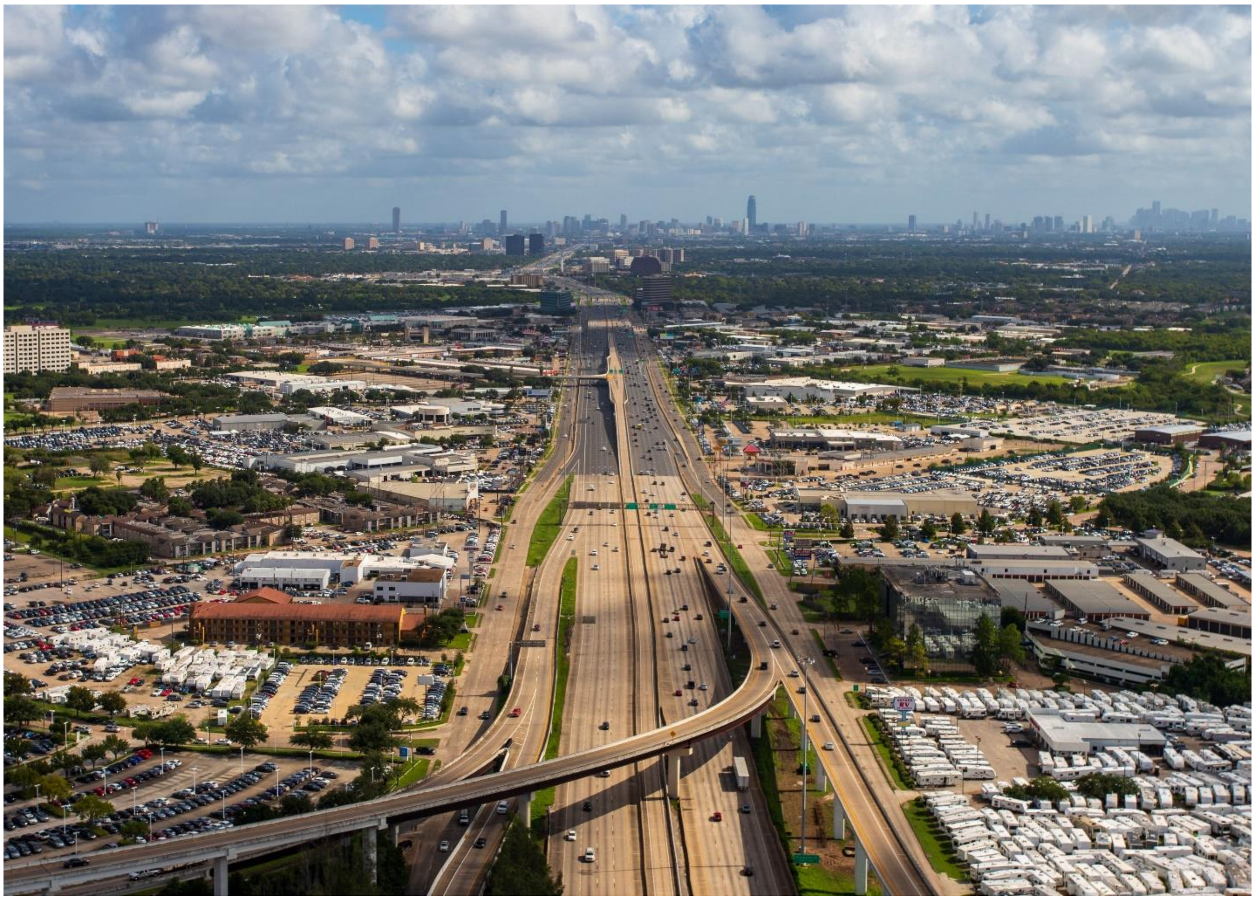
# Appendix A - FRM Measures in Context



**(NOTE: This page intentionally left blank.)**

# TABLE OF CONTENTS

# FIGURES

# TABLES

**(NOTE: This page intentionally left blank.)**

# 1 INTRODUCTION

This appendix presents an array of flood risk management (FRM) measures including structural, non-structural, and programmatic/regulatory. The information presented related to each is intended to provide basic information regarding their applicability, design and environmental considerations, and the long-term resilience of the feature. Future FRM studies should consider the full array of measures, and appropriate combinations as part of a layered or systems approach to FRM in the Metro Houston region by applying broader strategies.

Flood risk management project implementation benefits from an understanding of why flood risk management is needed in the first place, the array of available options to address it and the considerations, tradeoffs, and requirements of each. As development continues, habitats become at risk and storm severity worsens, a strategic, integrated approach has become increasingly necessary to address flood risk. Combining multiple measures into a layered solution can address various levels of flood risk while potentially delivering co-benefits. A layered solution can help achieve performance goals in terms of flood risk mitigation and sustainability of mitigation measures. FRM infrastructure is often referred to as "green," "gray," or a hybrid of both. Gray infrastructure refers to typically hardened structures, such as pipes, roads, levees etc. Green infrastructure typically refers to more nature-based "softer" solutions and is defined in detail in section 6 of this appendix. Traditional gray infrastructure strategies can be applied on a large scale but often lack robustness in terms of sustainability in their delivery due to unbalanced social, economic and environmental performance (DC Water, 2015; American Rivers et al, 2012). Low impact development (LID) and green infrastructure (GI) solutions provide more holistic social and environmental benefits, but some strategies are challenging in already urbanized areas or provide lower levels of service than traditional measures depending on their level of implementation. However, implementing hybrid solutions that combine master planning in less developed watersheds, green retrofits in highly developed watersheds and complementing those measures with gray infrastructure solutions where necessary may mitigate some of the shortcomings of both flood risk management approaches. The built components of flood risk management include traditional measures such as detention, flood walls, levees and channel improvements as well as natural and nature-based features (NNBFs), GI and LID alternatives. Non-structural measures focus on changes in land management, building acquisition and relocation, regulatory changes and enhanced flood warning systems.

## 1.1 Fundamentals

Floods are a natural hazard that have been with us throughout history. These hazards have been particularly persistent in the South/Central region of the country with Texas and Louisiana experiencing a higher frequency of events that have resulted in billion-dollar disasters than any other region (fig. 1).

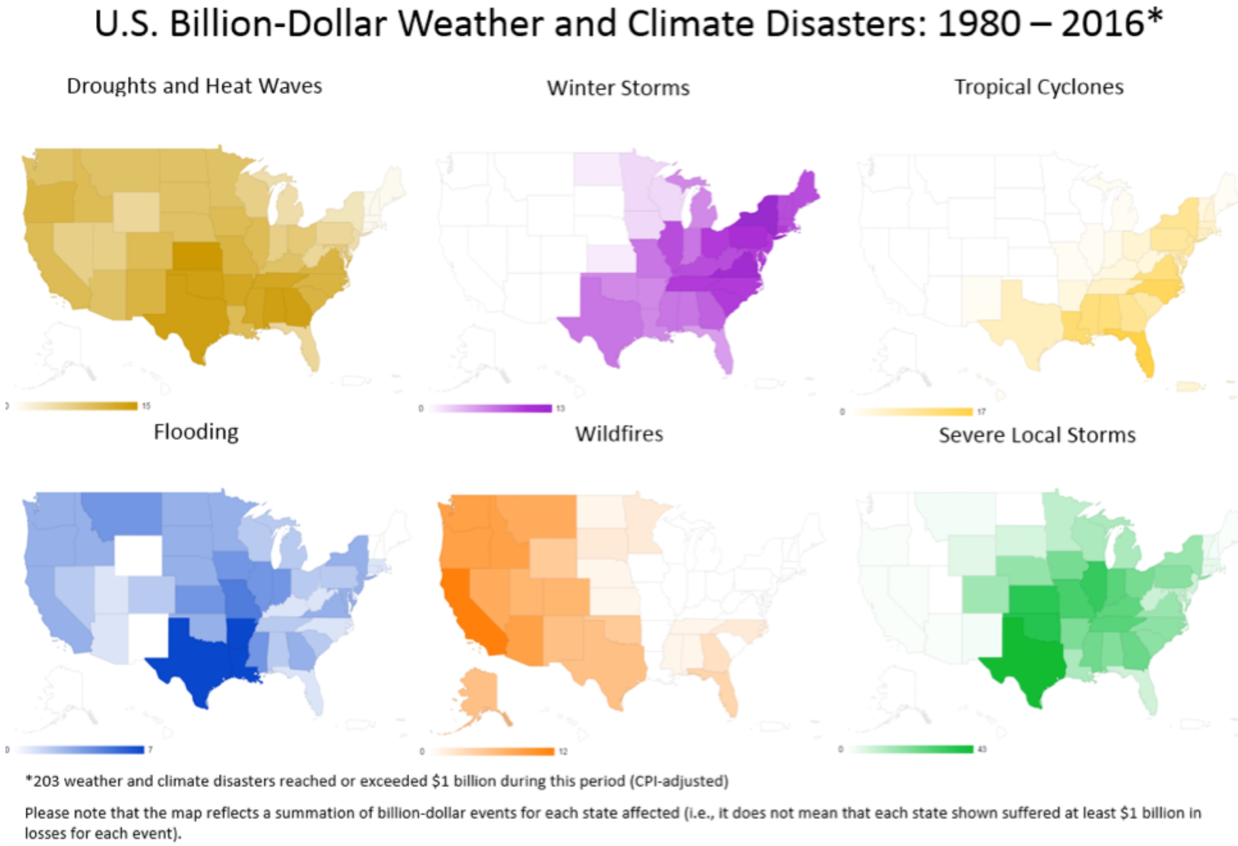



**Figure 1. U.S. Billion-Dollar Weather and Climate Disasters: 1980-2016 (Smith, 2017)**

There are multiple sources of flooding and levels at which their severity is categorized. Flooding can occur from rivers, drainage systems, sheet flow, tides or storm surge. Further, any individual or property can have exposure to multiple flood sources.

**River flooding** occurs when its flow can no longer be contained within its channel and the river overspills its banks. Flooding is a natural reality for many rivers and is instrumental in shaping and reshaping the water body and supporting ecosystems, such as wetlands and bottomland forests adapted to intermittent inundation.

**Drainage systems**, in the context of FRM, consist of infrastructure such as inlets, storm sewers, ditches, pipe systems, small-scale detention basins and even the roadway as a means of short-term storage/conveyance. This network of infrastructure is intended to remove stormwater from areas such as streets and sidewalks and direct it to receiving waterbodies such as rivers or lakes. These systems can back up if the receiving body has reached its capacity or become overwhelmed by intense rainfall even when the receiving waterbody has not reached capacity if their level of service is insufficient for a given storm.

**Sheet flow** describes runoff that spreads out over the ground surface as it moves to the drainage network or river channel. This type of flooding occurs in flat areas or areas with a shallow slope. Like with rivers, location of sheet flow flooding and its flow patterns may be altered due to anthropogenic changes

**Tidal flooding** is the temporary inundation of low-lying areas along the coast during high tide events. This type of flooding is becoming more frequent and severe as sea level rise associated with climate change, coastal erosion and land subsidence worsens. This type of flooding is also termed nuisance flooding or sunny day flooding.

**Storm surge** is an abnormal rise of water generated by a hurricane or tropical storm that results in water levels above the predicted astronomical tides. This can result in extreme flooding in coastal areas especially when it aligns with the normal high tide.

Rainfall and flood events are not only characterized by source (riverine, sheetflow, etc.) but by severity and chance of occurrence using statistical methods referred to as frequency analysis. Precipitation frequency analysis is used to estimate the probability that a given storm magnitude will be equaled or exceeded in any given year. This probability relates to an average recurrence interval, a nomenclature often used, e.g., 100-yr event. These events are better thought of in terms of annual exceedance probability (AEP) (description in box). The most recent update to the precipitation frequency estimates was released in 2018 in NOAA Atlas 14 Volume 11, with a dedicated report for the state of Texas that includes information relevant to the Houston region (Perica et al., 2018).

There is an important distinction between the precipitation frequency analysis and flood frequency analysis. The flood level refers to a streamflow that is equaled or exceeded while the storm level refers to a rainfall amount that is equaled or exceeded. Furthermore, the 100-year storm does not always result in a 100-year flood event (or any other frequency level). Many factors play into the translation of precipitation to water-surface elevations in a stream. This is studied by hydrology and hydraulics.

**ANNUAL EXCEEDANCE PROBABILITY (AEP)**
The probability that a given rainfall amount accumulated over a given duration will be equaled or exceeded in any given year.

**PRECIPITATION FREQUENCY ANALYSIS**
A technique used to predict precipitation magnitudes and durations corresponding to specific average return periods using observed rainfall data.

**FLOOD FREQUENCY ANALYSIS**
A technique used to predict the flow corresponding to specific average return periods using observed discharge data.

**Table 1.** Storm Frequency Statistics Summary

| Average Return Period [yr] | Annual Exceedance Probability | Probability of Exceedance over 30 years |
|---|---|---|
| 5 | 20% | 99.9% |
| 10 | 10% | 95.8% |
| 50 | 2% | 45.5% |
| 100 | 1% | 26.0% |
| 500 | 0.2% | 5.8% |

**HYDROLOGY**
The science that estimates how much water rainfall produces on the landscape.

**HYDRAULICS**
The science concerned with how water moves through drainage systems and channels.

Understanding the hydrology, or physical processes such as infiltration, runoff, and when rainfall occurs will inform how a watershed responds to an event. The hydrologic response depends on several basin properties including soil moisture conditions, impervious cover, the drainage system, etc. Understanding the hydraulics, or movement of water in drainage systems and rivers, informs the timing and extent of anticipated flooding. These processes can be simulated and better understood by running hydrologic and/or hydraulic models, to evaluate rainfall-runoff relationships and the response of waterbodies, such as rivers, and infrastructure to an event in urban, suburban and rural environments.

It's important to consider the larger context of the floodplain (Fig. 2) when investigating a watershed or sub-watershed and potentially implementing FRM infrastructure. The floodplain includes any land that is covered by floodwater during a flood. Each storm frequency has an associated geographical floodplain boundary and within it a floodway and flood fringe area. The floodway is the channel of a river, stream or bayou and the portions of its associated floodplain that carries the flood discharge while the flood fringe is the portion of the floodplain area outside of the floodway impacted by standing water during an event. The natural state of the floodplain provides several benefits that fall within three broad categories discussed throughout this assessment: water resources, living resources and societal resources. Over time, floodplains develop their own ways to provide flood storage while maintaining a sort of equilibrium that prevents erosion and sedimentation while reducing flood velocities and peaks. Beyond flood risk management functions, pervious floodplains filter nutrients and impurities from runoff, moderate temperature and allow for groundwater recharge. Floodplains support habitat and biological productivity through a high rate of plant growth and provide key breeding and feeding grounds for various aquatic and terrestrial species. Furthermore, the floodplain provides several societal benefits including but not limited to recreation, aesthetics, and overall quality of life (FEMA, 2005).

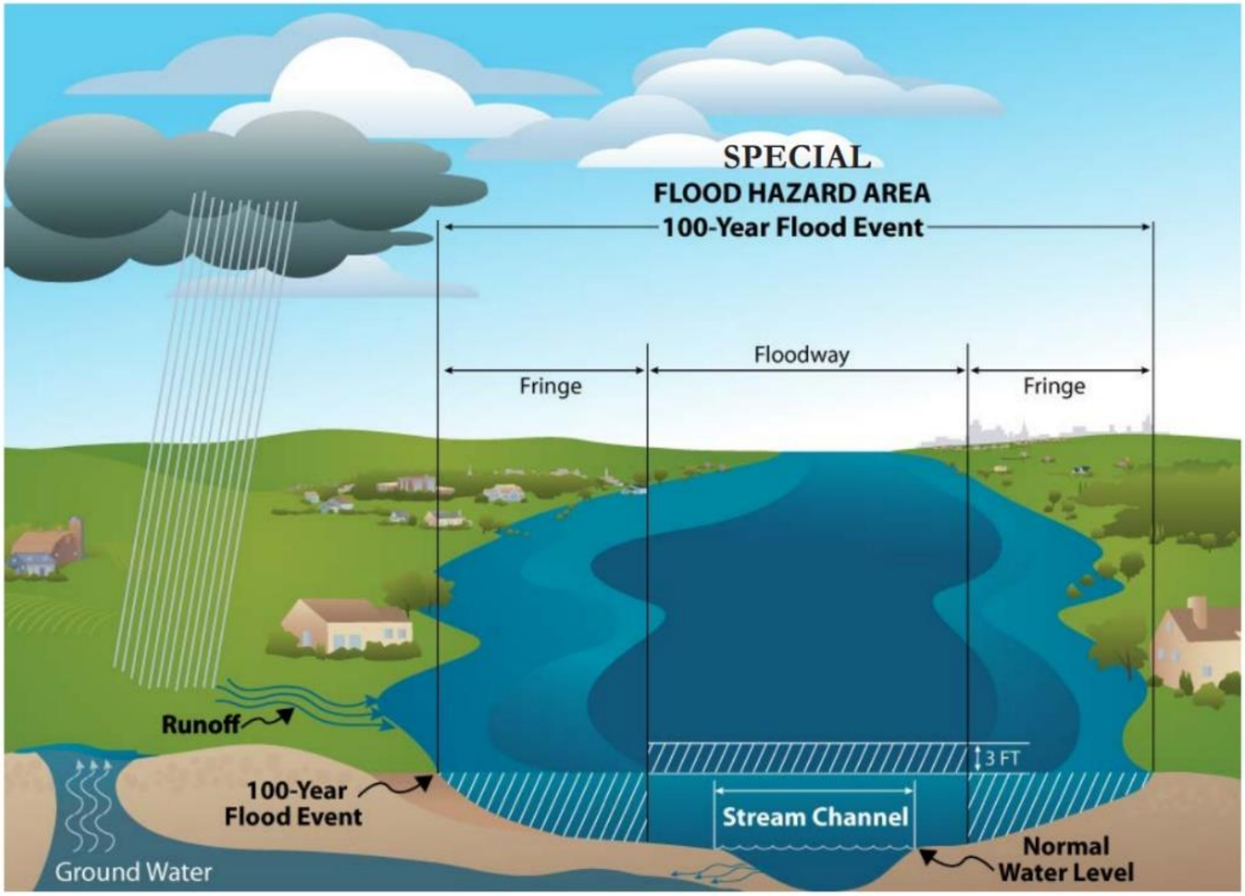



**Figure 2. Depiction of various zones within the floodplain (Source: FEMA, 2021)**

Naturally, moving water from floods alters the floodplain to maintain this dynamic system over time. Anthropogenic changes, such as development in the floodplain, restrictions of the floodplain, channel modifications, or hydrologic changes, can alter the nature of flooding associated with rivers. In recent history, human development has altered this landscape and the dynamics of flooding, putting buildings and infrastructure at risk for periodic flooding. The infrastructure solutions summarized in this appendix aim to manage some of that flood risk, some with lesser impact to the floodplain than others, some capable of higher levels of service and some that require little to no physical infrastructure at all, instead a change in approach to flood risk management that is more aligned with sustainability goals and comprehensive co-benefits in mind.

## 2 Overview of Measure Inventory

There exists a wide array of approaches to reduce flood risk generated by the aforementioned fluvial and pluvial sources, from structural to non-structural methods and from gray infrastructure to green infrastructure solutions. These efforts can be implemented at various scales, from individual households to collective efforts across a region and may be strategically implemented in a layered approach. Formulating an appropriate flood risk management strategy requires an understanding of the many factors that contribute to the level of risk exposure from flood hazards. This includes factors such as rainfall severity and frequency; topography of the surrounding landscape; downstream water levels; soil, vegetation, and groundwater characteristics as well as the size, shape and nature of existing water bodies. An important factor influencing flood risk that is critical to consider when strategizing ways to mitigate that risk is rainfall characteristics of the region.

An initial inventory of broad FRM strategies and approaches relevant to the Houston region was compiled and described based on a literature review and stakeholder input. The suite was organized into categories based on their primary function: conveyance improvements, flow reduction measures, GI, LID and Engineering With Nature (EWN), other structural measures and non-structural measures. Programmatic measures, such as regulatory changes, were included in the non-structural category.

Measures were also categorized based on applicable scale. Figure 4 shows the framework used in compiling measures. Table 2 shows the green and grey features along with a qualitative assessment of co-benefits and adaptive capacity. Co-benefits include the potential benefits beyond FRM for a measure, e.g., social or environmental. The adaptive capacity of a measure is a qualitative assessment of the ability to make changes to a feature as a response to changed future conditions. These considerations, and others, are further elucidated in the following sections.


**Figure 3. Flood risk management measures on the spectrum of "gray" to "green" based on measure characteristics and typical tradeoffs.**

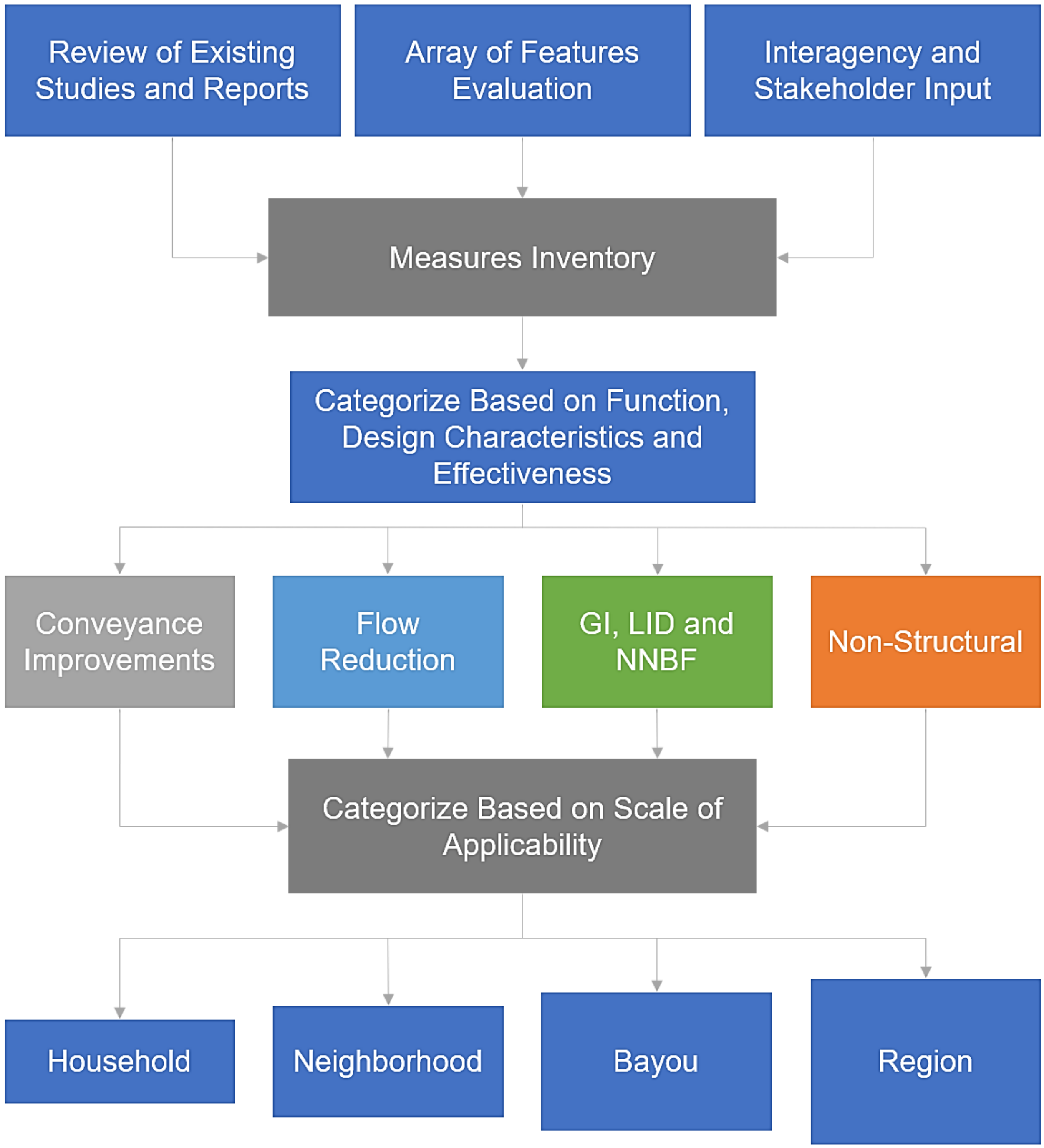



**Figure 4. Measures Compilation Process**

**Table 2. Flood Risk Management Measures and Attributes**

| ***Measure Type*** | **Category** | **Scale** | **Flood Risk Function** | **Co-Benefits** | **Adaptive Capacity** |
|---|---|---|---|---|---|
| *Channel Improvements (Concrete-Lined)* | Structural | Region/Bayou/Neighborhood | Conveyance | Low | Low |
| *Channel Improvements (Grass-Lined)* | Structural | Region/Bayou/Neighborhood | Conveyance | Medium | Low |
| *Channel Improvements (Nature-Based)* | NNBF | Region/Bayou/Neighborhood | Conveyance | High | Low |
| *Tunnels* | Structural | Region | Conveyance | Low-Medium | Low |
| *Roadside Ditches* | Structural | Household/Neighborhood | Conveyance | Medium | Medium |
| *Storm Sewers* | Structural | Household/Neighborhood | Conveyance | Low | Low |
| *Culverts* | Structural | Neighborhood/Bayou | Conveyance | Low | Low |
| *Detention* | Structural | Region/Bayou/Neighborhood | Storage | Low-Medium | Low |
| *Reservoir* | Structural | Region | Storage | None-Medium | Low |
| *Floodwalls and Levees* | Structural | Region/Bayou/Neighborhood | Barrier | None-Low | Medium |
| *Constructed Wetlands* | NNBF | Bayou/Neighborhood | Storage | High | Medium |
| *Bioretention Cells* | LID/GI | Household | Storage | Medium | Medium |
| *Bioswales/Vegetated Swales* | LID/GI | Household/ | Conveyance/Storage | Medium | Medium |
| *Rainwater Harvesting* | LID/GI | Household/ | Storage | Low-Medium | Medium-High |
| *Permeable Pavement* | LID/GI | Household/ | Storage | Low-Medium | Low |
| *Green Roofs* | LID/GI | Household/ | Storage | Medium | Low-Medium |

# 3 CONVEYANCE IMPROVEMENTS

## 3.1 Drainage Channel Improvements

Channel improvement projects are undertaken to increase the amount of flow the drainage network can convey. There are many established design concepts for channel improvements such as concrete lining, grass lining, channel widening and/or channel deepening. *Note:* Nature-Based channel designs are discussed in section 6.1.

*Applicable/Effective Scale:* Channel improvements are typically undertaken over relatively large areas. Smaller projects may be implemented to complement other features or meet a narrower purpose. Channel improvement projects are typically implemented at the county (e.g. HCFCD), state (e.g. TWDB) and/or federal (e.g. USACE) level often via partnerships between two or more entities.

*Design Considerations:* A channel improvement project considers physical features and an array of observed elements that characterize hydraulic and hydrologic conditions. Flow velocity, friction losses, slope, channel capacity and discharge are critical parameters in channel classification and improvement projects.

Physical features of importance include topography, width of available right of way, location of existing channel, adjacent existing structures (e.g., bridges, utility structures, buildings, transportation facilities) and existing hydraulic features such sewer outfalls and tributaries.

Key observed elements related to the hydrologic and hydraulic elements of the channel include precipitation frequency and intensity; flood discharges and volumes; and slope roughness coefficients. Roughness coefficients are determined by channel and overbank features such as vegetation type and channel shape. Channel stability and the presence of aggradation or degradation processes, bank erosion, cutoffs and bar formations are also important design considerations that should be investigated when making channel improvements and selecting the most fitting channel geometry (USACE, 1994).

*Spatial Requirements:* The space required for a channel improvement project varies depending on the design concept. Channel size may be limited by the available right-of-way, resulting in more limited design options if additional real-estate acquisitions become costly. Concrete lined channels require less space than grass lined channels and convey flow to the discharge point quicker but generally result in some form of environmental and/or aesthetic tradeoffs.

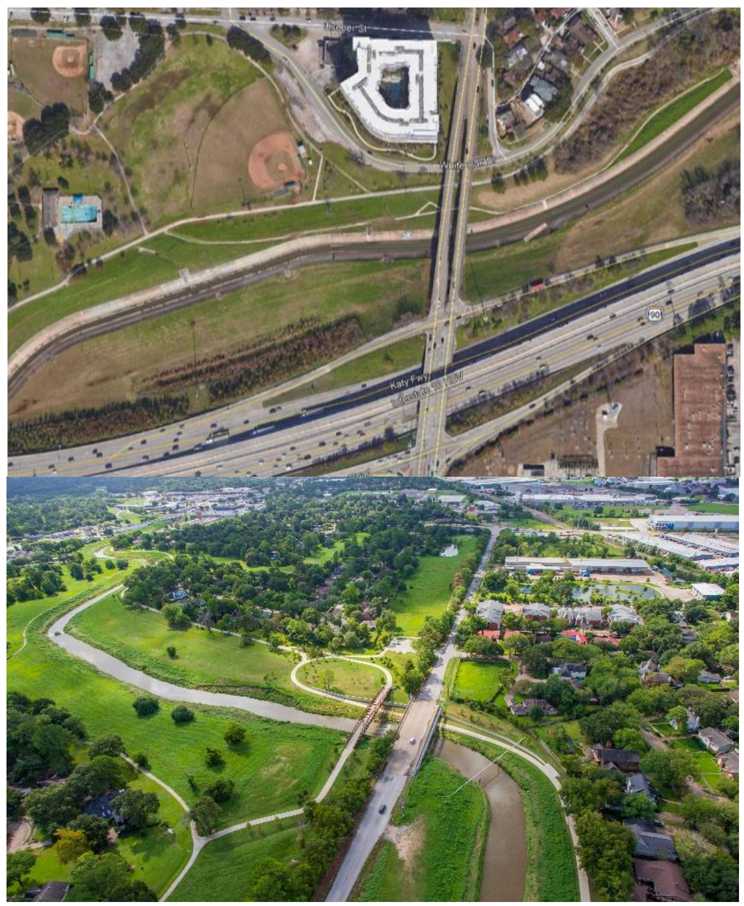


**Figure 5. Concrete-lined (top) and grass-lined (bottom) channel sections along White Oak Bayou in Houston, TX. (Source: Google Earth, 2018 (top); Molly Ross, 2019 (bottom))**

*O&M Requirements:* The O&M considerations for an improved channel depend on the design concept. Across all channel types, channel capacity and conveyance efficiency must be maintained. This may require regular sediment and debris removal. Depending on the size of accreted sediments and debris, heavy equipment may be needed. Concrete-lined channels typically have higher maintenance cost at present compared to other channel types over the course of their design life. The Lower White Oak Bayou Restoration Study investigated the viability of restoring a portion of White Oak Bayou instead of replacing the existing aged concrete lining, shown in Figure 5, that exists along a large portion of the bayou (HCFCD, 2017). Vegetation management may be required depending on the type of channel and typically involves cutting grass, large weeds, invasive shrubs and trees except in selective clearing situations such as nature-based channels. Nature-based channels are discussed further in Section 6 of this appendix.

*Environmental Considerations:* Channelization and associated channel improvements, such as widening, deepening, and armoring, are a major modification of natural form and function that results in habitat simplification and loss of floodplain connectivity. Channel improvements have changed the ability of natural systems to absorb hydraulic energy, filter pollutants, recharge groundwater, and support aquatic, riparian, and wetland-dependent species. Implementation of this kind of measure can also alter instream water temperature and sediment characteristics, as wells as the rates and paths of sediment erosion, transport, and deposition.

A frequent result of channelization and channel modifications is a diminished suitability of instream, wetland and riparian habitat for fish and wildlife. Hardening or turfing banks along waterways has eliminated instream and riparian habitat, decreased the quantity of organic matter entering the aquatic systems, and increased the movement of non-point source pollutants from the upper reaches of watersheds into downstream areas and as far as coastal waters. Typically, there is a substantial displacement of instream habitat due to the magnitude of the changes in surface water quality, morphology (e.g. loss of pool-riffle complexes), and composition of the channel, stream hydraulics, and hydrology. The bank and instream conditions are important habitat characteristics of many aquatic, wetland- and riparian-dependent species and as these conditions depart from baseline conditions the number and diversity of each of the species will decline or in most cases be completely lost or replaced with undesirable species.

Additionally, instream hydraulic changes can decrease or interfere with surface water contact to overbank areas during floods or other high-water events. Channelization and channel modifications that lead to a loss of surface water contact in overbank areas also may result in reduced filtering of pollutants by streamside area vegetation and soils. Areas of overbank that are dependent on surface water contact (i.e., riparian areas and wetlands) may change in character and function as the frequency and duration of flooding change. Loss of connectivity could result in draining of wetlands, oxbow and backwater habitats.

These physical, chemical, and ecological impacts are worsened the more the channel modification deviates from its natural function and would be most evidently in the immediate area of the engineered design, but such effects may also be manifested in reaches upstream and/or downstream of the engineered section, broadening the area of ecological disturbance. Innovative design such as nature-based channels, and to some degree grass-lined channels, that leverage the natural function of the floodplain can reduce these impacts but generally require more space to perform the same flood risk management function. Grass-lined channels may reduce water quality impacts and provide better recreational aesthetics for the community but provide limited habitat benefits compared to nature-based channel designs. Vegetation type and density in the channel as well as the floodplain are important considerations when evaluating the environmental function of the channel and connected wetlands.

*Social Considerations:* The loss of additional natural stream courses and bayous is concerning to many Houstonians because of the significant loss of these natural systems that has already occurred over the last century. Additional losses would result in these systems becoming even more rare than they already are.

As well, the loss of natural systems results in loss of recreational opportunities (e.g. wildlife watching, fishing, paddling, walking, biking, etc.) and a change in the aesthetic environment (e.g. conversion of natural, diverse elements to uniform turf or concrete). Designs can incorporate recreational features such as walk/bike paths to replace some lost recreational opportunities; however, the value of this replacement would be dependent on the personal values of the user (i.e. some wouldn't mind the change in character as long as they still have somewhere to run, but others would find the lack of vegetation and natural form unappealing or uninviting).

*Lead Time Considerations*: Most, if not all channel improvement projects would affect jurisdictional waters of the United States. No matter who implements the action compliance with the Clean Water Act would be required. If USACE is not involved, the action agency would be required to secure a Section 404 permit from the USACE Regulatory Program would be required. As part of the 404 permitting process, the National Environmental Policy Act (NEPA) regulations would be implemented and an Environmental Assessment (EA) or Environmental Impact Statement (EIS) would need to be prepared, which depending on the scale and scope of the design and environment, cultural, and social impacts could take several months to several years. Additionally, the public has expressed concern against the continued alteration of natural systems, so there is a risk that individuals or organized associations could litigate the action that would at a minimum delay implementation, but could stop implementation completely depending on the outcome of the litigation.

If the USACE is involved and a feasibility study is undertaken, compliance with all environmental laws including the Clean Water Act and NEPA would be required and the same risks of litigation are possible. The feasibility study takes approximately three years and authorization of the project would be entirely dependent on Congress's approval in a Water Resources Development Act (WRDA). Once authorization occurs, the project can move to the pre-construction, engineering design (PED) phase which can take another 1-5+ years. After PED, the timing of construction beginning is dependent on when Congress appropriates funding for the Federal cost-share portion of the project, which could occur with the next budget cycle or be several years.

*Reliability:* Channels can achieve a service life of 100-years or more. Channel conveyance improvements are generally reliable if maintenance requirements are met. Sedimentation and/or overgrowth of vegetation into the channel can impact capacity and reduce benefits the channel provides in terms of volume of runoff. Unstable channels may experience erosion, especially during higher flow events, and impact the banks integrity potentially putting nearby property at risk. The ability of channels to drain is impacted by downstream boundary conditions which could change over time (e.g., RSLC).

*Adaptability:* The adaptive capacity of channel improvement projects is typically low, particularly for concrete-lined channels. Increasing channel capacity is often constrained by space. The intrinsic trade-offs between FRM function, environmental function, and other social considerations are involved in the initial construction of the project and are typically not easily amended, particularly in more developed areas.

## 3.2 Tunnels

Tunnels are a larger scale version of the urban storm sewer constructed underground and often referred to as large-diameter deep tunnels. Tunneling options have been investigated by HCFCD and determined to be applicable to the region. Design criteria is summarized in the Phase 1 report as a tunnel with diameter ranging 25-foot to 40-foot and invert depths of up to 150-feet (HCFCD 2019a). Included in the report is a summary of some examples of existing tunnels constructed in

North America as shown in Table 3. The detailed report summarizes those listed most similar to conditions present in the Houston region (HCFCD, 2019b).

**Table 3. List of Previously Constructed Tunnels (HCFCD 2019b)**

| *Project* | Location | Year | Length (miles) | Finished Invert Depth (ft) |
|---|---|---|---|---|
| *Alaskan Way Tunnel* | Seattle, WA | 2019 | 2 | 52 |
| *Port of Miami* | Miami, FL | 2014 | 1.5 | 40 |
| *Mill Creek Tunnel* | Dallas, TX | 2018 | 5 | 35 |
| *Blue Plains Tunnel* | Washington, D.C. | 2011 | 4.6 | 26 |
| *San Antonio River Tunnel* | San Antonio, TX | 1998 | 3.1 | 24.3 |
| *San Pedro Creek Tunnel* | San Antonio, TX | 1987 | 1.1 | 24.3 |
| *Northeast Boundary Tunnel* | Washington, D.C. | 2017 | 5.1 | 23 |
| *Anacostia River Tunnel* | Washington, D.C. | 2015 | 2.4 | 23 |

*Applicable/Effective Scale:* Tunnel systems are mega-infrastructure projects applicable on a regional scale. This stormwater management option has been closely investigated to apply in the greater Houston area to mitigate impacts to the major bayous for storm frequencies up to and exceeding the 1% storm (HCFCD, 2019a). Projects of this scale are typically implemented through a partnership of regional bodies, such as federal agencies and county drainage districts.

*Design Considerations:* Investigations for large scale tunnel systems should include hydrologic/hydraulic, geotechnical and environmental conditions. Soil properties, groundwater conditions and fault zones should be evaluated when considering large scale subsurface tunnel conveyance systems. Obstructions, such as wells, should be avoided when routing the tunnel and use of the public right-of-way maximized as with most flood risk management infrastructure projects. The size of the tunnel may also be limited by the available boring technology at the time of construction. The design should take into account the most common floatables (e.g. bags, bottles, cans, and wood) and debris (e.g. tires, household goods, shopping carts, etc.) that could enter the system and design accordingly to filter out certain sizes.

Considerations when designing the measure should include disposal of sediment. Limited areas are available, particularly in the more urbanized areas, so the disposal site location could affect transportation costs and delivery times, as well as total emissions of the project (Clean Air Act compliance).

Tunnels can be dedicated to flood risk and stormwater management but may also serve water resource recovery purposes. In addition to conveyance and storage capacity, tunnels should be designed in consideration with water reuse facilities, pump and lift stations, dams and reservoirs, intakes and outfalls, drop shafts and diversion structures and small scale stormwater management including but not limited to green infrastructure (WEF, 2018).

*Spatial Requirements:* Tunnel systems are typically 10-foot or larger in diameter and designed to quickly convey a large amount of flow to the designated outlet (WEF, 2018). Since the design is primarily underground, the only surface needs would be at one or more intake locations, at the outfall location, and any access points, each of which typically require a small surface area (1-10 acres). Subsurface easements would need to be secured for the entire length of the project.

*O&M Requirements:* Passive conveyance, intake structures and general operation of the tunnel system should be maximized to minimize operations and maintenance costs. Tunnel access is an important consideration for O&M. While they are considered low maintenance, liners and all mechanical components (e.g. pump stations, gates) should be regularly inspected for signs of corrosion. Additionally, during storm events debris and floatables may need to be removed from gates or filters to prevent backup and after the event additional clean up at each of the structures, within the tunnel, and at the discharge site may be necessary.

*Environmental Considerations:*
Environmental considerations with tunnels are primarily associated with the discharge of stormwater into the receiving water body. Short-term changes in water quality during and after storm events would result in temporary, concentrated, increases in temperature, nutrients, freshwater, and pollutants and bacteria levels and decreased dissolved oxygen at the discharge site and downstream to the point where stormwater dilutes with the receiving water body and reaches equilibrium. This water quality degradation could contribute to the impairment of use and exceedance criteria included in state water quality standards and cause nuisance algal conditions including surface scum and odor problems during and after stormwater discharge. Depending on the frequency, volume, duration, and location of discharge these water quality changes could result in short-term disruptions to the aquatic environment or be longer term, resulting in permanently degraded conditions.

Additionally, stream channel erosion and channel bank scour are likely due to the volume and velocity of water being discharged. To mitigate this impact, armoring may be necessary which would permanently degrade the discharge site by removing the natural characteristics of the channel such as sediment bottoms and instream cover. Channel scour and bank erosion could be also observed for significant distances downstream.

Both water quality and water quantity impacts combine to impact aquatic and riparian habitat downstream of the discharge site. Higher levels of pollutants, increased flow velocities and erosion, alteration of riparian corridors, and sedimentation associated with storm water runoff negatively impact the integrity of aquatic ecosystems. These impacts include the degradation and loss of aquatic habitat, and reduction in the numbers and diversity of fish and macroinvertebrates.

Direct surface impacts could include loss of habitat in the immediate vicinity of the intake and outfall structures. Siting these structures away from wetlands and riparian areas would preserve the function of these habitats and avoid the costs of mitigation. If sensitive habitats cannot be avoided, reducing the long-term footprint of the structure to the smallest extent possible is recommended.

*Social Considerations:* This measure can reduce the flooding risk for a significant number of people without the land acquisition needs allowing individuals and businesses to stay where there are and not incur the economic and social costs relocation. Aesthetic and recreational opportunities may be temporarily to permanently diminished at the discharge site and downstream depending on the duration and scale of the impacts at the discharge site and downstream.

*Lead Time Considerations*: Because this measure has not been implemented in the Houston area or areas with similar geologic features, significantly more study on the design, potential impacts, and long-term operational risks may be required before designers and decision-makers are comfortable with recommending a project.

From an environmental compliance perspective, compliance with the Clean Water Act would most likely be require because discharge of flood waters and construction of intake and outfall structures would most likely occur in jurisdictional water of the US. As stated for the channel improvements, if USACE is not involved, the action agency would be required to secure a Section 404 permit from the USACE Regulatory Program and NEPA and public review would be required. Depending on the scale and scope of the design and environmental, cultural, and social impacts could take several months to several years. The likelihood of litigation is lower than several of the other measures but has not been eliminated particularly if downstream impacts are significant.

Compliance with the Clean Water Act would also require a water quality certification from the state for discharge of stormwater under Section 401 of the Clean Water Act indicating that the discharges would not cause the discharge site to exceed state water quality standards. This process can take several months to years and may require significant modeling of dilution rates and contaminant levels, testing of baseline conditions and monitoring after completion.

Similar to the channel improvements, if the USACE is involved, construction may not begin for several years to several decades after the initial start of a feasibility study. The length of time is entirely dependent on authorization and appropriation by Congress and if any litigation actions are pending.

*Reliability:* Tunnel systems can achieve a service life of 100-years or more. The ability of the tunnel to effectively drain can be impacted by downstream boundary conditions similarly to channel conveyance.

*Adaptability:* The adaptability of tunnel systems are generally low due to the nature of their subsurface construction.

## 3.3 Roadside Ditches

**Figure 6. Roadside ditch in Dayton, TX 9/21/`9, post-TS Imelda (Source: Molly Ross)**

Roadside ditches are generally small, shallow depressions used to temporarily store and convey runoff from contributing impervious areas. They typically have some maintained vegetation and are located between roadways and adjacent properties.

*Applicable/Effective Scale:* Roadside ditches may be applied from household to neighborhood scales and often tie in to the larger bayou and regional drainage systems. They may be implemented by individuals or at the community, city and/or county level.

*Design Considerations:* Important design considerations include the runoff volume, velocity and intensity as well as the physical characteristics of the location such as soil type and proximity to roadways. The slope of these features is a key consideration due to its impact on soil stability and roadside safety. Roadside ditches are typically connected via culverts or storm sewer when a space constraint is encountered and the capacity of these transitions should be consistent with the capacity of the ditch.

*Spatial Requirements:* Roadside ditches generally require more space than storm sewers, for example, due to their open nature and slope requirements, resulting in larger areas to achieve the same level of service, to ensure roadside safety.

*O&M Requirements:* Roadside ditches typically require vegetation maintenance and regular debris removal.

*Environmental Considerations:* In general, roadside ditches do not pose significant environmental concerns or provide many benefits. Roadside ditches can be modified to provide some water quality treatment to remove or reduce pollutants that are washed off the roadways or from nearby properties. This can be achieved by incorporating the principles of bioretention into the design which involves routing stormwater through dense, herbaceous vegetation, spreading the flow as much as possible, avoiding steep bank and instream slopes to slow the flow, and providing organic and amended soils to facilitate treatment through infiltration.

*Social Considerations*: Roadside ditches do not present any unique social impacts that should be considered during design or implementation.

*Lead Time Considerations*: This type of measure does not require a significant amount of lead time and in many cases is limited to local permitting requirements. Some existing roadside ditches may be considered a jurisdictional water of the US, so modifying existing ditches may require securing a section 404 permit of the USACE Regulatory Program. This effort would be much less intensive than other measures and would have minimal likelihood of public controversy or litigation.

*Reliability:* Roadside ditches typically achieve lower levels of service. For example the City of Houston requires a 2-year level of service (COH, 2020). They may be used to convey flow to larger FRM infrastructure such as channels.

*Adaptability:* Roadside ditches are moderately adaptable if space allows. They are generally considered a low-cost, low maintenance stormwater drainage measure.

## 3.4 Storm Sewers

A stormwater sewer is flood risk management infrastructure utilized to drain and convey runoff from impervious surfaces, such as paved streets, parking lots and buildings, to larger drainage infrastructure and/or natural pathways such as channels and bayous. Storm sewers are underground conduits and typically associated with a curb and gutter systems with various inlet points and a common outlet.

*Applicable/Effective Scale:* Storm sewers are typically implemented on a small household or neighborhood scale and tie in or exist as a part of a larger storm sewer network in urban settings. Storm sewers are typically implemented and managed by the city or county.

*Design Considerations:* Key design considerations for storm sewers include hydrologic (precipitation volume and intensity) and hydraulic (velocity, water surface elevations) properties relevant to level of service goals, geotechnical characteristics of the intended location, construction material, sewer network tie-in requirements and outlet conditions. In the City of Houston, newly constructed and redeveloped storm sewers are required to achieve a 2-year level of service (COH, 2020).

*Spatial Requirements:* Storm sewers and storm sewer networks are appropriate for urban settings constrained by space. They are typically constructed underground, below sidewalks, streets, and other infrastructure throughout urban environments.

*O&M Requirements:* Regular inspection and removal of debris is required to maintain the capacity and function of storm sewers. Any mechanical components, outlet or connecting structures should be inspected regularly.

*Environmental Considerations:* Because these structures are constructed underground, environmental concerns are primarily associated with the discharge site. Storm sewers can transport concentrated levels of debris, chemicals, sediment and other pollutants into the receiving water body, which may be used for recreational, support fish and wildlife, or provide drinking water.

*Social Considerations:* Modifications to existing storm sewers can involve significant temporary disruptions to communities including changes to traffic patterns, decreased access to businesses and increases in noise and decreased aesthetics. While these are temporary impacts lasting only as long as the construction is ongoing, the disruption can be significant. When possible, modifications should be coordinated to occur when other road or utility maintenance is needed to limit the extent of disruption.

*Lead Time Considerations*: The main permitting action for storm sewars is at the state and local permitting level. Compliance with the Clean Water Act and the National Pollutant Discharge Elimination System (NPDES) program would be required since this type of action is considered a Municipal Separate Storm Sewer System (MS4). It may take several months obtain permit coverage for the stormwater discharges and is entirely dependent on the type of permit required which is based on the size of the service area, location of discharge, and public commenting period required in regulation.

*Reliability:* Storm sewers are typically designed to achieve lower levels of service than larger infrastructure projects. They are generally reliable in achieving the intended levels of service assuming maintenance requirements are met and conveyance isn't constrained by the outlet.

*Adaptability:* The adaptability of storm sewers is generally low due to the underground, concrete nature of this type of FRM infrastructure.

## 3.5 Culverts

Culverts allow water to flow under roads, trails or similar obstruction from one side to the other. They are typically embedded in the ground and often used to relieve drainage of ditches and/or detention areas. Culverts can be bridge-like structures that allow pedestrian and/or vehicle traffic. They vary in shape, size and material from box to round in shape and can be constructed out of concrete, steel or plastic.

*Applicable/Effective Scale:* Culverts are typically installed in areas where space constraints exists or drainage relief is needed. They are typically implemented on a city and/or county level but may also be installed by individuals and/or developers.

*Design Considerations:* The expected flow volume, velocity and frequency of precipitation/flow from the contributing drainage area is an important design consideration when determining the size, shape and material of a culvert. Existing and post-installation hydraulic conditions are important to ensure slope, bank and/or soil stability as well as scour. The location of the culvert, such as under a roadway crossing, may influence the design of the structure.

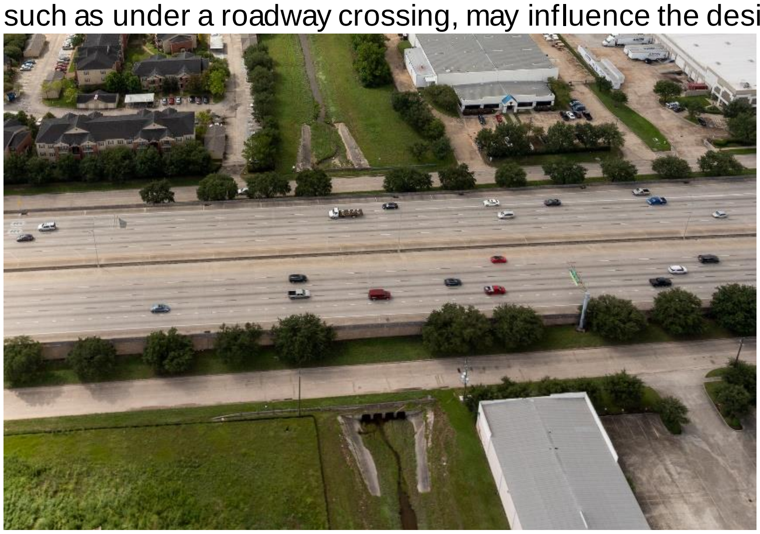


**Figure 7. Culvert transition from roadside ditch under Beltway 8 in Houston, TX (Source: Molly Ross)**

*Spatial Requirements:* Culverts are typically installed in locations constrained by space as they can be installed underground and convey the same volume of flow with a lesser footprint than a roadside ditch, for example.

*O&M Requirements:* Regular inspection as well as debris and/or sediment removal is recommended to maintain the intended level of service of culverts. Vegetation management and roadway inspection may also be required depending on the location.

*Environmental Considerations:* Culverts do not present any unique environmental impacts that should be considered during design or implementation.

*Social Considerations:* Culverts do not present any unique social impacts that should be considered during design or implementation.

*Lead Time Considerations*: Permitting of culverts is primarily at the state and/or local level and can take from weeks to months to secure, if needed.

*Reliability:* Culverts can achieve a service life of 100-years. The City of Houston requires that drainage analysis be performed on this type of infrastructure from the 2-year and 100-year storms (COH, 2020).

*Adaptability:* The adaptability of culverts is typically low due to the nature of construction. Increasing the capacity of a culvert requires the removal of the existing culvert from the sub-surface and reinstallation of a newly crafted piece of infrastructure.

# 4 FLOW REDUCTION

## 4.1 Detention

Detention measures are intended to reduce the flow in the drainage network. Detention generally falls in two groups: (1) detention constructed to mitigate impacts of development, and (2) detention meant to take flow off drainage channels (fig. 3). Mitigation detention is typically constructed as ponds adjacent to the site being developed. Mitigation detention can be constructed underground in more urban areas where space for a pond is limited. The premise of detention in association with development is to hold water where it falls and cause no peak flow impacts.

**Figure 8. Residential detention pond post-TS Imelda in Houston, TX (Source: Molly Ross).**

Detention in the drainage network can be inline or offline. Inline detention is not separated from the main channel and instead is located on the main stem of a watercourse. Inline detention often takes the form of an enlarged channel section designed to hold additional runoff. Offline detention, by contrast, is separated from the main channel and typically connected by a weir or similar diversion if utilized for peak flow reduction in a main watercourse. The diversion moves flow from the channel to the detention pond and returns after the water-surface falls in the channel through a culvert.

Detention basins can be dry or wet, with dry detention basins holding water only during storm events and for a short time after. Wet detention basins contain a permanent impoundment of water with flood storage volume provided above the permanent water surface.

Natural and nature-based detention can be achieved in multiple ways for wet or dry and online or offline measures. Traditional detention ponds are typically limited in terms of environmental benefits (i.e. wildlife habitat) but can be implemented in a way that they compliment the surrounding environment. Their design can be optimized to provide multiple ecosystem benefits and services if native vegetation and no-mow landscaping is implemented. The natural hydrologic function of the area can be mimicked when planning the detention location, for example by providing storage in natural valleys. Additionally, ponds may not have to be graded to geometric shapes or cleared of natural forest to provide storage. Preserving existing wooded areas surrounding detention ponds (wet to dry) may compliment co-benefits of this FRM method. Constructed wetlands are discussed further in Section 6.

_Applicable/Effective Scale:_ Detention works at many scales and the scale of implementation is suited to the scale of the problem. On-site LID features are a type of detention (more in a later section) on a small scale; detention can also be large and regional scale as summarized in the following reservoir subsection. Detention is typically implemented by entities at various levels of local government (HCFCD, COH) or by private developers to meet detention requirements.

_Design Considerations:_ The design considerations for a detention basin are dependent on the purpose of the detention – development mitigation or flow reduction along a stream. Detention basins constructed for development mitigation must follow the regulations implemented by the appropriate authority. Those regulations vary depending on the authority and typically depend on the size of the development. Ultimately the goal of mitigation detention should be to have no additional peak runoff from a site than in natural conditions. The City of Houston requires new construction provides protection from structural flooding for the 100-year storm event (COH, 2020).

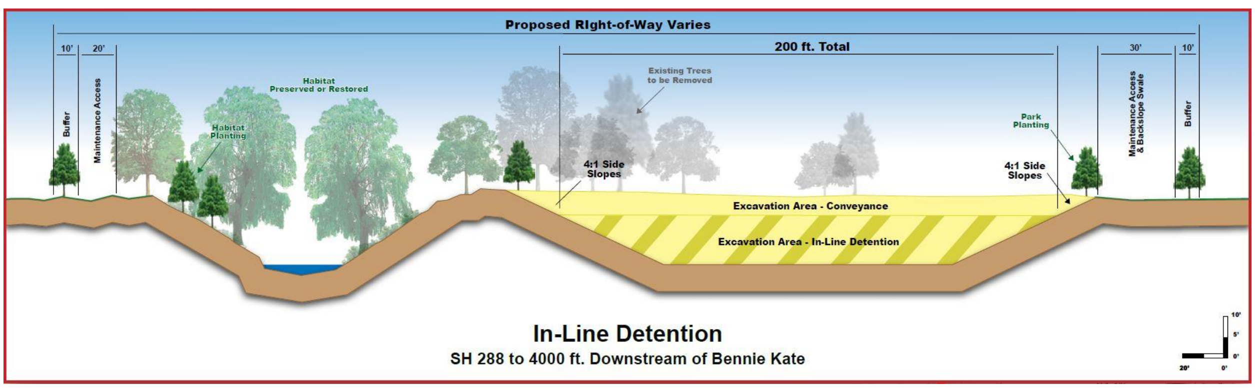



**Figure 9. Clear Creek Federal Flood Risk Management Project cross section with inline detention example (Source: HCFCD, 2020).**

Detention design for flow reduction in streams is dependent on whether the basin is inline or offline (e.g. Figure 9), though either is generally a candidate to be considered. In general, an offline detention basin is a more efficient use of space since it can be optimized to be utilized during only high flows. Inline detention basins by contrast begin filling early in a rain event and therefore do not reduce the peak flow for a large event as much as a similar sized offline detention basin.

Basins are often regional to mitigate peak-flow impacts associated with channel improvement projects. A standalone channel improvement plan increases conveyance and flows which are typically mitigated with a complementary detention project.

*Spatial Requirements:* The amount of space and depth required for a detention basin depends on the scale at which it's implemented and the target storage volume. Depth is typically limited by groundwater conditions or depth of the adjacent stream and informs the necessary surface area to meet storage volume requirements. Alternative methods to surface detention, such as underground detention, can be utilized beneath a parking lot or parking garage where surface space is limited.

*O&M Requirements:* Regular inspections should be performed to ensure adequate performance of the detention basin. Typical maintenance includes vegetation management (mowing, trimming), clearing trash and debris, excess sediment removal and slope stability. Maintaining functionality of mechanical elements and inflow / outflow pipes is important to preserving the overall performance of the detention basin when applicable.

*Environmental Considerations:* The primary purpose of most traditional detention and retention basins in urban developments has been to reduce peak flows during significant storm events. However, these basins provide little benefit to the environment. Loss of habitat is the most evident loss of ecological value with construction of the site. Other common problems include sediment and debris collection and clogging of low flow orifices, stagnant water and mosquito issues.

Traditional detention and retention basins are assets that can be transformed or retrofitted effectively to address these problems and realize other benefits. The design and/or retrofit of existing basins should consider ways to slow down stormwater runoff to provide the time and space for the water to infiltrate into the ground and filter out pollutants and sediments, while providing necessary flood protection, and ways to increase wildlife habitat. Examples include removing or not using a concrete pilot channel, performing minor excavation and grading, and installing influent sediment forebays, enhanced filtration, infiltration trenches, and native plantings.

*Social Considerations:* Detention generally has low aesthetic appeal and community use benefits. Designs should incorporate recreational amenities such as walk/bike paths, ball fields or playgrounds (for detention), fishing piers (for retention ponds), parking areas, sanitary facilities, etc., where possible and consistent with the level of use desired. The aesthetic value of the detention or retention pond can be increased by incorporating irregular shapes, varying elevations and slopes, and various textures from differing vegetation types. At a minimum, flow in retention ponds should be considered so that water does not become stagnant and an eyesore.

*Lead Time Considerations*: The permitting of detention and retention ponds is entirely dependent on the scale and location of the project. Small offline projects incorporated into a residential development would need to secure local building permits; however, inline detention or those of greater scale would most likely need to comply with the Clean Water Act and all the regulations that apply to securing a permit from the USACE regulatory or civil works process. In general, permitting of the projects can take several months to several years depending on the location, complexity, and design; however, the likelihood of litigation is usually much lower than other more intensive measures.

*Reliability:* Detention systems can achieve a service life of 100-years or more.

*Adaptability:* The adaptability of detention is typically low. Increasing detention capacity requires widening or deepening of the basin. This is typically constrained by space. As with other larger features, initial construction is the time to consider all tradeoffs.

## 4.2 Reservoirs

Reservoirs are large detention areas suitable to meet various infrastructure objectives, often multiple, including flood risk management, water resource management, hydroelectric power and/or recreation. Flood risk management reservoirs capture runoff from upstream and releases it from storage at a controlled rate.

Examples of reservoirs in the Houston region include Addicks and Barkers reservoirs and Lake Houston. Addicks and Barker are both dry reservoirs, meaning a conservation pool is not maintained to allow for maximum storage availability during a storm event. They are operated by USACE Galveston District and discharge into Buffalo Bayou. Alternatively, Lake Houston reservoir maintains a conservation pool and is utilized for municipal, industrial and irrigation water supply purposes. Lake Houston is owned by the City of Houston and operated by the Coastal Water Authority. Both of these regional examples provide recreational opportunities for the public while meeting primary objectives. The following reservoir considerations and characteristics are framed in terms of flood risk management for the purposes of this assessment.

**Figure 10. Addicks Reservoir 9/21/19, post-TS Imelda, in Houston, TX (Source: Molly Ross).**

*Applicable/Effective Scale:* Reservoirs are large-scale projects that aim to mitigate flood risk on a regional scale when local flood risk projects, such as channelization, prove to be less economical comparatively for the same level of protection. The probable maximum flood (PMF) is often considered when designing a reservoir. Due to the scale of , this type of FRM measure is typically implemented through partnerships between city, county, state and/or federal entities.

*Design Considerations:* Design considerations for reservoirs include storage capacity, elevation, geotechnical properties of reservoir, containment design (levee / floodwalls) and outlet structures. Each of these features have specific design considerations. The levee and/or floodwall design considerations are summarized in section 5.1. The capacity and reservoir pool elevation, if applicable, depend on design storm characteristics and intended level of protection. Design considerations for the outlet structure include outflow location, anticipated volumes and limitations in terms of the downstream boundary conditions. Downstream boundary considerations include channel capacity, local runoff and non-damaging release rates. These considerations are typically influenced by not only storm characteristics but also regulations, such as flow requirements at observable locations, environmental flow rates and/or structure exposure downstream.

If considering excavating an existing reservoir to increase capacity, the amount of material in relation to transport and disposal location needs should be considered. Significant quantities can pose challenges to high volumes of daily truckloads, long trips through traffic to disposal sites, and limitations to existing disposal sites and potentially the need for new disposal sites.

*Spatial Requirements:* Reservoirs are typically regional projects that require a large amount of space. Addicks reservoir is approximately 26.2 square miles and Lake Houston is approximately 18.5 square miles in area.

*O&M Requirements:* *O&M Requirements:* Reservoir operations depend largely on their purpose. A water management plan is typically developed and followed that outlines the appropriate release rates, conditions and other applicable procedures. To meet flood risk management objectives, operation plans consider expected storm severities, upstream watershed conditions, downstream watershed conditions, risk exposure and dam and levee safety protocol. The levees and/or floodwalls typically require regular inspection to confirm integrity of the structures. Siltation and sedimentation are considered when ensuring the intended capacity of the reservoir. Any mechanical parts, such as outlet gates, typically have a set of unique maintenance requirements to certify their successful operation. O&M requirements for each component of a reservoir system (levees, gates, etc.) are critical to maintain due to the increased risk incurred by downstream communities if failure were to occur.

*Environmental Considerations:* There is growing concern that dam projects cause irreversible environmental change, which is often complex, multiple, and essentially negative. Impounded water significantly alters the natural functioning of the entire ecosystem. Because of the extent of area that would be required to construct a reservoir, a new reservoir would most likely be constructed in the rural parts of the upper watersheds resulting in loss of native prairies and active agriculture and ranch lands. Impounding a naturally flowing waterway can have significant ecological consequences including but not limited to: affecting the abundance and diversity of physical habitats particularly some of the most sensitive habitats such as backwater/slack habitats, riparian areas, wetlands, bottomland hardwood forests, and native prairies; reduction and/or isolation of species; interruption of migration corridors; interruption of nutrient exchange between ecosystems; change in water quality; erosion of soils; alteration of channel geomorphology and sediment transport; significant reduction or elimination of long-term channel forming processes (channel migration and avulsions, formation of side channels, bars, and wetlands, etc.) dependent on higher peak flows and sediment inputs; changes in micro-climate or even regional climate if of significant size. Reservoirs, however, do provide some ecological benefits including filtering pollutants from released water and an increase in some desirable habitats.

These effects are most prominent in the area of inundation; however, effects can be observed over a significant distance downstream. The scale of the impact is also affected by the design and operation of the reservoir. A dry reservoir would result in conversion of existing habitats to other habitat types, but the value of the conversion would be dependent on the species of concern. When considering the operations of the reservoir, consideration should be given to how downstream peak flood elevations and frequencies can continue to support downstream channel forming processes and how overbank flow can support existing sensitive habitats while balancing the need for risk reduction to life and property.

_Social Considerations:_ Large dams can have significant consequences on people's lives and livelihoods, which include controversial issues such as displacement and resettlement. Of particular concern in the Houston Metro study area is the loss of agriculture and ranching lands. The study area has already seen a significant decrease in this livelihood that would be further restricted through construction of a new reservoir. As well, cultural resources such as historic sites, burial grounds, traditional cultural places, or artifacts may be permanently lost during or damaged during inundation periods.

Construction of a new reservoir preserves open space and creates new opportunities for recreation. Because of this, a new reservoir may stimulate growth in areas near the reservoir potentially shifting the density of populations within the watershed. Additionally, a new reservoir could induce development within the floodplains of currently undeveloped areas The lower frequency of flooding could potentially provide economic incentive for the addition of inventory to the existing floodplain (i.e. lower water elevations means construction of the first floor would not need to be as high and cost less than under the existing condition).

_Lead Time Considerations_: Permitting of a new reservoir can take several years to many decades depending on the scale of the actions and has a high likelihood of litigation due to the significant impacts and controversy between proponents and opponents of dams. Numerous federal, state, and local permits or reviews are required for construction of a new reservoir in Texas including compliance with environmental and cultural resource laws and dam safety; however, compliance with the Clean Water Act is generally considered the critical path schedule item. Several factors affect the schedule relating to acquiring necessary approvals, such as extent of recent applicable data and the proposed project's potential effects, the need for additional field surveys, the type of permit being sought, the development and acceptance of mitigation plans, the requirements for public notice, public comments, permit contests and review by other federal agencies as well as procedural requirements of securing the approval.

_Reliability:_ Reservoirs can achieve a service life of 100-years or more. In the case of extreme events, the reliability of reservoirs depends on the balancing of the integrity of the dams and limitations of releasing water from the reservoir which is dependent upon downstream conditions.

Construction of a new reservoir would reduce flood risk, but also results in risk exposure to the nearby population and infrastructure due to the proximity of the dam. This risk can be to the dam itself, it can be risk related to damage that occurs indirectly as a result of a dam failure, and it can be residual risk (risk that remains at any time after all mitigation actions and risk reduction actions have been completed). Some but certainly not all of the potential contributing factors to risk exposure and residual risk include: hazard creep, non-breach dam events, flawed design and construction, overdue maintenance and repair, earthquakes, uncertainties in inundation and/or forecasting models, extreme weather, and upstream dam events. As the structure ages, the potential for increased risk goes up.

*Adaptability:* While reservoirs can achieve a high service life, adaptability of this FRM method is typically low. Expanding the capacity is achieved through acquiring and damming additional land area, which is often constrained by real estate. Excavating a deeper reservoir is an option to increase capacity, but is often constrained by geotechnical and/or groundwater properties.

# 5 OTHER STRUCTURAL MEASURES

## 5.1 Floodwalls and Levees

Levees (typically earthen embankments) or floodwalls (typically concrete or steel walls) are measures constructed along the banks or in overbank areas of streams to contain flow along the channel and away from the protected area.

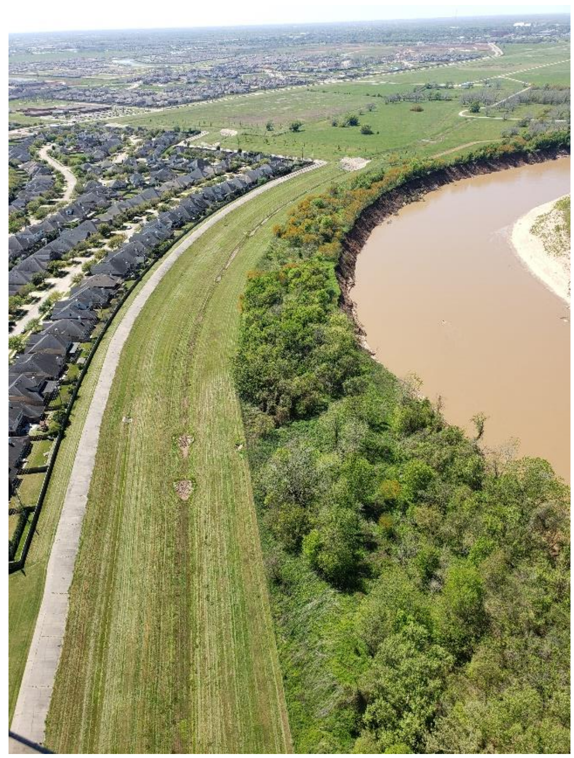


**Figure 11. MUD 121 Levee in Fort Bend County, TX between neighborhood and the Brazos River, looking upstream. (Source: Paul Hamilton)**

*Applicable/Effective Scale:* Floodwalls and levees can be constructed at a variety of scales (see section on retrofits for discussion of small scale implementation), however are generally constructed as large infrastructure projects. The most common applications are to protect areas from large rivers (e.g., Missouri River, Mississippi River) rather than to protect areas from smaller-scale waterways. The best example of levees in the Metro Houston area is along the Brazos River in Fort Bend County. Levees and floodwalls may be implemented at various levels of government including county, state and/or federal or by private developers.

*Design Considerations:* Design considerations include water surface elevation, duration of high water exposure, construction material type, seepage / underseepage potential, compaction and foundation / embankment stability. Wave action and overtopping potential typically contribute to design WSE determinations in coastal settings. Design considerations when joining a levee and floodwall include differential settlement and slope protection (USACE, 2000). Existing topography, historic floodplain maps, existing land use, geomorphology and potential encroachments into the floodplain should also be taken into consideration when considering alignments.

Interior drainage may be impacted as a consequence of installing a levee or floodwall. Detention or conveyance structures may be necessary to mitigate these impacts. Closure structures may be required at road crossings to block flow during events but otherwise allow passage across or over the protection measure. Human intervention and / or mechanical mechanisms may be required to implement temporary closure structures.

*Spatial Requirements:* Large scale earthen levees generally require substantial space, with the associated costs of real-estate acquisition. Floodwalls require less space and may be tied into areas of a protection system where space constraints exist.

*O&M Requirements:* Access roads are typically required to perform inspections and maintenance. Inspections are required annually and maintenance promptly addressed to avoid problems compounding and exponentially increasing failure risk. Erosion, slope stability, debris and animals should be monitored and repaired or removed promptly to avoid degrading integrity of levee systems. Vegetation maintenance is also required and includes monitoring vegetation type, periodic mowing and clearing of brush and trees for levees and removal from both sides of a floodwall to avoid potential damage from roots (USACE, 2006).

*Environmental Considerations:* Levees and floodwalls often lack ecological value except for incidental fish and wildlife benefits derived from borrow pits and collection ponds. The levee embankments provide very little ecological benefit due to the turf nature of the structure. Levees and floodwalls cut off the waterbody from its floodplain and can have significant indirect effects on the habitats and species dependent on the floodplain system on both sides of the structure. The structures alter the natural hydrology of the area by reducing groundwater recharge of aquifers and preventing seasonal overbank flooding that facilitates exchange of sediment and nutrients between the waterbody and floodplain critical to sustainment of various habitats and the species dependent upon them. Siting of the level or floodwall some distance from the channel that allows the watercourse to meander in a more natural manner and occupy some or all of its natural floodplain during high water events should be considered as a way to reduce direct and indirect ecological impacts. However, this will require sufficient land and may require changes in current land uses to ensure both the effectiveness of the strategy and that there is not infrastructure or human uses that are being put at greater risk.

Borrow pits and collection ponds offer numerous opportunities for environmental enhancement. Surface area, depth, and shoreline development are major characteristics associated with fish and wildlife productivity and species diversity where smaller shallower pits provide higher quality habitat as compared to very large deeper pits that may destroy habitat of other types to create relatively abundant and minimally productive open water habitat. Vegetation/open water ratios can be manipulated by excavating borrow pits with a variety of depths that foster or discourage vegetative growth. The design criteria are different for provision of aquatic habitat versus for wildlife and should be considered when designing these sites.

Right-of-ways also provide opportunity for habitat development. Plantings in foreshore areas must have a certain degree of flood tolerance to survive. Less flood-tolerant species with better wildlife value can be used on riverside berms or elevated foreshore areas built up by placement of dredged or excavated material. Although the management of vegetation on levees for wildlife and aesthetic benefits provides significant opportunity for environmental enhancement, such management is often considered to be at odds with structural stability and safety concerns. While it is prudent under the current limitations on available information to err on the side of safety, research into the structural effects of vegetation on levees could produce guidelines allowing a greater degree of environmental improvement while not sacrificing structural integrity.

*Social Considerations:* Levee and floodwall project often lack recreational and aesthetic values when not intentionally incorporated into the design. The floodwall and levee embankments are visually dominating because of their size and location and are often the most barren and unattractive components of the system due to their uniform appearance contributing to monotonous views. To improve aesthetics, consider folding or removable floodwalls, special treatments for concrete or masonry floodwalls, and landscaping designs that employ special vegetative plantings, creative use of excavated material, and natural construction materials. Aesthetic benefits of landscaping are increased by using a mixture of vegetation types, by judiciously selecting species, and by placing and arranging plants for maximum visual effect.

Recreational opportunities are often limited by funding and management of such activities. Borrow pits and collections ponds can be used for fishing, hunting, and water sports including boating if of sufficient size. When designing the sites, safety considerations should be incorporated if recreation opportunities are being incorporated or methods to prohibit incidental use if recreation is not intended. Levee access roads and crowns are easily developed into scenic drives and trails for hiking, biking, or horseback riding. Since not all of these activities are compatible, careful planning is needed to determine local demand and to avoid conflicts among users, as well as associated facilities (e.g. parking areas, picnic areas, benches, sanitary facilities and interpretative centers) that may be necessary.

*Lead Time Considerations*: Levee and floodwall construction is often a major construction project that will require securing a number of Federal, state and local permits and authorizations including compliance with the Clean Water Act. As well, it is also likely that a project will need a FEMA Letter of Map Revision, which signifies changes to flood maps based upon the effects of a project. Compliance will likely take several years and has a moderate likelihood of litigation.

*Reliability:* Floodwalls and levees can achieve a service life up to or exceeding 100-years. They are reliable in maintaining their designed risk reduction level if operation and maintenance is adequately performed.

Levees and floodwalls may reduce the risk of flooding events, but they do not eliminate flood risk. Regardless of how strong, tall, or well-maintained it is, residual risks remain. Floodwater can exceed the levee's designed level for flood hazard reduction whether that is through overtopping due to higher water levels than designed for and/or through collection of water landside of the levees due to inability to effectively drain interior waters in exceedance of the drainage designs. Despite routine maintenance and inspection, breaches are possible and could include part of the levee breaking away, water seeping underneath the levee and weakening the overall stability

*Adaptability:* Floodwalls and levees are moderately adaptable. As the design water surface elevation increases, the structures can be raised to the appropriate height through levee and floodwall enlargements. Enlargements may require reevaluation of foundation and/or embankment stability.

# 6 GREEN INFRASTRUCTURE, LOW IMPACT DEVELOPMENT AND ENGINEERING WITH NATURE

Low Impact Development (LID) is an approach to land management or development that aims to mimic natural processes to manage stormwater as close to its source as possible. By implementing LID principles and practices, water can be managed in a way that promotes the pre-development natural movement of water within a watershed and associated ecosystem(s) by reducing the impact of the built environment. LID practices can be structural or non-structural, with many structural LID measures being synonymous with green infrastructure.

Green infrastructure (GI) refers broadly to a system of engineered-as-natural control measures used to implement LID principles that overlap with respect to the control measures themselves.

A key distinction between the two is the intention for LID to mimic pre-development conditions at specific sites while GI describes an integrated system of natural features and LID practices that provide a wide array of benefits. While GI practices can be implemented without mimicking pre-development hydrology, both concepts can be combined to achieve comprehensive results.

The Engineering With Nature (EWN) initiative defines EWN as "…the intentional alignment of natural and engineering processes to efficiently and sustainably deliver economic, environmental and social benefits…" (USACE, 2021). Essentially, natural and nature-based features can be utilized to deliver a suite of benefits if leveraged strategically. In the context of flood risk management, GI/LID/NNBF aim to meet an FRM goal while minimizing tradeoffs, specifically environmental and social instead of just cost, as much as feasible. While the methodology of implementing each measure varies, they are similar in the overarching philosophies and are emerging alternatives to traditional gray infrastructure from the household to regional scale. Many of these features have seen success in other regions, and some have even been investigated and/or implemented in the Houston region. Further research and guidance are currently being developed, and is still needed in geographically specific locations, to effectively explore and implement in place of well establish infrastructure methods. The "International Guidelines on Natural and Nature-Based Features for Flood Risk Management" are expected to be available to the public in summer of 2021 (USACE, 2021).

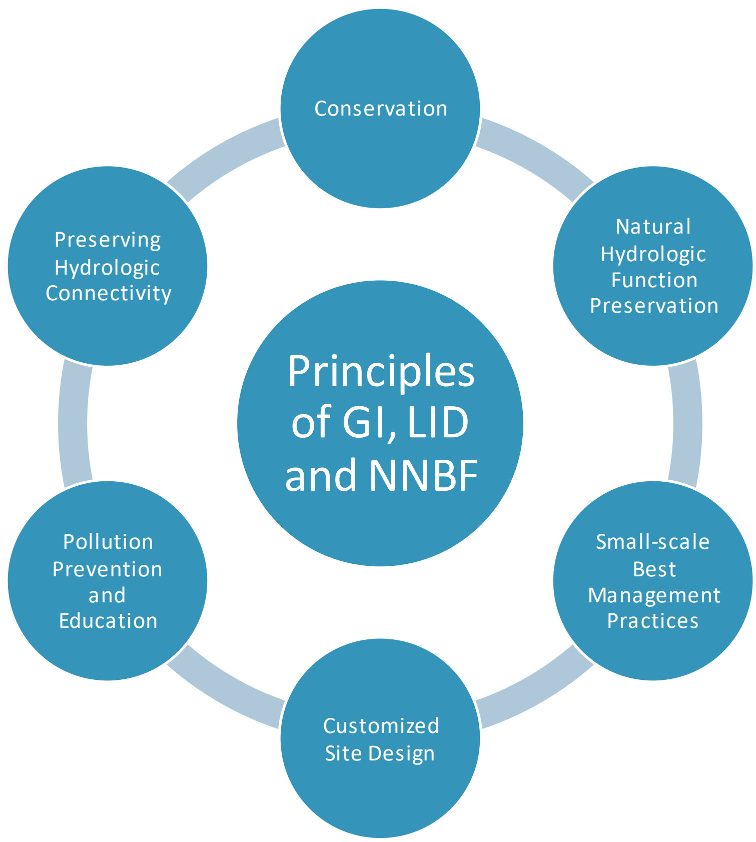



**Figure 12. Principles of Low Impact Development (LID) and Green Infrastructure (GI). Adapted from U.S. Army LID Technical Guide (USACE, 2013).**

There are many ecosystem benefits associated with healthy and extensive urban green infrastructure (e.g. reduced stormwater flows, improved water quality, carbon sequestration, reduced urban heat island effects, biodiversity). Studies also indicate that green urban areas can improve property values and have multiple social, economic, health, and psychological benefits.

However, there are green infrastructure synergies and trade-offs that are not yet well understood. For example, investments in green infrastructure may provide livability and resilience benefits in a neighborhood, contributing to economic renewal and beautification, but they may also drive processes of gentrification and give rise to related social justice concerns.

## 6.1 Nature-based Channels

Nature-based channels leverage the natural hydrologic and hydraulic function of the channel with innovative designs and differ from grass-lined channels in that they prioritize terrestrial and aquatic habitat preservation while delivering flood risk management benefits. While nature-based channels generally require more space to meet the same design requirements as a concrete-lined channel, their design aims to preserve native habitat, habitat connectivity and riparian corridors, provide green space for the community, protect water quality, prevent channel instability and mitigate erosion issues while also serving a flood risk management function. This results in a number of often desirable co-benefits and less environmental tradeoffs.

*Applicable/Effective Scale:* Nature-based channel improvements are typically undertaken over relatively large (bayou-level) areas. Smaller projects could be implemented to complement other features or meet a narrower purpose but typically provide greater benefits with greater scale. Channel improvements or restorations are typically implemented by the same parties that would implement concrete or grass-lined channel improvements.

*Design Considerations:* The goal of a nature-based channel improvement project is to develop a stable, non-aggrading (depositing), or non-degrading (scouring) channel that exchanges nutrients and retains sediments within the riparian zone, is connected to its floodplain or flood-prone area, and promotes the establishment of functioning aquatic and terrestrial habitat. This type of project considers the same array of physical features and observed elements that characterize hydraulic and hydrologic conditions as grass or concrete-lined channels.

Physical features of importance include topography, width of available right of way, location of existing channel, adjacent existing structures (e.g., bridges, utility structures, buildings, transportation facilities) and existing hydraulic features such sewer outfalls and tributaries.

The observed elements of importance include precipitation frequency and intensity, flood discharges and volumes, channel and overbank features. Channel stability and the presence of aggradation or degradation processes, bank erosion, cutoffs and bar formations are also important design considerations that should be investigated when making channel improvements and selecting the most fitting channel geometry (USACE, 1994).

*Spatial Requirements:* The space required for a channel improvement project varies depending on the design concept and project goals. Nature-based channels typically require more space to achieve the same level of service as grass or concrete-lined channels. Similarly to traditional channel design, size limited by the available right-of-way which may limit the design alternative options if additional real-estate acquisitions become costly.

*O&M Requirements:* Across all channel types, channel capacity and conveyance efficiency must be maintained which may require sediment and debris removal. Depending on the size of accreted sediments and debris, heavy equipment may be necessary. Nature-based channel vegetation maintenance prioritizes the removal of invasive vegetation but allowing trees to grow on overbanks and berms.

_Environmental Considerations:_ Nature-based channelization aims to reduce impacts to the floodplain and in degraded system could restore some of its natural function by reconnecting oxbows, supporting woody vegetation, connecting adjacent wetlands, facilitating groundwater recharge, filtering pollutants and sediments, reducing erosion and supporting native ecosystems. These benefits are minimized the more the channel modification deviates from its natural function.

Vegetation type and density in the channel as well as the floodplain are important considerations when evaluating the environmental function of the channel and connected wetlands in relation to the benefits of habitat provided, channel capacity, and flood risk reduction. Riparian vegetation offers a great variety of benefits to stream channels, including binding soil together to reduce erosion rates and increase bank stability; increasing bank and floodplain flow resistance, reducing near-bank velocities and erosive potential; inducing sediment deposition to support stabilizing fluvial processes; providing shade to decrease solar radiation and stream temperatures, cover for hiding opportunities for fish, and sources of coarse instream wood to the stream channel, for habitat; and feeding energy input to streams in the form of dropped leaves and terrestrial insects. While increases in riparian vegetation typically increase water surface stages along downstream higher-order streams, increased riparian vegetation along headwater streams can decrease flood discharges and stages on the higher-order streams, decreasing flood risk (Anderson 2006). In these situations, the increased roughness of the upstream riparian corridors increases flow resistance and flood attenuation, reducing discharges downstream while increasing flood duration.

The channel profile is also equally important to providing ecosystem and flood risk benefits. Reduction of shear stress within the channel should be achieved by excavating the channel bank to reduce the bank slope and by creating a flood-prone area, or bench, at the bankfull height. This bench allows flows greater than the bankfull discharge (the channel forming discharge) to expand into the flood-prone area and reconnected riparian fringe. Excavation of the bankfull bench over point bars located on the inside of the meander bend is most effective during flood-flow conditions. Resulting velocities and shear stress are reduced on the restored channel banks and bankfull bench to a level that can be readily stabilized with bioengineering-vegetative techniques. Pool-rifle complexes should also be designed into the overall profile to encourage areas of water storage and conveyance while also promoting spawning, refuge and foraging aquatic habitat.

Excessive bank erosion or channel scour can cause stream impairments and reduce the integrity of the channel. However, it is important to define what is considered excessive and acceptable when considering methods of stabilization given that these processes are normal processes in alluvial streams and fixing can lead to undesirable consequences. A common unintended consequence is a shift in the channel thalweg causing altered downstream meander translation that could then induce erosion up or downstream that would require additional structural streambank stabilization to mitigate the effect. Bank stabilization can be most effectively addressed through a combination of structures, to provide immediate relief to excessive erosion rates, and vegetation, to provide longer term stabilizations. In general, natural materials should be employed rather than relying on engineered materials such as concrete and rip rap. These types of materials should be minimized to the greatest extent practicable, since these types of materials prohibit vegetative growth and eliminate ecologically important undercut banks and sediments for many species.

In-steam structures, such as root wads, brush mattresses, log jams, etc. should be considered to provide channel stability and promote certain habitat types. In-stream structures may be necessary because newly constructed channels often do not have dense riparian vegetation and roots that provide bank stability, nor do they exhibit a natural distribution of stream bed material that provides armoring during sediment transport. In-stream structures are used to provide stability to the system until these natural processes evolve to provide long-term stability and function to the system.

*Social Considerations:* Nature-based channels offer opportunities to improve and take advantage of natural spaces and therefore the benefits they provide to society. The design can be guided by cultural expectations and values which determine both the goal of the effort and whether the projects is considered successful. Nature-based channels can bring aesthetic benefits with local users preferring restored landscapes which are naturalized, attractive, and offer access to the watercourse. However, sites valued by people as being more natural are not necessarily those which are most ecologically healthy. Local users' perceptions of the landscapes may be influenced more by local history and memory than by measurable outcomes and can sometimes result in opposition to the effort. Aesthetic and recreation enhancements such as instream riffles and falls, walking paths, stream access, debris removal, signage, and desirable streamside vegetation may have public appeal. Additionally, there are opportunities for educational, ethical, and community benefits associated with a closer connection between residents and a naturalized stream corridor.

*Lead Time Considerations*: The permitting of nature-based channels would be nearly identical to the more traditional channel improvements. Close coordination with natural resource agencies to determine the final design will be critical to implanting a project that fully meets the goals of maintaining or restoring natural features and maximizing ecological benefits. The permitting process will likely take several years and has a moderate likelihood of litigation. As indicated previously, project proponent and opponents may differ on their opinion of a successful project and could influence litigation actions.

When considering the lead time, it is important to acknowledge that it will take several years to potentially decades for the channel benefits to be fully realized. The channel would be able to accommodate capacities immediately after construction, but it will take several weeks to months for the base vegetative herbaceous layer to establish which can affect erosion and or sediment movement if flood events occur within that period. Woody vegetation will take several years to decades to establish depending on the species during which time bank stabilization may be reduced and terrestrial and aquatic habitat suitability may be diminished, but would improve with each year of growth and establishment.

*Reliability:* Channels can achieve a service life of 100-years or more. Channel conveyance improvements are generally reliable if maintenance requirements are met. Sedimentation and/or overgrowth of vegetation into the channel can impact capacity and reduce benefits the channel provides in terms of volume of runoff. The ability of channels to drain is impacted by downstream boundary conditions which could change over time (e.g., RSLC).

*Adaptability:* The adaptive capacity of nature-based channels is constrained by the available space. If the channel and associated floodplain can transform geomorphically over time, the equilibrium of the channel typically remains as it migrates back and forth over time. Adapting it to a higher level of service when constrained by infrastructure in the floodplain generally requires a shift to grass-lined or concrete-line channels to achieve the necessary level of service unless buyouts are initiated and the floodplain restored.

## 6.2 Stormwater Wetlands

Constructed stormwater wetlands are wetland systems design to store and convey runoff while simultaneously filtering pollutants and providing native habitat. Because of their low topographic position relative to uplands 9e.g. isolated depressions, floodplains), wetlands store and slowly release surface water, rain, groundwater, and flood waters. Trees and other wetland vegetation also slow the movement of flood waters and distribute them more slowly over floodplains. The combined water storage and slowing action lowers flood heights and reduces erosion downstream and on adjacent lands.

This type of nature-based flood risk management method can be employed in lieu of traditional detention and/or stormwater infrastructure, or in conjunction with it to achieve a higher degree of co-benefits. In addition to water quantity and quality benefits, stormwater wetlands provide aesthetic and even recreational benefits, in line with other nature-based infrastructure alternatives.

Like traditional detention, stormwater wetlands can be constructed on-line or offline. On-line wetlands receive upstream runoff from all storms while off-line systems service smaller storms are bypassed during larger events.

*Applicable/Effective Scale:* Stormwater wetlands are typically constructed on a neighborhood scale but may achieve greater results if applied throughout a bayou or region, especially if habitat and hydrologic connectivity is considered when implementing these measures.

*Design Considerations:* Key design considerations for stormwater wetlands include soil type, groundwater level, hydrologic and hydraulic properties of the watershed as well as habitat and vegetation requirements. Unlike traditional detention, a water management plan may be required to ensure the desired habitat is maintained as wetlands require water be supplied at varied levels throughout the year.

*Spatial Requirements:* Stormwater wetlands typically require more space than traditional detention to meet the same level of service, but vary in size depending on where and at what scale they're applied. The EPA estimates that one acre of wetlands can store 1 to 1.5 million gallons (3 - 4.6 AF) of water (EPA 2001).

*O&M Requirements:* A management plan of the site should be developed that factors in long-term maintenance inspections and needs to provide proper functioning of the wetland over time. Regular inspection and monitoring would be required. Reference sites may be useful as a basis of comparison to identify various changes and impacts the constructed wetland ecology and to evaluate its success. Examples of maintenance activities that you should conduct during these inspections include checking weir settings and the inlet and outlet structures, cleaning off surfaces where solids and floatable substances have accumulated to the extent that they may block flows, removing nuisance species and maintaining the appearance and general status of the vegetation and wildlife populations, and removing sediment accumulations in forebays.

*Environmental Considerations:* Wetlands are some of the most biologically productive natural ecosystems in the world, comparable to tropical rain forests and coral reefs in their productivity and the diversity of species they support. Abundant vegetation and shallow water provide diverse habitats for fish and wildlife. Additionally, they can improve the water quality in stormwater runoff through their ability to slow down flows allowing sediments and pollutants to settle out wetland plants transform and filter nutrients, biochemical oxygen demand, suspended solids, metals, and pathogens.

Where appropriate, the wetlands should be designed to provide diverse habitats comprised of native species comparable to natural wetland sites in the region. The biological diversity of the site may be linked to, or dependent upon, physical heterogeneity. This could include having both surface and subsurface flow while providing some areas of open water, creating elevated surfaces for nesting, and leaving some upland and buffer areas for other species as a travel corridor, nesting, or foraging habitat. Developing a wide variety of wetland types will provide a range of diversity for different types of wildlife. Considerations may include seasonal hydroperiods, depth-flow changes, vegetative succession, and accumulation of sediments.

_Social Considerations_: Wetlands provide many recreational, educational, and research opportunities. Wetlands, depending on their size can provide opportunities for hiking, biking, nature watching, hunting, and fishing and should be considered when designing the project commensurate with the level of management oversight, scale of the project and desired recreation provisions. Additionally, wetlands are studied in conjunction with environmental programs at universities, grade schools, and environmental or visitor centers where these ecosystems are used as outdoor laboratories to learn about vegetative structure (e.g., the density and cover of the vegetation) and ecological functions (e.g., nutrient cycling) , natural ecological processes (e.g., plant succession), biodiversity, and plant-animal interactions. As with other green infrastructure and nature-based measures, wetlands preserve open space, provide aesthetic value to the landscape, filter air pollutants, sequester carbon, and produce food and fiber for human consumption and use.

_Lead Time Considerations_: As with other measures, the location, scale, and design of the wetland will influence the permitting timeframe. Constructed wetlands where wetlands do not currently exist may need to secure local construction permits and the time to construction could be a couple of weeks to a couple of months. However, if jurisdictional wetlands or sensitive habitats may be temporarily or permanently modified, more significant federal, state and local permitting may be required and could take several months to several years to complete. In all instances, coordination with natural resource is strongly encouraged to ensure a design that meets the goals of the project while maximizing ecological and social benefits.

As with nature-based channels, the full benefits would not be realized upon completion of construction. It will take several growing seasons to fully establish a mature wetland and several years or decades to establish woody vegetation if part of the design.

_Reliability:_ Stormwater wetlands may be designed to contribute to a service life of 100-years or more alongside additional infrastructure if constructed as an online stormwater wetland but typically achieve lower levels of service if designed independently (off-line).

_Adaptability:_ Stormwater wetlands are moderately adaptable and increasing their capacity is generally limited by space.

## 6.3 Prairie Restoration

Restoration of Katy Prairie involves creating a complex of restored native grasslands and wetlands. This can be achieved by establishing native prairie and wetland species, removal and management of non-native and invasive species, restoring natural topographic features and creating unevenness, and reducing channelization by restoring oxbows and meanders in the bayous.

Much of the rain falling on the prairie-wetland complex soaks into the soil or is caught and stored in depressed areas. The remaining rainwater drains slowly across the prairie wetland surface as runoff and is slowed by vegetation and irregular ground surface, reducing the rate the water leaves the restored area.

Applicable/Effective Scale: Prairie restoration would typically be completed at the watershed scale.

Design Considerations: A successful prairie restoration is highly dependent on specific characteristics of the site including historic and current hydrologic connections to the floodplains, topographic variability, and the soil properties and chemistry. The restoration approach should closely mimic the natural geomorphology of the wetlands and uplands endemic to the Katy Prairie and the Gulf Coastal Plains. This can be achieved by reviewing historic aerial imagery prior to agricultural land manipulation to determine the location of depressions, prairie or "mima" mounds (elevated areas), and low sloping stream terraces. Excavated areas (depressions) should be oriented and designed to distribute overland flows across the site to maximize water retention from surface water and precipitation while also providing connectivity between the depressions and ultimately with the tributaries.

Unlike stormwater wetlands, incorporating in restored upland areas and vegetation communities is critical to increasing the overall ecological diversity and complexity of the site so that it will more closely match the natural prairie features that can slow floodwaters. Restoring the hydrology is also critical to storage capacity and designs should consider how existing ditches, canals, and other drainage features contribute to loss of water from the site; maximization of topographic relief to hold varying depths of water; and the need for any water control structures that can direct or hold flows.

Spatial Requirements: Due to the complex interactions of each of the systems within the Katy Prairie, more space would be required than traditional detention or conveyance measures. It is estimated that one acre of restored complex can retain 0.5 AF, detains 2.3 AF and infiltrate 2.1 AF of water. Because this measure would require a significant amount of land and has specific soil and hydrologic requirements, construction of this measure would be limited to undeveloped, rural areas in the upper watersheds.

O&M Requirements: A site management plan should be developed that describes monitoring requirements to determine success and continued performance of the site, long-term maintenance needs, and adaptive management actions to respond to changing conditions. Maintenance may involve period burning of the site to stimulate productivity of native prairie plants and prevent invasion of herbaceous perennial weeds and woody trees and shrubs. Early and frequent management is critical to prevent spread of weeds and woody species which can out-compete and displace establishing natives and can include frequent mowing and treatment with herbicides over large swaths of lands. After establishment, invasive and weedy species management may be limited to spot treatment, pulling, or mowing prior to flowering to prevent seed-set. If water control structures are employed, regular inspection, operation, and maintenance of the structures would be required.

Depending on the level of recreation and leases made available, the site could require dedicated staff to monitor conditions and oversee activities.

*Environmental Considerations:* Restoration of Katy Prairie would restore an ecologically important habitat that has been drastically diminished throughout its historic range over the last 100 years. Prairie and wetland restoration would provide many of the same benefits and ecosystem services as the nature-based channel and stormwater wetland measures including: water filtration, carbon sequestration, and habitat for fish and wildlife species, such of which are rare and endemic only to the Katy Prairie.
During design of the site and development of the long-term management plan, natural resource agencies and organizations with experience in restoring these communities should be consulted for their expertise in selection of appropriate vegetative species, proper placement of topographic variability, and monitoring and success criteria.

*Social Considerations:* Restoring Katy Prairie preserves open space and creates recreation opportunities, such as hiking, wildlife watching, and hunting for residents of the Houston metropolitan area. Additionally, the prairie's unique native grasslands and assemblage of migratory birds provides for ecotourism opportunities that attract birders and hunters from around the country, as well as providing volunteer and educational learning and outreach opportunities. Social opportunities should be considered when developing the site plan and should be commensurate with the long-term management strategies of the site. Features such as wildlife watching platforms, trails for hiking, biking, and/or equestrian use, picnicking or camping site, sanitation facilities, visitor information centers or kiosks, interpretative signs, and hunting leases or permits.

Because of the significant amount of rural land that would be required, a number of agricultural and ranching operations would need to be acquired resulting in further loss of economic income, cultural values, and local products from those industries. Opportunities to foster cultural practices should be considered when developing the long-term site management strategy and could include low-intensity grazing leases; however, it is unlikely that a site could continue to support existing levels of grazing intensity or crop production while maintaining the restored value.

As well, acquired lands would be unavailable for future development resulting in lost tax revenue from new development which would limit and likely shift growth to other areas.

*Lead Time Considerations*: Permitting of Katy Prairie Restoration actions is dependent on the scale, design, and location of the work being proposed. If jurisdictional waters and wetlands are avoid, environmental review would be limited to complying with state and federal endangered species regulations. However, if work involves modifying jurisdictional water or wetlands, compliance with the Clean Water Act and securing a section 404 permit from the USACE regulatory program would be required, which would include compliance with NEPA, Endangered Species Act, Farmland Protection Policy Act, and other state and federal environmental laws. Public review of the project would be required under section 404, but the likelihood of litigation is low. Permitting this kind of action could take several weeks to years.

Securing of sufficient real estate would be the greatest driver to being able to implement in a timely manner. Benefits will begin to be realized after construction is completed but at a greatly reduced rate until establishment of vegetation in the prairie-wetland complex, which will take a minimum of one growing season for the first herbaceous layers to establish and may take several years to fully establish the full suite of species. Establishment rates are highly dependent on soil moisture and climate conditions.

*Reliability:* Restoration of Katy Prairie provides flood risk benefits at all levels of events; however, the effectiveness of the measure to benefit watershed wide is limited on whether or not the storm passes over the site.

*Adaptability:* Similar to stormwater wetlands, Katy Prairie restoration is moderately adaptable and increasing their capacity is generally limited by space.

## 6.4 Bioretention Cells (Rain Gardens)

Bioretention cells, also called rain gardens, are vegetated depressions with engineered sub-grades to ensure infiltration. Their benefits are twofold: (1) reduced pollutant loading relative to direct urban runoff, and (2) an increase to the residence time of runoff on site. These systems usually have an underdrain to ensure the cell drains in a reasonable time period. Although they are applicable in most settings, rain gardens are best used on small sites, urban areas, suburban areas, and parking lots.

*Applicable/Effective Scale:* Bioretention cells are best implemented at small sites but can be implemented as a bioretention basin to treat parking lots or other large areas such as residential subdivisions or commercial/institutional areas. Bioretention used in urban settings may include tree filters, curb extensions and planter box filters (HCFCD, 2011). Bioretention cells are a viable option for retrofitting existing infrastructure.

*Design Considerations:* Bioretention cells feature a depressed ponding area below adjacent impervious surfaces typically excavated to a minimum depth of 1 to 3 feet (HCFCD, 2011). Inflow is typically low energy or sheet flow. An engineered soil mixture to ensure adequate percolation of runoff intercepted by the cell is an important design consideration. Underground detention or an underdrain may be required to avoid ponding in excess of local requirements. If an underdrain is required, a geotextile fabric or impermeable liner may be necessary. Design standards, including allowable detention offset, for the City of Houston are in the COH IDM Section 9.10.01.B; design standards for Harris County are in Harris County's LID Design Criteria Manual (HCFCD, 2011).

**Figure 13. Rain Garden at Aguirre & Fields parking lot in Houston, TX (Source: HGAC Designing for Impact)**

*Spatial Requirements:* Bioretention cells are suitable for areas with space constraints. The spatial scale of the feature can be tailored to match the available space, however the spatial scale of the feature will impact the storage capacity.

*O&M Requirements:* Bioretention cells should be inspected for erosion of the top mulch layer or sediment build up impacting design volume and repaired as needed. Mulch replacement is generally required yearly (HCFCD, 2011). Presence of vegetation considered in design should be verified regularly and dead vegetation removed and replaced seasonally, typically in the spring and/or fall. Invasive species should be removed.

*Environmental Considerations:* Rain gardens can be important features to the landscape by providing habitat for native wildlife in a developed area, reducing pollutants and excess nutrients through infiltration and filtration of stormwater, cleaning air of pollutants such as smog and carbon dioxide, increase groundwater recharge, and aid in reducing urban heat island effect.

Plant selection should consider native species over non-native species and completely avoid invasive species. A variety of plants that tolerate a wide range of conditions works including species that are tolerant to drought and inundation.

*Social Considerations:* Bioretention cells can add character and value to the property, neighborhood, and community while preserving open space in urbanized environments.

*Lead Time Considerations*: Local permitting or compliance with building codes may be required to install rain gardens and should be investigated prior to undertaken such a project. Construction of a rain garden is relatively quick and can be completed in a few days to a few months; however, benefits may not be fully realized until the vegetation has matured which can take at least one growing season.

*Reliability:* Bioretention cells serve as an alternative to traditional measures to meet on-site detention requirements. The reliability of bioretention depends on preserving its intended capacity and ability to drain which can be achieved by meeting maintenance requirements.

*Adaptability:* Bioretention cells are moderately adaptable to increases in capacity either by increasing the existing retention cell size or increasing the number of cells on the property.

## 6.5 Bioswales/Vegetated Swales

Bioswales are linear features which include the infiltration properties of bioretention cells, but can also be used for conveyance beyond the biofiltration purpose. They mimic natural drainage and are effective at slowing runoff and removing pollutants through vegetation along the bottom and sides of the swale channel, typically trapezoidal or parabolic in shape. Swales can be dry or wet, with dry cells featuring an underdrain system. They can be used anywhere and are best used on small sites, in urbanized and suburban commercial areas, residential areas, and parking lots.

*Applicable/Effective Scale:* Like bioretention cells, application is typically on smaller sites, though

**Figure 14. Exploration Green golf course repurposed into bioswales (Source: HGAC Designing for Impact).**

implementation can also be elsewhere. Swales are appropriate for many settings including residential, commercial, industrial and institutional sites but limited in highly urbanized areas. Roadside swales may be used in place of curb and gutter systems depending on local requirements. Bioswales can be incorporated into site drainage plans (existing or proposed) and used either stand-alone or in conjunction with other stormwater infrastructure, including other BMPs (such as wet ponds, wetlands, etc.).

*Design Considerations:* Infiltrative soils or an engineered subgrade are important design considerations for implementing vegetated swales to avoid excessive ponding. An underdrain may be required for dry swales. Check dams may be utilized to promote infiltration and further reduce flow velocities for areas with steeper slopes. Natural grades should be utilized when possible to achieve a gentle slope. Vegetation type and height on the bottom and side slopes of the swale is important in reducing runoff velocity and pollutant removal.

Roadway swales typically have more stringent design requirements than those used in other aforementioned settings, such as overflow structure or bypass requirements to accommodate more extreme events (HCFCD, 2011).

*Spatial Requirements:* Bioswales require more space than bioretention cells and have limited applicability in highly urbanized settings. A single bioswale should be sized to handle only a few acres of drainage but can be utilized in multiple segments to handle site runoff.

*O&M Requirements:* Dry swales may require mowing during growing season to maintain proper vegetation heights while wet swales, utilizing wetland vegetation, do not require frequent mowing. Sediment should be removed when it begins impacted design volume (COH, 2019). Maintenance capabilities should be considered in vegetation selection as some appropriate plants may require more maintenance than others.

*Environmental Considerations:* Bioswales provide many of the same ecosystem services as bioretention cells (e.g. habitat, filtration of stormwater and air, groundwater recharge, and lowering of temperatures) but at a larger scale.

Native vegetation should be selected consistent with the ecoregion, climate and soil type and be tolerant of wet and dry conditions. Construction timing/seasonality should be considered in properly establishing vegetation. Evapotranspiration rate, pollutant removal and maintenance requirements should all be considered in vegetation selected.

*Social Considerations:* Beyond its use for stormwater risk reduction, the swales provide attractive landscaping, open space, and community character. If the site is of significant size, the increased soil moisture, evapotranspiration and vegetation coverage creates a more comfortable local climate.

*Lead Time Considerations*: Construction of swales associated with new development or within public right of ways would most likely require local permitting. For an individual property owner, permitting may or may not be necessary depending on the location and scale of the project. An important consideration is that while some benefits may be realized as soon as construction is complete, full benefits will not be realized until the vegetation has fully established, which would be at least one growing season but could be more depending on the selected vegetation.

*Reliability:* Bioswales serve as an alternative to traditional detention and roadside conveyance measures. The reliability of bioswales depends on preserving the conveyance and infiltration capacity of the swale. Adhering to vegetation and siltation maintenance requirements preserves reliability of this measure.

*Adaptability:* The adaptability is moderate for bioswales and often constrained by space. If space allows, extending or expanding the swale requires minimal modification to the existing swale.

## 6.6 Rainwater Harvesting (Rain Barrels and Cisterns)

Rain barrels are used in rainwater harvesting schemes to intercept rainfall runoff from rooftops typically for on-site use. This contrasts with conventional stormwater practices where rooftop runoff, often relatively pollutant free, is directed into the greater stormwater management system. Rain barrels (or cisterns) can range from 55 gallons to several hundred gallons and are typically placed near the down spout of a house.

*Applicable/Effective Scale:* Rain barrels are most often implanted on a site-by-site basis, e.g., by individual homeowners. Their utility as a non-potable water source for on-site use, e.g., watering a garden, is a good way for users to save money on their water bill.

**Figure 15. Rainwater harvesting with cisterns at Houston Fire Station #90 (Source: HGAC Designing for Impact).**

*Design Considerations:* Acquisition, installation, and operation of a typical rain barrel is straightforward and could generally be easily accomplished. Installation of a larger cistern system is contingent upon site design constraints. Rain barrels should be equipped with a drain spigot and an overflow outlet must be provided to bypass the barrel during large rainfall events (COH, 2019)

*Spatial Requirements:* Rain barrels are generally small (typically 1.5-2 ft. in diameter and 2.5-3 ft tall). Rain barrels are a suitable alternative stormwater management practice on sites where other LID practices are limited, such as highly urbanized areas and/or where soil and groundwater conditions exist that limit or prohibit adequate infiltration.

*O&M Requirements:* Maintenance requirements are minimal for rain barrels. Rainwater harvesting systems should be drained between each storm, ideally to an infiltration BMP. Rain barrel components (gutters, downspouts, overflow pipes, spigot) should be inspected an nually for leaks and obstructions.

*Environmental Considerations:* Rainwater harvesting does not present any unique environmental impacts that should be considered during design or implementation.

*Social Considerations:* Rain barrels may be cost prohibitive for some residential homeowners or businesses particularly those in lower income communities. Consideration for credits or reduced stormwater fees is one potential way to encourage individual properties to install rain barrels.

*Lead Time Considerations*: Installing rain barrels does not require any permitting actions on residential structures, but may require local permitting on business and other larger structures.

They can be installed in a matter of hours to days depending on the complexity of the system and any retrofitting needs of the existing structure.

*Reliability:* Rainwater harvesting is reliable if they are properly maintained. Rain barrels and cisterns should be managed in accordance with a site specific water budget plan to allow for sufficient potable water use while maintaining appropriate storage capacity for when a storm event occurs.

*Adaptability:* The adaptability of rainwater harvesting relies on the user rather than the practice itself. The capacity can be increased by simply upgrading the barrel or cistern. Adjustments may also be made in the water reuse plan.

## 6.7 Permeable Pavement

**Figure 16. Pervious concrete example during installation. (Source: Molly Ross, 2018)**

Permeable pavement, contrary to typical pavement options, allows rainfall runoff to rapidly infiltrate the pervious media to mimic pre-development hydrologic conditions. Permeable pavement systems include a load-bearing layer and are typically designed to include an underdrain and/or subsurface detention/retention basin. A permeable pavement system can be made of a wide range of materials (porous concrete, porous asphalt, permeable pavers) and can be utilized in place of conventional pavement options on parking areas, roadways, playgrounds and plazas. Permeable pavements aid in mitigating runoff volume and peak flow rates while simultaneously capturing and reducing pollutant loads.

*Applicable/Effective Scale:* Permeable pavements can be used in place of conventional paving options for low traffic volume roadways such as residential street parking lanes, stopping lanes on divided highways, parking lots as well as sidewalks/walkways and patios in both commercial and residential areas. Permeable pavements are not currently suitable for high-traffic areas. Currently permeable pavement systems may not be used on driveway aprons or public streets (HCFCD, 2011) and are restricted to single family residential construction or commercial construction on private property (COH, 2019).

*Design Considerations:* Permeable pavement systems typically include multiple layers with varying aggregate sizes and void ratios. The surface layer typically consists of smaller stones and tighter voids with larger gravel comprising the sub-surface detention/retention basin layer below. The sub-surface basin must be sized appropriately considering both contributing drainage area and soil infiltration rate. Permeable pavement systems should drain the surface within 24 hours and will require sub-surface drainage (underdrain) in areas where soil infiltration rate is inadequate per local guidelines. (COH, 2019; HCFCD, 2011).

The surface and sub-surface layer must be of adequate strength for expected design loads. Systems with sub-surface storage basin may require a liner.

*Spatial Requirements:* Permeable pavement systems can be used to replace traditional pavement systems anywhere traffic volume (design load) and local regulations allow. These systems may be limited depth-wise depending on design volume requirements and local conditions such as depth of the groundwater table.

*O&M Requirements:* The key to maintaining permeable pavement systems is to avoid clogging of the void spaces. Accumulated debris and litter should be removed as needed and cleaned with a vacuum-type street cleaner at least twice a year. Permeable pavement systems should be inspected often during the first few storm events to ensure proper infiltration and drainage, then at least once per year after the first year (HCFCD, 2011).

The City of Houston requires permeable pavement systems be vacuum-swept followed by high pressure washing quarterly with regular inspections to ensure the surface layer and subsurface drainage system is functioning appropriately, as detailed in the City of Houston Design Manual, section 9.10.01 (COH, 2019).

*Environmental Considerations:* Permeable pavement treats rainfall and runoff from nearby impervious areas. They preserve natural drainage patterns, filter pollutant loads, enhance groundwater infiltration, mitigate Urban Heat Island effect and can help maintain roadside vegetation (Foster et al., 2011).

*Social Considerations:* Because the initial cost of permeable pavement is typically higher than traditional pavements, lower income communities may be at a disadvantage to benefiting from this form of flood risk management. At the individual property level, the costs may outweigh the benefits particularly if the individual does not observe a marked difference in their flood risk. Communities may be less likely to install such features in public roadways due budgetary constraints and inability to commit to the maintenance costs associated with permeable pavement. Incentives and grants should be considered as a means to encourage use of permeable pavement.

*Lead Time Considerations*: Installation of permeable pavement does not have significant permitting requirements and can be installed in a matter of days to months depending on the type, location, and scale of the project. Local permitting and compliance with building codes may be necessary for new developments and/or replacement of existing impervious surfaces.

*Reliability:* Permeable pavement systems serve as an alternative to traditional measures to meet on-site detention requirements. The reliability in terms of capacity is largely dependent on preserving adequate drainage of the surface and subbasin layers by meeting maintenance requirements. Permeable pavement is reliable in meeting load requirements for low traffic streets and other paved surfaces such as sidewalks or parking lots.

*Adaptability:* The adaptive capacity of permeable pavement systems is generally low as each layer of the structure would have to be excavated and reestablished if the storage volume became inadequate. However, permeable pavement systems can be placed adjacent to each other if space allows.

## 6.8 Green Roofs

Green roofs are vegetated roofing systems comprised of multiple layers that filter, absorb and/or detains rainfall. Layers include a waterproof membrane system, growing media (i.e. soil), root protection and vegetation. Green roofs reduce runoff volume and peak flow rates, as well as delay peak flow rates, through evapotranspiration and infiltration. Additionally, green roofs enhance water quality and reduce the urban heat island effect common in highly developed areas. Green roofs can be modular or built in place (Foster et al., 2011).

*Applicable/Effective Scale:* Green roofs are applicable in a wide variety of settings but are especially useful in highly urbanized areas where other LID techniques aren't possible due to space constraints. Green roofs are effective at individual sites by retaining rainfall from small storm, frequent storm events through storage in the soil layer allowing the water to evaporate and/or transpire through the vegetation. Site runoff and peak flow rate may be reduced during larger storm events due to temporary storage in the soil.

*Design Considerations:* Greens roofs are typically comprised of a waterproof membrane installed over a roof deck with an under-drain drainage system installed between the membrane and a light weight engineered soil media planted with vegetation. Green roof vegetation should be suitable to the climate and preferably drought-tolerant. Wind velocities should be considered when selecting vegetation.

The roof membrane should be designed to pond a minimum of 1 inch of water for 24 hours without leaks. Vegetation and root structure should be considered when selecting the waterproof membrane and a root barrier may be necessary to protect the barriers integrity. The under-drain system should take vegetation selection into account to maintain proper soil moisture and aerobic conditions. Excessive ponding, extended periods of saturation and erosion from high volume rainfall events should be prevented when designing the under-drain drainage system.

Additionally, the structure's ability to sustain the additional loading of the green roof system and maximum water weight should be evaluated (COH, 2019).

*Spatial Requirements:* Green roofs are ideal stormwater management alternatives for areas or sites with space constraints such as typical urban settings. They can cover all or part of a building's roof and are typically installed on flat or slightly sloped roofs.

*O&M Requirements:* A maintenance plan should be developed and should include provisions to maintain a minimum of 80% vegetation coverage/survival in order to comply with detention and stormwater quality credits. Any fertilizer or pesticide needs should be included in the plan whether for initial vegetation establishment or maintenance. Weeds, accumulated trash or debris and/or dying vegetation should be removed on a regular basis. The City of Houston requires green roofs be inspected 4 times annually (COH, 2019). Routine inspections should evaluate the system for leaks at joints, ceilings and electrical and air conditioning conduits. Drainage paths should be inspected to ensure conveyance of runoff through the green roof system and to avoid excessive ponding that may compromise vegetation health.

*Environmental Considerations:* Vegetation should be selected consistent with the ecoregion, climate and soil type and should be drought tolerant. Green roof systems create habitat for native species in highly developed areas, improve water quality by filtering pollutants and excess nutrients in runoff and aid in reducing the urban heat island effect (Foster et al., 2011). As well, green roofs filter airborne particles such as smog, sulfur dioxide and carbon dioxide through vegetation foliage.

*Social Considerations*: Green roofs can provide opportunities for urban agriculture and help increase food security in urban areas, while also providing green space where open space is limited. Additionally, the vegetation and naturalness of green roofs provide respite from the concrete hard-scape of urban areas.

Historic and lower income communities may be at a disadvantage from implementing this LID. Properties in these communities may not be structurally capable of constructing a green roof and bringing the structure up to a capable level may be cost-prohibitive. Incentives, grants, and other funding sources could encourage use in these areas.

*Lead Time Considerations*: All green roof projects will require a building permit which may take several weeks to moths to secure. Green roofs will begin providing some level of benefit upon installation but full benefits will not be realized until the vegetation has fully established which can be approximately one growing season.

*Reliability:* Green roofs serve as an alternative to traditional measures to meet on-site detention requirements. Their reliability is dependent upon inspection and maintenance requirements being met to ensure detention capacity is preserved.

*Adaptability:* The adaptability of green roofs is largely dependent on available space, typically limited by the building footprint, and the weight of the feature.

## 6.9 Resources

There are several resources available to assist project managers, engineers, and planners in implementing LID, GI and NNBF approaches to flood risk management. Tools such as mapping applications and modeling software are necessary to characterize the applicability and effectiveness of any flood risk management measure from the planning to implementation level. In addition to the literature and guidance referenced throughout this section, Attachment A includes a summary of tools and resources available for investigating FRM risk and planning solutions.

# 7 Non-Structural Measures

## 7.1 Buyouts

Buyout of structures with high flood hazard is a strategy for flood damage reduction where structural flood control projects are not cost-effective either in part or in whole. Often these structures were built in flood-prone areas prior to robust floodplain mapping and/or development and detention requirements being imposed. Home buyouts can be a lengthy process.

*Applicable/Effective Scale:* Home buyouts are done on an individual basis, though are typically part of a program.

*Design Considerations:* The “design” of a buyout program is influenced by the level of risk, residual risk following implementation of structural alternatives, and feasibility of other structural alternatives as a means of risk reduction in the area. Another important consideration of a buyout program is the long-term plan for the acquired properties. These areas could be incorporated into a larger structural FRM plan (e.g., conversion to a detention pond), restored to a more natural condition (e.g., ecosystem restoration efforts), or simply periodically mowed.

When considering large-scale buyouts, it is important to consider how and where the debris from removal of the structures would be disposed of. Using the FEMA Debris Estimating Field Guide, a typical 1,000-square foot house with medium vegetation (defined as a uniform pattern of open space and tree canopy cover [most common]) would have 260 CY of material, while a 2,600-square foot house with medium vegetation would have 676 CY. While individually this is not significant, if several hundred or thousand structures require removal, the average landfill would not be able to accommodate this level of disposal and a new disposal site would need to be sought. Additionally, there may be special handling requirements for older structures, such as for asbestos, lead paint, or other environmentally hazardous products.

*Spatial Requirements:* The spatial requirement of buyouts varies depending on the acquisition strategy, location of flood hazard areas, and disposal needs

*O&M Requirements:* The O&M requirements for a buyout area depend on the long-term plan for the land.

*Environmental Considerations:* In general, property acquisition is beneficial to the environment because the structures would be maintained as open space. When considering buyouts, attempts should be made to purchase multiple tracts of land in an area that can be restored to support riparian, wetland, or upland habitat environments. When single properties are acquired in a patchwork approach, there is a greater chance for the acquired areas to become vacant lots that become extremely expensive to maintain and provide low quality habitat sites with minimal to no productive use.

*Social Considerations:* Small scale, voluntary property acquisitions primarily impact the individual property owners, while large-scale, community-wide, mandatory buyouts can have much broader impact beyond the immediate properties. In all instances, relocating individuals would be separated from their communities, which may affect their quality of life by increasing the distance from their customary places of work, shopping, worship, and medical care (Perry and Lindell 1997) and induce psychological anxiety. For some relocation would pose an economic hardship to include inability to find comparable housing at a comparable cost and increase in commute time and distance leading to larger monthly expenses. This would be particularly hard on lower income communities. While others would find relocation a welcomed change. Additionally,

When considering large-scale buyouts, it is important to consider how the community as a whole would be affected including: the loss of social and community services (e.g. schools, libraries, places of worship, emergency services, grocery stores, restaurants, etc.) and the employment they provide; loss of property and business tax revenue contributing to utility and school districts, as well as cities and counties, particularly if there is no replacement housing available in the same boundaries; and availability of existing housing and the need for additional development to accommodate the relocations and yearly immigrations to the area. Environmental justice populations are most at risk of being significantly impacted, whether their property is acquired or not, from large-scale buyouts.

*Lead Time Considerations*: Voluntary buyouts are much less time intensive than mandatory buyouts where eminent domain would be enforced. Eminent domain situations are more at risk for litigation.

*Reliability:* If acquisition is successful, buyouts are very reliable as long as the long-term plan for the flood-prone area of interest is successful in keeping development off the properties.

*Adaptability:* The adaptability of buyouts is high since the structure is removed entirely from the flood hazard zone. The property can be repurposed in multiple ways to meet other goals.

## 7.2 Building Retrofits

Retrofitting consists of making physical changes to existing structures as a means of hazard mitigation. This practice can be in response to any environmental hazard; though here the focus is flooding. Examples of retrofitting methods for flood hazard reduction include:

- **Elevation in place** – raising the structure such that the lowest floor is above flood level.
- **Wet floodproofing** – allowing floodwater to enter uninhabited portions of the structure in such a way that significant damage is avoided to the structure itself or contents.
- **Dry floodproofing** – sealing the structure such that floodwater can not enter.
- **Relocation** – physically moving the structure to a location with low flood hazard.
- **Demolition** – demolishing a damaged structure to be rebuilt with reduced flood hazard in the same or different location.
- **Barrier systems** – construction of a floodwall or levee around a structure to reduce flood hazard. Temporary barriers that can be removed, stored and reused are also available.

| Construction Type | Existing Foundation | Measure | Retrofit | Relative Cost |
|---|---|---|---|---|
| Frame, Masonry Veneer, or Masonry | Crawlspace or Basement | Wet Floodproofing | Wet floodproof crawlspace to a height of 4 feet above lowest adjacent grade or wet floodproof unfinished basement to a height of 8 feet above basement floor | Lowest |
| Masonry Veneer or Masonry | Slab-on-Grade or Crawlspace | Dry Floodproofing | Dry floodproof to a maximum height of 3 feet above lowest adjacent grade | |
| Frame, Masonry Veneer, or Masonry | Basement, Crawlspace, or Open Foundation | Barrier Systems | Levee constructed to 6 feet above grade or floodwall constructed to 4 feet above grade | |
| Frame, Masonry Veneer, or Masonry | Basement, Crawlspace, or Open Foundation | Elevation | Elevate on continuous foundation walls or open foundation | |
| Frame, Masonry Veneer, or Masonry | Basement, Crawlspace, or Open Foundation | Relocation | Elevate on continuous foundation walls or open foundation | |
| Frame, Masonry Veneer, or Masonry | Slab-on-Grade | Elevation | Elevate on continuous foundation walls or open foundation | |
| Frame, Masonry Veneer, or Masonry | Slab-on-Grade | Relocation | Elevate on continuous foundation walls or open foundation | Highest |
| Frame, Masonry Veneer, or Masonry | Slab-on-Grade, Crawlspace, Base-ment, or Open Foundation | Demolition | Demolish existing building and buy or build a home elsewhere | Varies |

**Figure 17. Relative Costs of Retrofit Methods (Source: FEMA, 2014, Table 3-12).**

_Applicable/Effective Scale:_ Structural retrofits can be done on a site-by-site basis by individual property owners in reducing flood risk, or as part of a flood risk reduction project. This can be a cost-effective complement to larger structural flood risk management measures.

_Design Considerations:_ The design considerations are unique to the strategy, however a consistent consideration, and critical design parameter, is the flood hazard elevation. Floodplain maps are an important tool in understanding flood hazards at a specific location as well as an understanding of hydraulic conditions locally. Design considerations for specific retrofit strategies include:

- **Elevation in place** – design considerations vary depending on the method of elevating in place that is appropriate for the structure of interest. The selected method depends on flooding conditions, foundation type (i.e. open foundation versus slab-on-grade) and construction type. In addition to flood hazard exposure, other forces, such as wind, must be considered when making changes to the structure. Additional considerations include structure access and handling service equipment.
- **Wet floodproofing** – design considerations include flooding conditions as well as hazards such as hydrostatic pressure / opening requirements, erosion / scour and saturation of building elements. Additional considerations include service equipment exposure, dewatering and drying plan, post-flood cleanup and ongoing maintenance to ensure effectiveness of measures.
- **Dry floodproofing** – specific design considerations include flood duration, exterior wall type / sealant method, door / window configuration, underseepage, service equipment outside the home and post-flood cleanup. The wall type influences sealant method and the duration is tied to the seepage potential. Human influence is also a factor in terms of installing the temporary shields in windows and doorways when expecting a flood event. Drainage systems are required to account for underseepage and leaks in the sealant or shields.
- **Relocation –** the key design consideration in relocation is where the affected people, businesses or infrastructure will be relocated to. This can be particularly challenging in an already heavily populated city, like the Metropolitan Houston Area and the continuously growing suburbs.
- **Demolition –** design considerations specific to demolition depend on the post-demolish plan. A new compliant home can be built on site, on another property or the owner can move to a new structure elsewhere. Disposal of debris is an important consideration, especially if multiple properties are involved and large quantities of waste, often including hazardous material, accumulates.
- **Barrier Systems** – design considerations are dependent on the type of barrier, foundation, soil conditions, duration of flooding, access to the protected structure, local zoning and building codes and interior drainage. Temporary barriers typically require consideration of human intervention needed to put the protection mechanism in place.

*Spatial Requirements:* Retrofit strategies for structures are generally applied directly to the structure; significant additional space is generally not required. The exception in terms of footprint is barrier-type systems that are offset from the structure to be protected. The space requirements for individual structure barriers make them generally not applicable in the Metropolitan Houston area. In terms of waste disposal, demolition may potentially generate large quantities of debris that require not only transportation but post-demolition storage.

*O&M Requirements:* The majority of floodproofing methods, aside from elevation in place, require periodic and post-storm maintenance.

- **Elevation in place** – no maintenance required.
- **Wet floodproofing** –Inspect openings periodically to ensure adequate entry and exit of floodwaters. Post-flood cleanup and drying are required after each event.
- **Dry floodproofing** – Sealant and shields may develop leaks and require repair. An operation and maintenance plan is required for measures that involve human intervention

to implement. Mechanical components, such as pumps for interior drainage, require periodic maintenance based on manufacturers guidance.

- **Relocation –** the operation and maintenance requirements of relocation are minimal.
- **Demolition –** operations and maintenance requirements for demolition are minimal with the exception being the storage and disposal methods of waste, especially hazardous waste, generated by demolishing damaged homes.
- **Barriers** – similarly to large-scale barriers, floodproofing barriers require regular inspection and problems such as cracks, erosion or scour, trees and shrubs, loss of surface vegetation and animal tunnels repaired promptly to ensure the barrier is functioning at the design level of service when an event occurs. Interior drainage typically involves drains and pumps that require regular maintenance to ensure mechanical functionality and ensure water collected inside the system can be extracted effectively.

*Environmental Considerations:* Building retrofits do not present any unique environmental impacts that should be considered during design or implementation.

*Social Considerations:* The design and financial challenges of retrofitting multifamily buildings are complex and distinct from the challenges posed by smaller, single-family homes. Retrofits for flood protection can be both impractical and very expensive to implement in a multifamily building. In addition, multifamily rental buildings, especially those that are subsidized or otherwise provide housing to low-income households, may have a hard time raising funds to implement expensive retrofits. However, failure to implement retrofits will leave buildings vulnerable to flooding damage that can result in expensive repairs and displacement of tenants while building systems remain off-line.

*Lead Time Considerations*: Lead times for building retrofits are generally limited to securing any applicable building permits and the construction period.

*Reliability:* Elevating in place is the most reliable floodproofing method presented in this section.

*Adaptability:* The adaptability of floodproofing is low. Barrier systems and wet / dry floodproofing are vertically limited.

## 7.3 Enhanced Flood Warning Systems

Flood warning systems are an important part of public awareness and public safety before and during heavy rainfall events. Harris County has a dense network of rainfall and stream gages that transmit data in real time at https://www.harriscountyfws.org/. This platform also transmits data from other agencies.

*Applicable/Effective Scale:* Flood warning systems can be used across a range of scales – widespread for a whole region or targeted at particular critical infrastructure sites.

*Design Considerations:* Design considerations for flood warning systems include data collection, data processing and gage / observed data networks (type of data, monitoring location) and the hardware / software required to operate them. Type of communications used to disseminate flood warning information and telemetry capabilities are additional considerations.

*Spatial Requirements:* Housing and storage of data, software and hardware required to store massive amounts of data and communicate alerts on a large scale.

*O&M Requirements:* Gaging stations require routine maintenance to ensure that sensors and data transmission equipment are fully functional when needed during an emergency. Other important considerations include data quality assurance, as well as long-term data management.

*Environmental Considerations:* FWS do not present any unique environmental impacts that should be considered during design or implementation.

*Social Considerations:* When developing an enhanced FWS, consideration should be given to incorporating applicability and functionality of various users including non-English speaking individuals, those without internet or power, and those who are less familiar with technology.

*Lead Time Considerations*: Deployment of an enhanced flood warning system is generally limited by the amount of time it takes to design and develop the system. Significant public outreach is recommended to ensure the public is fully aware of the system, how it works, and what they should do if they get an alert.

*Reliability:* The reliability of a FWS is incredibly important; if the system is inoperable during an emergency it will not fulfill the mission. Outages can, and do, happen. Having a plan for that circumstance is important to preserve operational integrity.

*Adaptability:* A FWS is somewhat adaptable in that it can be expanded or amended over time to account for changes in watersheds and neighborhoods. For instance, areas where stream monitoring is not a priority now may become a priority as that area becomes developed.

## 7.4 Regulatory Changes

### *Changes in Land Management*

Changes in land management include minimizing the total disturbed area, preserving natural flow paths and patterns and protecting riparian buffers. The purpose of minimizing the total disturbed area during development is to reduce changes in land cover and that thereby limits change to the hydrologic function of the site. This strategy considers the building footprint and orientation including the roads and parking lots associated with development and applies during construction as well as final site design.

The preservation of natural flow patterns and pathways is a site planning strategy that aims to maintain the existing hydrologic function of the site by sustaining drainage patterns, depression storage locations, existing grades, ditches and channels. Maintaining flow path characteristics as much as possible reduces impacts to peak runoff discharges and volumes during a storm event. The need for stormwater infrastructure can be mitigated through this method of preservation and when infrastructure cannot be avoided, the natural flow pathways and patterns can be modified or increased in capacity to achieve stormwater management goals.

The protection of riparian buffers is a land management strategy that aims to preserve valuable vegetated areas along a water body. Riparian buffers vary by type and application from zones consisting of herbaceous vegetation along surface waters or contoured perpendicular to hill slopes between disturbed land to those with predominantly forested areas adjacent to water bodies such as rivers, streams, ponds, lakes and wetlands. Riparian buffers can help shade and partially protect water bodies from impacts of adjacent land uses. Existing buffers may be preserved or re-established. Protecting riparian buffers is instrumental in preserving habitat and the hydrologic function of the floodplain, including wetlands, along water courses.

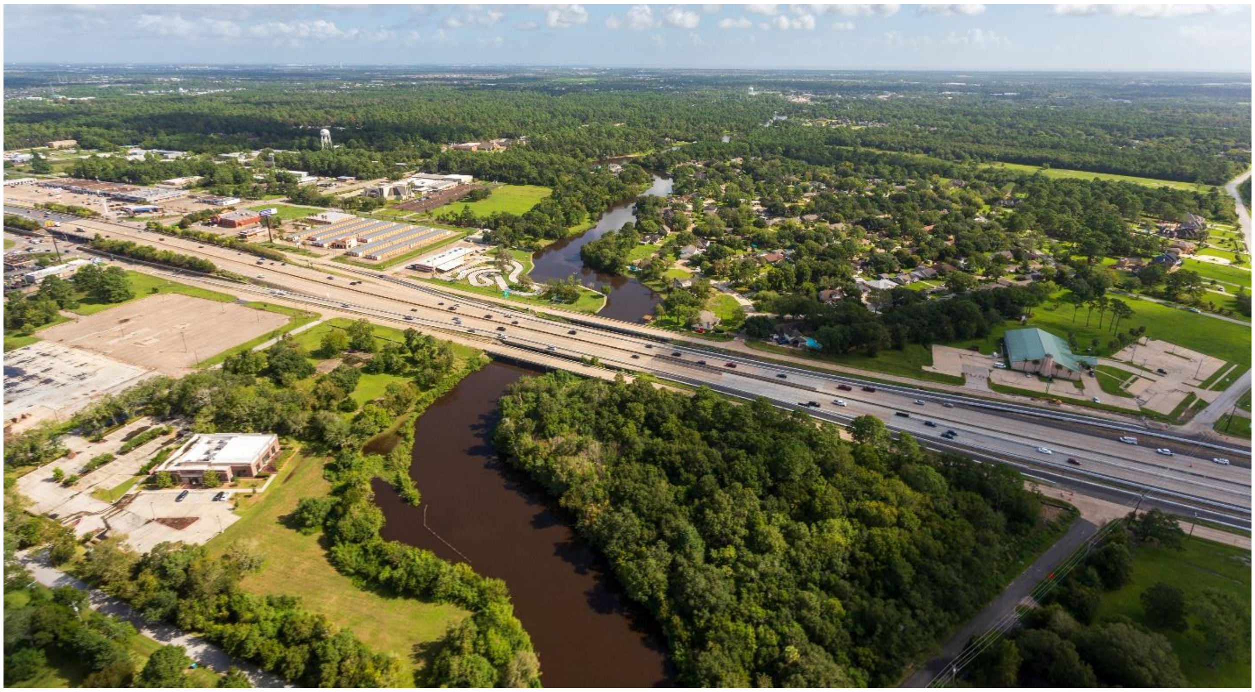


**Figure 18. Dickinson Bayou 9/21/10, post-TS Imelda (Source: Molly Ross).**

***Detention and Development Requirements***

Floodplain regulations and detention are an important part of development actions to minimize the hydrologic impact of the alteration from natural conditions. The requirements for development in the Metro Houston depend on the location of the construction and the outfall of site runoff. The applicable floodplain regulations are with a county or municipality. The detention regulations are often stipulated by entities such as TxDOT, HCFCD, or COH. These requirements can be revisited over time as a means of minimizing the impact of development based on observations regarding the effectiveness of the current policy.

*Applicable/Effective Scale:* Regulatory changes may be implemented on a neighborhood, city and/or county-wide scale.

- **Minimizing Total Disturbed Area** – this strategy is applied on a site-by-site basis but when applied at a large scale will have increased benefits in the watershed.
- **Preservation of Natural Flood Pathways and Patterns** – this strategy can be applied on a site-by-site basis and can provide more substantial benefits as the practice is scaled to neighborhood, bayou and regional scales.
- **Riparian Buffers** - protection or restoration of riparian buffers can be applied along any stretch of a water body where space allows and is appropriate in residential, commercial and industrial areas. This method can be applied at a bayou scale in sections or ideally along the entirety of a water body. Maximizing width, length and connectivity of riparian buffers improves effectiveness.
- **Floodplain and Detention Requirements** – These regulations are typically set on a regional scale. Regulations can be set on whatever scale is appropriate to ensure no hydrologic impacts from development. The effective scale should be throughout the watershed where development takes place.

*Design Considerations:* The design considerations are unique to the intention of the regulatory change.

- **Minimizing Total Disturbed Area** – design considerations include aiming to reduce grading and ground disturbance, preserve existing native vegetation and high infiltration soils on site and consider strategically implementing LID methods of flood risk management.
- **Preservation of Natural Flood Pathways and Patterns** – can be achieved by strategically managing the site/land to avoid altering or disturbing these pathways during and after construction. Land buffers may be required to accommodate river migration especially along larger drainage courses. If the existing pathways are inefficient to meet stormwater management goals and they must be altered or increased in capacity, transition zones between natural pathways and modified regions should be designed so that the pathway does not erode or degrade.
- **Riparian Buffers** - The type and width of riparian buffers should cater to site conditions, regional climate and the properties of the connected water body. Development footprints should avoid impacting existing riparian zones. In the case that the riparian buffer requires reestablishment, impacts from high flow rates of existing stormwater infrastructure can be lessened using vegetation or structural LID BMPs. Riparian buffers can be designed with herbaceous vegetation or wooded plants such as trees and shrubs.
- **Floodplain and Detention Requirements** – The intent of floodplain and detention requirements is to minimize the hydraulic and hydrologic impact of development. On the floodplain management side, the development should not be placed in an area where it would be susceptible to flooding or cause flooding elsewhere. The first floor elevation is typically required to be a certain elevation above the local 1% ACE water-surface elevation, though a larger event can be chosen. The first floor is also typically required to be a certain elevation above local infrastructure markers such as the top of roadway curb (often approximately marking the extent of the public right-of-way) or storm sewer manhole (a portion of the stormwater infrastructure used to convey runoff). Detention is meant to ensure minimal hydrologic impact of developments and should be stipulated accordingly.

*Spatial Requirements:* The spatial requirements depend on the regulatory goal.

- **Minimizing Total Disturbed Area** – total disturbed area minimization can be prioritized in residential, commercial, industrial and recreational areas. Application could be limited in highly urbanized areas, retrofits or highway/road projects. This method is easiest to implement pre-development or through a master-planned approach.
- **Preservation of Natural Flood Pathways and Patterns** – this strategy can be applied to residential, commercial, industrial areas and along roadways. The need for a land buffer between the flow pathway and developed areas may be impacted by space constraints. Natural flow path and pattern preservation is most difficult to accomplish in highly urbanized areas that have already extensively impacted the hydrology and require stormwater infrastructure. This method, like most changes in land management, is easiest to implement through a pre-development master-planned approach.
- **Riparian Buffers** - The optimal width of riparian buffers varies by region, buffer type and may be impacted by local requirements. The Houston-Galveston Area Council (HGAC) recommends various buffer widths dependent upon the type of buffer and specific goals as summarized in Table 4 (HGAC, Riparian Buffer Tool).

**Table 4. Riparian Buffer Width Requirements (Source: HGAC Riparian Buffer Tool)**

| *Type* | Buffer Width (ft) |
|---|---|
| *Vegetated Buffer/Filter Strip* | 50 + ft. |
| *Contour Buffer* | 15 - 30 ft. |
| *Forested Buffer* | 35 + ft. |

**Figure 19. San Jacinto River 9/21/19, post-TS Imelda, just upstream of Lake Houston (Source: Molly Ross).**

- **Floodplain and Detention Requirements** – The regulations in and of themselves have no spatial requirements though may have implications for the spatial needs of a development. The volume needed for detention, and indirectly the space, generally scales with the size of the development.

*O&M Requirements:*

- **Minimizing Total Disturbed Area** – the O&M requirements for undisturbed land is minimal. If any disturbance occurs, O&M depends on the long-term plan for the land and level of disturbance (if any) that's occurred.
- **Preservation of Natural Flood Pathways and Patterns** – maintenance should be minimal if natural flow paths and patterns are preserved. Pathways should be inspected periodically to investigate sediment and debris accumulation, erosion, bank stability and vegetation conditions. If the discharge to these features is increased, care should be taken to mitigate impacts such as erosion, downcutting and overall degradation of the natural flow path (USACE, 2018b).

- **Riparian Buffers** - periodic inspections, vegetation management (fertilized, pesticides), replacement of dead trees or shrubs and invasive species management are recommended O&M practices. Additional requirements include controlling livestock, harmful wildlife, and excessive pedestrian and/or vehicular traffic.
- **Floodplain and Detention Requirements** – These requirements can be revisited over time to ensure they are working as intended.

*Environmental Considerations:*

- **Minimizing Total Disturbed Area** – In addition to aesthetic benefits, preserving green corridors and established vegetation mitigates negative habitat impacts and may reduce habitat fragmentation of existing habitat features.
  **Preservation of Natural Flood Pathways and Patterns** – The type of vegetation in the buffer zone varies by region. Riparian buffers provide a suite of environmental benefits, including improved habitat for aquatic organisms by providing shade and maintaining water temperature, reduced suspended solids and other containments from entering waterways through runoff and increase carbon storage in plant biomass.
- **Riparian Buffers** - Water quality is an important consideration if fertilization or pesticide use is required as part of the vegetation management plan.
- **Floodplain and Detention Requirements** – No specific environmental considerations associated with these regulations.

*Social Considerations:* Changes in regulations would affect the ability of developers and individual property owners to continue operating in the historic manner. Modifications to existing or new structures would likely result in higher costs to meet more stringent standards and in some areas such as low income neighborhoods the cost to comply may be a hardship resulting in the area being remaining at risk. When considering whether “grandfathering” of existing properties should be permitted, careful consideration will need to be given to balancing the land owners rights against the overall purpose and functionality of the regulation.

*Lead Time Considerations*: Any change in regulation will require significant coordination with the developers and the public to ensure full compliance.

*Reliability:*

- **Minimizing Total Disturbed Area** – minimizing the total disturbed area prevents and/or minimizes undesirable hydrologic consequences and maintains the level of service the area provided as is.
- **Preservation of Natural Flood Pathways and Patterns** – this strategy is reliable in maintaining the existing level of service of the pathway and avoiding undesirable impacts to hydrology on or near the site.
- **Riparian Buffers** – riparian buffers are reliable in terms of creating roughness along the overbanks of a channel as long as they’re maintained.
- **Floodplain and Detention Requirements** – The reliability of development requirements is predicated on their design relative to the performance.

*Adaptability:*

- **Minimizing Total Disturbed Area** – Minimizing the total disturbed area is adaptable in terms of strategy. It can be implemented on a small or large scale and applies to various flood risk management options. In terms of level of service, typically the greater the level of service, the more space will be required and greater area disturbed.

- **Preservation of Natural Flood Pathways and Patterns** – In the case that natural flow pathways and patterns must be adapted to a higher level of service, strategies can be implemented to mimic and/or maximize existing drainage patterns and flow paths.
- **Riparian Buffers** – riparian buffers can be restored along modified channels but are typically sensitive to water level and salinity (where applicable).
- **Floodplain and Detention Requirements** – The regulations are changeable over time in response to changed conditions or better information. In that sense the regulations are highly adaptable. However, developments are constructed based on the existing regulations at the time of construction. In that sense the requirements are minimally adaptable. Retroactively implementing regulations would be an onerous endeavor. This is an important reason to ensure regulations are well maintained and are working based on observations.

# 8 SUMMARY

Presented in this appendix are the variety of options available for mitigating flood risk in the Houston Metropolitan region. The applicability of each is a function of project goals, constraints, and management approach. This assessment inventoried and characterized various FRM options that can be applied to reduce flood risk from a single household to a regional scale. Some management options are best implemented pre-development (e.g. changes in land management) while others are suitable retrofits (e.g. green roofs) or re-development options.

The tools presented may be implemented individually but benefits may be maximized if a holistic, master-planned approach is taken that aims to achieve a suite of benefits and meet multiple goals beyond just flood risk management. An example of this philosophy in the Houston region is demonstrated in The Woodlands, TX implemented a master-plan approach as development continued by preserving riparian corridors and natural drainage pathways were preserved (Doubleday et al., 2013). A layered approach may provide risk reduction for the array of expected storms while minimizing undesirable tradeoffs. An example of this philosophy in the Houston region is the Clear Creek Federal Flood Risk management project, where the PDT has investigated ways to utilize the natural channel alongside high-flow areas or inline detention that are only utilized during severe storms, such as to 100-year, as seen in Figure . This approach must be uniquely tailored to the geographic location, existing infrastructure, and the social and environmental conditions of the associated community.

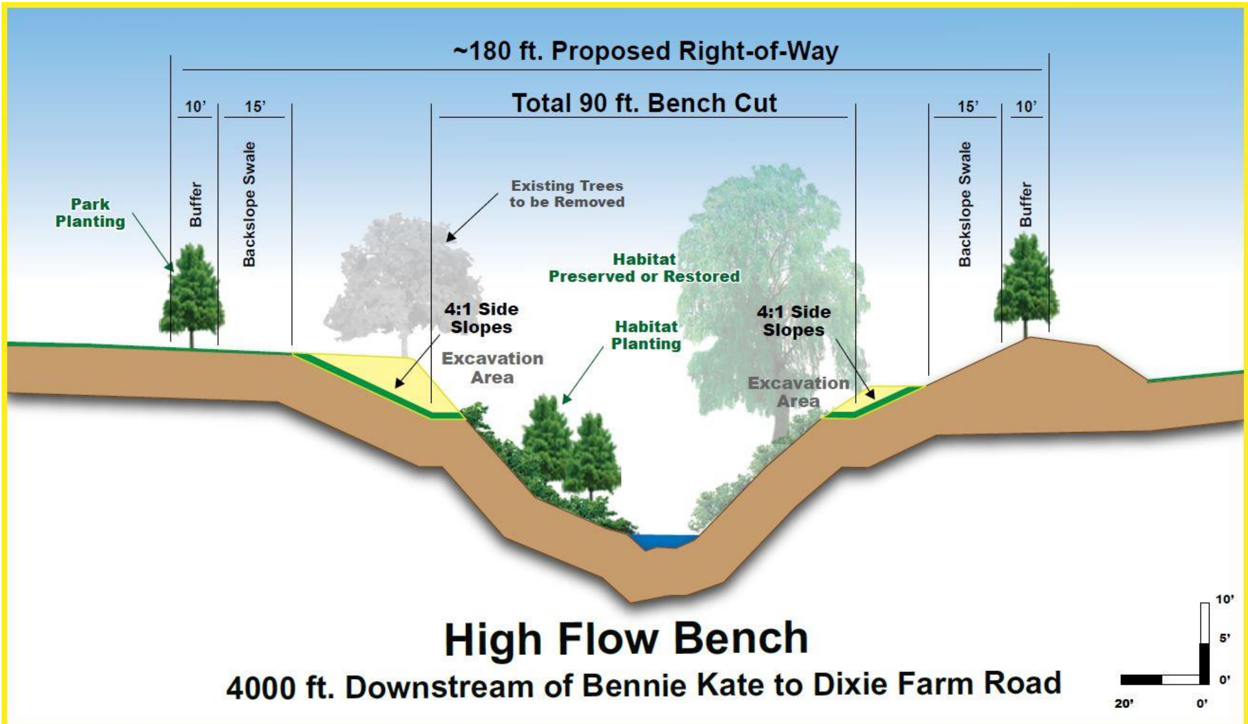



**Figure 20. Clear Creek Federal Flood Risk Management Project cross section example (Source: HCFCD, 2020).**

With any flood risk management project, the context of present and future conditions, such as storm severity and frequency, topography, soil conditions, climate change, are important factors in determining the best combination of measures. While there is evidence and success with green infrastructure, low-impact development, and natural and nature-based features delivering flood risk management benefits alongside co-benefits, the design and resulting performance of these structures in the Houston region would benefit from further research, most importantly regular monitoring of performance. Filling knowledge gaps in the performance of green and nature-based infrastructure provides engineers, planners and project managers with the support they need to investigate, and implement with confidence, green and/or green-gray hybrid flood risk management infrastructure solutions.

# 9 References

American Rivers, American Society of Landscape Engineers, ECONorthwest, Water Environment Federation. 2012. Banking on Green: A Look at How Green Infrastructure Can Save Municipalities Money and Provide Economic Benefits Community Wide. Retrieved from: https://www.asla.org/uploadedFiles/CMS/Government_Affairs/Federal_Government_Affairs/Banking%20on%20Green%20HighRes.pdf

Anderson, B.G. 2006. Quantifying the Interaction Between Riparian Vegetation and Flooding: From Cross-Section to Catchment Scale. PhD Dissertation. Department of Civil and Environmental Engineering, The University of Melbourne.

City of Houston (COH). 2020. Infrastructure Design Manual Chapter 9: Stormwater Design and Water Quality Requirements. Retrieved from: https://www.houstonpermittingcenter.org/office-city-engineer/design-and-construction-standards#agency-links-1471

DC Water and Sewer Authority (DC Water). 2015. Long Term Control Plan for Green Infrastructure.

Environmental Protection Agency (EPA). 2001. Functions and Values of Wetlands. Office of Wetlands, Oceans and Watersheds. EPA 843-F-01-002c.

Federal Emergency Management Agency (FEMA). 2014. Homeowner's Guide to Retrofitting: Six Ways to Protect Your Home from Flooding. FEMA P-213, 3rd Edition.

Federal Emergency Management Agency (FEMA). 2005. National Flood Insurance Program (NFIP) Floodplain Management Requirements: A Study Guide and Desk Reference for Local Officials. Retrieved from: https://www.fema.gov/sites/default/files/documents/fema-480_floodplain-management-study-guide_local-officials.pdf

Foster, J., Lowe, A., Winkelman, S. 2011. The Value of Green Infrastructure for Urban Climate Adaptation. The Center for Clean Air Policy Retrieved from: http://ccap.org/assets/The-Value-of-Green-Infrastructure-for-Urban-Climate-Adaptation_CCAP-Feb-2011.pdf

Freese and Nichols. 2019. HCFCD Design Criteria Memorandum Deep Tunnel Study Phase 1. Retrieved from: https://www.hcfcd.org/Portals/62/Downloads/Z08-Tunnel-Study/SM_HCFCD-Tunnel-Study-Phase-1-Design-Criteria-Memo-Final.pdf?ver=5wNWsV_Y09T-t_bf-fKjng%3d%3d

Freese and Nichols. 2017. Lower White Oak Bayou Channel Restoration Study, prepared for HCFCD.

Harris County Flood Control District (HCFCD). 2020. C-03 Federal Flood Risk Management Project. Retrieved from: https://www.hcfcd.org/C03

Harris County Flood Control District (HCFCD). 2019a. Preliminary Opinion of Tunneling Applicability. Retrieved from: https://www.hcfcd.org/Portals/62/Downloads/Z08-Tunnel-Study/Preliminary-Opinion-of-Tunneling-Applicability-Final-HCFCD-Tunnel-Study-Phase1.pdf

Harris County Flood Control District (HCFCD). 2019b. Design Criteria Memorandum Deep Tunnel Study Phase 1. Retrieved from: https://www.hcfcd.org/Portals/62/Downloads/Z08-Tunnel-Study/Design-Criteria-Memo--Final-HCFCD-Tunnel-Study-Phase1.pdf

Harris County Flood Control District (HCFCD). 2011. Harris County Low Impact Development & Green Infrastructure Design Criteria for Storm Water Management. Retrieved from: https://www.hcfcd.org/About/Technical-Manuals/Harris-County-Low-Impact-Development-Design-Criteria-Manual?folderId=16300&view=gridview&pageSize=10

Houston Galveston Area Council (HGAC). 2016. Designing for Impact A Regional Guide to Low Impact Development. Retrieved from: https://www.h-gac.com/low-impact-development/documents/Designing-For-Impact-Guide-for-Governments.pdf

Houston Galveston Area Council (HGAC). Riparian Buffer Tool. Retrieved from: https://h-gac.maps.arcgis.com/apps/MapSeries/index.html?appid=d87a240e6e134259997253810f16e555

Juan, A., Hughes, C., Fang, Z., Bedient, P. 2016. Hydrologic Performance of Watershed-Scale Low-Impact Development in a High-Intensity Rainfall Region. Journal of Irrigation and Drainage Engineering / Volume 143 Issue 4. https://doi.org/10.1061/(ASCE)IR.1943-4774.0001141

Perica, S., Pavlovic, S., St. Laurent, M., Trypaluk, C., Unruh, D., Wilhite, O. 2018. U.S. Department of Commerce (USDOC) – National Oceanic and Atmospheric Administration. National Weather Service. NOAA Atlas 14. Precipitation-Frequency Atlas of the United States. Volume 11 Version 2.0: Texas.

Smith, B. A. 2017. 2016: A Historic Year for Billion-Dollar Weather and Climate Disasters in U.S. Retrieved from: https://www.climate.gov/news-features/blogs/beyond-data/2016-historic-year-billion-dollar-weather-and-climate-disasters-us

U.S. Army Corps of Engineers (USACE). 2021. Engineering With Nature. Retrieved from: https://ewn.el.erdc.dren.mil/about.html

U.S. Army Corps of Engineers (USACE). 2018a. Engineering Manual 1110-2-1420 Hydrologic Engineering Requirements for Reservoirs. Retrieved from: https://www.publications.usace.army.mil/Portals/76/Users/182/86/2486/EM_1110-2-1420.pdf?ver=2018-11-29-122500-613

U.S. Army Corps of Engineers (USACE). 2018b. Army Low Impact Development Planning and Cost Tool User Guide. Retrieved from: https://rfpwizard.mrsi.erdc.dren.mil/MRSI/content/sustain/CX-KR%20Documents/LID/Design%20Tools/army-lid-planning-and-cost-tool-user-guide_jan-2018.pdf

U.S. Army Corps of Engineers (USACE). 2013. Army Low Impact Development Technical User Guide. Retrieved from: https://www.usace.army.mil/Portals/2/docs/Sustainability/Hydrology_LID/Army_LID_Technical_User_Guide_January2013.pdf

U.S. Army Corps of Engineers (USACE). 2006. Levee Owner's Manual for Non-Federal Flood Control Works – The Rehabilitation and Inspection Program. Public Law 84-99. Retrieved from: https://www.lrh.usace.army.mil/Portals/38/docs/civil%20works/Levee%20Owners%20Manual.pdf

U.S. Army Corps of Engineers (USACE). 2000. Engineer Manual 1110-2-1913 Design and Construction of Levees. Retrieved from: https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-1913.pdf?ver=FNvAjjrkr3DzvbKHsKbZIg%3d%3d

U.S. Army Corps of Engineers (USACE). 1994. Engineer Manual 1110-2-1601 Hydraulic Design of Flood Control Channels. Retrieved from: https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-1601.pdf?ver=2013-09-04-070804-047

U.S. Executive Office of the President (USEOP) Interagency Floodplain Management Review Committee. 1994. Sharing the Challenge: Floodplain Management into the 21st Century, prepared for the Administration Floodplain Management Task Force by Garold E. Galloway, U.S. Government Print Office, Washington D.C. Retrieved from: https://usace.contentdm.oclc.org/digital/collection/p266001coll1/id/2471/

Water Environment Federation. 2018. Deep Tunnels: Lessons Learned from Around the World. Retrieved from: https://www.wef.org/globalassets/assets-wef/direct-download-library/public/03---resources/wsec-2018-tr-002-lift-deep-tunnels-lessons-learned---final.pdf

# Attachment A - Engineering with Nature: Watersheds and Green Infrastructure Applications and Models

## 1. PURPOSE

The purpose of is catalog is for the ease of access to environmental tools that can fit be found suitable for the type of practices one is going for. The tools that are incorporated into the catalog are created by the U.S. Army Corps of Engineers (USACE), the Environmental Protection Agency (EPA), Harris County Flood Control District (HCFCD) and others. These tools are able to assist in different scales ranging from neighborhood/household to regional scales.

## 2. BACKGROUND

A healthy watershed benefits the ecosystem by providing several services in that ecosystem. This can include things such as improving the water quality, carbon storage opportunities, an increase in resilience from climate change threats and reducing the risk of invasive species. By also maintaining a watershed, they can also come with economic benefits as well. These benefits can come by reducing the cost of drinking water treatment and infrastructure, reducing flood mitigation cost and increase revenues and job opportunities. Several tools are included in an environmental tool catalog that can contains several different environmental tools by USACE, EPA, HCFCD and others. One of the tools that can be used for watersheds is known as the Watershed Management Optimization Support Tool.

The Watershed Management Optimization Support Tool (WMOST) is a decision-based support toll that can facilitate integrated water management at a local or small scale. The tool is able to model environmental effects and cost of management decisions in a watershed, factoring in direct and indirect effects of the decisions. WMOST is intended to be a screening tool that is part of an integrated watershed management process. This tool is a public-domain, efficient, and user-friendly tool for local water resources managers and planners to screen a wide range of potential water resources management options. Several practices that be assessed related to stormwater (i.e. green infrastructure and combined sewer overflow systems), stream restoration, water supply, wastewater and land resources like low-impact development and land conservation.

Green infrastructure is, in Section 502 of the Clean Water Act, defined as "… the range of measures that use plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evapotranspirate stormwater to reduce flows to sewer systems or to surface waters." As gray infrastructure is more of a human-engineered infrastructure by using pipelines and reservoirs. Green infrastructure uses cost effective approaches that are able to manage the wet weather impacts thus creating community benefits. This tool can be beneficial in the MHRWA study with its hazards.

The Metropolitan Houston Regional Watershed Assessment study area has two flood hazards: rainfall runoff and storm surge. Runoff is defined as the part of precipitation, snow melt, or irrigation water that is uncontrolled by surface streams, rivers, drains or sewers. It is classified by the speed of appearance after rainfall as direct runoff. It is also defined as the depth to which a watershed would be covered if all of the runoff for a given period of time were uniformly distributed around it. Storm surge is defined as the abnormal rise in seawater level during a storm, which is measured as the height of the water above the normal predicted astronomical tide.

The tool WMOST may be able to assist with green infrastructure practices as well as comparing it to grey infrastructure too. WMOST could assist in the rainfall runoff section of the Metropolitan Houston Regional Watershed Assessment. Green infrastructure can help assist with the rainfall runoff as well as storm surges. In South Norwalk, Connecticut, the city is working to install green infrastructure around set buildings to assist with storm surges.

There are several other studies about how green infrastructure can be effective on watersheds and constructed wetlands. Several sampling studies, databases, and articles supporting green infrastructure practices. According to a study at the University of New Hampshire Stormwater Center, performance summaries of 17 stormwater treatment practices and a detailed cost and data for nine stormwater treatment practices are detailed.

One such case of a successful mission with green infrastructure is Sheldon Lake State Park. The area around the state park was leveled for agricultural and developmental purposes for 50, however, the wetland was restored by using key mapping materials collected and digitized to identify mima mound signatures and upland brushes. The map was then layered together and by using GIS technology land bounders were identified before the land was leveled. Geocertifed maps were completed and engineering documents were created with excavation depths added, ponds were then excavated and planted with native wetland plants restoring the land.

## 3. WATERSHED

A watershed is a land area that channels rainfall and snow melt to creeks, streams, and rivers to outflow points such as reservoirs, bays, and the ocean. Having a healthy watershed can improve water quality by filtering pollutants by taking advantage of the natural landscapes and floodplains from point and nonpoint sources, thus promoting nutrient cycling, and retaining sediment.

Watersheds that have natural land cover and soil resources can sequester carbon and offset greenhouse gasses as well as increasing the resilience in climate changing threats. Having a healthy and maintained watershed can help reduce water treatment and infrastructure cost. Floodplains and natural landscapes are able to minimize area and impacts of floods, thus meaning that there is a reduction of the public drainage infrastructure and increase groundwater recharge.

There are factors that determine how much water will flow into a watershed. The amount of precipitation from the rain and the infiltration from the rain into the soil will determine the amount of water in the watershed. This can be caused by the type of soil, the saturation of the soil, and land cover, and the slope of the land that is provided. Evaporation of the water from rainfall, transpiration, as well as storage of the water is a deterministic of the amount of water that is within a watershed.

TOOL DISCUSSION (Appendix)

The tools below are tools developed by EPA, USACE, and Engineering With Nature (EWN) in order to help with stormwater management practices. These tools can be accessed on the EPA website and the EWN website which can also contain a fact sheet to give more of a description to what the tool specializes in. The tools are able to assist in green infrastructure design and modeling.

# 4. EPA

## 4.1. Storm Water Management Model (SWMM)

https://www.epa.gov/water-research/storm-water-management-model-swmm

SWMM is a software application that is used for large-scale planning, analysis, and design that is related to storm water runoff. This application allows users to represent combinations of green infrastructure practices to determine the effectiveness of how they manage water runoff. The application itself was developed to support local, state, and national stormwater management objectives to reduce runoff through infiltration and retention. The SWMM application was tested on low impact development models.

## 4.2. National Stormwater Calculator (SWC)

https://www.epa.gov/water-research/national-stormwater-calculator

SWC is an application that can estimate the annual amount of stormwater runoff from a location in the United States based upon soil conditions, land cover, and rainfall records. This tool is used to inform site developers on desired stormwater retention target with and without green infrastructure. The application itself is, "designed for the use by anyone interested in reducing runoff from a property, including site developers, landscape architects, urban panners, and homeowners." The software can be downloaded and used via mobile and desktop complete with user guides.

## 4.3. Green Infrastructure Wizard (GIWiz)

https://cfpub.epa.gov/giwiz/

GiWiz is a web application that can provide the user with customized reports that contain EPA tools and resources that they can select. The application can, "support and promote water management and community planning decisions."

## 4.4. Visualizing Ecosystems for Lang Management Assessment (VELMA) Model

https://www.epa.gov/water-research/visualizing-ecosystem-land-management-assessments-velma-model-20

VELMA is a software model that is used to improve the water quality of watersheds by using both natural and engineered green infrastructure to control loadings from nonpoint sources of pollution. The purpose of this is to, “help users asses green infrastructure options for controlling the fate and transport of water, nutrients, and toxics across multiple spatial and temporal scales for different ecoregions and present and future climates. The model can also be used with green infrastructure maintenance and longevity to predict how some riparian buffers can fail, due to contaminant loads, soil properties, change in the climate and other factors. This can quantify tradeoffs in clean water, flood control, food and fiber, climate regulation, fish and wildlife habitat. More information can be found on the page with also the downloadable ZIP file with user manual.

## 4.5. Green Infrastructure Flexible Model (GIFMod)

https://gifmod.com/download-gifmod-installation-file/

GIFMod is a program that can create models which can be used to evaluate the performance of stormwater green infrastructure and other urban and agricultural best management practices. Users are able to build models to predict hydraulic and water quality performance with selected weather scenarios available. The program is also able to interpret collected field and lab data that provides deterministic and probabilistic inverse modeling capabilities. The models can be created in three levels, which is hydraulics, particle transport, and constituent fate and transport. The program can be downloaded by registering for the latest version.

## 4.6. Natural Infrastructure Opportunities Tool (NIOT)

https://www.arcgis.com/apps/MapSeries/index.html?appid=18079f5b628b4a7bb52acbe089d80886

This tool is a decision-based support tool that uses ARCgis and can help discover available resources for natural infrastructure projects. This can include movement and content of dredged material though placement of area capacities, dredging plans, and sediment characteristic descriptions. This tool main use is to help the user provide data informed perspective for several stakeholders with the goal of finding beneficial strategies to improve and increase the investment for natural infrastructure. By using datasets from multiple sources, the user can identify current infrastructure projects, and add resource or project needs. The tool can be accessed online and works with a selected web browser.

## 4.7. Engineering With Nature Project Mapper (ProMap)

https://ewn.el.erdc.dren.mil/ProMap/index.html

This is a geography-based data viewer that allows users to explore information that can be potentially helpful with the development of Engineering With Nature ideas during the planning of their projects. The projects can be viewed by infrastructure type or by their environmental or social benefits.

## 4.8. Thin Layer Placement (TLP) Website

https://usace.maps.arcgis.com/apps/MapSeries/index.html?appid=a731fd32f85c44109b9269e7c8d9c68f

This website can be used to consolidate information and data available from projects and literature relevant to thin layer placement as a resource. It contains resources that have all stages of dredged material based upon projects.

## 4.9. USACE NAVIGATION PORTAL

https://navigation.usace.army.mil/DIF/Explore

The navigation portal collects, stores, visualizes, analyzes, and distribute navigation-related data. The Navigation Data Integration Framework (NDIF) establishes detailed methodology linked data and tools thus making it easily available to our stakeholders. This will include dredging, surveying and mapping, marine transportation system and analysis tools, sediment and ecosystem management.

## 4.10. DREDGING OPERATIONS TECHNICAL SUPPORT (DOTS) APPLICATIONS

https://dots.el.erdc.dren.mil/

DOTS provides dredging related models and applications, these applications includes Fish and Migration (FR-M) Probabilistic Bioaccumulation Model, Dredged Material Disposal Management mode (D2M2), Bioaccumulation Risk Assessment Modeling System (BRAMS), BEST, DREDGeABiLity (DREDGABL), and Automated Dredging and Disposal Alternatives Modeling System (ADDAMS).

## 4.11. BENEFICIAL USE OF DREDGED MATERIAL (BUDM)

https://budm.el.erdc.dren.mil/

Part of the Engineer Research and Development Center (EDRC), this tool is used to increase public awareness with the use of dredged material as a valuable resource. Dredged material is a viable alternative to traditional methods for many projects. The tool/website can document beneficial use success domestically and globally, prove guidance documents in USACE standards that includes manuals, techniques, and policy documents, provide technical publications that relate to beneficial use outside of the USACE, and provide links to other websites and resources that have beneficial uses. This can help understand and use dredged material be used in a vast majority of projects for environmental, economic, and social purposes.

## 4.12. SEDIMENT ANALYSIS AND GEO-APP (SAGA)

https://navigation.usace.army.mil/SEM/Analysis

An application, tool, and database for entering, organizing, analyzing, and presenting costal and riverine sediment sampling events, testing results and related reports.

## 4.13. STEADY STATE SPECTRAL WAVE (STWAVE)

https://ewn.el.erdc.dren.mil/tools/stwave/STWAVE_manual.pdf

A model that is created by the EDRC that can be used to manage successful costal engineering projects by understanding the changing of the environment.

A spectral wave model that was developed by U.S. Army Engineer Research and Development Center (ERDC), Costal and Hydraulics Laboratory to stimulate wave propagation nearshore and transformation. This will include also refraction, shoaling, breaking, and wind-wave generation. The model is capable of half-plane and full-plane capabilities that is compliant with Earth System Modeling Framework (ESMF) which allow for easier coupling with other use models.

The model itself can be used to manage successful costal engineering projects by understanding the changing of the environment.

## 4.14. Particle Tracking Model (PTM)

https://www.aquaveo.com/downloads-sms

Able to accurately predict sediments and water-borne particles to aid costal engineering and dredging material management. Can be used to assess the impact of dredging and placement operations on containment transport, sensitive habitat, endangered species, rehandling, and beneficial use.

## 4.15. AQUAVEO Surface-water Modeling System

A tool that is capable of building a conceptual model by constructing high level representation of the model by using GIS objects. Able to scale, use reference images, and photo-realistic renderings. The SMS interfaces with a wide range of numerical models for applications including: Riverine analysis, contaminant transport, sediment transport, particle tracking, rural & urban flooding, estuarine, costal circulation, inlet & wave modeling.

## 4.16. Flood Education Mapping Tools

https://www.hcfcd.org/Resources/Interactive-Mapping-Tools/Harris-County-Flood-Education

A mapping tool that's purpose is to give information on the floodplains in the Harris County area. Originally developed to be a mapping tool for the Tropical Storm Allison Recovery Project (TSARP), the tool itself replaced the former at www.tsarp.org. The mapping tool is regularly updated with information from Federal Emergency Management Agency's Flood Insurance Rate Map (FIRM).

## 4.17. Mowing Schedule

https://www.hcfcd.org/Resources/Interactive-Mapping-Tools/Mowing-Schedule-Explained

A map that allows for one to keep up to date with the regular maintenance of mowing, selective clearing, hazardous tree removal, herbicide application, tree pruning, and removing sediment with foreign materials that surround and conflicts with the channels. The map will display if a section is either: completed, in progress, scheduled, cancelled, or not mowed by the HCFCD.

## 4.18. Flood Warning System

https://www.hcfcd.org/Readiness

A mapping system that is able to measure the amount of rainfall and monitor water levels in bayous and major streams in real time. The system itself relies on interconnected gage stations that are placed throughout Harris County bayous and their tributaries. The stations are equipped with sensors that are able to transmit data during heavy rainfall, tropical storms, and hurricanes. Some of the stations are also able to measure wind speed and direction, barometric pressure, air temperature, road temperature and humidity. A variety of watershed layers in a given area, view currently flooded roads, parks, and low-lying tools can be selected in the mapping tool. The channel statuses are also shown to display the bayou flooding areas. Rainfall (from the past 24 hours) will be displayed.

## 4.19. Regional BMP Database

https://www.hcfcd.org/Resources/Interactive-Mapping-Tools/BMPbase-Regional-BMP-Database

The Regional Best Management Practice Database application provides the Flood Control District, regional partners, and other interested parties a way to access and evaluate the effectiveness of structural BMPs constructed within the southeast Texas region. This application provides access to BMP effectiveness data through a mapping interface. It also allows the user to readily prepare maps, reports and statistical plots of the BMP effectiveness data.

## 4.20. Model and Map Management (M3) System

https://www.hcfcd.org/Resources/Interactive-Mapping-Tools/Model-and-Map-Management-M3-System

The Harris County Flood Control District's Model and Map Management (M3) System is an interactive tool designed to communicate and share changes to the Federal Emergency Management Agency's (FEMA) effective floodplain models for Harris County. The goal of the M3 System is to distribute FEMA effective models to the general public, track ongoing changes to the models resulting from development projects, and facilitate communication between FEMA, Harris County Flood Control District, Local Floodplain Administrators, and the community.

## 4.21. Harris County Floodplain Reference Marks

The Harris County Floodplain Reference Marks interactive mapping tool provides information from the Flood Control District's countywide network of reference marks. This on-line tool allows users to search by watershed, street address and other parameters to access information about specific numbered benchmarks. For each benchmark, the tool includes a description of its site location, plus a photograph and sketch of the site to help in locating the marker within the site. PDFs of the information may be easily downloaded and printed for field use.

# 5. ADDITONAL

The catalog's purpose is for the ease of access and quick response to the vast majority of tools that is provided by the EPA, USACE, EWN, and the HCFCD. The use of these tools can help with stakeholders and engineering with their projects. However, these tools can also help with the usage of green infrastructure and hopes to have the stakeholders use the, "natural and engineering processes to efficiently and sustainably deliver economic, environmental, and social benefits though collaborative processes.

# 6. Closing Remark

The tools that have been listed are some the incorporate possibilities of green infrastructure, however, depending on the situation only certain tools will work. One situation cannot be solved with all tools, but only a select few, however due to how readily accessible and updated the models and applications improvements will be made in the future and more possibilities are yet to come.

EPA and other institutes have been researching the usage of green infrastructure and with the tools that has been made accessible by EPA also algins with the goals of Engineering with Nature. "Engineering With Nature is the intentional alignment of natural and engineering processes to efficiently and sustainably deliver economic, environmental, and social benefits through collaborative processes." Green infrastructure does work and the tools that have been created demonstrates that there any many possibilities for the route to go.

## 7. REF.


https://www.epa.gov/hwp/benefits-healthy-watersheds

https://www.epa.gov/green-infrastructure/what-green-infrastructure

https://www.usgs.gov/special-topic/water-science-school/science/runoff-surface-and-overland-water-runoff?qt-science_center_objects=0#qt-science_center_objects

https://oceanservice.noaa.gov/facts/stormsurge-stormtide.html

https://www.epa.gov/ceam/wmost#description

https://www.epa.gov/sites/production/files/2016-09/documents/wmostv2_fact_sheet_508.pdf

https://tomorrow.norwalkct.org/news/cities-incorporating-green-infrastructure-help-storm-surges/

https://www.epa.gov/water-research/green-infrastructure-modeling-toolkit

https://onlinelibrary.wiley.com/doi/full/10.1111/1752-1688.12832

https://www.epa.gov/sites/production/files/2016-11/documents/giwiz_fact_sheet_final103116.pdf

https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=345068&Lab=NHEERL&showcriteria=2&keyword=VELMA&timstype=&timssubtypeid=&epanumber=&ombcat=Any&datebeginpublishedpresented=&dateendpublishedpresented=&datebeginupdated=&dateendupdated=&deid=&personname=&personid=&role=Any&journalname=&journalid=&publishername=&publisherid=&sortby=relevance&count=50

https://www.arcgis.com/apps/MapSeries/index.html?appid=18079f5b628b4a7bb52acbe089d80886

https://ewn.el.erdc.dren.mil/Tools.html

https://tlp.el.erdc.dren.mil/

https://dots.el.erdc.dren.mil/models5.html

https://oceanservice.noaa.gov/facts/watershed.html

https://www.usgs.gov/special-topic/water-science-school/science/watersheds-and-drainage-basins?qt-science_center_objects=0#qt-science_center_objects

https://ewn.el.erdc.dren.mil/about.html

https://www.hcfcd.org/Resources/Interactive-Mapping-Tools/Harris-County-Flood-Education

https://www.hcfcd.org/Resources/Interactive-Mapping-Tools/Mowing-Schedule-Explained

https://hcfcd.maps.arcgis.com/apps/View/index.html?appid=cc83f2c52901481eabff8774e4e12b3d

https://www.harriscountyfws.org/?View=full

BMPbase - Regional BMP Database (hcfcd.org)

Model and Map Management (M3) System (hcfcd.org)

https://www.hcfcd.org/Resources/Interactive-Mapping-Tools/Harris-County-Floodplain-Reference-Marks