ecosystems. Where possible, environmental benefits should be quantified using established methodologies, such as ecosystem services to strengthen the overall case for NBS investment.

When a full BCA is not required or does not adequately capture all relevant project benefits, a triple bottom line analysis can serve as a valuable supplementary or standalone evaluation tool. Decision-makers and funding agencies are increasingly recognizing the importance of documenting co-benefits and social and environmental outcomes alongside traditional economic metrics. Presenting NBS projects through a triple bottom line lens can help communicate their full value to a broader range of stakeholders and strengthen the case for implementation and long-term investment.

8.5 Prioritizing NBS alternatives

Identified project alternatives often need to be compared against each other to prioritize community resources. Potential projects can be evaluated and prioritized through an iterative and comprehensive process called alternatives analysis that compares potential NBS to address flood risks while considering community objectives and stakeholder priorities. The alternatives analysis phase builds on the findings of the opportunity assessment by further investigating the viability of potential NBS projects. The primary goal of this phase is to evaluate alternatives to determine their effectiveness and long-term feasibility in addressing flood risks, providing co-benefits, and addressing community needs.

Stakeholder engagement is an important component of the alternatives analysis phase, since balancing trade-offs between different project alternatives requires robust input from diverse groups. Stakeholders, including community members and environmental advocates, provide valuable perspectives on the feasibility and/or desirability of different options. Engaging these stakeholders early and often allows for transparency and fosters the collaborative, multidisciplinary approach to decision-making that is valuable for community support and overall project success.

Comparing and contrasting performance can be done with computer models, or it can be based on scoring using proven instances of flooding. To evaluate both NBS and gray solutions, evaluation metrics should be used for each project goal. The project goal of flood risk reduction could be measured as the flood risk reduction to structures, roadways, agricultural land, utilities, or critical infrastructure.

Evaluation metrics for flood risk reduction could include the number of structures or length of roadway with reduced flood risk. Evaluation metrics for co-benefits of NBS could include benefits to impaired water bodies, area of habitat created or enhanced, or the area of park space created.

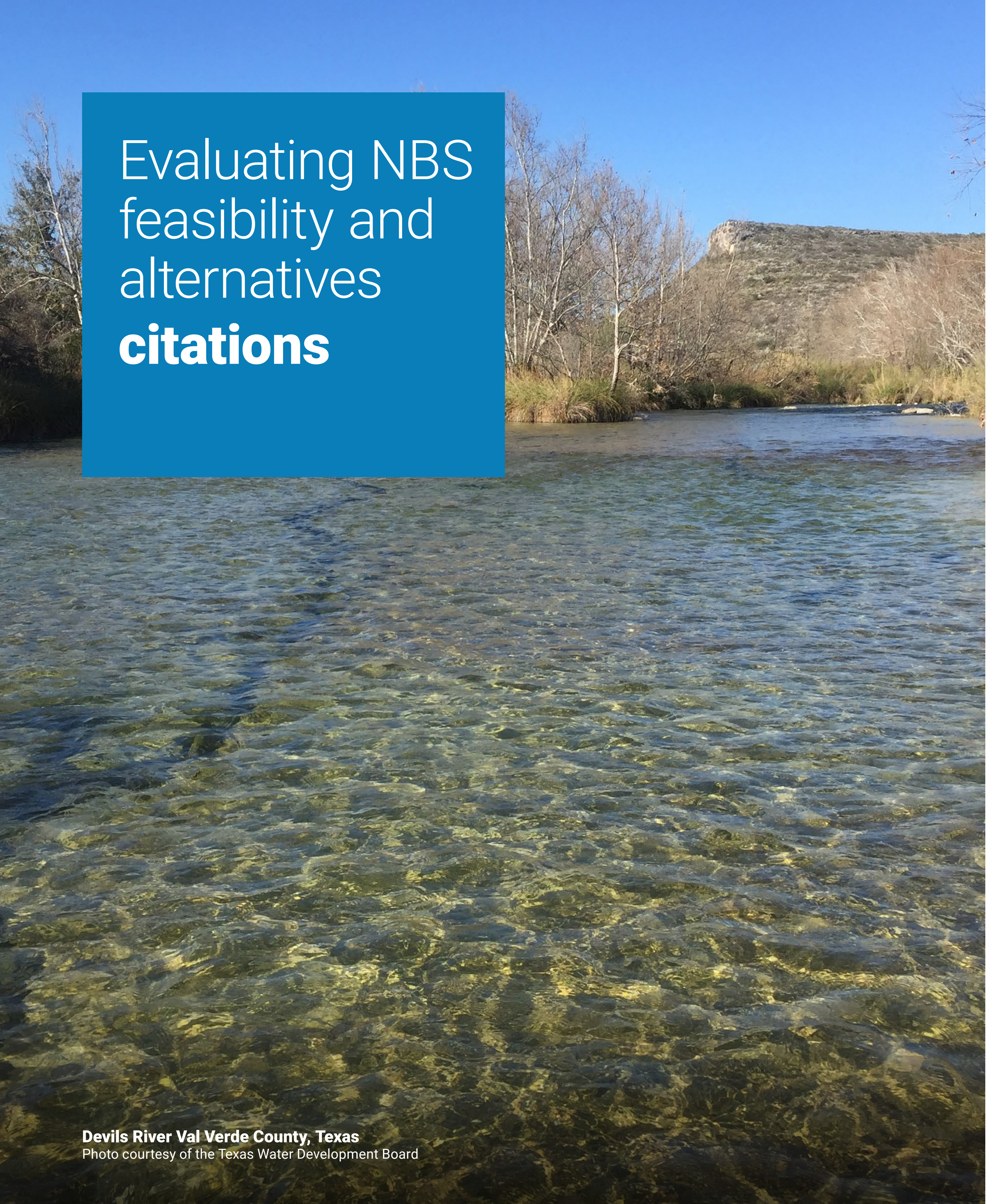
When evaluating alternatives, it is important to remember that NBS provide economic value to communities through co-benefits not directly related to flood risk and are often left out of a traditional flood mitigation BCA. Co-benefits beyond flood risk reduction should be quantified and considered for their relevance to community goals. Co-benefits, such as recreation or habitat restoration, realize value each year and are not linked to flood events.

Priority can also be given to flood resilience approaches which are adaptable over time, especially if there is uncertainty about future conditions. NBS can be explicitly prioritized by co-benefits such as improved air and water quality, reduced urban heat island effects, and recreational opportunities.

An alternatives evaluation table (**Table 8-5**) can be developed to help differentiate between alternatives that may receive similar BCAs and facilitate prioritization. It is possible that the decision context and criteria for this comparative evaluation will primarily focus on available project funding, regulatory requirements, and financial contribution from relevant stakeholders. In most instances, the project cost and its associated benefits are the deciding factors for the ultimate selection of NBS options.

Table 8-6. Example of project evaluation table to differentiate between NBS alternatives

Criteria Name	Criteria Type	Percent Weight
Flood damage reduction - structures	Flood risk reduction	50%
Flood damage reduction - roadways	Flood risk reduction	20%
Water supply benefit	Co-benefits	5%
Environmental benefit	Co-benefits	10%
Recreation, social assets	Co-benefits	15%
Total (Must add up to 100%)		**100%**



Evaluating NBS feasibility and alternatives **citations**

Devils River Val Verde County, Texas
Photo courtesy of the Texas Water Development Board

---

[1] Bridges, T. S., J. K. King, J. D. Simm, M. W. Beck, G. Collins, Q. Lodder, R. K. Mohan, eds. 2021, Overview: International Guidelines on Natural and Nature-Based Features for Flood Risk Management, Vicksburg, MS, U.S. Army Engineer Research and Development Center, https://ewn.erdc.dren.mil/international-guidelines-on-natural-and-nature-based-features-for-flood-risk-management/, accessed June 2026.

[2] Texas General Land Office, 2022, Sustainable stormwater drainage, Clean Coast Texas, Texas General Land Office, https://www.glo.texas.gov/sites/default/files/2025-01/2022-sustainable stormwater-drainage-cleancoasttexas.pdf, accessed June 2026.

[3] International Society of Arboriculture (ISA) Texas, n.d., Best management practices for tree protection, International Society of Arboriculture Texas Chapter, https://isatexas.com/wp-content/uploads/2015/11/BMPs-Tree-Protection.pdf, accessed June 2026.

[4] Gulf of Mexico Fishery Management Council and National Oceanic and Atmospheric Administration (NOAA) Fisheries, 2004, Final Environmental Impact Statement for the Generic Essential Fish Habitat Amendment to the Fishery Management Plans of the Gulf of Mexico: Shrimp, Red Drum, Reef Fish, Stone Crab, Coral and Coral Reef, Spiny Lobster, and Coastal Migratory Pelagic Resources, March 2004, Gulf of Mexico Fishery Management Council, Tampa, FL, NOAA Fisheries Southeast Region, St. Petersburg, FL, https://gulf-council-media.s3.amazonaws.com/uploads/2025/03/March-2004-Final-EFH-EIS.pdf, accessed June 2026.

[5] U.S. Environmental Protection Agency, 2022, Compendium of MS4 Permitting Approaches: Green Infrastructure, June 2022, U.S. Environmental Protection Agency, https://www.epa.gov/system/files/documents/2022-06/Green%20Infrastructure%20MS4%20Compendium%202022_3.pdf, accessed June 2026.

[6] Texas Commission on Environmental Quality, n.d., Stormwater requirements for construction activities, Texas Commission on Environmental Quality, https://www.tceq.texas.gov/permitting/stormwater/construction/index#stormwaterrequirements, accessed June 2026.

[7] Texas Commission on Environmental Quality, n.d., RG-348: Stormwater General Permit for Construction Activities, Texas Commission on Environmental Quality, https://www.tceq.texas.gov/publications/rg/rg-348, accessed June 2026.

[8] Texas Water Development Board, 2026, Benefit Cost Analysis Guidance: A Framework for Conducting Benefit Cost Analysis for Flood Risk Management Projects in Texas. Texas Water Development Board, https://www.twdb.texas.gov/financial/programs/fif/doc/TWDB_BCA_DRAFT_508.pdf, accessed June 2026. .

[9] Federal Emergency Management Agnecy, 2020, FEMA Ecosystem Service Value Updates, https://www.fema.gov/sites/default/files/documents/fema_ecosystem-service-value-updates_2022.pdf, accessed June 2026.

[10] Texas A&M AgriLife Extension Service, 2025, Ecosystem service values for Texas—Quantifying environmental benefits for benefit cost analysis of green infrastructure, https://agrilife.org/gift/files/2025/08/Ecosystem-Service-Values-for-Texas_FINAL-August-2025.pdf,accessed June 2026.

9

Designing and building NBS

This chapter reviews general design, bidding, and construction best practices applicable to all NBS contexts for effective implementation and long-term performance.

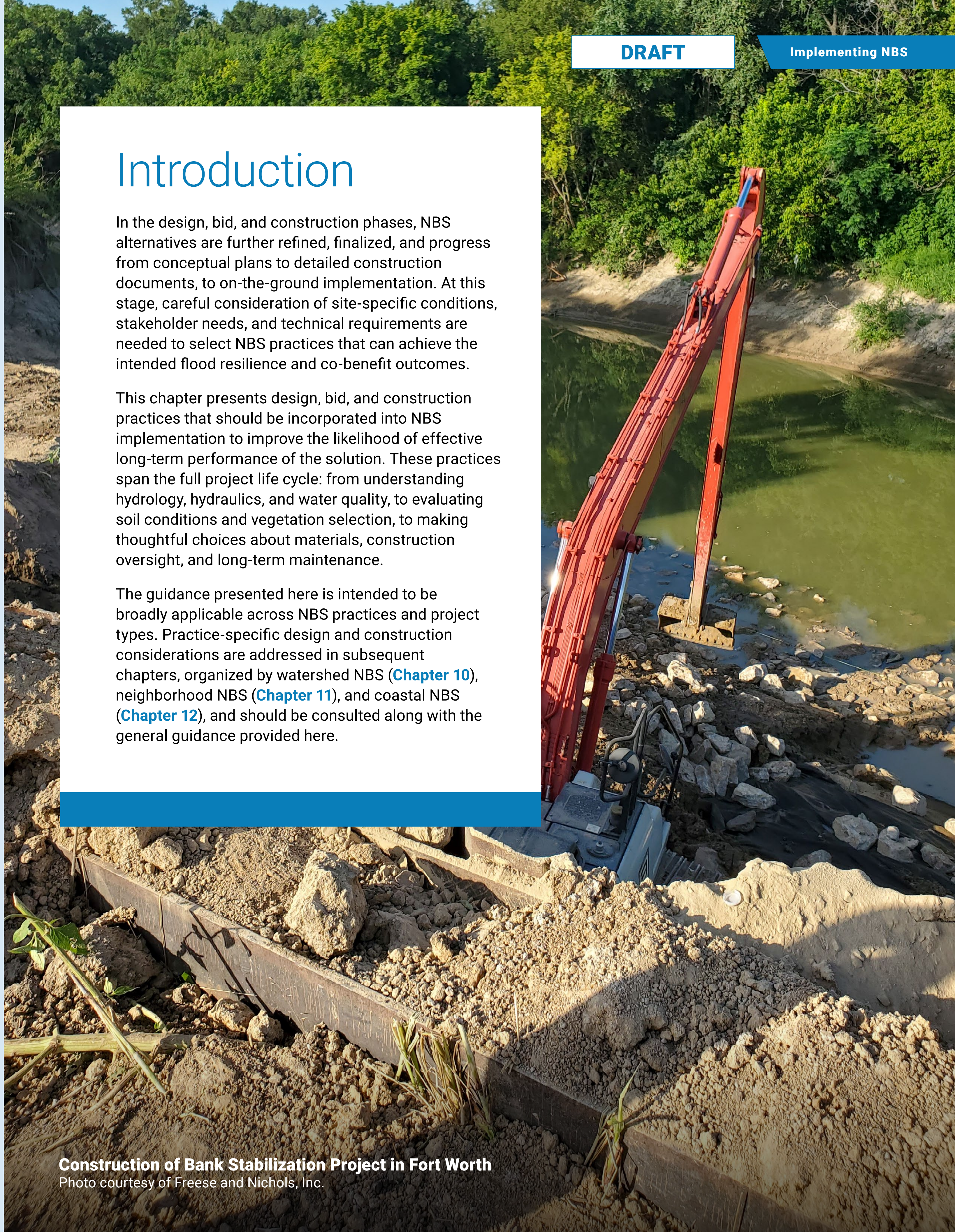
Key takeaways

- The design phase converts project concepts into detailed construction documents, the bid phase selects a contractor to perform the work, and the construction phase builds the project.
- Integrating design, bid, and construction best practices that consider hydrology, hydraulics, water quality, vegetation selection and establishment, contractor prequalification, compaction avoidance, construction oversight, and maintenance enhances project success.

Riverside Park in Brownwood, Texas
Photo courtesy of Freese and Nichols, Inc.

How the guiding principles apply to this chapter

Engage and include	Engage community members, operation and maintenance staff, and permitting agencies in design development so NBS meet functional, aesthetic, and maintenance expectations.
Apply systems thinking	Design NBS to deliver multiple benefits – flood risk reduction, habitat creation, recreational opportunities – by integrating hydrology, ecology, geomorphology, and community needs into a unified solution.
Work across boundaries	Collaborate across departments and with engineers, landscape architects, ecologists, urban planners, contractors, and funding specialists during design and construction to align performance, cost, and constructability.
Learn and adapt Continuously	Document design decisions and construction practices and develop post-construction feedback loops and performance monitoring protocols to inform future projects and maintenance strategies.



Introduction

In the design, bid, and construction phases, NBS alternatives are further refined, finalized, and progress from conceptual plans to detailed construction documents, to on-the-ground implementation. At this stage, careful consideration of site-specific conditions, stakeholder needs, and technical requirements are needed to select NBS practices that can achieve the intended flood resilience and co-benefit outcomes.

This chapter presents design, bid, and construction practices that should be incorporated into NBS implementation to improve the likelihood of effective long-term performance of the solution. These practices span the full project life cycle: from understanding hydrology, hydraulics, and water quality, to evaluating soil conditions and vegetation selection, to making thoughtful choices about materials, construction oversight, and long-term maintenance.

The guidance presented here is intended to be broadly applicable across NBS practices and project types. Practice-specific design and construction considerations are addressed in subsequent chapters, organized by watershed NBS (**Chapter 10**), neighborhood NBS (**Chapter 11**), and coastal NBS (**Chapter 12**), and should be consulted along with the general guidance provided here.

Construction of Bank Stabilization Project in Fort Worth
Photo courtesy of Freese and Nichols, Inc.

9.1 NBS design best practices

The design phase focuses on converting conceptual NBS project alternatives into detailed construction documents. Collaborative and multidisciplinary teams typically include engineers, environmental scientists, landscape architects, and project managers who work to address technical requirements, efficacy evaluation, stakeholder considerations, and regulatory compliance. Effective coordination among these disciplines from the outset enables decisions to be technically sound, ecologically appropriate, and aligned with both community needs and regulatory expectations.

The design phase also provides an important opportunity to identify and resolve potential conflicts between performance goals, site constraints, and funding or regulatory requirements before they become costly construction-phase issues. Equally important to the design phase is the integration of adaptive management principles — recognizing that NBS implementation is an iterative process of continuous learning and improvement. By incorporating lessons learned from past projects and real-world performance data into design decisions, communities can refine standards over time, build institutional knowledge, and increase long-term confidence in NBS as a reliable tool for flood risk reduction.

When approached thoughtfully, the design process not only produces construction-ready documents but also builds the technical record needed to demonstrate project efficacy, support permitting, and satisfy the requirements of funding programs.

Hydrology and hydraulics

The purpose of NBS design is to achieve the goals set previously in the planning process and comply with all applicable regulations and criteria. Designers should relate overall project goals to specific design targets. Design storm targets are measurable such as a maximum water surface elevation, discharge, or velocity, or a minimum volume of detention at selected designed storms. Design storms are hypothetical rainfall events characterized by the probability of occurrence, commonly 10 percent (10-year), 4 percent (25-year), 1 percent (100-year), or 0.2 percent (500-year) annual chance flood events.

Many communities in Texas have adopted stormwater design manuals that prescribe preferred or required hydrologic and hydraulic methods and minimum or maximum values for design inputs that should be followed within the appropriate jurisdiction. Beyond local criteria, NBS designs must also satisfy the requirements of applicable regulatory agencies and any external funding programs financing the project. See **Chapter 8 for more information on assessing regulations and permitting requirements**.

Notably to be recommended in the state flood plan and eligible for Flood Infrastructure Fund (FIF) funding, NBS designs are subject to a no adverse impact requirement. No Adverse Impact floodplain management takes place when the actions of one property owner are not allowed to adversely affect the rights of other property owners.[1] In other words, when implemented the proposed infrastructure must not increase water surface elevations on neighboring or downstream properties. This standard reinforces the importance of thorough hydrologic and hydraulic analyses to demonstrate that a project's design does not shift flood burdens onto others.

Water quality

Water quality is impacted by factors within the channel corridor and in the contributing drainage area. Increased impervious cover and other human activities can degrade water quality in small streams, large channels and rivers, and coastal bays and estuaries. NBS design, including vegetation selection, should be informed by what impairment, if any, is present in streams within the contributing drainage area of the NBS site. TCEQ maintains the ***Surface Water Quality Segments Viewer*** ↗, an interactive map that allows a user to determine information about a stream—including whether it is classified as impaired. TCEQ biennially assesses surface water quality across the state and publishes results in an integrated report. **The latest integrated report can be assessed here: *www.tceq.texas.gov/waterquality/assessment*** ↗

TCEQ published a design and construction guidance for NBS that can help address water quality issues. For example, the TCEQ ***Complying with the Edwards Aquifer Rules: Technical Guidance on Best Management Practices (BMPs) (RG-348)*** ↗ provides design criteria, sizing calculations, and specifications. TCEQ also provides discussion on landscaping and vegetation, pesticide and fertilizer management, management of sensitive areas, and opportunities for innovation. Although the TCEQ published this guidance specifically for areas within the Edwards Aquifer Zones the general principles can be applied across other parts of Texas.[2]

The design of neighborhood NBS should consider pollutant removal efficiency through appropriate media selection, flow path design, and pretreatment strategies. Engineered soil media should be specified to target common pollutants such as bacteria, nutrients, metals, and hydrocarbons, with adequate infiltration rates to prevent surface ponding and maintain treatment function. Pretreatment components like sediment forebays, curb cuts with energy dissipation, or trash racks should be integrated to reduce clogging and maintenance frequency (see **Chapter 11**).

The water quality treatment capacity of NBS should also be considered during design. The water quality treatment volume is typically based on the rainfall depth targeted for capture and treatment in accordance with local regulatory requirements or design guidance. Where local standards are unavailable, many guidance documents recommend capturing and treating runoff from approximately the first 1 inch of rainfall to maximize pollutant removal benefits. ***The Green Infrastructure for Texas (GIFT) Toolkit*** ↗ provides additional guidance on water quality volume calculations, BMP sizing approaches, and treatment considerations for green stormwater infrastructure practices across Texas. Overflow or bypass structures should also be incorporated to safely convey storm events that exceed the water quality treatment capacity.

Vegetation selection and establishment

Plant selection should prioritize native or climate-appropriate species that provide long-term sustainability and biodiversity. Native plants have a higher probability of survival when used in NBS practices compared to non-native plants. Practitioners should consider all components that make plants resilient: soil type, slopes, surrounding vegetation, water usage, and sun and water exposure.

Tools and resources

- **TCEQ**
  - *Texas Integrated Report of Surface Water Quality for Clean Water Act Sections 305(b) and 303(d)* ↗
  - *Surface Water Quality Segments Viewer* ↗
  - *Complying with the Edwards Aquifer Rules: Technical Guidance on Best Management Practices (BMPs) (RG-348)* ↗
- **Texas A&M AgriLife Green Infrastructure for Texas**
  - *Green Infrastructure Toolkit Implementation Guide* ↗

When selecting vegetation for flood mitigation projects, designers should consider the types of pollutants likely present in runoff, such as heavy metals, nutrients, oils, or salts, and match these with species capable of tolerating or effectively absorbing them. Vegetation should also be selected for its resilience to local climate extremes. Contextualizing species selection in this way increases both performance and durability of NBS features. Species should be capable of withstanding both drought and flooding conditions experienced in the project region.

To maintain ecological resilience, vegetation should include a mix of vegetative types such as grasses, forbs, shrubs, and trees with varied root structures and growth forms. Plant monitoring should track species diversity and adjust composition as needed to prevent monocultures. Plant lifespan (annual, biennial, perennial) also impacts monitoring and maintenance needs. Annuals, which have shallower root systems, tend to require more frequent watering and fertilizing than biennials and perennials. Care for biennial and perennials can vary from year to year and may require winter protection. It is important to understand the maintenance implications of picking plants with different lifespans.[3,4]

Integrating adaptive management into the establishment of vegetation involves continuous monitoring of vegetation health, allowing for adjustments in plant selection or maintenance practices based on performance and changing site conditions over time. Regular site inspections should be completed to check that vegetation is installed correctly.

The life cycles of the selected vegetation should be leveraged when determining construction sequencing to align planting with the vegetation's growing season. Construction sequencing also requires careful consideration to avoid undue disturbance to adjacent habitats. For example, the timing of coastal NBS implementation should align with the stages of marine life cycles and periods of environmental conditions that result in minimal ecological effects. Restoration activities should avoid disrupting wildlife during breeding or migration seasons, plant vegetation during optimal growing periods, and take advantage of favorable weather and tidal conditions to minimize ecological and logistical challenges. Proper timing also minimizes conflicts with human activities, such as fishing or recreation, which allows for smoother implementation and maximizes ecological benefits.[5]

To best determine the appropriate time for coastal NBS implementation, coordination with organizations like the TPWD Coastal Fisheries or Wildlife Divisions is encouraged. Fostering community involvement through partnerships with volunteer organizations, providing clear communication about project timelines and purpose to local officials, and creating or protecting public access to alternate recreational spaces can mitigate these socio-economic disruptions. Through time, the long-term ecological and economic advantages of coastal NBS will far outweigh the initial challenges.

The logistics of plant sourcing, installation methods, construction scheduling of planting, and temporary irrigation should be considered during the design phase to verify the feasibility of vegetation selection. It is important to include critical ecological milestones in the construction schedule such as planting season, coordination with native plant nurseries, and seasonal constraints related to habitat and wildlife activity.

Adaptive management process

Adaptive management formalizes improvement of NBS performance through a structured, evidence-based process that links planning, implementation, monitoring, evaluation, and adjustment. This cycle provides the foundation for continuous learning, allowing managers to adapt maintenance schedules, vegetation management, and performance-monitoring protocols based on evidence rather than assumptions.

The U.S. Department of Interior Nature-Based Solutions Roadmap and San Antonio River Authorities (SARA) Green Stormwater Infrastructure (GSI) Master Plan have adopted the following six-step process, as shown in **Figure 9-1**, that allows data from the field to directly shape project planning and implementation.

1. **Assess:** Define the desired goals and objectives, evaluate alternative actions, and select a preferred strategy while recognizing sources of uncertainty.
2. **Design:** Identify and design a flexible management action to address the challenge.
3. **Implement:** Implement the selected action according to its design.
4. **Monitor:** Monitor the results or outcomes of the implemented management action.
5. **Evaluate:** Evaluate the system response in relation to the specified goals and objectives.
6. **Adjust:** Adapt the action if necessary to achieve the stated goals and objectives.

Creating an adaptive management plan is discussed in **Chapter 13**.

Tools and resources

- **U.S. Department of Agriculture (USDA)**
  Plant List of Attributes, Names, Taxonomy, and Symbols (PLANTS) Database ↗
  Texas Plant Materials Center ↗
  South Texas Plant Materials Center ↗
  National Plant Materials Centers (NRCS) ↗
- **Texas Smart Scape**
  Plant Database Search ↗
- **Lady Bird Johnson Wildflower Center**
  Plant Lists and Collections ↗

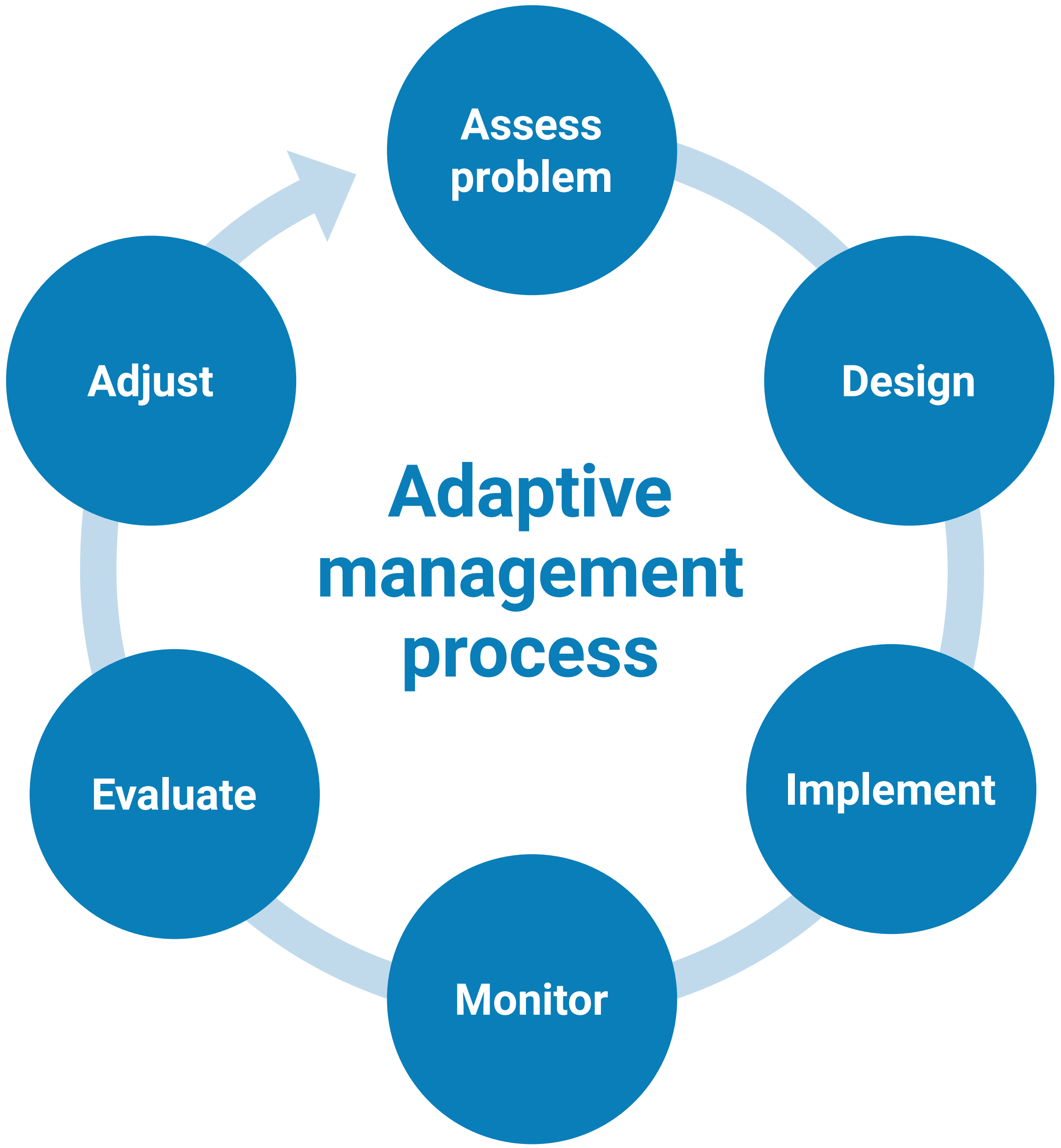


Figure 9-1. Adaptive management process. Incorporating lessons learned through a formalized adaptive management process is considered best practice for NBS implementation.

9.2 NBS bidding best practices

The bid phase focuses on selecting a contractor to perform the construction work. In traditional bidding processes, contractors submit proposals to the owner and selection is often based on the lowest bid. However, this approach may not always lead to the best outcome for complex or specialized design work. Qualification-based or value-based procurement offer alternative approaches, prioritizing contractor competence, relevant experience, and past performance over cost alone. While many bid advertisements include qualification requirements, such as references or licensing, the final selection is still typically based on price. **Hiring experienced contractors familiar with NBS is beneficial to implement NBS designs in compliance with environmental regulations.** Coordination between designers, contractors, and regulatory agencies is beneficial to adapting designs to field conditions and success of NBS implementation.

NBS require specialized knowledge of soils, hydrology, and ecological systems and contractor expertise in these areas can be invaluable to project success. Because NBS involve techniques that may differ significantly from traditional construction, selecting a contractor solely based on cost can lead to performance issues or even project failure. Given the importance of experience in executing these types of projects effectively, qualification-based selection, or hybrid approaches that incorporate both cost and qualifications, may be especially appropriate for NBS implementation. The following procurement approaches provide varying levels of emphasis on contractor qualifications, technical approach, project understanding, and cost when delivering NBS projects:

Standard competitive bid is a procurement method where construction contracts are typically awarded to the lowest responsive and responsible bidder.[6] For NBS projects, owners may strengthen this approach by incorporating minimum qualification requirements or contractor prequalification processes prior to bidding. These requirements may include demonstrated experience with similar project types, references, specialized subcontractor qualifications, or personnel certifications relevant to the project's needs.

Competitive sealed proposals (CSP) is a method where qualifications, technical approach, and pricing are evaluated concurrently. Similar best-value procurement approaches, including some design-build delivery methods, allow project owners to consider technical approach, project understanding, implementation strategy, staffing, schedule, and relevant experience alongside cost.

Construction manager at risk (CMAR) is a project delivery method in which a construction manager is selected early in the design phase to provide input on constructability, cost estimates, and scheduling. The CMAR commits to delivering the project within a Guaranteed Maximum Price (GMP), assuming the risk for construction performance and budget. Selection is typically qualifications-based and follows a best-value process similar to CSP. Project owners may shortlist firms based on qualifications and request pricing from the shortlist for final selection.

Although these options are not solely qualification based, they place greater emphasis on the quality of the construction process and the final design outcome. When using any bidding method for NBS, the effect of the timing of bid advertisement on the overall project schedule should be considered. Because NBS often involve seasonal constraints—such as high-water season, optimal planting windows, or the need to avoid construction during nesting or mating seasons for threatened and endangered species—the timing of bid advertisement should be aligned with the desired construction start date. Advertising too late could push the construction window into a period where work is restricted or less effective, resulting in project delays or reduced project performance.

9.3 NBS construction best practices

The construction phase focuses on implementing NBS practices correctly, efficiently, and with ecological sensitivity. This requires close collaboration among owners, contractors, engineers, landscape architects, and environmental professionals to balance construction activities with minimal ecological and environmental disruption and to properly implement the design. Because many NBS elements are living systems and depend on natural processes, increased involvement from the design engineer or landscape architect may be necessary throughout construction, compared to construction of gray infrastructure. All construction activities should aim to minimize disturbances and integrate seamlessly with the surrounding environment. This is especially important for sites located in or around sensitive ecological areas.

Construction sequencing

Construction activities for NBS projects should begin with reviewing the design intent with the contractor to support a full understanding of the natural systems involved, including ecological processes and long-term functional goals. Important ecological milestones should be incorporated into the construction schedule, such as planting seasons and seasonal constraints related to habitat and wildlife activity. Coordination with native plant nurseries can confirm that the quantity and species of vegetation are available in alignment with the construction schedule.

Inspection hold points should be identified in the project manual and reviewed at the pre-construction meeting. The contractor should not proceed past a hold point without documented engineer approval. Hold points are necessary for work that cannot be easily inspected after burial or coverage so that all elements are verified before construction continues. To support this, practitioners may reference tools such as the Construction Inspection Checklists provided in the ***Georgia Stormwater Management Manual*** ↗ (Volume 2, Appendix C-1). These templates outline step-by-step inspection points for NBS elements during construction, including grading, media placement, planting, erosion control, and overall site stabilization. Adapting these checklists for local conditions can help with oversight, promote accountability, and consistency in the delivery of NBS projects.

Minimizing disturbances can include limiting the area of construction, using low-decibel or low-emission machinery, shortening the construction period where feasible, and selecting materials that pose no harm to existing flora and fauna. Construction plans, project manuals, and any other associated documents should collectively encourage low impact construction practices to minimize the disturbance of the surrounding ecosystems and align with the performance goals and environmental values of NBS being implemented.

Erosion and Sediment Control

Premature runoff from disturbed areas can clog engineered soil media, reduce available storage volume. Temporary erosion and sediment control measures should be used throughout active construction until adjacent surfaces are stabilized and inspected after every rain event. Effective erosion control measures are also necessary to protect side slopes of ponds, channels, and swales during the establishment phase. Temporary erosion control methods, such as blankets, mats, or mulch, should be implemented. In areas with high water flow, turf reinforcement matting may be necessary.

Improper grading, inadequate slopes, or excessive vegetation can lead to standing water that can attract biophysical vectors. Biophysical vectors, such as mosquitoes, flies, or rodents, are an important consideration given their potential to transmit diseases to humans and animals. Contractors should avoid creating conditions that attract these vectors such as standing water.

Soil compaction prevention

Construction activities can cause compaction, especially when using heavy machinery. Compaction conflicts with the goals of many NBS, as it decreases infiltration rates in soil due to less space between individual soil particles. Soil compaction should be mitigated when possible, and resolution strategies should be determined for high compaction sites. Compaction can be reduced by placing materials using manual labor rather than heavy machinery. Access to infiltration areas should be restricted with tarps or barriers while the area is not worked on.

Vegetation protection and establishment

Vegetation should be planted only after grading and all structural elements are complete and stable to minimize exposure to construction-generated sediment, fines, and debris. Vegetation should be planted during the appropriate seasonal window. Species must be placed at correct elevations, as incorrect elevation results in plant mortality.

During the establishment period, the contractor may be responsible for monitoring and re-seeding as needed, including irrigation, and removal of invasive species. Contractors should be familiar with contract requirements for plant survival rates, re-planting thresholds, and the length of the establishment monitoring period. Post-storm coordination with contractors during a warranty period, combined with internal monitoring, helps assess site conditions and determine whether changes to the design or schedule are needed to protect ecosystem integrity and project functionality.

Tree protection during construction is important for preserving existing canopy, maintaining soil stability, and supporting the long-term ecological function of NBS. Construction activities can damage trees through root compaction, trenching, grade changes, or equipment impacts within the critical root zone. Soil compaction caused by construction traffic can significantly reduce soil pore space, limiting oxygen and water availability to roots and contributing to long-term tree decline.[7] To minimize impacts, temporary fencing and clearly delineated tree protection zones should be established, while equipment access, grading, trenching, and material storage within root zones should be avoided whenever possible.[8]

> “The best time to plant trees in Texas is November through early spring, and a little research before planting will increase your chances of long-term success.”
>
> - Texas A&M Forest Service[9]

Where utility installation or excavation near trees is unavoidable, construction methods should minimize root disturbance. Protecting mature trees during construction preserves stormwater interception, evapotranspiration, shading, habitat value, and other co-benefits provided by existing vegetation while supporting the long-term hydraulic and ecological performance of NBS.

Construction in or near water

All work conducted in or adjacent to water bodies requires advance planning for water control, regulatory compliance, and protection of aquatic habitat. Contractors should review all permit conditions related to in-water work windows before mobilizing. Properly install and maintain flow bypass systems to keep water out of the active work zone. Schedule in-channel work during approved low-flow windows and have contingency plans for unexpected flow events.

Install and maintain temporary measures to control turbid discharge from active channel work; inspect turbidity controls after every rain event and following any in-channel disturbance. Staging areas should be located upland and away from sensitive marsh and wetland areas to prevent fuel, concrete washout, or other contaminants from reaching the water.

Tools and resources

- **EPA**
  - *Construction Sequencing* ↗
  - *Bioretention Design Handbook Chapter 13 Managing the Construction Process* ↗
- **GLO**
  - *Guidance for Sustainable Stormwater Drainage on the Texas Coast: Construction Phase Erosion and Sediment Control Planning* ↗
- **Texas A&M Forest Service**
  - *Put the right tree in the right place to maximize benefits to landscape* ↗
- **Houston Parks Board**
  - *Riparian Technical Field Guide* ↗
- **Hill County Alliance**
  - *Riparian Management* ↗
  - *Georgia Stormwater Management Manual (Volume 2, Appendix C-1)* ↗

Figure 9.2. Riparian vegetation establishment. This occurred along the West Fork Trinity River in Fort Worth, Texas.

Photo courtesy of Freese and Nichols, Inc.

Designing and building NBS **citations**

Blue Hole Park in Georgetown, Texas
Photo courtesy of the Texas Water Development Board

[1] Association of State Floodplain Managers (ASFPM), 2008, No Adverse Impact Floodplain Management White Paper: Association of State Floodplain Managers, https://asfpm-library.s3-us-west-2.amazonaws.com/ASFPM_Pubs/ASFPM_NAI_White_Paper_2008.pdf.

[2] Texas Commission on Environmental Quality, n.d., Complying with the Edwards Aquifer Rules: Technical Guidance on Best Management Practices (RG-348): Texas Commission on Environmental Quality, https://www.tceq.texas.gov/downloads/publications/rg/complying-with-the-edwards-aquifer-rules-rg-348.pdf.

[3] Bale, S., and Durham, R., 2024, Annual and perennial flowers: University of Kentucky Cooperative Extension Service, Kentucky Master Gardener Manual, chap. HO-102, https://publications.mgcafe.uky.edu/ho-102.

[4] Oregon State University Extension Service, 2014, Annuals, biennials, & perennials, Oregon State University Master Gardener, https://extension.oregonstate.edu/sites/extd8/files/documents/12281/annualsperennials.pdf.

[5] Washington Department of Fish and Wildlife. 2021. The value of estuary habitat restoration for Skagit Chinook salmon recovery. https://wdfw.wa.gov/sites/default/files/2021-02/skagitchinookestuaryhandout.pdf

[6] Texas Department of Transportation, 2026, Local Government Projects Policy Manual, Section 7. Plans, Specifications, & Estimates (PS&E) Development) https://www.txdot.gov/manuals/tpd/lgp/plans_specifications_estimates_pse_development/bid_document_preparation-i1026420/method_of_construction_or_method_of_bidding-i10283.html.

[7] Purcell, L., 2012, Construction and Trees: Guidelines for Protection, Purdue Extension, https://www.extension.purdue.edu/extmedia/FNR/FNR-463-W.pdf.

[8] Dennis, C. and Jacobi, W.R., 2020, Protecting Trees During Construction, https://csfs.colostate.edu/wp-content/uploads/2024/01/Protecting-Trees-During-Construction-Fact-Sheet-7.420.pdf.

[9] Texas A&M Forest Service, 2022, Put the Right Tree in the Right Place to Maximize Benefits to Landscape, https://tfsweb.tamu.edu/put-the-right-tree-in-the-right-place-to-maximize-benefits-to-landscape/.

10

Applying watershed NBS design and construction considerations

This chapter provides an understanding of design and construction best practices for watershed NBS through preserved, restored, or enhanced flood conveyance and storage.

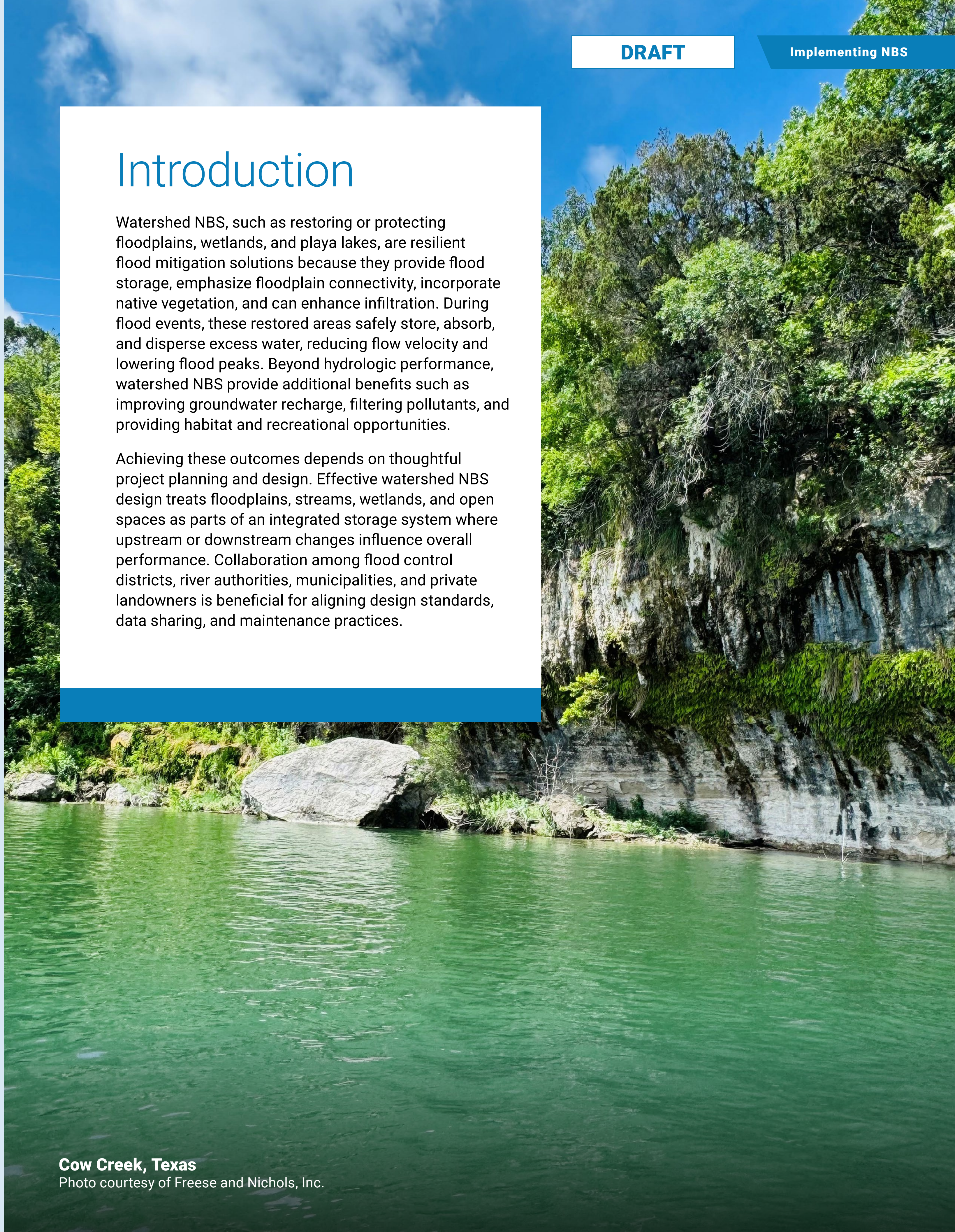
Key takeaways

- Effective watershed NBS designs seek to preserve, restore, or enhance natural floodplains and wetlands.
- Watershed NBS often require large areas of land and function best as part of an interconnected system of features, requiring strategic planning and design coordination.
- Successful watershed NBS designs account for site access, construction sequencing, material sourcing, climate and land-use changes, the durability of features under design flood conditions, and the establishment of native vegetation.

Photo courtesy of the Texas Water Development Board

How the guiding principles apply to this chapter

Engage and include	The large scale of many watershed NBS provide significant co-benefit opportunities – water quality and supply, habitat and ecotourism, recreation – that can be used to leverage partnerships, resources, and funding streams across numerous stakeholder groups.
Apply systems thinking	To realize their full potential, watershed NBS require careful consideration of the hydrologic and physical systems in which they are being designed and constructed.
Work across boundaries	Watershed NBS are most effective and cost-effective for flood resilience when they are part of a network of projects that fit into long-term strategic plans that seek to maximize benefits across time and space. This will require looking—and ultimately working collaboratively—beyond jurisdictional and political boundaries to larger hydrologic boundaries.
Learn and adapt continuously	Watershed NBS are often restoration projects that take place in a highly altered landscape and hydrologic context that can continue to change over time. Monitoring watershed NBS performance and adapting future designs accordingly will always be necessary.



Introduction

Watershed NBS, such as restoring or protecting floodplains, wetlands, and playa lakes, are resilient flood mitigation solutions because they provide flood storage, emphasize floodplain connectivity, incorporate native vegetation, and can enhance infiltration. During flood events, these restored areas safely store, absorb, and disperse excess water, reducing flow velocity and lowering flood peaks. Beyond hydrologic performance, watershed NBS provide additional benefits such as improving groundwater recharge, filtering pollutants, and providing habitat and recreational opportunities.

Achieving these outcomes depends on thoughtful project planning and design. Effective watershed NBS design treats floodplains, streams, wetlands, and open spaces as parts of an integrated storage system where upstream or downstream changes influence overall performance. Collaboration among flood control districts, river authorities, municipalities, and private landowners is beneficial for aligning design standards, data sharing, and maintenance practices.

Cow Creek, Texas
Photo courtesy of Freese and Nichols, Inc.

10.1 General considerations

Watershed NBS are large, interconnected systems of natural areas and open space designed to store and slow floodwaters across a watershed. Recognizing the flood resilience provided by existing natural areas and restoring or preserving that capacity is valuable when linking land-use decisions with long-term flood management. Because watershed NBS can require more land area and connectivity, strategic planning and design coordination are needed to identify and link opportunities across multiple parcels and jurisdictions. In urbanized watersheds, designs should adapt to constraints such as limited right-of-way, infrastructure, and space availability, often resulting in a combined approach that leverages engineered solutions with natural function through hybrid designs.

Channel and floodplain geometry

When considering watershed NBS, it is important to understand the physical processes that influence river health. Fluvial geomorphology is the scientific study of physical processes including erosion, and sediment transport, that shape river channels, floodplains, and valleys. It examines the interactions between flowing water, sediment supply, and channel geometry to understand how rivers evolve over time and respond to anthropogenic influences.

Streams are dynamic systems comprised of interacting channel and floodplain components, defined by their dimension, pattern, and profile. These characteristics reflect the balance of water, sediment, and energy moving through the watershed. Channel planform, the shape of a channel as seen from above, and longitudinal slope adjust over time in response to changes in flow regime, sediment supply, vegetation, and boundary conditions such base flow or confinement.

Stream adjustments are expressed through erosion, deposition, migration, or incision until a new equilibrium is reached. These adjustments influence the physical, chemical, and biological processes within the stream corridor, which typically operates within a “dynamic equilibrium”, a natural balance of flow, sediment transport, channel geometry, and bank stability. A channel in dynamic equilibrium is a self-adjusting system in which erosion, sediment transport, and deposition are balanced over time, so that short term changes occur but the long term average form is maintained.

Definition

Dynamic equilibrium

A stream channel is considered stable, or in dynamic equilibrium, when the existing flow and sediment regimes do not lead to long-term aggradation or degradation.[1]

Over time, water supply development, irrigation, transportation, hydropower, waste disposal, sand mining, flood control, timber harvesting, recreation, aesthetics, and other human activities have altered stream corridors and floodplains nationwide. These changes impact the natural balance of flow, sediment transport, channel geometry, and bank stability, often resulting in a disruption in dynamic equilibrium resulting in ecosystem adjustments. Increasing population and land development have placed growing pressure on these systems, resulting in cumulative impacts that degrade water quality, reduce water storage, and affect the health of both stream corridors and the ecosystems they support.

The channel evolution model shown in **Figure 10-1**, is a conceptual model[2] based on a predictable sequence of change in a disturbed channel system.

To describe common channel conditions and responses to disturbance, streams are grouped into six channel classes (I–VI) based on their stability, geometry, and degree of floodplain connectivity.

Class I channels are generally stable systems that exhibit a natural, sinuous planform and maintain frequent hydrologic connectivity with their floodplains. These channels can convey flow within their banks during more frequent events while allowing floodwaters to overtop the banks and access the floodplain during larger events. **This floodplain interaction is critical for dissipating energy, depositing sediment, and supporting mature riparian vegetation and unique soil and hydrologic conditions.**

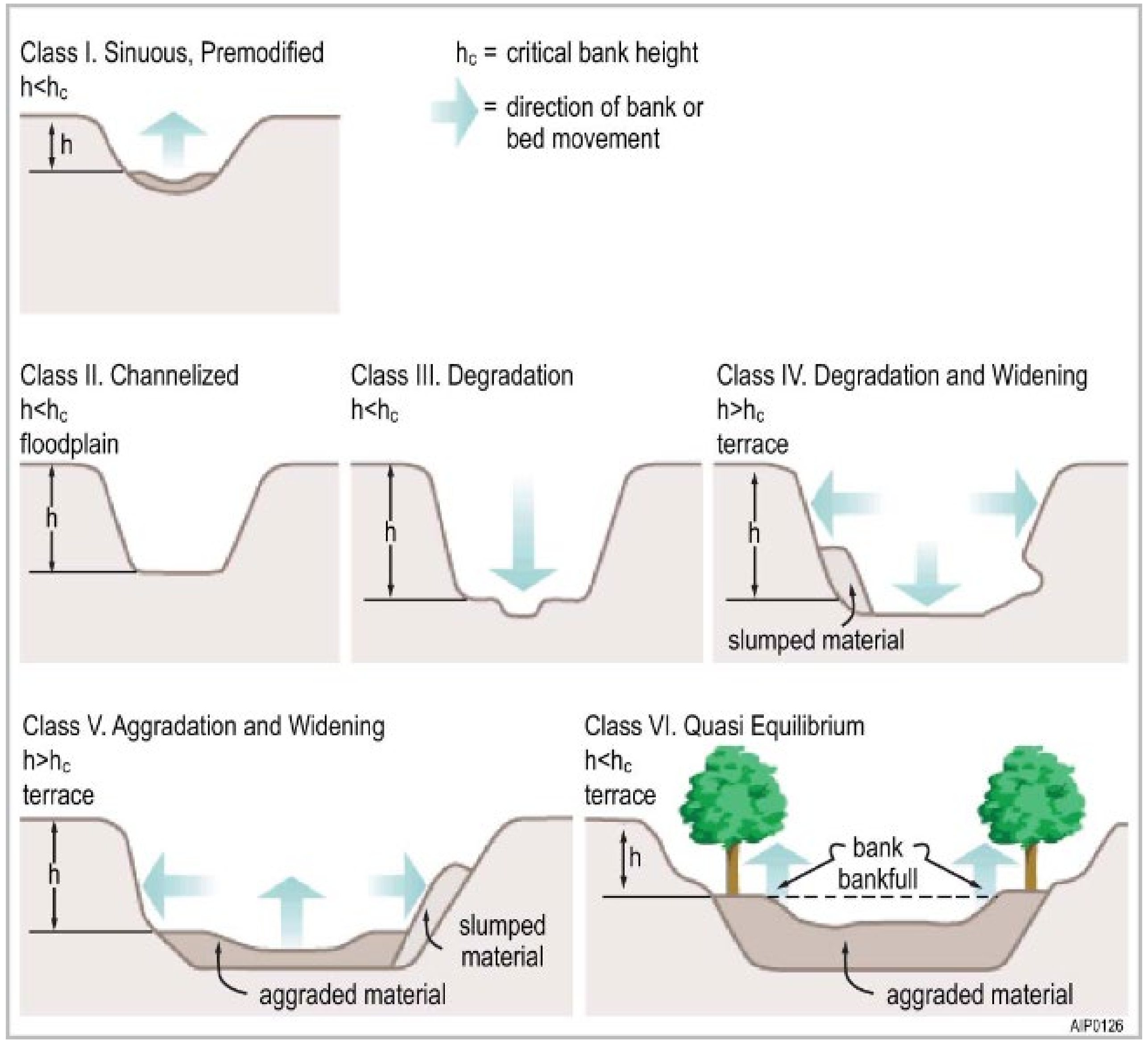


Figure 10-1. Channel evolution model diagram

Source: Simon, 1989; US Army Corps of Engineers, 1990

Class II channels represent systems that have been straightened, deepened, widened, or otherwise modified by human activity. These alterations disconnect the channel from its natural floodplain, reducing the frequency the floodplain is inundated which increased stream power by steepening the slope or constraining the flow. Class II channels are common in monofunctional flood mitigation projects which have altered stream geometry to increase flood conveyance. The altered geometry could initiate downstream or upstream instability, setting the stage for degradation.

In **Class III**, the channel begins to incise vertically as stream power exceeds the ability of the bed to resist erosion. This incision deepens the channel, lowering the bed elevation and increasing bank height. The channel becomes further disconnected from its floodplain, causing higher velocities and shear stresses during storm events. This phase is commonly triggered by upstream hydrologic change, channelization, or increased runoff from land-use change. As degradation continues, over-steepened banks exceed the critical height and begin to fail through mass wasting processes such as slumping or block failure.

Class IV is characterized by both vertical and lateral adjustments as the channel attempts to re-establish a stable geometry. As a result, the banks become unstable and prone to collapse. Sediment from failed banks is delivered to the channel and transported downstream. This phase is highly dynamic and often produces rapid changes in channel width, sediment loads, and overall form.

In **Class V**, the channel begins to stabilize as vertical incision slows, and sediment supplied from upstream degradation and bank failures deposits on the channel bed. This aggradation helps to reduce bank height and shear stress, though lateral migration may continue as the channel works toward a new equilibrium width. The stream begins to build inset floodplains or low terraces within the incised corridor, gradually forming the foundation for reestablishing floodplain connectivity.

Class VI channels reach a dynamic equilibrium in which sediment supply and sediment transport capacity are balanced. The channel has often widened and aggraded enough to form a new floodplain surface at a lower elevation than the original one. Vegetation and geomorphic processes become re-established, stabilizing the banks and allowing the channel to function more naturally. Although not identical to the original Class I condition, Class VI represents a stable state with improved floodplain connectivity, reduced erosion, and enhanced ecological function.

Sediment supply and transport

Rivers and creeks transport water and sediment, and that sediment can range in diameter size from a clay, silt, sand or grave to boulders. Ineffective watershed NBS designs often overlook sediment supply and transport rates. Excessive sediment deposition or erosion can result in ongoing maintenance challenges or stream instability. To address this, a sediment impact assessment should be conducted to compare the baseline condition to the proposed condition and identify how the proposed project will affect both water and sediment supply and transport.

A sediment impact assessment is a study used to evaluate how construction, land-disturbance, or water-related activities will affect sediment movement and how that sediment may impact downstream waterways, infrastructure, habitats, or water quality. Effective NBS designs consider the stream's sediment transport capacity and competence to support resilience and facilitate dynamic equilibrium. A stream's capacity refers to the mass/volume of sediment that it can transport for a given flow. A stream's competence refers to the maximum particle size that the stream is capable of moving.

If a channel is not in a dynamic equilibrium state, then two common systems encountered in watershed NBS designs are

1. sediment supply-limited systems, and
2. transport capacity-limited systems.

Sediment supply- and transport capacity-limited systems indicate that the stream is not in a state of dynamic equilibrium which can lead to ecological disruption.

Sediment supply-limited streams have the energy to move a larger volume of sediment than what is being delivered from upstream (excess capacity), resulting in channel degradation. Sediment-supply streams are NBS designs in these systems could include incorporating gentle slopes, increased sinuosity, and wider floodplain connection to reduce the energy in the system. Alternatively, additional roughness through the placement of larger particles and a more robust planting plan can add value and reduce the deleterious effects of a "sediment-hungry" system.

Transport capacity-limited streams receive more sediment than they can effectively transport, resulting in channel aggradation. NBS designs in these systems should avoid over-widening, stabilize excessive sediment sources upstream, and should consider multi-stage channels and the discharge that maintains a dynamic but generally stable channel geometry over the long-term.

There are multiple methods to complete a sediment impact analysis and selecting the appropriate method will depend on the river's sediment load composition (sand, gravel, etc.) and available data. By incorporating a sediment impact assessment into project planning and design, practitioners can better anticipate how proposed interventions will influence sediment dynamics and overall channel behavior. This proactive approach helps NBS and other watershed improvements function as intended, remain stable over time, and minimize unintended downstream effects. Understanding and accounting for the balance between sediment supply and transport capacity is fundamental when creating resilient, sustainable watershed NBS

Definitions

Degradation

The lowering of the streambed by scour and erosion.

Aggradation

The rising of a streambed due to sediment deposition.

Figure 10-2. Turtle Creek in Austin, Texas. This is an example of a Class III channel. The image shows the degradation associated with an unstable, sediment limited stream.

Source: Freese and Nichols, Inc.

10.2 Stream restoration and stabilization

Stream restoration and stabilization encompass a range of techniques aimed at returning degraded waterways to more natural, stable, and ecologically functional conditions. Primary objectives include stabilizing eroded banks, reducing sediment loads, enhancing wildlife habitat, improving water quality, and reconnecting streams to their floodplains for flood management. As a nature-based solution (NBS) for flood mitigation, stream restoration emphasizes restoring a stable and persistent connection between the channel and its floodplain, which increases storage and helps attenuate flood flows.

While stream restoration can improve flood resilience, achieving meaningful flood reduction requires a comprehensive understanding of the watershed system as a whole. Channel geometry, vegetation, flow regimes, and sediment dynamics all influence system performance. In some cases, restoring natural channel form and roughness can slow in-channel velocities, potentially increasing localized flooding or prolonging inundation. As a result, successful application of stream restoration as a flood mitigation strategy requires careful consideration of both local channel conditions and broader watershed-scale processes.

The analyses selected for a nature based solution design should align the design approach that best fits the site's setting, goals, and objectives. A process-based approach is used when it is acceptable to allow the stream to naturally evolve through fluvial processes and riparian succession, creating more complex and dynamic habitats over time. This builds resiliency by allowing for changes in landuse, climate or wilfires. A process-based approach is not appropriate if nearby land is threatened by channel or floodplain adjustments. In this instances a form-based approach may be most appropriate. A form-based approach specifies the channel's pattern, profile, and dimensions and relies on structural elements—such as structures made of rock, wood, concrete or synthetics —to limit channel adjustments and maintain a desired form.

Restoration and stabilization analysis and design approaches that are often used are: the analogy method, which bases channel design on a reference reach, the geometric relationship method which relies on relationships between a single measurable dimension (such as bankfull depth) to select other dependant design variables (such as bankfull width or channel slope) and the analytical method which uses physics-based equations and computational modeling. Nature based solutions are often best developed when a combination of all three are used especially when there is a lack in data availability and site constraints.

Stream restoration approaches are commonly described as form-based, function-based or process-based. These approaches represent different philosophies, often dictated by site or system constraints, that guide the goals and objectives of a stream restoration project.

Process-based restoration focuses on restoring hydrologic, geomorphic, and ecological processes that create and maintain a stable stream system. Typical objectives include restoring natural sediment supply, channel migration processes, and flow regimes. Rather than prescribing a fixed channel geometry, the design seeks to restore the conditions that allow the stream to evolve and adjust over time while maintaining dynamic equilibrium. Because these systems retain the ability to adapt, process-based approaches can provide greater long-term resilience to watershed changes associated with land use conversion, climate variability, or wildfire. However, this approach may be not be appropriate where channel migration, floodplain adjustment, or other natural processes could threaten adjacent infrastructure, property, or other assets.

Where process-based restoration is not feasible, function-based restoration focuses on restoring physical and/or biological functions of the stream and its floodplain. Design objectives focus on functional outcomes such as improving floodplain connectivity, sediment continuity, biodiversity, and water quality. Function-based restoration provides flexibility to improve system performance when the underlying system processes (e.g., when sediment supply has decreased or runoff has increased) cannot be restored.

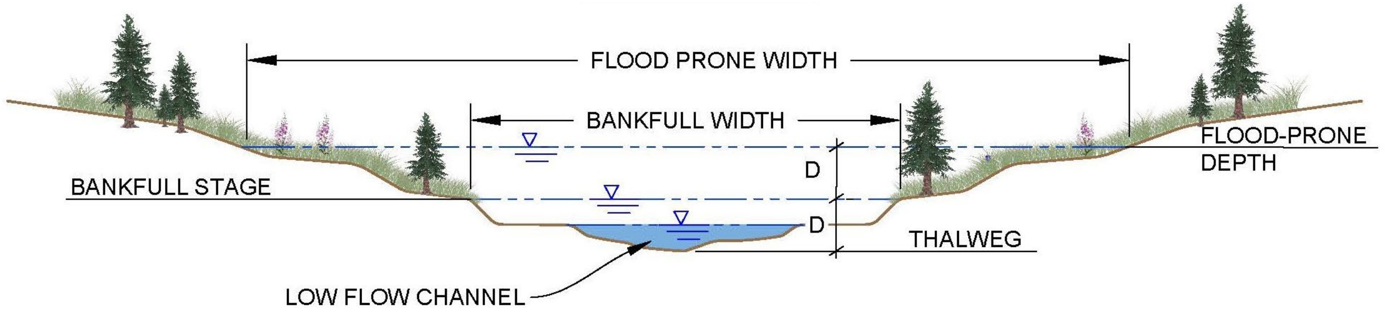


Figure 10-3. A channel in dynamic equilibrium with its floodplain

Source: US Fish & Wildlife

Form-based restoration focuses on establishing a target channel geometry by specifying the channel's dimension, pattern, profile, and bedform characteristics. The objective is to create a channel configuration that remains stable under anticipated flow and sediment conditions while minimizing future adjustment and associated risks. This approach is often appropriate where site constraints limit floodplain access and channel adjustment and a well-defined channel configuration is needed.

All three approaches seek to create a stream system that is stable and sustainable under its expected watershed conditions. Depending on project goals, stability may be achieved through natural adjustment processes, restoration of key functions, or maintenance of a specified channel form. In practice, many successful stream restoration projects combine elements of all three approaches. For example, a project may establish a stable channel geometry near critical infrastructure while restoring floodplain connectivity and sediment processes elsewhere in the system.

Analytical and empirical methods are used to develop and evaluate designs within any of these restoration approaches. Analytical methods use physics-based equations and computational modeling to evaluate hydraulic capacity, sediment transport, velocity, and shear stress, allowing practitioners to predict how a channel will perform under specific flow and sediment conditions. Empirical methods are based on observed relationships from natural, stable channels. The two most common empirical methods are the analogy method, which bases channel design on a reference reach, and the geometric relationship method which relies on relationships between a single measurable variable to select other dependent design variables. For more information on determining the appropriate design approach for stream restoration see the ***National Engineering Handbook Stream Restoration Design ↗***.

Figure 10-3 displays an alluvial, perennial channel cross-section used to benchmark design goals. The bankfull, or channel-forming, stage shown is the elevation of flow that just fills the channel to the top of its banks. Bankfull stage represents a balance point where flows are high and common enough to drive channel equilibrium through sediment transport and channel maintenance. As a result, bankfull is a key reference for understanding channel geometry, stability, and design, because it reflects the integrated influence of watershed hydrology and sediment supply on the long-term form of the stream.

When banks are stable and vegetated, the roughness along the channel increases. This slows the flow of water and dissipates energy. In contrast, eroded or bare banks create straighter, smoother channels where water moves faster. As water slows, its ability to carry sediments like silt, sand, and organic material decreases. This means particles start to settle out of the flow and deposit along the streambed or floodplain. Over time, this process helps rebuild natural features such as point bars or terraces, which can further stabilize the system. Slower water also allows more time for infiltration, replenishing groundwater and reducing surface runoff. Vegetation roots along stabilized banks also enhance soil porosity, further aiding infiltration. Additionally, these methods support habitat restoration, improve water quality, and maintain the ecological integrity of riparian zones, making them a sustainable and multifunctional solution for flood management.

The stream restoration design process requires an understanding of technical terms that are not commonly used in traditional gray infrastructure designs. Table 10-1 defines terms commonly used in stream restoration and stabilization design. These terms are often used in nature base solution design in perennial or ephemeral alluvial streams in humid environments, and perennial alluvial streams in semiarid or arid environments. In flashy, arid, intermittent streams, or highly-urbanized watersheds, other mechanisms can be dominant and these terms may not be applicable.

Table 10-1. Stream Restoration and Stabilization Design Definitions[3]

Term	Definition
Active floodplain	The land above bankfull that is inundated by floodwaters on a periodic basis. This is not synonymous with the FEMA Special Flood Hazard Areas.
Bankfull stage[4]	The water level, or elevation, at which a stream or river is at the top of its banks and any further rise would result in water moving into the flood plain. It may be identified by physical characteristics such as a clear, natural line impressed on the bank, shelving, changes in the character of soil, destruction of terrestrial vegetation, the presence of litter and debris, or other appropriate means that consider the characteristics of the surrounding areas.
Bankfull Depth	The average depth measured at Bankfull Discharge.
Bankfull Discharge	The dominant channel forming flow at the bankfull stage.
Bankfull Width	Channel width at Bankfull Discharge.
Flood-Prone Depth	The average stream depth at a discharge level defined as twice the maximum Bankfull Depth.
Flood-Prone Width	The stream width at a discharge level defined as twice the maximum Bankfull Depth.
Thalweg	Longitudinal outline/trace/survey of a deepest part of riverbed from source to mouth (upstream/downstream). Line of steepest descent along the stream.
Low Flow Channel	Channel the conveys the average daily flow.

Design considerations

Successful stream restoration and stabilization design requires an understanding of watershed processes and site conditions. Designers should first collect site data using topographical surveying and historical floodplain data, including historical aerial imagery, to establish a baseline relative to the project goals. By evaluating the watershed's hydrology and sediment regime, designers can work to accommodate the magnitude, frequency, and duration of flows in the proposed channel while maintaining a balance between sediment supply and transport capacity. Geomorphic field data collection helps to understand the natural reference that is being targeted for project goals because it helps define dynamic equilibrium and if the stream is sediment supply or transport limited. The collected field data is important in establishing the channel geometry that align with the site's geomorphic context, including appropriate bankfull dimensions, meander patterns, slopes, and riffle–pool sequences that reflect a stable state.

Bank stability assessments should consider cross sectional geometry, soil properties, erodibility, vegetation reinforcement, and the risk of toe scour or mass failure to inform the selection of stabilization treatments and materials. To help protect the banks of the channel, designers should conduct a sediment impact assessment for the project reach. Projects should seek to enhance ecological function by restoring habitat complexity, supporting native riparian vegetation, and maintaining aquatic organism passage. Designers should evaluate whether projects may cause adverse impacts to the area's hydrology, sediment distribution, or ecosystem and appropriately mitigate any impacts that may occur.

Constructability, long-term maintenance, and resilience should be considered throughout the design process. Successful designs account for site access, material sourcing, environmental and land-use changes, and the durability of features under design flood conditions so that the restored stream remains stable and functional well into the future.

Since streams or creeks can be in varius states of equilibrium or disequilbrium, a priority level list should be considered for each restoration option in priority order before settling on a final design. For example, when a dam reduces sediment supply, the excess energy that would normally transport sediment is instead expended on bed erosion, resulting in channel downcutting. The priority level list would guide the designer to the appropriate solution. These priority levels outline the progression of restoration strategies, from re-establishing floodplain connectivity to stabilizing the existing channel in place. They recognize that given site constraints full restoration may not be feasible and provide a practical framework for practitioners to use to maximize stream function based on channel condition, available space, and economic considerations.

Priority Level 1

Establish bankfull stage at historical floodplain elevation[5]: Where land is available and free of structures and infrastructure, a degraded stream is moved, channel bed elevation raised, and a new alignment, profile, and channel dimensions are constructed. This improves the stream's relationship with its floodplain by reconnecting it with its historic or abandoned floodplain so that overbank flows can spread out during high water events. By giving floodwaters more space to dissipate energy and be temporarily stored, this method significantly reduces downstream flood peaks and improves flood resilience. This strategy is used in rural areas where there is ample room.

Figure 10-4. Natural Channel Design of Kee Branch. The image on the top is an eroded reach of Kee Branch in Arlington, Texas. The image on the bottom shows the same channel after a natural channel design that stabilized the creek and improved flood storage.

Priority Level 2

Channel modification with floodplain benching[5]: Use this strategy in areas that lack the available area for a full floodplain reconnection project or near vertical constraints such as road crossings or culverts. This method may include adjustments to the stream's current alignment and profile but focuses more on reshaping the channel dimensions, and adds inset floodplain benches that activate during moderate floods. The added floodplain surface stores excess water, slows velocities, and lowers flood stages without fully relocating the stream.

Priority Level 3

Channel stabilization[5]: This approach is used where there is little to no opportunity to improve the channel cross section or its floodplain connection. Degraded streams are prevented from degrading further by using instream structures (such as cross vanes, stream barbs, etc.), streambank structures (bioengineering, vegetated soil rock riprap, log revetments), and grade control (bed control structure, gabion grade control, hydraulic control structure, etc.). The channel's alignment, slope, and dimensions are locked into place by these improvements which improve flood conveyance and restore more natural hydraulic conditions. A stable, well aligned channel reduces excessive velocities during floods, promotes predictable flow paths, and increases the system's ability to distribute floodwaters across the floodplain.

Priority Level 4

Bank stabilization or channel margin enhancement[5]: Use this strategy where channel instability is localized. Bank stabilization uses vegetation, natural materials, or engineered structures to reduce erosion and prevent channel widening or collapse. By maintaining a stable channel shape, the stream is better able to convey flood flows safely without creating new hazards or increasing sediment loads that can worsen flooding downstream. With installation of localized stabilization, an understanding of the larger stream process (degradation or aggradation) is fundamental to prevent failure of local solutions due to erosion or excessive sedimentation

When reconnecting the floodplain, the implications of limited right-of-way and water surface elevation changes associated with altering the channel bottom should be considered because of their impact on constructability, regulatory compliance, and compatibility with existing infrastructure.

Floodplain reconnection when paired with the establishment of a stable channel cross-section, pattern, profile, and/or riparian buffer introduces opportunity for a multitude of co-benefits by restoring dynamic equilibrium of the channel. The addition of complexity to the stream channel can delay runoff, limit hydrograph peaks downstream, and provide riparian habitat.

Understanding the causes and consequences of stream channel changes is an important and often complex step in the stream restoration process. To support this, rigorous field protocols, including geomorphic assessment, are useful for collecting consistent, quantitative, and comparative data on watershed and channel stability. There are numerous methods to design resilient stream restoration and stabilization projects and such methods are described in detail in the tools and references section below.

Nature-based streambank stabilization enhances the resilience of fluvial systems by using natural materials and processes to reduce erosion and manage floodwaters. Instead of relying solely on hard infrastructure like concrete walls or riprap, this approach incorporates vegetation, bioengineering techniques, and other natural features to reinforce streambanks. **Stabilized banks slow down water velocity, promote sediment deposition, and improve infiltration, which collectively reduce flood peaks and downstream impacts.**

When banks are stable and vegetated, the roughness along the channel increases. This slows the flow of water and dissipates energy. In contrast, eroded or bare banks create straighter, smoother channels where water moves faster. As water slows, its ability to carry sediments like silt, sand, and organic material decreases. This means particles start to settle out of the flow and deposit along the streambed or floodplain.

Over time, this process helps rebuild natural features such as point bars or terraces, which can further stabilize the system. Slower water also allows more time for infiltration, replenishing groundwater and reducing surface runoff. Vegetation roots along stabilized banks enhance soil porosity, further aiding infiltration. Additionally, these methods support habitat restoration, improve water quality, and maintain the ecological integrity of riparian zones, making them a sustainable and multifunctional solution for flood management.

Construction considerations

Effective construction of stream restoration and stabilization projects requires careful planning, implementation, and sensitivity to the stream corridor. Construction contractors may not be familiar with this type of construction therefore construction oversight (preferably full-time) is recommended to verify that designs are successfully constructed. For construction sequencing, work should occur during low-flow periods and temporary diversions, dewatering methods, and sediment controls should be in place to maintain water quality and protect completed features. Material sourcing and placement should follow design specifications closely, using appropriately sized rock, properly anchored large woody material, and carefully installed soil lifts or bioengineering components to provide structural support. Locally sourced material or material sourced from the construction site may help lower construction costs.

Maintaining strict tolerances for elevations, slopes, and alignments—supported by ongoing as-built verification—is recommended, as small deviations in grade control elevations can significantly alter channel hydraulics and sediment transport. Vegetation installation plays a central role in long-term stability, requiring proper timing, native species selection, and protection during establishment. Finally, thoughtful access and staging can minimize disturbance to sensitive riparian areas, reduce unnecessary erosion or compaction, so that heavy equipment use does not compromise the restored channel. Together, these considerations help stream restoration and stabilization projects perform as intended and remain resilient over time.

Tools and resources

- **Natural Resources Conservation (NRCS)**

  Part 654 Stream Restoration Design National Engineering Handbook Chapters 4 thru 12 ↗

- **U.S. Department of Agriculture (USDA)**

  NRCS Soil Bioengineering for Streambank and Shoreline Protection USDA/NRCS National Engineering Handbook (NEH) Part 650, Ch 16 ↗

  NRCS Soil Bioengineering for Upland Slope Protection and Erosion Control USDA/ NRCS National Engineering Handbook (NEH) Part 650, Ch 18 ↗

  Streambank Soil Bioengineering A Proposed Refinement of the Definition, USDA/PMC Riparian/Wetland Project Information Series No. 23 ↗

- **USACE**

  Channel Restoration Design for Meandering Rivers, Chapters 1.4-1.5 ↗

  International Guidelines on Natural and Nature Based Features for Flood Risk Management, Chapter 17 ↗

  National Large Wood Manual ↗

  A Function-Based Framework for Stream Assessment & Restoration Projects ↗

- **North Carolina Stream Restoration Institute and North Carolina Sea Grant**

  Stream Restoration: A Natural Channel Design Handbook ↗

- **USDA**

  USDA Part 654 Stream Restoration Design National Engineering Handbook ↗

- **Texas Riparian Association**

  Urban Riparian and Stream Restoration Program ↗

- **San Antonio River Authority**

  Natural Channel Design Protocol Manual ↗

- **Harris County Flood Control District**

  Streambank Stabilization Handbook ↗

Priority 1 stream restoration and reconnection of abandoned floodplains at Riverby Ranch in Fannin and Lamar Counties.
Photo courtesy of Freese and Nichols, Inc.

Case Study

San Pedro Creek Culture Park

Location: San Antonio

Opportunity: To reduce flood risk, additional capacity was needed in an existing channel that would also benefit from water quality improvements and cultural enhancements

Lessons learned: Early collaboration and a system-wide approach helped reduce flood risk while supporting community values.

San Pedro Creek places a significant role in of stormwater management in San Antonio. However, it was discovered that the current FEMA 1 percent annual chance flood event (100-year) floodplain was based on an assumed channel section much larger than occurred in several places and that the flood risk from the local watershed posed a significant risk. San Pedro Creek (Figure 10-5) was reconstructed first and foremost to reduce this flood risk, but also to enhance the creek's water quality and habitat quality.

At the core of the project is a fundamental transformation of what had become a heavily constrained, concrete-lined urban flood channel into a functioning, naturalized stream corridor spanning over two miles through downtown San Antonio. The channel reconstruction involved deepening and widening the existing creek section to meet true 100-year flood conveyance capacity. This work removed approximately 40 acres and 38 structures from the 100-year floodplain, delivering meaningful and measurable flood risk reduction to surrounding neighborhoods and downtown properties.

To restore stream function beyond hydraulic capacity alone, the reconstructed channel incorporates a natural-looking cobble bottom, which mimics natural streambed conditions, reduces flow velocities, and promotes sediment settling and aquatic habitat establishment. Constraining bridges that had previously restricted flow were replaced, and new crest gates were installed to provide additional flood control flexibility and water surface management.

The channel's banks and riparian corridor were replanted with native vegetation and aquatic plantings designed to stabilize the streambanks, filter urban runoff, and re-establish habitat connectivity along the creek corridor. These plantings support the return of native species that had been absent from the urban stream for decades.

The project uses many neighborhood NBS practices including bioswales, bioretention, tree trenches, and aquatic plantings to manage stormwater, improve water quality, and sustain habitats. It also creates accessible public trails and green space for residents and visitors to enjoy.

San Pedro Creek is where the Spanish first settled in the area but was home to the Payaya people lived for thousands of years prior to the Spanish settlements. In the last 300 years, many groups lived, worked, and worshipped along San Pedro Creek. Through educational interpretive panels and works of public art, the narrative of the human interaction along San Pedro Creek is displayed along the park's paths. Accessible public trails and green space connect residents and visitors to the restored waterway.

This major public investment of over $300 million, primarily funded by Bexar County, in collaboration with San Antonio River Authority, and City of San Antonio, created 1.5 billion economic impact by creating 2,100 new housing units, 1,428 new downtown jobs, 7,300 new downtown residents, a 150% increase in new property value, and $225 million in ad valorem tax revenue.[6] A citizens' advisory committee was established which includes various community organizations, residents, business and landowners, and project partners.

The park reached full completion in May 2025 and has received national recognition as a model for integrating flood control, ecological stream restoration, and community investment in an urban setting.

Figure 10-5. San Pedro Creek Stream Restoration in San Antonio, Texas. The image on the top is a channelized reach of Pedro Creek in San Antonio, Texas. The image on the bottom shows the same channel after a natural channel design that stabilized the creek and improved flood storage.

10.3 Floodplain connection and stabilization

Floodplain connection and restoration projects restore natural floodplain processes and support multiple ecological and hydrologic objectives. When properly implemented, they can become self-sustaining over time and are a long-term strategy for recovering lost floodplain functions regardless of watershed size, from small streams to large river networks.

Floodplain connection and restoration solutions are particularly effective in inland river systems where floodplains play an important role in

- flood attenuation,
- supporting terrestrial and aquatic ecosystems,
- influencing channel dynamics and sediment-bedform interactions,
- regulating sediment supply and transport,
- shaping hydraulic patterns along channel margins, and
- facilitating surface water and groundwater exchange.

Generally, floodplain connection is achieved by reducing the vertical distance between the channel bottom elevation and floodplain elevation using one or a combination of several techniques:

- Removing native or artificial fill on the floodplain, hence lowering the floodplain elevation.
- Lifting the channel bottom elevation closer to the existing floodplain.
- Building inset floodplains within the channel.

Unlike the Rosgen Priority 1 stream restoration approach discussed in **Section 10.2**, which restores the channel to its historical floodplain elevation, floodplain restoration focuses on reconnecting the active channel to its adjacent floodplain to reestablish hydrologic functions such as storage, sediment deposition, and riparian habitat. Rosgen Priority Level 1 and Level 2 represent specific restoration approaches within this broader objective: Priority 1 achieves reconnection by elevating the channel to its historic floodplain, while Priority 2 applies channel modification with inset floodplain benching to provide partial connectivity and storage without fully relocating the stream[5]. In contrast, floodplain reconnection is a more flexible, outcome-based concept that may be achieved with or without significant in-channel modification, depending on site constraints and project goals.

Additionally, when discussing floodplain connection, the primary goal is to connect the stream to its geomorphic floodplain, not FEMA floodplain. A geomorphic floodplain is the area next to a stream that naturally reflects where the stream has historically moved and interacted with the land (e.g., repeated flooding, sediment deposition, erosion). Alternatively, a FEMA floodplain is used for regulatory and planning purposes and shows the boundaries of a particular modeled flood event. Establishing a stable connection from a stream to its geomorphic floodplain will not necessarily alter the corresponding FEMA floodplain.

Multi-stage or two-stage channel designs are an NBS approach that reconnect channels to a restored or naturalized floodplain bench at higher flows. Floodplain benches form at elevations between the riverbed and the higher floodplain or terrace, offering many ecological and hydrological benefits. They differ primarily in the amount of habitat they create and the frequency with which they are inundated. Like floodplains, benches develop naturally through a complex interaction of geologic conditions, geomorphic processes, sediment supply and transport, flood and drought cycles, and ecological factors. These features typically form through vertical accretion of fine sediments and organic matter deposited during frequent high-water events.

Benches may appear on one or both sides of a river channel, and in some systems, multiple benches can form at varying elevations. Due to their frequent inundation and fine sediment deposition, benches help attenuate flood flows, support unique soil development, foster niche ecosystems within the fluvial environment, and enhance the quality of water returning to the river.

Levee setback

Levee setbacks are an NBS approach that moves a levee back so the river can reconnect with the floodplain and help restore it. The primary objective of a levee setback project is to restore a riverine corridor so that it can accommodate a range of flow conditions while increasing the level of flood risk reduction. This strategic approach involves relocating a section of levee farther away from the river channel to alleviate pressure on the levee system. Energy is dissipated by reconnecting the floodplain area to the river channel to increase flood storage space, thereby reducing flood risk, restoring natural floodplain functions, and enhancing ecological benefits. A levee setback NBS is used if the existing levee can be moved, but the need for the levee remains.

Oxbow lakes and resacas

Oxbow lakes, called resacas in the Lower Rio Grande Valley, are a floodplain feature that have potential to reduce flood risk when designed to provide additional flood storage. Oxbows and resacas are formed when natural processes or human intervention reroute a stream and cut off a section of the stream channel, effectively creating a lake and wetland complex that is isolated from the main channel during low flows but reconnects during flood events. Over time, these floodplain lakes and wetlands can fill with sediment or undergo land use/land cover change due to agriculture or development and lose their flood carrying capacity.

The design of an oxbow lake restoration project varies based on how much sedimentation has been deposited in the oxbow. Oxbows with minimal sedimentation and that connect in major flood stages require less modification compared to oxbows with significant sedimentation and/or modified connection to the river system. **Figure 10-6** shows a cross section of a multi-stage channel with a floodplain bench.[7] Understanding the hydraulic behavior of an oxbow, especially sediment transport dynamics, is beneficial for designing effective restoration measures that provide flood storage and improve habitat. Hydraulic modeling tools are often used to simulate different alternatives and assess the impact of proposed restoration measures.

Restoration of oxbow lakes or resacas involves re-establishing native ecosystem and natural hydrologic regimes. Restoring oxbow lakes and resacas increases available flood storage, improves water quality and flow, and restores aquatic and riparian habitats. Common restoration methods include dredging, removing debris, stabilizing banks, and reintroducing native plants to improve water depth, quality, and circulation, which have been negatively impacted by sedimentation and urban and agricultural development.

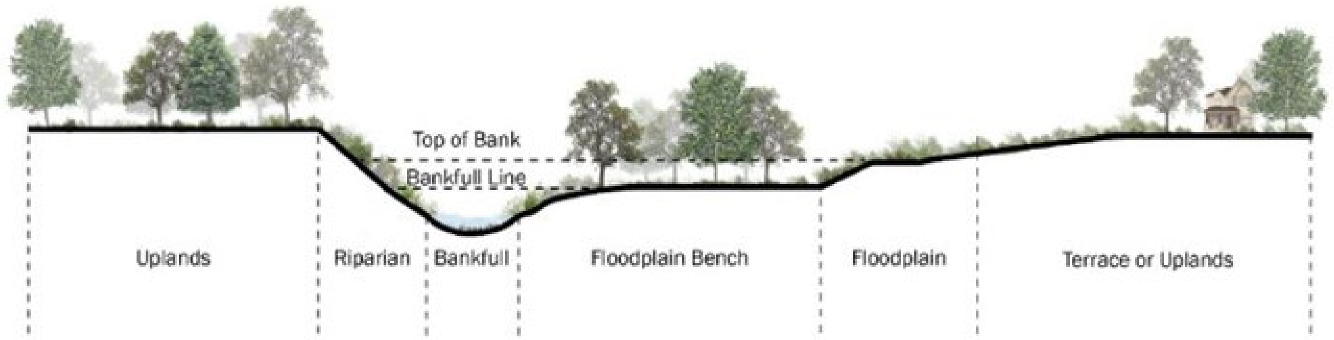


Figure 10-6. Multi-stage channel. Cross section of multi-stage channel with floodplain bench[7]

Source: US Army Corps of Engineers

Design considerations

When designing floodplain connection and restoration projects, it is important to assess the site's terrain, including an analysis of historic floodplains and floodplain connectivity using both geotechnical and survey data. A project area can then be made using both the terrain assessment and a land use analysis of surrounding areas.

The design of the floodplain connectivity can be developed utilizing both hydraulic and hydrologic assessment. Additionally, geomorphic assessment and field data collection can help corroborate effective flow targets and project goals. Grading design should consider how floodwaters can access the floodplain during high-flow events. Smooth transitions between the channel and floodplain help maintain natural flow patterns. The connection between the main channel and the floodplain should be designed to allow flow to easily access the additional storage. Structures like flow spreaders can help distribute water evenly across the floodplain and can help with floodplain drainage during flood recession, avoiding stranding of fish in isolated floodplain pools. Establishing native vegetation is crucial for stabilizing soils, reducing erosion, and enhancing water absorption. Design should include soil preparation and planting plans that support long-term ecological function.

Construction considerations

Many of the considerations previously discussed with stream restoration and stabilization apply to floodplain connection and restoration as well. Additionally, constructability considerations include access to the site, the availability of construction materials, and the potential for disturbance to surrounding habitats. Depending on access roads, bank height, and bank stability, special construction methods, potentially including barges, may be required. Floodplain connectivity projects that include construction activity within Waters of the U.S. may require permits from USACE. Projects that are to be built within a FEMA Special Flood Hazard Area will often need a permit from the floodplain administrator to demonstrate that the project causes no adverse impacts to adjacent landowners. Proper planning improves the likelihood that the project can be implemented and maintained efficiently and effectively.

Tools and resources

- **US Army Engineer Research and Development Center**

  Engineering Practice Guide for Floodplain Benching: A Natural Infrastructure Approach for Riverine Systems. ERDC TR-25-15 ↗

  Levee Setbacks: An Innovative, Cost-Effective, and Sustainable Solution for Improved Flood Risk Management ↗

  Considerations and Resources for Vegetation Selection on Levees ↗

  The Resacas – In the Vicinity of the City of Brownsville, Texas Interim Ecosystem Restoration Feasibility Study and Environmental Assessment ↗

- **USDA**

  Part 654 Stream Restoration Design National Engineering Handbook Chapter 10 Two-Stage Channel Design ↗

  Overview of Levee Setback Projects and Benefits ↗

- **National Center of Biotechnology Information**

  Restoring the Lost Resaca: Wetland Restoration in the Lower Rio Grande Valley, TX ↗

- **The Nature Conservancy**

  Large-Scale Levee Setback Playbook ↗

  Oxbow Restoration Toolkit ↗

- **American Rivers**

  Reconnecting Rivers to Floodplains: Returning Natural Functions to Restore Rivers and Benefit Communities Planting ↗

Case Study

Town Resaca system restoration

Location: Brownsville

Opportunity: Historic resacas that were filled with sediment have potential for additional flood storage.

Lessons learned: Early coordination among agencies and stakeholders streamlines permitting and improves long-term project management.

The restoration of the town resaca system in Brownsville represents a major multi-phase effort to revitalize the city's network of historic resacas. In the initial phase, more than 100,000 cubic yards of accumulated sediment were removed from four sites—City Cemetery, Dean Porter Park, Gladys Porter Zoo, and Resaca Boulevard—to restore depth and increase floodwater storage. In Phase II, an additional 57,136 cubic yards of material were dredged and dewatered, restoring the system's capacity and ecological function. Key actions included comprehensive dredging to restore depths from under 2 feet to as much as 8 feet in some zones, the natural regrading and stabilization of banks with native vegetation to reduce erosion and enhance infiltration, and the installation of infrastructure improvements such as 10 stormwater interceptors, two weirs, and a new gate valve to enhance flow management and water quality control.[8]

The project was supported by a strong partnership of funding sources. The RESTORE Act, via the U.S. Treasury and administered in Texas by the TCEQ, contributed grant funds—about $4.68 million for Phase I and an additional $1.91 million in 2024. The Brownsville Public Utilities Board (BPUB) provided a significant local match, contributing over $21.35 million through September 2024. USACE, through its ***Resaca Boulevard Section 206 Aquatic Ecosystem Restoration Project*** ↗ ecosystem restoration project and subsequent study, also played a key role, with a 2024 Community Project Fund award of $2.017 million. Collectively, these partnerships enabled the town resaca system restoration to progress from degraded, sediment-filled channels into functional floodwater conveyance and habitat systems that serve both ecological and community benefits.

Figure 10-7. Resaca system restoration in Brownsville, Texas

Photo courtesy of Freese and Nichols, Inc.

10.4 Wetland restoration and creation

Wetlands that are not directly connected to streams and floodplains still play an important role in moderating floodwaters, reducing peak flows, and enhancing overall watershed resilience. These wetlands act as natural detention basins that capture stormwater and surface runoff from surrounding uplands. By holding this water and allowing gradual infiltration and evapotranspiration, isolated wetlands help reduce the volume and speed of downstream flow and decrease flood risks to developed areas.

When heavy rainfall occurs, wetlands provide zones of slower water movement where sediment can settle, and excess runoff can be temporarily stored. This "sponge effect" attenuates flood peaks, reduces erosion, and helps sustain groundwater recharge during dry periods. In landscapes with limited floodplain connectivity, these wetlands serve as valuable decentralized storage features that complement larger-scale flood mitigation systems.

A notable example of how wetlands store rainfall runoff are playa lakes, which are a type of ephemeral wetland commonly found in the High Plains of Texas. Their hydrology relies on rainfall and surface accumulation for their water source. These unique ecosystems play a crucial role in groundwater recharge, wildlife habitat, and flood control. Between wet periods the surface of the playa typically dries out, forming cracks and fissures in its clay-rich sediments.[9] For playa lakes to store floodwater, the surrounding topography should direct floodwater to the playa and be shaped to store the captured floodwater. The stored water then seeps through the soil into the aquifer below or is taken up by vegetation.

The restoration or creation of wetlands often involves grading or excavation to reestablish natural depressions that collect and retain surface water. Topographic and aerial data can help identify natural depressions and potential wetland sites. A geospatial "sink analysis" produces a map that identifies bowl-like depressions in a Digital Elevation Model (DEM) which could be degraded playas or locations for new ones. The drainage area is then mapped to the location. Identifying suitable sites can be supported by resources such as the ***National Wetlands Inventory*** ↗ (NWI) or state environmental agency GIS databases, which highlight recognized wetlands, but do not provide an exhaustive list of all wetlands. It is recommended to perform an in-field wetland delineation when performing a project so that all wetland habitats are accounted for and being protected.

Wetlands support diverse vegetation communities adapted to seasonal saturation and specific soil conditions. Reviewing soil data in tools such as the ***Web Soil Survey*** ↗ can help determine whether a site has hydric soils appropriate for wetland restoration or creation. In some cases, engineered soil and underground drainage are needed. Because these wetlands retain water for extended durations, project designs should also consider surrounding land use and local regulatory requirements for determining maximum ponding depth and drain time.

The hydraulic design of isolated wetland restoration focuses on balancing water retention and ecological function. Hydraulic and hydrologic modeling can evaluate inflow from precipitation and runoff, estimate residence time, and predict water level fluctuations. This analysis improves the likelihood that restored wetlands effectively store floodwater, improve water quality, and provide habitat without causing unintended impacts to adjacent properties. Topography or outlet structure design can help to control water levels within the wetland and protect downstream properties.

Vegetation selection in constructed wetlands should reflect the natural zonation shown in Figure 10-8. Each zone supports plants adapted to specific moisture and depth conditions. The upland zone features terrestrial species that stabilize surrounding soils and provide a buffer habitat. In the wet meadow zone, grasses and sedges tolerant of periodic saturation thrive and filter runoff to serve as a transitional area. The emergent zone hosts rooted species with stems above water, like cattails and bulrush, which offer key nutrient uptake and wildlife habitat. In the submergent zone, fully submerged plants such as pondweeds improve oxygenation and trap suspended sediments. The open water zone supports floating species like duckweed that shade and cool surface water, reducing algal growth. Selecting native species across these zones is intended to improve hydraulic efficiency, biodiversity, and long-term system resilience while mimicking the natural gradient from dry upland to open water within constructed wetland systems.

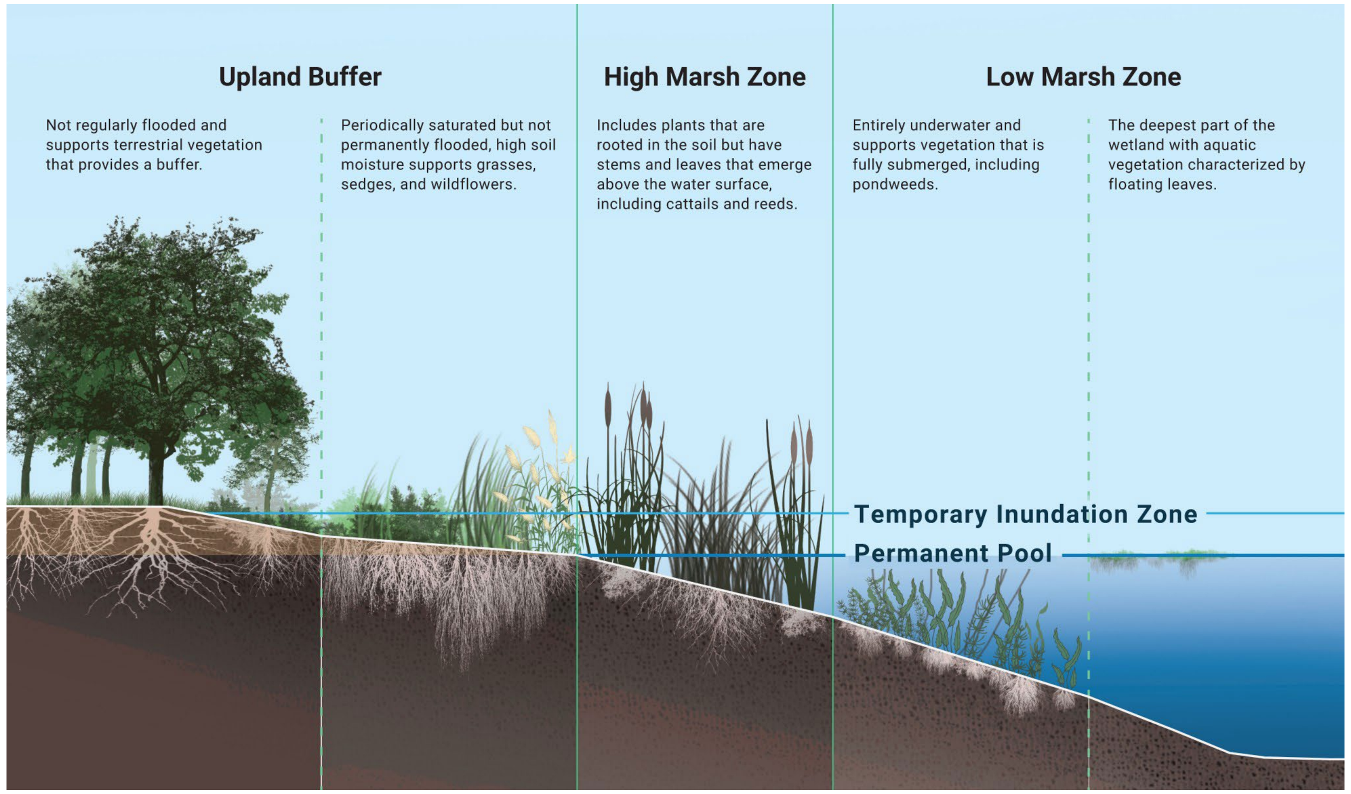


Figure 10-8. Wetland zones

Illustration courtesy of Texas AgriLife Extension

Design considerations

Wetlands are most effective for improving flood resilience when designed to connect with upstream and downstream water courses and to interact with and recharge groundwater. Wetlands receive, store, and slowly release floodwaters which helps reduce peak flows and downstream flood risk. The size, depth, and vegetation of the wetland should be designed to maximize water storage during storm events. Proper grading and basin design help retain water long enough to reduce flood intensity while supporting ecological functions. For long-term flood and water quality benefits, wetlands should be designed to handle expected sediment loads without clogging or losing capacity. See Chapter 11 for more information on site scale design considerations for constructed wetlands.

Wetlands attract wildlife that could be hazardous to aviation. Because of this, the Federal Aviation Administration (FAA) advises against the creation of wetlands or standing water near airports. FAA recommends that wetlands and similar wildlife attractants be located at least 10,000 feet from the airport operations area. For piston-powered aircraft, the distance is 5,000 feet.[10] For more information on FAA's guidance on constructed wetlands near airports, review ***Advisory Circular 150/5200-33C*** ↗.

When designing playa lake ephemeral wetlands, excess sedimentation, especially erosion from adjacent cropland, should be considered. Excess sedimentation can reduce the capacity of playa lakes to store and slow stormwater runoff and can increase evaporation in regions of Texas that rely heavily on groundwater. Additionally, excess sedimentation can harm native wetland vegetation by altering hydrologic patterns within the playa, particularly when channel-forming flow occurs over clayey soils, whether from concentrated runoff or anthropogenic channelization.

Construction considerations

Construction within wetlands may be regulated under municipal or county flood damage prevention ordinances. If modifications to existing wetlands are pursued, this may require a review or permit under Section 404 of the Clean Water Act. See **Chapter 8** for more information on regulations and permitting.

The success of the restored wetland depends on achieving the correct water levels and timing. Small landform variations or shallow depressions support plant diversity and wildlife use, so contractors should understand where fine-scale grading precision matters. Erosion and sediment controls should also be in place to protect adjacent waters during earthwork.

Construction should account for the uneven distribution of sediment within the wetland, as depth varies depending on how the sediment was deposited. Heavy equipment, such as bulldozers and excavators, may be needed for removal, but the spoil should be spread out in areas where it will not create new erosion problems. Driving heavy equipment over native soils may cause soil compaction and reduce infiltration rates. Compaction can be mitigated by discing and ripping compacted soils.

Finally, vegetation and invasive species management should be planned from the start. Native wetland plants often have long procurement times and are sensitive to timing, so planting schedules should be aligned with seasonal windows to improve survivability. Post-construction, invasive species can quickly take advantage of disturbed soils, so a strong monitoring and control plan is valuable. Wildlife impacts like deer browse or goose grazing may also require protective measures to protect young vegetation before establishment.

Tools and resources

Wetlands:

- **EPA**

  An Introduction and User's Guide to Wetland Restoration, Creation, and Enhancement ↗

  Incorporating Wetland Restoration and Protection in Planning Documents | US EPA ↗

- **GLO**

  Wetland Protection Resiliency Design Guide ↗

Playa Lakes:

- **Playa Lake Joint Venture**

  pljv.org/docs/Playa-Restoration-Guide.pdf ↗

- **Texas Playa Conservation Initiative**

  Playa Recharge and Wetness Estimators ↗

- **Texas Tech University**

  Classification of Playa Lakes Based on Origin, Morphology, and Water Quality Parameters ↗

- **New Mexico State University**

  Playa Lakes: Understanding Their Importance and How to Protect Them and Improve Their Function ↗

Figure 10-9. Playa lake conservation. A subdivision development was redesigned to maintain the natural playa on site. Developers incorporated the playa as a multifunctional stormwater feature, including walking trails and educational signage. The city permitted reduced detention basin construction in exchange for maintaining the natural playa basin, saving developers over $200,000.

Photo courtesy of the Texas Water Development Board

10.5 Land conservation

Conservation of prairies, grasslands or flood prone areas offers a long-term strategy to preserve the flood resilience function of Texas landscapes while protecting ecological, agricultural, and community values. As described in **Section 7.3**, priority conservation areas — including upland forests and grasslands, wetlands, riparian corridors, and floodplains — function as natural sponges, absorbing and slowing surface runoff, stabilizing soils, and reducing erosion that can degrade flood infrastructure and channel stability. **Section 7.3** also identifies key geospatial resources, including the NRCS ***Web Soil Survey*** ↗ and the USGS ***National Land Cover Dataset*** ↗, that practitioners can use to identify high-priority sites for conservation efforts.

Prairies and grasslands are among the most valuable landscapes for flood resilience in Texas. The deep, fibrous root systems characteristic of native prairie plants (**Figure 10-9**) stabilize soils, enhance infiltration, and reduce erosion and sediment transport. Aboveground foliage intercepts rainfall before it reaches the ground and slows overland flow, while evapotranspiration further reduces soil moisture and runoff volumes. As these landscapes are converted to impervious surfaces, runoff is more rapidly conveyed to receiving channels, increasing flood peaks and volumes downstream.

Voluntary conservation easements and land acquisitions can help protect flood-prone areas from development, maintaining natural floodplain storage capacity and reducing downstream flood peaks. Prairie restoration — including the reestablishment of native grasses and forbs — can meaningfully improve infiltration rates, reduce surface runoff, and support groundwater recharge in areas where urbanization or agricultural conversion has degraded natural hydrology.

In inland flood-prone areas, land conservation strategies may also include the preservation of riparian corridors, oxbow lakes, and low-lying agricultural lands that provide natural detention storage during storm events. These approaches not only reduce flood risk but also support wildlife habitat, working lands, and open space that are integral to the cultural and economic identity of many Texas communities. **Chapter 7** outlines geospatial data useful in determining ideal sites for conservation.

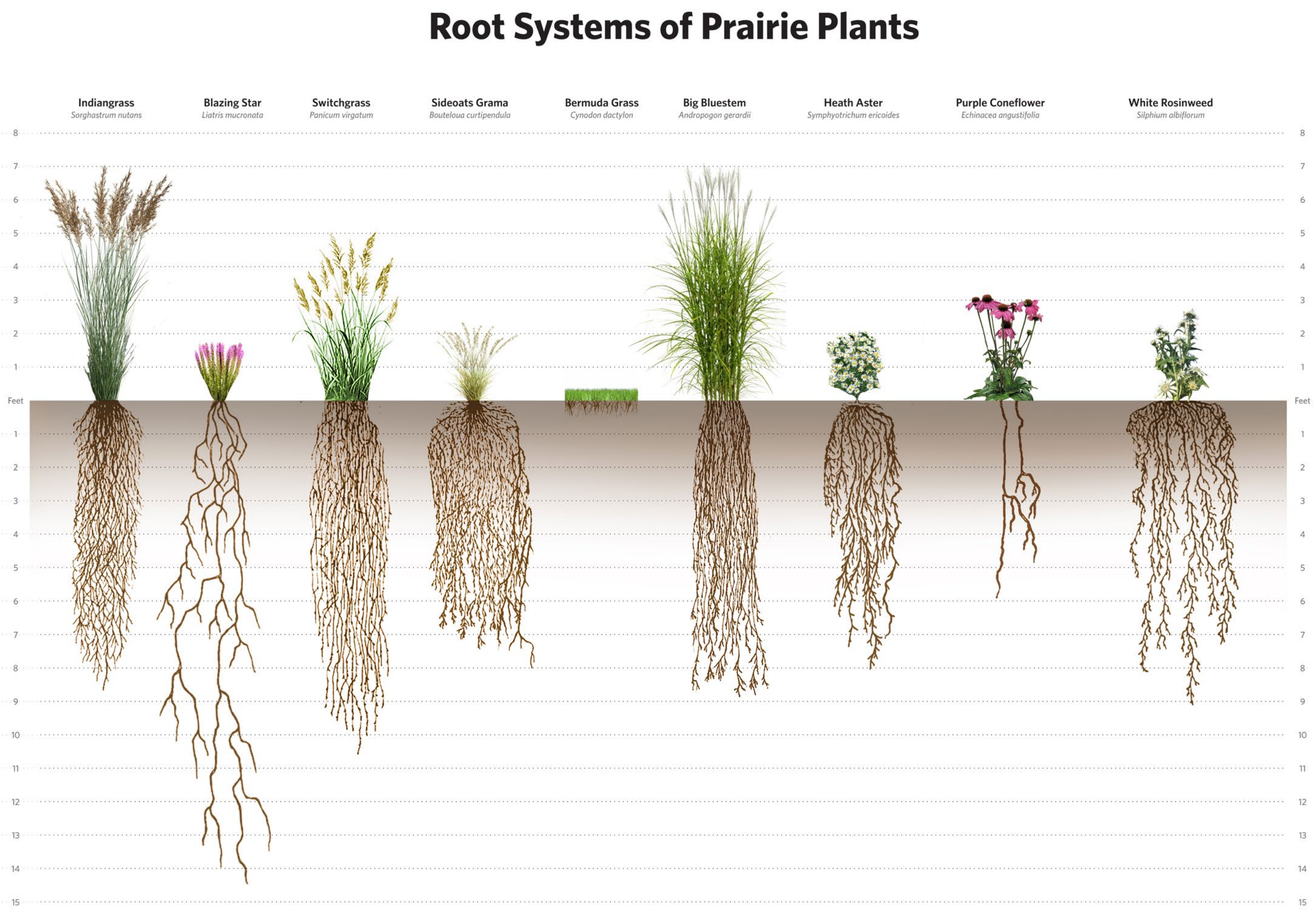
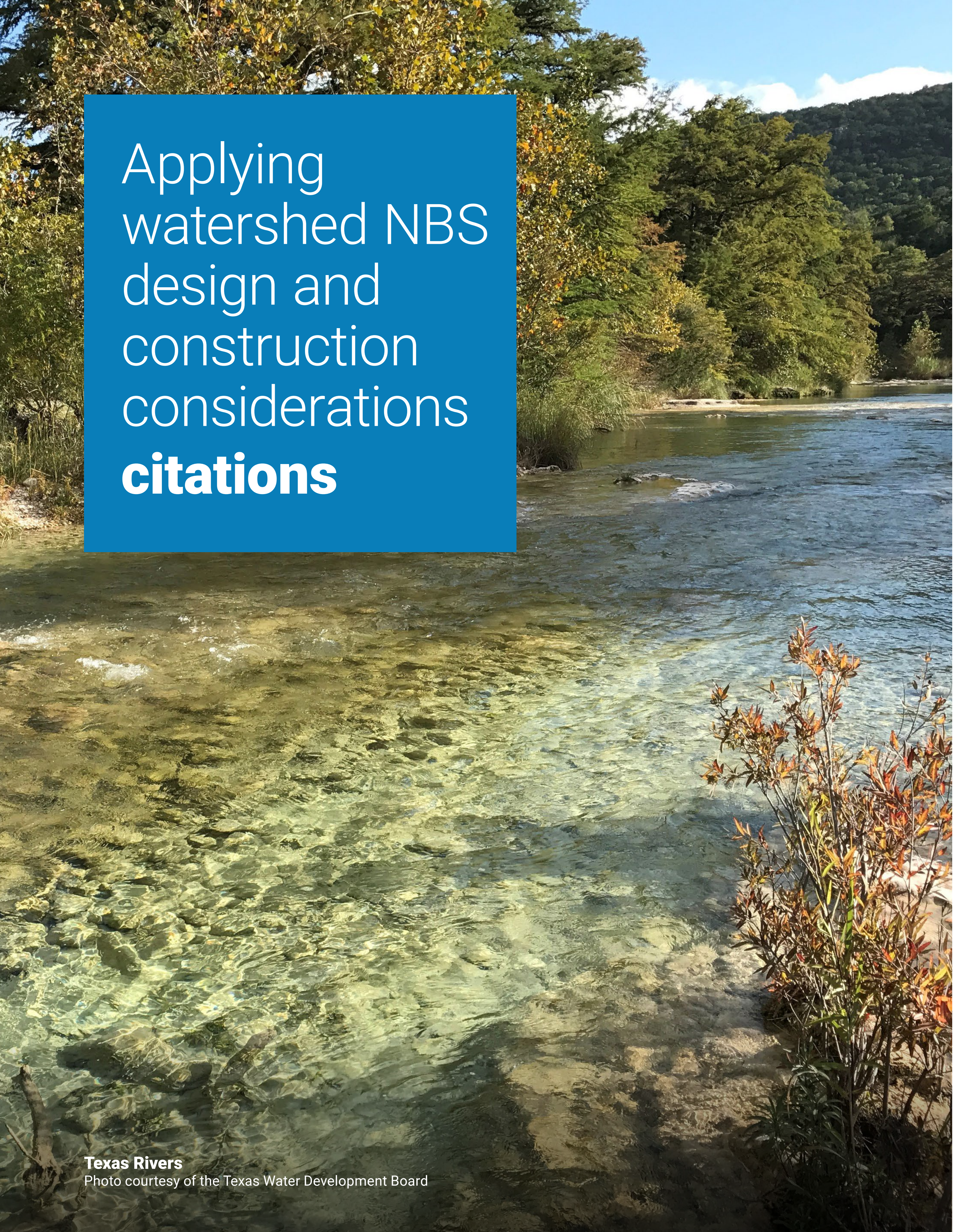


Figure 10-10. Root systems of common prairie plants

Source: The Nature Conservancy

Land Conservation at Rock Creek Ranch in Fort Worth, Texas
Photo courtesy of City of Fort Worth



Applying watershed NBS design and construction considerations **citations**

Texas Rivers
Photo courtesy of the Texas Water Development Board

[1] U.S. Department of Agriculture, Natural Resources Conservation Service (USDA NRCS). 2007. Stream Restoration Design: National Engineering Handbook, Part 654 (210–VI–NEH, August 2007), U.S. Department of Agriculture, Natural Resources Conservation Service. Available online at: https://www.epa.gov/system/files/documents/2022-11/U.S.%20Department%20of%20Agriculture%2C%20Stream%20Restoration%20Design.pdf

[2] Simon, A. 1989, A model of channel response in disturbed alluvial channels. Earth Surf. Process. Landforms, 14: 11-26. https://doi.org/10.1002/esp.3290140103

[3] U.S. Army Corps of Engineers, 2013, Stream terminology: Galveston, Texas, U.S. Army Corps of Engineers, Galveston District, Regulatory Division, 17 p., accessed at https://www.swg.usace.army.mil/Portals/26/docs/regulatory/Streams/Terminology%20June%202013.pdf

[4] Biedenharn, D.S, Copeland, R.R, U.S. Army Corps of Engineers, 2000, Effective Discharge Calculation Vicksburg, Mississippi, U.S. Army Corps of Engineers, Waterways Experiment Station, Technical Report accessed at: https://erdc-library.erdc.dren.mil/server/api/core/bitstreams/81b728f8-6eb9-4ef8-e053-411ac80adeb3/content

[5] Doll, B. et. All, 2003, Stream Restoration: A Natural Channel Design Handbook, North Carolina Stream Restoration Institute and North Carolina Sea Grant, accessed at: https://semspub.epa.gov/work/01/554360.pdf

[6] San Antonio River Authority, n.d., San Pedro Creek Culture Park, accessed at: https://spcculturepark.com/about/the-project/

[7] Crowe Curran, Joanna, S. Kyle McKay, Julie R. Beagle, Edward J. Brauer, Christopher P. Haring, Jeremy Thomas, Joe Lange, Daniel Buhr, Nich Van Buecken, Clara Rose, Debra Bishop, and Sage Jensen. 2025. Engineering Practice Guide for Floodplain Benching: A Natural Infrastructure Approach for Riverine Systems. ERDC TR-25-15, U.S. Army Engineer Research and Development Center, Vicksburg, MS. Available online at: https://www.erdc.usace.army.mil/Media/Publication-Notices/Article/4258410/engineering-practice-guide-for-floodplain-benching-a-natural-infrastructure-app

[8] Brownsville Public Utility Board, n.d., Resaca Restoration, accessed at: https://www.brownsville-pub.com/projects/resaca-restoration/

[9] Stoffer, P. 2004. Desert landforms and surface processes in the Mojave National Preserve and vicinity U.S. Geological Survey Open-File Report 2004-1007. Available online at http://pubs.usgs.gov/of/2004/1007/playas.html

[10] Federal Aviation Administration. 2018. Hazardous wildlife attractants on or near airports (Advisory Circular No. 150/5200-33C). U.S. Department of Transportation. https://www.faa.gov/documentLibrary/media/Advisory_Circular/150-5200-33C.pdf

[11] Playa Lkes Joint Venture, n.d., Conservation Planning Tools, accessed at: https://pljv.org/planning-tools/

11

Applying neighborhood NBS design and construction considerations

This chapter provides practice-specific design and construction considerations for neighborhood-scale NBS used for flood resilience including: bioretention basins or rain gardens, bioswales, vegetative filter strips, wet ponds, constructed wetlands, rainwater harvesting, and stormwater parks.

Key takeaways

- Neighborhood NBS practices have a greater flood resilience benefit when implemented across a community or watershed.
- Across all neighborhood NBS practices, designs should account for soils, drainage patterns, hydrology, hydraulics, available space, and existing utilities and infrastructure.
- Neighborhood NBS practices require distinct design approaches based on their primary function (conveyance, storage, infiltration, or treatment) and local site constraints.

Six Points UV Streetscape in Fort Worth, Texas

Photo courtesy of Freese and Nichols, Inc.

How the guiding principles apply to this chapter

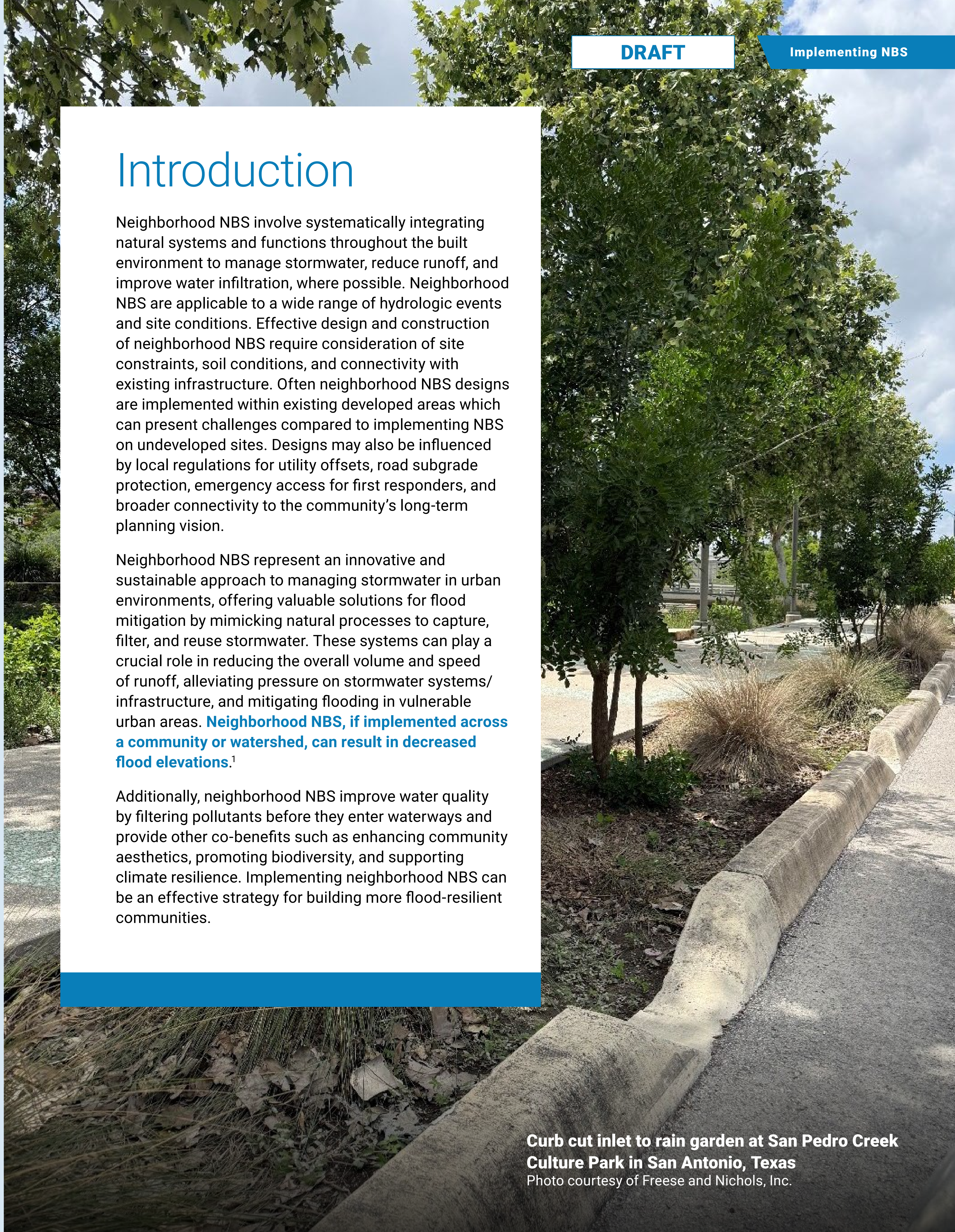
Engage and include	Local communities will interact with neighborhood NBS, so the involvement of local stakeholders in the design and construction process helps the project be compatible with community goals.
Apply systems thinking	Neighborhood NBS are most effective when designed to work with and enhance the efficiency of existing stormwater infrastructure through incorporation during initial planning stages.
Work across boundaries	The design and construction of neighborhood NBS requires coordination and collaboration with numerous departments to navigate site constraints and comply with local regulations.
Learn and adapt continuously	The complex nature of developed areas means the design of neighborhood NBS will need to adapt over time to changing needs and shifting community priorities.

Introduction

Neighborhood NBS involve systematically integrating natural systems and functions throughout the built environment to manage stormwater, reduce runoff, and improve water infiltration, where possible. Neighborhood NBS are applicable to a wide range of hydrologic events and site conditions. Effective design and construction of neighborhood NBS require consideration of site constraints, soil conditions, and connectivity with existing infrastructure. Often neighborhood NBS designs are implemented within existing developed areas which can present challenges compared to implementing NBS on undeveloped sites. Designs may also be influenced by local regulations for utility offsets, road subgrade protection, emergency access for first responders, and broader connectivity to the community's long-term planning vision.

Neighborhood NBS represent an innovative and sustainable approach to managing stormwater in urban environments, offering valuable solutions for flood mitigation by mimicking natural processes to capture, filter, and reuse stormwater. These systems can play a crucial role in reducing the overall volume and speed of runoff, alleviating pressure on stormwater systems/infrastructure, and mitigating flooding in vulnerable urban areas. **Neighborhood NBS, if implemented across a community or watershed, can result in decreased flood elevations.**[1]

Additionally, neighborhood NBS improve water quality by filtering pollutants before they enter waterways and provide other co-benefits such as enhancing community aesthetics, promoting biodiversity, and supporting climate resilience. Implementing neighborhood NBS can be an effective strategy for building more flood-resilient communities.



Curb cut inlet to rain garden at San Pedro Creek Culture Park in San Antonio, Texas
Photo courtesy of Freese and Nichols, Inc.

11.1 General considerations

Neighborhood NBS maintain or restore the ability of sites to absorb, slow, store, and infiltrate rainfall before it becomes runoff. Preserving or increasing pervious cover, native vegetation, high infiltration soils, and providing storage can reduce the volume and velocity of runoff reaching downstream drainage infrastructure.

When implemented across multiple sites, neighborhood NBS can collectively improve local drainage performance and reduce pressure on storm drain systems beyond an individual project's footprint.

Typical contributing drainage area ranges for common neighborhood NBS practices are summarized in **Figure 11-1**.

Pretreatment

Pretreatment is important for preserving the long-term functionality and hydraulic performance of neighborhood NBS and is generally recommended to be installed at all inflow points. Without adequate pretreatment, sediment, debris, organic matter, and other pollutants can enter NBS practices and reduce treatment capacity, clog soil media, and diminish storage volume over time. Pretreatment features help slow incoming runoff, dissipate energy, capture coarse sediment and floating debris, and protect downstream systems from excessive maintenance needs.

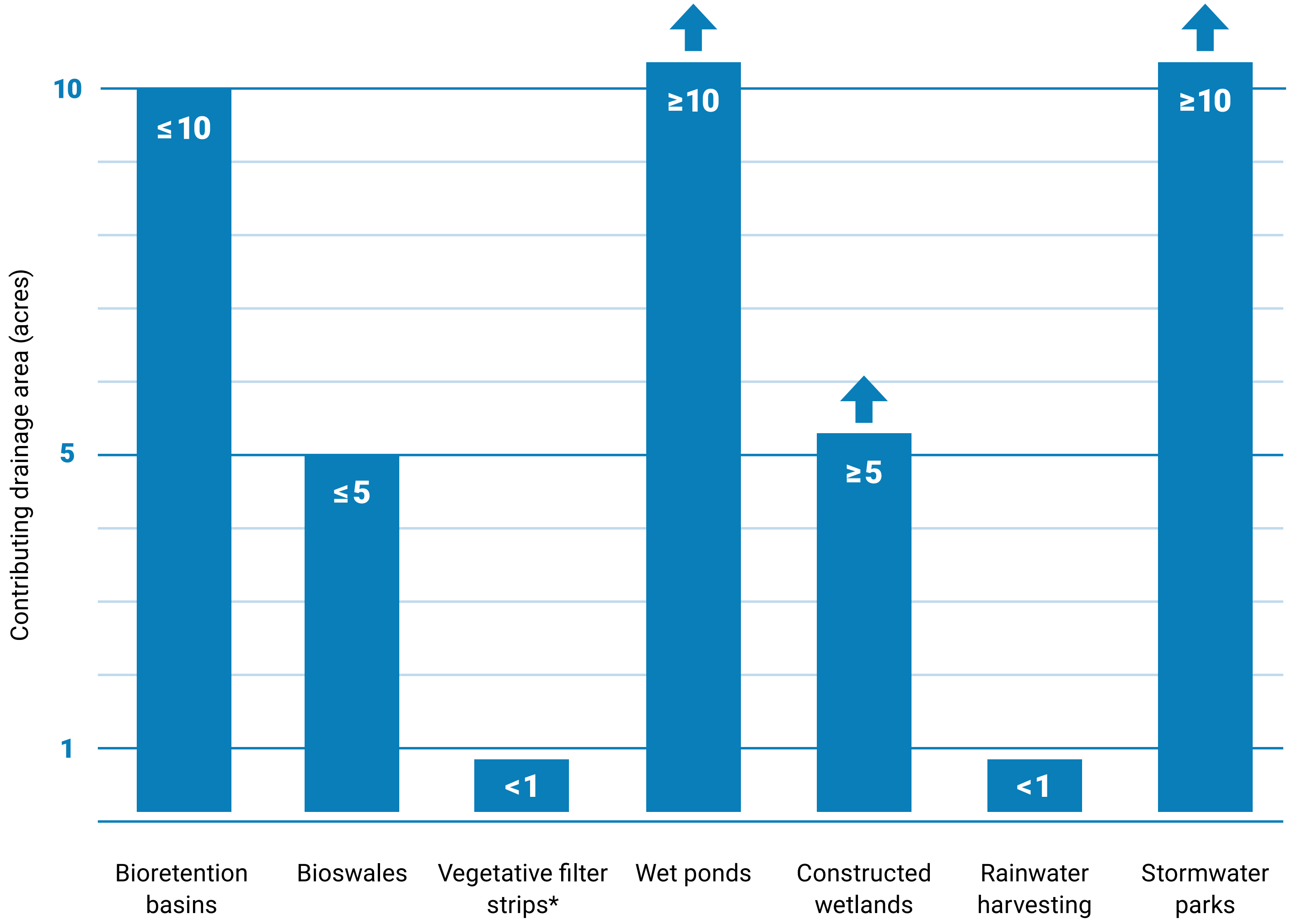


Figure 11-1. Typical contributing drainage areas of neighborhood NBS practices

**Vegetative filter Strips are designed based on length of the contributing drainage area*

Recommended pretreatment strategies may include gravel diaphragms, vegetative filter strips, sediment forebays, sump boxes, curb inlet screens, level spreaders, or bioswales depending on site conditions and the selected NBS practice. Pretreatment components should be designed for easy maintenance access so accumulated debris, trash, and sediment can be removed regularly without damaging surrounding vegetation or infrastructure, while also allowing for ongoing vegetation and tree maintenance.

Pretreatment is especially important when multiple NBS practices are connected as part of a treatment train. Treatment trains route stormwater runoff through a sequence of practices that collectively slow flow, improve water quality, reduce runoff volume, and enhance flood mitigation performance. For example, runoff may first pass through a vegetated filter strip or vegetated swale before entering a rain garden, bioretention basin, stormwater tree trench, constructed wetland, or other downstream practice. Connecting practices in series can improve overall system resilience and reduce pollutant loading to downstream infrastructure.

The depth to groundwater and groundwater protection zones should be considered when designing NBS to increase infiltration. EPA notes that infiltration practices in karst regions can create a risk for sinkholes or groundwater contamination, and therefore should be avoided.[2]

Vegetation selection

Vegetation plays an important role in the long-term success of neighborhood NBS by stabilizing side slopes, slowing runoff, trapping sediment, and removing pollutants through biological uptake. Wetland plants oxygenate the water, enhance habitat value, and improve the overall aesthetics of pond environments. In addition to supporting stormwater function, plantings can provide pollinator habitat and contribute to the aesthetic value of a site.

Vegetation should be selected based on anticipated ponding depth and hydrologic zones typically categorized as deep water, emergent, and upland fringe zones. Grouping plants by tolerance to water depth and inundation frequency will improve establishment, survival, and ecological function over time. Using native or regionally adapted species supports local biodiversity, improves resilience, and reduces long-term maintenance needs. Where trees and shrubs are incorporated, consideration should be given to protecting underdrain systems and any nearby underground utilities from deep rooted species. Woody vegetation should be avoided in areas where concentrated flows may contribute to erosion around the tree trunks.

The ***USDA Plant Hardiness Zone Map ↗*** provides a helpful reference for selecting vegetation that will survive regional minimum winter temperatures, which is especially important when designing for long-term resilience and low-maintenance plantings. Regional maximum summer temperatures and typical annual rainfall should also be considered in vegetation selection. By referencing USDA Plant Hardiness Zones in tandem with hydrologic planting zones, designers can select vegetation that is suited to site hydrology and capable of surviving local winter conditions. This dual consideration supports plant longevity, reduces replanting costs, and helps to achieve consistent ecological and water quality performance.

Bioretention basins and bioswale features are typically planted with small to medium-sized vegetation including groundcover, shrubs, and trees that can tolerate urban environments, well-drained soils, and periodic inundation and—depending on the location—extended dry periods. A diverse mix of erosion-resistant, low-growing plants suited to the site's conditions should be used.

The treatment zone is the area where stormwater is treated through processes like infiltration, filtration, sedimentation, and biological uptake. This zone typically includes the lower portions of the side slopes, where water flows and interacts with vegetation and soil to remove pollutants and manage stormwater runoff. The treatment zone improves water quality and reduces stormwater volume, so vegetation and design within this area must support these functions without impeding flow or treatment processes.

In some cases, sod may be used as an alternative planting strategy to simplify maintenance activities; however, sod has a lower capacity to uptake pollutants. It is recommended that bioretention basins planted with sod be designed with an extended drawdown period to provide water quality benefits. A mixture of grasses adapted to both dry and wet conditions may be necessary to support establishment and long-term performance under varying moisture conditions. Sod can also be effective for establishing vegetation in swales and if used, should be laid perpendicular to flow to prevent channelization. While larger vegetation, such as native tall grasses, shrubs and trees, require routine pruning, sod-planted basins typically only need mowing. The City of Austin Watershed Protection Department has successfully utilized sod in their capital improvement projects, such as the Todd Lane Improvements project (Figure 11-2), to streamline long-term maintenance.

Urban heat island mitigation and habitat enhancement

Many neighborhood NBS practices mitigate urban heat island effects as a co-benefit, in addition to improved flood resilience. To maximize urban heat island benefit, NBS design can include tree canopy coverage and vegetated surfaces with high evapotranspiration potential. According to the USDA Forest Service[9], providing a minimum of 1,000 cubic feet of soil volume per tree significantly improves tree health and canopy development. Trees can be strategically placed to shade impervious surfaces and building façades, especially on west and south exposures.

It is recommended to use native or climate-adapted plant species that tolerate urban stressors, support biodiversity, and require less irrigation once established. Construction should protect uncompacted, well-aerated soils with adequate organic matter, and temporary irrigation infrastructure should be installed to support early plant establishment. Layered vegetation and structural features, like downed logs or pollinator-friendly plantings, can enhance habitat complexity without requiring additional space.

These co-benefits are often amplified when multiple neighborhood NBS practices are integrated into connected urban systems such as green streets, which combine stormwater management, ecological function, and multimodal public infrastructure within the public right-of-way.

Figure 11-2. Sod-planted bioretention basins. City of Austin's Todd Lane Improvement Project.

Source: Austin Watershed Protection

Engineered soils

Assessing soil conditions early in the design process is recommended to avoid issues with waterlogging or poor drainage that could eventually undermine the functionality of the NBS system.[3] Poorly draining soils, common in developed areas, may require amendment with more porous materials to enhance permeability and facilitate water adsorption. Low-permeability soils like clay-heavy soils (Type D), may significantly limit infiltration and plant growth. Amendments such as incorporating sand, compost, or organic materials can improve permeability, nutrient availability, and biological activity.

Engineered soils are used in many NBS practices to achieve ideal infiltration, permeability, and nutrient performance. Typically composed of sand, compost, and topsoil, these mixes promote infiltration and root health in cases where native soils are compacted, infertile, or otherwise unsuitable. Compost can introduce excess nitrogen and phosphorus in the soil mix. It is recommended that only stable and mature compost should be used in bioretention media[4] and *City of Austin Standard Specifications Manual* ↗ limits organic matter in biofiltration medium to between 0.5 to 5 percent.[5]

Commercially available fill material such as sandy loam should be avoided due to poor fertility and drainage. This product is often referred to by landscapers as "red death", which refers to the color of the material, and is an infertile fill material that has poor drainage characteristics. Source materials should also be free of weeds, stones, debris, and other similar objects larger than 2 inches.

Sourcing materials locally and using high-quality materials contribute to both the performance and sustainability of neighborhood NBS. Locally sourced materials typically have lower transportation costs and support the regional economy. The selection of durable, weather-resistant materials improves project longevity, even under prolonged flooding conditions. Proper inspection of materials before installation should be completed to check for compliance with design standards and to avoid issues like potential contamination or subpar quality.[6,7] In some cases, engineered soils require perforated underdrains (see Figure 11-3, Item L) to prevent waterlogging and should be tailored to local conditions.

The design team should include percentages for each material used in engineered soils in technical specifications and have construction documents that describe sourcing, handling and transporting, and installation requirements. Contractors and design teams should work together, when possible, to adapt to sourcing constraints.

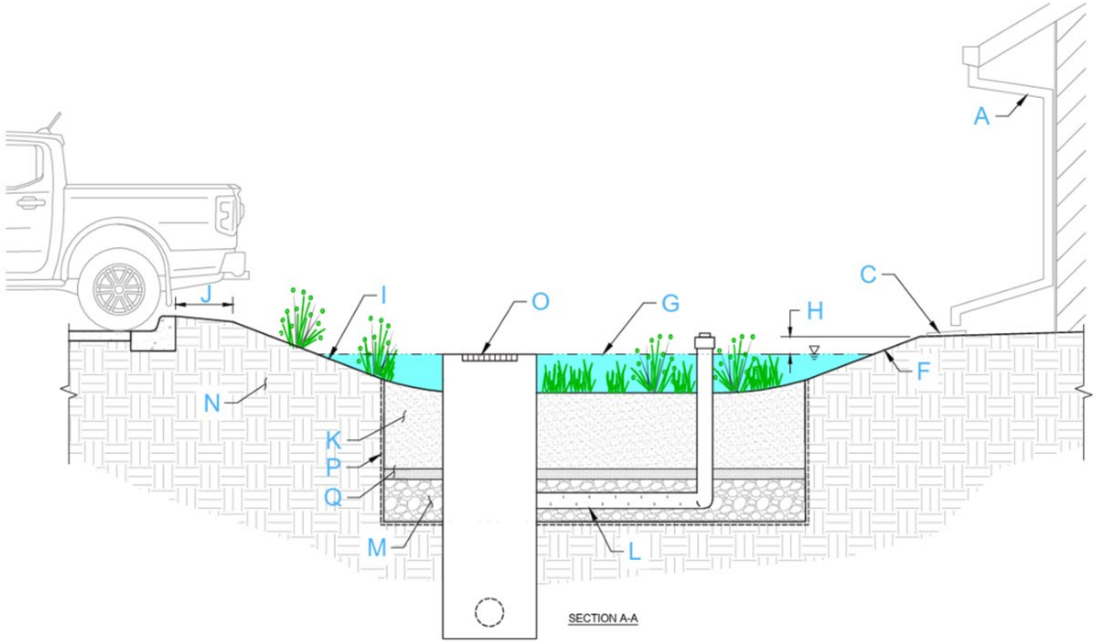


Figure 11-3. Bioretention cross section. A is drainage downspout, C is energy dissipation at flow inlet, F is vegetative groundcover, G is water surface at desired ponding depth, H is freeboard, I is side slope, J is a step out when bioretention is along the roadway, K is engineered media, L is perforated underdrain, M is drainage layer, N is embankment material, O is overflow structure, P is non-woven geotextile, and Q is media barrier.

Source: Green Infrastructure Toolkit for Texas Communities – Bioretention Design Set

Inlet and outlet structures

How stormwater enters and exits neighborhood NBS affects the system's ability to achieve the intended flood resilience and co-benefits. Many neighborhood NBS have direct connections to existing or new gray infrastructure components. Components like inlet structures and outlet systems should be optimized to handle varying flow rates, allowing for energy dissipation to prevent erosion and sediment accumulation. **Neighborhood NBS can be implemented in communities that experience large volume storms if properly designed to manage the anticipated runoff.**

Inlet structures should be strategically placed to efficiently capture runoff while preventing clogging and potential bypass, which can occur in areas with high debris or inadequate slope.[8] It is recommended that inlet and outlet structures are located as far apart as possible to maximize time for pollutant settling. Energy dissipation mechanisms at inlets are beneficial at reducing the velocity of incoming stormwater, minimizing erosion, and preventing damage to the infrastructure itself.

Outlet structures should be designed to control the flow of water leaving the system to avoid downstream impacts. The ability to drain through gravity should be carefully considered to support upstream and downstream tie-ins, while tailwater conditions should be evaluated to identify potential impacts on hydraulic performance and overall design. The design should account for allowable ponding depths so that the system can handle peak design rainfall without inundating the surrounding site or area.

Figure 11-4. Stormwater overflow structure with domed debris grate

Source: Freese and Nichols, Inc.

Construction considerations

Construction of neighborhood NBS should prioritize grading accuracy, hydraulic connectivity, and vegetation establishment to support long-term performance. Erosion and sediment controls should be installed prior to clearing and grading to minimize premature sediment loading of NBS soils and storage zones. NBS features should be protected from compaction by heavy equipment, particularly within vegetated treatment zones, and grading should be closely monitored to maintain design elevations and hydraulic control.

Infiltration areas should be protected from compaction by heavy equipment, particularly within vegetated zones, and grading should proceed from downstream to upstream to maintain hydraulic control. Construction specifications should include guidance for soil decompaction or scarification where necessary, especially after heavy equipment operation.

Basin and swale excavation, side slopes, and outlet elevations should be constructed to design grades to establish intended storage volumes, treatment depths, and permanent pool elevations where applicable. Improper grading can reduce available storage and compromise peak flow attenuation. Where liners are required, they should be properly installed and protected with adequate planting soil prior to vegetation establishment.

Planting elevations and zones should be verified during construction to ensure vegetation is installed at appropriate depths and hydrologic conditions. Following planting, the vegetation should achieve stable hydrology within a short period; rapid drawdown may indicate issues with liner integrity, outlet configuration, or water balance assumptions.

Construction sequencing should limit runoff from disturbed upstream areas until contributing drainage is stabilized. Sediment forebay and inlet structures should be constructed and stabilized early to protect the main system from construction-generated sediment and debris.

Prior to project closeout, constructed NBS features should be inspected to confirm that storage volumes are within design tolerances and that vegetation has achieved initial establishment necessary to support treatment and flood mitigation functions.

Maintenance

Maintenance access and long-term performance should be considered early in design. Features such as a mow strip, stabilized access paths, and strategically placed maintenance openings should be incorporated to allow maintenance teams to perform sediment removal, plant management, and underdrain inspections without damaging sensitive vegetation or compacting soils. Pretreatment components should be inspected and cleared regularly to prevent sediment and debris accumulation from reducing system performance over time. Learn more about NBS maintenance in **Chapter 13**.

Tools and resources

- **Texas A&M AgriLife**
  Green Infrastructure for Texas
  Green Infrastructure Toolkit for Texas Communities Implementation Guide ↗
- **EPA**
  Large Volume Storms and Low Impact Development ↗
- **USDA**
  Plant Hardiness Zone Map ↗

Green streets

Green streets are roadway corridors designed with neighborhood NBS practices to manage stormwater runoff at its source rather than relying solely on traditional storm drain infrastructure. These streets can include a combination of NBS practices such as rain gardens, stormwater tree trenches, and bioswales.

Green streets often include additional features like permeable pavement along sidewalks and bike lanes and traffic-calming measures to improve multimodal access and enhance public space.

When designed effectively, green streets reduce the volume and velocity of stormwater runoff by intercepting rainfall, promoting infiltration, and providing temporary detention. This can contribute to reducing local flooding and improving water quality.

Green streets are especially effective in dense urban areas, where space is limited and decentralized stormwater control would be beneficial. By using native or adaptive vegetation, green streets also help mitigate the urban heat island effect and improve air quality.

While typically implemented at the neighborhood scale, green streets can be planned as part of a broader flood management strategy to increase long-term regional impact.

Green streets can be integrated with broader initiatives such as "Vision Zero"—a traffic safety movement adopted by many Texas cities including Austin, San Antonio, Dallas, and Houston. These cities have adopted "Vision Zero" plans to reduce traffic fatalities and injuries through safer street design.

Green streets can improve mobility, safety, and accessibility for all users alike. They demonstrate how roadway corridors can serve multiple purposes—flood mitigation, ecological function, and community connectivity—making them a smart and scalable NBS strategy for flood resilience.

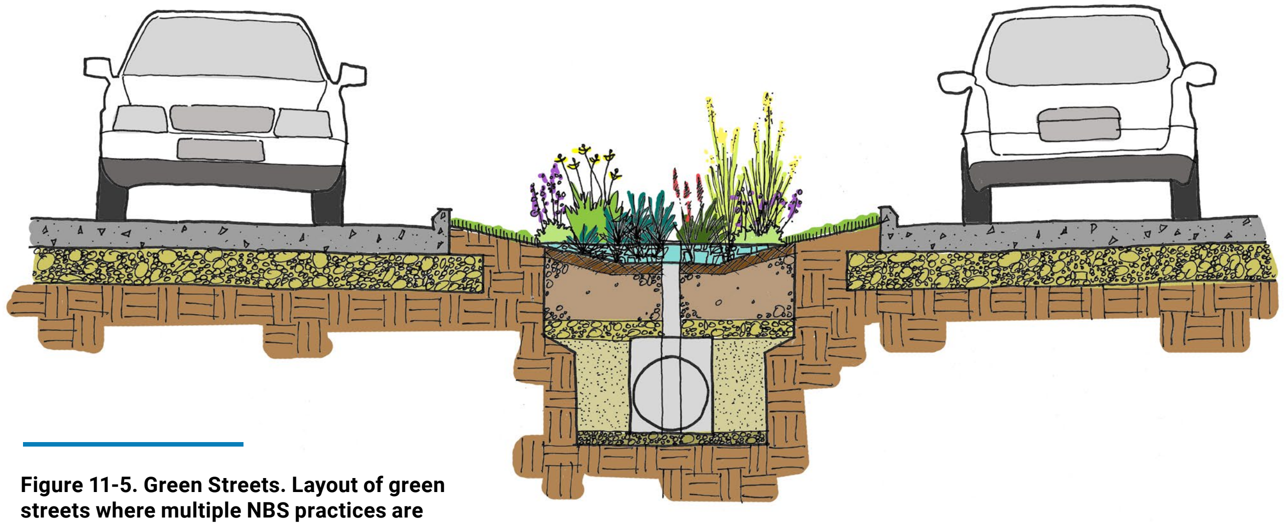


Figure 11-5. Green Streets. Layout of green streets where multiple NBS practices are combined along a roadway.

Source: Freese and Nichols, Inc.

Figure 11-6. Green street example. Rain garden along Caroline St. in Houston, Texas.

Photo courtesy of the Freese and Nichols, Inc.

11.2 Bioretention basins and rain gardens

Bioretention basins are shallow, vegetated depressions that capture and temporarily store stormwater runoff. These systems use engineered or well-draining native soils and vegetation to filter, treat, and infiltrate runoff on-site. Bioretention basins can be designed throughout a site utilizing areas typically designated for landscaping.

In locations with highly permeable native soils, bioretention basins can infiltrate runoff directly into the subsurface. In contrast, sites with lower infiltration capacity may require underdrain systems to convey filtered runoff into the storm drainage system. Bioretention basins typically have a shallow basin depth but may vary depending on the site-specific infiltration rates and drawdown time requirements, as stormwater volume reduction is largely governed by subsoil infiltration capacity and available storage.

Bioretention can take many forms that offer different advantages depending on site conditions, scale, and project goals. Common types include rain gardens, retrofitted detention ponds, infiltration basins, and stormwater trees and tree trenches.

Rain gardens are shallow basins that typically serve small drainage areas—often residential yards, curb bump-outs, or courtyards. Rain gardens are ideal for treating runoff from rooftops, roadway blocks, or small parking lots and can be integrated into existing landscape designs without requiring significant space. Effective design requires runoff to be intentionally directed into the system through features such as curb cuts, curb openings, or sheet flow grading. **Figure 11-7** shows a rain garden designed with a curb-cut to receive runoff from the adjacent roadway, the elevated outfall allows for discharge into the storm drain system, while allowing time for infiltration.

Retrofitted detention ponds are existing dry basins that temporarily hold water during storm events and are modified to include biofiltration media. These retrofits improve water quality treatment while maintaining and/or enhancing flood control functions. By integrating vegetation and engineered soils, retrofitted ponds can support pollutant removal, promote infiltration, and provide habitat or amenity value—turning otherwise underutilized infrastructure into multi-benefit spaces.

Infiltration basins are similar to traditional detention ponds but are specifically designed to retain and infiltrate water into the subsurface. These basins require well-draining soils or underdrains to convey additional runoff. Infiltration basins can be used to treat areas of high impervious cover, but should not be used in areas with high total suspended solids to avoid clogging. Infiltration basins may be designed as gravel beds, planted with xeric vegetation.

Stormwater trees and tree trenches are specialized forms of bioretention designed for dense urban environments where stormwater management, tree canopy establishment, and streetscape integration are desired simultaneously. Stormwater trees may appear like ordinary street trees, but they are integrated into a specially designed system that includes a subsurface stone basin to capture, store, and infiltrate stormwater runoff. Typically installed in urban sidewalks or plazas, stormwater trees are planted in engineered tree pits that allow runoff to enter either through sheet flow or curbside inlets connected directly to the pit. Trees also contribute to canopy interception which reduces the volume of rainfall that reaches the ground and evapotranspiration, which returns captured water to the atmosphere.

Design considerations

Successful bioretention basin design requires careful evaluation of site conditions, system configuration, and long-term performance needs. The following subsections outline key considerations that should be addressed during the design process, from initial site assessment through integration with surrounding infrastructure.

Soil conditions

The process to design bioretention systems begins with assessing the infiltration capacity of the existing subgrade soils. Infiltration rates directly influence the sizing, depth, and overall configuration of the bioretention basin, including whether an underdrain system or soil amendments will be required. The hydraulic properties of engineered soil media also play an important role in determining ponding depth, storage volume, and overall system performance.

Bioretention basins are commonly sited adjacent to roadways and parking lots, where they can effectively capture and treat stormwater runoff. However, infiltrating water near a roadway can pose a risk to the underlying subgrade materials, potentially leading to structural degradation over time. Installing an impermeable liner between the engineered soil media of the bioretention system and the roadway base helps to prevent subgrade impacts.

Typical liner materials include synthetic sheets made from high density polyethylene (HDPE), clay or concrete. The appropriate liner type and configuration should be determined in consultation with geotechnical engineers so the design is capable with local soil conditions and structural requirements.

Soil modifications and engineered soils and are discussed further in **Section 11.1**.

Figure 11-7. Infiltration Trench in Bee Cave, Texas

Source: Freese and Nichols, Inc.

Underdrain systems

Bioretention basins are typically designed to fully drain (surface drawdown time) within 48 hours after a storm event to maintain functionality and prevent prolonged ponding. An underdrain system should be considered if the infiltration rate of the existing subgrade soils is low (typically less than 0.5 inches per hour) or if the bioretention basin includes an impermeable liner that prevents infiltration into the native soils. The infiltration capacity of existing soils and the hydraulic properties of engineered soil media directly influence bioretention sizing, ponding depth, storage volume, and drawdown performance.

The use of an upturned underdrain outlet should be considered to promote additional infiltration into the subgrade by temporarily holding water within the basin before draining. This extended retention can enhance groundwater recharge and support healthy plant establishment within the basin.

Integration with existing infrastructure

Bioretention basins may require integration with gray infrastructure components to properly connect the NBS design into its surrounding urban environment and maximize both flood mitigation and ecological goals. While bioretention systems are fundamentally nature-based, the engineered elements allow the system to function reliably during a range of storm events.

Outfall structures, inlets, and/or overflow systems are likely required to manage larger storm events safely and maintain appropriate water surface elevations. Properly sizing and siting overflow pathways allows excess stormwater to be conveyed downstream without causing damage to the bioretention feature or adjacent infrastructure.

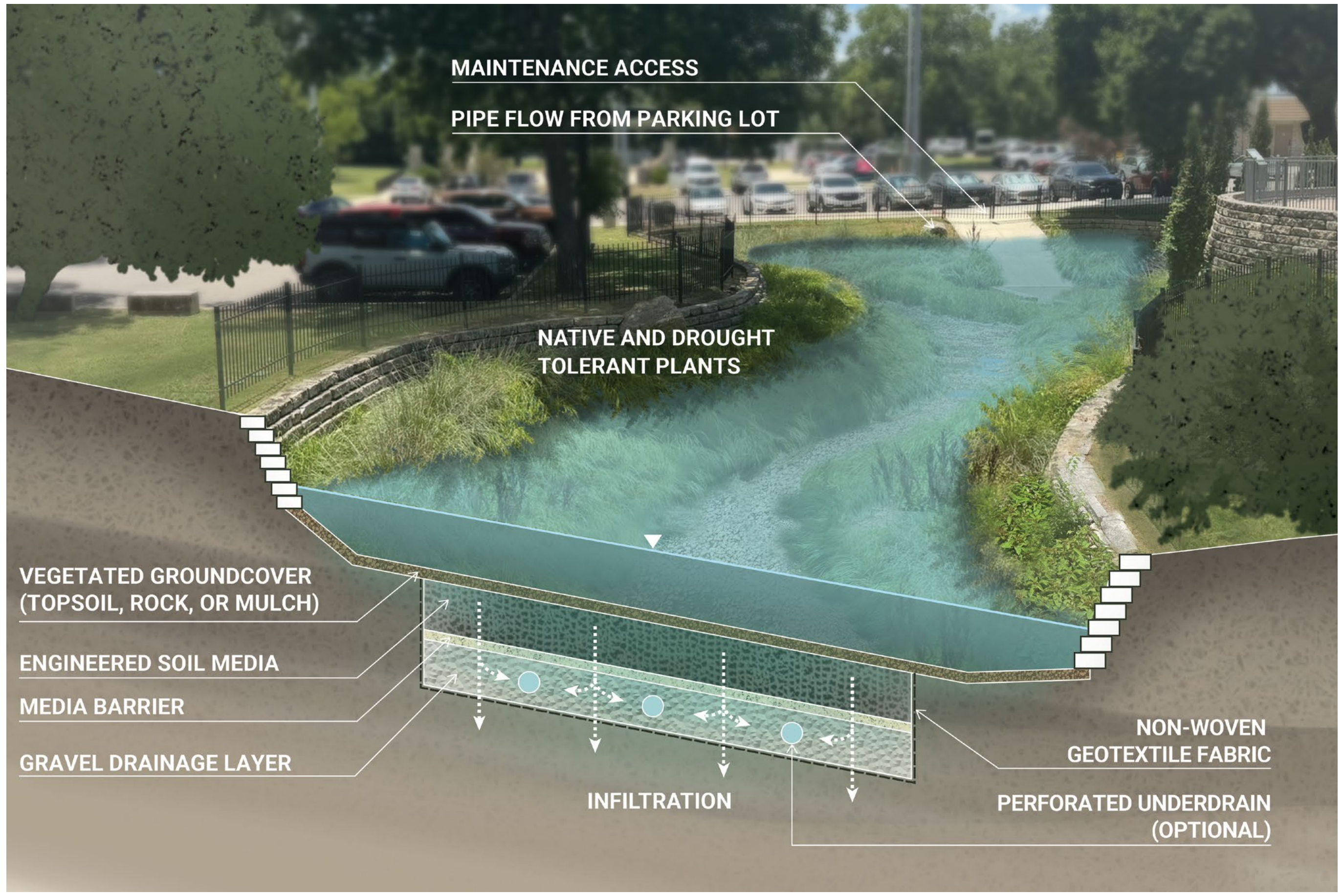


Figure 11-8. Example of bioretention media cross section

Source: Green Infrastructure Toolkit for Texas Coastal Communities – Bioretention Design Set

Tools and resources

- **San Antonio River Authority**

  San Antonio River Basin Low Impact Development Technical Design Guidance Manual ↗

- **Texas A&M AgriLife**
  Green Infrastructure for Texas

  Green Infrastructure Design Toolkit Bioretention Basin Design Set ↗

  Green Infrastructure Design Toolkit Rain Garden Design Set ↗

  Green Infrastructure Design Toolkit Infiltration Trench Design Set ↗

- **North Central Texas Council of Governments**

  Integrated Stormwater Management (iSWM) ↗

- **EPA**

  Stormwater Best Management Practice Bioretention - Rain Gardens ↗

  Stormwater Best Management Practice Urban Forestry ↗

  Stormwater Best Management Practice Street Design and Patterns ↗

11.3 Bioswales

Bioswales are shallow, vegetated open channels designed to convey stormwater runoff while simultaneously improving water quality through sedimentation, filtration, and biological uptake within the vegetation itself. Native grasses and deep-rooted plants are particularly well-suited for bioswale applications, as their dense root systems enhance infiltration, stabilize side slopes, and increase pollutant removal efficiency compared to traditional turfgrass.[11]

These swales are especially effective as a pretreatment measure for concentrated stormwater flows prior to discharge into downstream drainage infrastructure, helping to reduce sediment loads and associated pollutants before they enter receiving water bodies. Bioswales can be designed along roadways or within a site. **Figure 11-9** shows an example of a bioswale with curb openings to receive concentrated runoff from adjacent impervious surfaces.

Design considerations

Effective bioswale design requires attention to site geometry, soil conditions, flow dynamics, and vegetation selection. The following subsections outline the design considerations that can improve bioswale performance and long-term reliability.

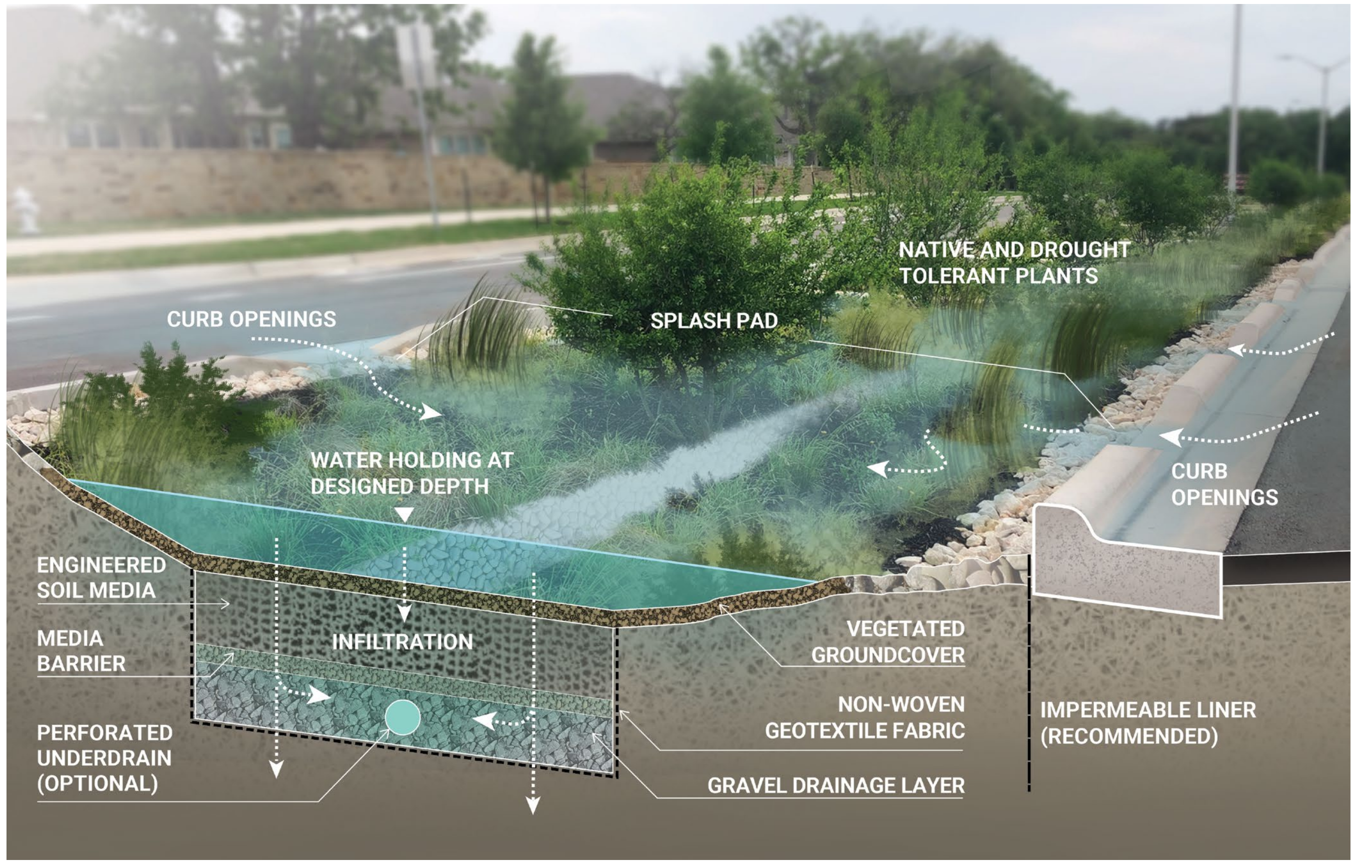


Figure 11-9. Example of bioswale media cross section

Source: Green Infrastructure Toolkit for Texas Communities – Bioswale Design Set

Soil conditions

Bioswales should be located in areas with moderate- to well-draining soil, or designed to modify the native soil. Infiltration rates should be sufficient to allow some water to infiltrate during smaller storm events, while still enabling the swale to convey larger volumes during more significant events. Poorly draining soils may require alternative approaches, such as providing underdrains or routing excess flows to downstream conveyance systems via overflow structures. High groundwater tables can also limit the infiltration capacity and effectiveness of vegetated swales. Soil modifications and engineered soils and are discussed further in **Section 11.1.**

Slope and velocity

Maintaining an appropriate longitudinal slope is necessary in order for bioswales to function effectively as stormwater conveyance systems with water quality benefits. Bioswales should be designed with longitudinal slopes that promote settling and reduce velocity and the associated shear stress within the swale. The appropriate longitudinal slope is dependent on the intended vegetation, stabilization practice, and drawdown rate.

Steep slopes can increase flow velocities and contribute to head cutting, erosion, and downstream sediment deposition. Head cuts can generate significant maintenance requirements in addition to causing sediment bars or swale constrictions downstream.

To mitigate high-velocity flows in steeper swales, check dams, rock berms, or vegetated check structures should be integrated at appropriate intervals. These features slow runoff, promote limited infiltration, and prevent channelization along the swale.[12] Inflow and outflow points should be designed with energy dissipation measures like riprap aprons to protect against scour. Proper control of slope and flow velocity helps bioswales maintain their intended hydraulic performance and desired drawdown while safely conveying runoff downstream without compromising soil stability or vegetation health over time.

Bioswales are typically designed with a trapezoidal or parabolic cross-section to promote even flow distribution across the channel. This geometry allows the vegetation to achieve effective pollutant removal and infiltration. Proper control of slope and flow velocity, and geometry help bioswales maintain their intended hydraulic performance while safely conveying runoff downstream without compromising soil stability or vegetation health over time. **Figure 11-9** shows a bioswale designed within a roadway median that includes check dams.

Tools and resources

- **Texas A&M AgriLife Green Infrastructure for Texas**
  Green Infrastructure Design Toolkit Bioswale / Linear Site Control Design Set ↗
- **San Antonio River Authority**
  San Antonio River Basin Low Impact Development Technical Design Guidance Manual ↗
- **National Pollutant Discharge Elimination System (NPDES)**
  Stormwater Best Management Practice - Grassed Swales ↗
- **Native Plant Society of Texas**
  Native Landscape Certification Program ↗
- **EPA**
  Check Dams ↗

11.4 Vegetative filter strips

Vegetative filter strips are areas of dense, permanent vegetation with a consistent slope. They are typically designed to treat sheet flow runoff from relatively small contributing drainage areas before runoff becomes concentrated. On highly permeable soils, vegetative filter strips can enhance infiltration, which aids in reducing stormwater runoff volumes. Increased infiltration can also minimize the required horizontal length, making them particularly effective along roadside shoulders or safety zones.

As stormwater passes across the vegetated strip, the dense vegetation slows flow, promotes sedimentation, and filters out suspended particles and associated contaminants. This pollutant removal is most pronounced during the initial stages of a storm event when the highest concentrations of accumulated pollutants are mobilized from impervious surfaces and carried with runoff.

Design considerations

Vegetated filter strips designed upstream of drainage infrastructure such as bioretention or storm drains can reduce sediment load and preserve system capacity. The effectiveness of this removal process depends on factors such as the slope, length, gradient, and overall condition of the vegetation within the system.

Vegetative filter strips are often perceived as a simple design approach, consisting mainly of a grassed slope. Selecting native or deep-rooted vegetation will enhance infiltration, pollutant filtration, and soil stabilization, and incorporate level spreaders to uniformly distribute flow across the strip.

Hydraulically, it is imperative to maintain uniform sheet flow across the filter strip to avoid concentrated flows that can cause erosion or bypass treatment. Grading should provide consistent, mild slope to support infiltration while preventing water from ponding or bypassing the system. For effective flood mitigation, the slope and width of the vegetative filter strip should be carefully calibrated to handle expected stormwater volumes.

To help reduce concentrated flow conditions, designs could incorporate a level spreader such as a pervious 6-12 inch berm of gravel or vegetated sand that is resistant to erosion.[13]

For more information on vegetated filter strips on rock outcrops, visit the Lower Colorado River Authority's ***Water Quality Management Technical Manual*** ↗.

Tools and resources

- **San Antonio River Authority**
  San Antonio River Basin Low Impact Development Technical Design Guidance Manual ↗
- **Lower Colorado River Authority**
  Water Quality Management Technical Manual ↗
- **National Pollutant Discharge Elimination System (NPDES)**
  Stormwater Best Management Practice Vegetated Filter Strip ↗
- **Texas NEMO**
  Vegetated Filter Strips: Stormwater Best Management Practices ↗
- **EPA**
  Stormwater Best Management Practice Vegetated Filter Strip ↗

Vegetative filter strip in Bee Cave, Texas
Photo courtesy of Freese and Nichols, Inc.

11.5 Wet ponds

Wet ponds, also known as wet extended detention basins, are NBS designed to retain and treat runoff through gravitational (quiescent) settling and biological uptake, particularly of nutrients, until it is eventually displaced by runoff from the next storm event. The permanent pool provides moisture for wetland vegetation, protects deposited sediment from resuspension during storm events, and enhances visual appeal when well maintained. Above the permanent pool, flood storage is provided to capture and slowly release runoff, reduce peak flows and contribute to flood mitigation.

Design considerations

Not all wet-bottom detention ponds qualify as NBS. Wet ponds differ from common detention or retention ponds in the use of features intentionally designed to uplift and maintain aquatic ecosystems. This includes elements such as vegetated shelves, aeration devices, native plantings, and wildlife habitat support, rather than solely engineered detention facilities.

As with most green infrastructure, wet ponds require periodic removal of accumulated sediment once they have reached a certain level to maintain performance and storage capacity. To support this, designs should incorporate a sediment forebay—a dedicated zone at the inlet that captures coarse sediment before it reaches the main treatment pool. Forebays should include a fixed vertical marker to measure sediment accumulation over time, and the bottom of the forebay should be hardened to facilitate efficient sediment removal using standard equipment.

To support maintenance and emergency operations, ponds should also include a mechanism to lower or completely drain the permanent pool when sediment removal or structural repairs are required. This may involve a drain valve, sluice gate, or other drawdown structure integrated into the outlet design. Pond depth should be carefully considered to maintain aerobic conditions and prevent excessive nutrient cycling or odor caused by anoxic zones.

When deeper pools are unavoidable or nutrient loads are high, designers should include aeration devices—such as surface aerators or diffused air systems—to promote oxygenation and support biological treatment processes. Wet ponds are commonly stocked with mosquito fish (*Gambusia*) as a natural mosquito control method, particularly in warm climates with extended wet periods. Fish stocked in wet ponds may contain unsafe levels of toxic contaminants and it is not advised for residents to eat fish harvested from the wet pond.[14] Signage should be included across the pond telling residents to convey this message.

A common long-term maintenance concern for retention basins is clogging of the outlet structure. Outlet designs should minimize this risk by preventing debris from obstructing flow.

Inverted sloped pipes are recommended to draw water from beneath the surface and are less likely to be clogged by floating materials.[12] Alternatively, weir outlets with trash racks can be used to block debris at the outlet face, but maintenance access should be considered in the design.

Water balance

The permanent pool should always remain full to sustain the ecological function of the wetland vegetation and prevent turbulence, which could resuspend accumulated sediments. It is recommended that wet ponds have a minimum contributing drainage area, typically 10–20 acres, so inflow is reliable. The permanent pool volume should be sized to support both water quality treatment objectives and long-term ecological function while providing flood storage. In arid or semi-arid regions with low or infrequent rainfall, wet ponds require a supplemental (make-up) water source which makes this practice less sustainable. More regionally appropriate NBS practices should be implemented in arid or semi-arid regions to conserve water.

Any supplemental water source should be unchlorinated and non-potable to avoid damaging aquatic organisms and native wetland vegetation. Some designs use rainwater harvesting from nearby rooftops while others designs collect runoff from underground cisterns to collect and convey harvested stormwater to the pond.

A water balance analysis should be performed during design to confirm whether sufficient inflow—either from direct runoff, baseflow, or supplemental water—is available to maintain the permanent pool year-round, accounting for evaporation and transpiration. Wet ponds are designed to include a liner that prevents water loss through infiltration or drawdown.

Detailed guidance on how to perform a water balance may be found in the ***Design Guidelines for HCFCD Wet Bottom Detention Basins with Water Quality Features*** ↗ and the ***City of Austin's Environmental Criteria Manual*** ↗.

Soil conditions

Depending on the subsurface soil type, an impermeable liner may be required to maintain the permanent pool and prevent excessive seepage. Hydrologic soil group D is often sufficient to maintain the permanent pool without a liner, though field verification of infiltration rates is strongly recommended. Liners may also be used in karst regions or other groundwater-sensitive areas to protect groundwater from contamination. In some cases, contaminated subsurface soils or groundwater may require a liner to prevent exfiltration of pollutants into the pond. Acceptable liner materials include compacted clay, geomembranes, or a combination of both.

Tools and resources

- **Texas A&M AgriLife Green Infrastructure for Texas**
  Green Infrastructure Design Toolkit for Texas Communities Wet Pond Design Set ↗
- **HCFCD**
  Design Guidelines for HCFCD Wet Bottom Detention Basins with Water Quality Features ↗
- **City of Austin**
  Environmental Criteria Manual ↗
- **EPA**
  Stormwater Best Management Practice: Wet Ponds ↗
- **Georgia Department of Transportation**
  Advanced Design Workshops: Wet Detention Pond Design ↗

Figure 11-10. Wet Pond in Leander, Texas

Source: Freese and Nichols, Inc.

11.6 Constructed wetlands

Constructed wetlands are shallow-water basins designed to mimic the hydrologic and ecological functions of natural wetlands. In addition to improving water quality, they can provide flood risk reduction benefits when designed to temporarily store and attenuate storm flows. Constructed wetlands designs include staged hydrologic zones, controlled release structures, and flood storage volume that reduces peak flows before water is released downstream.

In addition to flood mitigation and water quality improvement, constructed wetlands can provide habitat enhancement, aesthetic value, recreation opportunities, and other ecological co-benefits when integrated into parks, open space systems, and community developments.

Design considerations

Before advancing in design, a water balance should be performed to determine whether baseflow, groundwater, or stormwater runoff can maintain the permanent pool during extended dry periods. Water balance considerations are discussed in the previous section on wet ponds. The ***San Antonio River Authority Low Impact Development Technical Design Guidance Manual*** ↗ notes that wetlands should be designed such that the permanent pool should not drawdown more than approximately 2 feet after a 30-day drought.[12]

Geotechnical investigations should be performed during design to evaluate subsurface conditions, confirm if a liner is required to maintain the permanent pool, and assess long-term hydraulic feasibility. In high-permeability soils or groundwater-sensitive settings an impermeable liner (e.g., compacted clay or geomembrane) should be installed and covered with at least 12 inches of protective soil.

Constructed wetlands in areas with tidal influence should be designed to include anti-buoyancy measures and backflow prevention devices.

Similar to wet ponds, in arid or semi-arid regions with low or infrequent rainfall, constructed wetlands require a supplemental (make-up) water source which makes this practice less sustainable. More regionally appropriate NBS practices should be implemented in arid or semi-arid regions to conserve water.

Where long-term supplemental water sources are required to maintain permanent pool conditions, designers should evaluate applicable regulatory and water supply requirements during project planning.

Constructed wetlands should be located in the lowest part of the site with adequate hydraulic head to the outlet. Where one basin cannot meet volume requirements, multiple smaller "pocket wetlands" can be linked by vegetated channels or underground conduits.

To avoid short-circuiting (where flow moves directly from inlet to outlet without fully utilizing the wetland area) and preserve treatment, the length-to-width ratio from inlet to outlet should be at least 2:1, or internal berms, baffles, or meanders should be incorporated to lengthen the flow path and improve treatment performance.

As a planning-level rule, wetland surface area should be approximately 5-10 percent of the contributing drainage area, which may be later refined during detailed design.[15]


Constructed Wetland in San Marcos, Texas
Photo courtesy of Freese and Nichols, Inc.

Inlets and outlets

Sediment forebays at all major inlets protect downstream wetland zones from sediment overload. Design guidance recommends sizing forebays for at least 10 percent of the water quality volume.[15] Inlet structures should incorporate energy-dissipating features such as riprap aprons, flared ends, or level spreaders to protect vegetation during high-flow events. Fixed sediment depth markers can easily show the amount of sediment in the forebay, which can be use in maintenance scheduling.

The water quality treatment and flood attenuation performance of a constructed wetland depends on well-proportioned, hydraulically connected zones. **Figure 11-11** shows a cross section of the wet zones. Deep pools, shallow water areas, and temporary inundation zones should be sized to balance pollutant removal and storage. The ***Texas A&M AgriLife Extension GI Toolkit*** ↗ recommends shallow marsh depths of 6–18 inches, supporting emergent vegetation while maintaining treatment function. Above the permanent pool, an extended detention layer can attenuate larger storms, releasing flows gradually over 24–48 hours to reduce downstream peaks.

A multi-stage outlet allows separate control of water quality volumes and flood volumes, with low-flow orifices for treatment and higher weirs for storm conveyance. Outlets should be fitted with trash racks and draw from below the surface. An armored emergency spillway is necessary to safely pass extreme events without overtopping embankments, and where possible, an emergency drawdown feature should be incorporated for maintenance or repairs.

Tools and resources

- **Texas A&M AgriLife**
  Green Infrastructure for Texas
  Green Infrastructure Design Toolkit for Texas Communities Constructed Wetland Design Set ↗
- **EPA**
  Stormwater Best Management Practice Bioretention – Stormwater Wetlands ↗
- **Society of Wetland Scientists**
  Professional Certification Program ↗

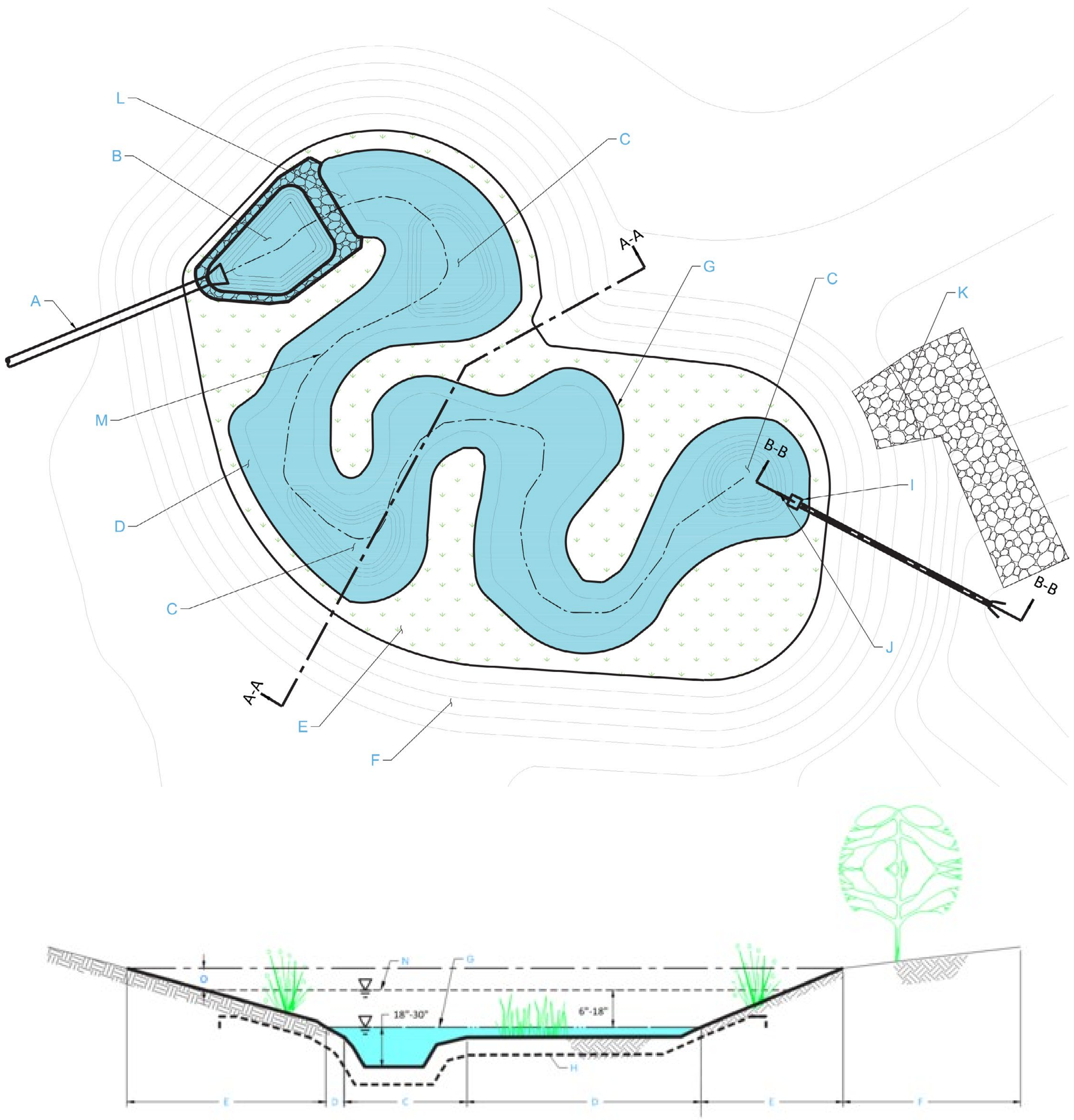


Figure 11-11. Wetland design cross-section. A is the inlet pipe, B is the sediment forebay, C is deep pool, D is shallow zone, E is temporary inundation zone, F is upland buffer, G is permanent pool elevation, H optional impermeable liner, I is outlet structure, J is extended detention inverted pipe, K is overflow spillway, L is earthen berm, M is main channel centerline, N is water quality elevation, and O is extended.

Source: Green Infrastructure Toolkit for Texas Communities – Constructed Wetland Design Set

11.7 Rainwater harvesting

Rainwater harvesting is the collection and storage of rainwater. Rainwater harvesting systems consist of one or more storage tanks known as cisterns that capture and store runoff from rooftops or other impervious areas. The cisterns may be aboveground or belowground, although aboveground is more common as belowground cisterns may require pumping if elevation is not available to gravity drain.

Rainwater harvesting allows for the beneficial use of runoff including non-potable applications such as irrigation, toilet flushing, cooling system makeup, and equipment/vehicle washing, or even potable use depending on the level of treatment. Rainwater harvesting may also be used as makeup water when used in a treatment train with a retention basin. It provides multiple benefits, including a reduction in the amount of runoff generated by a site as well as a reduction in a user's utility bills and decreased demand on other water supplies.

Design considerations

When designing a rainwater harvesting system, site planning and design teams should consider the size of the contributing drainage area, local rainfall and runoff patterns and projected water demand, to determine how large the storage tank must be to provide enough water for the desired use. Guidance on rainwater harvesting sizing is available in ***The Texas Manual on Rainwater Harvesting*** ↗.

In rainwater harvesting systems, conveyance may be designed as either dry or wet depending on how captured runoff is routed between collection, storage, and overflow components. Dry conveyance systems drain completely between storm events and are typically used to maximize flood storage and to route runoff to storage or downstream controls. On the other hand, wet conveyance systems store water and may be used where continuous storage, water reuse, or gravity-fed distribution is desired.

Figure 11-12. Rainwater harvesting conceptualization

Source: Green Infrastructure Toolkit for Texas Coastal Communities – Rainwater Harvesting Design Set

Selection of conveyance type should consider a given project's flood mitigation performance, system maintenance requirements, long-term operability, and the potential for water quality or public safety concerns.

Based on the intended use, different levels of pretreatment may be required. All rainwater harvesting systems should include leaf screen guards. These guards typically consist of mesh screens that cover the gutters and downspouts and prevent clogging of the system by removing debris before it reaches the cistern.

When designed for water conservation and reuse, a first-flush diverter will route the initial runoff from the roof or other catchment area away from the cistern, typically the dirtiest water that often contains dust, pollen, and animal feces. When designing to maximize pollutant removal, a first-flush diverter should not be used to capture the pollutants.

An overflow pipe should be included to divert excess runoff in a controlled manner. The overflow pipe should be designed to release the volume of captured runoff at a rate below the design storm rate at its maximum capacity. The outfall of the cistern should be armored to prevent erosion, and discharges should be directed to landscaped areas, if possible, such as bioretention basins, if used as a treatment train.

Cisterns should be located as close to the supply and demand points as possible to reduce the distance water is conveyed. Cisterns should be placed as high as possible to allow for gravity flow instead of pumping. It is recommended that cisterns be completely opaque and protected from direct sunlight, which can degrade plastic or composite materials and promote algal growth. The cistern inlet should be lower than the lowest downspout from the catchment area.

All openings should be screened to prevent mosquito breeding. Pretreatment and screening components should remain accessible for routine inspection, cleaning, and debris removal to maintain system functionality over time.

Cisterns can be very heavy due to the combined weight of the cistern and water and should be placed on a stable, level pad. For small tanks, sand or pea gravel over well-compacted soil may be sufficient. For larger tanks, a concrete pad may be required.

Where non-potable water is stored or reused, systems should include appropriate signage, pipe labeling or color coding, and secure access features such as locking lids or restricted access points to help protect public safety and support proper system operation.

Tools and resources

- **TWDB**

  The Texas Manual on Rainwater Harvesting ↗
- **San Antonio River Authority**

  San Antonio River Basin Low Impact Development Technical Design Guidance Manual ↗
- **Texas A&M AgriLife Extension**

  Green Infrastructure Design Toolkit ↗

  Rainwater Harvesting Supply Calculator ↗
- **National Pollutant Discharge Elimination System (NPDES)**

  Stormwater Best Management Practice On-Lot Treatment ↗
- **EPA**

  Rainwater Harvesting: Conservation, Credit, Codes, and Cost Literature Review and Case Studies ↗

11.8 Stormwater parks

A stormwater park, often called a floodable park, is a multifunctional green space designed to temporarily store and manage stormwater runoff. Stormwater parks can be designed to handle large contributing drainage areas and typically feature multiple NBS including, but not limited to, permeable pavement, rainwater harvesting, restored habitat, retrofitted detention basins, tree trenches, and/or wet ponds. NBS can act parallel to each other or be put in sequences to create a "treatment train."

Design considerations

Stormwater park designs should balance functionality with community use and environmental sustainability. Incorporating multi-use spaces, such as recreational fields or walking trails can provide temporary stormwater storage during larger rainfall events. Paths, bridges, and lawns should remain functional after floods by using durable materials or elevation adjustments like raised bridges or permeable pathways. Long-term park programming and operations should also be considered during design to ensure recreational uses and maintenance requirements remain compatible with periodic stormwater storage and temporary inundation.

Additionally, stormwater parks typically provide community amenities such as green spaces, trails, sports fields, and/or picnic areas—blending environmental resilience with recreational use. Design specifications for stormwater parks can vary significantly across various projects, depending on local environmental conditions, community needs, and stakeholder input. These projects often prioritize community engagement and the inclusion of amenities that benefit residents while addressing flood mitigation and achieving social and environmental goals.[16]

Effective hydraulic design in stormwater parks seeks to provide proper water flow and storage capacity. Incorporating features like bioswales, bioretention basins, or infiltration basins can increase infiltration and reduce the overall runoff volume(s). Emergency spillways or weirs prevent flooding when retention basins reach capacity, which helps to maintain the park's resilience during extreme weather events.

Hydrologic and hydraulic modeling tools and software can simulate water flow and drawdown rates under various scenarios and can be used to optimize the stormwater park's layout for the greatest flood mitigation benefits and park use and to ensure no adverse impact upstream or downstream. Proper conveyance systems, including culverts or channels, direct water efficiently while minimizing erosion and sediment transport during high flows.

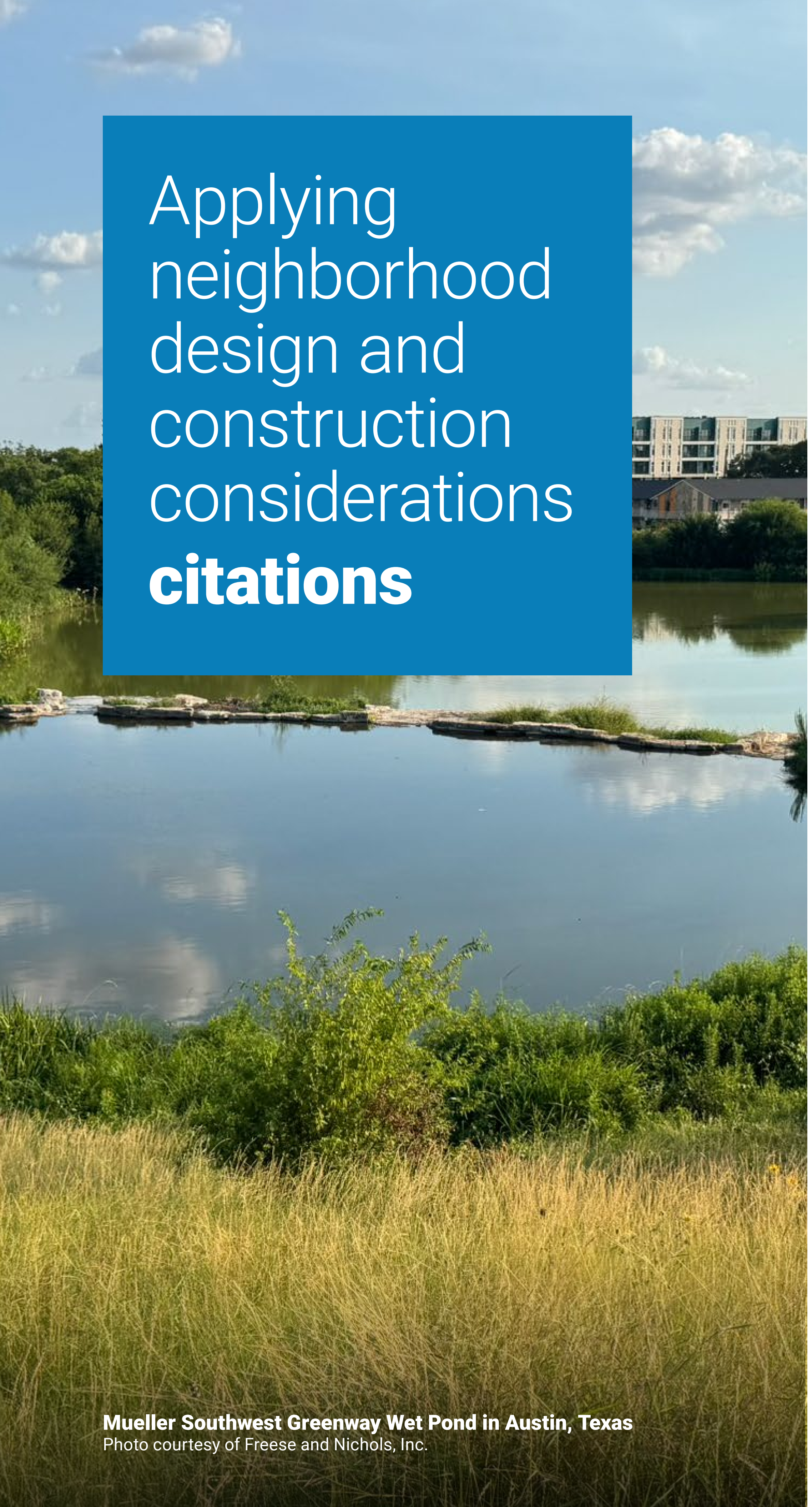
Design features should also prioritize ecological restoration, like planting native vegetation to enhance biodiversity and reduce the overall system maintenance. Zoning the park into functional areas (e.g., retention, recreation, and facilities) allows for efficient stormwater management while maximizing usability. The design should include ample capacity to store stormwater from surrounding areas using engineered soils, perforated pipes, and drainage systems to convey runoff to designated retention areas.

During construction, erosion control measures like silt fences, sediment traps or barriers, and mulching are necessary to protect water quality and prevent soil loss. With stormwater parks commonly having larger drainage areas, the importance of erosion control measures is amplified. Construction should ideally be phased out to limit environmental disturbances, especially when there are existing systems or environmentally sensitive areas near the site. Grading should create positive drainage and avoid prolonged standing water, which could lead to soil instability or mosquito breeding.

Tools and resources

- **City of Houston**
  Multi-Use Park Facilities: A Guide to Applying Mitigation in Parks ↗
- **EPA**
  Green Infrastructure in Parks: A Guide to Collaboration, Funding, and Community Engagement ↗
- **City of New York**
  NYC Department of Parks & Recreation's Design and Planning for Flood Zones ↗
- **Puget Sound Regional Council**
  Guidance on Planning Stormwater Parks ↗
- **National Recreation and Park Association**
  Resource Guide for Planning, Designing, and Implementing Green Infrastructure in Parks ↗


Arlington Heights Stormwater Park, Fort Worth
Photo courtesy of Freese and Nichols, Inc.



Applying neighborhood design and construction considerations **citations**

Mueller Southwest Greenway Wet Pond in Austin, Texas
Photo courtesy of Freese and Nichols, Inc.

[1] Jack, K., and others, 2021, Green stormwater infrastructure for urban flood resilience: opportunity analysis for Dallas, Texas: The Nature Conservancy, https://www.nature.org/content/dam/tnc/nature/en/documents/GSIanalysisREVFINAL.pdf, accessed June 2026.

[2] U.S. Environmental Protection Agency, 2026, Green infrastructure and groundwater protection: U.S. Environmental Protection Agency, https://www.epa.gov/green-infrastructure/green-infrastructure-and-groundwater-protection, accessed June 2026.

[3] USDA Natural Resources Conservation Service, no date, Web Soil Survey: USDA Natural Resources Conservation Service, https://websoilsurvey.nrcs.usda.gov/app/, accessed June 2026.

[4] California Stormwater Quality Association, no date, BASMA bioretention soil mix: California Stormwater Quality Association, https://www.casqa.org/wp-content/uploads/2022/12/basma_bioretention_soil_mix.pdf, accessed June 2026.

[5] City of Austin, no date, Item no. 660S — bioretention/infiltration media: City of Austin Standard Specifications Technical Manual, series 600, https://library.municode.com/tx/austin/codes/standard_specifications_manual?nodeId=AUSTIN_TX_STANDARD_SPECIFICATIONS_TECHNICAL_MANUAL_SERIES_600ENEN_ITEM_NO._660SBIME1-4-16, accessed June 2026.

[6] Center for Watershed Protection, 2012, LID construction guidebook: Center for Watershed Protection, https://www.ci.missoula.mt.us/DocumentCenter/View/42844/Recommended-by-the-EPA-2012-CVC-LID-Construction-Guide-Book?bidId=, accessed June 2026.

[7] U.S. Environmental Protection Agency, no date, Overcoming barriers to green infrastructure: U.S. Environmental Protection Agency, https://www.epa.gov/green-infrastructure/overcoming-barriers-green-infrastructure, accessed June 2026.

[8] Philadelphia Water Department, no date, Inlet controls: Philadelphia Water Department, Stormwater Management Guidance Manual, chap. 4, https://water.phila.gov/development/stormwater-plan-review/manual/chapter-4/4-11-inlet-controls/, accessed June 2026.

[9] Pokorny, J., O'Brien, J., Hauer, R., Johnson, G., Albers, J., Bedker, P., and Mielke, M., 2003, Urban tree risk management: a community guide to program design and implementation: USDA Forest Service Northeastern Area State and Private Forestry, https://www.fs.usda.gov/nrs/pubs/na/NA-TP-03-03.pdf, accessed June 2026.

[10] San Antonio River Authority, 2023, Low-impact development technical design guidance manual, appendix B: San Antonio River Authority, https://staticfiles.sariverauthority.org/site_files/pdf/lid_tech_manual-3rded-app_b.pdf, accessed June 2026.

[11] Houston Wilderness, 2024, Riverine targeted use of buyouts (TUBs) — native grass bioswale best management practices handout: Houston Wilderness, July 2024, https://static1.squarespace.com/static/52387981e4b0a2c53f25a411/t/67acf918462c64650ce402b4/1739389210983/HW+Native+Grass+Bioswale+BMPs+Handout+-+reduced+%28July+2024%29.pdf, accessed June 2026.

[12] San Antonio River Authority, 2019, San Antonio River Basin low-impact development technical design guidance manual: San Antonio River Authority, San Antonio, Texas.

[13] U.S. Environmental Protection Agency, 2021, Vegetated filter strip (VFS): U.S. Environmental Protection Agency, EPA 832-F-21-010, https://www.epa.gov/system/files/documents/2021-11/bmp-vegetated-filter-strip.pdf, accessed June 2026.

[14] Clemson University Extension, 2026, Stocking and harvesting stormwater ponds: Clemson University Extension, https://www.clemson.edu/extension/water/stormwater-ponds/problem-solving/stocking-harvesting.html, accessed June 2026.

[15] Texas A&M AgriLife Extension, 2026, Green infrastructure design sets: Texas A&M AgriLife Extension, Green Infrastructure for Texas (GIFT), https://agrilife.org/gift/gift-resources/green-infrastructure-design-sets/, accessed June 2026.

[16] Metropolitan Area Planning Council, 2018, Designing parks and playgrounds as green infrastructure for stormwater and climate resilience: Metropolitan Area Planning Council, https://www.mapc.org/wp-content/uploads/2018/07/FINAL.Designing-Parks-and-Playgrounds-as-Green-Infrastructure.Chelsea.6.29.18.pdf, accessed June 2026.

12

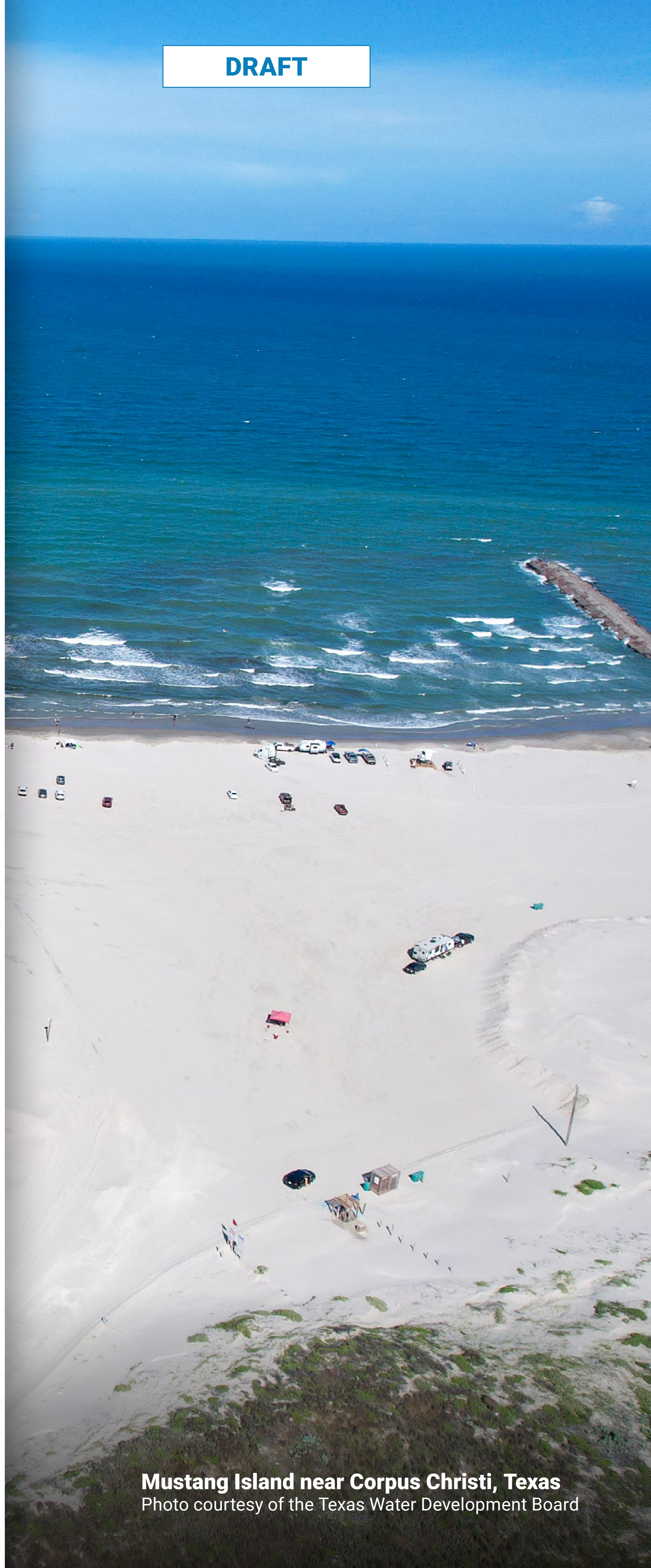
Applying coastal NBS design and construction considerations

Understanding hydraulic and hydrodynamic processes alongside shoreline features, sediment, and native vegetation are key design and construction considerations for effective coastal NBS.

Key takeaways

- The implementation of hard, impervious infrastructure such as seawalls and bulkheads inhibits natural coastal processes and exacerbates long-term erosion.
- Coastal NBS design requires understanding hydraulic factors, including wave setup and runup impacts, and the likelihood of compound flooding.
- Material selection for coastal NBS should align with sediment, vegetation, wave dynamics, and climate conditions.

DRAFT



Mustang Island near Corpus Christi, Texas
Photo courtesy of the Texas Water Development Board

How the guiding principles apply to this chapter

Engage and include	Coasts are places people value to live and recreate. Community members and other stakeholders should be included in many ways in the design and construction of coastal NBS.
Apply systems thinking	Coastal NBS for flood resilience typically operate within gray and green infrastructure systems. Design and construction of coastal NBS should align with system-wide dynamics, including avoiding unintended impacts elsewhere in the system.
Work across boundaries	An array of policies, rules and regulations apply in coastal systems and are designed to conserve scarce resources and protect the environment in areas that are also often critical to local economies such as ports, navigation, or tourism. This means working with state and federal agencies, local businesses and interest groups through the design and construction phase is needed to enable coastal NBS implementation and realize the diverse benefits it can provide.
Learn and adapt continuously	Coasts can change dramatically during a single storm, and each storm is different. Monitoring and understanding these changes is essential for designing, maintaining and adapting NBS, but also for planning future projects.

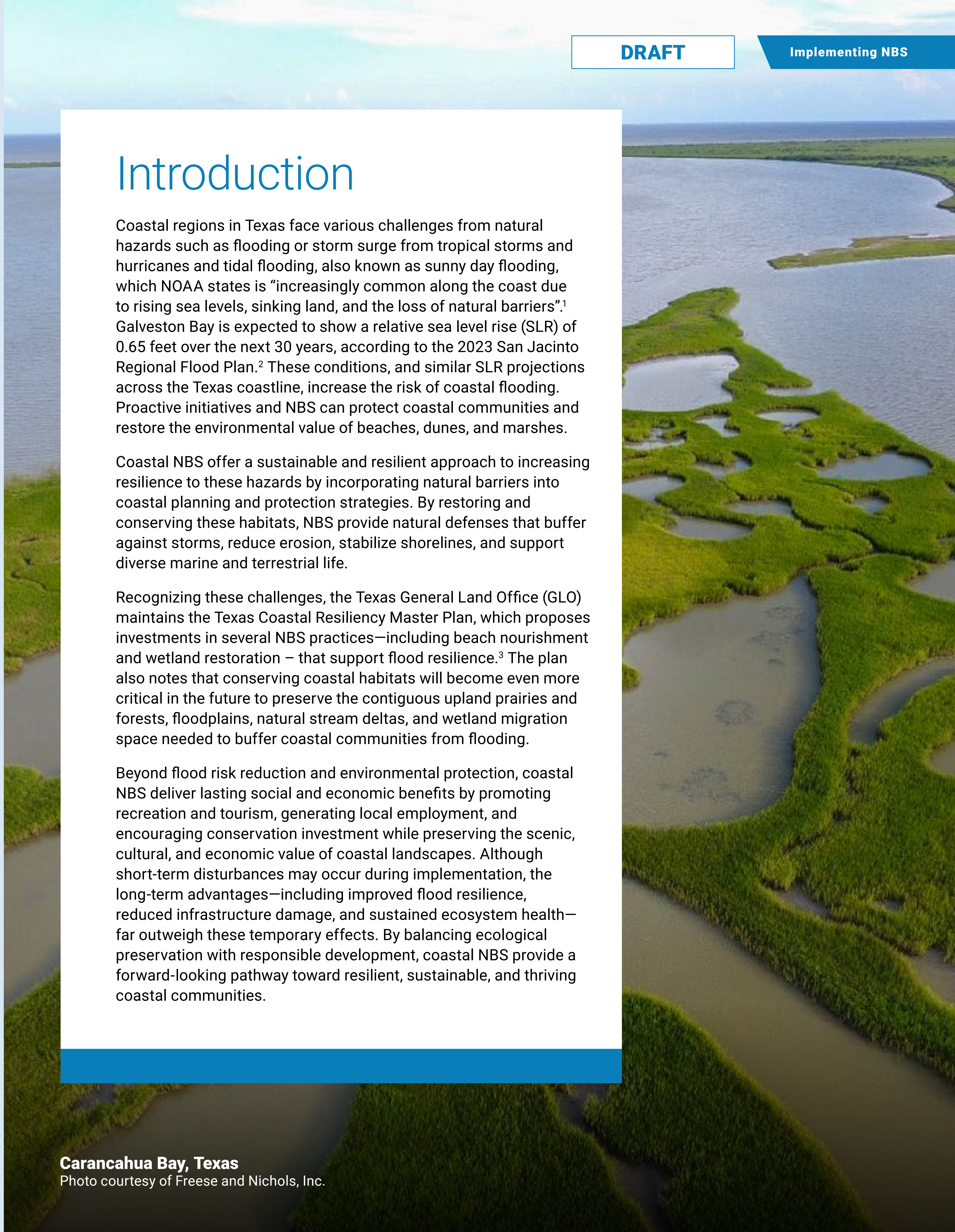
Introduction

Coastal regions in Texas face various challenges from natural hazards such as flooding or storm surge from tropical storms and hurricanes and tidal flooding, also known as sunny day flooding, which NOAA states is “increasingly common along the coast due to rising sea levels, sinking land, and the loss of natural barriers”.[1] Galveston Bay is expected to show a relative sea level rise (SLR) of 0.65 feet over the next 30 years, according to the 2023 San Jacinto Regional Flood Plan.[2] These conditions, and similar SLR projections across the Texas coastline, increase the risk of coastal flooding. Proactive initiatives and NBS can protect coastal communities and restore the environmental value of beaches, dunes, and marshes.

Coastal NBS offer a sustainable and resilient approach to increasing resilience to these hazards by incorporating natural barriers into coastal planning and protection strategies. By restoring and conserving these habitats, NBS provide natural defenses that buffer against storms, reduce erosion, stabilize shorelines, and support diverse marine and terrestrial life.

Recognizing these challenges, the Texas General Land Office (GLO) maintains the Texas Coastal Resiliency Master Plan, which proposes investments in several NBS practices—including beach nourishment and wetland restoration – that support flood resilience.[3] The plan also notes that conserving coastal habitats will become even more critical in the future to preserve the contiguous upland prairies and forests, floodplains, natural stream deltas, and wetland migration space needed to buffer coastal communities from flooding.

Beyond flood risk reduction and environmental protection, coastal NBS deliver lasting social and economic benefits by promoting recreation and tourism, generating local employment, and encouraging conservation investment while preserving the scenic, cultural, and economic value of coastal landscapes. Although short-term disturbances may occur during implementation, the long-term advantages—including improved flood resilience, reduced infrastructure damage, and sustained ecosystem health—far outweigh these temporary effects. By balancing ecological preservation with responsible development, coastal NBS provide a forward-looking pathway toward resilient, sustainable, and thriving coastal communities.



Carancahua Bay, Texas
Photo courtesy of Freese and Nichols, Inc.

12.1 General considerations

Coastal landscapes have long provided natural flood and erosion protection through features such as wetlands, dunes, and reefs. Incorporating or restoring these natural features should be considered for flood resilience in coastal areas. The International Guidelines of Natural and Nature-Based Features for Flood Risk Management[4] identify several key success factors for coastal NBS. These include raising the cross-shore profile and increasing frictional resistance to water movement — both of which can attenuate waves and reduce water levels. Successful coastal NBS also requires planning to be self-sustaining given the physical environment, available sediment supply, and ecological setting; and recognizing the practical constraints of implementing NBS processes within an already-engineered coastline.

Before designing coastal NBS, practitioners should understand the hydraulic factors impacting the location of the proposed solution. **Chapter 7.1** discussed how coastal inundation is driven by stillwater elevations (baseline water level, storm surge and astronomical tides), and wave propagation.

Another consideration for coastal flood risk is compound flooding. Compound flooding, shown in **Figure 12-1**, occurs when two sources of flooding, such as storm surge and riverine flooding, coincide to produce inundation extents greater than either source would generate independently.[5]

The Texas Integrated Flooding Framework (TIFF), established in 2020, was created to equip local, regional, and state entities with compound flood risk information. Learn more: ***Texas Integrated Flooding Framework ↗***

These events pose heightened risks to life safety and infrastructure. When evaluating flood risk reduction solutions in a coastal zone, practitioners should account for the probability that multiple flood risk sources may occur at the same time.

Beyond hydraulic factors, practitioners must be aware restrictions associated applicable to the proposed project location. Coastal projects may require construction on state-owned submerged lands. The GLO issues leases for state-owned tracts in bays and gulf waters, and early coordination with the GLO is strongly recommended to avoid permitting delays and ensure project feasibility.

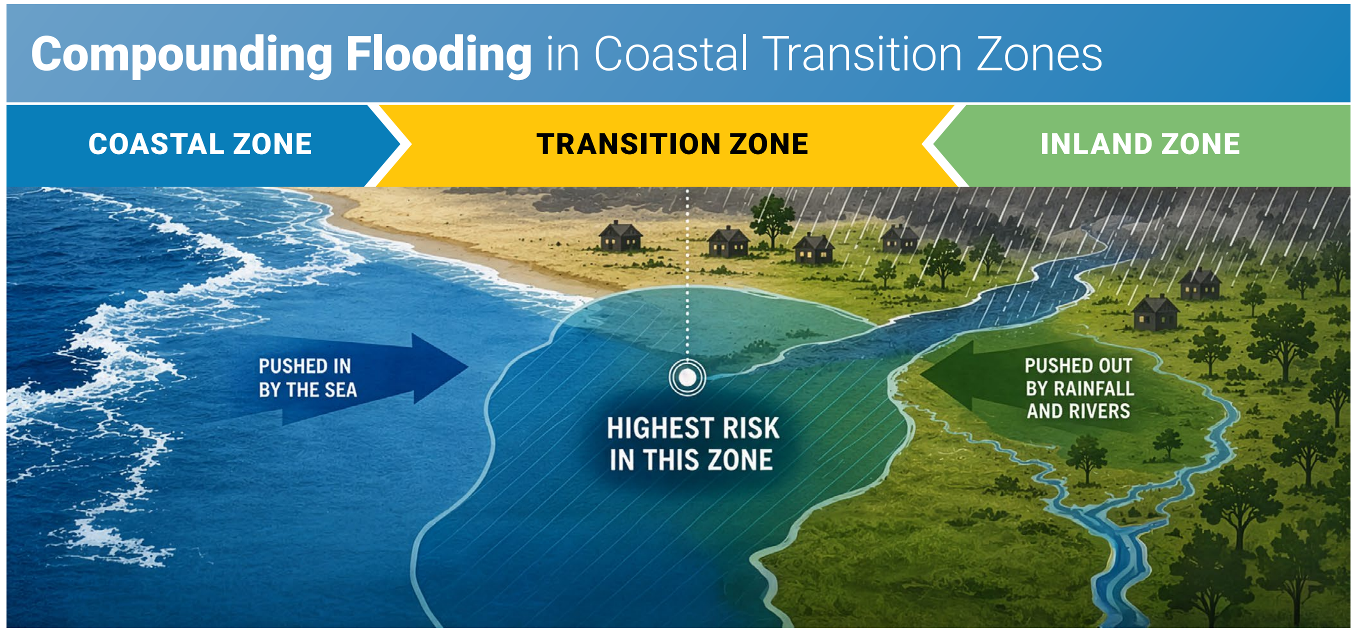


Figure 12-1. Illustration of Compounding Flooding

Tools and resources

- **GLO**
  Texas Coastal Resiliency Master Plan Overview ↗
- **Texas Living Waters**
  Climate Resilient Galveston: Understanding Climate Vulnerabilities and Adaptation Strategies to Build Resilience ↗
- **GLO**
  A Guide to Living Shorelines in Texas ↗
  Texas Submerged Land Tracts ↗

Beach Nourishment on South Padre Island Beach
Photo courtesy of Texas General Land Office

12.2 Beach nourishment and dune restoration

Beaches and dunes are highly dynamic, interconnected coastal features composed of unconsolidated sand or gravel. They are subject to recurrent natural disturbances and experience significant geomorphic changes (due to seasonal variations in sediment deposition), accretion and exchange (due to variations in wave energy), near-shore circulation patterns, and wind climate. Coastal dunes serve as the land's boundary with the sea, creating a unique and biologically diverse habitat as well as providing a protective barrier against storm surge flood events. These features are particularly important for coastal communities because they act as the first line of defense against the threat of flooding and infrastructure damage caused by storm surges.

Beach nourishment and dune restoration efforts are particularly suitable where the application of traditional engineering methods might conflict with the intrinsic value of the ecosystem and its biodiversity, such as in coastal natural areas or reserves.[6]

Beach restoration involves the strategic placement of sand landward of the beach face to rebuild and stabilize beach and dune systems.[7] This method aims to improve the ability to mitigate the impacts of waves and storm surges while providing ecological and flood protection benefits to coastal ecosystems and inland communities. As human activities such as urban development, river damming, and channel dredging disrupt natural sediment deposition processes, beach and dune restoration are becoming increasingly necessary.

Dune restoration structures strategically designed and place to promote the accumulation of windblown sediment and the establishment of vegetation. In contrast, beach restoration extends horizontally and requires more extensive construction and labor efforts to build out the shoreline.

Material selection

There are several factors that inform material selection and influence the success of the coastal NBS project. During preliminary desktop analysis and site assessment data should be collected on sediment characteristics, condition of native vegetation, presence of non-native or invasive vegetation, severity of wave action along the coastline, and variations in climate.

Sediment composition, including grain size and the ratio of organic to inorganic material, can significantly affect biodiversity development, native vegetation establishment, coastal feature function and stability, and flood mitigation potential. Sourced sand should closely match the grain size and gradation of the existing in-situ material. A significant mismatch in sediment size can accelerate fluvial and aeolian (wind) erosion, resulting in the loss of finer-grained sand and increased flood risk exposure for coastal communities. Dredged material repurposing is a primary sediment source for coastal NBS projects. Where local sand supply is insufficient, imported sand may be required; imported sand must be of the appropriate grain size for dune construction and should be vegetated immediately upon placement to ensure stability.[8]

The specific sources of dredged material will likely be determined during project implementation but should be considered early in the design process to avoid delays during implementation. Any dredged material used must satisfy all applicable all environmental compliance and permitting requirements before it can be deemed suitable for the project.[9]

Vegetation

Vegetation along dunes is necessary for stability. Native plants bitter panicum (*Panicum amarum*), sea oats (*Uniola paniculata*), and marsh hay cordgrass (*Spartina patens*) are recommended by the GLO across the Texas coast.[8] The ***Dune Protection and Improvement Manual for the Teas Gulf Coast ↗*** provides additional recommendations from the GLO for the placement of vegetation in dune restoration projects. Transplanting native and local vegetation is preferred over imported vegetation to reduce cost and increase survival rates.

GLO recommends only removing vegetation from dense sands with sufficient vegetation and removal should occur in a scattered pattern, as opposed to a single patch, to minimize impacts to the borrow site. Vegetation should be considered in project schedule and construction sequencing. The best time of year to transplant vegetation south of Corpus Christi is January or February. The optimum time for transplanting north of Corpus Christi is February, March, or April.

Temporary sand fencing may be necessary while vegetation is being established but should not be used as a permanent feature in a project's design. During sea turtle nesting season, it is recommended to avoid sand fencing entirely or utilize a discontinuous configuration to allow sea turtle access to the dunes.

Construction within dunes

The dune protection line is a designated boundary established to protect dunes. Permits are required for building structures, clearing vegetation, or altering the landscape in any way.

Construction within or across dunes may be required to provide beach access. Dune walkovers provide beach access while minimizing damage to the dunes. Walkovers are elevated pathways that allow pedestrians to cross over the dunes without trampling the vegetation or destabilizing the sand. This helps maintain the natural barrier that dunes provide against storm surges and erosion.

Beach access roads are another important consideration in dune construction. These roads should be carefully planned and constructed to avoid disrupting the dune system. The GLO's guidelines emphasize the need for access roads to be located in areas where they will cause the least amount of damage to the dunes and their vegetation. In some cases, access roads may need to be elevated or constructed with materials that minimize their impact on the environment.

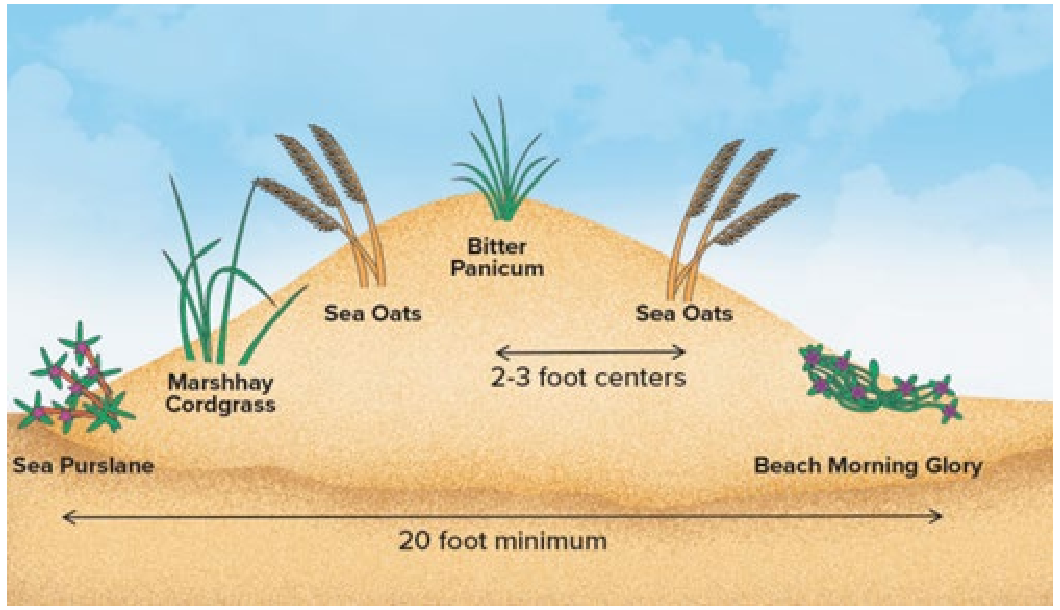


Figure 12-2. Example vegetation placement for dune restoration

Source: Texas General Land Office, Dune Protection and Improvement Manual, 2021

Figure 12-3. Beach and Dune Restoration at McFaddin National Wildlife Refuge

The image on the top is an eroded shoreline of McFaddin Beach. The image in the middle shows restoration efforts in progress. The image on the bottom shows the same shorelines after the beach and dunes were restored.

Photos courtesy of Texas General Land Office

Tools and resources

- **GLO**

  Coastal Dunes: Dune Protection and Improvement Manual ↗

  Beach Nourishment Resiliency Design Guide ↗

  Dune Construction and Restoration ↗

  Wetland Protection Resiliency Design Guide ↗
- **USDA**

  Plant Materials Center Resources for Coastal Restoration Efforts ↗
- **FEMA**

  Beach Nourishment and Dune Construction ↗
- **DOI**

  Coastal Habitats Dune's Restoration ↗
- **USACE**

  Coastal Sand Dunes: A Review of Management Strategies for Dune Stabilization ↗

12.3 Coastal marsh restoration

Coastal marshes and wetlands play a crucial role in flood resilience as natural buffers that locally attenuate waves and surges approaching the shoreline. In addition to their storm mitigation benefits, coastal wetlands provide valuable habitat for diverse flora and fauna, enhance water quality, supply food resources, and provide recreation and cultural value to inland communities.[10] Urbanization has led to wetland degradation/deterioration, resulting in carbon storage loss, biodiversity loss due to non-native/invasive species establishment, and decreased water quality and coastal protection from hurricanes and storms. Nature-based coastal protection holds that resilient, wave- and surge-absorbing wetlands such as saltmarshes and coastal prairies should be integrated into coastal planning and management to more sustainably and effectively mitigate flood risk and impacts.[11]

The purpose of coastal marsh restoration is to improve the current hydraulic condition, hydrophytic plant communities, and biological habitat to restore the historic wetland type and natural function.
The ***Wetland Protection Resiliency Design Guide*** ↗ developed by the GLO provides considerations for effectively designing coastal wetlands for flood mitigation support and shoreline enhancement.[12] An effective example of a coastal marsh restoration is establishing a perennial vegetation buffer around a prairie pothole wetland to trap sediment and maintain wetland water storage capacity.[13]

Tidal exchange

Tidal exchange is the natural flow of seawater into and out of coastal wetlands. Coastal marshes, wetlands, and estuaries rely on tidal exchange to maintain salinity levels and cycle nutrients.

Over time, communities have built barriers such as levees, roads, or culverts that either block or inhibit tidal exchange in coastal areas. Regardless of intent, this infrastructure obstructs tidal exchange. Levees or roadway obstructions can be fully removed, elevated, or partially breached. Culvert obstructions can be widened to increase flow. Flap gates on culverts near coastal marshes should allow two-way flow. Opening up culverts or modifying bridges can improve flood resilience and provide important ecological benefits, but thoughtful designs should consider and optimize how the restriction impacts storm surge exposure.

When coastal marshes are disconnected from native tidal patterns, salinity levels are altered, sediment is lost or accumulated, and invasive species dominate native vegetation. Restoring tidal exchange seeks to reverse these degradations and reinstate natural coastal dynamics. In addition to ecological benefits for vegetation and sediment processes, improving tidal connectivity also enhances aquatic organism passage, which is increasingly recognized as a critical component of marsh and estuarine restoration.

Many species in Texas—such as eel, mullet, and striped bass—are catadromous, anadromous, or otherwise diadromous and rely on unimpeded movement between freshwater and marine environments. Sturgeon, which are federally protected, also depend on functional passageways. Restoration designs that reestablish tidal flow therefore support both physical marsh processes and the life cycle needs of sensitive and migratory aquatic species.

Tools and resources

- **DOI**

  Coastal Marsh Restoration ↗
- **GLO**

  Delta Management Resiliency Design Guide ↗
- **American Shore and Beach Preservation Association**

  U.S. coastal marsh restoration: The role of sediment placement ↗
- **NOAA**

  Guidelines for the conservation and restoration of seagrasses in the United States and adjacent waters ↗

Material selection

Local dredged material can be utilized as a resource instead of treated as a waste product and to provide a sustainable solution for coastal NBS material sourcing while also creating societal, environmental, and financial benefits. Beneficial use of dredged material includes flood and coastal protection, habitat improvement and ecosystem service functions, and construction material.

Dredged sediments are an important component of natural sediment cycles and ecosystems. The option of retaining dredged material within the same aquatic system (sustainable relocation) should be considered first.[14] As **Figure 12-4** shows, the evolution of coastal wetlands restoration during construction may appear to degrade the area before it is restored. While existing wetland vegetation may be damaged during the construction phase, the restored wetland will be a more effective flood mitigation as dredged material increases elevation and provides a foundation for robust plant growth. Education and communication with stakeholders should be considered throughout construction and vegetation establishment. Sediment can be added to create suitable elevations for marsh growth based on healthy adjacent wetlands and historical data, while considering sediment compaction and sea level rise.[15]

Figure 12-4. Evolution of restored coastal wetlands

Source: US Geological Survey

Mad Island Marsh Preserve in Matagorda Bay
Photo courtesy of the Texas Water Development Board

Vegetation

Several studies have used high-resolution hydrodynamic simulations to investigate how vegetation state and storm intensity affect the degree of protection from flooding and resulting economic damage provided by marshes.[16,17] These studies found that vegetated salt marshes reduced the extent and depth of flooding across all estuaries and storm scenarios. Along with the reduction in flood extent and depth, vegetated marshes also reduced the relative economic costs from damage to residential and commercial properties, infrastructure, and agricultural land compared to unvegetated scenarios. Other examples include managing site hydrology to enhance plant community composition and native wetland function by rehabilitating or constructing levees to optimize water levels.

Vegetation for marsh restoration can be transplanted or propagated; some species can also be grown from seeds. Successful wetland enhancement projects require planning, implementation, monitoring, and management. Restoration project teams should include expertise in ecology, hydrology, soils, engineering, and environmental planning.

Invasive species can negatively impact coastal marsh habitats and its effectiveness at reducing flood risk. Controlling or removing invasive species requires an understanding of the target species, minimizing adverse impacts of removal practices to native species, and routine monitoring.[18] Best practices include mechanical removal to prepare the site, followed by targeted chemical treatment to eradicate invasive species. Once invasive species have been removed, hydrologic restoration can reestablish site conditions that support the successful establishment and long-term resilience of native vegetation. Combining multiple strategies typically gives the best long-term results. Multi-year monitoring should be established to prevent reinvasion. Table 12-2 includes methods to control or remove common invasive species in coastal wetlands in Texas.

Figure 12-5. Invasive common water hyacinth in Rio Grande near Brownsville, Texas

Source: Texas Water Development Board

Table 12-2. Common invasive species in Texas coastal marshes

Invasive species	Type	Impact	Recommended control strategy
Alligatorweed *(Alternanthera philoxeroides)*	Aquatic / Semi-aquatic plant	Dense mats along shorelines or in shallow water; displaces native marsh/shoreline vegetation; impedes flow and habitat use	Mechanical removal; Biological control; Hydrologic restoration / prevent spread
Brazilian Peppertree *Schinus terebinthifolius*	Shrub / Tree	Displaces native coastal prairie or marsh-edge vegetation; reduces biodiversity and alters structure of native plant communities	Mechanical removal; Replace with native plants / restoration planting
Chinaberry *Melia azedarach*	Tree	Fast-growing, aggressive shading; displaces native woody and understory species; alters site hydrology and structure	Mechanical removal; Replace with native trees / shrubs
Chinese Privet *Ligustrum sinense*	Shrub / Small tree	Forms dense understory thickets; outcompetes native shrubs and young trees; reduces native biodiversity	Mechanical removal; Chemical control if needed; Replant native understory vegetation
Chinese Tallow Tree *Triadica sebifera*	Tree	Highly invasive; spreads rapidly; displaces native flora; alters soil chemistry; significant biodiversity loss	Mechanical removal; Careful disposal of cut material / follow-up; Restoration with native species
Common Water Hyacinth *Eichhornia crassipes*	Floating aquatic plant	Rapid surface coverage; blocks sunlight; depletes dissolved oxygen; degrades water quality and aquatic habitat	Mechanical removal; Biological control; Prevent spread / early detection
Deep-rooted Sedge *Cyperus entrerianus*	Sedge / Grass-like plant	Disrupts native wetland or prairie communities; alters soil and hydrology; can dominate ground layer	Mechanical removal; Site rehabilitation and re-vegetation with natives
Giant Salvinia *Salvinia molesta*	Floating fern / Aquatic plant	Forms thick mats on water surface; blocks light, reduces oxygen, degrades aquatic habitat; interferes with water flow	Mechanical removal; Biological control; Spread prevention and early detection
Japanese Honeysuckle *Lonicera japonica*	Vine / Shrub	Rapidly spreads and climbs; smothers native understory and groundcover plants; reduces native plant diversity	Mechanical or chemical control; Replant native groundcover and shrubs; Monitor regrowth
Saltcedar *Tamarix spp.*	Shrub / Tree	High water use; depletes soil moisture; alters soil salinity; displaces native riparian vegetation; degrades riparian habitat	Mechanical removal; Biological control (where feasible); Hydrologic restoration; Restoration planting
Trifoliate Orange *Poncirus trifoliata*	Shrub / Small tree	Invades coastal prairie or disturbed sites; competes with native shrubs/trees; can form impenetrable thickets	Mechanical removal; Replace with native shrubs/trees; Monitor for resprouts

Source: Texas Invasive Species Institute[19]

12.4 Natural breakwaters, oyster reefs, and living shorelines

As climate variability increases, coastal and inland communities face escalating flood risk from storm surge, intensified wave action, and sea level rise. Anthropogenic degradation of coastal landscapes has compounded these risks, accelerating erosion driven by currents, wind-generated waves, and chronic inundation. Historically, shoreline hardening through traditional gray infrastructure – such as seawalls and bulkheads – was seen as the only option for coastal communities to combat storm-related flooding and damages. However, impervious infrastructure of this type suppresses natural coastal processes and has been shown to exacerbate long-term erosion by reflecting wave energy rather than dissipating it. Coastal NBS offer an alternative approach by working in concert with natural coastal processes to preserve and enhance ecosystem services while attenuating wave energy and reducing flood risk.

Natural breakwaters represent one such coastal NBS strategy. Natural breakwaters are multifunctional coastal structures that integrate green and gray engineering techniques, installed parallel to the shoreline to intercept and dissipate wave energy before it reaches the coast. By serving as a first line of defense against wave energy, natural breakwaters mitigate shoreline erosion and reduce flood-related hazards to coastal communities. In high wave energy environments, nearshore natural breakwaters have demonstrated effectiveness in attenuating wave impacts and promoting the establishment and persistence of coastal wetland vegetation in the sheltered zone landward of the structure. Beyond wave attenuation, natural breakwaters facilitate sediment accumulation in the nearshore-to-inland transition zone, creating suitable substrate conditions for the colonization of reef-forming species and coastal vegetation. This dual function — shoreline protection and habitat creation — enhances marine biodiversity and supports the long-term health and resilience of coastal ecosystems.

Natural breakwater design is highly site-specific, informed by the historic, current, and projected coastal conditions of the project area. Key design elements — including crest height, structure width, distance from the shoreline, construction materials, and the potential for artificial reef establishment — collectively determine the structure's wave attenuation capacity and storm mitigation performance. Crest height is measured relative to the mean higher high water (MHHW) datum and should be established with consideration for the elevational requirements of intended vegetation. Natural breakwaters should be designed with shallow side slopes (5:1) and incorporate a stable primary foundation layer. Where ecologically appropriate, structural design should emulate the microhabitat complexity of natural reefs, incorporating features such as crevices for fish refuge, surface landings for shorebirds, and inter-structural gaps to facilitate sediment transport and fish passage.

Hybrid living shoreline structures — such as submerged oyster shell beds or riprap combined with marsh plantings — help counteract hydrodynamic and anthropogenic stressors by dissipating wave energy, stabilizing intertidal sediments, promoting oyster reef development, and supporting marsh recovery. Oyster shell is a particularly viable construction material in the Gulf Coast region; local initiatives such as the Galveston Bay Foundation's oyster-shell recycling program repurposes discarded shells for use in reef-building and shoreline stabilization projects.[20] Natural breakwater systems may also incorporate soft stabilization methods, including the planting of salt-tolerant species such as smooth cordgrass (Spartina alterniflora), to complement structural elements and enhance ecological function. The native vegetation best practices and invasive species control practice discussed in **Section 12.5** should be incorporated into living shorelines designs.

Material selection

Selecting appropriate materials for natural breakwaters, reef components, and other living shoreline elements impacts structural performance, ecological compatibility, and compliance with regulatory standards. Whenever possible, source materials locally to minimize transportation impacts and support regional economies.

Durable aggregates such as crushed limestone, river rock, or similar stone are commonly used for breakwaters and nearshore structures. These materials provide stability under wave action while allowing sediment movement and habitat complexity. Pre-approval by permitting authorities such as USACE and GLO is required before placement.

Recycled oyster shell is effective as a substrate for reef development and bivalve recruitment. Because oyster shell is not commercially abundant in Texas, it is typically sourced through partnerships with wholesalers, nonprofits, or shell recycling programs (e.g., Galveston Bay Foundation's shell recycling). Substrates should support colonization by oysters, algae, and invertebrates and avoid introducing contaminants.[21]

Newer porous concrete products and reef ball systems are designed to create structural complexity, enhancing habitat while providing wave attenuation. These materials should be selected based on estuarine durability and ecological performance. Coir logs, brush mats, and fiber rolls can be used where softer stabilization is appropriate or to support plant establishment. These materials are biodegradable and help trap sediment while vegetation becomes established.[22]

Vegetation

The performance of a living shoreline is highly dependent on appropriate vegetation species selection. Vegetation plays a critical functional role in living shoreline systems — stabilizing sediments, dissipating wave energy, improving water quality, and providing wildlife habitat. Species selection must be carefully tailored to site-specific conditions, including salinity gradients, tidal elevations, soil type, and hydrologic regime. Proper planting strategy and spacing are equally important factors in ensuring long-term plant survival and establishment.[23]

Native species adapted to the Texas Gulf Coast and its local hydrologic and salinity regimes are strongly recommended for living shoreline applications. The use of native vegetation enhances ecological resilience, supports wildlife habitat, and reduces long-term maintenance requirements. To optimize plant survival and ecological function, species should be matched to their corresponding shoreline zones as illustrated in **Figure 12-6**.

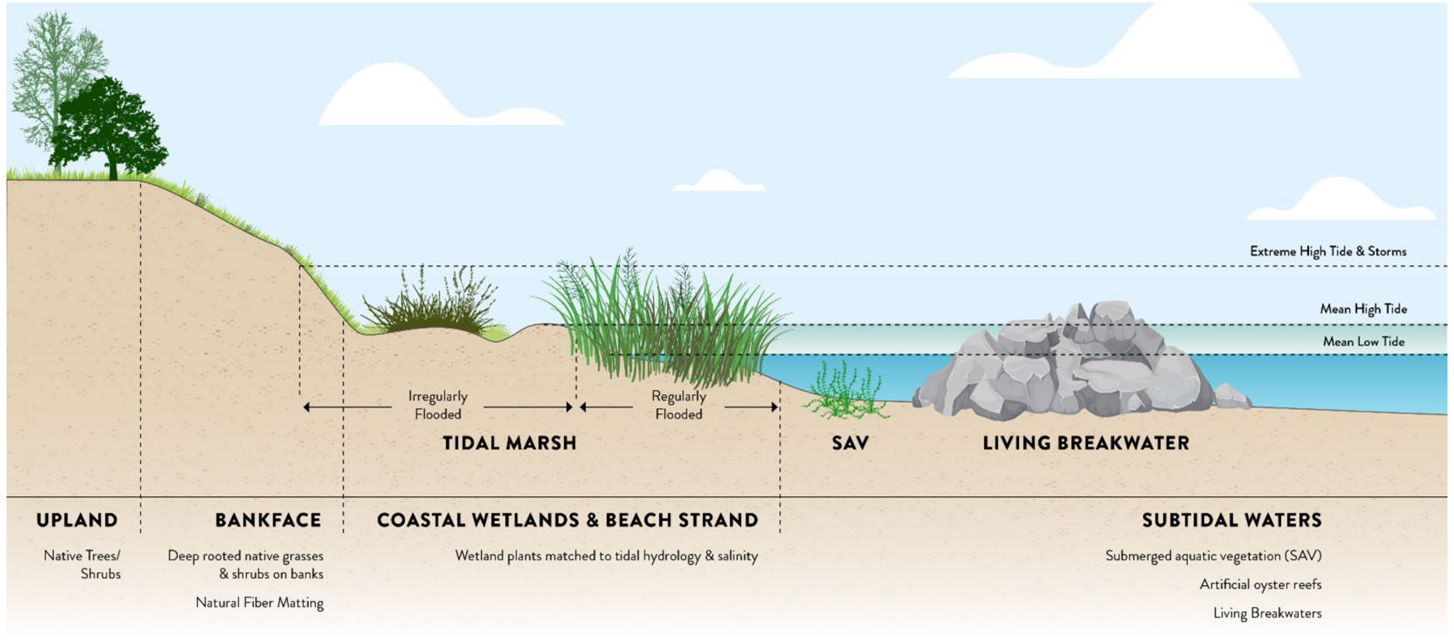


Figure 12-6. Living Breakwater Site Conditions

Source: Texas General Land Office[24]

Construction considerations

When sourcing materials for living breakwaters, such as oyster reefs, it is important to consider substrates known for successful bivalve attachment, as well as the durability of the material to wave stress. Allowable materials for artificial reefs are determined by the USACE and state agencies with jurisdiction over marine and estuarine resources. Recent technological advancements have resulted in new kinds of more porous concrete and reef substrate designs that create structural complexity, which has increased the likelihood of successful colonization of these reefs by oysters.[25]

Successful implementation of living shorelines requires selecting the correct practice based on the site's characteristics. The GLO has identified four broad categories of living shorelines commonly used along the Texas coast. The four categories include Soft Stabilization (Marsh Grass Plantings), Hybrid Stabilization (Breakwaters, Submerged Oyster Shell Beds, Reef Balls, Articulated Blocks or Mats, and Riprap), Retrofit: Soft Stabilization, and Retrofit: Hybrid Stabilization.

Construction and implementation of living shorelines should not interfere with or obstruct maritime traffic, making the understanding of vessel shipping patterns a significant variable in determining placement.

Tools and resources

- **GLO**
  A Guide to Living Shorelines in Texas ↗
  A Guide to Plants Commonly Used In Living Shorelines Along the Texas Coast ↗
- **Natural Resources Conservation Service**
  Plant Materials Program ↗

Case Study

Baronridge Park living shoreline

Location: Seabrook

Opportunity: Existing bulkhead presented maintenance challenges for community.

Lessons learned: Living shorelines reduce long-term maintenance costs and improve park aesthetics.

In 2010, the Galveston Bay Foundation worked with the Clear Lake Forest Homeowners Association to implement a 650-foot-long living shoreline in Baronridge Park. The north section is a low-profile breakwater with a gradual slope from wetland habitat to the uplands. An existing bulkhead on the southern portion was retained, and a low-profile breakwater was installed about 30 feet offshore and the additional area between the bulkhead and the breakwater was planted with marsh grass.

The community chose a living shoreline over a hardened structure to reduce long term maintenance costs and improve park aesthetics. Marshes have a natural ability to absorb wave energy and flood waters, to increase water infiltration rates, and to improve water quality. The living shoreline has been successful in keeping the shoreline of the park from moving upland. As long as a living shoreline has the correct grade of shoreline behind it, it can rise and grow with the rising sea levels and give the same shoreline protection over time.

Baronridge Park, Seabrook, Texas
Photo courtesy of The Nature Conservancy

12.5 Waterfront parks

Waterfront parks are multifunctional parks located along the edges of bodies of water that are designed accommodate periodic inundation while providing flood buffering for adjacent communities. As a coastal NBS, waterfront parks offer a sustainable and resilient approach to managing flood risk. When carefully planned with respect to siting, material selection, vegetation, and regulatory compliance, these parks can effectively reduce flood risks, enhance biodiversity, and provide valuable recreational spaces for communities. The integration of natural systems and processes into coastal land use planning not only mitigates impacts of climate variability but also strengthens the connection between communities and their natural environment, fostering environmental stewardship and community well-being.

The placement of waterfront parks is a crucial factor in their effectiveness as NBS for flood resilience. Strategic placement allows waterfront parks to serve as buffers against flooding and capture and store floodwaters during storm events. This reduces the impact of floods on surrounding communities and infrastructure. Waterfront parks are particularly well-suited for placement in areas with a history of repetitive flood loss, converting chronically flood-prone land into resilient, publicly beneficial green space that enhances both public safety and environmental health. Site selection also should consider accessibility, ensuring that parks are reachable by residents and support active recreational use and community engagement.[26]

Vegetation is a key component of waterfront parks that provide numerous ecological and social benefits. Appropriate species selection will vary if the site is located in a coastal, estuary, or upland riverine area, due to distinct hydrologic and ecological conditions that govern plant community composition and long-term establishment success.

Tools and resources

- **Naturally Resilient Communities**
  Solution: Waterfront Parks ↗
- **NOAA, EPA, ICMA, Sea Grant**
  Smart Growth for Coastal Waterfront Communities ↗

12.6 Coastal conservation

Coastal conservation encompasses the protection, management, and stewardship of coastal ecosystems to prevent further degradation of biodiversity, natural resources, and critical habitat. Effective coastal conservation serves multiple interdependent functions: reducing future flood risk, mitigating physical damage associated with severe weather and storm events, safeguarding freshwater and coastal water resources, improving water quality, fostering biological diversity, and enhancing the ecological resilience of native flora and fauna. Collectively, these functions support the maintenance of ecological equilibrium necessary for the long-term survival and function of numerous coastal-dependent species.

Coastal conservation is not a single-method approach but rather a continuum of strategies that may be applied individually or in combination depending on site conditions, land ownership, regulatory context, and conservation objectives. These strategies include the active restoration techniques discussed in previous sections — such as living shoreline construction, marsh and wetland restoration, and dune stabilization — as well as passive protection measures that prevent future degradation. Passive protection strategies may include the acquisition of conservation easements, fee-simple land acquisition, deed restrictions, and coordination with local, state, and federal land protection programs. Together, active restoration and passive protection measures form a comprehensive and complementary framework for long-term coastal conservation and flood resilience. Chapter 7 outlines geospatial data useful in determining ideal sites for conservation.

Tools and resources

- **NOAA**
  The Texas Coastal and Estuarine Land Conservation Program Plan ↗
  Southeast Conservation Blueprint Summary for Texas ↗
- **EPA**
  Coastal Bend Bays Plan Protecting the Coastal Bend bays and estuaries ↗

Baytown Nature Center, Texas
Photo courtesy of the Texas Water Development Board

Case Study

Coastal Texas Protection and Restoration Feasibility Study

Location: Texas Coastal Counties

Opportunity: Funding Constraints, Political and Cultural Constraints

Lessons learned: Utilizing the guiding principles leads to increased resilience for coastal communities.

The Coastal Texas Protection and Restoration Feasibility Study (Coastal Texas Study), conducted by the U.S. Army Corps of Engineers in partnership with the Texas General Land Office, was initiated in 2014. The Coastal Texas Study planning process aimed to identify projects needed to support a comprehensive state-wide approach to Coastal Storm Risk Management (CSRM) and Ecosystem Restoration (ER) while recognizing the great differences in coastal storm risk and restoration needs across the Texas coast.[2]

Due to the complexity and extent of the study area, extensive stakeholder engagement was incorporated into the feasibility study. Outreach included, formal scoping meetings required by the National Environmental Policy Act (NEPA), community work groups, open houses and briefing sessions, both in-person and virtually. The study team provides updates and address concerns to stakeholders, upon request. These activities generated thousands of comments which helped to shape and refine the plan. Community identity, natural features, culture, and sources of community pride were all key considerations throughout the planning process. Actions identified in the Recommended Plan sought to reduce risk without sacrificing the characteristics that make the community a desirable place to live and work. In one community, a levee design with beach access was initially proposed to reduce flood risk, but after stakeholder outreach, beach and dune restoration was recommended to enhance habitat value, to not limit beachfront view, and to not leave some community areas outside of protection.

A key planning consideration in the Coastal Texas Study was resilience—the ability of a system to withstand, recover, and adapt to disturbances. Multiple systems of interest in the coastal region—including social, natural, and economic systems—were considered in this plan. The proposed South Padre Island (SPI) Beach Nourishment and Sediment Management CSRM measure exemplifies systems thinking by reducing coastal flood risk to people, property, and infrastructure while also improving nesting habitats for sea turtles. Similarly, the Ecosystem Restoration (ER) Plan was formulated to restore degraded ecosystems that buffer coastal communities from erosion, subsidence, and storm losses. These ER projects work in concert with coastal storm risk management (CSRM) features to create a comprehensive, interconnected strategy for reducing risk from storm events. For example, ER feature G28, located on the backside of Bolivar Peninsula, enhances resilience by reducing storm impacts from inland flow and channel overtopping. While the gate system protects against front-facing surge from the Gulf, G28 fortifies the interior, illustrating how coordinated measures can collectively strengthen the system's adaptive capacity. Together, these CSRM and ER measures reflect a holistic, systems-based approach to coastal protection and restoration.

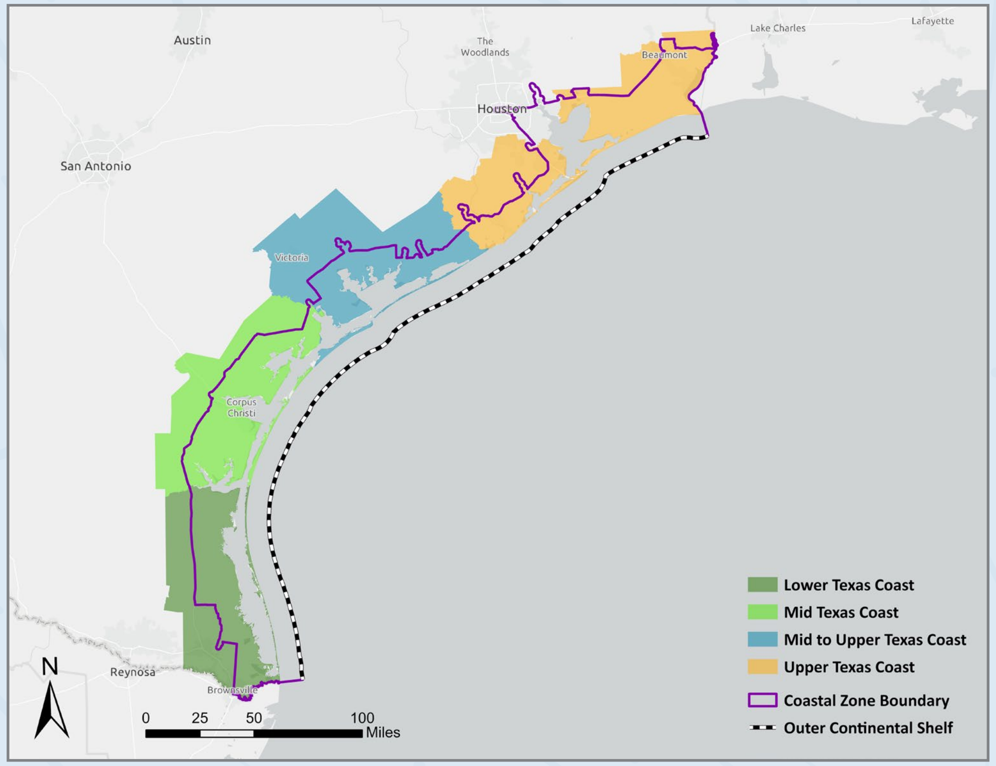


Figure 12-7. Coastal Texas Study area[26]

Source: Texas General Land Office

Federal, state, and local agencies and Tribal Nations met monthly to discuss study progress and environmental issues related to the Coastal Texas Study. These meetings were used to:

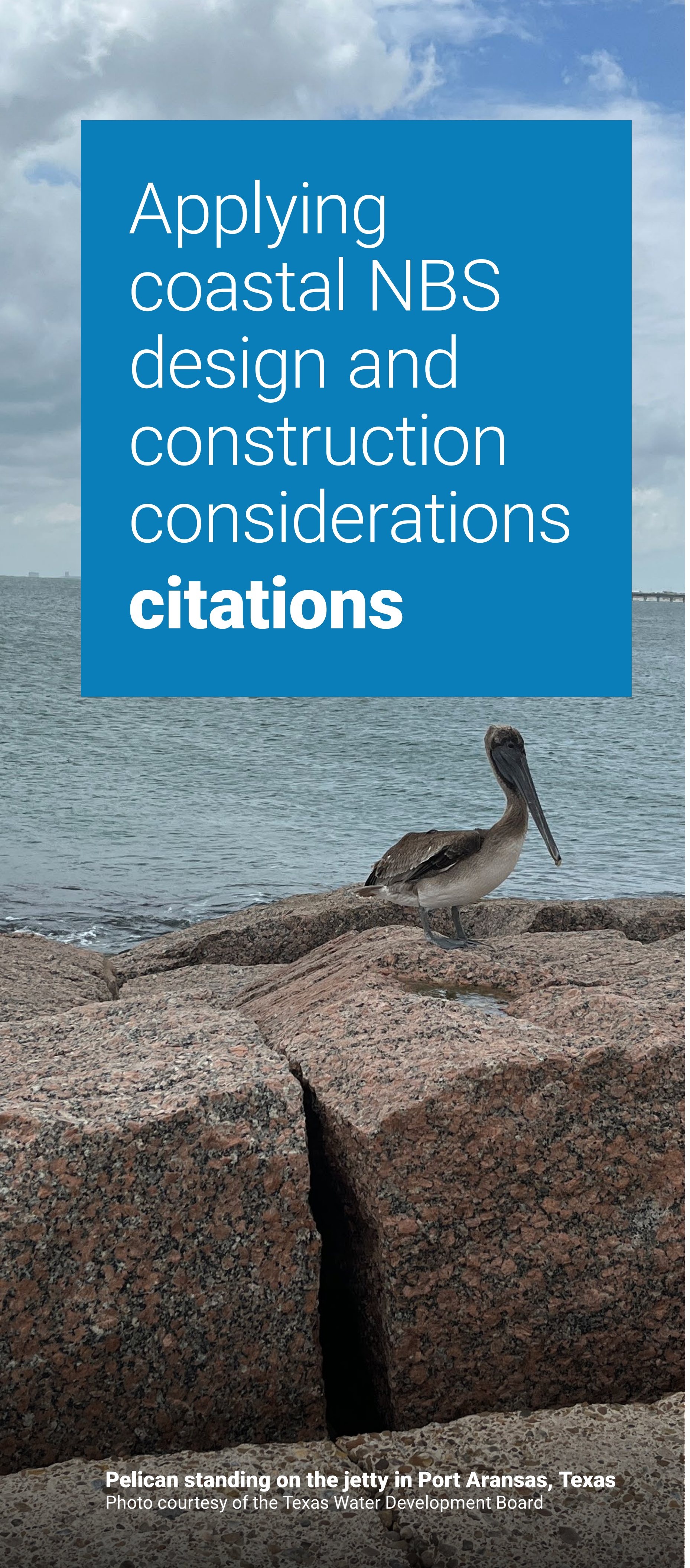
- Share updates on pending decisions
- Comment on and approve methods to assess performance and impacts of features proposed to reduce risk and restore habitat and natural coastal processes
- Consider restoration measure performance metrics
- Screen and refine coastal restoration alternatives
- Develop habitat modeling assumptions

This collaboration expanded available expertise, brought in existing institutional knowledge, and provided an opportunity to leverage efforts and to reduce storm risk and protect coastal resources. In recognition that CSRM and ER have many overlapping interests with state and federal agencies, an adaptive management and monitoring plan was developed.

The Coastal Texas Study includes a Monitoring and Adaptive Management Plan (MAMP) that identifies potential and necessary monitoring activities for ecosystem restoration and mitigation features, outlines how results from the monitoring would be used to assess feature success, and (if needed) adaptively manage the project features to achieve the desired objectives. The MAMP establishes a framework for decision-making to guide future adaptations and to ensure the features succeed. It recommends specific monitoring practices to update area conditions and establishes "success criteria" for each type of habitat to guide and adjust management actions.

Importantly, the MAMP also specifies who would be responsible for monitoring and adaptive management activities and provides estimated associated costs. Since changes to projects can occur during the engineering and design phase, the MAMP is revised accordingly during that phase to incorporate more detailed monitoring, adaptive management plans, and cost breakdowns.

Applying coastal NBS design and construction considerations **citations**



Pelican standing on the jetty in Port Aransas, Texas
Photo courtesy of the Texas Water Development Board

[1] NOAA, What is high tide flooding? National Ocean Service website, https://oceanservice.noaa.gov/facts/high-tide-flooding.html, accessed June 2026.

[2] San Jacinto Regional Flood Planning Group, 2023, Chapter 2.B—Future condition flood risk analysis, In 2023 San Jacinto (Region 6) Regional Flood Plan, v. 2, appendix 2B-7, Texas Water Development Board, https://www.twdb.texas.gov/flood/planning/plans/2023f/doc/R06_RFP_Final_Plan_V2_Part10_5-6_to_10-13_revised.pdf, accessed June 2026.

[3] Texas General Land Office, 2023, Texas Coastal Resiliency Master Plan (TCRMP) overview, Texas General Land Office, https://www.glo.texas.gov/sites/default/files/resources/glo/coast/coastal-management/coastal-resiliency/resources/files/2023-tcrmp-overview.pdf, accessed June 2026.

[4] Bridges, T.S., Bourne, E.M., King, J.K., Kuzmitski, H.K., Moynihan, E.B., Suedel, B.C. 2021, Engineering with Nature®—An atlas, volume 2, ERDC/EL TR-21-6, U.S. Army Engineer Research and Development Center, https://doi.org/10.21079/11681/41946, accessed June 2026.

[5] The Water Institute, Compounding Flooding, https://thewaterinstitute.org/projects/compound-flooding, accessed June 2026.

[6] Olson, J.S. 1958, Lake Michigan dune development 2—Plants as agents and tools in geomorphology, Journal of Geology 66:345–351.

[7] Texas General Land Office, 2022, Beach and dune design guide, Texas General Land Office, https://www.glo.texas.gov/sites/default/files/resources/glo/coast/coastal-management/coastal-resiliency/resources/final_beach-dune_designguide.pdf, accessed June 2026.

[8] Texas General Land Office, 2023, Dune protection and improvement manual for the Texas Gulf Coast, Texas General Land Office, https://www.glo.texas.gov/sites/default/files/resources/glo/coast/coastal-management/forms/files/dune-protection-manual-gpb.pdf, accessed June 2026.

[9] Texas Trustee Implementation Group (Texas TIG), 2025, Deepwater Horizon Oil Spill Texas Trustee Implementation Group, Draft Restoration Plan/Environmental Assessment #3: Restoration of Wetlands, Coastal, and Nearshore Habitats, https://www.gulfspillrestoration.noaa.gov/sites/default/files/2025-01/Texas%20TIG%20RP_EA%20%233_508.pdf, accessed June 2026.

[10] Texas General Land Office, n.d., CMP 309 assessment and strategies 2021-2025, https://www.glo.texas.gov/sites/default/files/resources/glo/coast/grant-projects/forms/cmp-309-assessment-and-strategies-2021-2025.pdf, accessed June 2026.

[11] Zhu Z., Vuik V., Visser P. J., Soens T., Van Wesenbeeck B., Van De Koppel J., Jonkman S. N., Temmerman S., Bouma T. J., 2020, Historic storms and the hidden value of coastal wetlands for nature-based flood defense Nat. Sustain. 3 853–62.

[12] Texas General Land Office, 2021, Wetland protection design guide, Texas General Land Office, https://www.glo.texas.gov/sites/default/files/resources/glo/coast/coastal-management/forms/files/design-guides/final_wetland-protection_designguide.pdf, accessed June 2026.

[13] Paxton, A.B., Riley, T.N., Steenrod, C.L., and others, 2024, Evidence on the performance of nature-based solutions interventions for coastal protection in biogenic, shallow ecosystems—A systematic map, Environmental Evidence 13:28, https://doi.org/10.1186/s13750-024-00350-5, accessed June 2026.

[14] Central Dredging Association and International Association of Dredging Companies, 2021, Beneficial use of dredged material, https://dredging.org/media/ceda/org/documents/resources/cedaonline/fact-sheet-beneficial-use-of-dredged-material-ceda-iadc-final.pdf, accessed June 2026.

[15] Narayan, S., Beck, M. W., Reguero, B. G., Losada, I. J., van Wesenbeeck, B., Pontee, N., Sanchirico, J. N., Ingram, J. C., Lange, G. M., Burks-Copes, K. A., 2016, The effectiveness, costs and coastal protection benefits of natural and nature-based defenses, PLOS ONE, 11(5), e0154735, https://doi.org/10.1371/journal.pone.0154735, accessed June 2026.

[16] Zeng, X., Long, D., Hashida, Y., Bilskie, M. V., Valuing Salt Marshes as Nature-based Infrastructure for Coastal Flood Mitigation: A Case Study of Chatham County, GA, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2026-1475, 2026. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0226275, accessed June 2026.

[17] Texas Invasives, n.d., Gulf Coast Prairies and Marshes, https://www.texasinvasives.org/i101/ecoalert_detail.php?ecoregion_id=2, accessed June 2026.

[18] Invasives Database, Texas Invasive Species Institute, https://www.texasinvasives.org/plant_database/tpwd_results.php, accessed June 2026.

[19] Safak, I., Norby, P.L., Dix, N., Grizzle, R.E., Southwell, M., Veenstra, J.J., Acevedo, A., Cooper-Kolb, T., Massey, L., Sheremet, A., Angelini, C., 2020, Coupling breakwalls with oyster restoration structures enhances living shoreline performance along energetic shorelines, Ecological Engineering 158:106071, https://doi.org/10.1016/j.ecoleng.2020.106071, accessed June 2026.

[20] Texas General Land Office, 2025, Guide to living shorelines in Texas, Texas General Land Office, https://www.glo.texas.gov/sites/default/files/2025-01/guide-to-living-shorelines-in-texas.pdf, accessed June 2026.

[21] Nicholas Institute for Energy, Environment & Sustainability, Duke University, 2023, Nature-based solutions roadmap strategy—Living shoreline creation, https://nicholasinstitute.duke.edu/sites/default/files/project/nature-based-solutions-roadmap/strategy/doi-nbs-roadmap-strategy_living-shoreline-creation.pdf, accessed June 2026.

[22] Texas General Land Office, n.d., Living shorelines—Planting guidance, Texas General Land Office, https://www.glo.texas.gov/coastal/living-shorelines/planting-guidance, accessed June 2026.

[23] Texas General Land Office, no date, What is a living shoreline?: Texas General Land Office, https://www.glo.texas.gov/coastal/living-shorelines/what-living-shoreline, accessed June 2026.

[24] National Resilience Initiative, n.d., Living breakwaters, https://nrcsolutions.org/living-breakwaters/, accessed June 2026.

[25] Journal of Civil Engineering and Urban Planning, 2023, Clausius Scientific Press, Canada, https://dx.doi.org/10.23977/jceup.2023.051210, accessed June 2026.

[26] U.S. Army Corps of Engineers, (2021), Coastal Texas Protection and Restoration Study: Final Feasibility Report. U.S. Army Corps of Engineers, Galveston District., https://coastaltexasproject.com/wp-content/uploads/2022/08/Coastal-TX-Protection-and-Restoration-FINAL-Feasibility-Report_20210827.pdf, Accessed June 2026.

13

Maintaining and adaptively managing NBS

This chapter discusses maintenance best practices across the project life cycle that apply to NBS of all scales and in all contexts, supporting effective implementation and long-term performance.

Key takeaways

- Some NBS can self-maintain, while others benefit from regular maintenance.
- Adaptive management helps achieve long-term effectiveness of NBS for flood resilience.
- Vegetation maintenance helps plant species thrive, contribute to ecosystem services, and improves the likelihood that NBS function effectively.

Colorado River near La Grange, Texas
Photo courtesy of Freese and Nichols, Inc.

How the guiding principles apply to this chapter

Engage and include

Involving community members fosters local ownership and stewardship while building awareness of the flood risk reduction, water quality, and habitat benefits that NBS provide. Partnerships with academic institutions and community organizations can strengthen monitoring efforts, improve performance evaluations, and educate residents about the role these systems play in building a more resilient community.

Apply systems thinking

Maintenance activities should consider how system-wide factors such as upstream development, land-use changes, or drainage alterations affect NBS performance. Viewing maintenance within this broader context allows for proactive adjustments that sustain long-term functionality and resilience.

Work across boundaries

Effective NBS management requires coordination among departments, agencies, and various partners. Involving stakeholders in identifying issues and design feedback promotes shared accountability. Providing adequate funding for monitoring, adaptive management, and maintenance within project budgets supports consistent, long-term care.

Learn and adapt continuously

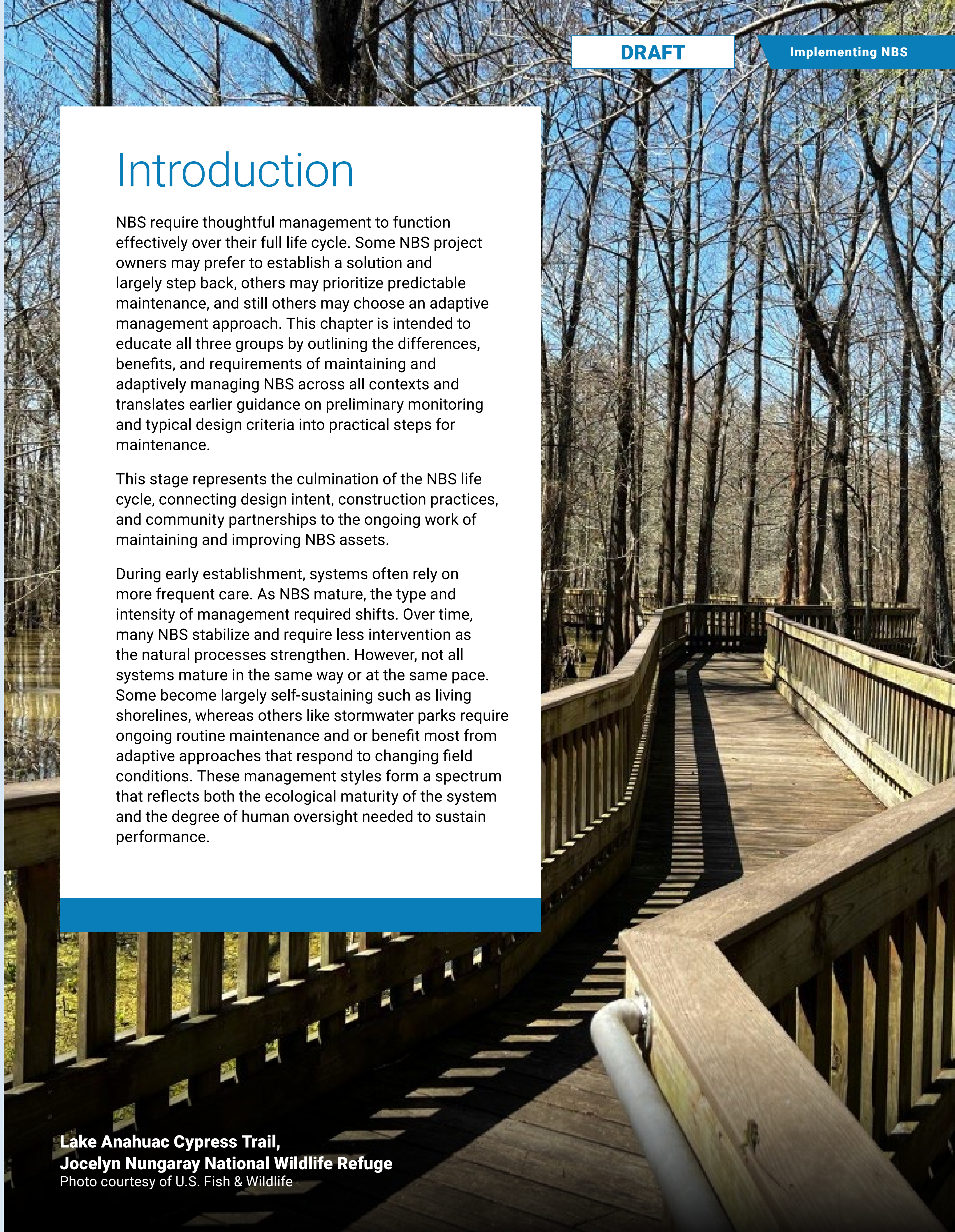
Adaptive management transforms maintenance into an ongoing learning process. Documenting results, evaluating trends, and applying lessons learned improves efficiency and cost-effectiveness of future efforts. Regular monitoring and data-driven adjustments allow NBS to adapt to shifting environmental and social conditions.

Introduction

NBS require thoughtful management to function effectively over their full life cycle. Some NBS project owners may prefer to establish a solution and largely step back, others may prioritize predictable maintenance, and still others may choose an adaptive management approach. This chapter is intended to educate all three groups by outlining the differences, benefits, and requirements of maintaining and adaptively managing NBS across all contexts and translates earlier guidance on preliminary monitoring and typical design criteria into practical steps for maintenance.

This stage represents the culmination of the NBS life cycle, connecting design intent, construction practices, and community partnerships to the ongoing work of maintaining and improving NBS assets.

During early establishment, systems often rely on more frequent care. As NBS mature, the type and intensity of management required shifts. Over time, many NBS stabilize and require less intervention as the natural processes strengthen. However, not all systems mature in the same way or at the same pace. Some become largely self-sustaining such as living shorelines, whereas others like stormwater parks require ongoing routine maintenance and or benefit most from adaptive approaches that respond to changing field conditions. These management styles form a spectrum that reflects both the ecological maturity of the system and the degree of human oversight needed to sustain performance.



Lake Anahuac Cypress Trail,
Jocelyn Nungaray National Wildlife Refuge
Photo courtesy of U.S. Fish & Wildlife

13.1 Monitoring, maintaining, and adapting

Traditional gray infrastructure loses its efficacy without maintenance and periodic upgrades. NBS are dynamic systems built upon natural processes and elements that strengthen as they mature toward the natural functions they are designed to emulate. For example, a concrete flood conveyance channel will degrade and require repair over time; however, its natural counterpart, a flood conveyance channel, can sustain itself over time.

Nature has conveyed floods across Texas landscapes long before concrete was used to line waterways. This demonstrates that natural flood conveyance can be inherently self-sustaining. Adaptive management builds on this principle by emphasizing flexibility, iterative evaluations, proactive responses and continuous improvement as the NBS progress toward ecological maturity. This stands in contrast to static management approaches, which rely on fixed design, rigid implementation, and prescribed maintenance routines.

NBS management ranges from walk-away, to routine maintenance, to systems where adaptive management allows systems to respond to evolving site conditions, environmental pressures, or performance trends. Ultimately, the project owner, maintenance crew, and maintenance funding dictate what level of maintenance is feasible for each NBS. The level of maintenance needed should be considered when selecting the type of NBS to implement during a site suitability assessment. See Table 8-2 in Chapter 8 for more information of NBS site suitability decisions.

As discussed in Chapter 9, adaptive management is both the final step and an ongoing cycle of NBS implementation. Adaptive management promotes data-driven and risk-responsive decision-making that can be adjusted as field conditions or monitoring results change. It extends project life, improves performance, and generates lessons learned that inform design criteria, funding priorities, and maintenance strategies across stakeholders and agencies. Ultimately, adaptive management bridges the gap between implementation and long-term resilience, safeguarding communities and ecosystems long term.

A fundamental principle of adaptive management is the feedback loop that links early design decisions with long-term performance. By using monitoring data, project owners can verify whether the NBS is functioning as intended and make adjustments as needed. For example, if post-construction monitoring shows a bioretention system is draining slower than specified in the design, maintenance staff can adjust soil media, clean underdrains, or modify vegetation to restore hydraulic performance. Establishing this feedback loop is especially important in Texas, where changing rainfall patterns, rapid development, and shifting social needs challenge the longevity of traditional flood management systems.

While earlier chapters of this manual address the first three steps of the adaptive management cycle assessing the problem (Chapters 7 and 8), designing (Chapter 9), and implementing (Chapter 10-12), the following sections focus on the latter stages of the cycle: monitoring, evaluating, and adjusting.[1]

Definitions

Maintenance

Routine, predictable scheduled activities such as vegetation care, debris removal, sediment removal, and repairs.

Adaptively Manage

A flexible, iterative process that establishes performance benchmarks, compares future conditions against those benchmarks, and adjusts the methods and timing of maintenance when conditions do not meet expectations.

Why is adaptive management important?

- **Long-term effectiveness:** Ensures NBS projects continue to meet flood mitigation and community resilience goals over their lifespan
- **Responsiveness:** Helps manage unforeseen challenges such as extreme storm events, vegetation damage, and urban growth
- **Enhanced co-benefits:** Maximizes additional benefits, such as improved biodiversity, water quality, and community wellness
- **Knowledge building:** Provides insights and data for future NBS projects, addressing knowledge gaps and improving overall practice.

Flooding at McFadden National Wildlife Refuge
Photo courtesy of U.S. Fish and Wildlife Service

Creating an adaptive management plan

An adaptive management plan provides the framework for stakeholders to proactively prepare for changing environmental conditions and community needs, supporting the long-ter success of NBS. The plan can guide operational tasks such as providing appropriate maintenance access, managing vegetation health, and coordinating maintenance requirements specific to each NBS type.

An adaptive management plan provides a documented roadmap for maintaining functionality over time. The plan should identify objectives, performance metrics, and maintenance actions that will be monitored, evaluated, and adjusted as conditions evolve. Integrating the adaptive management plan into NBS planning and design phases helps stakeholders allocate resources proactively.

Adaptive management depends on coordination amongst designers, engineers, maintenance personnel, and community partners. An adaptive management committee can be established to provide oversight, review data, and recommend adjustments. The committee typically would meet annually or after major events to review monitoring data and maintenance outcomes, evaluate whether objectives and performance targets are being met, identify emerging issues and potential improvements, and document lessons learned and update the adaptive management plan accordingly. Formalizing this structure creates accountability, transparency, and institutional memory. Including public agencies, local jurisdictions, and community representatives strengthens shared ownership of both outcomes and responsibilities.

In cases where maintenance of the NBS will be performed by partner organizations or contractors, a detailed and legally binding maintenance agreement should define performance standards, reporting expectations and protocols, and contract duration.

The implementation of many NBS practices is an evolving science where new research, monitoring data, and community priorities should be incorporated into updates to the adaptive management plan. It is also recommended that the plan be updated every 3-5 years or after major storm events that alter site conditions. Each update should incorporate findings from monitoring reports and note specific adjustments to maintenance schedules. Embedding these updates within regional reporting frameworks works to transfer knowledge across projects.

Tools and resources

- **TWDB**
  Guidance on Asset Management of Community Storm Water Systems ↗
- **Tarrant Regional Water District**
  Stormwater Facility Maintenance Agreement Water Quality Devices ↗
- **Pennsylvania Association of Conservation Districts**
  Riparian Planting Habitat Restoration Agreement ↗
- **Stormwater Association**
  Stormwater Maintenance Agreement ↗
- **USACE**
  Conservation Easement Agreement ↗
  Monitoring and Adaptive Management Plan for the River Road Aquatic Ecosystem Restoration Feasibility Study ↗
- **Atlanta Regional Commissions**
  Example Stormwater Facility Maintenance Agreement ↗
- **San Antonio River Authority**
  GSI Master Plan ↗

How To

Elements of an adaptive management plan

- **Clear objectives, targets, and expectations:** Understand how the system is designed to function. Define specific goals, such as improving water quality, enhancing biodiversity, mitigating flood risk.
- **Baseline assessments:** Conduct initial surveys to understand the pre-project conditions, which will help in evaluating the success of the NBS and monitoring future changes.
- **Maintenance:** Clearly define tasks, frequencies, responsible parties, and resources required for routine maintenance and operation.
- **Monitoring and evaluation plan:** Develop indicators and a monitoring schedule to assess the success and effectiveness of NBS over time.
- **Stakeholder engagement:** Involve local communities, governmental bodies, and environmental organizations to provide input and feedback on the management plan.
- **Funding and budget resources:** Secure funding and outline resource needs for ongoing management tasks, including human resources, tools, and materials.
- **Adaptive management procedures:** Develop a framework to track progress, document changes, and assess the adaptive management plan and how it will be updated based on monitoring data and changing conditions.

Alage in Wetland in Laguna Atascosa National Wildlife Refuge
Photo courtesy of U.S. Fish & Wildlife Service

Monitoring and performance assessment

Monitoring is the cornerstone of adaptive management. It provides the data needed to evaluate whether NBS are functioning as intended and to guide future design, implementation, and maintenance decisions. Historically, many NBS, especially neighborhood NBS, have emphasized water quality outcomes, while flood mitigation and peak-flow performance have received less consistent attention.[2]

Thus, a key component of using NBS for flood resilience is monitoring to assess performance on the ground compared to what was predicted during the planning and project design process. Monitoring data can also help locally to address knowledge gaps and contribute more broadly to empirical research on the effectiveness of NBS for flood resilience. Monitoring NBS performance and evaluating ongoing NBS projects will be crucial for building the evidence base to support wider uptake of similar projects.[3]

For example, comparing actual infiltration rates or water-storage volumes with modeled estimates can reveal whether design assumptions hold true under real-world conditions. Performance data such as peak flood levels, infiltration rates, vegetative health, sediment accumulation, and soil stability provide quantitative measures of how well NBS meet project goals. Qualitative observations, such as habitat development or community use of NBS spaces, can capture co-benefits that quantitative data alone might miss. This ongoing evaluation allows the project team to identify areas where performance falls short, meets, or exceeds initial expectations.[4]

Monitoring should occur across three phases:

Construction and establishment: Test drawdown time to verify infiltration capacity and verify that design specifications are met and that vegetation and hydraulic structures perform as intended during the warranty period.

Post-construction: Track system stabilization and identify early maintenance or replanting needs.

Long-term operation: Evaluate ongoing performance and detect trends over time, such as changes in infiltration capacity or vegetation succession.

Monitoring frequencies and data-collection methods should be scaled to the project context, risk level, and available resources. **Ideally, every NBS project should be checked after each storm event.** Establishing standard performance metrics and reporting templates allows for comparability across projects and jurisdictions.

Monitoring results should be incorporated into the adaptive management plan for each project. Findings should also be shared with partner agencies, industry professionals, research institutions, and community groups to strengthen collective knowledge and improve future NBS planning. Agencies and stakeholders can create a feedback loop between field performance, project design, and policy ensuring that NBS projects continue to evolve, perform, and deliver lasting resilience benefits.

Inspection results can be recorded in a digital maintenance database and reviewed during adaptive-management meetings to identify trends or recurring issues. Documenting each inspection with geotagged photographs and notes in a digital maintenance database supports adaptive management by providing time-stamped, site-specific performance data. These records help identify recurring vulnerabilities such as erosion hotspots or vegetative failure and inform long-term design or operational adjustments.

Effective data management can translate inspection records into actionable maintenance decisions. It is recommended that communities adopt a centralized work order and asset management database that links each NBS site to its design documents, maintenance history, access information, and site-specific considerations such as entry codes or equipment requirements. A well-structured database allows maintenance teams to sort sites by inspection frequency, prioritize work orders, and track the status of corrective actions over time. The City of Austin utilizes a GIS-integrated asset management system, **Figure 13-1** where each site is linked to plans, maintenance schedules, and operational notes. This allows staff to efficiently manage a large and geographically distributed network of NBS features.

Asset Management of Flood Infrastructure

TWDB developed reference sheets, inspection checklists, and maintenance forms for several stormwater management asset types including dams, weirs, levees, pump stations, rivers, stormwater channels, detention ponds, playa lakes, storm drain systems, and low water crossings, This initiative was designed to create practical, publicly available guidance tools to help Texas communities establish and sustain effective stormwater asset management programs.

The tools produced through this effort provide example inspection criteria, condition rating frameworks, and operational documentation approaches that can help communities establish scalable operations and maintenance programs and support maintenance staff implementation over time.

For more information on these resources, see ***www.twdb.texas.gov/flood/research/storm-water-systems.asp***

Bluebonnets in a detention pond in New Braunfels, Texas
Photo courtesy of U.S. Fish & Wildlife Service

Training and workforce development

A lack of NBS-trained maintenance professionals was noted as a barrier to NBS implementation in Chapter 2. Adaptive management requires personnel who understand the unique characteristics of NBS and can apply monitoring results to refine maintenance practices. Table 13-1 describes an example of a comprehensive program that includes orientation, field safety, vegetation management, inspection techniques, data interpretation, and continuing education.

Table 13-1. Example training framework for NBS maintenance staff

Example training category	Purpose	Example topics and learning objectives
Orientation	Introduce staff to NBS concepts, system functions, and site-specific context(s).	• Overview of (applicable) NBS types and functions • Design intent/performance goals • Site layout, access points, roles and responsibilities
Field safety	Ensure safe practices in diverse environments, including urban sites, riparian corridors, wetlands, and coastal zones.	• Personal protective equipment requirements and tool safety • Site conditions safety (working near water, slopes, tidal zones) • Heat stress, wildlife awareness, environmental hazards
Vegetation and ecological management	Build skills to maintain plant communities that support ecological function across NBS types.	• Native versus invasive species • Seasonal care and upkeep strategies • Protecting habitat and ecological structure(s) during maintenance
Inspection techniques	Train staff to assess NBS condition and performance at applicable contexts.	• Routine inspection procedures • Hydrologic & Hydraulic observations • Stability checks and signs of erosion • Structural checks
Data interpretation	Support decision-making using monitoring data.	• Interpreting hydrologic, geomorphic, and ecological data • Applying performance benchmarks • Identifying trends and system stressors • Documenting and communicating findings
Continuing education	Maintain staff proficiency as practices, science, and regional standards evolve.	• Updates to NBS standards • Context-specific flood resilience topics • Lessons learned • Regional training programs

Case Study

Maintenance workforce development

Location: Philadelphia, Pennsylvania

Opportunity: Workforce development can transform green infrastructure maintenance from a reactive process into an adaptive learning system.

Lessons learned: Establishing structured training, certification programs, and feedback mechanisms linking field observations to program management builds the institutional capacity needed to scale and sustain a growing NBS network.

The Philadelphia Water Department (PWD) provides a strong example of how long-term workforce development and institutional capacity can sustain a large-scale green infrastructure program. The PWD ***Green Stormwater Infrastructure Planning and Design Manual*** ↗ and ***Maintenance Manual*** ↗ established recurring staff training, contractor education, and certification programs that helping field crews and managers possess the skills to maintain system functionality, collect performance data, and support adaptive management. The program includes structured job classifications, standard operating procedures, and a feedback mechanism linking field performance to ongoing workforce training.

As the city's GSI network has expanded, PWD developed a dedicated maintenance division and partnered with local workforce organizations to scale institutional capacity alongside infrastructure growth. Crews document observations such as vegetation health, sediment buildup, and structural wear, feeding information back to program managers who update procedures and training materials accordingly — transforming maintenance from a reactive process into an adaptive learning system. PWD's partnership-based approach also created equitable economic opportunities in the green infrastructure sector while ensuring reliable staffing for an expanding network. This integration of workforce development, institutional coordination, and performance-based maintenance offers a replicable model for agencies across Texas building sustainable NBS programs.

Embedding training and certification programs within maintenance workflows builds institutional capacity and supports alignment with sustainability frameworks such as the ***Institute for Sustainable Infrastructure*** ↗ Envision LD2.3: Plan for Long-Term Monitoring and Maintenance.

13.2 Providing access and safety

Maintenance access and safety are foundational to the effective and sustainable operation of NBS. Both should be considered during design, construction, and long-term operation to ensure that maintenance staff can safely and efficiently inspect, repair, and adapt systems without damaging sensitive vegetation, compacting soils, or compromising hydraulic performance. Public safety is an equally important consideration. Deep water pooling in retention basins, bioretention cells, and constructed wetlands could present drowning hazards.

Incorporating these considerations early reduces life cycle costs, limits site disturbance, and supports consistent proactive maintenance, which are key pillars of the adaptive management process. Well-designed access and clear safety protocols allow maintenance crews to perform inspections and repairs efficiently while protecting the ecological integrity of NBS installations and minimizing risk to the surrounding community.

Design for maintenance access

Designers should treat maintenance access as a permanent project feature. Access routes should accommodate routine inspection and heavy equipment operations while minimizing environmental disturbances. Coordination between designers, landscape architects, and maintenance staff during project development improves the likelihood that access routes are functional for the establishment period and long-term operation. A dedicated easement encompassing the NBS feature and its associated maintenance access routes should be established during the design phase to ensure perpetual legal access for inspection, maintenance, and repair activities.

Recommended practices for maintenance access include providing direct, stabilized routes from public or private roads to key maintenance points such as forebays, inlets, risers, outlets, and monitoring stations. Routes should be designed using local drainage-entity standards for width, slope, and stabilization. Generally, a 10-foot-wide stabilized path with slopes less than or equal to 15 percent and four to one slope down into basins can be used for maintenance. Turnarounds, lay-down areas, and staging zones should be incorporated and sized for large vehicles, pumps, or vacuum trucks to maneuver safely. Low-impact surfacing materials such as graded rock or grass pavers are recommended to maintain permeability while supporting the load from maintenance vehicles. Graded approaches and cross-slopes should be designed to prevent rutting, erosion, and concentrated flows along access paths. Where feasible, design as multi-use maintenance corridors that double as trails or park service lanes to maximize community and operational benefit.

Design drawings should clearly delineate these corridors with specifying the material, grade, and turning radius on plan sheets. Easement boundaries should also be shown on all relevant plan sheets, plats, and legal documents to ensure they are recorded and enforceable. Establishing maintenance access during the design phase allows for maintenance activities to be performed safely, efficiently, and with minimal ecological disturbance.

Preventing damage and protecting vegetation

Uncontrolled travel, whether vehicle or pedestrian, through newly planted or established vegetated areas can reduce plant survival and increase long-term costs. Maintenance routes should be clearly delineated including signage, bollards, and/or fencing. Warning signs (temporary or permanent) should be incorporated to educate the public and maintenance personnel about sensitive zones, seasonal restrictions, and species protection areas. Co-branding signs with municipal or community logos reinforces local stewardship and awareness of NBS benefits (see example shown in Figure 13-1).

Educational signage and wayfinding can further support stewardship by informing the public about NBS function, appropriate use, and the importance of protecting sensitive features. Crews should be briefed before every maintenance cycle on site-specific constraints to avoid damage to root zones, infiltration zones, and/or habitat areas.

Figure 13-1. Native grassland restoration signage, Memorial Park, Houston

Source: Freese and Nichols, Inc.

Public access, protection, and stewardship

Many NBS features attract public interaction due to their visibility and integration into community spaces. While this creates opportunities for co-benefits such as recreation, education, and community engagement, it also introduces risks to system performance if access is not thoughtfully designed and carefully managed. Uncontrolled access, foot traffic, or off-trail use can degrade vegetation, compact soils, and reduce intended hydraulic performance over time.

Design and maintenance strategies should incorporate controlled access and clear wayfinding to guide public use while protecting system function. This may include designated paths, boardwalks, fencing, or subtle barriers that direct movement away from sensitive areas. When thoughtfully designed, these features can support safe public use while reinforcing stewardship and maintaining long-term performance. However, initial design assumptions about how the public will navigate these spaces may not always reflect actual use patterns. Monitoring foot traffic and observed access behaviors over time allows managers to identify where adjustments are needed, whether relocating paths, adding barriers, or opening new corridors, making public access management an important component of the adaptive management process.

Safety and worker protection

Maintenance of NBS requires careful attention to worker safety and clear operational procedures, particularly under the variable conditions that follow heavy rainfall. Each agency or jurisdiction should develop standard operating procedures and training programs that comply with Occupational Safety and Health Administration (OSHA) requirements. Potential hazards include extreme heat exposure/stress, unstable slopes, confined spaces, high-flow water, wildlife encounters, heavy equipment operation, and debris or contaminant exposure. These risks are heightened after storm events when access paths may be wet, eroded, or obstructed.

Supervisors should hold tailgate safety briefings before every field operation and review site-specific hazards. Crews should be trained in safe equipment operation, confined-space awareness, and flood-related risk assessment. Basic requirements include the proper use of personal protective equipment (PPE) including helmets, gloves, reflective vests, eye protection and safety boots. High-risk tasks such as confined-space entry or slope stabilization should be assigned to two-person crews at minimum. Lock-out/tag-out protocols should be followed for all pumps, mechanical systems, and electrical systems before work begins. Established emergency response procedures and communication protocols, including first aid readiness or clear excavation routes, should be in place and reviewed with crew prior to each field operation. When maintenance activities occur in public, recreational or shared spaces such as parks or trails, public and maintenance areas should be clearly separated with temporary barriers, cones, and signage to protect both the workers and the public.

Post-construction monitoring

Vegetation monitoring should begin immediately after construction and continue throughout the warranty period to confirm that establishment goals are met. For vegetation, warranty periods are recommended to last two years or more, especially for trees. This allows the vegetation time to establish itself and reduce failures that don't present themselves immediately following construction. During this phase, the contractor or responsible party should conduct inspections after planting, following major storm events, and at regular intervals. Typically, inspections are completed monthly during the first growing season and quarterly thereafter. Monitoring should include documenting plant survival rates, species composition, and indicators of stress such as die-off, invasive growth, or pest damage.

Post-construction monitoring is intended to check that vegetation is established successfully, and that hydrologic and soil conditions meet design expectations. It is important to monitor drawdown rates following storm events as prolonged inundation can stress or kill newly established vegetation and may indicate subsurface drainage deficiencies. Any deficiencies identified during this period should be corrected before project hand-off to the owner or operating agency. Plant replacement, sediment removal, or irrigation adjustments performed during this stage protect early ecological investments and reduce long-term maintenance costs.

Post-storm inspection and response

The primary objectives of post-storm inspection are to verify hydraulic and structural integrity, assess vegetation health, and identify erosion or debris that could impair performance. Post-storm inspections can be potentially hazardous as crews are deployed after major rainfall or flood events, when slopes, structures, and vegetation may be unstable. Incorporating post-storm procedures into the overall safety plan can support effectives inspections. Because storm-related conditions can change rapidly, inspection crews should maintain real-time communication with supervisors and avoid entering hazardous areas.

It is recommended that post-storm inspections should be triggered by storms exceeding approximately two inches of rainfall within 24 hours, storms exceeding the design storm capacity, or any localized flooding that indicates potential system stress. For coastal NBS, post-storm inspections may be triggered by tropical storms, hurricanes, storm-surge events, high-tide events or other coastal conditions that exceed design assumptions, regardless of rainfall totals.

Table 13-2. Typical post-storm inspection and response checklist

Inspection element	Purpose (what to check)	Typical findings or indicators	Example actions and responses
Inlets, outlets, and conveyance structures	Verify flow paths and drainage connectivity	• Sediment or debris blockage • Standing water > 48 hours • Structural cracking	• Remove debris • Remove sediment • Repair damage to restore flow
Slopes and banks	Check for erosion and structural stability	• Rills, gullies, rutting, or undercutting along slopes	• Fill and compact eroded areas • Install erosion control • Re-vegetate exposed soil
Vegetation	Assess health and survival after storm	• Uprooting • Burial • Broken stems, or leaf die-off	• Replant or stabilize • Maintain ≥70% cover • Replace damaged species
Access routes and paths	Confirm safe and functional entryway	• Ponding • Rutting • Soft ground • Debris blocking routes	• Repair surfacing • Stabilize with aggregate or matting • Remove obstructions
Safety features	Ensure visibility and safety for crews and public	• Missing, damaged, or obscured signage • Bent or rusted rails	• Replace or repair guardrails, bollards, or signage • Clean or re-paint signage
Monitoring equipment	Maintain functionality of sensors and gauges	• Displaced or water-damaged sensors • Missing covers	• Realign or replace sensors • Record anomalies in AMP database

13.3 Maintaining vegetation

Plant maintenance helps plant species thrive, contribute to ecosystem services, and helps the system function effectively. Programs such as ***San Antonio River Walk Mission Reach*** ↗ and the ***Louisiana Watershed Initiative*** ↗ demonstrate that proactive vegetation management helps prevent hydraulic loss and supports ecological biodiversity.

Vegetation management should therefore be proactive, emphasizing prevention of decline rather than reactive replacement. Maintenance strategies should anticipate how vegetation evolves over time and balance hydraulic performance with ecological maturity. The type of maintenance activities needed will vary across Watershed, Neighborhood and Coastal NBS and will need to be tailored to the species, local conditions and their role in the NBS.

Coordination across departments is also important where NBS include naturalized areas such as “no mow zones” or “grow zones”. These areas are intentionally managed differently than conventional landscaping to support stormwater filtration, bank stabilization, habitat, and reduced mowing frequency. Clearly identifying no mow zones in project plans, maps, signage, and operator procedures can help prevent unintended mowing that could undermine intended NBS function.

Post-warranty monitoring

After the warranty period, responsibility for monitoring typically transitions to the project owner or operating agency. Monitoring frequency can be reduced to semi-annual or annual inspections but should remain consistent enough to capture long-term trends in vegetation health, hydrologic function, and soil stability. Findings from ongoing monitoring should be used to refine species selection, maintenance frequency, and replanting strategies as conditions evolve.

The distinction between warranty-period and post-construction monitoring helps identify and address establishment issues early while long-term observations continue to refine maintenance practices and inform future NBS designs.

Tracking vegetation health during and after establishment provides an early indicator of NBS functionality and resilience. Inspections should verify that water is entering the system as intended by checking that inlets, curb cuts, and flow spreaders remain clear and unobstructed by vegetation, sediment, or debris.

Routine maintenance activities

Establishing a routine maintenance schedule that includes pruning, soil aeration, and sediment removal helps the system remain functional and effective over time.[5] Vegetation can vary by NBS type but typically includes the following recurring tasks:

Watering: Ensure that newly planted vegetation receives adequate water during establishment, particularly in the first 18 months. Implement temporary irrigation systems (such as drip irrigation or watering trucks) in areas with insufficient rainfall to increase survival rates. Reduce irrigation gradually once vegetation is established to encourage deep root growth and drought tolerance.

Pruning: Regularly prune plants to prevent overcrowding and maintain visibility and access around inlets, outlets, and monitoring points. Remove dead or diseased plants to prevent spread of pathogens and to maintain overall vegetation health. Plants considered hazardous material should be disposed of at the proper facility.

Mulching: Maintain a two to three inch layer of shredded hardwood mulch to conserve soil moisture and suppress weeds. Shredded hardwood mulch is recommended over other mulch types as its interlocking texture reduces the risk of floating and displacement during storm events. Mulch should be at least 6 inches away from structures and inlets to prevent clogging.

Fertilization: Apply organic or slow-release fertilizers sparingly and only after soil testing indicates nutrient deficiency. Avoid high nitrogen chemical fertilizers that can degrade water quality.

Pest and disease management: Monitor for pests and diseases using integrated pest management (IPM) strategies to minimize chemical use. Emphasize early detection, manual or mechanical control, and selective chemical treatments only when necessary.

Sediment and debris removal: Remove accumulated sediment and debris that could smother vegetation or impede stormwater flows. It is recommended that sediment be cleared biannually or when accumulation exceeds two inches at the toe of slopes, berms, or filter strips to maintain infiltration and hydraulic performance. Sediment removal frequency and handling procedures should account for pollutant loading from the contributing drainage area. In watersheds with industrial land uses, high-traffic roadways, or known contamination sources, accumulated sediment may contain elevated levels of heavy metals or other hazardous materials requiring special handling, disposal, and worker protection protocols in accordance with applicable local, state, and federal regulations.

Erosion repair: Inspect vegetated slopes and filter areas for erosion or bare soil and repair promptly through re-grading, reseeding, or installation of erosion-control matting.

Ecological milestones

Established vegetation should include periodic assessments to evaluate ecological milestones such as canopy closure, pollinator habitat establishment, and replacement ratios for failed plantings. The initial establishment period of vegetation is typically complete after three to five years. These metrics link vegetation programs to broader co-benefit indicators described in **Chapter 7** and support evaluation of ecosystem services provided by each NBS. Adaptive maintenance should anticipate vegetative succession, replacing early-stage colonizers with longer-lived, native species as systems mature.

Critical ecological milestones such as planting windows, nursery coordination, and seasonal wildlife constraints should be incorporated into construction schedules to improve survival and minimize environmental conflicts. Planting should align with regional wet and dry seasons for optimal establishment conditions. Avoid heavy maintenance operations during sensitive periods such as bird-nesting or pollinator activity when possible. During droughts, prioritize watering and mulching to protect root zones; during wet seasons, reduce mowing and avoid equipment operation in saturated areas to prevent compaction and soil disturbance.

Integrating construction and seasonal scheduling with vegetation maintenance supports successful establishment of plants and promotes synchronization of long-term care with environmental cycles and ecosystem objectives.

Tools and resources

- **NCTCOG**
  Let It Grow: A Showcase of No Mow Zones in North Central Texas ↗
- **Texas A&M AgriLife Extension**
  Native Seeding Certification ↗
- **Native Plant Society of Texas**
  Native Landscape Certification Program ↗
- **Society of Wetland Scientists**
  Professional Certification Program ↗
- **U.S. Fish & Wildlife National Conservation**
  Training Center ↗
- **Bureau of Land Management**
  Knowledge Resource Center ↗
- **ASCE Journal of Environmental Engineering**
  Comparison of Maintenance Cost, Labor Demands, and System Performance for LID and Conventional Stormwater Management ↗

Greenhouse at the San Marcos Aquatic Resources Center
Photo courtesy of U.S. Fish & Wildlife Service

13.4 Sustaining watershed NBS performance

Watershed NBS play role in maintaining regional flood resilience, water quality, and ecosystem connectivity. At this scale, maintenance requires systems thinking rather than site-specific intervention. Each reach, floodplain, or restoration area functions as part of a larger hydrologic network, where changes upstream or downstream can influence system performance. Maintenance activities, therefore, should consider how individual elements interact to support flood attenuation, landscape dynamics, and ecological health throughout the watershed.

Watershed NBS maintenance is inherently multi-jurisdictional and collaborative, involving flood-control districts, river authorities, municipalities, and private landowners. Watershed NBS maintenance extends beyond individual project sites and focuses on the integrated performance of stream, floodplain, and infrastructure systems. Activities conducted upstream can directly affect downstream system performance, requiring coordinated scheduling and data-sharing between agencies. Because stream corridors and floodplains frequently cross property and jurisdictional boundaries, maintenance responsibilities should be formalized through interlocal agreements, memoranda of understanding, or joint-maintenance partnerships to ensure accountability and continuity across ownership lines. Agreements should outline responsibilities, cost-sharing structures, and data-sharing protocols to maintain transparency and accountability.

Institutional partnerships can also engage community stewardship groups and nonprofit organizations for litter removal, riparian planting, and invasive management. These partnerships not only supplement agency capacity but also strengthen public awareness and stewardship of regional water resources.

The primary objective of watershed NBS maintenance is to **sustain the functional connectivity of floodplains, streams, and wetlands**. This means maintaining the physical linkages that allow stormwater, sediment, and biota to move naturally through the system, while preserving designed flood storage capacity and stability. Unlike neighborhood NBS, which focuses on localized runoff, watershed systems prioritize:

- hydraulic performance by maintaining floodplain storage and channel conveyance,
- sediment balance by balancing degradation and aggradation, and
- ecological continuity by maintaining vegetation and wildlife corridors.

At the watershed scale, success is measured through regional performance metrics such as sediment transport and balance, flood-storage volume, and channel stability, which are evaluated across multiple reaches rather than at individual sites. Long-term monitoring should focus on identifying trends such as sediment accumulation, vegetation succession, and channel migration and using those observations to refine maintenance frequencies and management practices. Monitoring efforts rely on aerial imagery, LiDAR, and GIS-based inspection mapping to efficiently track system performance over time and across large geographic areas. Programmatic adaptive management is applied at the watershed or basin level, where adjustments are informed by cumulative data from multiple sites rather than isolated maintenance findings.

Collectively, these considerations make watershed NBS maintenance both complex and strategic, which demands cross-agency cooperation, centralized data management, and a shared understanding of system-scale performance.

Routine maintenance activities

Routine maintenance increases the likelihood that watershed NBS practices continue to provide hydraulic and ecological benefits while minimizing costly emergency interventions. Maintenance actions should be scheduled to coincide with low-flow periods to reduce sediment disturbance and ecological disruption. These are the typical tasks:

Bank stabilization and erosion repair: Inspect streambanks for undercutting, slumping, mass wasting, or loss of vegetation. Stabilize using bioengineering techniques such as live staking, brush mattresses, soil lifts, or vegetated geogrids. Prioritize natural stabilization methods over structural solutions to preserve habitat and infiltration.

Sediment management: Monitor sediment deposition in floodplains, pools, and wetlands to maintain flood-storage capacity and aquatic habitat. Remove excess sediment strategically, focusing on forebays and sediment-trapping areas to minimize ecological disturbance.

Vegetation management: Maintain a balance between vegetative roughness and hydraulic function. Remove invasive species and encourage diverse native plant communities that support floodplain stability and habitat quality. When removing invasive or overgrown vegetation, avoid scalping large areas at once, as bare soil patches can destabilize banks and slopes and increase erosion risk. Removed vegetation should be replaced with native species to restore ground cover and maintain soil stability. Coordinate vegetation work with ecological monitoring schedules to avoid nesting or spawning periods.

Structural maintenance: Inspect grade-control structures, culverts, and weirs for displacement, scour, or debris blockage. Realign or repair damaged elements to preserve design elevations and flow continuity.

Debris and trash removal: Clear obstructions that could reduce conveyance, exacerbate flooding, or degrade habitat. Debris removal should follow best practices to protect aquatic organisms and minimize sediment resuspension.

Access route maintenance: Keep maintenance roads and crossings stable and accessible during wet conditions, following the access and safety standards outlined in **Section 13.2**.

Post-storm inspections and adaptive response

After major storms or flood events, watershed-scale systems should be assessed for structural integrity, erosion, sediment redistribution, and vegetation damage. These inspections differ from site-scale inspections in both scope and logistics, often requiring coordination between multiple agencies and the use of aerial or drone imagery for efficient assessment.

Immediate priorities include stabilizing eroded banks, clearing obstructed channels, and documenting floodplain inundation extents and high-water marks to update hydrologic models.

Because of the spatial scale, post-event adaptive management focuses not only on repairing physical damage but also on evaluating how the system functioned as a whole. Evaluations may consider whether floodwaters were retained as designed, or if sediment deposition shifted downstream capacity. Findings from each event should inform basin-scale models and guide future maintenance scheduling, plant selection, and design modifications.

Tools and resources

- **North Carolina Stream Restoration Institute and North Carolina Sea Grant**

  Stream Restoration: A Natural Channel Design Handbook (Chapter 12: Restoration Evaluation and Monitoring) ↗
- **NRCS**

  USDA Part 654 Stream Restoration Design National Engineering Handbook - Chapter 16: Maintenance and Monitoring ↗
- **San Antonio River Authority**

  Natural Channel Design Protocol Manual - Chapter 17: Monitoring and Evaluation ↗

13.5 Sustaining neighborhood NBS performance

Neighborhood NBS are often located within urban or suburban environments where space, access, and public use present unique operational challenges. At this scale, maintenance should balance hydraulic performance, aesthetics, and community expectations while ensuring safety and accessibility. Systems are often smaller and more numerous than watershed-scale projects, making standardized procedures, clear inspection criteria, and reliable data tracking critical to program success.

The goal of neighborhood-scale maintenance is to preserve design functionality within constrained, high-use environments. Integrating maintenance needs into NBS design is beneficial in the neighborhood context, where space constraints, higher pollutant loads, and frequent public interaction can complicate operations. As discussed in **Chapter 11**, design features such as sediment forebays, curb cuts, and trash racks should be incorporated to allow easy inspection and clean-out, especially in areas where staff access or equipment maneuverability is limited. Including maintenance staff in the design-review phase helps identify potential challenges such as debris accumulation, vegetation overgrowth, or restricted access for vacuum trucks before construction, reducing long-term costs and avoiding conflicts between infrastructure and landscape function.

Maintenance programs should focus on maintaining infiltration and conveyance capacity by preventing clogging, sediment accumulation, or vegetation overgrowth, while also protecting public safety and accessibility, maintaining clear sightlines, level surfaces, and unobstructed pedestrian areas. Aesthetic goals can be supported through well-maintained plantings that reinforce public confidence in NBS performance.

Because these systems are widely distributed, maintenance programs should emphasize consistency and scalability. Establishing inspection routes, standardized checklists, and GIS-based tracking tools allows project owners to efficiently manage large numbers of small assets. At this scale, maintenance is most effective when integrated into existing municipal operations such as linking daily tasks such as street sweeping, vegetation care, and litter removal to overall NBS performance objectives.

Many NBS are integrated into streetscapes, medians, or community spaces where they are subject to public interaction, litter, and wear. Maintenance staff should balance technical performance with visual quality. Neighborhood NBS systems are often adjacent to utilities or located within narrow easements, which can limit equipment access and increase the importance of hand maintenance and coordinated scheduling. High pollutant and debris loads in urban environments require more frequent cleaning, vegetation management, and sediment removal compared to larger naturalized systems.

Routine maintenance activities

NInstitutional capacity is beneficial for maintaining large inventories of neighborhood NBS. Agencies should designate clear points of responsibility for inspection and maintenance, supported by consistent funding streams and ongoing workforce training. Cross-departmental coordination among public works, parks, and transportation reduces potential duplication of effort.

The proximity to neighborhood NBS to residents offers opportunities for community stewardship. Community stewardship programs like litter-removal events, replanting days, or "adopt-a-planter" initiatives can supplement municipal capacity and build community ownership of NBS. Training for staff and volunteers should emphasize safety, vegetation management, and the role of maintenance in flood mitigation and environmental quality. Partnerships with community groups can also extend monitoring coverage and foster awareness of NBS performance, strengthening local stewardship and long-term sustainability.

Although specific maintenance needs vary by practice type, common recurring tasks include:

Sediment and debris removal: Inspect inlets, forebays, and permeable surfaces for sediment buildup, trash, or clogging. Remove materials manually or by vacuum truck to maintain infiltration and storage capacity.

Vegetation management: Maintain appropriate plant height and density to sustain design performance and aesthetics. Remove weeds and invasive species, prune vegetation for visibility and access, and replace dead or damaged plants promptly.

Soil and media maintenance: For infiltration-based practices, monitor infiltration rates and replace or rejuvenate media when performance declines.

Hydraulic and structural inspection: Inspect underdrains, overflow structures, curb cuts, and risers for clogging or damage, ensuring unobstructed flow.

Public interface upkeep: Remove litter, graffiti, and obstructions promptly to maintain appearance and safety and reinforce community confidence in NBS performance.

Post-storm inspections and response

After heavy rainfall or local flooding, neighborhood NBS practices should be inspected for standing water, erosion, or clogged outlets. Because these systems are smaller and located within dense urban areas, rapid response is often beneficial to prevent minor issues from escalating into failures that affect surrounding infrastructure or properties. Inspection findings should be recorded in a digital database and reviewed during adaptive-management meetings to identify recurring maintenance patterns across multiple sites or neighborhoods.

Green stormwater infrastructure maintenance manual and training videos

The type and amount of maintenance required is highly dependent on the NBS practice and its level of establishment. In general, the newer the NBS installation, the more routine check-ups and maintenance are required for proper functionality. The Arid LID Coalition's ***Green Stormwater Infrastructure Maintenance Manual*** ↗ and series of GSI Maintenance Field Training Videos cover maintenance requirements for several typical neighborhood NBS practices.

The manual also provides maintenance inspection checklists for the NBS types covered as well as discussion of tools and specialized equipment that may be needed. The NPDES Training Institute hosts the ***MS4 Green Infrastructure Technician Certification*** ↗ which includes additional neighborhood NBS practices and stormwater pollution prevention plan compliance.

These resources cover the monitor, evaluate, and adjust steps of the adaptive management process, including tasks like

- visiting stormwater infrastructure during storm events to check performance in action,
- inspecting and maintaining irrigation systems,
- managing vegetation that supports natural filtering but does not block the flow of water,
- removing sediment and trash and clearing inlets and outlets of debris and vegetation,
- maintaining and refreshing mulch,
- repairing erosion and human-caused damage, and
- adjusting maintenance schedules over time as issues arise and landscapes mature.

Tools and resources

- **San Antonio River Authority**
  Low Impact Development Maintenance & Inspection Checklist (Appendix F) ↗
- **City of Austin**
  City of Austin Green Infrastructure Maintenance (Rain Gardens, Vegetated Filter Strips, Biofiltration) ↗
- **City of Houston**
  A Guide to Developing & Maintaining LID Techniques in Houston ↗
- **Texas A&M AgriLife Green Infrastructure for Texas Communities**
  Green Infrastructure Toolkit for Texas Communities (See O&M Sections of Design Sets) ↗
- **EPA**
  Green Infrastructure Installation, Operation, and Maintenance ↗
  The Importance of Operation and Maintenance for the Long-Term Success of Green Infrastructure ↗
  Operation and Maintenance Considerations for Green Infrastructure ↗
  Stormwater Wet Pond and Wetland Management Guidebook ↗
- **Arid LID Coalition**
  Green Stormwater Infrastructure Maintenance Manual ↗
- **Philadelphia Water Department**
  Green Stormwater Infrastructure Planning and Design Manual ↗
  Green Stormwater Infrastructure Maintenance Manual ↗

Rain Garden, Harris County, Texas
Photo courtesy of Harris County Office of the County Engineer

13.6 Sustaining coastal NBS performance

Coastal NBS are beneficial for reducing shoreline erosion, enhancing water quality, and protecting critical habitats. Because these systems are continuously influenced by tides, waves, and salinity, their maintenance demands are distinct from neighborhood or watershed contexts. Coastal NBS should be monitored and managed as dynamic, adaptive systems that evolve in response to changing shoreline processes and sea-level trends.

The purpose of coastal NBS maintenance is to sustain protective function and ecological integrity while allowing for natural adaptation. Unlike inland systems where conditions can remain relatively stable, coastal features undergo continual physical change from sediment transport, wind, tidal cycles, and sea-level rise. The dynamic nature of coastal environments requires flexible inspection schedules and frequent post-event assessments to identify damage and prioritize response actions. Effective maintenance should combine engineering precision with ecological flexibility so that dunes can retain storm-buffer capacity, oyster reefs can accrete vertically with sea-level rise, and shoreline vegetation can persist through salinity and inundation stress.

Maintenance programs for coastal NBS should monitor and repair erosion or scarping caused by storms or human activity, while also maintaining vegetation cover and dune structure to support sediment retention and habitat connectivity. Living-shoreline elements should be regularly inspected to confirm they remove structurally sounds and continue to attenuate wave energy effectively. Many coastal NBS incorporate hybrid infrastructure including engineered components such as breakwaters, terraces, and geotextile cores that require structural inspection in addition to ecological monitoring to ensure both engineered and natural elements are performing as intended.

Coastal NBS maintenance often requires multi-agency coordination across federal, state, and local entities. Inter-agency frameworks should define roles for routine inspections, emergency response, and data reporting. Formal agreements or MOUs between coastal-management agencies, park departments, and non-governmental organizations (NGOs) clarify jurisdictional responsibilities, cost-sharing, and permitting compliance. Monitoring data should be integrated into adaptive management cycles that account for sea-level rise and long-term morphologic change, allowing programs to evolve alongside the dynamic conditions that characterize coastal environments.

Coastal NBS differ from watershed and neighborhood systems because of their exposure to highly variable physical forces and ecological sensitivities. These factors make coastal maintenance both technically complex and time-sensitive, requiring specialized expertise and inter-agency collaboration. Because individual coastal NBS sites contribute to larger regional sediment transport and habitat systems, maintenance programs should also consider up- and down-drift impacts and align site-level activities with regional shoreline management plans to avoid unintended consequences on adjacent coastal areas.

Engagement strategies such as volunteer monitoring programs and educational partnerships can strengthen coastal stewardship and complement formal maintenance programs. Partnerships with initiatives such as the GLO ***Texas Beach Watch*** ↗ and local conservation groups can expand monitoring capacity through volunteer programs. These partnerships build stewardship and public awareness and foster shared responsibility for coastal resilience.

Routine maintenance activities

Routine coastal NBS maintenance focuses on preserving physical form and ecological function while preventing minor issues from escalating after storms or seasonal changes. Routine maintenance schedules should align with seasonal patterns, for example conducting inspections after high tides or storm seasons and adjusting activities to minimize disturbance during nesting or spawning periods. These are key activities:

Erosion control and sand management: Inspect dunes and beaches for scarping or blowouts; reshape and re-grade eroded areas; replace sand through small-scale nourishment where feasible.

Vegetation management: Maintain and replant dune or marsh vegetation such as sea oats (*Uniola paniculata*), saltgrasses (*Distichlis spicata*), and cordgrasses (*Spartina*) to stabilize sediments. Replace vegetation after over wash or die-off events to sustain 70 percent minimum cover.

Invasive-species control: Remove non-native or aggressive vegetation such as torpedo grass (*Panicum repens*) and Chinese tallow (*Triadica sebifera*) that can displace native dunes or marsh species.

Structural inspection: Examine oyster-reef modules, breakwaters, or sill structures for displacement, material loss, or scour; replace rock or shell material and reset units as needed.

Trash removal: Clear trash regularly to prevent interference with vegetation or wildlife, particularly plastics and other non-biodegradable litter.

Public-access infrastructure: Inspect boardwalks, access stairs, and fencing for damage and repair promptly to direct foot traffic away from sensitive vegetated areas.

Post-storm inspections and response

Major coastal storm events demand immediate and coordinated action. Post-storm response often requires temporary stabilization, such as sand fencing, re-planting, or shell replenishment, followed by long-term assessment to determine if design modifications are necessary.

After hurricanes, tropical storms, or king tide events, inspections should evaluate dune height and cross-sectional loss, marsh-edge retreat or subsidence, structural displacement of reefs, sills, or terraces, and vegetation burial or mortality. These assessments should be conducted as soon as site conditions allow safe access, as timely documentation of storm impacts is valuable to prioritizing repairs and restoring protective capacity before the next storm season. Post-storm survey data should be incorporated into the adaptive management plans allow future design standards for durability and adaptability to be informed by previous recovery measure.

Tools and resources

- **GLO**
  A Guide to Living Shorelines in Texas ↗
- **NOAA**
  A Framework for Developing Monitoring Plans for Coastal Wetland Restoration and Living Shoreline Projects in New Jersey ↗

Maintain and adaptively manage NBS **citations**

Matagorda Bay Rookery Islands, Texas
Photo Courtesy of Freese and Nichols

---

[1] Williams, B. K., R. C. Szaro, and C. D. Shapiro, 2009, Adaptive Management: The U.S. Department of the Interior Technical Guide. Adaptive Management Working Group, U.S. Department of the Interior, Washington, DC.

[2] Esraz-Ul-Zannat, M., Dedekorkut-Howes, A., & Morgan, E. A., 2024, A review of nature-based infrastructures and their effectiveness for urban flood risk mitigation. Wiley Interdisciplinary Reviews: Climate Change, e889.

[3] Chiu, Y. Y., Raina, N., & Chen, H. E, 2021, Evolution of flood defense strategies: Toward nature-based solutions. Environments, 9(1), 2, Accessed June 2026.

[4] San Antonio River Authority, 2019, San Antonio River Basin Low-Impact Development Technical Design Guidance Manual. San Antonio, TX, USA.

[5] Philadelphia Water Department, 2021, Green Stormwater Infrastructure: Planning & Design Manual. Philadelphia, PA, USA.

www.TWDB.texas.gov

www.twdb.texas.gov/flood/research/Nature-based-Solutions-2022/index.asp

TEXAS WATER
DEVELOPMENT BOARD