North Central Texas Council of Governments

Integrating Transportation and Stormwater Infrastructure

Literature Review

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integrating Transportation & Stormwater Infrastructure

Integrating Transportation and Stormwater Infrastructure (TSI)

Literature Review

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1 Executive Summary

The purpose of this document is to present a survey of the literature and documentation applicable to the integrating Transportation and Stormwater Infrastructure (TSI) study. A comprehensive literature review was conducted, covering hydrology and hydraulics (H&H), transportation, and environmental perspectives. The resulting literature review document overviews methodologies and models related to the TSI project, previous studies conducted in the TSI study area, and similar efforts conducted across the globe.

An overview of the TSI project is provided in Section 2. Section 3 includes case studies, similar studies, and relevant concurrent studies. Section 4 overviews flooding, including types, mitigation methods, disasters, and damage information. Section 5 outlines future conditions, including population growth and projections, land use and imperviousness projections, and climate change. Section 6 covers planning, manuals, and guidance documents. Sections 7 and 8 include infrastructure, modeling, and optimization, respectively. Finally, Section 9 provides a list of references utilized in this research.

2 Introduction

This chapter presents an introduction to the TSI study, including an overview, background and motivation, and general information about the area of interest.

2.1 Background and Motivation

Despite significant technological and societal advances in recent decades, society and its' infrastructure continue to be impacted by natural disasters. Flooding is the costliest disaster and a component of 90 percent of natural disasters in the U.S. (FEMA, 2010). The U.S. has experienced 41 billion-dollar inland flooding events from 1980 to 2022, totaling approximately $187.6 billion (Consumer Price Index (CPI)-adjusted) (NOAA NCEI, 2023). Because of its size, the state of Texas experiences the most frequent and variable natural disasters, including floods, wildfires, tornados, hurricanes, hailstorms, sinkholes, erosion, and drought (California Institute of Technology, 2017). Texas alone accounts for nine of the 41 inland flooding events, resulting in a total of $10 to $20 billion in damages (NOAA NCEI, 2023). By the end of 2022, Texas has experienced 371 federally declared disasters since 1953, including 40 floods (FEMA, 2021).

Considering the scope of flood-induced destruction, the potential effects of climate change on flood events have become an ever-increasing concern. Research suggests climate change could impact the frequency and severity of floods through changes in spatial and temporal precipitation patterns (Ebi et al., 2018). While an increase in average annual precipitation has been observed from 1986 to 2015, average annual precipitation in Texas is not anticipated to change significantly in the future (Easterling et al., 2017). However, heavy precipitation events, a direct contributor to flash and urban flooding, have been increasing based on historical observations, and researchers are projecting further increases in frequency and intensity (Easterling et al., 2017; IPCC, 2014). Future changes in water quantity and quality, in addition to deteriorating water infrastructure, contribute to increased climate risk, necessitating water management and planning principles that adequately address these increased risks (Lall et al., 2018). While there are inherent uncertainties associated with climate change, the impact of urbanization on floods is clear.

At its core, urbanization refers to the movement of people to create areas with more densely packed populations, while urban sprawl refers to the expansion of cities outward, creating larger urban areas (Berry, 2008). While the definition of an urban area can vary throughout the world, approximately 55 percent of the world's population lives in urban areas (UN, 2019). In North America, the urban population percentage is even higher, over 80 percent, with a projected increase of over 50 million by 2050 (UN, 2019). Urbanization has an impact on flooding through increases in impervious areas and decreased hydrologic response time, leading to higher peak discharges occurring sooner after rainfall (Konrad, 2003; Feng et al., 2021). While climate change and urbanization are phenomena with intrinsic uncertainty, stormwater management is an established practice for addressing flooding. The water within the urban landscape must be stored and eventually transported downstream. Within an urban landscape, inadequate facilities for the storage of surface water coupled with increased, faster-responding runoff results in urban flooding. Large flood control projects in the form of reservoirs for water impoundment are found throughout the Texas landscape, more increasingly toward the eastern portions of the state that typically receive more rainfall. While these reservoirs can provide multiple benefits, including flood control, recreation, and water supply, they are not always a feasible solution for flood control, especially in rapidly urbanizing areas, due to the time required to plan, construct, and fill the reservoir. Additionally, they might not be required as flood storage when less flood storage is needed.

Stormwater management is not often considered on the watershed or regional scales. Rather, developments are built according to county or city criteria and fulfill a simple condition that the development cannot release more discharge from a specified event than the pre-development condition would create (Chen, 1995). Due to the increased imperviousness, on-site detention ponds are often employed to temporarily store water to reduce the release within the specified regulations. Stormwater detention ponds are a well-established and effective solution to reduce peak runoff from a developed land parcel and act to mitigate the adverse impact of urbanization on regional hydrology (Bennett & Mays, 1985). However, on-site detention ponds can have maintenance issues (Drumond et al., 2020) and inconsistent design due to variable design criteria. Because of these issues, regional stormwater infrastructure has been recommended for decades (McCuen, 1974; James et al.,1987; Chen, 1995; Yeh & Labadie, 1997). According to the literature, proper detention pond design should incorporate strategic locations (James et al., 1987), not be applied on a broad scale (Malcom, 1980), and consider volume-based runoff reductions (Emerson et al., 2005) and full catchment analysis (Beecham et al., 2005).

One potential area that can be utilized in an urban landscape for the storage of water is transportation systems. Paul et al. (2018) reported that flooding caused 65 percent of fatalities occurring on transportation routes and further recommended investment in reducing this risk should be prioritized. While roadways themselves are not a safe storage option, the land containing transportation infrastructure affords opportunities for TSI to create a proactive regional stormwater management strategy. At the regional level, population growth and land use changes are anticipated by transportation planners, who then adjust regional transportation plans for their impact (TxDOT, 2020). With these opportunities in mind, the Texas Water Development Board (TWDB) has recently been tasked with creating the first regional and state flood plans to begin a proactive approach to stormwater management (TWDB, n.d.-a).

Previous efforts to combine TSI have been documented at both the national (AASHTO, 2012) and state levels (Rogers et al., 2020). Within the available literature, the reported benefits of TSI include cost savings, fewer disruptions, and a better understanding of other management systems (Araya & Vasquez, 2022). In addition to the consideration of integration between transportation and stormwater systems, environmental impacts and solutions should be considered. Many studies and reviews have been conducted on the environmental considerations of stormwater management. Topics including green stormwater infrastructure (GSI), low-impact development (LID), best management practices (BMPs), water-sensitive planning (WSP), and sustainable urban drainage systems (SUDS) (Duan et al., 2016; Eckart et al., 2017; Fletcher et al., 2015; EPA, 2008; EPA, 2016; Rashetnia et al., 2022; Haris et al., 2016). Of these, three notable literature reviews were conducted: LID performance and implementation (Eckart et al., 2017); aims, achievements, strengths, and limitations of water-sensitive urban design (WSUD) (Rashetnia et al., 2022); and common urban stormwater management models, for example, Storm Water Management Model (SWMM), U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS), along with how they can be used for simulations with GSI (Haris et al., 2016). Furthermore, multiple manuals for the implementation of these features within the state of Texas have been developed (San Antonio River Authority, 2019; Harris County Flood Control District, 2011; City of Waco, Texas, 2011). An area projected to increase urbanization affords an opportunity to make use of these and other sustainable practices as methods of stormwater management.

While the frequency and severity of natural disasters and urbanization cannot be controlled, regional stormwater management can be planned. A regional stormwater planning approach projects future potential stormwater management needs and provides proactive solutions. Moreover, studies call for "institutional reform" (Brown, 2005) and a "paradigm shift" (Dhakal & Chevalier, 2016; Novaes & Marques, 2022) where urban stormwater policy is concerned.

2.2 Project Overview

The TSI study aims to approach stormwater management regionally and proactively. In the past, stormwater management has neglected to consider valuable planning opportunities that the transportation planning sector has considered through five-year metropolitan planning organization (MPO) cycles. By utilizing the existing documentation and data from the transportation and urban planning sectors, plans for optimized locations of regional infrastructure can mitigate future flooding before development occurs. The TSI study aims to create a catalog of proactive infrastructure options to present to cities and counties within their jurisdiction that are anticipated to experience urbanization. The study focuses on providing practical infrastructure options that lessen the impact of urbanization on downstream communities. The results of this study can be shared to help other metropolitan areas proactively deal with anticipated population growth through the development of plans to approach stormwater infrastructure and flooding mitigation. Through the integration of transportation, environmental, and stormwater planning, the project aims to provide regional benefits for multiple parties, including cities, counties, developers, transportation entities, and utilities responsible for water and wastewater services, ultimately increasing community resiliency.

2.3 Study Area

Areas west and north of the Dallas–Fort Worth (DFW) Metroplex located within the North Central Texas Council of Governments (NCTCOG) boundary have been selected as the "study area" and are referred to separately as the North Study Area and the West Study Area (shown in Figure 1). The West Study Area consists of less developed areas to the south, west, and northwest of the DFW Metroplex, while the North Study Area is generally characterized by less developed areas north and northwest of the core DFW Metroplex. The North Study Area population is approximately 580,555 according to the 2024 U.S. Census Bureau, while the West DFW Study Area population is 442,171 according to the 2018 U.S. Census Bureau. The North Study Area currently encompasses approximately 1,125.50 square miles and includes all of Denton County and portions of eastern Wise County and northern Tarrant County. The West Study Area encompasses approximately 1,750 square miles and is bound by county lines between Wise County and Jack County to the west and Wise County and Montague County to the north. Both study areas are bounded by county and watershed boundaries, with county boundaries aligning with the NCTCOG boundary and watershed boundaries ensuring that the study areas include only areas within the Trinity River Basin. The West DFW Study Area includes portions of Ellis, Hood, Johnson, Parker, Tarrant, and Wise counties.

The study area is upstream of the DFW Metroplex and is anticipated to experience urbanization and population growth, making it an ideal candidate for proactive regional stormwater management. Any increase in runoff or adverse effects from urbanization may cause or worsen flooding in communities in the DFW Metroplex along the Trinity River, notably Fort Worth, Arlington, Grand Prairie, and Dallas. Future conditions in the DFW Metroplex, including changes in frequency, duration, and intensity of storms, can present additional challenges for stormwater planning.

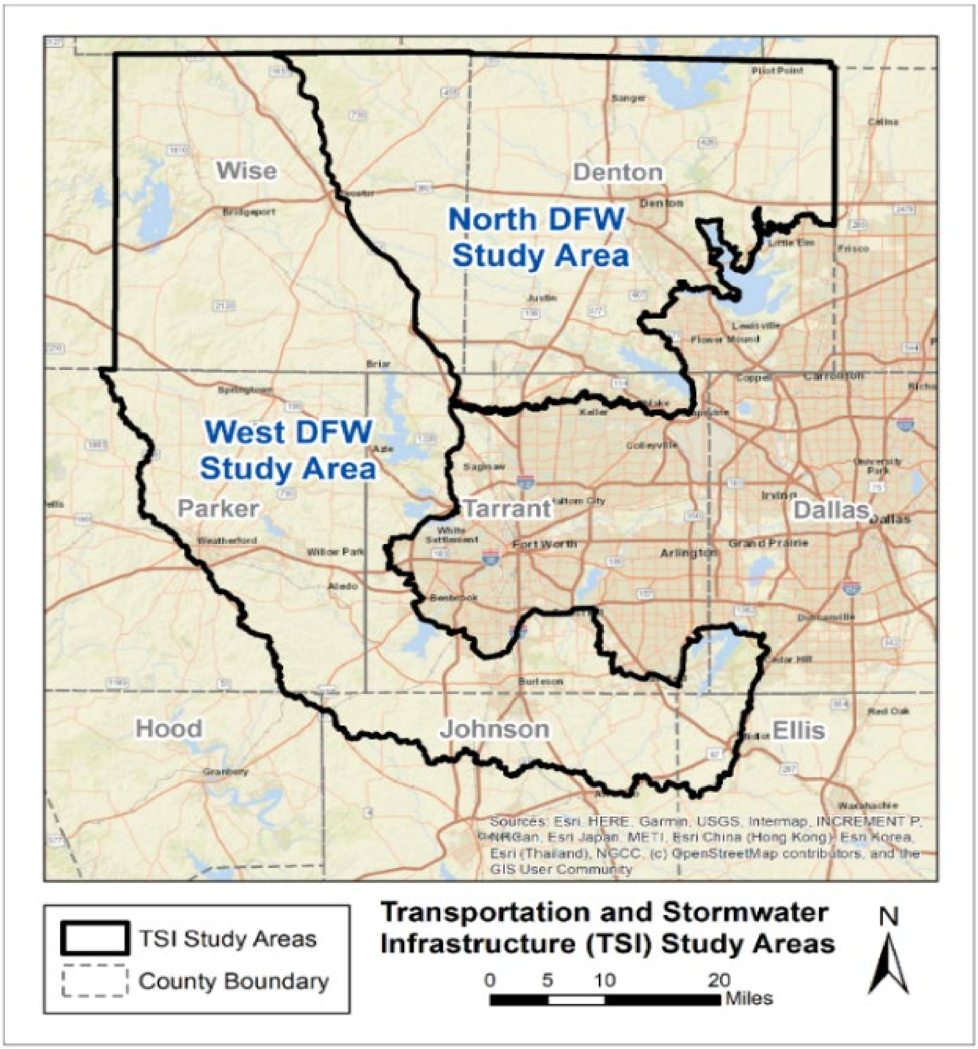

Figure 1: **TSI Study Area Map**

3 Case Studies, Similar Studies, and Concurrent Studies

Existing MPO and related resiliency studies show that flooding is an increasing threat to transportation systems. The literature indicates that no single study fully integrates transportation planning, stormwater infrastructure, environmental considerations, economic analysis, and interdisciplinary coordination at a regional scale—the key gap the TSI study is intended to address.

3.1 Case Studies from Municipal Planning Organizations

Flooding is the most frequent and expensive environmental threat to transportation infrastructure (Fletcher & Ekern, 2021), according to a National Cooperative Highway Research Program report. This report identifies the top ten research needs in transportation resiliency. Five of those research needs are addressed by the TSI study, including integrating resilience into transportation project development, economic benefits from making investments in resilient transportation assets, design guidance and standards for resilience, assessing and managing the vulnerability of transportation assets, and using improved hydrological forecasting to improve transportation resilience.

Existing transportation resiliency studies also have addressed some of these research needs. The TSI study team reviewed these resiliency studies to identify the extent to which existing studies addressed these and other research needs and which gaps remained to be addressed. The study team also sought to identify whether the TSI study was breaking new ground in integrating planning for transportation and stormwater infrastructure. MPOs conduct metropolitan transportation planning in urbanized areas where populations exceed 50,000 (FTA, 2022). The NCTCOG and the Regional Transportation Council operate as the MPO for North Central Texas.

The U.S. Department of Transportation (USDOT) issued a policy statement on climate change adaptation in June 2011 (Federal Highway Administration, 2011). Additional memorandums and orders followed from the Federal Highway Administration (FHWA) to promote planning and construction of surface transportation infrastructure that enhances resiliency in the face of increasingly extreme weather. Federal transportation legislation signed in 2015 mandated states and MPOs' obligation to improve the transportation system's resiliency. This legislation, the Fixing America's Surface Transportation Act, resulted in transportation planning regulations requiring MPOs to consider resiliency and reliability during planning, consult with natural disaster risk reduction experts when developing a metropolitan transportation plan, and assess strategies for the reduction of transportation system vulnerabilities in the face of natural disasters (FHWA, 2017a). Current legislation provides more than $8.7 billion for resiliency projects. The Bipartisan Infrastructure Law, signed in 2021, also promotes natural infrastructure, which utilizes the natural environment to prevent flooding and other natural disasters (U.S. Department of Transportation, 2022).

The FHWA has funded resiliency pilot projects since 2010. MPOs, councils of governments (COGs), and state departments of transportation have conducted at least 56 studies with FHWA funding (Federal Highway Administration, 2021). However, TSI diverges from FHWA’s vulnerability assessment frameworks (FHWA, 2012; Filosa et al., 2017) by incorporating interdisciplinary components into the TSI study. Additionally, the distance between the North Central Texas study area and the Texas Coastal Plains is a limiting factor for this literature review, focusing instead on studies related to riverine flooding and increased precipitation.

Existing studies utilize a range of data and expertise to predict future flooding and infrastructure at risk from this flooding. Studies with the most robust methods to predict future flooding relied on H&H modeling tools, including modeling systems from the USACE Hydrologic Engineering Center, future precipitation data from National Oceanic and Atmospheric Administration (NOAA) Atlas 14, LiDAR (Light Detection And Ranging) data, and global climate models.

A Pennsylvania Department of Transportation (PennDOT) study incorporated H&H modeling to estimate future flood discharges (Pennsylvania Department of Transportation, 2020). This pilot study focused on three study sites identified by a collaboration between MPOs and the PennDOT. Existing and future conditions were modeled using the USACE HEC-HMS models, integrating precipitation ratios to predict future conditions (one case included future land use). As part of a statewide analysis, the study investigated the use of future precipitation values in

H&H modeling. Localized Constructed Analogs were also employed to conduct statistical downscaling of global climate data sets while using rainfall projections based on NOAA Atlas 14, Volume 2. The study identified inconsistencies in the results and found some projections to be unrealistic. The PennDOT study proposed a direction for future research that addresses the following questions:

1. How should those precipitation ratios be applied within the H&H process?
2. What future precipitation ratios are appropriate for application?
3. What hydraulic parameters should be evaluated under existing and future precipitation scenarios to help identify resilient design options?
4. What resilient design options should be considered?

The Pennsylvania study team further noted that global climate models resulted in significant variability, and precipitation forecasts had low probability. However, there was a consensus of recommendations for substantial design changes.

An FHWA-funded study in Colorado included engineering analyses on watershed hydrology and culvert hydraulics (FHWA, 2017b). The study is part of the broader Transportation Engineering Approaches to Climate Resiliency Study, which seeks to incorporate climate considerations into transportation project development (FHWA, 2020). While the Colorado study was not conducted by an MPO or COG, it was included in this literature review because of its applicability to TSI. The Colorado study leveraged future climate simulations to estimate future precipitation and stream flow rates for extreme precipitation events. A hydrologic watershed model was created using HEC-HMS Version 4.1 based on existing land cover and observed precipitation. The model was calibrated with historical data on stream flow, including data from a Federal Emergency Management Agency (FEMA) Flood Insurance Study. Following calibration, future climate predictions were then incorporated into the hydrologic model. The output identified stream flows for selected extreme precipitation events. The future conditions included projections for 2045, 2065, and 2085. The hydraulic engineering process then evaluated the performance of a culvert on US 34 utilizing the USACE Hydrologic Engineering Center's River Analysis System (HEC-RAS) Version 4.1.

Important lessons learned related to flood predictions were included in the Colorado Study. First, averaging the results of statistics for multiple climate scenarios may mask likely future conditions because the climate scenarios can predict both significant increases and decreases in projected precipitation. Instead, the study team processed data using a "binned approach" (p 112) and samples of future conditions. Second, sub-24-hour data for precipitation projections (i.e., precipitation events lasting less than 24 hours) resulted in uncertainties. However, sub-24-hour data is needed to calibrate the peak stream flows of the watershed. The resulting conclusion is that additional research is needed in this area.

In a study conducted by the Austin, Texas, MPO future flows through approximately 2040 were considered (Cambridge Systematics, Inc., 2015). The study team modeled flooding using a physics-based model called V*flo*. V*flo*, developed for the city's Flood Early Warning System, has undergone accuracy tests against storms since 2008. While considering projected climate change scenarios, this study incorporated projected changes to demographics to increase the percentage of impervious surfaces within the model. The model assimilates data on land use/land cover, soils, imperviousness, hydraulic capacity of stream channels and drainage ways, slope, and drainage direction. Results have been tested via comparison to Light Detection and Ranging (LiDAR) data at a 10-meter resolution, and baseline inundation maps and future inundation maps were produced (incorporating impervious surface growth and increased rainfall intensity).

The culmination of results from the Austin study determined that increases in imperviousness alone generated little increase in flooded extent. These findings led to a decision to model inundation based on increased imperviousness and projected rainfall. Another relevant finding distinguished the relationship between flooding and rainfall as nonlinear, with flooding increasing at a rate greater than the increased precipitation rate. Lastly, the geometry of the stream channel was found to impact the range in peak discharge and inundation extent.

In another study, the Southeast Michigan Council of Governments (SEMCOG) partnered with the Michigan Department of Transportation (MDOT) to develop its Climate Resiliency and Flooding Mitigation Study on the vulnerability of infrastructure to flooding (Bhat et al., 2020). Factors in calculating exposure to flood risk included past flooding experience, FEMA flood zone location, flow accumulation and ponding, impervious surface, and change in days with precipitation greater than 3 inches. Precipitation projections used in this study were developed in a 2020 report entitled Southeast Michigan Current and Future Precipitation (TetraTech, 2020). This report calculated future rainfall within the SEMCOG region for storm events ranging from 1-year to 100-year events, for durations ranging from 5 minutes to 24 hours, and for two-time scales, mid-century and end-of-century. The base data adopted for the study was NOAA's Atlas 14. Calculations of precipitation frequency considered intensity-duration frequency equations. Temporal rainfall distributions, which describe the variation of rainfall intensity during a storm, are considered synthetic rainfall distributions from Natural Resources Conservation Service (NRCS) Type II, NRCS Midwest and South-East, Huff distributions, and NOAA Atlas 14. The results of this study were developed into a Flooding Risk Tool that is presented in an interactive viewer. A primary finding determined that much of the high-risk infrastructure is located along high-risk road segments (Bhat et al., 2020).

NCTCOG conducted an FHWA-funded resiliency pilot study that helped identify the need for a more in-depth TSI study (Winguth et al., 2015). The pilot study predicted increases in rainfall, spring thunderstorms, and flooding from autumn tropical storm systems. Quantifiable results indicated the escalation of mean rainfall escalating 10 percent and severe thunderstorms swelled by up to 40 percent in the spring season. The study found that these changes likely lead to a higher risk of flooding affecting transportation infrastructure. A notable variation in precipitation across the NCTCOG region is a significant distinction for the study, with a difference of about 12 inches per year from western counties to eastern counties. Climate inputs relied on data from the Intergovernmental Panel of Climate Change and Community Earth System Model Version 1.2 from the National Center of Atmospheric Research. However, due to time constraints, the study neglected the use of elevation data, local drainage/runoff characteristics, and other engineering factors being used to assess the vulnerability of transportation infrastructure, instead focusing on infrastructure located in the 100-year floodplain. The conclusion of the study suggests improving precipitation projections by using high-resolution data from the Center for

Collaborative Adaptive Sensing of the Atmosphere (CASA), and three-dimensional models such as LiDAR to better identify transportation infrastructure at risk of flooding.

The Metropolitan Council (Met Council) is the regional planning agency for Minnesota's seven-county Twin Cities region. The Met Council conducts planning related to housing, parks, transportation, wastewater, and water. It serves as the region's public transit provider. This range of services led the Met Council to conduct a resiliency assessment beyond the scope of most agencies that conduct metropolitan transportation planning. The Regional Climate Vulnerability Assessment evaluated potential impacts to transit and wastewater infrastructure, water supply, water quality, and the health and safety of the region's residents (Metropolitan Council, 2018a; Metropolitan Council, n.d.) while relying on geospatial analysis to predict future flooding hotspots. Flood risk was measured using 100-year and 500-year floodplains from FEMA's Digital Flood Insurance Rate Maps (DFIRM). The study used NOAA's Atlas 14 precipitation data to aid in analyzing blue spots or low-elevation areas that could experience localized flooding during short-term, extreme rain events. Utilizing ArcGIS's Spatial Analyst to determine the level of water in each blue spot, a spectrum of blue coloration allows the evaluator to visualize the depth of flooding and the extent of flooding within Met Council facilities (Metropolitan Council, 2018b). The study concluded that varying degrees of vulnerability existed for the sites tested and further recommended site-by-site potential localized flood risks to all facilities (Metropolitan Council, 2018b).

The MPO in Broward County, Florida, used geospatial data to predict future flooding while acknowledging the challenges of making an accurate prediction (Parsons Brinckerhoff, Inc., 2015). This 2015 pilot project funded by FHWA implemented the federal agency's Climate Change and Extreme Weather Vulnerability Assessment Framework. Data included LiDAR elevation contours and digital elevation maps; transportation network elevation, including transportation facilities constructed on embankments; and baseline flood information rectified for inaccuracies of topographic data used to develop 100-year flood data. Segments of the transportation network received vulnerability scores based on three factors; one of these factors, exposure, included future potential flood exposure due to precipitation. Future potential flood exposure was determined based on distance and elevation between transportation facilities and FEMA 100-year flood zones and flood levels, respectively. This method identified future flooding hotspots. The study noted challenges in predicting future flooding from precipitation, including the need for accurate data on the elevation of transportation facilities, which may have been constructed on an embankment or bridge; the limited accuracy of 100-year flood data; the effect of Florida's relatively flat topography on flood elevations; and the need to develop data and methodology that was consistent across the region. A second study conducted by the Broward County MPO in 2016 (WSP | Parsons Brinckerhoff, 2016) identified two actions relevant to predicting future flooding. These actions were incorporating FEMA analysis and models into planning and design and conducting risk-based design that includes climate change impacts when calculating the whole lifecycle cost.

Partners in the Tampa Bay, Florida region also relied on geospatial data as they reviewed the impact of increased precipitation on the region's transportation network. The Resilient Tampa Bay study found that nine inches of precipitation in one day would impact more than 400 centerline miles in the region's three counties (Kiselewski et al., 2020). The nine-inch threshold was selected based on historical precipitation data. A ponding and flow accumulation model incorporated four Geographic Information System (GIS) layers to calculate flow into lower topographic areas. The four GIS layers included a precipitation modifier surface, land use/land cover, U.S. Geological Survey soils, and the LiDAR elevation model. Public works drainage infrastructure and facilities were excluded from the analysis because of the timeframe of the study. The study ultimately determined that nearly 20 percent of the region's highly critical roadway infrastructure was classified as highly or moderately vulnerable and further advocated for the identification of locations where improving resilience should be prioritized (Kiselewski et al., 2020).

The Houston-Galveston Area Council (H-GAC) conducted a resiliency pilot study that incorporated NOAA's Atlas 14 data, which has been updated for Texas (Sambidi et al., 2021). This update showed that precipitation from a 100-year storm over 24 hours has increased by 30 percent in the study area, from 13 to 17 inches. The study team used GIS data to create flood depth grids. FEMA-identified Special Flood Hazard Areas and flood risk maps, derived from H&H modeling, were also implemented to identify floodplains and 100-year and 500-year flood risk. LiDAR-driven Digital Elevation Models determined the elevation of the boundaries of 100-year and 500-year flood polygons. Water surface elevations for 100-year, 500-year, and Hurricane Harvey scenarios were created using a GIS interpolation tool. Flood depth was calculated by comparing water surface elevations, topography, and digital elevation models. While the study presents valuable findings for the Houston-Galveston region, four areas were noted as important areas of consideration for those pursuing similar research. These areas included the importance of available, quality data for the study, capable computer processors and software modelers for data analysis, providing easy access to findings through interactive web mapping, and a strong commitment to stakeholder engagement (Sambidi et al., 2021).

Ultimately, transportation resiliency studies varied in their methodology to predict future flood risk. The expertise to conduct H&H modeling typically would require MPOs and COGs to partner with another agency. Existing transportation studies address differing degrees of modeling to predict future flooding, stormwater infrastructure, environmental planning, economic analysis, and interdisciplinary partnerships and stakeholders. Few studies used H&H modeling to improve the accuracy of future flooding locations; some relied on geospatial analysis, such as proximity to the 100-year floodplain. While based on FEMA modeling, the 100-year floodplain can be outdated and does not address future land use, increased imperviousness, and future precipitation. Modeling is incomplete without incorporating stormwater infrastructure. Data on stormwater assets is limited, presenting a challenge to its use in transportation resiliency studies. Environmental considerations also are important in predicting and mitigating future flooding; this requires information on future land uses and plans to preserve open space and implement GSI (see more on studies that incorporate environmental planning in section 6.6). Economic analysis is necessary for prioritizing stormwater infrastructure tied to transportation facilities and incorporating such infrastructure into MPOs' long-range transportation plans. Finally, the breadth of knowledge required to study and plan to address flooding requires interdisciplinary partnerships and stakeholders.

While existing transportation studies cover each element of the TSI study, no one study ties all these elements together to plan to reduce flooding of transportation, residential, and critical infrastructure at a regional scale. The interdisciplinary study team and stakeholders of the TSI study will address important research gaps and produce a study that can be replicated to benefit other regions in Texas and the United States.

3.2 Similar Studies from Academic Journals

Searches for similar studies from academic sources is complicated by the expanse of the TSI project. However, TSI is primarily focused on planning for stormwater management, specifically for urban or urbanizing regional areas. Thus, a search for similar studies has focused on this element, while specific elements are investigated with the following chapters of the document.

Multiple review papers covering topics related to regional stormwater management have been published, highlighting the importance of regional stormwater management topics. Because of the expanse of the topic, the review papers themselves also fall into different categories, with some considering multiple angles: development condition, scale, environmental considerations, modeling, and optimization. The review papers range from broad studies to those considering only studies from specific angles. Wu et al. (2019) conducted a bibliometric overview of the stormwater management topic from 1980 to 2019, covering 3,080 articles. Approaching the topic from a bibliometric point of view, Wu et al. (2019) found that the stormwater management field is rapidly developing, with continuous hotspots and many research branches developing vigorously.

The topic is complicated by its relationship to policies and regulations. Novaes and Marques (2024) conducted a hybrid literature review covering the policies, institutions, and regulations surrounding stormwater management and found that there were still significant knowledge gaps in this coverage.

The scale focus of stormwater management literature can have a significant impact on the focus of the study. As discussed by Xu et al. (2023), stormwater management studies often occur at the micro-level, meso-level, or macro-level. In the micro-level, the study typically focuses on a parcel or site. In a meso-level study, the focus is typically on a catchment, block, community, neighborhood, or group of sites. In a macro-level study, regional watersheds, city drainage systems, or urban planning are often the focus.

Stormwater management literature is often defined by the development condition of the area being studied. Studies for urban or urbanizing areas are often a focus of research due to the increased imperviousness caused by urbanization, leading to increases in stormwater volumes. Moore et al. (2017) summarized the results from 246 studies on urban stormwater characterization, control, and treatment. Moore et al. (2017) subdivided their review into characterization of stormwater quantity and quality, engineered systems including GSI, and watershed application of stormwater practices. Concerns about effectiveness and urban watershed function inspired Jefferson et al. (2017) to review 100 empirical and modeling studies with the intent to quantify cumulative effectiveness of stormwater control measures. Bertrand-Krajewski (2021) provided a review of integrated urban stormwater management, including discussion of how the field has evolved while emphasizing a multidisciplinary perspective. Xu et al. (2023) reviewed 66 urban stormwater management studies performed at the meso-level. As identified by Roy et al. (2008), there were previously many impediments to sustainable, watershed-scale urban stormwater management, focused mainly on uncertainties due to their use being relatively new and lack of legislation, standards, and guidance for their implementation. However, Roy et al. (2008) provides lessons learned from the U.S. and Australia on how to overcome these challenges.

Modern urban stormwater management cannot be separated from environmental considerations, including water quality concerns and environmental impacts of stormwater management practices. As a result, GSI is a focus of many recent studies.

On the environmental side, Prudencio and Null (2018) reviewed stormwater management as it relates to ecosystem services, reviewing 170 publications and recommending additional investigation of GSI. Also, Tsihrintzis and Hamid (1997) had previously reviewed urban stormwater management and modeling from the perspective of runoff quality. Chang et al. (2017) analyzed policies for LID in urban regions worldwide. Barbosa et al. (2012) identified key issues for sustainable urban stormwater management, urging a flexible approach considering local characteristics and considering temporal, spatial, and administrative factors. Qiao et al. (2018) also highlight the challenges of implementation of urban sustainable stormwater management from a governance perspective in a review paper. Rentachintala et al. (2022) reviewed sustainable and resilient measures and practices for urban stormwater management.

Webber et al. (2022) reviewed the area of smart stormwater management, providing a future framework for terminology, research, and future perspectives. While Webber et al. (2022) acknowledges that there is universal agreement that smart technology can be beneficially applied to stormwater management, the field remains fragmented with underutilized implementation. Furthermore, Sweetapple et al. (2023) reviewed barriers of smarter stormwater management and provided a roadmap for application.

There are also studies that approach the topic of stormwater management from a modeling perspective. Jayasooriya and Ng (2014) reviewed stormwater management tools and economic tools for GSI practices. Similarly, Haris et al. (2016) reviewed various urban stormwater management models and tools for designing GSI. Niazi et al. (2017) reviewed the application of the U.S. Environmental Protection Agency's (EPA) SWMM, which is a urban drainage design and planning tool that includes capabilities for analyzing GSI and/or LID.

Branching off from modeling-based analysis of stormwater management, there are also a significant number of studies that utilize models to optimize various aspects of the stormwater systems. Shishegar et al. (2017) reviewed the application of optimization methods to stormwater management problems. The optimization problems within the studies reviewed by Shishegar et al. (2017) were separated by control approaches, performance criteria, stormwater management approach, and consideration of uncertainty. Shishegar et al. (2017) found an increasing trend toward sustainability within the optimization problems to tackle climate change concerns.

3.3 Financial Considerations for Similar Programs

Some cities make use of payment-in-lieu programs to provide funding for the construction of drainage infrastructure improvements rather than requiring on-site detention. The City of Austin, Texas has two related programs, including a Regional Stormwater Management Program

(RSWMP) and an Urban Watersheds Structural Control Fund (UWSCF). Through the RSWMP, qualified developments may construct or contribute financially to offsite drainage infrastructure improvements instead of constructing onsite stormwater detention (City of Austin, Texas, n.d.-c). Financial contributions are given to the city's Watershed Protection Department (WPD) who then allocates the funds to projects within the same watershed, emphasizing a watershed approach. The city's UWSCF "provides a payment in lieu option for on-site water quality improvement facilities. Participation in the UWSCF is currently restricted to watersheds designated as Urban whereas RSWMP participation may be available in any watershed that is within City of Austin full purpose jurisdiction." (City of Austin, Texas, n.d.-a).

In November 2019, the City of Austin directed an investigation into the methodology used for the costs for these programs, including comparison data from 10 localities that have similar programs. The 10 localities are Alpharetta, Georgia; DuPage County, Illinois; Green Bay, Wisconsin; Louisville Metropolitan Sewer District (MSD), Kentucky; New Braunfels, Texas; Redmond, Washington; San Antonio, Texas; Tulsa, Oklahoma; Universal City, Texas; and Washington, DC (led by the Department of Energy and Environment), with reviews for San Antonio, Louisville MSD, and Washington, DC in further detail (City of Austin, Texas, n.d.-b).

4 Flooding

Flooding is a pervasive issue across Texas due to the state's variation in topography, climatic features, proximity to the Gulf of Mexico, and other factors.

4.1 Flooding Type

In 2015, almost every major city in the state of Texas was impacted by a major flood. Since then, Texas has experienced 12 federally declared disasters related to flooding, with billions of dollars in damages and loss of life (TWDB, 2019; FEMA, 2022a). In addition, certain cities, such as Beaumont, have experienced severe repetitive flooding in recent years. Further complicating the issue, Texas is susceptible to four different types of flooding: riverine, stormwater, coastal, and structural failure.

Riverine flooding, alternatively called fluvial flooding, occurs when a channel such as a river, stream, or bayou overflows and water spills into the surroundings. Eleven percent of the state's population is exposed to moderate-to-high riverine flood risk, as defined by FEMA. Riverine flooding and the associated risk are usually defined in terms of a recurrence interval (frequently called the X-year flood), which is derived using historical flow data. A 100-year flood event has a 1 percent probability of occurring in any given year. It is important to keep in mind that a 100-year flood may occur multiple times in a 100-year period. Riverine flooding can occur as either flash flooding, when heavy rainfall rapidly generates runoff, or slow-rise flooding when upstream runoff arrives downstream. Flooding has taken more lives than any other weather-related disaster in Texas between 1996 and 2006 (TDEM, 2018).

Stormwater flooding is similar to flash flooding with a rapid onset but differs in its cause. While flash floods occur near rivers, stormwater flooding is associated with urban and other developed areas. This association is due to stormwater flooding being caused by rainfall exceeding the capacity of a city or municipality's drainage system. A major impact of this type of flooding is the inundation of roadways, damaging vehicles, and inhibiting emergency responses.

Coastal flooding is caused by elevated sea levels, usually due to tropical weather or tidal events. Tropical weather can create storm surges that push water over 25 feet above normal sea levels. Coastal flooding poses a severe economic threat to Texas, causing 21 percent of weather-related property damage from 1996 to 2006 (TDEM, 2018). This is second only to hurricanes, which accounted for 36 percent of weather-related damages during the same time period.

Structural failure of stormwater control structures is not common in Texas but should still be considered, as structural failures can release massive amounts of floodwater. Examples include the failures of the Oroville Dam in California and the Edenville Dam in Michigan. Out of the 7,372 dams in Texas, 1,547 are considered high hazard (NOAA NCEI, 2023), meaning a dam failure would result in heavy casualties and property damage (USACE, 2004).

The Texas State Flood Assessment (TWDB, 2019) and the Texas State Hazard Mitigation Plan (TDEM, 2023) have additional information regarding flood types and associated statistics.

4.2 Flood Mitigation Methods

Flood mitigation methods have increasingly drawn attention due to their significant role in safeguarding both communities and infrastructure from devastating losses. These methods fall under two broad categories, which are structural and non-structural measures. Structural efforts typically include drainage and stormwater infrastructure, levees and flood walls, and reservoirs; non-structural measures include education and outreach, emergency action plans, and early warning systems (Texas Flood Information Clearinghouse, 2020). These strategies offer protection but also offset their initial cost by providing a substantial return on investment (ROI) (FEMA FIMA, 2018). This section briefly overviews these methods, exploring their effectiveness, cost-efficiency, and the ROI they offer. The mitigation method to use depends on many factors, including cost, physical limitations, ease of construction (need of engineers) and environmental requirements, historic preservation, compliance with floodplain management requirements, degree of required maintenance, permits (local or federal), and others.

Flood Early Warning Systems (FEWS), as non-structural flood mitigation tools, have increased in popularity among flood-prone communities due to their life-saving functions like rainfall and river level monitoring, real-time flood forecasting, and estimating potential damages to different communities while remaining relatively low-cost compared to other structure-related mitigation solutions. As such, a specific section for their use has been prepared.

4.2.1 Structural Methods

Structural mitigation measures involve direct, physical alterations to the landscape or built environment to reduce flood risks. These are often engineered solutions that encompass the construction of physical barriers such as seawalls, floodwalls, breakwaters, jetties, groins, levees, detention basins, and flood channels. Besides this, retrofitting existing structures to enhance their flood resilience is another crucial structural measure. This includes the implementation of preventative measures that bar floodwater entry and sustain critical infrastructure.

Mitigation measures may include the construction of physical barriers like levees and floodwalls to protect against storm surges and tidal flooding, retrofitting structures to make them flood-resistant, and utilizing measures such as dry floodproofing (making a structure watertight) and wet floodproofing (allowing floodwaters to flow through a structure but minimizing damage). Guidelines for protecting roadways from moving water by stabilizing roadways are also an important avenue for a structural mitigation measure. This includes resurfacing and reshaping the roadway. Shoulder protection is also an important measure for protecting roadways. Subgrade drainage and strength can be improved by using geosynthetics as needed. In addition to protecting roadways from running water, reducing flood hazards directly on a roadway is a good preventative measure. This includes increasing roadway elevation, rerouting roadways, and using permeable pavements. In cases where frost heave is an issue, drainage improvement, stabilizing subgrade soils, and increasing pavement thickness can be viable solutions. Issues with drainage culverts that are at risk of failure can be addressed by increasing design capacity, shaping culvert entrances, using check dams, energy dissipators, and linings, or improving alignment to prevent embankment erosion (FEMA, 2022a).

Coastal shoreline management introduces the unique vulnerability of shorelines to flood and storm impacts. Structural stabilization methods recommended include constructing seawalls, bulkheads, revetments, breakwaters, jetties, groins, and reinforcing dunes. Living shoreline stabilization (NOAA, 2016) using vegetation combined with geogrids, crib walls, brush mattresses, root wads or other bioengineered construction materials can mitigate erosion in lesser-developed areas that do not experience high-velocity waves.

Resilience is also required in transportation infrastructure, considering a wide variety of structures, including mass transit facilities and equipment, railways, and catenary overhead systems. Their mitigation strategies are centered around preventing floodwater entry and maintaining the power supply during extreme weather events. This includes innovative solutions such as inflatable plugs for tunnel protection, and traditional measures like covering vents to sealing street-level openings, installing floodwalls, elevating utilities, sealing conduits and openings, and improving drainage systems. Backup power systems and holistic system strengthening are important. Special attention has also been given to the catenary overhead systems in the past, which are vital for mass transit, and there is a need to fortify these against flood and storm impacts (Phythyon, 2011).

The Federal Transit Administration (FTA) has regularly funded mitigation measures for transit systems under its emergency relief program, which helps pay for protecting, repairing, and/or replacing equipment and facilities that may suffer or have suffered serious damage as a result of an emergency. The vulnerability of transit facilities such as pump buildings, electrical substations, offices and control rooms, stations, platforms, parking lots, vents, generators, fueling stations, fences, and maintenance facilities to flood damage is high. The potential hazards include equipment and system failure due to inundation, power loss and subsequent corrosion, and physical damage to infrastructure that can lead to prolonged service disruption. Mitigation strategies include elevating or relocating vulnerable structures, floodproofing, providing redundant systems, and ensuring the security of chemical and fuel storage tanks. The importance of building utility systems (HVAC, electrical, plumbing, etc.) with consideration of their vulnerability to flooding is emphasized. (FEMA, 2022a)

Earth slope stabilization measures can be used to decrease the likelihood of landslides or earth movements on slopes, which pose risks to roads and other infrastructure. Mitigation measures include excavation techniques such as removal or replacement of material at the top of the slope, building benches or terraces, and reducing the slope angle. Reinforcing or strengthening slopes can be done using geosynthetics, construction of a toe buttress or berm, deep soil mixing, and installation of soil nails. Drainage plays a significant role in slope stabilization, with strategies like constructing interceptor trenches, subsurface drains, and check dams. Another significant aspect is the installation of several types of retaining walls and the use of natural and hybrid approaches for slope stability, underlining the importance of integrating GSI in resilience planning. (FEMA, 2022a)

Protection of coastal facilities such as piers, boardwalks, docks, wharves, floating docks, boat launch ramps, boat storage facilities, beach accesses, restrooms, lifeguard stations, police stations, administrative offices, educational centers, and other amenities are all important. A systematic approach is proposed that includes monitoring, inspecting, and repairing structures, optimizing maintenance programs, and retrofitting and reinforcing infrastructure based on their type and vulnerability. The National Park Service (NPS) emphasizes the importance of regular inspections and prompt repair of damages to prevent progressive damage and to ensure readiness before the next storm season. The importance of considering the relocation and elevation of structures, where necessary, is underscored, reinforcing the need for adaptive strategies in response to evolving flood risk scenarios. (NPS, 2012)

4.2.2 Non-Structural Methods

Non-structural mitigation measures emphasize policy, planning, and awareness over physical alterations, i.e., without physically altering the environment. They often involve regulatory initiatives, like zoning laws that restrict construction in flood-prone areas or involve initiatives to raise public awareness and preparedness for floods. They include floodplain management, building regulations, and other policies that guide development away from flood-prone areas. Resilience planning should include thorough assessments of existing infrastructure, regular and proactive maintenance, structural adjustments, reinforcements, and, where necessary, relocation. Measures include planning, property acquisition and relocation, flood forecasting and warning systems, flood insurance, and public awareness programs (FEMA, 2022a). Regular maintenance and inspection, emergency planning, and employee training are equally important measures.

Beach nourishment and dune restoration are some measures for coastal regions (USACE, 2020). Particularly innovative is the advocacy for living shorelines, which use a combination of vegetation and bioengineered construction materials for shoreline stabilization, thus harmonizing structural resilience with ecological preservation (NOAA, 2016).

An effective FEWS represents a pivotal non-structural measure. It involves predicting floods and providing timely and effective information, allowing individuals and communities to act to prevent loss of life and reduce property damage. Entities like the National Weather Service (NWS) utilize an array of radars, river gages, and weather models to predict floods and disseminate warnings promptly.

4.2.3 Summary and Return on Investment (ROI)

Flood and storm mitigation measures are crucial to protect communities. An integrated approach that combines structural modifications with proactive planning, education, and regulatory measures can provide the most effective flood mitigation. The substantial ROI, underpinned by the potential for significant savings in future flood damage, underscores the need for these measures. The importance of a comprehensive, multifaceted, and proactive approach to flood and storm mitigation is a recurring theme in all sources reviewed. It demonstrates the necessity of a comprehensive, proactive approach amalgamating physical alterations, regulatory measures, and community education. Understanding the specific needs of various structures, ranging from transportation infrastructure to public facilities, is fundamental to devising efficient mitigation strategies. Moreover, with climate change exacerbating the frequency and severity of flood events, these strategies become paramount in preserving communities and infrastructure.

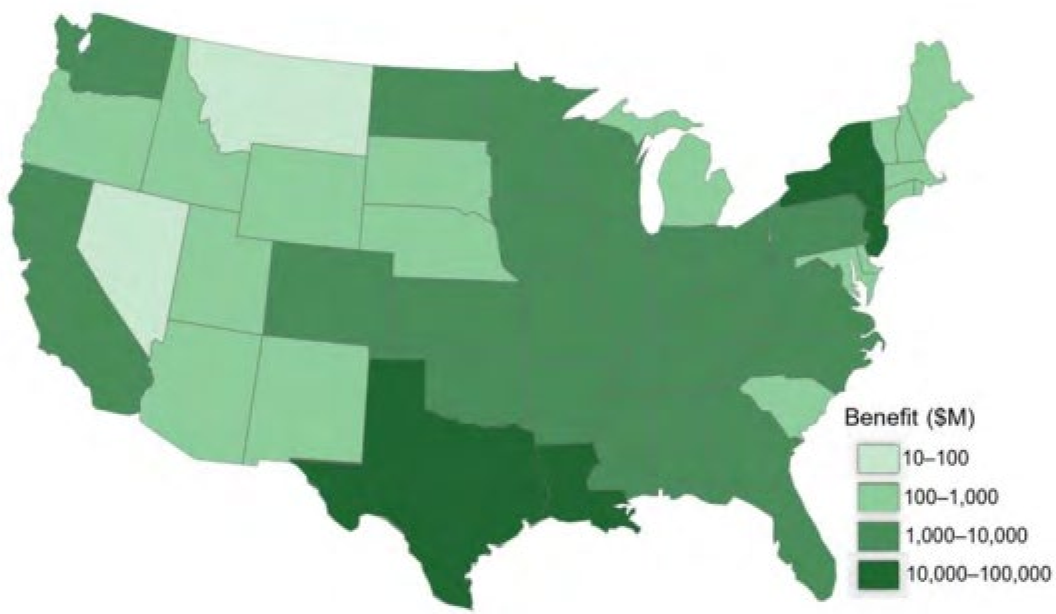

Figure 2: Aggregate benefit by state from federal grants for flood, wind, earthquake, and fire mitigation (MMC, 2019)

As shown in Figure 2 and according to the Multi-Hazard Mitigation Council (MCC), a cost-benefit analysis of flood mitigation measures indicates that these investments yield positive returns over time by reducing flood damage costs (MCC, 2019). There are several tools used to determine the cost-effectiveness of mitigation methods. One is the Federal Transit Association's Hazard Mitigation Cost Effectiveness (HMCE) Tool (FTA, 2018). Every $1 invested in flood mitigation saves six U.S. dollars in future disaster costs (FEMA FIMA, 2018). This illustrates the high ROI of implementing effective flood mitigation measures.

4.3 Flood Damage

It has been observed that flood damages are responsible for about one-third of the economic losses from natural hazards in Europe, according to two studies by Munich Re in 2005 and EEA et al. in 2008. Recent studies have demonstrated that due to climate change, increased flood frequencies will increase future flood damages (te Linde et al., 2010). As areas are becoming increasingly urbanized and thus becoming more flood-prone, the potential damages will also rise significantly.

Studies show that several damage models have been created to represent the uncertainty in flood risk estimates (Merz & Thieken, 2009; Apel et al., 2008; and Meyer et al., 2008). The research study does, however, illustrate that the estimation of the probability contributes to the uncertainty, in severe events. Moel et al. (2011) conducted a research study focusing on uncertainty in flood damage estimates contrary to flood risk which is the product of probability and damage. The research focuses on assessing the uncertainty surrounding the flood damage estimates, considering four model sources: inundation depth, land use, the value of elements at risk, and depth-damage curves.

The most important factor for flood damage is the inundation depth. Several studies represent that for assessing the damages, the main parameter utilized is the inundation depth (Aertz et al., (2008); Merz et al., (2007); Wind et al., 1999). It is important to note that the flood duration and the direct damages are also considered. Land use, on the other hand, is often utilized as an indicator of potential flood damage, as mentioned in the study by Hall et al. (2005a) and Klijin et al. (2007). Land-use databases are sourced from various means like aerial photography or satellite imagery. These databases are then classified into land-use classes by various algorithms. Estimating flood damages is utilized by three different damage models (DMs). The uncertainty in flood loss estimations due to the difference in depth-damage curves is calculated using DMs (de Moel et al., 2011). The study by de Moel et al. (2011) compared the flood damage estimates using the three DMs by taking the land-use classes of the various land-use maps to determine the number of classes classified by the DMs.

Brody et al. (2008) notes that Hurricane Harvey in 2017 was one of the most extreme storms in the U.S., resulting in long-term increasing flood loss in the southeastern part of Texas. With research showing that flood damages are worsening over time, the impacts are also increasing out of FEMA’s 100-year boundaries.

4.4 Flood Risk

FEMA defines flood maps as a “representation of the community’s risk of flooding, illustrating a community’s flood zone, floodplain boundary, and base flood elevation.” The National Flood Insurance Program (NFIP) and FEMA work together with areas and communities around the U.S. to identify flood risk. According to FEMA, flood risk is categorized into moderate-to-low-risk flood areas designated with the letters B, C, and X on FEMA flood maps. In these areas, the risk of being flooded is reduced but not completely removed. The high-risk flood areas, however, begin with the letters A or V on FEMA flood maps, according to FEMA. Property owners in these areas are required to have flood insurance.

With Dr. Brody and a team of researchers at Texas A&M University supported by FEMA, the National Academies of Sciences, Engineering, and Medicine, or NASEM, and the Texas General Land Office (GLO), a study will be conducted to map and explain flood risk and search for potential ways to mitigate future storm impacts and aftermath. This is important work, given the number of people estimated to be affected by flooding in 2100 is 16 to 388 million people per year for the mid (55-cm) global-mean sea level rise (SLR) scenarios and up to 510 million people per year for the high (96-cm) scenario (Nicholls, 2002).

Within the currently available research, Passeri et al. (2015) demonstrated that tidal amplitudes along the Northern Gulf of Mexico coast increased by 67 percent of 10.0 cm under the highest sea level rise (SLR) scenario, and the ratio of the maximum flood to maximum velocity decreased in the future scenarios by 26 and 39 percent. Additionally, Chen et al. (2014) evaluated the Apalachicola River basin in Florida and concluded that the seasonal responses of runoff and sediment loads are slight by comparing them to various models.

In its 1990 report entitled, Natural Disaster and Vulnerability Analysis, The United Nations Disaster Relief Organization (UNDRO) developed an operational definition for disaster risk, defining disaster risk as the multiplication of hazard potential and vulnerability (UNDRO, 1980). With technological advances, this definition has become more refined and nuanced as researchers have grown in their understanding of the topic.

Samarasinghea et al. (2010) conducted a study in Sri Lanka leveraging a hybrid GIS and remote sensing-based approach for flood risk determination. Data for the study included satellite imagery, topographic and GIS data, and hydro-meteorological data from rain gages. The flood simulation and analysis included two components: hydrologic and hydraulic. The hydrologic component simulated rainfall runoff in river basins, while the hydraulic component generated flood extents and depths. The analysis and simulation verified the flood extent regions for hazard determination.

A study performed by Ahmad et al. (2013) described the development of a flood risk analysis using GIS in conjunction with wireless sensor networks. Sensors were used to capture climate-based elements such as humidity levels, air pressure, and wind speed. These parameters were used to determine rainfall intensity.

Another study described by Pregnolato et al. (2015) performed a survey of literature in an attempt to establish “best-practice methodologies for flood vulnerability assessment.” The researchers review existing empirical vulnerability and fragility curves associated with flood risk. The result is a compilation and guide to the utilization of vulnerability and fragility curves for future use.

Researchers have also explored the use of machine-learning (ML) strategies for flood hazard mapping. A study by Nandi et al. (2016) the development of a GIS-based statistical methodology based on the use of principal component analysis and logistic regression (LR). The outcome was the creation of Jamaica’s first flood hazard map, segmenting areas into five flood hazard categories ranging from very low and very high. While this approach was designed for a

Caribbean Island prone to tropical storms and Atlantic hurricanes, researchers suggest up to 86.8 percent accuracy in classifying flood events.

The random forest (RF) approach also employs ML in the development of a classification system for flood risk (Wang et al., 2015). An analysis of flood risk in the Dongjiang River Basin of China, Wang et al. (2015) determined RF to be a successful method for assessing flood hazard risk. Similarly, Feng et al. (2015) took a flood mapping approach based on RF to classify flooded and non-flooded regions within Yuyao, China. The study, combining the use of multiple endmember spectral analysis (MESMA) and RF, found classification accuracy was in the range of 94 percent when compared to physically inundated areas.

4.5 Flood Disasters

FEMA estimated that flood events have been responsible for the deaths of more than 10,000 persons in the U.S. since 1900 (FEMA, 2014). According to the United Nations Development Programme (UNDP) in 2004, "vulnerability" has been defined as "the conditions determined by physical, social, economic, and environmental factors or processes, which increase susceptibility to the impact of hazards." Other studies, such as Ouma and Tateishi (2014), outline flood vulnerability assessment as the process of determining the susceptibility of a given location.

Hurricanes Katrina and Rita in 2005 highlighted the disproportionate impact of disasters on minority and low-income status populations, as validated in a study (Zahran et al., 2008). Other studies represent that the human cost of hurricanes and other natural disasters demonstrates that communities of color suffer in regard to injury and death (Wright et al., 1979). A study by Zahran et al. (2008) conducted vulnerability assessments on the physical or structural properties of a hazard and on features of the natural and built landscape, such as proximity to water bodies, fault lines, floodplains, wind fields, the resilience of built surfaces, and structures to hazard impacts. With regard to flood disasters, hydrologic or physical variables, such as the amount of rainfall and flood duration, and built environment characteristics, such as the presence of water embankments and the permeability and slope of built surfaces, are standard vulnerability predictors.

According to the Biggest Waters Flood Insurance Reform Act of 2012, Congress requests to create a financial framework for the NFIP by leading FEMA to remove discounted prices for owners with insurance by the NFIP (FEMA, 2021). This will allow policyholders to be given flood insurance rates that are accurate for the flood losses.

4.6 Flood Planning

Flood planning in Texas was significantly expanded with TWDB's creation of the fifteen Regional Flood Planning Groups (RFPGs) following the 2019 Texas Legislative session. Operating on a five-year cycle, the RFPGs will prepare regional flood plans, which will then be incorporated into a state flood plan. The first round of regional flood plans was submitted in early 2023, and amended plans were finalized in July 2023. The first state flood plan was finalized in 2024.

This study falls within Region 3 – Trinity RFGP. The 2023 Amended Region 3 Trinity Regional Flood Plan contains chapters on the Planning Area Description; Flood Risk Analyses; Floodplain

Management Practices and Flood Protection Goals; Assessment and Identification of Flood Mitigation Needs; Recommendation of Flood Management Evaluations, Flood Management Strategies, and Associated Flood Mitigation Projects; Impact and Contribution of the Regional Flood Plan; Flood Response Information and Activities; Legislative, Administrative, and Regulatory Recommendations; Flood Infrastructure Financing Analysis; and Public Participation and Plan Adoption. Various GIS data are available as a result of the study as well. (TWDB, n.d.-a; Region 3 Trinity Regional Flood Planning Group, n.d.).

5 Future Conditions

To provide proactive solutions, effects from future conditions must be considered. Future conditions that will be investigated in this study include but are not limited to population growth and projections, land use and imperviousness projections, future transportation networks, and climate change.

5.1 Population Growth and Projections

According to a regional report from the Texas Comptroller's Office, the DFW Metropolitan area had a population of nearly 8 million people in 2019 (Texas Comptroller of Public Accounts, 2020). With some areas of the DFW Metroplex growing by more than 30 percent between 2010 and 2019, the trend of population growth is projected to continue in the future. With the fourth-highest rate of inbound migration in the nation, DFW is projected to have a population that eclipses 10 million people at some point in the 2030 decade (Kotkin & Clark, 2021). At that point, DFW would become the third-largest metropolitan area in the U.S.

5.2 Land Use and Imperviousness Projections

Future land use and the resulting imperviousness are important components of the TSI study as they relate to both the runoff generated by rainfall and the transportation planning process. As a result, the proceeding paragraphs explain the methodology, indices, image classification methods, and forecasting methods used in the projection of future land use. Within the final subsection, the precise methodology used by NCTCOG is presented because this is considered the most up-to-date land use available.

5.2.1 Methodology Overview

Land use changes in urban and rural areas will have significant impacts on climate change on a global scale, mobility in towns and cities, transportation, and regional agriculture (small scale). Therefore, we need to have data and information to analyze the magnitude and the degree of importance of these impacts and changes. Land use and imperviousness projections utilize classification of satellite data to project the classification for the future.

Data used in land use and imperviousness projections is typically from satellite sensors. The most popular sensors for land use and land cover data are MODIS (Moderate Resolution Imaging Spectro Radiometer) from the Terra and Aqua satellites, OLI (Operational Land Imager) from Landsat, and DMSP/OLS (Defense Meteorological Satellite Program/Operational Linescan System) from Landsat. The number of spectral bands for the satellites and, thus, the information provided can vary. After obtaining information from satellites, data and image processing are performed to improve image clarity. Processing may include data mining, clustering, and using algorithms and indices.

5.2.2 Indices

Some notable challenges of using satellite data include varying image clarity, cloud-cast shadows that hamper image processing, and similarities in certain land cover classifications. To minimize the impact of these challenges, indices are typically applied, such as NDUI (Normalized Difference Urban Index), NDVI (Normalized Difference Vegetation Index), BCI (Biophysical Composition Index), MNIDSI (Multi-source Normalized Difference Impervious Surface Index) (Zhang et al., 2015).

For instance, in terms of species of vegetation, the boundary of wavelengths has different structures, and plants of differing physiology have the same reflection, making it difficult to distinguish differences. There is a need for band ratio and spectral indices in these cases, which are remarkably useful for emphasizing the differences and varieties. NDVI is one of the indices for the analysis of different vegetation (McGwire et al., 2000; Underwood et al., 2003; Yamano et al., 2003; Galvao et al., 2005). PCA is another index for the analysis and assessment of distinguishing vegetation areas from non-vegetation areas. (Castro-Esau et al., 2004).

These indices help in deciding which classifier algorithms are proper for implementation. "Pureness" is the reference that can be relied on as a factor of the classification result. Assessment of hyperspectral and Multispectral images is based on the operation of classification algorithms or statistical classifiers (Castro-Esau et al., 2004; Govender et al., 2007). Gaussian maximum likelihood, Spectral angle mapper, and parallelepiped classification are used to classify images based on some properties.

5.2.3 Image Classification

Images show different spectral ranges, and before using normalizing difference indices, an image classification technique can be applied (Nijhawan et al., 2019). Image classification has two types of techniques: supervised learning and unsupervised learning. Examples of supervised learning algorithms are Artificial Neural Networks and Maximum Likelihood Field Classifiers, and examples of unsupervised learning algorithms are K-means clustering and Isi-Cluster algorithms (Nijhawan et al., 2019). These algorithms are selected based on the computational expense and size of the study area.

Govender et al. (2007) used hyperspectral and multispectral data for land use and land cover changes. The multispectral method provides information in coarser dimensions, whereas hyperspectral data are more detailed for smaller places. A multispectral remote sensing system measures between 3 and 6 spectral bands within the visible to middle infrared region of the electromagnetic spectrum. Multispectral can derive the discrimination of different types of vegetation, rocks, and soils (Smith, 2001a). Multi-spectral remote sensing has several wavelength ranges, but hyperspectral sensors detect hundreds of very narrow spectral bands throughout the visible, near-infrared, and mid-infrared portions of the electromagnetic spectrum.

5.2.4 Forecasting Methods

Forecasting data or projection has been performed using traditional econometric methods as well as ML methods. The important note is that statistical methods are more accurate and have better results in predicting the data. In terms of transportation and its variables and predicting these variables, many methods can be applied. ML uses algorithms (statistical approaches) to predict the wanted variables (Li & Kockelman, 2022). Today, the most used ML algorithms appear to be logistic regression (LR) and then for calibrating parameters using gradient ascent (Caruana et al., 2006; Chen et al., 2016; Delen et al., 2017).

Data Mining models have more flexible structures than traditional econometric models in representing the relationship between the attributes of alternatives and choices (Li & Kockelman 2022). Hou et al. (2018) used many ML techniques such as Decision Tree (DT), RF, eXtreme Gradient Boosting (XG-Boost), light Gradient Boosting Machine (GBM), Extra trees, AdaBoost, Gradient Boosting Decision Tree (GBDT), Cat boost, Neural Network (NN), Nayes, Multinomial Logistic Regression and Spatial Autoregressive (MNL SAR) to predict travel mode choices and land use change (Li & Kockelman, 2022).

Forecasting and projecting land use and land cover data can be based on scenario-based simulation (Ruben et al., 2020). The cellular automata-Markov (CA-Markov) model is efficient and simple to calibrate. Cellular automata can integrate geospatial and remote sensing data, quantitative data, and socioeconomic data. CA-Markov predicts the Land Use and Land Cover (LULC) classes. The Cellular Automata solves the limitation of prediction based on the Markov chain by adding a spatial dimension to the model. The transition probability is based on the previous years by, for example, 10 or 5 increment period time for instance (1970, 1980, 1990, 2000, 2010) by the index like Kappa, which has a negative value to the upper value of one $(-\infty,1]$ the simulation validates. The best value is one. The next step leads to the model being calibrated, and the final step is a simulation of future projection LULC data based on the previous and historical data.

Many deep learning (DL) methods exist to process the remote sensing and GIS images and then recognize them in terms of variables. Banumathiet al. (2020) used a DL based vision-like ray perceptron (VLRP) model using optimized K-means (OKM) (clustering for segmentation). The first stage is License plate (LP) images processed and detected by algorithms with the name of Improved Bernsen Analysis (IBA) and Connected Component Analysis, and then OKM clustering and KH (Krill Herd algorithm) segment the LP images. In the final stage, LP images get recognized by Convolutional Neural Networks (CNN).

In this study, localization of the LP images has been done by some procedures. The first step is removing the shadow and uneven illumination images by using binary techniques like an algorithm called IBA. IBA is the best way of resolving the noise from the images. LP image detection is done by using the help of connected component analysis (CCA) to process the images. It means images are screened, pixels are labeled, and then linked to one another. The LP images have two characteristics: black and white characters with inverse backgrounds. Two detection models used CNN. LP detection model produces two procedures, one LP location with a frame and another without a frame. While the LP images with frames can be predicted, the LP images without frames cannot. (Banumathi et al., 2020)

The Segmentation process is done by the OKM to evaluate the uncertainty of an image dataset. Three degrees of falsity (F), indeterminacy (I), and truth (TR) are determined for Membership Function (MF). Three entropy subsets are depicted as (ETR, EI, and EF). The probabilities of the elements are defined by (PTR(p), PI(p), PF(p)). Also, the deviations of F and TR develop the distribution and entropy of I to create F and TR with I (Banumathi et al., 2020). The optimization process is done by the algorithm of Krill Herd (KH), and the optimum value of α is calculated by this algorithm with the clustering process categorizing the objects into K groups.

Next, deep learning models such as CNN are applied to recognize characters to segment LP images. CNN includes layers with the name Fully Connected (FC). The Convolutional (CONV) Layer varies from one Neural network to another. This layer does not contain pixels with weights that are not connected to subsequent layers. The Pooling layer is defined to reduce the spatial dimension of the images and the parameter count; it is then utilized to minimize the cost of computational resources. The FC layer of each neuron is connected to the earlier layer and the current layer. An activation function, such as a nonlinear activation function, is applied to accelerate the process (Banumathi et al., 2020).

5.2.5 NCTCOG Land Use Projection Methodology

In some approaches like NCTCOG's, in terms of demographic forecasting, data is gained from many sources like cadastral based on land use data, census data, and remote sensing data acquisition. All these data are georeferenced and converted into a common spatial reference system, which makes a raster an ideal format. Folden (2017) indicated that ML algorithms, in some ways, are ignored because they are not easily interpretable. Finding the variables for use in the algorithms is not easy, but there are some tools like Principal Components Analysis (PCA) that perform a transformation on the continuous independent variables, the transformations that capture the most variance like returning correlation coefficients with the individual variables and the transformed data. At NCTCOG, Folden used it to show a high correlation with the top two or three principal components. In this study, Folden utilized univariate linear regression as a simple algorithm and used boosted ensembles as an advanced algorithm. A series of night-time light (NTL) data has been made available with the Defense Meteorological Satellite Program (DMSP) sensor to capture information on human activity. Though this sensor has some problems, the Visible Infrared Imaging Radiometer Suite (VIIRS) is a newer sensor designed to replace the DMSP sensor. When NTL data is not available, the Multispectral Scanner (MSS) sensor with four bands of data, two visible light bands and two infrared bands, can process the information, but the images that are derived from this sensor are challenging for classification. Thematic mapper (TM) is another sensor that Folden used in the study. OLI is another sensor that collects imagery with the help of the "Coastal Aerosol" band. In this study, all the images were analyzed by the bias method as an ML approach.

5.3 Climate Change

Climate change is likely to lead to substantial increases in flood vulnerability due to increases in extreme rainfall. Evidence of such an increase is found in observed trends, climate model simulations and projections, and the basic thermodynamic principles of precipitation rate dependence on temperature.

Of particular importance are changes in rainfall events, leading to more frequent and severe storms. The study by Nielsen-Gammon et al. (2020) suggests that the DFW area will experience an increase in heavy rainfall events due to climate change. This is consistent with the findings of Allan et al. (2014) and Pfahl et al. (2017), who noted that climate models predict an increase in extreme precipitation events due to the warming climate. (Nielsen-Gammon, 2020) A positive trend in estimated 1-day 100-year rainfall amounts from 1960 to 2020 of about 15 percent in central and eastern parts of Texas and 6 percent in western Texas has been observed. These trends are consistent with trends found in other similar studies and imply that the stationary NOAA Atlas 14 values underestimate present-day return values and will further underestimate future return values. These trends are similar to or greater than what would be expected from thermodynamic considerations alone, with a warmer atmosphere accommodating more water vapor when at 100 percent relative humidity. According to Nielsen-Gammon and Jorgensen (2021), the direct effect of temperature seems to be dominant across the U.S. compared to other factors brought about by climatic change visible through changes in storm frequency and intensity. Several studies verify the stated trends with real events. The Intergovernmental Panel on Climate Change (IPCC, 2022) has noted that the global warming of 1.5°C above pre-industrial levels could lead to an increase in heavy precipitation events, a primary cause of flooding. A study by Mallakpour and Villarini (2015) found that the central U.S., including the DFW area, has experienced a significant increase in flooding events over the past several decades. They attributed this increase to changes in rainfall patterns, which have been linked to climate change.

In addition to changes in environmental factors, increased flood risk can also be attributed to rapid development in the U.S. In urban areas with high impervious cover and small catchments, the increased intense rain should translate directly into increased runoff. There, proportional increases in discharge can be assumed, and in the absence of special hydrologic simulations, increased flood levels can be inferred from extrapolation/interpolation of existing flooding simulations using relationships between flood elevation and flow volumes. However, despite the unanimity among models for an increase in intense precipitation, models project flooding outcomes for Texas ranging from increased river floods to decreased peak stream flows in some cases. The dichotomy between extreme rainfall and decreases in river basin flooding is due in part to decreases in soil moisture, which lead to greater amounts of rainfall required for runoff over initially dry soils (Nielsen-Gammon & Jorgensen, 2021). In general, the lower flood peaks are less frequently observed compared to increases in higher-intensity events. The increased intensity of rainfall can lead to an increased risk of flooding. Asadieh and Krakauer (2017) found that global changes in streamflow extremes under climate change could lead to increased flooding in the 21st century. This is particularly relevant for the DFW area, which is prone to flash floods due to its urbanized environment and numerous waterways. With the increase in rainfall intensity, the risk of flooding has also increased. A study by Wasko and Sharma (2017) found that with every degree rise in global temperatures, the intensity of rainstorms could increase by 7 percent, leading to more severe flooding events. This is particularly relevant for the DFW area, which has been experiencing an increase in heavy rainfall events.

An inherent uncertainty exists in these projections. Future river flooding projections are the least constrained aspect of future rain and flood hazards. In the face of such uncertainty, it may be inappropriate to assume that river floods will not change at all. Suggested scenarios include both increases and decreases, hence involve a larger range of possibilities than extreme rainfall to reflect the larger uncertainty. If decreased soil moisture does indeed lead to a larger rainfall threshold for flooding, minor floods may become less likely, while major floods may become more likely (Nielsen-Gammon & Jorgensen, 2021). While it is clear that climate change will increase the intensity of rainfall, the impact on river flooding is less certain. Do et al. (2020) conducted a study on historical and future changes in global flood magnitude and found that while some areas will see an increase in flood magnitude, others may not. This uncertainty makes it difficult to predict the exact impact of river flooding in the DFW area.

The impact of climate change on river flooding is complex and can vary depending on a range of factors. A study by Wasko and Nathan (2019) found that changes in rainfall and soil moisture significantly influence trends in flooding. However, the specific impacts of river flooding in the DFW area are uncertain, and more research is needed to understand these impacts fully. Given the increased risk of extreme weather events, it is crucial for the DFW area to plan for these future risks. The study by Nielsen-Gammon et al. (2020) from the Office of the Texas State Climatologist suggests that local authorities need to consider the changing climate when planning for future infrastructure and emergency response measures. Based on the above considerations, a relationship of a 7 percent increase in extreme rainfall amounts per Kelvin (K) global temperature increase is suggested as a basic projection. Since present-day global temperatures are 0.5-1 K warmer than they were over most of the historical NOAA Atlas 14 analysis period, extreme rainfall return values should already be 5 percent above NOAA Atlas 14 values in most of the state. An additional 1K of warming is generally anticipated by 2050-2060, according to moderate climate mitigation scenarios, which would correspond to a total increase over NOAA Atlas 14 of 12 percent. Therefore, in a basic climate change scenario, a present-day enhancement of 5% and a mid-21st-century enhancement of 12 percent would be appropriate (Nielsen-Gammon & Jorgensen, 2021).

The increasing risk of flooding due to climate change underscores the need for effective flood risk management. A study by Zaherpour et al. (2018) found that ML could be valuable for weighted multi-model combinations of an ensemble of global hydrological models. This could help in better predicting and managing flood risks in the DFW area in the face of climate change. The report does not provide specific information on temperature changes in the DFW area. However, it is generally accepted that global temperatures are increasing due to climate change, which is contributing to increased rainfall intensity and flooding risk.

As a result of increasing temperatures, the DFW area is expected to experience many environmental effects, among which of particular importance is more frequent and severe heatwaves. This could have significant impacts on public health, energy consumption, and water resources. Changes in temperature and precipitation patterns due to climate change can have significant impacts on ecosystems, including changes in species distributions, population sizes, the timing of reproduction or migration events, and an increase in the frequency of pest and disease outbreaks. The changing climate can also have significant impacts on local ecosystems. Increased temperatures and changes in rainfall patterns can affect the distribution and behavior of plant and animal species. This could lead to shifts in the composition of local ecosystems, with potential impacts on biodiversity and ecosystem services.

Rising temperatures due to climate change can exacerbate flooding in several ways. Flooding can lead to habitat loss, population declines, and changes in community composition. Additionally, changes in flooding patterns can affect the timing of life cycle events for many species, potentially disrupting ecological interactions.

6 Planning, Manuals, and Guidance

This section reviews the planning frameworks, technical manuals, and policy guidance that shape how floodplain management, stormwater, transportation, and environmental considerations are addressed across the TSI study area. It examines regional programs, county and city regulations, planning documents, and state and federal guidance to identify common approaches, notable innovations, and opportunities to better integrate flood resilience into local decision-making. Together, these resources provide important context for understanding existing practices and for informing recommendations that strengthen coordination between land use, infrastructure planning, and flood risk reduction.

6.1 City and urban planning

Urban planning will be integral to implementing the TSI study recommendations. NCTCOG has reviewed city, town, and county regulations and planning documents to identify how floodplain management is currently addressed in the study area. Many commonalities existed between jurisdictions. This section of the literature review documents those commonalities and highlights exceptions that go above and beyond. This review looks at regional and local efforts.

NCTCOG provides regional programs that support city, town, and county planning efforts related to flooding. These voluntary programs can influence how these jurisdictions address flooding in planning documents and regulations. Specific programs such as Floodplain Management Workshops and Technical Assistance offered by NCTCOG can help align local jurisdictions' efforts.

Separately, the study team surveyed cities and counties in 2022 to identify which regulations addressed floodplain management. The 85 cities in the study area were divided into buckets based on natural breaks in population size to ensure information was included from cities of all sizes. Surveys were distributed to half of the cities in each population size bucket; surveys were distributed to all counties in the study area. If cities or counties did not respond to the survey, the study team sought information via an internet search. Responses and documents provided during the survey and subsequent research informed this literature review.

Additional research of city and county websites was conducted to identify how cities and counties incorporated floodplain management into planning documents.

6.2 Regional Planning

Regional programs support city, town, and county efforts to address floodplain management. Several regional programs are supported by NCTCOG, including the Corridor Development Certificate (CDC) process, *integrated* Stormwater Management (iSWM) program, Cooperating Technical Partners (CTP) program, support for FEMA's Community Rating System (CRS) program, Texas Community Development Block Grant (TxCDBG) Program, and Hazard Mitigation Action Plans (HMAPs).

The CDC regulatory process aims to stabilize flood risk in participating communities along the Trinity River. The CDC process does not prohibit floodplain development but ensures any development that does occur in the floodplain will not raise flood water levels or reduce flood storage capacity. A CDC permit from the U.S. Army Corps of Engineers (USACE) is required to develop land within a specific area of the Trinity floodplain called the Regulatory Zone, which is similar to the 100-year floodplain. Under the CDC process, local governments retain ultimate control over floodplain permitting decisions, but other communities along the Trinity River Corridor are given the opportunity to review and comment on projects in their neighbors' jurisdiction. As the North Central Texas economy continues to grow and develop, the CDC process will prevent increased flood risks (NCTCOG, n.d.-e). Developers wishing to develop in the floodplain insert the CDC hydraulics model into their project and submit an application to the city. The city submits the CDC application via the Trinity CDC website, trinityrivercdc.com. Municipalities in the CDC program review and provide comments on the application, which is then sent to USACE for review. If a CDC permit is granted, the project is added to the CDC hydraulics model (NCTCOG, n.d.-j).

The iSWM™ Program for Construction and Development is a cooperative initiative that helps cities and counties achieve their goals of water quality protection, streambank protection, and flood mitigation while also helping communities meet their construction and post-construction obligations under state stormwater permits (NCTCOG, n.d.-g). Development and redevelopment, by their nature, increase the amount of imperviousness in the surrounding environment. This increased imperviousness translates into a loss of natural areas, more sources of pollution in the runoff, and heightened flooding risks. To help mitigate these impacts, more than 60 local governments are cooperating to create sound stormwater management guidance for the region proactively through iSWM. A community can become an iSWM Certified Community by documenting their implementation of iSWM practices and applying to be reviewed by the iSWM Implementation Subcommittee. To achieve certification, a community must fully apply certain iSWM criteria from the iSWM Criteria Manual. These criteria have been divided into categories of mandatory outcomes, recommended outcomes, and optional outcomes. When a community applies to be certified, they must document their implementation of a minimum number of mandatory and recommended outcome criteria. The community will be classified based on the total number of successful outcomes. The Transportation Integrated Stormwater Management (TriSWM) Appendix of the iSWM Criteria Manual provides for the planning and design of stormwater management systems associated with the construction of public transportation infrastructure.

In 2004, FEMA and NCTCOG launched a CTP Agreement. The CTP program helps update flood hazard maps and additional flood hazard information (NCTCOG, n.d.-d). NCTCOG has applied for funding on behalf of cities and counties to conduct Phase 1 Discovery efforts to identify areas at risk for flooding, which aid the prioritization of future mitigation effort and to participate in the Risk Mapping, Assessment, and Planning (Risk MAP) program. Risk MAP assists individuals, organizations, and communities planning and taking action to reduce flooding. Communities can use flood hazard data and maps produced during the Risk MAP process to plan to reduce flood risk and communicate with residents and neighboring communities. In the TSI study area, Denton, Ellis, Parker, and Tarrant counties have participated in Risk MAP projects, as well as five cities and one town.

NCTCOG also supports cities as they pursue a FEMA CRS rating. The CRS program is voluntary and provides an incentive for communities to adopt floodplain management practices that exceed the minimum requirements of the National Flood Insurance Program (NFIP) (NCTCOG, n.d.-c). Communities that adopt these practices can earn a rating from 9 to 1 (highest rating). Community residents receive flood insurance discounts that vary depending on their community's rating. Activities that help communities earn ratings include public information, mapping and regulations, flood damage reduction, and warning and response. NCTCOG hosts meetings for communities who participate in the CRS program or who would like to participate in the program. The meetings are opportunities for education and peer exchange.

The TxCDBG Program provides infrastructure funding to low- to moderate-income rural communities. Communities that are eligible for the TxCDBG funding are called non-entitlement communities, which are cities with populations under 50,000 and counties with a non-metropolitan population under 200,000. The program is funded by the Texas Department of Agriculture. NCTCOG's role is to promote the program to eligible communities in North Central Texas (NCTCOG, n.d.-b). From 2012 to 2022, about $70 million was committed to 88 different communities to complete 226 public improvement projects in the region. Most of the projects addressed water system or sewer system improvements. Flood drainage improvements are also eligible (Texas Department of Agriculture, 2023).

NCTCOG's Emergency Preparedness Department has helped several counties develop or update their FEMA-approved HMAPs, making the participating communities eligible for FEMA mitigation funding. Approved plans must be updated every five years (FEMA, 2008). More information on HMAPs is provided in section 6.2.5.

Regional programs play a critical role in enhancing floodplain management by fostering collaboration, innovation, and resource-sharing among communities, agencies, and stakeholders. One such initiative is the NCTCOG Floodplain Management Task Force (FMTF) (NCTCOG, n.d.-f.), which facilitates cooperation among local communities to improve floodplain management practices and policies. The FMTF emphasizes regional coordination, ensuring that communities work together to address shared flood risks and implement best practices.

In addition to the NCTCOG FMTF, other regional programs, such as the CDC process and the iSWM program, contribute to the advancement of floodplain management by promoting innovative solutions and encouraging regional collaboration. These programs emphasize the importance of coordinated efforts to manage flood risks and improve stormwater infrastructure across multiple jurisdictions.

Several key organizations further support local efforts to address floodplain management, providing resources ranging from technical assistance to financial support. The USACE, for example, operates several programs focused on improving flood risk management. The USACE Flood Risk Management (FRM) Program offers technical assistance, project funding, and comprehensive flood risk assessments to help communities reduce flood risks. Additionally, the USACE Silver Jackets Program brings together federal, state, and local agencies to develop coordinated approaches to flood risk management, fostering collaborative efforts and enhancing the effectiveness of regional flood protection strategies.

The TWDB is another critical partner in regional flood management. TWDB administers a variety of programs that support flood mitigation efforts across the state. The Flood Infrastructure Fund (FIF) provides financial assistance for flood mitigation projects, encompassing activities such as planning, design, and construction. The TWDB also offers Flood Protection Planning Grants, which support regional flood planning and mapping efforts essential for identifying and mitigating flood risks. Furthermore, the TWDB coordinates the State Flood Plan, collaborating with regional flood planning groups throughout Texas to develop comprehensive, long-term strategies for flood mitigation.

The Texas Floodplain Management Association (TFMA) plays a significant role in enhancing the professional capacity of floodplain managers, planners, and engineers. TFMA offers training, certification programs, and a wealth of resources to support practitioners in the field. The association also organizes workshops and conferences to promote the adoption of best practices and facilitate ongoing professional development.

Together, these regional programs foster collaboration among local governments, state agencies, federal partners, and other stakeholders, which is essential for effective floodplain management. By encouraging coordinated efforts and providing critical resources, these programs help ensure that flood mitigation strategies are both innovative and sustainable across various regions.

6.2.1 County Rules and Regulations

In Texas, counties have fewer regulatory tools than cities. Counties are unable to adopt ordinances for zoning, with some exceptions. One exception occurs in the TSI study area. Denton County Commissioners may adopt ordinances within 5,000 feet of Lake Ray Roberts, a recreation site. The ordinances can control the height and size of buildings in the area, percentage of lots occupied, size of yards, population density, location and use of buildings, and construction standards (State of Texas, 1989).

Despite limits on zoning, Texas Water Code Section 16.3145 provides cities *and* counties with the authority to regulate floodplain management by adopting ordinances and orders needed for the jurisdiction to be eligible to participate in the NFIP (State of Texas, 1999a). The NFIP makes federally-backed flood insurance available in states and communities that agree to adopt and enforce floodplain management ordinances to reduce future flood damage. Floodplain regulations are usually found in zoning ordinances, building codes, subdivision regulations, sanitary regulations, or stand-alone ordinances (FEMA, 2005).

Additional actions by political subdivisions to comply with NFIP are authorized by various amendments to the water code resulting in the current Texas Water Code Section 16.315 (State of Texas, 2007):

> "(5) engaging in floodplain management and adopting and enforcing permanent land use and control measures consistent with the criteria established under the National Flood Insurance Act.
>
> (6) declaring property, when such is the case, to be in violation of local laws, regulations, or ordinances which are intended to discourage or otherwise restrict land development or occupancy in flood-prone areas and notifying the director, or whomever the director designates, of such property; …
>
> (13) adopting permanent land use and control measures with enforcement provisions which are consistent with the criteria for land management and use adopted by the director;
>
> (14) adopting more comprehensive floodplain management rules that the political subdivision determines are necessary for planning and appropriate to protect public health and safety;
>
> (15) participating in floodplain management and mitigation initiatives such as the National Flood Insurance Program's Community Rating System, Project Impact, or other initiatives developed by federal, state, or local government; and
>
> (16) collecting reasonable fees to cover the cost of administering a local floodplain management program."

The survey and further review found all eight counties in the study area had stand-alone flood damage prevention ordinances or orders; these regulations are usually based on a FEMA ordinance model. Three counties also contained regulations in subdivision regulations, and two counties included regulations in sanitary regulations.

One tool political subdivision used in floodplain management is freeboard – the height that a structure's lowest floor must be built or floodproofed above a flood level for purposes of floodplain management. Freeboard provides a level of safety (FEMA, 2020). All counties in the study area have adopted a freeboard of at least 2 feet; Johnson County has a freeboard of 3 feet. Freeboard is not required by NFIP standards, but FEMA recommends at least 1 foot.

All counties have adopted floodplain regulations or orders that identify a floodplain administrator and his or her role, describe permit and variance procedures, include provisions for flood hazard reduction for different kinds of construction and in floodways, and identify penalties for noncompliance (Dallas County, Texas, 2019; Denton County, Texas, 2020; Ellis County, Texas, 2013; Hood County, Texas, 2020; Johnson County, Texas, 2019; Parker County, Texas, 2008; Tarrant County, Texas, 2011; Wise County, Texas, 2019). All counties' documents were similar, including verbatim language in some sections. Denton and Johnson counties referred to the need for Letters of Map Amendment (LOMA), Conditional Letters of Map Amendment (CLOMA), and Conditional Letters of Map Revision (CLOMR) (Denton County, Texas, 2020; Johnson County, Texas, 2019). These documents are related to comments from FEMA on whether a proposed project or hydrology change would meet minimum NFIP standards (FEMA, 2022a).

In addition, Dallas, Hood, and Johnson counties responded in the survey that they also include floodplain regulations in subdivision regulations. For example, Johnson County's subdivision rules, adopted in 2023, include an appendix describing drainage requirements criteria and design standards (Johnson County, Texas, 2023). Hood and Johnson counties also responded that they address floodplain management in sanitary regulations.

6.2.2 County Planning Documents

Counties in the study area utilize a variety of planning documents to address floodplain issues despite being unable to adopt ordinances under state law. Counties vary in population from 60,000-70,000 at the 2020 Census (Hood County, Wise County) to more than 2.6 million (Dallas County), creating a range of ability to develop and implement planning efforts.

Dallas County has employed multiple planning documents over the past 20 years that could be utilized to implement TSI goals. Dallas County comprises a small section of the study area, but other counties could (and some do) adopt similar planning documents. However, Dallas County is the most populous county in North Central Texas; smaller counties may not have the resources to duplicate Dallas County planning efforts. The Dallas County plans and programs include the Mobility Plan, the Annual Objectives and Key Results and Administrative Plan, the Major Capital Improvement Program, the Strategic Plan, the Community Development Block Grant Program, and the Open Space Plan.

The Mobility Plan, previously the Dallas County Thoroughfare Plan, identifies strategic opportunities for travel throughout the county (Dallas County, n.d.-a). Cities in the county can implement these opportunities or partner with Dallas County to implement them. The Mobility Plan could include strategies to prevent future flooding of transportation improvements.

Dallas County piloted an objectives and key results program called the Annual Objectives and Key Results and Administrative Plan in fiscal year (FY) 2019 and used the program in FY 2020 (Dallas County, 2020a). It identified objectives, strategies to achieve key results or goals, and a timeline for implementing strategies. The ten objectives for FY 2021 included investing in infrastructure, setting a standard for transportation and development, and improving health and wellness for Dallas County residents. TSI goals could be incorporated into each of these objectives.

The Major Capital Improvement Program was initiated by Dallas County in FY 2000 to replace the bond-financing method of funding infrastructure improvements. The program, which occurs every two to three years, includes a call for projects and a scoring process. Selections ultimately are approved by the Dallas County Commissioners Court (Dallas County, n.d.-b). Projects' ability to reduce flood risk or integrate GSI could be addressed in project application forms and the pre-screening process (Dallas County, n.d.-c).

The county developed a Strategic Plan for 2007-2017 (Dallas County, 2007). The plan identified five visions for the county and identified strategies to assist the county in accomplishing the visions. While counties in Texas do not have "home rule" and are not able to adopt ordinances, they can implement strategies to reduce flood risk as described in section 6.2.1 of this literature review. Flood risk reduction strategies could be incorporated into county strategic plans.

The Community Development Block Grant (CDBG) Program, funded by the U.S. Department of Housing and Urban Development, provides approximately $2 million per year to 15 cities in Dallas County with populations less than 50,000. Funding can be used for multiple purposes, including those that "eliminate a community-threatening condition" (Dallas County, n.d.-d).

The county planned to complete its update of the Open Space Plan in 2024. The existing plan was completed in 1991. The update process includes surveys of random households and public meetings. The plan is intended to prioritize projects over a 10-year timeline and will assess the existing program for parks and preserves, including demand, access, connectivity, and equity. It also will review recreational opportunities and natural and cultural resources (Dallas County, n.d.-e).

Tarrant County, the second-most-populous county in the TSI study area, also has a CDBG Program (Tarrant County, Texas, n.d.-a).

Denton County adopted a thoroughfare plan in 2017 (Denton County, 2017). The plan references floodplains in a case study on the Regional Outer Loop expansion in the county. The case study proposes the roadway has no frontage lanes in the floodplain for a portion of the roadway that crosses an environmentally sensitive area.

Parker County Commissioners Court developed a strategic plan for 2019-2021. An analysis of the county's strengths, weaknesses, opportunities, and threats (SWOT) found the county could be a "collaborative leader when it comes to growth" (Wieder, 2019). The plan also identified managed growth as an objective that would protect the county's small-town feeling. Natural disasters were identified as a threat. Planning efforts to reduce future flood risk could grow from documents such as the county strategic plan. The county adopted a thoroughfare plan in 2018. The plan was intended to be a living document to be amended as needed for reasons including changing land development patterns (Parker County, Texas, 2018). A map in the plan identifies the FEMA 1 percent flood risk zone and water bodies, large floodplains, or the presence of multiple creeks informed planning of the transportation network.

Ellis County also maintains a thoroughfare plan. The 2019 plan describes large floodplains that are a barrier to mobility and identifies flooding as a connectivity issue (Ellis County, Texas, 2019). County commissioners provided input on flooding problems as the plan was developed. The plan noted large floodplains that have created a gap in the transportation system. Addressing non-transportation development in the county, Ellis County's Growth Assessment Team seeks to ensure growth in unincorporated areas complies with county regulations (Ellis County, Texas, n.d.). The team suggests developers schedule a pre-application meeting. Members of the team included leadership of the planning & development group, county engineers, construction and environmental inspection managers, and the assistant fire marshal.

Wise County provides its residents with an emergency alert system that communicates about emergencies by email, text, and/or phone (Wise County, Texas, n.d.). Other jurisdictions can and do implement a similar system that could alert residents to flooding.

Hood County provides a map of development districts. The map includes two water-quality-related districts – one within 1 mile of the Brazos River and one within 0.5 mile of the major creeks (Dunkin Sefko & Associates, Inc., 2000). The majority of the county drains into the Brazos River; the northeastern corner of the county drains into the Trinity River and is part of the TSI study area. However, this area is not in proximity to the Trinity River itself. Counties also have HMAPs that include content related to flooding, covered in section 6.2.5.

6.2.3 City Rules and Regulations

NCTCOG received survey responses from or researched half of the 85 cities in the study area. Of these, 26 included flood regulations in stand-alone ordinances. These ordinances are usually based on a FEMA ordinance model. Stand-alone ordinances benefit communities because requirements can easily be found, and FEMA can easily ensure that the latest requirements have been adopted (FEMA, 2005).

6.2.3.1 Cities With Populations Less Than 20,000

The study area includes 65 cities of this size. Approximately half of these smaller cities (population less than 20,000) that were surveyed have adopted a stand-alone ordinance. These ordinances are designed to contain all floodplain development standards. However, stand-alone ordinances can result in inconsistencies with other regulations and a lack of coordination among departments (FEMA, n.d.). More than half of the small cities surveyed regulate the floodplain via other regulations (e.g., zoning ordinances, building codes, subdivision regulations, and/or sanitary regulations) or in tandem with a stand-alone ordinance.

For example, the City of New Fairview, population 1,386 according to the 2020 Census, includes floodplain regulations in zoning, building, and subdivision regulations. Zoning General Provisions reference the purpose of zoning regulations to facilitate the adequate provision of water, among other purposes (City of New Fairview, n.d.-a). Building regulations include Article 4.05 Flood Damage Prevention, which describes five methods of reducing flood losses (City of New Fairview, n.d.-b). The city's Subdivision Standards include Drainage Adequacy Regulations that describe storm drainage facilities, creek preservation and protection, and oversizing off-site improvement to accommodate flows caused by proposed development. Subdivision Standards also include Drainage System Design Standards, including a Stormwater Management Plan for all new subdivisions (City of New Fairview, n.d.-c).

The City of Rhome, population 1,630 according to the 2020 Census, includes floodplain regulations in zoning, building, and oil and gas well regulations. Article 4.09 of the Municipal Code states that "No gas well permit shall be issued for any well to be drilled within any floodway" (City of Rhome, n.d.-b).

6.2.3.2 Cities with Population of 20,000 to 51,000

The study area includes 11 cities with populations of 20,000 to 51,000. Of the cities surveyed, all but one had a stand-alone ordinance. The City of Keller, population 45,776 according to the 2020 Census, did not have a stand-alone ordinance, but it referenced floodplain regulations in its building and subdivision regulations, according to the city's survey response. The City of Weatherford, population 30,854 according to the 2020 Census, has a stand-alone ordinance and refers to floodplain regulations in subdivision regulations and in the city's Engineering Design and Construction Manual (City of Weatherford, Texas, 2020). The manual includes a section on drainage and design requirements. The manual highlights three requirements, that include required downstream assessment for developments that propose 5,000 square feet of impervious area, use of open channels in some cases, and reference to requirements for development within the floodplain.

6.2.3.3 Cities with Populations of More than 51,000 to 150,000

The study area includes four cities with populations of more than 51,000 to 150,000. Of the cities surveyed, floodplain regulations were included in stand-alone regulations, zoning, building and subdivision regulations, and land usage regulations. The City of Mansfield's Land Usage Code includes a chapter on Flood Damage Protection. The language mirrors the content of stand-alone ordinances based on FEMA requirements (City of Mansfield, Texas, n.d.).

6.2.3.4 Cities with Populations of more than 150,000 to 400,000

The study area includes three cities with populations of this size. Of the cities surveyed, both provided stand-alone ordinances on floodplain regulations. The City of Grand Prairie, population 196,100 according to the 2020 Census, also addressed floodplains in its Unified Development Code (City of Grand Prairie, Texas, 2023). Article 12: Subdivision and Utilities includes a section on drainage and floodplain management. These regulations call for land subject to flooding or deemed uninhabitable because of the potential for flooding to not be platted for residential development and not be used for any use threatened by inundation. The regulations also address conformance for drainage facilities and bridges.

6.2.3.5 Cities with Populations of more than 400,000

The study area includes two cities with populations of this size. The City of Fort Worth had a population of 918,915, according to the 2020 Census. The city addresses flooding in regulations for planning and development, subdivisions, water and sewers, and zoning. The city includes language on development within the Trinity River Corridor because it participates in the CDC process coordinated by NCTCOG and described in section 6.2 (City of Fort Worth, Texas, n.d.-b).

Development application fees include those for drainage study review and a stormwater facilities management agreement (City of Fort Worth, Texas, n.d.-c). The subdivision ordinance includes subdivision design standards for stormwater management. This ordinance states that all plats must conform to the stormwater management policy. The ordinance includes requirements for easements for storm drainage, floodplains, stormwater storage, dams and lakes, and levees. The ordinance requires creeks, streams, rivers, or drainage channels to be kept clear from obstructions and maintained by individual lot owners (City of Fort Worth, Texas, n.d.-a).

6.2.4 City Planning Documents

Flooding is frequently addressed in city comprehensive plans. These plans typically call for conservation to protect floodplains and their functions as part of dedicated open space; this includes the acquisition of floodplain property by the city. Floodplains are noted as opportunities for trails but a limiting factor for other kinds of development. Parks and open space plans reiterate the opportunity to conserve floodplains as part of parks and open space programs. Cities in less developed areas frequently reference a need to maintain the rural or natural heritage of the cities.

Comprehensive plans frequently cite the need for new developments to ensure stormwater runoff does not exceed the existing runoff rate. Some comprehensive plans identify locations that frequently flood. Master thoroughfare plans may map floodplains and note their impact on limiting locations of new transportation infrastructure. Capital improvement programs describe funding dedicated to drainage studies and infrastructure implementation. Cities that go above and beyond these discussions of floodplains in their planning documents are described below.

6.2.4.1 Cities with Populations Less Than 20,000

The Town of Bartonville's comprehensive plan calls for new or reconstructed collector roadways to be designed at the above-accepted floodplain high-water elevation. It also seeks alternate routes for local streets that experience low-water crossings (Town of Bartonville, Texas, 2017). Also, the City of Oak Point comprehensive plan reports that residents responding to a survey complained most frequently about flooding stormwater drainage that resulted from rainwater run-off (City of Oak Point, Texas, 2019). The city identified the need to develop a stormwater master plan. In addition, the City of Pilot Point seeks to develop a drainage master plan and amend development ordinances to enable cluster development that preserves open space near conservation areas (City of Pilot Point, Texas, 2018). The city also seeks to create zoning districts, allowing only appropriate development in environmentally sensitive areas and preserving agricultural areas. The plan cites the opportunity for conservation easements and the potential to fund conservation areas with bonds. It proposes creating landscape buffers on streets between curbs and sidewalks. In master-planned developments, a reduced credit or fee for park development could be available to communities that place trails or recreation within floodplains.

The Town of Providence Village comprehensive plan cites GSI as a strategy to reduce flood risk and address climate change. The plan identified a need to revise ordinances to require green and gray infrastructure for development within 0.5 mile of a floodplain (Town of Providence Village, Texas, 2021). The town seeks to educate residents on installing rain gardens. The town identified a need to develop zoning and floodplain regulations requiring elevation at least 2 feet above the base flood elevation.

Lastly, the City of Rhome's comprehensive plan suggests that the floodplain fringe in the current ranch land could be developed for large residential lots that preserve areas for open space. It encourages GSI and LID in areas neighboring floodplains (City of Rhome, Texas, n.d.-a).

6.2.4.2 Cities with Population of 20,000 to 51,000

The City of Burleson's comprehensive plan update reports that 59 percent of survey respondents support requiring business parking areas to drain into GSI that improves water quality and slows stormwater runoff (City of Burleson, Texas, 2020). A larger number, 72 percent, supported preserving and planting trees. Additional comments supported the use of permeable surfaces. The plan calls for a site design that preserves natural areas but notes that while floodplains must be dedicated, sometimes this is forgotten; policies are needed to ensure that floodplains should not be used as manicured parkland yet should serve some purpose for residents. The plan recommends the Engineering Division continue watershed studies that identify opportunities to create regional or shared detention ponds.

The City of Benbrook's comprehensive plan identifies an open space plan as an action item; the plan would identify properties located in the floodway or floodplain that could be preserved using no-build easements or dedication of the land as public land (City of Benbrook, Texas, 2020). The plan indicates the city could relocate development that exists within flood-prone areas. It also calls for educating residents about flood risks and flood insurance. The plan describes the city's participation in FEMA's NFIP and CRS programs. It calls for the city to update local floodplain mapping studies, adopt an ordinance to control erosion and seek to improve the city's CRS score. A Capital Improvement Program is an appendix to the comprehensive plan. The program proposes an assessment of the existing storm drain system to record the system's condition. Drainage improvement needs are identified, including a low water crossing where currently the city closes gates to close the road during heavy rain.

Some cities have begun to start integrating new approaches to address stormwater management such as the use of GSI (e.g., rain gardens, permeable pavements, etc.). Cities like Corinth have a GSI page on their website which shows how these techniques can be applied to both residential and nonresidential properties (City of Corinth, Texas, n.d.).

6.2.4.3 Cities with Populations of More than 51,000 to 150,000

The City of Denton calls for cluster development and the protection of rural open space, including floodplains and stream corridors, using conservation easements (City of Denton, Texas, 2022). It calls for a green buffer between development or roads and floodplains. The city has identified Ecologically Sensitive Areas, including a 100-year floodplain, riparian buffers, and water-related habitat. The plan calls for a framework of GSI to connect open spaces and natural resources. The city reports that preserving floodplains can improve water quality and maximize water storage, which reduces flood risk to people and property and reduces the need to repair infrastructure. The plan includes sections on GSI and LID.

The City of Lewisville's vision plan cites its central floodplain as a "treasure" that provides recreational opportunities for residents and visitors (City of Lewisville, Texas, 2014). The city seeks to protect the area to serve as an amenity that makes the city unique from other DFW communities.

6.2.4.4 Cities with Populations of more than 150,000 to 400,000

Some larger cities have developed floodplain management plans, master drainage plans, or drainage design manuals. For example, The City of Grand Prairie's five-year floodplain management plan reports that the public identified urban flooding and flash flooding as the greatest flood risks in responses to a questionnaire (City of Grand Prairie, Texas, 2021). The plan notes that 36.7 percent of the city's area is floodplain. It identifies locations experiencing flooding, including areas outside the floodplain. The plan describes projects that have reduced flooding in the city, including local drainage plans, buyouts, channel improvements, and a detention pond. It also identifies future drainage projects. The city participates in NCTCOG's CDC and iSWM programs. The city's Stormwater Utility District collects fees used in part to reduce residential, non-residential, and street flooding and to maintain existing drainage structures. The city maintains and updates a StormCAD model representing the city's storm drainage facilities. The plan describes the city's flood warning and monitoring system. The city's Drainage Design Manual establishes standard criteria, principles, procedures, and practices for the design of storm drainage facilities (City of Grand Prairie, Texas, 2017).

In contrast to other cities' plans that seek to conserve floodplains, the City of Grand Prairie's comprehensive plan update references floodplain reclamation as a "good option" to convert undevelopable floodplain into developable land, thus regaining the land and creating an opportunity for additional tax dollars (City of Grand Prairie, Texas, 2018). The area east of Belt Line Road is identified as a good opportunity for this strategy. Floodplain reclamation would require engineering studies of the impact of reclamation on the remaining floodplain system.

The City of Arlington's comprehensive plan identifies proper care of stream banks and vegetation as essential to avoiding problems with erosion, flooding, and water quality; the plan notes that much of the city's creek-side property is privately owned (City of Arlington, Texas, 2015).

6.2.4.5 Cities with Populations of more than 400,000

Similar to Dallas County, the City of Dallas comprises a small section of the study area and has financial and staffing resources that are unavailable to smaller cities. The city's planning documents can still provide helpful insight into the TSI study. The city's Drainage Design Manual (City of Dallas, Texas, 2019) provides standard principles and practices for the design of the city's drainage facilities. The manual covers hydrologic methods and analysis criteria; criteria and parameters for roadway drainage design; methodology and criteria for bridge hydraulic design; methodology, design procedures, and criteria for open channel design; methodology, design procedures, and criteria for drainage storage design; guidance for temporary and permanent erosion and sediment control measures; design criteria and regulatory requirements for floodplain and sump design requirements; regulatory requirements for permitting, easements, and submittals to regulatory agencies; requirements for construction plan submittals; and parameters for operation and maintenance of stormwater infrastructure.

The Floodplain Management Plan for the City of Fort Worth documents flood hazards, identifies potential mitigation actions, and utilizes stakeholder input to create a Mitigation Action Plan (City of Fort Worth, Texas, 2021). This plan focuses on flooding within the FEMA floodplain. The plan shows that flood insurance claims and the total value of claims have been reduced by more than 80 percent following the implementation of floodplain standards higher than those required by the NFIP. The plan ranks potential mitigation activities, including preventative activities, property protection, natural resource protection, emergency services, structural projects, and public information. The city gathers drainage complaints in a database; 81 percent of complaints from 2009 to 2015 occurred outside FEMA floodplains and repetitive loss areas. The city developed a Flood Response Plan under a grant from TWDB (City of Fort Worth, Texas, 2019). This plan identifies flood threats, outlines efforts to prepare for floods, and describes the city's response to floods. The study addresses flash flooding, riverine and levee breach flooding, and flooding from dam breaches. The city's Fort Worth Open Space Conservation Program seeks to conserve high-quality open space (City of Fort Worth, Texas, 2023). Areas targeted for conservation were selected based on their ability to meet seven goal areas, including flood control. The city also has developed a Stormwater Management Program Master Plan (City of Fort Worth, Texas, 2018).

6.2.5 Hazard Mitigation Action Plans

NCTCOG supports multiple counties in the development of HMAPs, which are essential for enhancing regional flood risk management. These county-level plans involve input from relevant cities and towns within each county, ensuring that the unique needs and conditions of local jurisdictions are addressed. Notable counties involved in the planning process include Hood, Wise, Parker, Johnson, and Tarrant Counties. The plans include data important to the TSI study, including low water crossings, historic flood events, the value of repetitive losses and severe repetitive losses, critical facilities in the floodplain, proposed mitigation strategies to reduce flood risk, and broad estimates on the cost-benefit of implementing each strategy. The plans also identify city and county departments that participated in developing the plans. They also identify the capacity cities and counties have to implement planning and mitigation for flooding. This information can guide the TSI study team's outreach efforts.

Many plans in the TSI study area include flash flooding as a flood hazard in addition to floodplains, including Dallas, Ellis, Hood, Johnson, Parker, Tarrant, and Wise counties (Dallas County, Texas, 2020b; NCTCOG, n.d.-f) and City of Decatur (City of Decatur, Texas, 2016). In some cases, the plans identify development as a cause of flash flooding.

Local governments measure their capacity to implement mitigation strategies through various methods, including assessing budget constraints, staffing issues, and political will. Specific challenges or limitations may impact their ability to fund and carry out the strategies outlined in their HMAPs. Additionally, outreach strategies used by NCTCOG or local governments to engage the public and stakeholders in the mitigation planning process include community workshops and public comment periods, ensuring that community input is considered.

Flash flooding presents unique challenges compared to standard floodplain concerns in terms of planning and mitigation. Certain plans identify flash flooding as a risk, but specific examples from the counties or cities can illustrate these unique challenges. These plans often consider the immediate and severe impacts of flash floods, which require different mitigation approaches compared to gradual flooding in floodplains.

6.2.6 *Summary of City and Urban Planning*

In conclusion, several regional programs provide innovations in floodplain management within the study area. The CDC process and iSWM program provide regulatory and voluntary opportunities, respectively, for participating communities to exceed the requirements of the NFIP.

All eight counties in the study area have stand-alone floodplain regulations. Three counties address floodplains in their subdivision regulations, and two counties address floodplains in their sanitary regulations. An outlier is Johnson County; their 3-foot freeboard requirement exceeds those of other counties.

Forty-four of the 85 cities and towns in the study area were surveyed on their floodplain regulations. Fifty-nine percent of surveyed municipalities provide stand--alone floodplain regulations. Sixty-four percent of surveyed municipalities provide other regulations instead of or in addition to stand alone regulations. Two municipalities in the study area are not participants in the NFIP; therefore, they were not surveyed on their floodplain regulations. Three additional municipalities' NFIP status is unconfirmed. All five had populations less than 20,000. Municipal floodplain regulations outside of stand--alone regulations were typically found in regulations associated with land usage, zoning, building, subdivision, and oil and gas wells. One surveyed city addressed floodplain requirements in its engineering design and construction manual. Of the cities surveyed, outliers in freeboard are the cities of Benbrook and Mansfield, which in some cases call for 3 feet of freeboard, and the cities of Annetta, Northlake, Mansfield, Arlington, and Fort Worth, which use fully developed water surface elevations, base flood elevations, or urbanized base flood elevations.

Counties may have thoroughfare plans that identify floodplain locations and the limitations these floodplains pose on constructing new roadways. Larger, better-resourced counties may develop additional plans, such as open space plans or strategic plans, that address flood risk.

Cities most frequently address flood risk in comprehensive plans and open space or park plans. Some cities support the use of GSI, cluster development, zoning districts, LID, and conservation easements as tools to reduce flooding. Some cities view floodplains as a factor that limits development, other cities view floodplains as an amenity for their communities and visitors. HMAPs are sources of data on low-water crossings, repetitive flood losses, and critical facilities that could be useful to the TSI study team. While some of these plans focus only on floodplain flooding, others include flash flooding.

6.3 Transportation Planning

Varying degrees of consideration have been given to the transportation and stormwater nexus across the national, state, and local municipal levels. The identification of current transportation planning manuals and their consideration for stormwater integration is thus an integral component to aid in the overall development of the TSI study. The purpose of the Transportation Planning section is to present some of the findings from a survey of literature at each planning level.

6.3.1 FHWA White Paper – Ongoing and Current Research on Resilience

In the FHWA white paper for Ongoing and Current Research on Resiliency, FHWA identified that 25 out of 50 states are currently utilizing a significant consideration of resilience in their transportation planning process. As of 2022, Texas is not on the list of those states.

The main first step identified by all the MPOs currently considering resiliency is to first understand what hazards and vulnerabilities threaten their systems. Many are undergoing this through scenario planning and workshops.

Stormwater management and flooding related mitigation is the most common being assessed by MPOs and Departments of Transportation (DOTs) currently. For example, the Southern New Hampshire Planning Commission's (SNHPC) (Manchester, NH) 2040 transportation plan indicates that SNHPC is working to develop the Piscataquog Watershed Culvert Prioritization Model, which is designed to help communities make proactive decisions about culvert upgrades rather than making emergency repairs after an extreme event (SNHPC, 2017). The model will be built in Excel using existing stream-crossing infrastructure and vulnerability assessment data and will allow users to input their own decision-making variables to customize the results to the specific community's needs (SNHPC, 2017).

6.3.2 Stormwater and Flooding ON TO 2050 Strategy Paper

The Chicago Department of Transportation (CDOT) and Chicago Metropolitan Agency for Planning (CMAP) recognized that achieving a reduction in the negative impacts of flooding will take a variety of approaches and will require participation from a variety of different partners involved in land use and transportation decisions. The agency recognizes that as a region, they need to set baseline priorities as well as expectations. The following strategies have been identified to be implemented by the agency (CMAP, 2017).

The first strategy is to identify and communicate flooding risk and exposure. Reliance on outdated floodplain mapping and precipitation data is hampering the region's ability to identify and communicate flooding risk to stakeholders. Second, advanced planning efforts are intended to reduce current and future risks. The agency is beginning to consider implementing similar protection techniques in areas outside the floodplain as those in the floodplain. Current precipitation patterns exceed those used in current regional ordinances for floodplain mitigation measures; updates are required on countywide and local ordinances to the most current precipitation data. This further necessitates the incorporation of floodplain mapping into zoning overlay districts to allow better direction on the types of appropriate uses for areas. The third strategy is to invest in and maintain grey and green infrastructure. Routine maintenance of grey and green infrastructure is a critical step to ensure optimal performance and lengthen its lifespan.

Assessing the condition of the entire grey and green drainage system, developing plans to bring it to a good state of repair, and funding the activities on a regular basis are all necessary components of this strategy. However, some neighborhood stormwater facilities are under private ownership and, like public assets, require maintenance and rehabilitation to meet performance goals. Additionally, these facilities can be problematic for communities and stormwater agencies without long-term maintenance requirements built in from the outset. The fourth strategy is to increase the resiliency of the transportation system. Active forms of transportation, such as bicycling and walking, decline during storms and flooding and can affect mode choice and increase congestion. Therefore, local and county vulnerability assessments are necessary for the transportation system: bridges, roadway corridors, and railway corridors are necessary. Lastly, the final strategy improves state and regional coordination for the establishment of baseline priorities and expectations.

6.3.3 Texas River Basin Flood Studies

As of September 2020, the Texas GLO implemented the Combined River Basin Flood Studies (RBFS), which will result in detailed flood risk information and mitigation strategies for the 49 counties that received a presidential disaster declaration due to the impact of Hurricane Harvey plus four counties in the Lower Rio Grande Valley that received a presidential disaster declaration for flooding in 2015 and/or 2016. As of July 2026, RBFS was completing its Alternatives Analysis phase, and entering its Funding and Technical Assistance phase. The data and information produced by the GLO will be utilized to support current and future Texas State Flood Plans led by TWDB (Texas General Land Office, 2026).

6.3.4 Transit Resilience Guidebook (USDOT Volpe Center, 2024)

The Transit Resilience Guidebook, published by the USDOT's Volpe Center, offers comprehensive guidance for improving the resilience of transit systems in the face of natural hazards, with a strong emphasis on climate-related threats such as flooding and extreme weather events. The document outlines a structured, risk-based approach to evaluating vulnerabilities across transit assets and planning targeted interventions to reduce disruption and damage. While primarily developed for transit agencies, many of the recommendations are directly applicable to broader transportation infrastructure and are highly relevant to the TSI study.

A key recommendation from the guidebook is the use of flood exposure and vulnerability assessments to identify critical infrastructure at risk. These assessments are intended to inform both near-term operational preparedness and long-term capital planning. This aligns closely with TSI's emphasis on H&H modeling and regional-scale flood risk mapping to guide transportation investment decisions. The guidebook also encourages integration of GSI and nature-based solutions (NBS)—such as vegetated swales, permeable surfaces, and constructed wetlands—as dual-purpose strategies that enhance both stormwater management and system resilience.

In terms of adaptation, the guidebook advocates for elevating or floodproofing essential infrastructure, including rail alignments, signal houses, and maintenance facilities—strategies that parallel TSI's engineering-focused interventions for roadway and drainage system adaptation. Furthermore, the guidebook emphasizes collaborative planning across agencies, including MPOs, transit authorities, public works, and emergency managers. This recommendation supports the TSI study's commitment to stakeholder engagement and interagency coordination.

Finally, the guidebook stresses the importance of monitoring resilience performance using key performance indicators (KPIs), such as service recovery time after extreme events or frequency of flooding-induced disruptions. This performance-based approach complements the TSI study's goal of quantifying benefits from proposed infrastructure solutions and pilot programs.

6.4 Transportation Planning, Manuals, and Guidance

The purpose of this section is to identify current transportation planning manuals and their consideration for stormwater integration.

6.4.1 2022 Transportation Asset Management Plan (TxDOT)

The Texas Department of Transportation (TxDOT) currently utilizes many different factors to measure performance of its assets in the capital decision making process. There is also consideration given to risk and resiliency, but its definitions are much broader; natural disaster (flooding) is one of ten total evaluation factors. TxDOT has adjusted their process for bridge maintenance to address and reduce bridge scour in flood-prone areas: strengthening channels and embankments as well as raising bridges where necessary to prevent future damage from extreme storms. TxDOT intends to develop a Statewide Resiliency Plan including tools for Divisions and Districts to incorporate resiliency into their planning process. Additionally, they intend to develop an implementation plan including strategies and planning tools to improve the resiliency of the transportation system. TxDOT is also part of an ongoing project titled "Establish TxDOT Transportation Resilience Planning Scorecard and Best Practices" which has completed a system-level resilience assessment on road networks in Texas. The four-criticality metrics capture different dimensions of vulnerability and criticality including: (1) the loss of connectivity of road segments in road networks, (2) vulnerability of road segments to extreme events such as flooding and hurricanes, (3) disrupted access to critical facilities in the districts, and (4) interdependence of road network with facility networks. Chapter 5 of the plan concludes by identifying the current challenges in promoting resiliency across the entire state of Texas. (TxDOT, 2022a)

6.4.2 Advancing Stormwater Resiliency in Maryland (A-StoRM)

Maryland Department of Transportation (MDOT) and Maryland Department of the Environment (MDE) have recognized that urban and riverine flooding is a growing issue in Maryland. Steps needed to be taken to mitigate the impacts. Maryland worked to address these flooding issues in 2020 by updating Maryland's stormwater management law, signed by Governor Hogan, that became effective on June 1, 2021. The state's Stormwater Management Law, Environment Article 4-201.1, now requires the MDE to report on the most recent precipitation data available, investigate flooding events since 2000, and update Maryland's stormwater quantity management standards for flood control. The project to advance stormwater resiliency in Maryland consists of 6 components:

- Community Engagement
- Information Exchange
- Data Gathering
- Watershed Mapping and Assessment
- Updating Stormwater Standards

- Targeting Funding Opportunities

The first year of the program (June 2021 – June 2022) has resulted in successful outcomes including the following:

- Addition to National Pollutant Discharge Elimination System (NPDES) Phase 1 Municipal Separate Storm Sewer System (MS4) permits to require conveyance system maintenance.
- Modifications to impervious restoration practice crediting to allow credit for additional storage volume of rainfall (up to 3 inches).
- Considering regulatory change from managing 2.7 inches of runoff to managing 3 inches of runoff.
- Local and regional partnerships on flood initiatives and projects are being developed.
- MDE's internal research on characterizing flood events and watershed governance is ongoing.
- Stakeholder engagement and comments have been sought out and summarized regarding proposed updates to stormwater design manual. Stakeholders included but not limited to the following:
    - University professors
    - Local and county officials
    - Association of floodplain managers
    - Nature Conservancy Center
    - Soil Conservation District
- Generally, it appears that most stakeholders' comments indicated that the proposed revisions would still not capture the necessary changes to control the current and future climate changes anticipated. (MDE, 2021)

6.4.3 iSWM Criteria Manual for Site Development and Construction

The TriSWM Appendix presents an integrated approach for reducing the impact of stormwater runoff associated with public linear transportation infrastructure projects. The TriSWM Appendix has been incorporated as an expansion of the iSWM Criteria Manual for Site Development and Construction for use by cities, counties, and transportation agencies (and in some cases private developers) in the planning and design of stormwater management systems for public streets, roads, and highways. The TriSWM Appendix does not apply to streets within residential subdivisions, unless required by the local jurisdiction. However, when a city or county cooperates with a developer in the construction of a collector or arterial street for access, the local government may require the use of the TriSWM Appendix for that portion of the project.

The goals of the TriSWM Appendix are as follows:

- Control runoff within and from the site to minimize flood risk to people and properties;

- Assess discharges from the site to minimize downstream bank and channel erosion; and
- Reduce pollutants in stormwater runoff to protect water quality and assist communities in meeting regulatory requirements.

TriSWM is currently only applicable for projects that will ultimately disturb one or more acres of land, including projects less than one acre that are part of a larger common project plan or scope that will disturb one acre or more. (NCTCOG, 2014b)

Table 1. **TriSWM design is based on four storm events.**

Storm Events

Storm Event Name	Storm Event Description
Water Quality	Criteria based on a volume of 1.5 inches of rainfall, not a storm frequency
Streambank Protection	1-year, 24-hour storm event
Conveyance	25-year, 24-hour storm event
Flood Mitigation	100-year, 24-hour storm event

6.4.4 Mobility 2050: The Metropolitan Transportation Plan for North Central Texas

Mobility 2050 is a blueprint for the North Central Texas region's transportation system that aims to respond to regional mobility goals and guides the expenditure of federal and state transportation funds. The plan includes recommendations for all travel modes through policies to guide transportation infra implantation, programs to improve mobility, and projects to increase transportation system capacity and reliability.

The Chapter on Environmental Considerations focuses largely on health and air quality. Projects are subject to Natural Environment Screening under Mobility 2050, which is a screening in conjunction with the Regional Ecosystem Framework (REF). The Regional Ecosystem Framework, or REF, is a tool that identifies areas of relative ecological importance in the DFW region. Transportation partners and local governments that are developing infrastructure projects can use the REF as a preliminary screening tool to identify environmental impacts their projects may have and identify mitigation areas to offset any impacts. The REF tool is only as reliable as the data that is input into it.

There are a number of resilience policies, programs, projects, and maps which can be reviewed in greater detail in the Environmental Considerations Index of the Mobility 2050 document (NCTCOG, 2025).

6.4.5 TxDOT Texas Transportation Plan 2050

Scenario planning helps transportation decision-makers and their stakeholders consider performance implications associated with different investment strategy choices under different projections of what the future might look like. The Texas Transportation Plan (TTP) 2050 assesses the system performance outcomes of five different investment strategies on safety, congestion, asset conditions, the economy, and non-highway travel options in response to expected and optimistic scenarios of changes over time for emerging technology and freight volumes, which are considered to be the greatest uncertainties affecting transportation in Texas.

The plan recognizes and acknowledges that increased hurricane intensity, storm surge, rainfall, sea level rise, and other extreme weather events like drought and extreme heat are potential disruptors to the Texas transportation system. The plan also mentions consideration of flooding among other potential resiliency issues to be reviewed in its top 25 corridors for study prioritization.

6.4.6 TxDOT Hydraulic Design Manual

The TxDOT Hydraulic Design Manual offers the following chapters which are relevant to the subject of this literature review (TxDOT, 2019a). The definitions for bridge and culvert are identified further in subsection on Transportation Infrastructure.

6.4.6.1 Chapter 8: Culverts

Chapter 8 outlines the hydraulic design essentials for culverts, including conveying surface water through roadway embankments. It stresses the dual roles of culverts:

- Hydraulic functionality: sizing based on hydrologic inputs (flood magnitude, inlet/outlet control, headwater depths, outlet velocities), with iterative hydraulic modeling procedures such as inlet/outlet control analysis and step-backwater methods.
- Structural resilience: selection of materials, shapes, and inlet/end treatments that ensure durability under traffic and erosion conditions.

Special considerations include:

- Roadway overtopping design: ensuring safe overflow conditions during extreme events.
- Risk-based design for temporary culverts: applying probability of exceedance (AEP) during detours and accounting for flood risk over construction durations.

6.4.6.2 Chapter 9: Bridges

Chapter 9 addresses hydraulics for stream crossings via bridges, emphasizing:

- Bridge vs. culvert decision-making: based on hydraulic capacity, embankment design, and FHWA definitions.
- Hydraulic modeling techniques: use of 1-dimensional (D) (HEC-RAS) and selective 2D analyses to address backwater, flow distribution, scour, freeboard, and overtopping.
- Flood risk and scour mitigation: design of approach embankments, piers, abutments, guide banks, and erosion control as part of flood damage prevention.

The manual recommends freeboard standards (0.5 to 1 feet above high frequency events and higher along coasts), and detailed risk assessments for scour and wave forces for coastal and inland structures.

Chapter 9 contributes critical methodologies for bridge hydraulics, risk-informed design, scour resistance, and overtopping considerations that are core to TSI’s resilience framework.

Some examples which support asset resilience are the menu of engineered and nature-based scour countermeasures as well as design options to support resilience such as open railings, and approach profiles that can control overtopping behavior.

6.4.6.3 Chapter 13: Stormwater Management

Chapter 13 integrates transportation and stormwater through:

- BMP implementation: for both construction and long-term operations, including erosion and sediment control and water quality compliance with NPDES/MS4 requirements
- Quantity control strategies: integrated use of storm drains, detention/retention basins, pump stations, biofiltration, and wetlands for runoff mitigation.
- Documentation standards: mandates hydrologic assumptions, model outputs, and inspection documentation in alignment with regulatory frameworks, such as NFIP, Edwards Aquifer rules, and Storm Water Pollution Prevention Plan (SWPPP) requirements.

6.5 Stormwater

TSI aims to integrate transportation, stormwater, and environmental planning. Transportation infrastructure and stormwater management are already intrinsically interconnected. Roads and highways often include drainage systems that collect stormwater and direct it to designated treatment facilities. Therefore, coordinating the planning and design of transportation and stormwater infrastructure can lead to more efficient and effective systems. The goal of this literature review is to review the current stormwater management practices of communities in the study area and to identify challenges and gaps that can be solidified with more proactive planning. Note that this section was compiled in 2023 and changes may have occurred since.

6.5.1 Clean Water Act

Stormwater management practices and requirements have their origins in the U.S. Clean Water Act (CWA). The CWA is a federal law that was enacted in 1972 to protect the nation's water sources from pollution. The CWA is enforced by the EPA and sets the standards for discharge and pollution into the waters of the U.S. (EPA, 2022a). Under the CWA, it is illegal to discharge pollutants from a point source into water without a permit to do so. A point source is defined by the EPA as “any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged” (EPA, 2023a).

The CWA established the NPDES permit program. The program’s goal is to regulate the discharge of pollutants from point sources. The CWA also includes provisions for controlling non-point source pollution, which includes sources that do not originate from a point – such as runoff from urban areas. The NPDES determines the Total Maximum Daily Loads (TMDLs) for bodies of water that have been deemed at risk, which sets the maximum pollutants that can be discharged into a body of water and still meet water quality standards. In addition to regulating TMDLs from point and non-point sources, the CWA establishes water quality standards for surface water. This requires states to adopt water quality standards that meet or exceed the EPA's recommendation and develop plans for achieving those standards (EPA, 2023a).

6.5.2 State Level – TCEQ

In Texas, the Texas Commission on Environmental Quality (TCEQ) is responsible for implementing and enforcing the CWA (TCEQ, 2020). A primary function of the TCEQ is issuing and enforcing permits for the discharge of pollutants for bodies of water and surface waters in Texas. TCEQ issues permits to municipalities and facilities that discharge pollutants, like wastewater treatment facilities, industrial facilities, and construction sites. Permits establish limits and requirements on the number of pollutants that are allowed to be discharged. The permits also require monitoring and reporting to ensure compliance with regulations. In addition to issuing permits and enforcing compliance, TCEQ is responsible for enforcing water quality standards in the state of Texas. The agency works with stakeholders to identify overly polluted water sources and develop plans to restore them.

6.5.3 Municipal Separate Storm Sewer Systems

In the U.S., there are around 7,000 MS4s nationwide operating under an NDPES MS4 permit. MS4s are systems of stormwater drains and conveyances that are owned or operated by a municipality or other public entity (EPA, 2023c). The NPDES MS4 permit requires permittees to develop and implement a comprehensive Storm Water Management Program (SWMP).

In Texas, MS4s are required to obtain a permit from TCEQ. The permit outlines specific requirements for managing stormwater runoff. The specific requirements of the MS4 permit can vary depending on the size and complexity of the MS4, as well as other factors such as the area's land use and water quality. However, all MS4 permit holders in Texas must implement measures to prevent or minimize the discharge of pollutants into the storm sewer system and, ultimately, into nearby waterways. Failure to comply with the MS4 requirements may result in fines or other penalties.

MS4 communities are classified as either Phase I or Phase II. Phase I MS4s refer to the large, urbanized areas. These communities are classified as having a 1990 U.S. Census population of 100,000 or more. Phase II communities are smaller areas and typically have a population between 10,000 to 100,000 (TCEQ, 2018). Some smaller communities could be considered Phase II depending on their population density, proximity to urban areas, and potential for water quality impacts. There are approximately 270 Phase I communities and over 6,000 Phase II communities in the U.S. Both Phase I and Phase II MS4s are required to develop and implement a SWMP to reduce the discharge of pollutants.

6.5.3.1 Stormwater Management Programs

A SWMP typically includes an assessment of the existing stormwater management system, identification of potential sources of pollution, a description of BMPs to mitigate stormwater impacts, and a schedule for implementing the BMPs. The SWMP may also include provisions for monitoring and reporting on the effectiveness of the BMPs (TCEQ, 2018).

The goal of a SWMP is to reduce the negative impact of stormwater runoff on the environment, public health, and property. SWMPs are typically required by local, state, or federal regulations and are often required for new developments or redevelopment projects. By managing stormwater runoff through SWMPs, communities can protect water resources, reduce flooding, and improve the quality of life for residents.

Texas, like other states in the U.S., is required to implement the minimum control measures (MCMs) outlined by the EPA. The MCMs are designed to reduce the discharge of pollutants from MS4s and improve water quality in nearby waterways. Each state may also have additional MCMs based on the state's unique climate, geography, and environmental concerns.

Regional collaboration is vital for effective stormwater management. Programs like the NCTCOG's RSWMP provide smaller communities with technical support and shared resources to develop and implement SWMPs. Partnerships between local jurisdictions, state agencies, and federal entities enhance flood risk reduction and hazard mitigation efforts, demonstrating the power of collaborative approaches.

For Texas, Phase II communities' SWMPs include five MCMs that the communities must implement:

- Public Education, Outreach, and Involvement
- Illicit Discharge Detection and Elimination
- Construction Site Stormwater Runoff Control
- Post-Construction Stormwater Management in New Development and Redevelopment
- Pollution Prevention and Good Housekeeping for Municipal Operations

For Phase I communities, the application reorders the MCMs and includes additional measures:

- MS4 Maintenance Activities
- Post–Construction Stormwater Control Measures
- Illicit Discharge Detection and Elimination
- Pollution Prevention and Good Housekeeping for Municipal Operations
- Industrial and High-Risk Runoff
- Construction Site Stormwater Runoff
- Public Education, Outreach, Involvement and Participation
- Monitoring, Evaluating, and Reporting

Because most communities in the TSI study area are Phase II communities, this literature review focuses on the MCMs for smaller areas. Below are brief descriptions of each measure:

- Public Education, Outreach, and Involvement: Educate and engage the public on stormwater pollution and ways to prevent it (e.g., educational campaigns, outreach events, and public meetings).

- Illicit Discharge Detection and Elimination: Develop and implement programs to detect and eliminate illegal discharges to the storm sewer system (e.g., inspections, monitoring, and enforcement).
- Construction Site Stormwater Runoff Control: Develop and implement a program to control stormwater runoff from construction sites (e.g., erosion and sediment control measures, stormwater management plans, and inspections).
- Post-Construction Stormwater Management in New Development and Redevelopment: Develop and implement a program to manage stormwater runoff from new development and redevelopment projects (e.g., stormwater management plans, low-impact development practices, and inspections).
- Pollution Prevention and Good Housekeeping for Municipal Operations: Develop and implement a program to prevent pollution from municipal operations (e.g., BMPs for vehicle and equipment maintenance and storage and handling of materials).

6.5.3.2 Best Management Practices

BMPs are techniques or technologies designed to reduce the number of pollutants in stormwater runoff. Implementing BMPs can help prevent pollutants from entering the stormwater system and improve water quality (EPA, 2022c). Communities use BMPs to track activities and maintenance procedures, promote ordinances, and other practices to prevent and reduce discharge. After reviewing multiple communities' SWMPs in the study area, the study team compiled common BMPs for each of the MCMs for Phase II communities.

Public Education, Outreach, and Involvement

- Keeping an up-to-date stormwater website that houses the SWMP (City of Grapevine, Texas, 2019)
- Distributing materials (City of Lake Dallas, Texas, 2019)
- Household hazardous waste program (City of Joshua, Texas, 2019)
- Hosting cleanup days (City of Crowley, Texas, 2019)
- Fat, oils, and grease education (City of Kennedale, Texas, 2019)
- Conducting public awareness campaigns (City of Crowley, Texas, 2019)
- Providing education/trainings for commercial and industrial sectors
- Forming advisory committees
- Using water bill inserts (City of Sansom Park, Texas, 2019)
- Pet waste management (City of Kennedale, Texas, 2019)
- Stream cleanup event (City of Joshua, Texas, 2019)
- Stormwater education at public events (City of Cedar Hill, Texas, 2019)
- Brochure and fact sheet distribution at public meetings and the City's Newsletter (Highland Village, Texas, 2019)

Illicit Discharge Detection and Elimination

- Stormwater management ordinance (City of Cedar Hill, Texas, 2019)
- Mapping stormwater drainage systems (City of Crowley, Texas, 2019)
- Staff training (City of Cedar Hill, Texas, 2019)
- Providing education/trainings on illicit discharges (City of Crowley, Texas, 2019)
- Developing reporting and response policies (City of Joshua, Texas, 2019)

Developing policies to investigate source discharges (City of Lake Dallas, Texas, 2019)

- Creating a system to detect and eliminate illicit discharges (City of Joshua, Texas, 2019)
- Local Ordinance adoption (City of Corinth, Texas, 2010)
- Public hotline or online reporting system to report suspicious discharges or pollution events (City of Roanoke, Texas, 2019)

Construction Site Stormwater Runoff Control

- Developing erosion control requirements (City of Kennedale, Texas, 2019)
- Conducting construction plan reviews and site inspections (City of Joshua, Texas, 2019
- Construction inspector training program (City of Cedar Hill, Texas, 2019)
- Construction site stormwater education (City of Crowley, Texas, 2019)
- Creation of mechanism to receive comments (City of Lake Dallas, Texas, 2019)
- Developing erosion control requirements (City of Argyle, Texas, 2022)

Post-Construction Stormwater Management in New Development and Redevelopment

- Creating post-construction ordinances (City of Kennedale, Texas, 2019)
- Developing long-term maintenance plans for post-construction (City of Sansom Park, Texas, 2019)
- Developing landscape ordinances (City of Joshua, Texas, 2019)
- Stormwater management ordinance (City of Cedar Hill, Texas, 2019)
- Mapping stormwater drainage systems (City of Crowley, Texas, 2019)
- Developing reporting and response policies (City of Joshua, Texas, 2019)
- Developing investigating policies of source discharges (City of Lake Dallas, Texas, 2019)

Pollution Prevention and Good Housekeeping for Municipal Operations

- Municipal employee training program (City of Crowley, Texas, 2019; City of Roanoke, Texas, 2019)

Maintaining municipal stormwater facilities and infrastructure (Town of Shady Shores, 2019)

- Conducting audits on operational activities (City of White Settlement, Texas, 2019)
- Contactor requirements and oversight (City of Joshua, Texas, 2019)
- Street and Parking Lot Sweeping Program (City of Crowley, Texas, 2019)
- Pollution prevention training (City of Cedar Hill, Texas, 2019)

6.5.4 Challenges

The North Texas population is growing rapidly. Counties, entirely or partially, in the study area are projected to see population increases from 35 to 67 percent by 2045 (NCTCOG, n.d.-h). Phase II communities are identified at different levels, from Level 1 to Level 4, based on their population size. Different levels can have different permitting requirements (TCEQ, 2018). Higher-level communities have more stringent regulatory requirements. Phase II communities that increase in level will have to implement additional BMPs and develop more comprehensive SWMPs to meet these requirements. Additionally, implementing these additional BMPs and SWMP requirements can be expensive for communities. A higher-level designation may require more staff, equipment, and resources to manage the program effectively. Also, communities may not have the technical expertise or capacity to develop and implement more complex BMPs and SWMPs.

6.5.5 Conclusion

Communities should keep in mind future projected growth when creating SWMPs for long-range planning. Smaller communities will be the most affected as they will have to scale their efforts to existing and limited resources and funding available. These communities should be empowered to access regional programs that assist communities with stormwater management, such as the RSWMP offered by NCTCOG.

6.6 Environmental

Environmental planning comprised a minor component of most transportation resiliency studies conducted by MPOs or transportation planning organizations (see section 6.3 for more information). Studies that addressed environmental planning typically addressed land use, imperviousness, and GSI. However, some studies that addressed environmental planning expanded upon these concepts.

A study conducted for the Cape Cod, Massachusetts, area by Rasmussen et al. (2012) identified the preservation of natural/existing ecosystems as one of five key performance indicators. Performance measures identified for this indicator consisted of the following: percentage of new population in critical habitat areas, percentage of land area developed (from previously undeveloped or rural) in addition to percentage of new population in undeveloped or rural lands, and percentage of new population in other high priority conservation areas.

While this study focused on sea level rise and greenhouse gas emissions and did not focus on increased precipitation, it is being included in this literature review because of its emphasis on environmental planning. The Cape Cod study explored future growth scenarios with varying development intensity and disbursement; some scenarios showed growth across the geographic area, while others showed growth concentrated in existing areas of high residential density. The team used CommunityViz software to help workshop participants visualize real-time changes to housing and employment overlaid with environmental data related to conservation, water resource protection, historic preservation, and areas vulnerable to climate change. Local stakeholders identified areas that required protection, including those potentially affected by rising sea levels, and areas for future economic development. This study's scenario planning also sought to reduce greenhouse gas emissions to address climate change. This included promoting LID. The report noted the CommunityViz software was a learning curve for workshop participants, and the technology may have overshadowed the scenario planning process. The team recommended that before using such technology, planners should consider the time available and should introduce the technology to participants before the workshop. Workshop attendees should be allowed enough time to experiment with all the data layers. The TSI study originally intended to use CommunityViz software during stakeholder engagement, but has shifted away from these plans due to technical difficulties with using the software.

Additional transportation resiliency studies restricted their environmental planning content to land use and impervious surface discussions. The Capital Area Metropolitan Planning Organization (CAMPO) used projected demographics to increase impervious surface for future years without conducting actual future land use projections (Cambridge Systematics, Inc., 2015). SEMCOG's Climate Resiliency and Flooding study assigned binary imperviousness scores to current land uses but did not project future land uses (Bhat et al., 2020). The 2015 Broward study noted that climate changes could disrupt or alter existing land uses, but the study did not use potential future land uses in its analysis (Parsons Brinckerhoff, Inc., 2015). The Tampa Bay study's Adaptation Strategy Toolbox (Kiselewski et al., 2020) included NBS or GSI and identified in which circumstances the strategies were or were not applicable. NBS or GSI for inland flooding included swales or ditches, retention or detention ponds, permeable pavements, depressed medians (for water storage), vegetation, and GSI described as bioswales, planter boxes, green streets, and green parking. The Toolbox described the limitations and benefits of the strategies and, in some cases, referred readers to state and FHWA design manuals.

6.6.1 Regional planning

One study expanded on green infrastructure strategies to describe land use planning, including open space planning, in its matrix of adaptation strategies. The H-GAC study by Sambidi et al. (2021) described reducing development in floodplains as a strategy to preserve open space and enhance drainage. The study suggested land-use codes and regulations as tools to prevent this development. It also described maintaining and restoring wetlands, which can store water and reduce flooding. H-GAC plans to conduct a LID study to expand on adaptation strategies.

There are also design recommendations, which consist of the following: green roofs that increase stormwater infiltration, reduced parking requirements to reduce impervious surface and free up space for park space, trees, GSI, and green stormwater management, as well as permeable pavement.

NCTCOG, separately from its FHWA-funded resiliency study, commissioned a study on the economic benefits of ecosystem services generated by GSI that mitigates biophysical changes generated by adding new or expanding existing transportation facilities (Highland Economics, LLC, 2018). These biophysical changes included stormwater runoff, which was quantified to be 929,381 annual gallons of runoff/acre of impervious area/year. The report also identified mitigation measures that could capture stormwater, reducing water quantity. Mitigation measures included bioretention, detention ponds, wetlands, natural areas, and pervious pavement. Wetlands and preservation/restoration of natural areas provided the highest ranges of stormwater capture, with pervious pavement providing the lowest ranges.

6.6.2 Manuals and guidance

The Met Council's Climate Vulnerability Assessment expanded on GSI strategies to include a component of human vulnerability. A report was created by a team of graduate students consisting of mitigation, adaptation, and resiliency strategies for surface flooding (Ferguson et al., 2017).

The human vulnerability assessment called for the use of GSI to prevent stormwater systems from being overwhelmed. It called for stormwater to be kept and treated onsite for new development and redevelopment. It noted the Minnesota Pollution Control Agency has existing, extensive best practices for stormwater and wastewater management. Policy recommendations have been evaluated and included targeting vulnerable populations when funding green and resilience strategies and the adoption of resolutions that focus on climate change and its impacts. In addition, zoning codes that require stormwater should be kept and treated onsite, requiring native vegetation, support for urban agriculture, permeable pavement, complete streets, density bonuses for developments that utilize green design features, and incorporating resiliency into comprehensive plans.

6.7 Water Distribution and Wastewater

The contribution of current and future treated wastewater effluent will require a thorough review of existing wastewater outfalls from TCEQ and coordination with wastewater treatment operators and planners (TCEQ, n.d.). Previous regional wastewater studies have been prepared for eastern Parker County (Alan Plummer Associates, Inc., 2007) and southeastern Wise County (Roth, 2010). The most recent Water Quality Management Plan for the NCTCOG region provides additional insight into the impact of wastewater in the region (NCTCOG, 2023). Without the opportunity to calibrate or validate the results from the future conditions scenarios, these and future wastewater studies should be reviewed to ensure the water balance within the Trinity River Basin is properly accounted for in future conditions models.

7 Infrastructure

This section introduces how integrated planning for transportation and stormwater infrastructure can reduce flood risk and strengthen regional resilience. It highlights that, although the National Environmental Policy Act (NEPA) and similar state environmental review frameworks encourage coordination during project development, they generally do not require comprehensive regional integration. Instead, the strongest opportunities for collaboration often emerge in the early, pre-NEPA stages of planning, such as corridor and area studies. The section also outlines key challenges that have limited the incorporation of stormwater infrastructure into transportation resilience efforts, including data gaps, fragmented planning processes, funding constraints, and limited design guidance. Finally, it previews how both gray and green stormwater strategies—as well as broader NBS and land conservation approaches—can work together to provide cost-effective flood mitigation while also delivering water quality, habitat, and recreational benefits.

7.1 Transportation Infrastructure

The purpose of transportation infrastructure section for this review is to provide a list of all related transportation infrastructure physically associated with the TSI study. Included below is a list of transportation elements and definitions.

- Bridge: A bridge is a structure, including supports, erected over a depression or an obstruction, such as water, a highway, or a railway; having a roadway or track for carrying traffic or other moving loads; and having an opening measured along the center of the roadway of more than 20 feet between faces of abutments, spring lines of arches, or extreme ends of the openings for multiple box culverts or multiple pipes that are 60 inches or more in diameter and that have a clear distance between openings of less than half of the smallest pipe diameter.
- Culvert: A culvert is a structure (including multiple boxes) that measures greater than 20 feet (6 meters) along the roadway centerline and between the insides of end walls. This includes pipes or pipe arches if the inside opening of a single pipe or pipe arch exceeds 20 feet (6 meters).
- Asphalt Concrete Pavement: Pavement layer composed of Portland cement, coarse/fine aggregates and water mixed in a mixing plant.
- Hot Mix Asphalt Pavement: Pavement layer composed of a compacted, dense-graded mixture of aggregate and asphalt binder mixed hot in a mixing plant.
- Embankment: An embankment is a raised structure of soil, soil aggregate, rock, or combination of the three.

7.1.1 National Environmental Policy Act (NEPA[1]) Integration

The analysis below first explores the extent to which NEPA invites federal agencies from engaging in planning and construction of interdisciplinary, interagency, and comprehensive planning efforts for TSI projects, and then discusses other federal and state-based NEPA-like policies in Texas and several other states that may facilitate such efforts. Based on the information provided, it was presumed the NCTCOG is interested primarily in encouraging greater federal and state participation in integrated regional TSI planning.

7.1.2 NEPA and Sovereign Community

It is important at the outset to emphasize that NEPA only applies to federal agencies and does not subject them to the requirements of the laws and policies of state and local governments. Therefore, unless Congress has by some other statute clearly and unequivocally waived

[1] NEPA, as amended, is in 42 U.S. Code 4321-4347; this statute was enacted in 1969 and received no amendments until June 2023.

sovereign immunity, no federal agency would be legally bound to comply with NEPA-like policies enacted by a state legislature or local government.

Although it is generally politically expedient for a federal agency to acknowledge the existence of state and local government environmental requirements, acceptance of and adherence to any such requirements may be done as a matter of comity to foster goodwill between agencies at different levels of government. Thus, even if other states incorporate stormwater/infrastructure planning into a state-level NEPA-like process, or any other body of legal requirements or policies applicable to state agencies or local governments, such requirements or policies would have no legally binding effect on federal agencies absent a specific Congressional waiver of sovereign immunity.

The foregoing legal principle also applies to TxDOT which, as a result of statutory authorization, acts as the agent for FHWA in pursuing federally funded transportation projects and does so with the same federal legal protections that apply to FHWA. However, the existence of state NEPA-like processes and policies would be expected to have the potential to encourage (but not require) agencies such as FHWA (or a state transportation agent such as TxDOT) to engage in TSI project planning within the types of limitations pointed out below.

7.1.3 NEPA and Its Relation to TSI Planning

Before exploring how Texas and a sampling of other states may be utilizing NEPA-like processes to encourage TSI projects with federal agencies, this section discusses the extent to which NEPA addresses this topic either directly or indirectly.

7.1.3.1 Direct NEPA Influence on TSI Projects

Since NEPA's inception, one of its hallmark tenets is the mandate for federal agencies to implement a process of disclosing to other agencies and the public the agency's proposed plans for all major federal "actions significantly affecting the quality of the human environment."[1] NEPA also requires federal agencies to consider "the views of the appropriate" federal, state, and local agencies "which are authorized to develop and enforce environmental standards"[2] and to request and consider comments from the pubic "on alternatives or impacts and on relevant information, studies, or analyses with respect to the proposed agency action."[3] These provisions and over half a century of NEPA's application underscore its fundamental purpose of making information about a proposed federal project available to relevant federal and non-federal agencies as well as the public and thoughtfully consider feedback from all sources.

A second primary mandate of NEPA is for all federal agencies to promulgate regulations to implement the 'notice and opportunity to comment' provisions of NEPA as a routine part of federal agency planning. However, NEPA and agency regulations implementing it only prescribe a process that may influence an agency's decision about a proposed project but does not

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[1] NEPA statute: 42 U.S. Code 4332, Section 102 (2)(C).

[2] NEPA statute: 42 U.S. Code 4332, Section 102 (2)(C).

[3] NEPA statute: 42 U.S. Code 4336a, Section 107 (c).

otherwise restrain any federal agency in making its final decision. To illustrate federal agency implementation of NEPA, the discussion below focuses on the FHWA as nearly all transportation projects include cross drainage of stormwater as an integral component of project design. Although other federal agencies operating within the NCTCOG area could also have interplay with local government stormwater planning (e.g., FEMA and USACE), the FHWA will provide a typical example of how any federal agency would be expected to implement NEPA in reference to integrated agency stormwater management infrastructure planned, constructed and maintained by local governments. NEPA includes a requirement for environmental documents to "include a statement of purpose and need that briefly summarizes the underlying purpose and need for the proposed agency action."[1] Council on Environmental Quality (CEQ) regulations[2] elaborate on this by stating that purpose and need is a statement as to the reasons behind the federal agency's decision to "proposing the alternatives including the proposed action."[3] Notably, although it is an important aspect of NEPA for federal agencies to articulate why a particular proposed action is being planned, NEPA and CEQ regulations are silent as to the content of an agency's purpose and need statement.

Additionally, CEQ's NEPA regulations authorize federal agencies to "cooperate" with state, Tribal, and local agencies that are responsible for preparing environmental documents to comply with NEPA and further require the following:

> "To the fullest extent practicable unless specifically prohibited by law, agencies shall cooperate with State, Tribal, and local agencies to reduce duplication between NEPA and State, Tribal, and local requirements, including through use of studies, analysis, and decisions developed by State, Tribal, or local agencies." The regulation also states that "such cooperation shall include, to the fullest extent practicable: (1) Joint planning processes. (2) Joint environmental research and studies. . . ."[4]

The foregoing provision and other similar admonitions clearly encourage federal agencies to work cooperatively with other agencies at all levels, particularly to promote buy-in from others in the development and selection of a preferred project alternative. However, this policy is clearly tempered by the "practicable" constraints the federal agency may face such as funding, schedules, and agency mission requirements.

In summary, NEPA lays out a generic process that requires federal agencies to articulate the purpose and need for a project, prepare technical studies that assess impacts of a proposed alternative and demonstrate compliance with applicable legal requirements, and solicit and consider the comments from other agencies and the public before making a final decision. While NEPA encourages "practicable" cooperation with local agencies, including participation in joint planning processes, it does not require federal agencies to engage in TSI-type projects.

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[1] NEPA statute: 42 U.S. Code 4336a, Section 107 (d).

[2] 40 CFR Chapter V (CEQ), Subchapter A (NEPA Implementing Regulations), Parts 1500-1508.

[3] See CEQ NEPA Regulation 40 CFR 1502.13.

[4] 40 CFR 1506.2

7.1.3.2 Indirect NEPA Influence on TSI Projects

The implementation of objectives of Congress in enacting NEPA have been developed by CEQ and by the NEPA regulations prepared by individual federal agencies. The requirements for federal agencies to coordinate with state agencies and local governments are opportunities to facilitate synergies between otherwise independent projects. For example, FHWA's NEPA regulations provide flexibility to consider transportation alternatives "in the best overall public interest based on a balanced consideration of the need for safe and efficient transportation; of the social, economic, and environmental impacts of the proposed transportation improvement; and of national, State, and local environmental protection goals."[1]

However, while NEPA may provide the forum for the federal agency to engage with other agencies to benefit both, the federal agency will always be subject to practicable constraints such as the agency's mission, the purpose and need for the project, and funding limitations. For example, it is not uncommon for TxDOT (acting as FHWA's agent) to modify a project design to add a turn lane or access ramp to a roadway at the request of a municipality; however, the scarcity of funding available for other competing transportation projects generally prevents TxDOT from responding favorably to local government requests that add substantially to overall planning and construction costs. Likewise, TxDOT may modify the planned sizing or location of cross-drainage structures in response to a municipality, but estimated costs would be a constraint.

It may be stated that a fundamental challenge with looking to NEPA for TSI project guidance is NEPA is triggered at the point when a federal agency proposed a specific project. Thus, NEPA by design does little to encourage preliminary pre-NEPA planning, including regional integrated TSI planning. However, FHWA's NEPA regulations also incorporate by reference[2] pre-NEPA multimodal planning processes that authorize FHWA to "undertake a multimodal, systems-level corridor or subarea planning study as part of the metropolitan transportation planning process."[3] Although FHWA's focus is clearly on transportation projects and working with MPOs to develop projects before the NEPA process begins, the scope of these studies to develop alternatives is broad enough to include potential environmental impacts and mitigation to non-transportation facilities and planned projects within a transportation corridor or subarea.[4] These pre-NEPA regulations include provisions authorizing MPOs to develop programmatic mitigation plans (PMPs) as part of the MPO "transportation planning process to address the potential environmental impacts of future transportation projects."[5] The MPO defines the geographic

[1] See FHWA NEPA regulations in 23 CFR Part 771; quotation from 23 CFR 771.105(b).

[2] 23 CFR 771.105(a), "supplementary guidance" in Appendix A of 23 CFR Part 450 that implements statutory emphasis on greater use of pre-NEPA interagency planning of transportation projects to minimize/mitigate environmental impacts of interest to agencies at all levels.

[3] FHWA regulations implementing Section 1308 of the Transportation Equity Act for the 21st Century (TEA-21, Public Law 105-178) address Metropolitan Transportation Planning and Programming generally at 23 CFR Part 450, Subpart; quotation from 23 CFR 450.318(a), which also states that "To the extent practicable, development of these transportation planning studies shall involve consultation with, or joint efforts among, the MPO(s), State(s), and/or public transportation operator(s)."

[4] See 23 CFR 450.318(a)(4) and (5).

[5] 23 CFR 450.320(a)(1).

scope of a PMP to meet its planning needs and the content of the PMP can include a wide variety of natural and cultural resources including "stormwater."[1]

In summary, NEPA is triggered by "federal action" but it does not prescribe any limits to the shape and size of action. Factors external to NEPA form the primary controls on the actions a federal agency may choose to undertake. Chief among these are governing statutes and regulations and Executive policies that define the scope of an agency's areas of interest, and the fiscal limitations on the amount, purpose, and time limits for the federal funds to finance the action in whole or in part. NEPA is essentially neutral as to the action a federal agency may want to propose and the extent to which a federal agency should be expending its fiscal and manpower resources to promote working in tandem with another agency at the federal, state, or local level to plan projects. However, authorization for agencies such as FHWA to engage in pre-NEPA planning processes suggests the greatest opportunity is to participate in TSI-type project planning, subject to practicability constraints discussed above.

7.1.3.3 Texas NEPA-like Laws Relevant to TSI Projects

The Texas Transportation Code (TTC) includes NEPA-like provisions requiring environmental review of proposed state-sponsored and funded projects.[2] The TTC requires the Texas Transportation Commission to promulgate rules prescribing a review process for transportation projects that are not subject to NEPA.[3] The statute generally outlines requirements for TxDOT to seek public comment on proposed projects, assess environmental impacts, and commit to an appropriate level of mitigation for those impacts. The TTC supports TxDOT's coordination with local governments, particularly when local governments participate in funding a roadway project. However, specific provisions addressing joint planning for TSI-type projects are absent from the statute.

TxDOT rules implementing the TTC environmental policies require TxDOT to "integrate environmental considerations" into its activities, focusing on "a balanced consideration of transportation needs and of social, economic and environmental impacts of proposed transportation improvements."[4] When considering potential mitigation for impacts, TxDOT's rules require it to "identify any agency, department or other unit of federal, state, local, or Indian tribal government, including a local flood control authority, that may have an interest in a transportation project. . ." and coordinate "regarding the project, as appropriate based on the nature of the project, its potential impacts, and the specific interest of the entity."[5] TxDOT's rules also allow the agency to seek to avoid and minimize adverse environmental impacts and consult with appropriate agencies when developing proposed compensatory mitigation commitments.[6]

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[1] 23 CFR 450.230(a)(2)(ii) and (iii).

[2] See Texas Transportation Code Title 6 - Roadways, Chapter 201 - General Provisions, Subchapter H – Plans and Projects, Sections 201.604 – 201.620 and 201.751 – 201.762.

[3] TTC 201.604(a)

[4] 43 Texas Administrative Code (TAC) Part 1, Chapter 2, Subchapter A, Rules 2.1 – 1.110.

[5] 43 TAC Rule 2.12(a).

[6] 43 TAC Rule 2.13(b).

As with NEPA, Texas NEPA-like provisions encourage TxDOT to coordinate with other agencies at all levels of government on project-specific design and impact mitigation actions, including coordination with local flood control authorities, but do not address an integrated approach to areawide TSI planning. As emphasized above, state-derived law and policies affecting TSI-type projects would not be binding on federal agencies.

7.1.3.4 Other States' NEPA-like Laws Relevant to TSI Projects

This section provides a brief overview of NEPA-like statutes of several states that may have relevance to joint state-federal TSI planning efforts. As noted above, however, in the absence of a waiver of sovereign immunity by Congress, any state laws or policies addressing joint TSI projects would not be binding on federal agencies but could have the effect of encouraging such joint planning. Research presented below focuses on statutory policies, as these would have the greatest influence on encouraging federal participation in TSI projects, as opposed to policies created by subordinate state agencies or local government.

- California Environmental Quality Act (CEQA). Since its passage in 1970 CEQA[1] is probably the most well-known NEPA-like state program in America. CEQA and judicial interpretations of it have broadened its application to any public project or land development requiring government approval. CEQA applies to all persons, entities, state and local governments/agencies, and "to the extent permitted by federal law, the United States, or any of its agencies or political subdivisions."[2] Although a key purpose of CEQA is to impose NEPA-like scrutiny and planning for public projects, a review of the statute did not indicate any specific reference to TSI-policies.
- Minnesota Environmental Policy Act (MEPA). The MEPA was passed in 1973 to establish a state-level counterpart to NEPA.[3] The MEPA applies to all departments and agencies of the state government, requiring them to use a "systematic, interdisciplinary approach" to project planning, including a stated policy to share information with federal agencies in seeking the objective of minimizing environmental impacts and developing sound and sustainable alternatives.[4] This approach includes a requirement for state agencies to continually "seek to strengthen relationships between state, regional, local, and federal-state environmental planning, development, and management programs."[5] A search of the statute did not indicate any policy that specifically addressed TSI-type projects.
- Washington State Environmental Policy Act (SEPA). The State of Washington passed SEPA in 1971 to essentially mirror NEPA at the state level, making it applicable to "all branches of government of this state, including state agencies, municipal and public corporations, and counties."[6] SEPA requires a systemic, interdisciplinary approach to

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[1] California Public Resources Code (PRC) 21000-21189.91.
[2] California PRC 21066.
[3] 2023 Minnesota Statutes Chapters 114C-116I (Environmental Protection), Chapter 1116D – Environmental Policy. Sections 116D.01-116D.11.
[4] MEPA Section 116D.03(2-6) – Action by State Agencies, Subdivision 2 – Duties.
[5] MEPA Section 116D.03(1) – Action by State Agencies, Subdivision 2 – Duties.
[6] Revised Code of Washington (RCW) 43.21C.030.

analyzing environmental impacts and prescribes processes for disclosing information about proposed public projects to the public and other government agencies (including the federal government). State agencies are required under SEPA to seek out the "comments and views of the appropriate federal" and other agencies.[1] However, there are no references in SEPA to TSI projects.

- Connecticut Environmental Policy Act (CEPA). The CEPA[2] was passed in 1971 to establish policies and processes that parallel NEPA as applied to "Each state department, institution or agency. . ."[3] As with NEPA, the CEPA process is triggered by a state-sponsored action that may result in significant environmental impacts and imposes a requirement to cooperate "with federal and local governments, and other concerned public and private organizations" in minimizing environmental impacts from planned projects. Unlike the other NEPA-like state statutes, there is very little verbiage in CEPA that encourages close cooperation with federal agencies for proposed projects, and nothing to suggest any pre-NEPA joint planning for TSI-type projects.

7.1.3.5 Conclusions

NEPA and its state NEPA-like counterparts are generally triggered when an agency proposes a project. Such statutory processes encourage interagency cooperation in the development of alternatives and mitigation of impacts but simply do not address pre-NEPA joint agency planning. However, Congress has authorized the FHWA to engage in pre-NEPA corridor or area planning studies that could extend to regional TSI planning endeavors, subject to practicability constraints. NEPA and NEPA-like statutes, by requiring coordination with other government agencies in the context of project development, may imply authorization to engage in TSI-type advance planning but do not require such efforts. The independent constraints related to government agency mission/objectives, fiscal and manpower resources, and project timelines are the key practicability impediments to joint, regional TSI planning.

7.2 Stormwater Infrastructure

Predicting and mitigating future flood risk can both rely on stormwater infrastructure data. The FHWA Vulnerability Assessment and Adaptation Framework calls for studies to obtain data on transportation assets (Filosa et al., 2017). The framework notes the most readily available data includes roadways and bridges. Data on culverts or other stormwater infrastructure may be less available. Resiliency studies typically did not include stormwater infrastructure data in modeling future impacts on transportation facilities; however, stormwater infrastructure was addressed in discussions about design, implementation, and adaptation strategies.

SEMCOG's study addressed stormwater infrastructure design and implementation in more detail than other MPOs or COGs (see section 3.1 for more information studies as described in this section). As a COG, SEMCOG addresses planning in sectors outside transportation. SEMCOG hosted a 2021 roundtable to discuss water infrastructure and flooding. It was determined that

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[1] RCW 43.21C.030(d).
[2] Connecticut General Statutes (CGS), Sections 22a-1 – 22a-1h.
[3] CGS Section 22a-1b.

water infrastructure needed a $3.5 billion annual investment to achieve 100 percent good or fair condition (SEMCOG, n.d.). Investments included water mains, lead service line (LSL) replacement, sanitary sewer investment, and storm sewer investment. It did not include water treatment plants, wastewater treatment plants, culverts, bridges, or pump stations. The roundtable noted that no funding source existed to maintain and improve stormwater systems. The $3.5 billion amount did not include increasing the size of stormwater collection systems to address increasing levels of rainfall. SEMCOG concluded that the council should appoint an infrastructure task force and develop a regional stormwater management strategy. The roundtable led to a call on SEMCOG's website (SEMCOG, n.d.) for infrastructure coordination: "Strategic investments for long-term improvements requires coordinated management of vital infrastructure assets across all infrastructure classes and jurisdictions. This includes public and private utilities and transcends planning, design, and construction. At the same time, this also requires improved data collection and asset management programs. Local asset management programs are critical to understanding the condition of water infrastructure to support strategic, coordinated investments."

Both studies from the Broward MPO addressed stormwater infrastructure design and implementation. The 2015 study by Parsons Brinckerhoff Inc. called for the infrastructure to be addressed in the rehabilitation or reconstruction of existing facilities, construction of new facilities, and maintenance. The study suggested reconstruction and rehabilitation should include a project-specific drainage design that is sensitive to the context of the project; the long-range transportation plan could identify vulnerable infrastructure where this project-specific approach should be applied. The study called for drainage systems to be redesigned to address the high levels of flooding that result from intense precipitation. The study suggested that maintenance – including debris removal – is an important component of stormwater infrastructure because debris can reduce the flow of water through a culvert. It stated that transportation agencies should monitor debris in culverts. The 2016 Broward study called for culverts and bridges to be resized during maintenance and replacement activities to accommodate higher potential water flows resulting from precipitation (Brinckerhoff et al., 2016). The study called for a county-wide design policy requiring climate change to be considered during system design and maintenance.

A synthesis paper called for regionwide asset management planning as a requirement to plan and design stormwater infrastructure effectively. FHWA's Transportation Engineering Approaches to Climate Resiliency paper synthesized lessons learned from FHWA-funded studies and pilot projects (Rodehorst et al., 2018). The paper identified the early stages of transportation project development as the most effective time to include "engineering-informed adaptation studies" (p. 121). These stages are typically referred to as planning, scoping, and preliminary design/engineering. The paper urged considering the cost and benefits of adaptation (such as improving infrastructure to convey stormwater) and the life cycle of the existing infrastructure. If transportation infrastructure is near the end of its life cycle, for example, it may not make financial sense to retrofit it to meet future precipitation/flooding possibilities. The paper also emphasized considering adaptations on a regional scale rather than a facility-by-facility scale. This is because increasing the size of one culvert may have little benefit if impacts that occur upstream or downstream from the culvert are not considered or if nearby culverts are not also increased in size. Multiple stakeholders would need to coordinate to protect assets on a regional scale, as determined by a Massachusetts DOT pilot study. The synthesis paper recommended incorporating planning for adaptation into asset management. It said this can reduce costs by implementing adaptations during regular reconstruction or replacement of infrastructure.

The 2018 Met Council report called for new facilities to incorporate a design that promotes stormwater infiltration or diverts water from infrastructure (Metropolitan Council, 2018b). The study noted the lack of regionwide data on stormwater hampered the ability to analyze flooding impacts. The study also referred to adaptation strategies, encouraging stormwater to be managed locally using permeable pavement, GSI, and adopt-a-drain programs that could improve the maintenance of existing stormwater conveyance.

Other studies focused on identifying adaptation strategies. The Resilient Tampa Bay study by Kiselewski et al. (2020) identified adaptation options and the circumstances where the options were preferred or not applicable. Adaptation options included swales or ditches, retention or detention ponds, permeable pavements, protected or depressed medians, and vegetation. The study referred readers to FHWA's Urban Drainage Design Manual, Hydraulic Engineering Design Circular No. 22, for more detailed guidance on drainage structure sizing and implementation. The report suggested drainage structures be reinforced with concrete surfaces to prevent erosion. Drainage swales were identified as the preferred solution to roadway flooding when there is available width next to a road. It was noted that depressed medians can function as drainage swales. Detention ponds were noted as a solution when a large volume of water must be retained, and land for the detention pond is available. The report described GSI as an alternative to traditional engineered approaches.

The Tampa Bay study suggested adaptation strategies be incorporated into the MPO's long-range transportation plan. The study identified drainage adaptation strategies as short-term solutions while working toward other strategies, such as raising the profile of a transportation facility. It was noted that partners would be needed to implement some adaptation strategies, and stormwater solutions could be funded by stormwater fees or capital improvement bonds. This would preserve transportation funds for protection and avoidance solutions not included in stormwater infrastructure.

Similar to Resilient Tampa Bay, the H-GAC study by Sambidi et al. (2021) incorporated a matrix of adaptation strategies, including stormwater infrastructure. The strategies described gray and green stormwater infrastructure, where they could be used, which climate stressors they would mitigate, their benefits and limitations, and the criteria to be used in deciding whether to implement the strategy. The strategies included developing a stormwater management plan and referring readers to the National Cooperative Highway Research Program (NCHRP) Research Report 922, Stormwater Infiltration in the Highway Environment: Guidance Manual. The H-GAC study included smart stormwater systems in its adaptation toolbox to improve monitoring of the stormwater system during rainfall events.

Transportation resiliency studies address stormwater infrastructure to a limited extent. Those that do address stormwater infrastructure note the following challenges: limited data on stormwater assets, piece-meal planning that does not address a watershed or regional need, the need for design guidance, the need for planning to incorporate construction/reconstruction into the infrastructure lifecycle, and lastly, lack of funding for implementation.

7.2.1 Traditional/Grey Stormwater Infrastructure Projects

Gray infrastructure is traditional stormwater infrastructure in the built environment, such as gutters, drains, pipes, and retention basins (EPA, 2024). Gray infrastructure for stormwater management refers to a network of water retention and purification infrastructure (such as pipes, ditches, swales, culverts, and retention ponds) meant to slow the flow of stormwater during rain events to prevent flooding and reduce the number of pollutants entering waterways. (Duke University, n.d.)

7.2.2 Types of Gray Stormwater Infrastructure for TSI Consideration

Small/regional detention ponds are depressed basins to treat stormwater runoff during severe storms. Structure life is typically ten years or more, and embankment slopes are typically 2.5:1 or flatter. However, the iSWM Manual allows for slopes no greater than the angle of repose on material or 4:1 if the geotechnical study is not performed (NCTCOG, 2021). Detention ponds hold runoff for between 24 to 48 hours from the design storm, and an inspection is needed after each storm event. Texas design-build projects request any length-to-width ratio variation, which shall require review and concurrence by TxDOT prior to completion of 100 percent design. A 10-foot bench with a 10:1 slope or flatter must be provided at the normal water level for safety and maintenance.

Embankment compositions include a roadside ditch that is placed parallel to the roadway to collect surface runoff from the roadway. The road profile or other constraints generally dictate channel front slopes.

Bridge class culverts and outlet appurtenances are defined as those having an opening (i.e., distance) of more than 20-ft between the extreme inside faces as measured along the highway centerline (TxDOT, 2019).

Energy dissipator for bridge class culverts include stilling basins and streambed level structures. Although effective, stilling basin design, installation, and maintenance are expensive and have potential issues with silting (TxDOT, 2019).

Roadside channel or ditch usually parallels the highway embankment and within limits of the right-of-way. The design frequency usually corresponds with storm drainage frequency. The maintenance cost of these structures is typically high.

Pipes are typically used to convey stormwater runoff from one location to another (EPA, n.d.; San Antonio River Authority, 2019). They are considered minor structures to carry runoff; prefer minimum 3 feet per second and maximum 12 feet per second. Usually, storm pipes are designed during the Plans, Specifications, and Estimate (PS&E) phase.

Culverts are structures that are designed to convey stormwater runoff under roads, highways, and other infrastructure (Minnesota Pollution Control Agency, n.d.). A major culvert provides an opening of more than 35 square feet in single or multiple installations. Bridge-class culverts shall have a minimum rise of 4 feet. Texas design-build project requests for major culverts are analyzed using HEC-RAS (TxDOT, 2017).

Infiltration trenches are structures that are designed to allow stormwater runoff to infiltrate into the ground. These structures typically involve the excavation of a trench or trench-like structure that is backfilled with a porous material such as gravel or crushed stone (EPA, 2023b).

Off-channel storage options include the construction of a bypass channel adjacent to the main channel that creates floodwater storage as well as wetland habitat similar to the ongoing USACE Central City project in Fort Worth, Texas (USACE, 2008).

7.2.3 Green Stormwater Infrastructure Projects

The EPA defines GSI as systems and practices that use or mimic natural processes that result in the infiltration, evapotranspiration, or use of stormwater to protect water quality and associated aquatic habitat (EPA, n.d.-b). The terms NBS, LID, and Green Infrastructure (GI) have been interchangeably used to describe these practices. By implementing GSI, water can be managed in a way that reduces the impact of built areas and promotes the natural movement of water within an ecosystem or watershed. Applied on a broad scale, GSI can maintain or restore a watershed's hydrologic and ecological functions (EPA, n.d.-b). There are many practices that have been used to adhere to these principles such as rain gardens, green roofs, rainwater harvesting systems, permeable pavements, and detention ponds.

7.2.3.1 Bioretention areas/Rain gardens

Bioretention areas or rain gardens (Figure 3) are designed to capture stormwater runoff, filter it through a special media and allow it to infiltrate, evapotranspirate, or flow out. Rain gardens are depressions of 4 to 8 inches that are planted to capture and filter runoff before it reaches a stormwater inlet or water body. Bioretention areas consist of excavated basins equipped with a perforated pipe underdrain. The underdrain is covered by an engineered soil/compost mixed media in which specific wetland facultative native or adapted vegetation is planted (Jaber, 2015). Bioretention/rain gardens can be implemented in areas that require stormwater management to regulate the runoff velocity and decontaminate the runoff. Bioretention/rain gardens are created to handle the first flush of pollutants during the event of rain, therefore, locations that have high areas of impervious surface such as roads, parking lots, or rooftops can benefit from additions of bioswales, or areas that function as described but move water. They can also be integrated into road medians, curb cutouts, sidewalks, or any public space (NACTO, 2013). While originally the terms “rain gardens” and “bioretention areas” have been used interchangeably, recent applications are separating the definitions to indicate a depression with plants for rain gardens and a bioretention for practices that include engineered soils and underdrains (e.g. SWMM 5.1) (EPA, 2015).

Figure 3. **A bioretention area at a parking lot (Texas A&M AgriLife Extension Dallas Center, photo by Yufan Zhang)**

7.2.3.2 Green roofs

Green roofs consist of a modified base covered in filter strips, water storage, soil media, and vegetation instead of traditional roofing material such as asphalt and tiles. Green roofs have a layer of plant material that absorbs water like a sponge. They capture water when it rains, slowly releasing it through evaporation and plant use. Green roofs can significantly reduce the amount of rainwater that would otherwise run off an impervious roof surface. A typical green roof (Figure 4) may include these following components: plants, growing medium, filter fabric, drainage layer, root barrier, thermal insulation, waterproof membrane, and roof deck (EPA, 2021a).

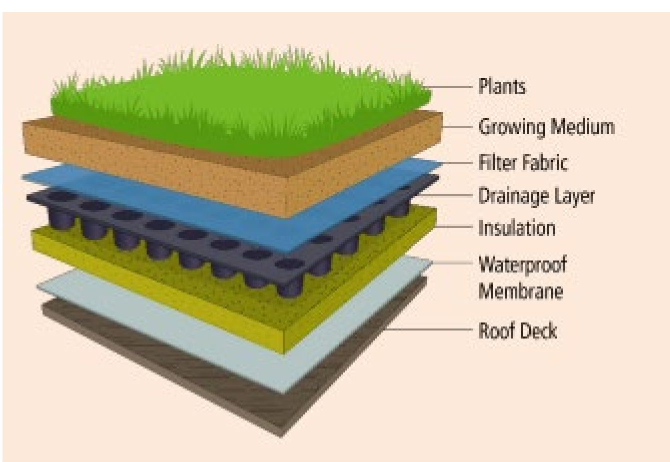

Figure 3. **Green roof multiple layers (EPA, 2021a)**

Figure 4. **Green roof (Fort Worth Botanic Garden, n.d.)**

7.2.3.3 Rainwater harvesting systems

Rainwater harvesting (Figure 5) is an alternative water supply approach that captures, diverts, and stores rainwater for later use and is available to anyone. Captured rainwater can be used for watering landscapes and gardens and to provide water for pets, wildlife, and livestock. Rainwater can be filtered, sanitized, and used for non-potable and potable water uses in homes and businesses instead of other sources of water. The process is simple and often less expensive than drilling a well (Mechell et al., 2009).

Figure 5. **Rainwater harvesting system (Texas A&M AgriLife Extension Dallas Center, photo by Yufan Zhang)**

7.2.3.4 Permeable pavements

Permeable pavements are alternatives to traditional impervious pavement systems (Figure 7). These are comprised of a load bearing, durable surface layer, with additional underlying layers that temporarily store runoff, letting it infiltrate or drain into a controlled outlet. The main mechanism of runoff reduction is infiltration from the top layer, storage within the underlying structure with appropriate flow control. They allow for stormwater runoff reduction and treatment, with slow infiltration into subsoil. They are typically used in low traffic areas, such as parking lots, driveways, fire lanes, and overflow parking areas (Jaber, 2015).

Figure 6. Close-up view of permeable concrete (EPA, 2021)

7.2.3.5 Detention ponds

Detention ponds are basins that hold stormwater runoff and release it slowly to a nearby water course or water body. A detention pond can be dry, (i.e. hold water only during and right after storms) or wet (i.e. have a permanent pool of water). Dry detention ponds (Figure 8) have outlets (usually a culvert) located at the same level as the bottom of the pond. The culvert's size limits the outflow thus reduces the flow rate from large storms. Wet detention ponds (Figure 9) have a permanent pool of water. By placing the outflow at an elevated location, a wet detention pond stores the water from the previous storm, to release it only during the next storm. This allows for the sediments in the stormwater to settle, and biological and chemical reactions with vegetated benches can then improve the quality of the water (Jaber, 2015).

Figure 7. **Dry detention pond (Minnesota stormwater manual, 2012)**

Figure 8. **Wet detention pond (Minnesota stormwater manual, 2012)**

7.2.3.6 Tree Box

A tree box is a small biofiltration system that performs pollutant removal via filtration and adsorption (Figure 10). It is a pre-manufactured concrete box which is installed in-ground, filled with soil media, and typically planted with native, non-invasive tree or shrub. Tree boxes generally capture and treat stormwater runoff from small frequently-occurring storms but are not designed to capture runoff from large storms or extended periods of rainfall. Each tree box is designed to treat approximately 0.25 to 0.5 acre. When looking at a large treatment area, multiple tree boxes or an alternative control measure will be required (New Jersey Agricultural Experiment Station, 2013).

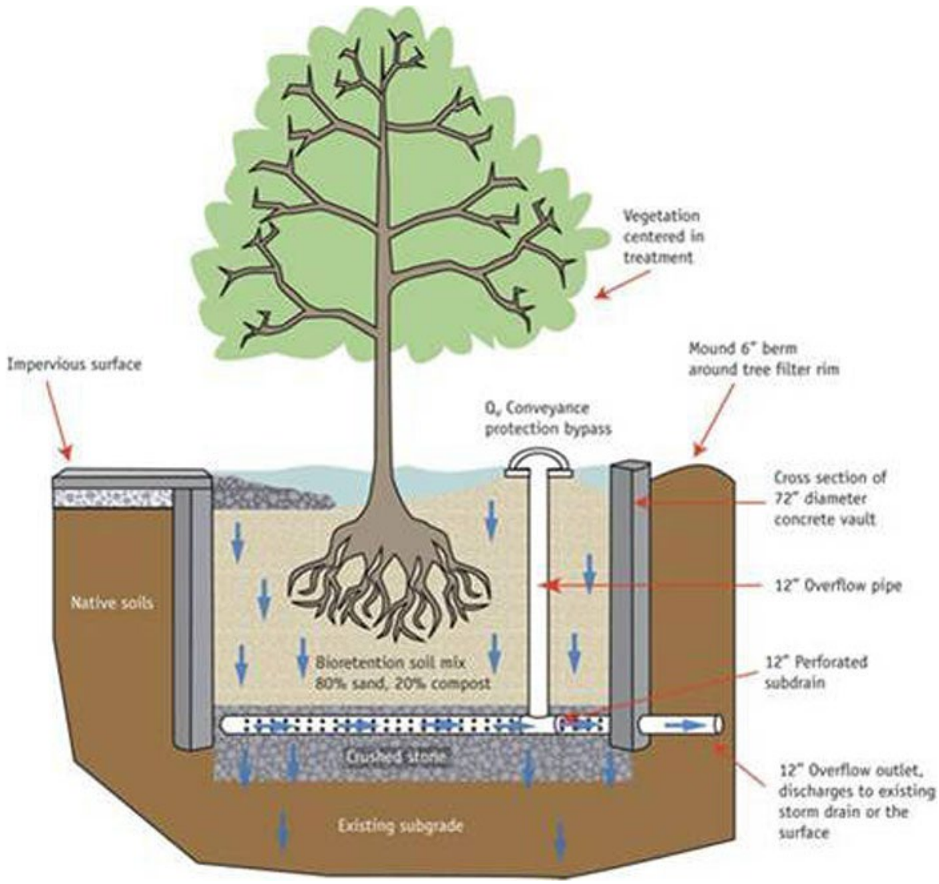

Figure 9. Tree box (New Jersey Agricultural Experiment Station, 2013)

7.2.3.7 Bioswale

Bioswales are sloped drainageways designed to convey stormwater runoff efficiently (Figure 11). A bioswale has an engineered subgrade with amended soil, aggregate and subsurface drain that is designed to treat the water quality volume and convey larger rainfall events typically to flood management practices (wetlands, retention or detention basins). They consist of a series of vegetated cells with level bottoms that have check dams spaced between them. They are an effective option when water can be routed through a channel long enough to allow flow to pass at slow velocities for the desired residence time. Bioswales differ from bioretention areas or rain gardens in that they are in sloped areas so that when larger storms occur, they are safely conveyed to flood management practices such as constructed wetlands, retention or detention basins before draining into the nearest stream or waterbody (Iowa Stormwater Education Partnership, n.d.).

Figure 10. Bioswale at a parking lot (Texas A&M AgriLife Extension Dallas Center, photo by Fouad Jaber)

7.2.3.8 Constructed Wetlands

Wetlands are transition areas. They have both aquatic and terrestrial features. They are dominated by vegetation adapted to life in saturated soil conditions. Constructed wetlands are treatment systems that use natural processes involving wetland vegetation, soils, and their associated microbial assemblages to improve water quality. It can be built from scratch or retrofitted from an existing detention pond. The single most important issue that determines how well a stormwater wetland works is the size of the wetland relative to the contributing watershed. A fully functional stormwater wetland needs to be about 5 to 10 percent of the contributing watershed in size. The most important feature (Figure 12) in constructed wetland is forebay/deep pool, where the surface runoff is collected, and pollutants are removed due to an aerobic environment. The forebay/deep pools are usually 18 to 30 inches deep and should account for 20 to 25 percent of the total area of wetland (Jacob et al., 2012; EPA, 2004). Such a constructed wetland was built at the Tarrant Regional Water District (TRWD) headquarters in Fort Worth, Texas (Figure 13).

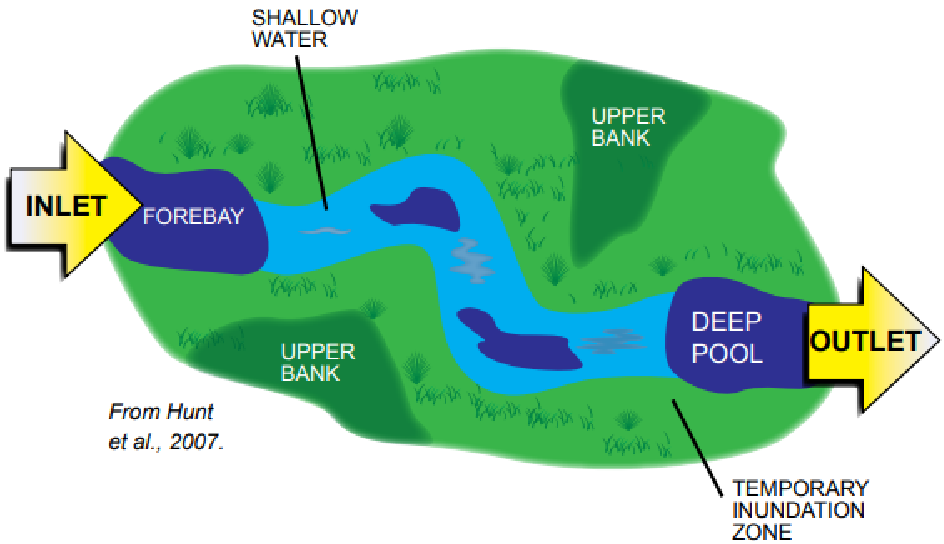

Figure 11. Constructed wetland features (Hunt et al., 2007)

Figure 12. Constructed wetland at the TRWD headquarters in Fort Worth, TX (Photo by Fouad Jaber)

7.2.4 Flood Mitigation

Each GSI may show some or all of following functions such as pollutants removal, biodiversity enhancement, energy conservation, and aesthetic value depending on the type and design;

however, almost all GSI have a fundamental effect on flood risk mitigation considering the conservation of surface water runoff. Some studies have demonstrated the capability of GSI in alleviating flood risk.

The Nature Conservancy (TNC) and Texas A&M AgriLife found that bioretention areas, rain gardens, and rainwater harvesting systems can reduce overflows for all storms modeled by 17 to 31 percent and to delay peak flows potentially reducing areal flooding, creek flows, and overbank flooding (Heidari et al., 2023a). Several studies showed that a bioswale can significantly reduce stormwater runoff volume with water retention rate of at least 40 percent (Shetty et al., 2019; Askarizadeh et al., 2015; Davis et al., 2012, 2009; Lord et al., 2013; Roy-Poirier et al., 2010). Additionally, green roofs are known to intercept 15 to 90 percent of rooftop runoff. However, type of growth medium, thickness, and plant cover variability can cause differences in runoff of 50 to 60 percent (Jaber, 2015). Since constructed wetlands can be easily transformed from an existing detention pond, other than the pollutants removal functionality, the basin must still be able to serve its flood mitigation purposes after wetland construction (Jacob et al., 2012). Likewise, most studies on permeable pavement show that it can retain at least 30 percent precipitation inputs or surface runoff (Drake et al., 2013).

7.3 Land Conservation and Nature-Based Solutions for Flood Risk Reduction

There are two primary land management strategies for reducing flood risk: permanent conservation of open space or rural properties, and NBS in urban areas. Conservation easements, which are voluntary agreements between a landowner and a land trust to restrict certain rights, such as building homes and subdividing, are an effective tool to permanently preserve lands. In urban areas where space is limited for large scale projects, NBS offer practices, such as rainwater harvesting and bioswales, that can be adapted for smaller areas and provide significant flood reduction.

7.3.1 Conservation Easements

Landowner interest in conservation easements is high, as shown in a survey by the Natural Resources Institute that found 80 percent of landowners were open to permanently protecting their land, while 15 percent indicated they were likely to implement a conservation easement in the next 10 years (Lund et al, 2019). The 1.2 million acres of conserved lands in Texas have the potential to capture 980,000 acre-feet of water annually, representing a water replacement cost of over $1.7 billion for the state each year (Lund et al, 2019). Farm Bill programs through the U.S. Department of Agriculture – NRCS provides $450 million per year in federal funds with potential to leverage $9 in matching funds for every $1 of state investment through the Texas Farm and Ranchlands Conservation Program (TFRLCP), administered by the Texas Parks and Wildlife Department (TPWD) (Siglo Group, 2019). Lund, Smith and Lopez (2024) found that nearly 60 percent of applications to the TFRCLP were not accepted due to lack of state funding. Of the 37 easements executed or pending under TFRLCP between 2016 and 2024, Lund, Smith and Lopez (2024) found that the state gained a 23:1 return on investment with a 9:1 leverage on external funds at only $222 per acre that the state contributed.

Flooding has caused an average of $8 billion in damage since 2000, and future damage costs are expected to rise as continued development in flood-prone areas and risks from climate change increase (Johnson et al., 2020). Johnson et al. (2020) conducted a BCA for purchasing all 675,919 square kilometers in the 100-year (1 percent) floodplains across the U.S. would cost $306 billion and would avoid flood damages of nearly $600 billion by year 2070. The authors noted that since this would be the cost to purchase the land at full price, the use of conservation easements or changes in zoning or land use regulations could achieve the same outcome at a much lower cost.

7.3.1.1 Ecosystem Services of Conservation Lands

Every $1 invested in land conservation can avoid $6 in water infrastructure costs for Texas taxpayers. Likewise, every $1 spent on flood risk reduction produces $4 in disaster cost savings (Siglo Group, 2019). TFRLCP properties have the potential to provide $590 million in ecosystem services over 20 years, with benefits including carbon sequestration, erosion control, flood mitigation, water quality and quantity, food and fiber production, wildlife habitat and biodiversity, and recreation (Lund, Smith and Lopez, 2024). These properties have the potential to:

- Support water needs of 182,000 Texas households,
- Save $16.4 million in water replacement costs, and
- Provide $22.6 million in coastal and inland flood prevention.

7.3.2 Nature-Based Solutions

NBS, also commonly known as GSI, are practices that can be implemented in urban areas to capture excess stormwater due to significant amounts of impervious cover, such as parking lots and rooftops. Common practices include rainwater harvesting, bioswales, and rain gardens. Jaber (2021) created a GIS mapping tool to identify location and implementation of GSI BMPS to mitigate specific identified localized flood hazards in Denton County. The integration of GSI into emergency plans will provide great benefits to the county and increase the implementation of GSI programs while providing low-cost flood reduction. In addition, by stewarding riparian areas and urban green open spaces (pocket parks, urban parks, lawns, etc.), these areas can provide water capture to reduce flooding, along with other benefits, such as recreation and wildlife and aquatic habitat.

Even though the benefits of NBS, such as GSI, are well studied and widely known, barriers to implementation remain as determined by Heidari et al. (2023b) through an extensive literature review. These barriers include socio-cultural, financial, institutional and governance, legislative and regulatory, technical, and biophysical. Solutions that were extracted from these same literature sources include public education campaigns and engagement in community-based GSI installations, clear regulatory requirements for developers, and improved partnership and communication between stakeholders among others. Moreover, Heidari et al. (2023b) emphasized that GSI solutions should involve input and participation from local communities where they will be implemented.

Kim and Park (2016) examined the impacts of the spatial configuration of GSI to reduce flooding in the four largest metropolitan areas in Texas. Their study found that size, fragmentation and connectivity of landscape and GSI practices are likely to reduce peak runoff, although connectivity seems to only be important at the macro-scale. The authors recommend regional-level plans that target areas where GSI should be strategically preserved and connected.

7.3.2.1 City of Dallas Study

Jack et al (2022) conducted a study in the City of Dallas to answer the question: Where can GSI most effectively enhance urban flood management within the City of Dallas, Texas, when considering capacity, cost, and future impacts of climate change? The focus was on evaluating opportunities to enhance flood management where the existing drainage network may be limited. Three types of GSI—bioretention areas, rain gardens, and rainwater harvesting cisterns—were considered.

If GSI were deployed in all identified opportunity areas, representing the maximum implementation scenario, approximately 31 percent of the 2-year storm, 25 percent of the 10-year storm, and 17 percent of overflows resulting from the 100-year storm could be managed at an average cost of approximately $2.4 per gallon. When compared to the capacity and costs for upgrading gray infrastructure for the 100-year design storm, GSI was approximately 77 percent less costly. However, more stormwater could be managed with a combined implementation of green and gray for a 45.1 percent reduction in modeled overflows for the 100-year design storm, and at a lower per gallon cost than for gray alone. GSI was found to reduce modeled overflows for all storms (17 to 31 percent reduction) and to delay peak flows which can reduce area flooding as well as creek flows and overbank flooding. GSI was found to be 77 percent less costly than upgrading gray infrastructure alone to meet modeled overflows, and a combination of green and gray provides the maximum cost-effective benefits. Of the systems studied, bioretention areas—particularly in parking lots—represent the "biggest bang for the buck," with the most widely available siting opportunities. Their findings identify bioretention as the most cost-effective and potentially impactful of the GSI practices considered—in area and volume captured for the study area. Bioretention provides approximately 71 percent of the overall stormwater volume managed by GSI (Jack et al., 2022).

7.3.2.2 Ecosystem Services of Nature-Based Solutions and Green Stormwater Infrastructure

According to FEMA (2022b), riparian areas are estimated to contribute $37,199 per acre-year in ecosystem services. Aesthetic value, air quality, biological control, climate regulation (Carbon sequestration), erosion control, flood reduction, food provisioning, habitat, recreation, water filtration, and water supply were the benefits listed. In addition, Urban green open spaces (pocket parks, urban parks, lawns, etc.) were estimated to contribute $7,010 per acre-year in ecosystem services. Aesthetic value, air quality, climate regulation, erosion control, flood reduction, habitat, pollination, and recreation were the benefits listed.

Protecting floodplains from development is crucial as these areas, especially when forested, remove pollutants from soil and water, reducing water temperatures due to shading, stabilizing bank soils, and promoting infiltration of water (Cappiella et al., 2012). Floodplain ordinances that protect vegetation not only benefit the community by preventing flood-related damage and death but also help protect downstream water sources by allowing vegetation to stabilize stream banks, thereby reducing sedimentation and pollutants in reservoirs and protecting stream aquatic habitat.

7.3.3 Case Studies

The following examples from the TSI study area illustrate how local governments are applying site design and GSI strategies to address runoff, improve water quality, and reduce flood risk. Together, these case studies from Flower Mound, Denton, and Frisco demonstrate the practical benefits of conservation development, watershed-based BMP planning, and bioswale implementation in rapidly growing communities.

7.3.3.1 Town of Flower Mound Better Site Design

Better Site Design, including cluster or conservation developments, reduce impervious cover on the land surface and promote more open space that will allow more infiltration of rainwater and reduce flooding risk (Cappiella et al., 2012). A local example of this can be found in the Town of Flower Mound's Cross Timbers Conservation Development District (CTCDD), requiring 50 percent of the land area to be preserved as natural open space and allow for denser and smaller lots to benefit developers (n.d.). In 2006, American Forests conducted an Urban Ecosystem Analysis for Flower Mound and found that the town's 28 percent tree canopy provided 54 million cubic feet in stormwater management worth $109 million in runoff retention, not to mention other benefits including carbon sequestration, pollutant removal, etc. (American Forests, 2006). In addition, more compact land development lowers the cost for built infrastructure by decreasing street utility line length.

7.3.3.2 City of Denton Hickory Creek Watershed Protection Plan

As part of the development of the Hickory Creek Watershed Protection Plan for the City of Denton, a series of BMP optimization analyses were conducted to demonstrate a systematic approach to site identification and BMP type selection for planning purposes (CH2M Hill, 2012). While the focus of this study was water quality protection through pollutant removal, the same method can be applied for flood risk reduction. The project team found that riparian buffers were the most cost-effective strategy for reducing sediment, phosphorus, and nitrogen on a per pound basis (CH2M Hill, 2012).

7.3.3.3 *City of Frisco Bioswale Study*

The City of Frisco has been rapidly urbanizing since the 2000's, and the need to manage stormwater has increased dramatically. In addition to regulations enacted by the city on new developments to manage stormwater, the City of Frisco Stormwater Department (FSD) has built bioswales as demonstrations, including in the Public Works Facility (PW) parking lot (Bustetter, Harman and Harts, 2024). FSD conducted a study to compare two bioswales: one at PW which consists of native clay soil and native prairie plants and the other bioswale at the Frisco Badminton courts which was built by the developer and includes an engineered soil mix and mainly turfgrasses.

FSD hypothesized that the PW bioswale would remove more pollutants (Total Suspended Sediments, Nitrate, Ammonia, Total Kjeldahl Nitrogen, Phosphorus) than the Badminton bioswale. Results showed that their hypothesis was correct in that the PW bioswale had performed better at reducing Total Suspended Sediments, Nitrates and Ammonia. FSD also found that the PW bioswale captured more stormwater than the Badminton bioswale, showing that GSI practices can utilize on-site native soil and native plants to function effectively, greatly reducing the cost of construction and engineered soil mixes (Bustetter, Harman, and Harts, 2024).

7.4 Infrastructure/Transportation and Stormwater Integration

The purpose of this section is to present a survey of the literature that has established a collaborative plan for the integration of transportation and stormwater management together as opposed to a more compartmentalized perspective.

7.4.1 Types of Transportation and Stormwater Integration ideas for consideration

According to TxDOT, the primary objective in designing drainage systems is to properly accommodate surface runoff along and across highway right-of-way through the application of sound hydraulic principles (TXDOT, 2022b). Given that there are clear design criteria for these drainage facilities (see below) and that they can be accounted for in the hydraulic models, these are ideal candidates when planning the integration of transportation and stormwater management.

7.4.1.1 Parallel drainage outlet appurtenances

The inlet and outlet points of culverts handling drainage parallel to the travel lanes, such as at driveways, side roads, and median crossovers are concerns in providing a safe roadside environment. Flow quantities for parallel drainage situations are generally low, with drainage typically accommodated by a single pipe. TxDOT roadway design manual specifies side slopes from driveway embankment, median crossover, and side road at a rate of 1 vertical (V):6 horizontal (H) maximum steepness. If open channels are upsized with cross bridges or bridge-class culverts, drainage easements need to be purchased to ensure accessibility and discharge from outlet/downstream will not be restricted because of right-of-way and appurtenances side slope requirements.

7.4.1.2 Design Treatment of Cross Drainage Culvert Ends

Cross-drainage culverts are defined as those conveying drainage across and beneath the highway. Selection of an appropriate end treatment is primarily related to culvert size, culvert end location, side slope rate, terrain characteristics, drift conditions, right-of-way availability, and other considerations that may influence treatment selection at individual sites. Specific examples and technical considerations are found in the TxDOT manual for drainage facility placement (TxDOT, 2022b).

7.4.1.3 Roadside Channel/Ditch with Embankment

According to the AASHTO Roadside Design Guide (AASHTO, 2011), a roadside drainage channel is an open channel usually paralleling the highway embankment within the limits of the right-of-way. The primary function of a drainage channel is to collect surface runoff from the roadway and areas that drain to the ROW and to convey the accumulated runoff to acceptable outlet points (TxDOT, 2019c). For design, TxDOT recommends that the front slope, adjacent to the roadway/shoulder, be 1V:6H or flatter. Steeper slopes can be adopted in some locations. TxDOT documented 1V:4H or flatter facilitates the efficient operation of construction and maintenance. Bridge embankment and bridge-class culvert embankment side slope rates of 1V:2H are recommended and they require riprap. If the slopes are greater than 1V:2H, TxDOT requires evaluation from geotechnical engineers. The back slope is typically 1V:4H or flatter. When roadside ditches are required, the toe and slopes should follow the roadway vertical profile grade to ensure they are sufficiently capturing the design runoff (TxDOT, 2024). Roadside channels or ditches can incorporate GSI such as bioretention cells (or bioswales), vegetative swales, and infiltration trenches (EPA, 2016).

7.4.2 Other Drainage Facilities for Consideration

The following measures outline other practical strategies for reducing stormwater impacts associated with transportation infrastructure while improving long-term system performance and resilience. These considerations range from preventing scour and erosion at storm drain outlets and embankments to incorporating LID and GSI, on-site detention and retention practices, and broader integrated stormwater management planning. Together, these approaches support both effective drainage design and the protection of surrounding water quality, habitat, and watershed function.

7.4.2.1 Consideration for Scour at Storm Drain Outlet, Approach Embankment, and Abutment

Note that scour is a frequently reported source of storm drain maintenance needs. At many locations, the use of a simple outlet treatment (e.g., cutoff walls, aprons of concrete, or riprap) will protect against scour. Prudent design of riprap aprons or energy dissipators at the bridge downstream and outlet of the culvert can be minimized. Embankments that encroach on floodplains are commonly subjected to scour and erosion damage by overflow and by flow directed along the embankment to the waterway openings. Erosion can also occur on the downstream embankment due to turbulence and eddying as flow expands from the openings to the floodplain and due to overtopping flow (TXDOT, 2019).

7.4.2.2 Other Low Impact Development/Green Stormwater Infrastructure

According to the EPA, LID refers to systems and practices that use or mimic natural processes that result in the infiltration, evapotranspiration, or use of stormwater in order to protect water quality and associated aquatic habitat (EPA 2023c). At both the site and regional scale, LID/GSI practices aim to preserve, restore, and create green space using soils, vegetation, and rainwater harvest techniques. There are many practices that have been used to adhere to these principles, such as bioretention facilities, rain gardens, vegetated rooftops, rain barrels, and permeable pavements. By implementing LID principles and practices, water can be managed in a way that reduces the impact of built areas and promotes the natural movement of water within an ecosystem or watershed. Applied on a broad scale, LID can maintain or restore a watershed's hydrologic and ecological functions (U.S EPA, 2023e). For more information, see section 7.3.

7.4.2.3 On Site Detention/Retention

Transportation projects may be designed to retain and/or detain stormwater on-site to control the amount of runoff and/or the timing of that runoff. There are additional aesthetical/ecosystem benefits, and examples include retention/detention basins and vegetative swales (TxDOT, 2018). Detention basins can be classified into two major categories: flood control detention basins and stormwater quality control basins. A flood control detention basin temporarily stores excess storm runoff and then discharges it at a rate not to exceed the downstream channel capacity.

Often, it is designed as a regional facility that provides the 100-year runoff storage volume at the outfall point of the developed watershed. Between events, a detention basin remains dry. Conversely, a retention basin has a permanent water pool. The solids and pollutants in stormwater can mostly be removed by the settlement process in the pool (WaterWorld, 2007).

7.4.2.4 Integrate Comprehensive Stormwater Management Planning

Integrated stormwater management plans are designed to manage runoff from multiple sources, including transportation infrastructure. Lessons learned from these comprehensive assessments of the existing infrastructure present an opportunity for improvement moving forward with programs such as iSWM (NCTCOG, n.d. g; NACTO,2017).

8 Modeling and Optimization

This section provides an overview of the transportation, stormwater, hydrologic, hydraulic, environmental, and optimization modeling approaches being applied in the TSI study. Together, these tools are intended to evaluate how future precipitation, land use change, demographic growth, and transportation development may affect flood risk and transportation infrastructure across the study area. The discussion summarizes the primary models under consideration—such as NCTCOG's Regional Travel Demand Model (TAFT), HEC-HMS, HEC-RAS, SWMM, SWAT, and related GIS and optimization tools—and highlights the types of outputs they can provide to support integrated planning, infrastructure assessment, and identification of potential mitigation strategies.

8.1 Transportation Modeling

The purpose of this section is to identify transportation modeling techniques that are being utilized in the TSI study and the data outputs from them. The use of transportation/travel modeling is to attempt to predict which critical infrastructure may go underwater based on different scenarios of precipitation and demographic growth.

NCTCOG's Regional Travel Model (RTM) is a multi-step, trip-based analysis tool. The model components and the processes are streamlined into the analytical tool and are based on various data collection efforts and travel surveys conducted between 2008 and 2016. The calibration year for the current regional model is 2014. The key elements of the travel demand model are the traffic analysis zones, demographic data, including market segmentation, and the trip generation/distributions. The NCTCOG model is based on the textbook concept of travel demand modeling; however, since each region of the country is different, the NCTCOG team developed their own model parameters. For more information, refer to the DFW Regional Travel Demand Model (TAFT) Executive Summary (NCTCOG, 2023).

8.2 Stormwater Modeling and Optimization

Stormwater modeling typically includes H&H modeling efforts that aim to determine peak flows and inundation extents. Hydrologic models focus on the processes involved in rainfall becoming runoff, while hydraulic models focus on the movement of water from one point to another. Modeling practices, in conjunction with optimization methods, that are currently used in the field of hydrology, couple different hydrologic techniques to integrate models or results created at differing scales or locations.

Modeling for future conditions aims to create a model that best represents an anticipated future scenario. For hydrologic modeling, HEC-HMS will be used to determine streamflow at designated locations within the study area. U.S. Geological Survey stream gauge locations will be utilized foremost, especially points that were used in previous model calibration (InFRM, 2021). Modeling for future conditions, including climate change impacts, has been achieved with the HEC-HMS model (Bai et al., 2019; Meenu et al., 2013). In considering climate change, the Hadley Centre Coupled Model version 3 (Meenu et al., 2013) and Coupled Model Intercomparison Project Phase 5 (CMIP5) general circulation model (Bai et al., 2019) have been used. SWMM is also commonly utilized for related studies (Todeschini et al., 2012; Huong & Pathirana, 2013; Li et al., 2015; Yazdi, 2019).

Optimization of the resulting future conditions of the HEC-HMS model is typically performed utilizing an optimization script. Optimization methodologies for similar types of work usually incorporate a hydrologic model combined with an optimization algorithm (James et al.,1987; Oxley & Mays, 2014; Duan et al., 2016; Ngo et al., 2016; Zope et al., 2017; Cimorelli et al., 2016; Chung et al.,2011; Ngo et al., 2018; Li et al., 2015; Yazdi 2019; Yadzi & Khazaei, 2019; Yeh & Labadie, 1997). Optimization using hydraulic models such as HEC-RAS may also be explored.

8.2.1 Modeling

HEC-HMS is a commonly used rainfall-runoff model. The existing model has been validated and calibrated through previous USACE efforts (InFRM, 2021), providing a solid foundation for model verification. The HEC-HMS model also creates an opportunity to incorporate "future conditions" that anticipate land use changes and transportation planning data. "Future conditions" hydrologic models up to the year 2070 describe future land cover/land use data from NCTCOG and are capable of being modeled through changes to imperviousness percentages. Additionally, any major planned infrastructures, such as reservoirs and dams, are made available through the TWDB, ultimately with the aspiration of creating a model with future simulations for years up to 2070 (TWDB, 2012; TWDB, 2021a; TWDB, 2021b).

The basis for hydrologic modeling for TSI is intended to be the Trinity River Watershed Hydrology Assessment (WHA), which relies on HEC-HMS rainfall-runoff analysis. HEC-HMS is designed to simulate the complete hydrologic processes of dendritic watershed systems. The software includes many traditional hydrologic analysis procedures, such as event infiltration, unit hydrographs, and hydrologic routing. HEC-HMS also includes procedures necessary for continuous simulation, including evapotranspiration, snowmelt, and soil moisture accounting. Advanced capabilities are also provided for gridded runoff simulation using the linear quasi-distributed runoff transform (ModClark). Supplemental analysis tools are provided for model optimization, forecasting streamflow, depth-area reduction, assessing model uncertainty, erosion, sediment transport, and water quality (USACE, n.d.-a).

The basis for hydraulic modeling for TSI is intended to be FEMA/TWDB BLE, which relies on HEC-RAS hydraulic analysis. This software was developed by the USACE Hydrologic Engineering Center and allows you to perform one-dimensional steady flow, one and two-dimensional unsteady flow calculations, sediment transport/mobile bed computations, and water temperature/water quality modeling (USACE, n.d.-c).

Several sources of terrain and topographic information will be utilized and processed as part of TSI utilizing this software. One example is Hydrologic Engineering Center's Meteorological Visualization Utility Engine (HEC-MetVue) in the TSI effort to facilitate viewing and manipulation of meteorological datasets as well as performing a variety of computations and analyses, including temporal and spatial aggregation of datasets and areal average computations (USACE, n.d.-b). In addition, real-time river forecasting and reservoir operations (Corps Water Management System, CWMS) models and data may be leveraged as needed for TSI. CWMS is an automated information system used by USACE to support its water control management mission.

Table 2. The following table represents each software with its purpose and link.

Software	Purpose	Link
HEC-DSSVue	"HEC-DSSVue is a Java-based visual utilities program that allows users to plot, tabulate, edit, and manipulate data in a HEC-DSS database file."	https://www.hec.usace.army.mil/software/hec-dssvue/
HEC-HMS	"The Hydrologic Modeling System (HEC-HMS) is designed to simulate the complete hydrologic processes of dendritic watershed systems."	https://www.hec.usace.army.mil/software/hec-hms/
HEC-RAS	"This software allows the user to perform one-dimensional steady flow, one and two-dimensional unsteady flow calculations, sediment transport/mobile bed computations, and water temperature/water quality modeling."	https://www.hec.usace.army.mil/software/hec-ras/

Land use and demographic information (via NCTCOG and EPA ICLUS), transportation networks, and other information will be processed and visualized through ESRI ArcGIS software. The software supports data visualization, mapping, advanced analysis, and authoritative data maintenance in 2D, 3D, and 4D. Examples of ArcGIS outputs that may be leveraged by other software include spatial shapefiles/feature classes/geodatabases, raster imperviousness grids, etc.

SWMM is used throughout the world for planning, analysis, and design related to stormwater runoff, combined and sanitary sewers, and other drainage systems. It may be used on TSI to evaluate gray infrastructure stormwater control strategies, such as pipes and storm drains, and is a useful tool for creating cost-effective green/gray hybrid stormwater control solutions. SWMM was developed to help support local, state, and national stormwater management objectives to reduce runoff through infiltration and retention and help to reduce discharges that cause impairment of water bodies (EPA, 2016).

Stormwater structures related to transportation, such as small channels, culvert boxes, pipes' capacities, and estimated flow depth, may be modeled in TSI by Federal Highway Toolbox V5.2, HY-8 V7.70.2.0, and Flowmaster Connect Edition 3 to check capabilities and evaluate the stormwater structure size, as necessary. It should be noted that many transportation projects are historically small-scale, and runoff is calculated by the rational method, which can apply if the area is less than 200 acres (TXDOT, 2019 b).

However, it is unlikely that the TSI study team will calculate runoff with the rational method for all small stormwater infrastructure at this stage since it is usually designed in the PS&E phase. Analyzing inlets, storm pipes, and ditches requires much effort and time and roadway cross-sections and profiles from roadway engineers. Hydraulic engineers repeatedly collaborate with roadway engineers to adjust stormwater or roadway design for the best options. It seems SWMM also has the function of estimating the size of the drainage system.

The Illinois Association for Floodplain and Stormwater Management (IASFM) published a document titled "Hydrologic and Hydraulic Model Review: A Review and Assessment of Software for Illinois Practitioners," which includes a comprehensive analysis of various H&H modeling software. They identified InfoWorks, ICM, PCSWMM, and SWMM as the top three H&H software that would meet their specific needs (IAFSM, 2023). An example of their ranking criteria has been provided below (Figures 14 and 15).

	Infoworks ICM	PCSWMM	ICPR	Mike+	Bently Openflow	TUFlow	FLO-2D	EPA-SWMM
Unsteady Flow Regimes	x	x	x	x	x	x	x	x
Open Channel 1D	x	x	x	x	x	x	x	x
Storm Drains 1D	x	x	x	x	x	x	x	x
Rain-on-Mesh	x		x	x	x	x	x	
2D	x	x	x	x	x	x	x	
XPSWMM Conversion	x	x						x
FEMA Approved			x				x	x
Local Knowledge	x	x						
Free								x
	4	3	3	2	2	2	3	3

Figure 14. IAFSM H&H model initial review

	Weight	Infoworks ICM	PCSWMM	ICPR	TUFlow	FLO-2D	EPA-SWMM
GIS Integration	15	3	3	3	3	2	1
XPSWMM Conversion	15	3	3	1	1	2	3
Cost	15	1	2	2	2	2	3
2D Capability	10	3	2	3	3	3	1
Local Knowledge	15	2	2	1	1	1	3
GUI	5	3	2	3	2	2	1.5
SCS Hydrology	5	3	3	3	1	1	3
Results Reporting	5	3	2	2	2	2	2
FEMA Approved	5	2	2	2	2	2	3
Learning Curve/Support	5	2	3	2	2	2	3
Rain-on-Mesh	5	3	1	3	3	3	1
	300	**245**	**235**	210	195	195	**227.5**

Figure 15. IAFSM H&H model initial review

This study cited two other studies for various H&H software alternatives, including "Software Evaluation and Analysis for Stormwater Infrastructure Modeling," performed by Halff Associates on behalf of the City of Houston, Texas. This analysis included an initial screening of 15 software programs. Of these, seven programs were considered further. These programs were then analyzed in more detail and scored on a variety of parameters. "Model Platform Selection" was performed by Freese and Nichols for the City of Fayetteville, North Carolina. Six software programs were considered for the development of the city's watershed masterplan, which would involve the modeling of both open channels and collection systems. Freese and Nichols recommended HEC-RAS for main channels and InfoWorks ICM for pipes and local drainage.

Viable H&H modeling software that the publisher included in their analysis is as follows: (note that XPSWMM was excluded since it will soon no longer be supported) EPA SWMM; EPA, HEC-RAS; USACE, HEC-HMS; USACE, PCSWMM; CHI, ICPR; Streamline Technologies, Mike+; OHi Group, TuFlow; BMT, Flo-2D and Flow-3D Software, PondPack; Bentley Systems, StormCAD; Bentley Systems, HydroCAD; HydroCAD Software Solutions, lnfoSWMM; lnnovyze (Autodesk), SRH-2D; Aquaveo, OpenFlows; Bentley Systems, and Autodesk SSA; Autodesk.

8.2.2 Optimization

Optimization of the size, location, and quantity of stormwater infrastructure options will depend on setting the design parameters and selecting suitable locations for the infrastructure before the development of an optimization model due to the size of the study area. The design of stormwater infrastructure is limited by established design standards for the study area as well as the physical limitations of the suitable properties. A sensitivity analysis of infrastructure parameters will reduce computational time for optimization by determining which parameters should be changed in the model to obtain the optimal result.

8.2.2.1 Development of Design Parameters for Optimization Constraints

The first step toward optimization will be to analyze the results from the “future conditions” model to determine locations with significant changes to the peak discharge or volume among the (1) existing conditions model, (2) the future conditions model with existing rainfall, and (3) the future conditions model with climate change effects. Similar to Bai et al. (2019), the climate change rainfall scenarios will be based on the more updated Coupled Model Intercomparison Project Phase 6 (CMIP6) scenarios (U.S. Department of Energy, 2022). The results of a comparison between current and future conditions (e.g., runoff volume, peak flow rate, flow hydrograph) will be used to identify subbasins that would potentially benefit from a regional stormwater infrastructure. A threshold will be set to determine the significance of the change in peak flow and/or runoff volume. Due to the differences in stream or river channel capacity, a percentage increase will be used as the threshold.

Subbasins with insignificant future changes in peak flow and/or runoff volume may not benefit from stormwater infrastructure on this scale, while “connected” subbasins that both (or all) indicate a need for regional infrastructure can be investigated more closely to determine which subbasin within the cluster would provide the most benefit, or if multiple regional infrastructure will be required. Because the effectiveness of storage depends on the location of flood control storage within a basin in relation to the proposed development (Fang et al., 2010), subbasins will be subdivided if necessary to determine more precisely which areas are most affected for the future scenario. Ngo et al. (2017) suggest that a decentralized approach to optimization, where multiple locations are considered, outperforms utilizing only one downstream point for comparison. For this reason, impacts will be considered at multiple points within the system, not just at the most downstream point.

Because of its establishment as a traditional stormwater infrastructure solution, detention ponds will be used to develop the initial scripts, which will then be applied to all the stormwater infrastructure solutions, including GSI and NBS. Preliminary calculations of the detention storage required for the identified subbasins will be determined using the methodology documented in the NCTCOG iSWM Hydrology manual (NCTCOG, 2014a). The required detention storage based on peak flow reduction and maximum allowable outflow rates (25-year) will be determined (NCTCOG, 2014a). Detention ponds shall be designed to reduce post-development peak flow to existing pre-development peak flow for the 2-, 10-, 25-, and 100-year storm events at locations/junctions of interest. A sensitivity analysis will be conducted on the physical dimensions of the pond (e.g., area, depth, slope, side slope, etc.) (NCTCOG, 2014a) necessary to hold the estimated required storage. Different pond shapes will be evaluated, and slopes must be designed to resist erosion, to be stable in all conditions, and to be easily maintained. Side slopes for regional facilities shall be designed based on appropriate geotechnical analyses.

For a detention pond, the appropriate type of outlet and size of the outlet structure should be determined. The estimated peak stage will be obtained for the estimated volume. The outlet structure should be sized to convey the allowable discharge at this stage (NCTCOG, 2014a). If overland flows are conveyed through the pond, the pond outlet structure must be designed to safely pass 100-year fully developed overland flows in accordance with the safety criteria. The recommended hydraulic design specifications based on calculations (e.g., stage-discharge and stage-storage curves) will be determined. Stage-discharge rating data shall be presented in tabular form with all discharge components, such as orifice, weir, and outlet conduit flows. A stage-storage table shall also be provided. In all cases, the effects of tailwater or other outlet control considerations should be included in the rating table calculations. As with all of the steps in this portion of the analysis, the goal is to determine what parameters should be set before optimization and what parameters related to detention ponds should be determined during optimization through an iterative process.

8.2.2.2 Detention Pond Size, Quantity, and Location Optimization

To make the best use of land resources and to accommodate urban and transportation growth in a smart and sustainable way, detention ponds should be located and sized properly. In this task, the size, quantity, and location of infrastructure are optimized. Multiple objective functions are evaluated to perform a more thorough optimization analysis. Multiple optimal (or near-optimal) solutions may be obtained that will be further compared. A scripted optimization procedure will be developed to perform optimization using the HEC-HMS model.

An infrastructure "guidance" based on the sensitivity analysis and calculations performed previously will be developed to include parameters and their acceptable ranges based on local (city/county) and regional (iSWM) requirements, as well as initial parameters for the optimization algorithm. The HEC-HMS model will have to be modified, either before optimization and/or as part of the optimization script, to incorporate possible detention pond locations. First, only one location per subbasin will be considered, but more refined models will be developed if needed.

Mathematical optimization models (Shishegar et al., 2018) can be defined as:

$$\max(min)\, f(x) \tag{1}$$

Subject to:

$$g_i(x)\{\leq,=,\geq\}b_i \ \ \forall i \in I \tag{2}$$

$$x_j \in S \ \forall j = 1,2,\dots,n \tag{3}$$

Where x_j is a set of decision variables, f(x) is the objective function, $g_i(x)$ represents the functions that, together with b_i, the boundaries, and S, as the set constraints on x, determine the problem constraints. For a problem with multiple objectives, additional functions can be added to the objective function f(x). Shishegar et al. (2018) reviewed stormwater management problems and the optimization methods used within them. To develop an optimization model, the objective function(s), constraints, and decision variables must be defined. Thus, the decision variables must be established. The main decision variables for the detention ponds are (1) whether the infrastructure should be placed at a particular location or not and (2) the size of the infrastructure, which is specified based on comparison with the infrastructure suitability map. Within a detention pond, for example, additional decision variables can be defined, such as weir crest height, working depth, maximum water depth, detention basin volume, overflow weir length and height, number and diameter of outlet pipes, and downstream channel design.

Detention pond optimization problems often make use of multiple objectives (Li et al., 2015; Duan et al., 2016). In fact, Hajkowicz and Collins (2007) reviewed the use of multiple criteria analysis (MCA) in water resources planning and management and found that it was quite common, with 113 published studies from 34 counties. While the main objective function will likely be to minimize the increase in runoff volume and/or peak flow from each subbasin or at specified junctions, a minimized cost function will also need to be enacted. Cost itself can include total land usage and/or potential construction cost. Additional objectives may be to minimize the difference between peak water level and maximum design depth at each potential (selected) outlet location and to minimize maximum crest elevation for detention ponds. Designation of constraints will help obtain feasible solutions. Possible constraints for detention ponds include maximum pond size based on property size, maximum distance to transportation infrastructures, minimum storage based on construction feasibility, and maximum number of detention ponds.

Optimization algorithms include derivative-based algorithms, derivative-free algorithms, and metaheuristic algorithms (Koziel and Yang, 2011). Detention pond and reservoir optimization problems often utilize metaheuristic algorithms, such as simulated annealing (Oxley & Mays , 2014), genetic algorithms (Yeh & Labadie,1997; Park et al., 2012; Cimorelli et al., 2015) and differential evolution (Yazdi, 2019), particle swarm optimization (Li et al., 2015; Ngo et al., 2016; Ngo et al., 2018), and harmony search (Yazdi & Khazaei, 2019). Because of the broad applicability of optimization algorithms, an appropriate optimization algorithm will be selected after the objective function and constraints are determined. Optimization software packages will be explored in more detail at this time as well. The end goal will be to run the optimization script utilizing the objective functions, constraints, and the updated HEC-HMS model. Once a technique is selected, an optimization procedure script will be developed for the optimization process with the developed HEC-HMS model.

8.3 Environmental Modeling

SWMM is used for single-event or long-term simulations of water runoff quantity and quality in primarily urban areas. SWMM can be used to design and size drainage systems and detention facilities per the EPA SWMM website (EPA, 2023).

Soil and Water Assessment Tool (SWAT) is a physically based distributed parameter model that has been developed to predict runoff, erosion, sediment, and nutrient transport from agricultural watersheds under different management practices.

The HEC Ecosystem Functions Model (HEC-EFM) is designed to help study teams determine ecosystem responses to changes in the flow regime of a river or connected wetland. HEC-EFM analyses involve statistical analyses of relationships between hydrology and ecology, hydraulic modeling, and the use of GIS to display results and other relevant spatial data. Through this process, study teams will be able to visualize and define existing ecologic conditions, highlight promising restoration sites, and assess and rank alternatives according to predicted changes in different aspects of the ecosystem (USACE, n.d.).

8.4 Combined, Coupled, and Interdisciplinary Planning and Modeling

Reducing flood risk to transportation infrastructure requires coordination across disciplines, agencies, and modeling platforms. This section highlights how interdisciplinary planning efforts, cross-agency partnerships, and integrated hydrologic, hydraulic, and environmental models strengthen resilience planning and flood management. It also summarizes the compatibility of widely used modeling tools and presents case studies showing how combined approaches and NBS can improve flood prediction, reduce stormwater impacts, and support more effective infrastructure decision-making.

8.4.1 Interdisciplinary Planning Efforts

Addressing flood risk to transportation infrastructure is an interdisciplinary undertaking. MPOs do not have the staff to conduct H&H modeling or the authority to address land use and stormwater infrastructure beyond that associated with roadways. An effective effort to reduce flooding of transportation infrastructure, therefore, requires interdisciplinary partnerships and stakeholders – as noted in the Austin MPO's "Lessons for MPOs and State DOTs" section, where the agency said communications with non-transportation disciplines brought to the fore perspectives that otherwise would have been underrepresented (Cambridge Systematics, Inc., 2015).

As regional councils, the Metropolitan Council and SEMCOG benefited from authority beyond the transportation sector. Studies from these agencies (Metropolitan Council, 2018a; Metropolitan Council, n.d.; SEMCOG, n.d.) could utilize data from existing studies on future precipitation and non-transportation stormwater infrastructure. H-GAC plans to conduct a study on LID to expand its resiliency efforts.

One resiliency study even had a goal to emphasize interagency coordination. The Cape Cod study (Rasmussen et al., 2012) sought to integrate the planning processes of federal, regional, and local stakeholders. Partnerships existed between some of these groups because of the presence of Cape Cod National Seashore, a National Park. The study's scenario planning workshop was attended by local staff from Cape Cod towns, Martha's Vineyard Commission, and the Nantucket Planning office; regional government staff from Cape Cod Commission and Cape Cod Regional Transit Authority; state government staff from Massachusetts National Guard and Massachusetts Office of Energy and Environmental Affairs; federal government staff from EPA, FEMA, FHWA, FTA, Fish and Wildlife Service, NOAA, National Park Service; and scientific experts from Provincetown Center for Coastal Studies, USGS, Water Energy and Ecology Information Services, Woods Hole Oceanographic Institution, and Waquoit Bay National Estuarine Research Reserve.

The 2015 Broward study (Parsons Brinckerhoff, Inc., 2015) brought together stakeholders from beyond local governments and the transportation sector, including universities, consultants, and the media. However, the study describes the challenges of bringing together an interdisciplinary group: "Marshalling the resources of the many different agencies (even just participating in the planning process) that should be interested in a study such as this can be challenging. A key lesson for the process is that agreements and understandings among the major participants should be put in place as early as possible in the study."

Interdisciplinary partnerships and stakeholders provide skills, data, and perspectives necessary to implement a study of the breadth of the integrating Transportation and Stormwater Infrastructure initiative. Potential partners and stakeholders include local governments, state and federal agency engineers and scientists, non-profit organizations; universities, consultants, and the private sector.

8.4.2 Coupling of H&H Models with Environmental Models

Working in conjunction with relevant stakeholders, the Sustainable Rivers Program (SRP) incorporates environmental strategies into the management of USACE water infrastructure (USACE, n.d.-d). The project stems from a partnership between TNC and USACE, with the shared goal of achieving ecologically sustainable flows that also enhance project benefits. The program couples HEC's environmental model, HEC-EFM, with HEC-RAS to develop flood inundation maps for different ecological habitats. SRP efforts complement other reservoir-centric water resource projects by demonstrating that a strategic and science-based approach can be used at USACE projects to maintain or enhance benefits provided to the nation. Currently, six of the eight SRP sites have developed environmental flows, while five of the sites have applied experimental releases based on the environmental flow recommendations. Monitoring for these sites is ongoing.

8.4.2.1 Cross-Platform Model Compatibility

This section summarizes the compatibility of commonly used hydrologic and hydraulic modeling platforms with supporting data systems, GIS tools, and external file formats. Each provide different capabilities for storing, importing, exporting, and integrating model data. Understanding these compatibilities is important for evaluating how each model can support data exchange, geospatial analysis, watershed representation, and ecosystem-based applications within the broader modeling framework.

8.4.2.1.1 HEC-DSS Compatibility

The USACE HEC's Data Storage System, or HEC-DSS, is a database system designed to efficiently store and retrieve scientific data that is typically sequential. Such data types include but are not limited to, time series data, curve data, spatial-oriented gridded data, and others. The system was designed to make it easy for users and application programs to retrieve and store data. HEC-DSS is incorporated into most of HEC's major application programs. (USACE, n.d.)

8.4.2.1.2 HEC-RAS Compatibility

In Version 2.0, HEC-RAS introduced a geospatial component to the geometry for the description of river networks and cross sections. This capability makes it possible to import channel geometry from Computer-Aided Design (CAD) or GIS programs through automated data extraction procedures. Similarly, water surface elevations and other HEC-RAS results can be exported to CAD and GIS, where they can be used to create model water surfaces for inundation mapping.

The spatial data the HEC-RAS can import and export is evolving with each new version of the software, resulting in additional capabilities. HEC-RAS Version 3.1.3 will import and export data using a spatial data format in an ASCII text file. (USACE, n.d.)

8.4.2.1.3 HEC-HMS Compatibility

HEC-HMS includes GIS tools that allow modelers to delineate elements, define a discretization, compute subbasin and reach characteristics, and estimate model parameters. The HEC-HMS team is no longer investing resources in developing, testing, and supporting HEC-GeoHMS. Instead, efforts will continue to be directed at improving and adding GIS capabilities directly to the HEC-HMS software (USACE, n.d.).

8.4.2.1.4 SWAT

SWAT models use various input sources defined at the watershed, subbasin, or Hydrologic Response Unit (HRU) level of detail. Unique features such as reservoirs or point sources must have input data provided for each individual feature included in the watershed simulation and a complete list of input files (with names and descriptions). SWAT also has the ability to model GSI components through the LID features.

8.4.2.1.5 SWMM

A SWMM project file is a plain text file that contains all of the data used to describe a study area and the options used to analyze it. The file is organized into sections, where each section generally corresponds to a particular category of object used by SWMM. The contents of the file can be viewed from within SWMM while it is open.

Normally, a SWMM user would not edit the project file directly since SWMM's graphical user interface can add, delete, or modify a project's data and control settings. However, for large projects where data currently reside in other electronic formats, such as CAD or GIS files, it may be more expeditious to extract data from these sources and save it to a formatted project file before running SWMM. After a project file is saved to disk, a settings file will automatically be saved with it. This file has the same name as the project file except that its extension is .ini (e.g., if the project file were named project1.inp, then its settings file would have the name project1.ini). It contains various settings used by SWMM’s graphical user interface, such as map display options, legend colors, intervals, object default values, and calibration file information. Users should not edit this file. A SWMM project will still load and run even if the settings file is missing.

8.4.2.1.6 HEC-EFM Compatibility

HEC-EFM links ecology with established hydrologic, hydraulic, and GIS tools. The software can be applied quickly and inexpensively and can incorporate expert knowledge. HEC-EFM is also a generic software tool applicable to a wide range of riverine and wetland ecosystems.

8.4.3 Cross-Platform Case Studies

The integration of advanced technologies and innovative approaches has significantly improved the effectiveness of flood prediction and management systems in urban areas. Lee et al. (2020) highlight the utilization of radar data for rainfall prediction, coupled with sophisticated models like SWMM and HEC-RAS, to enhance short-term inundation prediction accuracy. By incorporating automatic simplification and calibration modules along with inundation databases, communities can be efficiently warned and provided with flood-related data, surpassing the performance of existing systems. Similarly, Raimondi et al. (2021) emphasize the effectiveness of sustainable drainage systems and river restoration in mitigating flood risks, showcasing how transforming a fraction of paved surfaces into permeable ones can significantly reduce stormwater runoff and flooded areas, particularly in densely populated urban regions like the Milan area.

Moreover, Rosa et al. (2022) shed light on the potential of green and blue infrastructure (GBI) in alleviating the adverse impacts of urbanization on the water cycle. Through simulation studies, they demonstrate that despite considerable urban expansion, deploying GBI techniques can bring hydrological conditions closer to the current scenario, highlighting the cost-effectiveness and resilience of such approaches. These findings underscore the significance of integrating NBS into urban planning to manage flood risks sustainably. Additionally, the combined use of H&H models, as demonstrated by various researchers (Akter et al., 2020; Bulti et al., 2021; Jha & Afreen, 2020), proves instrumental in accurately predicting flood extent and supporting informed decision-making in urban flood risk management and infrastructure planning.

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