Chapter 2: Flood Risk Analyses

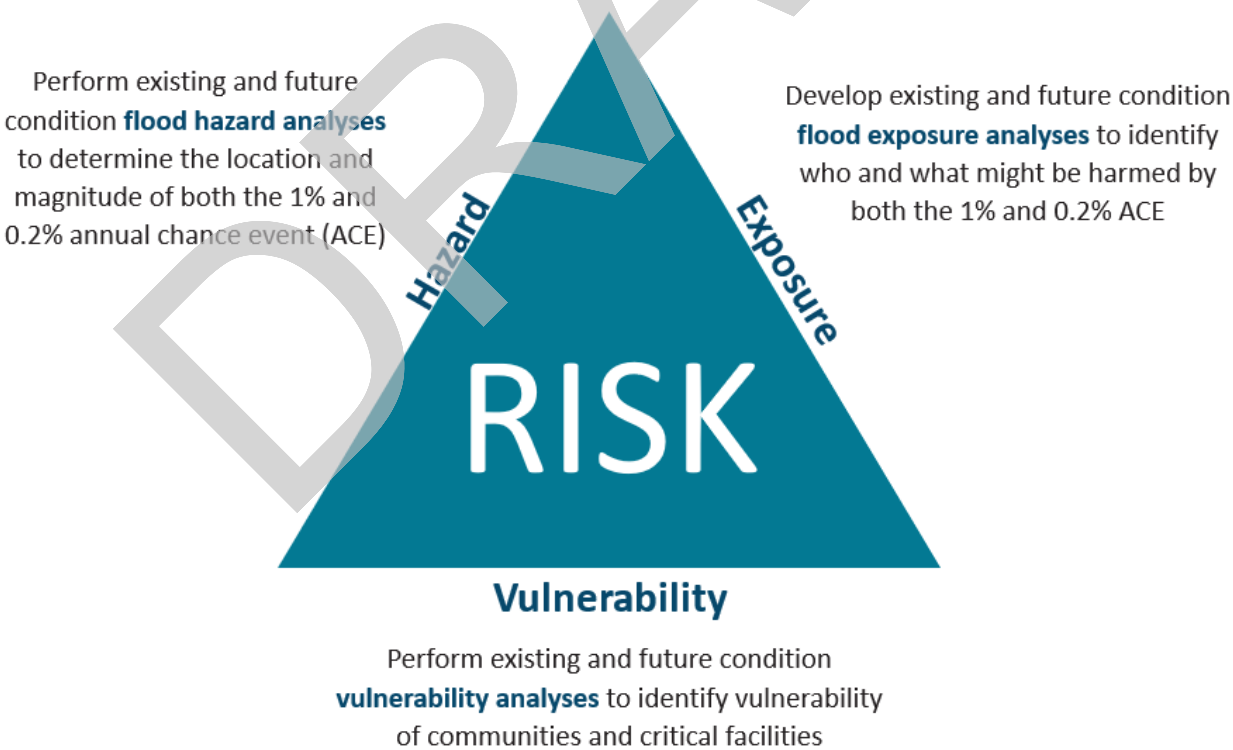
An important aspect of developing a regional flood plan involves providing an accurate assessment of flood risk. This includes a description of flooding, identification of what is at risk, and estimation of the associated impacts. In terms of understanding the environment, the Trinity Regional Flood Plan assessed flood risk for existing and future conditions.

In this Trinity Region Regional Flood Plan, the existing and future conditions flood risk assessment focused on the following three components:

1. Flood hazard analyses to determine the location, magnitude, and frequency of flooding
2. Flood exposure analyses to identify who and what might be harmed within the Trinity Region
3. Vulnerability analyses to identify the degree to which communities and critical facilities may be affected by flooding

Figure 2.1 below shows the risk triangle framework applied to the Trinity Regional Flood Plan Flood risk analyses.

Figure 2.1: Flood Risk Analyses Triangle Framework



Source: TWDB

Task 2A – Existing Condition Flood Risk Analyses

Existing Condition Flood Hazard Analysis

Sufficiency of Existing Conditions for Planning Purposes

In terms of potential flood hazard analysis, existing conditions refers to the hydrologic and hydraulic conditions that were present at the time the analysis was performed. These conditions include current land use, estimated precipitation data, and constructed drainage related infrastructure. Existing conditions in relation to the Trinity Region do not consider projected changes in rainfall patterns, future land use/population growth, or planned new/improved infrastructure. Federal Emergency Management Agency (FEMA) Flood Insurance Rate Maps (FIRMs) Special Flood Hazard Areas (SFHAs) are generally based on existing conditions. The FEMA regulatory SFHA boundaries from these maps form the foundation of the Trinity Region existing conditions flood hazard analysis.

Land Use

Land use is an important factor in determining existing conditions flooding limits. It affects the hydrological processes such as evapotranspiration, interception, and infiltration. As urban development (impervious area) is added to a watershed, the hydrologic response is changed, and surface runoff often increases. As demonstrated in ***Chapter 1***, most of the urban development occurs in the Upper Basin of the Trinity Region watershed located in Collin, Dallas, Denton, and Tarrant counties. These four counties are surrounded by heavy agricultural use which extends to the headwaters of the to the mid basin areas. From the mid basin area, extending to the coast, the existing land use is forested, interspersed with agriculture. Localized urban development is largely confined within city boundaries and the extraterritorial jurisdiction (ETJ). While not as prolific as urban development, cultivated agricultural and grazed land use still quickens the watershed's response time in comparison to natural forested ground cover increasing existing flood risk. The rate of development and changes in land use since the initial determination of the flooding limits affects the validity of the analysis for planning purposes. For example, FEMA's SFHA within the Trinity Region is based on hydrologic and hydraulic analyses that were performed between the mid-1970s and today. While the 1970s studies are nearly 50-years old, the flood limits may still be valid due to little change in land use and basin size.

Precipitation

When planning for existing conditions flood risk, assessing potential anomalous flood causing precipitation is crucial. Precipitation as it relates to flood risk is commonly analyzed in terms of inches of rainfall that occur within a 24-hour duration. In 1973 the FEMA National Flood Insurance Program (NFIP) set the standard for flood hazard areas based on the 1-percent annual chance event (ACE) or as it is commonly referred to as the 100-year flood. For the purposes of the State Flood Plan, all risk assessments will be based on this recurrence interval in addition to the 0.2-percent ACE (500-year flood). A majority of FEMA's SFHA boundaries within the Trinity Region were developed using hypothetical rainfall data from the *National Weather Service (NWS) Technical Paper No. 40/NWS Hydro-35* (Hershfield, 1961) or *The United States Geological Survey (USGS) Atlas of Depth-Duration Frequency of Precipitation Annual Maxima for Texas* (Asquith & Roussel, 2004). Rainfall data was broken down in terms of duration and recurrence interval. In 2019, National Oceanic and Atmospheric Administration (NOAA) developed updated hypothetical rainfall in Texas based on historic rainfall data in its Atlas 14 study. The NOAA Atlas 14 study anticipates significant differences between hypothetical rainfall in the lower portion of the Trinity Region watershed when compared to the 1961/1977 and 2004 rainfall data. ***Table 2.1*** below shows the range of rainfall for each data source.

Table 2.1: Precipitation Data Comparison

Trinity Region Watershed	TP40/Hydro 35 100-year, 24-hour Rainfall (inches)	USGS 2004 100-year, 24-hour Rainfall (inches)	NOAA Atlas 14 100-year, 24-hour Rainfall (inches)
Upper Basin	8.8-10.5	8.5-11.0	8.5-11.0
Middle Basin	10.5-12.0	11.0-12.0	11.0-14.0
Lower Basin	12.0-13.5	12.0-14.0	14.0-18.5

Infrastructure

Drainage related infrastructure is a key element in determining existing conditions flood risk. Drainage related infrastructure includes but is not limited to, dams, levees, detention/retention ponds, bridges, culverts, low water crossings (LWCs), tunnels, urban storm drain networks, breakwaters, bulkheads, and revetments. The Trinity Region has eight major flood control reservoirs owned and operated by the United States Army Corps of Engineers (USACE). These include Benbrook Lake, Joe Pool Lake, Grapevine Lake, Ray Roberts Lake, Lewisville Lake, Lavon Lake, Navarro Mills Lake, and Bardwell Lake. In addition to the major reservoirs, the region contains nearly 1,000 Soil Conservation Service (SCS) minor reservoirs, which control flood waters along the major and minor tributaries. There are 22 levee districts located within the Trinity Region, which accounts for over 134,000 acres of flood protection.

While flood control infrastructure mitigates existing flood risk, some older drainage-related infrastructure contributes to flooding. Bridges, culverts, and storm drain systems that were designed and constructed before major land use changes and higher standards were implemented, impound flood water, and overtop during major storm events. The result is increased flood risk to both property and life which is expanded upon in the existing conditions exposure analysis.

Existing Hydrologic and Hydraulic Model Availability

Hydrology and hydraulic (H&H) modeling is a necessary component in determining how water flows over land. It is a crucial element in developing effective flood planning strategies.

Hydrology is the scientific study of earth's natural water movement with a focus on how rainfall and evaporation affect the amount of flow of water in streams and storm drains. Hydraulics represents the engineering analysis of the flow of water in streams and infrastructure, such as channels, pipes, and other man-made structures.

Applied since the 1970s, H&H uses computer software applications that simulate the flow of rainfall runoff over the land to predict the rise of creek and river water levels and potential flooding, as well as test ways to reduce flooding without constructing projects. H&H modeling simulates flow, frequency, depth, and extent of flooding over land. These models assist with making informed decisions about selecting and implementing flood reduction and restoration projects. H&H modeling also satisfies regulatory requirements and confirms that natural, agricultural, and social resources are not damaged by flooding induced by modifications to creeks, rivers, and channels.

Within the Trinity Region's 13 eight-digit Hydrologic Unit Code (HUC-8) watersheds, there are hundreds of H&H models, each calibrated for the specific region, and spanning from the late 1970s to present. All the data output from the various modeling efforts is ultimately incorporated through geographic information system (GIS) mapping into the Trinity Region floodplain quilt as described in ***Figure 2.2*** shows stream model location in the Trinity Region.

Best Available Existing Flood Hazard Data

Flooding within the Trinity Region is mostly riverine (based on Region's location, availability flood mapping data, and historical data) with some coastal influence in Chambers and Liberty counties in the south, where they are directly (and frequently) affected by hurricane storms from the Gulf of Mexico. Hurricanes typically fade and downgrade to tropical storms or tropical depressions as they move inland away from the coast. Riverine flooding often occurs from general rainfall and thunderstorm floods. Flash floods are common from these rainfall events, which can occur within a few minutes or hours of excessive rainfall, exposing valuable public and private properties to flood risk. A portion of the region lies in the flash flood alley of Texas. ***Figure 2.3*** shows reported and documented flood events by county, as well as location band of the flash flood alley.

Figure 2.2: Existing Conditions Model Availability

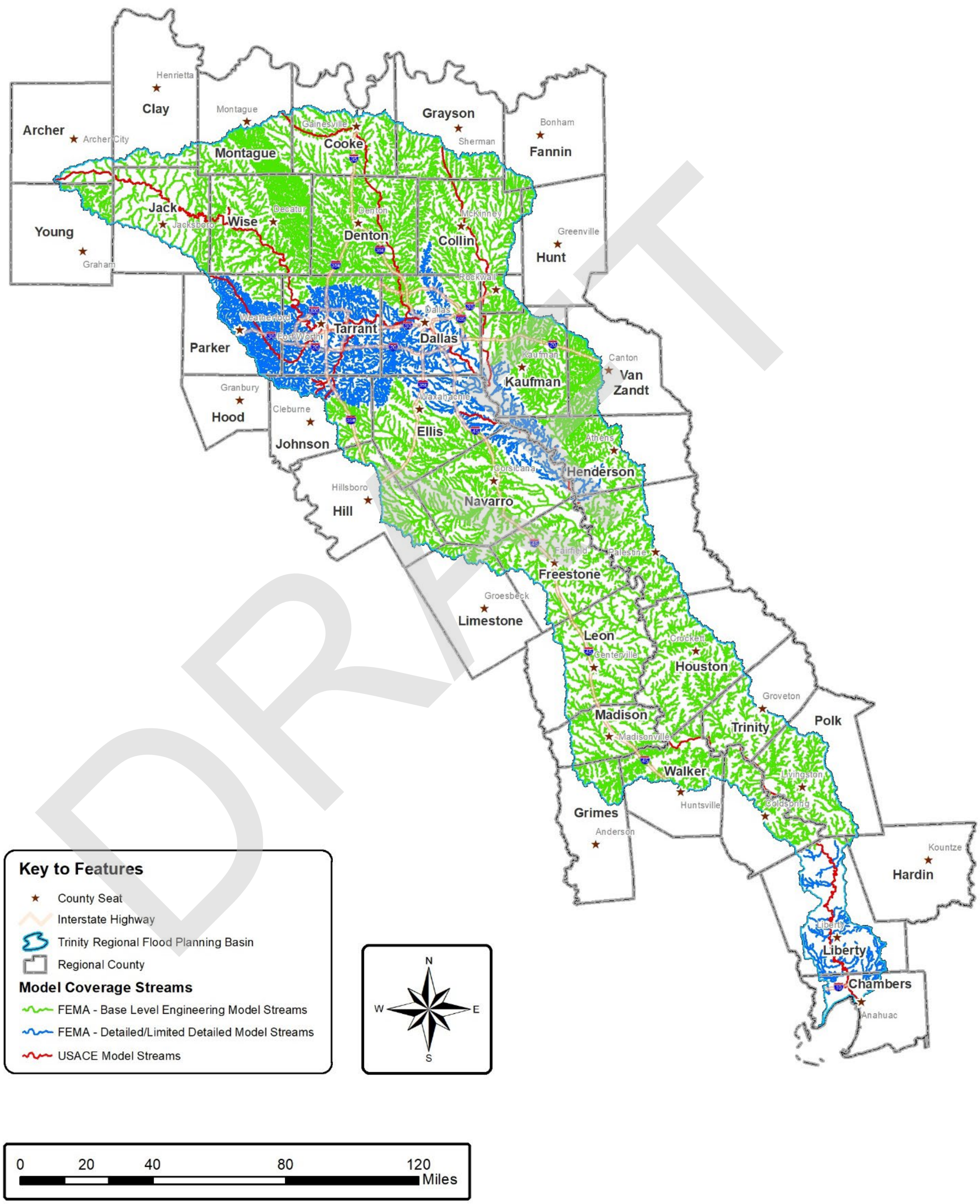
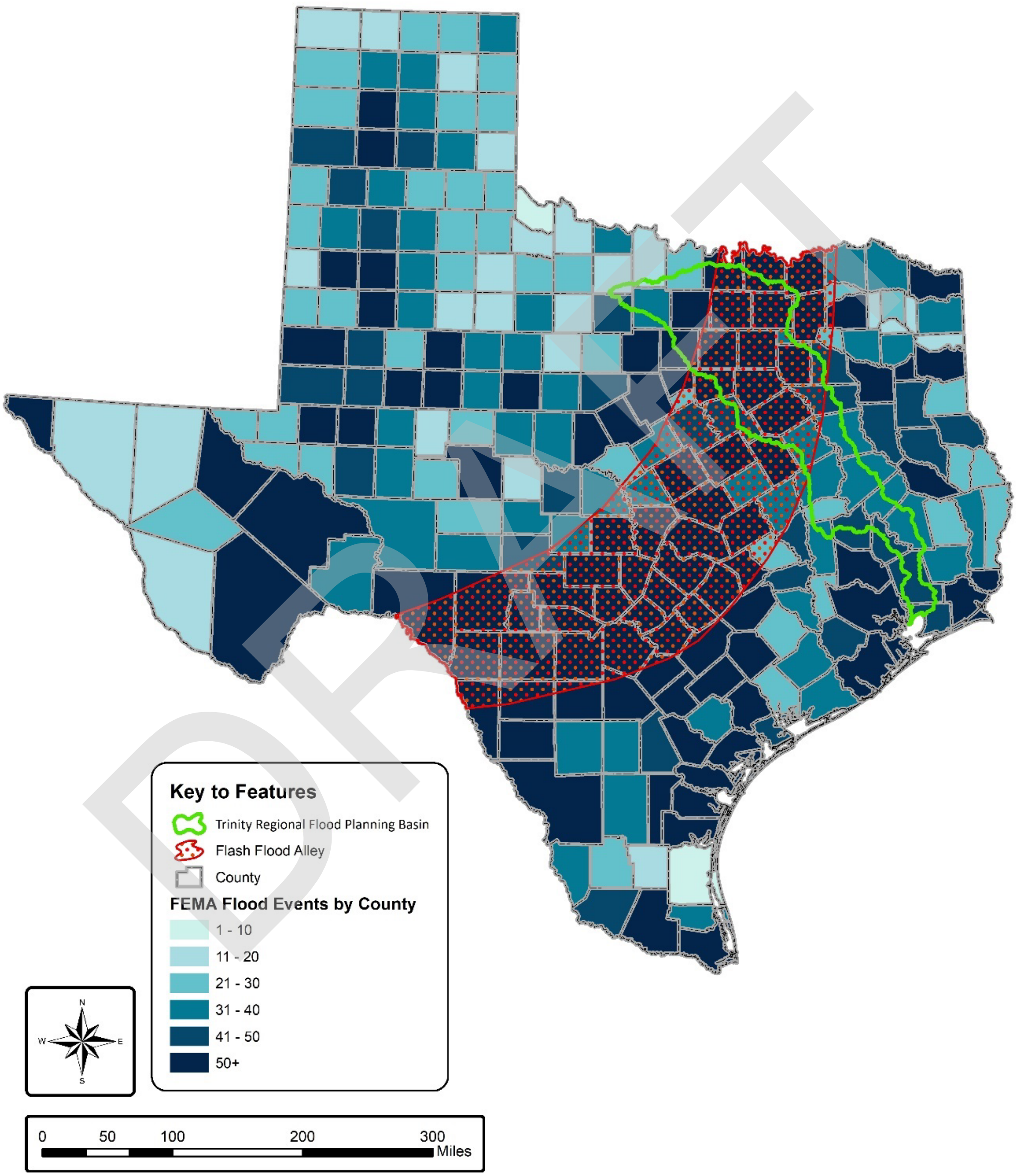


Figure 2.3: Major Documented Storm Events and Flash Flood Alley (1996 through 2019)



Source: FEMA/NOAA Storm Data (1996 – 2019)

Even though riverine and coastal-based flooding are the dominant types of flooding in the Trinity Region, urban flooding data was evaluated for inclusion in the existing floodplain quilt where available. Urban flooding (off-floodplain, pluvial, or surface flooding) is caused by intense local precipitation running-off impermeable surfaces such as paved streets, sidewalks, and structures, and overwhelms local drainage systems and overflows small waterways. This flooding may enter buildings and properties, which often occurs in locations such as historic downtown areas and residential neighborhoods which predate floodplain maps. Communities have done a great job in generally mitigating upland flooding, but this will continue to be much more significant regarding flood infrastructure and on-going operations and mitigation activities. Flood Mitigation Projects (FMPs) are discussed in ***Chapter 4***.

Existing flood hazard mapping estimation is based on the use of current land use and precipitation data to estimate hydrologic condition parameters and discharges. Data is then used to simulate water surface elevations (WSELs) to create existing floodplain mapping extents.

The most current existing flood hazard mapping data from multiple sources was compiled by Texas Water Development Board (TWDB) to create a comprehensive, single, coherent, continuous set of best available existing floodplain data quilt for the Trinity Region. Mapping data was compiled and included the 1-percent ACE and 0.2-percent ACE data. The existing floodplain quilt data was then updated with data obtained from FEMA, USACE, USGS, and local communities where available. The main data sources comprising the existing floodplain data for the Trinity Region are described below.

Regulatory Federal Emergency Management Agency Floodplain Data

FEMA maps flood zones on their FIRMs, which forms the basis of regulatory floodplain management for communities and mandatory flood insurance requirements for structures in the mapped SFHA floodplains. The regulatory FEMA floodplain data used in the Trinity Regional Flood Plan ranged from digital FEMA floodplain datasets from those that were already effective and have become available for NFIP regulatory use, to those that are at the Letter of Final Determination stage and are pending, with six months to become effective. FEMA's preliminary datasets issued for public review, and in due process, were also utilized, including Letter of Map Revision (LOMR) data that has become effective as of March 2022.

1-percent Annual Chance Floodplains

On FIRMs, FEMA maps both the 1-percent ACE and the 0.2-percent ACE. Floodplain data developed for the Trinity Region included only the 1-percent ACE and 0.2-percent ACE to describe the flood hazards and perform the exposure and vulnerability analyses.

The 1-percent ACE has a one percent chance of being equaled or exceeded in any given year, and it has an average recurrence interval of 100 years. Also referred to as the SFHA, or 100-year flood, this boundary is mapped as a high-risk flood area subject to a one percent or greater annual chance of shallow flooding in any given year, where shallow flooding is usually in the form of ponding or sheet flow with average depths between one and three feet. Along the coast, these high-risk areas are associated with velocity wave action. In the Trinity Region, coastal wave action only affects Chambers County. The 1-percent ACE areas may also be susceptible to erosion, deposition, and mudflow. It is sometimes referred to as the "Base Flood" and is the national standard used by the NFIP and other federal agencies for the purposes of regulating development and requiring the purchase of flood insurance.

0.2-percent Annual Chance Floodplains

The 0.2-percent ACE has a 0.2-percent ACE (or one in 500 chance) of occurring in any given year and is also referred to as the 500-year flood or Non-Special Flood Hazard Areas (NSFHAs). The 0.2-percent ACE refers to areas of moderate flood risk that are not considered to be in immediate danger from flooding caused by overflowing rivers; areas in the 100-year flood with average depths less than one foot or drainages areas less than one square mile; or areas protected by levees from the 100-year flood.

Other Floodplain Data

Where only paper-based FEMA data was available, digitally converted FIRMs from First American Flood Data Services (FAFDS) was utilized. FEMA and TWDB's Base Level Engineering (BLE) study data, including model-backed HUC-8 wide level studies, was leveraged to revise the existing floodplain quilt.

TWDB provided modeled flood data from the 2021 Fathom data set to be used where applicable. Fathom was developed by a research group at the University of Bristol in England. The Fathom model has been peer reviewed and compares reasonably well to FEMA flood data. The Fathom model is a two-dimensional (2D) hydraulic framework developed at a national scale using 30 meter (30m) Digital Elevation Models (DEMs). The results have been mapped on 10-foot LiDAR for Texas to create statewide flood depth rasters for fluvial; pluvial; as well as coastal mapping for the 1-percent ACE and 0.2-percent ACE and other frequencies. The fluvial, pluvial, and coastal flood depth rasters from the Fathom data for the Trinity Region were mosaicked together with maximum depths taken where datasets overlap each other. The combined rasters were processed into flood polygon boundaries using guidance provided by the TWDB. The Fathom data served as a supplemental dataset for inclusion in the existing flood boundaries where data was not available or the approximate study extents was abruptly truncated as a limit of study.

Regional Data Collection and Possible Flood-Prone Areas

A regional online data collection website was created as an outreach tool to work closely with regional entities (counties, municipalities, state and federal agencies, or political subdivisions with flood related authorities) to gather local flood-risk information. The website included a web mapping application that enabled entities to document other possible flood-prone areas not previously identified as mapped flood hazard areas. These included areas of historic flooding events, roads that frequently overtopped, and past flood claims hot spots.

The Trinity Regional Flood Planning Group (RFPG) team also collected data related to areas subject to inundation from reservoirs and levee inundation areas. Dam breach inundation areas were included where data is publicly available. Data submitted to the Trinity RFPG through the online GIS-based data collection tool was also added. Cities, counties, entities with flood control responsibilities, and the general public had the opportunity to submit data to the Trinity RFPG.

The Trinity RFPG team weaved the existing conditions flood quilt together. The existing conditions flood quilt was presented at the Trinity RFPG meeting on February 17, 2022 and posted to the Trinity RFPG website for public review and comment on February 21, 2022. The deadline for community, county, entity, and public review and comment period for the existing conditions flood quilt was March 25, 2022. The various data sources received were compiled according to TWDB's ranking hierarchy as shown in ***Table 2.2***. The data ranking was based on a quality and coverage extent relative to other datasets.

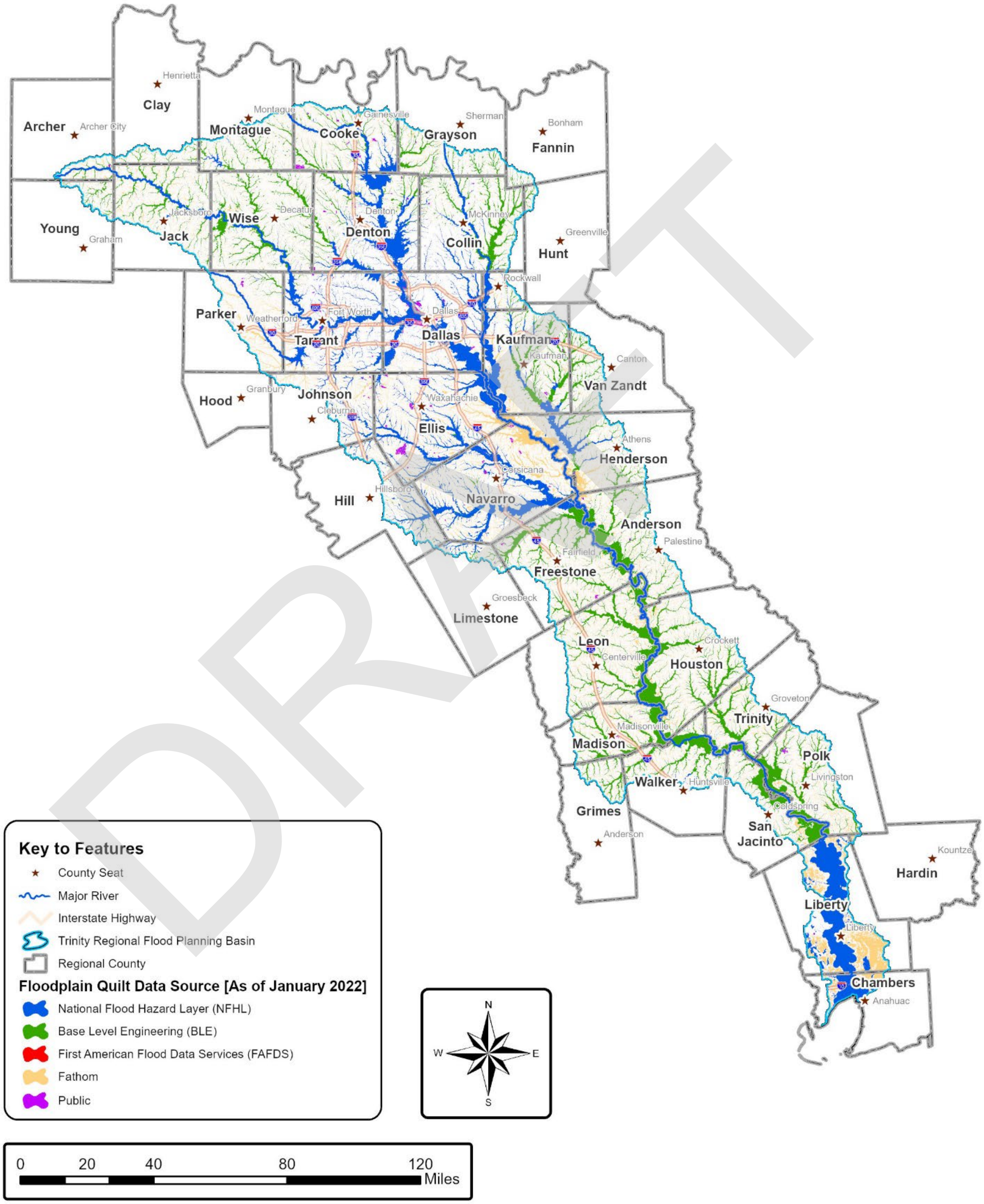
Figure 2.4 shows the floodplain data sources by location developed for the Trinity Region. A larger version of this map is included in ***Appendix B***

Table 2.2: Floodplain Quilt Data Hierarchy and Sources

Ranking	Data Category	Source
1	NFHL Pending (Detailed and Approximate Studies)	FEMA
2	NFHL Preliminary (Detailed and Approximate Studies)	FEMA
3	NFHL Effective (Detailed Study Only)	FEMA
4	BLE	FEMA
4.5	FATHOM	FEMA
5	NFHL Effective (Approximate Study Only)	FEMA
6	Digitized Effective FIRMs	CoreLogic FAFDS
	Other Potential Data Sources	USACE or Other Federal Data (0.5 to 4.5 Ranking)
		Regional or Local Community Data (0.5 to 6.5 Ranking)

Source: TWDB Technical Guidelines for Regional Flood Planning

Figure 2.4: Floodplain Quilt Data Sources



The compiled existing condition floodplain quilt data for the Trinity Region is included in the submittal GIS database layer named "ExFldHazard". ***Figure 2.5*** shows a GIS coverage map of the comprehensive existing floodplain data compiled for the Trinity Region showing the 1-percednt ACE and 0.2-percent ACE. Larger detailed maps are included in ***Appendix B***.

The total floodplain area for each county and associated percentage distribution within the Trinity Region are also shown in ***Figure 2.6*** and ***Table 2.3***.

When this compiled existing floodplain quilt was shown to the public either through an online web map or in-person meeting, the disclaimer note below was used:

> *"The floodplain quilt is a compilation of data from multiple sources and is intended to approximate the extent of existing flood risk in the Trinity Region. This data layer is for planning purposes only and is not to be used for any regulatory activities. For regulatory floodplain maps, contact your local floodplain administrator or visit the FEMA Map Service Center."*

Overall, the Trinity Region covers a total land area of approximately 18,000 square miles with about 22 percent (4,000 square miles) in the existing conditions floodplain. Noteworthy, Chambers County has a high percentage of floodplain area, due to its Gulf Coast location along the Trinity Bay and East Bay and relatively flat terrain. The County experience both inundated coastal flooding, as well as riverine flooding from the Trinity River. Hardin and Hood counties exhibit small floodplain area percentages, as they have less than one percent of their land area located in the Trinity Region.

Flood Data Gaps

Once the best available comprehensive existing flood data was complied, data gaps were assessed to identify any remaining areas where flood inundation boundary mapping was missing, lacked modelling and/or mapping, used outdated modeling and/or mapping, or had prepared more accurate topographic data since the last map update. Other contributing engineering factors considered to identify data gaps included modeling technology, significant land use and/or impervious area change, change in flood control structures, channel configuration (including erosion and sedimentation) changes, as well as rainfall pattern changes, which altered peak discharges.

Figure 2.5: Existing Condition Floodplain Quilt

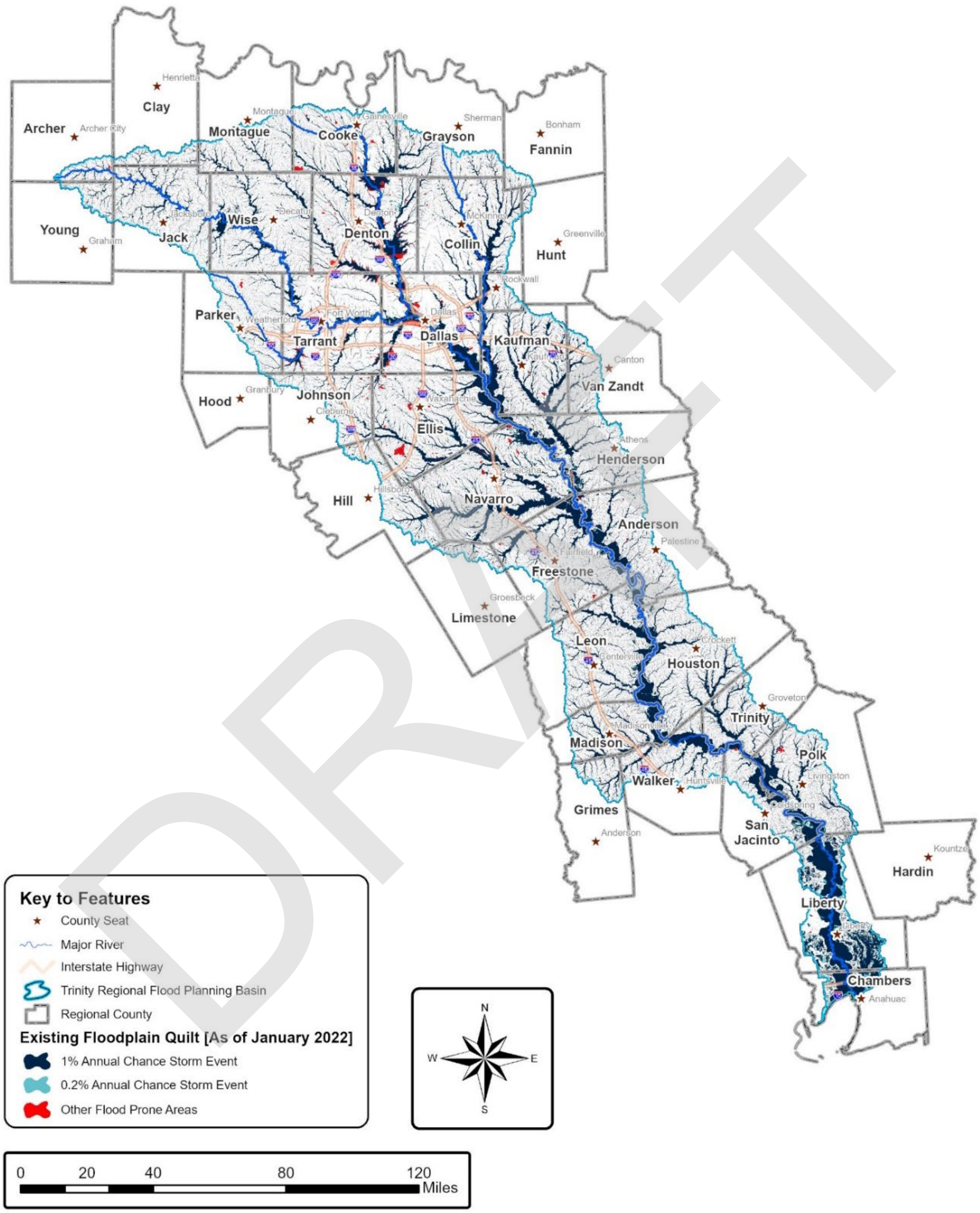


Figure 2.6: Existing Condition Flood Hazard Areas (in Square Miles) by County

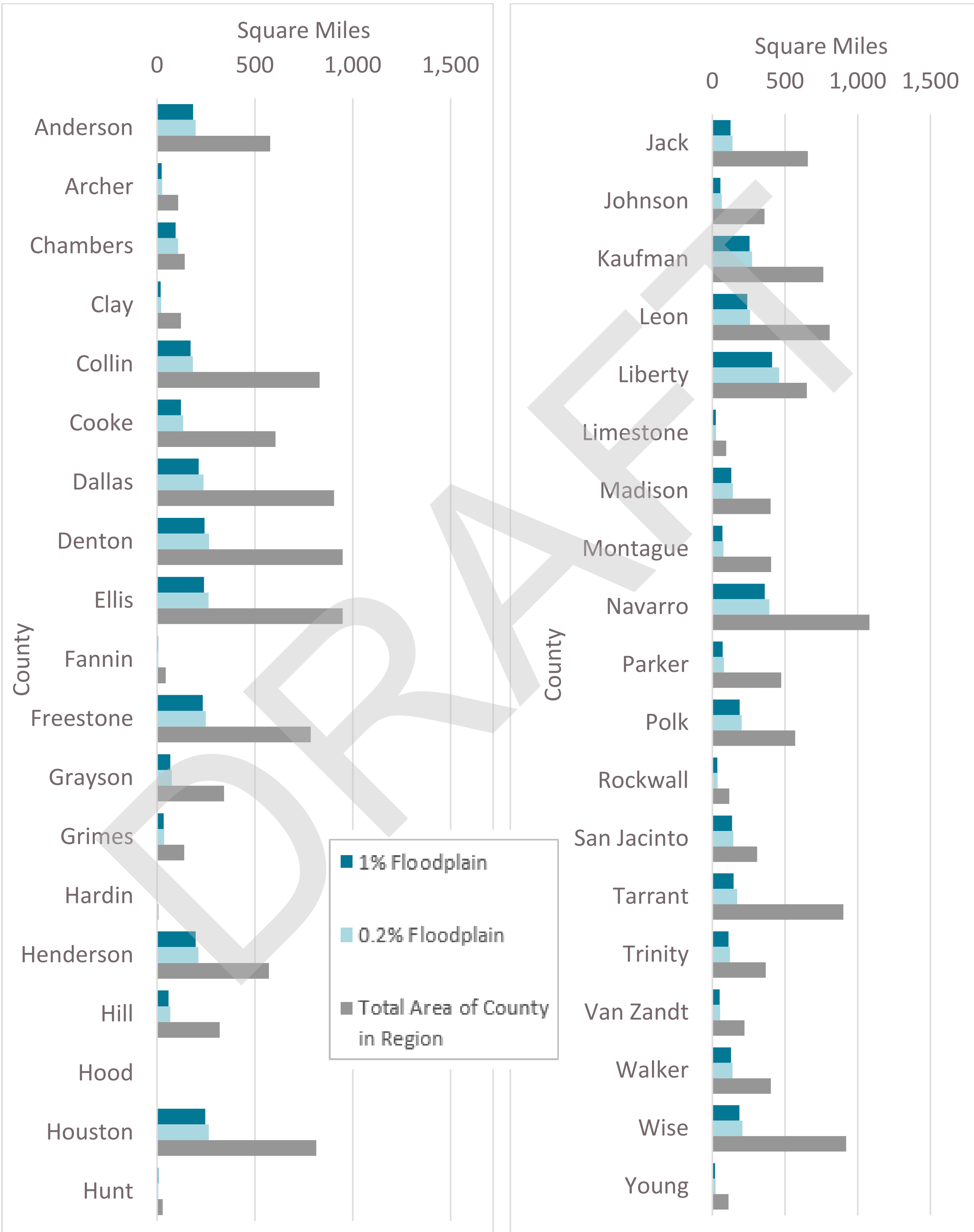


Table 2.3: Percentage of Land Area in Existing Condition Floodplain Quilt by County

County	% of County in Region		
	1% Flood Hazard	0.2% Flood Hazard*	Combined Flood Hazard
Anderson	24%	1%	25%
Archer	13%	1%	14%
Chambers	56%	5%	61%
Clay	16%	1%	17%
Collin	18%	1%	18%
Cooke	14%	0.4%	14%
Dallas	21%	6%	27%
Denton	23%	1%	25%
Ellis	19%	1%	21%
Fannin	10%	1%	11%
Freestone	22%	1%	23%
Grayson	13%	0.3%	14%
Grimes	17%	1%	19%
Hardin	0%	0%	0%
Henderson	26%	1%	27%
Hill	12%	2%	14%
Hood	1%	0%	1%
Houston	21%	1%	23%
Hunt	15%	0.1%	15%
Jack	12%	1%	13%
Johnson	11%	1%	12%
Kaufman	28%	1%	29%
Leon	20%	1%	22%
Liberty	45%	5%	50%
Limestone	17%	2%	18%
Madison	25%	2%	26%
Montague	8%	1%	8%
Navarro	26%	1%	27%
Parker	8%	0.2%	9%
Polk	24%	2%	26%
Rockwall	28%	1%	28%
San Jacinto	37%	2%	39%
Tarrant	15%	2%	18%
Trinity	21%	2%	23%
Van Zandt	17%	1%	18%
Walker	25%	2%	27%
Wise	13%	0.4%	14%
Young	9%	0%	9%

**The 0.2-percent flood hazard does not incorporate the 1-percent flood hazard to avoid overlapping polygons*

Within the Trinity Region, the average age of the effective FIRMs within the study watersheds is nine years. Among the counties with no new Digital FIRM, Clay County had the oldest FEMA effective map, dated 1991. Within the modernized counties, the FIRM effective dates range from 2008 to 2021, with Archer and Jack counties being recently modernized in 2021. As of 2022, all communities (except for Clay, Freestone, and Trinity counties and their respective incorporated communities) in the Trinity Region have modernized FEMA digital county-wide effective FIRMs. With recently completed BLE flood data, the non-modernized counties have the potential to be eligible for FEMA's Paper Reduction projects and become modernized.

The Trinity RFPG team attempted to determine the validation status (whether a stream model was new or has updated engineering) of the associated H&H models supporting the mapped floodplains using the contributing engineering factors listed earlier. For example, Chambers, Liberty, Polk, San Jacinto, and Walker counties, located in the southern portion of the Trinity Region, were greatly affected by NOAA Atlas 14 which showed higher rainfall events, invalidating their effective floodplain information contained within the floodplain quilt. Because of this, these counties are being reported as data gaps. Model-backed (H&H) detailed stream study flood data varied in age and conformance to current technologies, even for modernized county-wide FIRMs. In the urban areas, a large percentage of the H&H model data is outdated (HEC-2 or not in digital format), with only a few models revised recently (HEC-RAS, XPSWMM, etc.) and in digital format.

The gap areas data is included in the "Fld_Map_Gaps" GIS database layer. ***Figure 2.7*** shows the locations of identified existing flood data gaps. Additional detailed data gap maps are provided in ***Appendix B***. While areas were identified within the floodplain quilt as data gaps with outdated information, the compiled existing floodplain quilt still comprised the best available floodplain datasets for the Trinity Region and was used for the flood risk analysis in the Trinity Regional Flood Plan. It is the goal of this plan to further evaluate these data gaps for inclusion as Flood Management Evaluations (FMEs). See ***Chapter 4***.

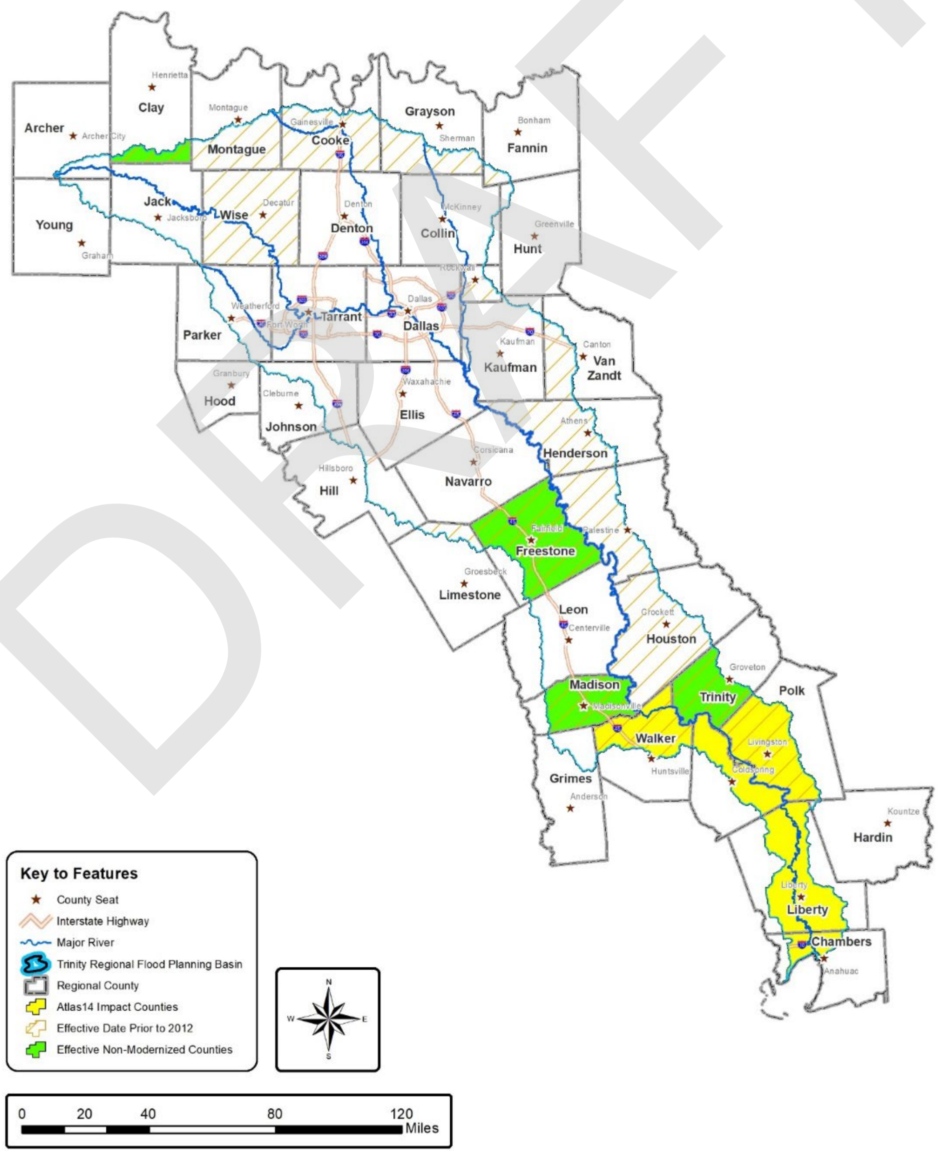
Existing Condition Flood Exposure Analysis

Flooding is a common occurrence within the Trinity Region (***See Figure 2.3***). Flooding can become a significant hazard when it inundates the built environment and causes direct damage to buildings, critical facilities, crops, or significant injuries and sometimes death to people. Flooding frequency and intensity have been increasing in recent years, often necessitating state and federal relief, which has risen to record levels. The existing condition flood risk exposure analysis leveraged the compiled existing conditions 1-percent ACE and 0.2-percent ACE in the Trinity Region to determine existing flooding exposure to buildings, critical facilities, and agriculture. Results from the flood exposure analysis were utilized to estimate the impact to socially vulnerable populations or communities discussed in later in this chapter.

Existing Development within the Floodplain

A regionwide inventory of buildings, population, critical facilities, utilities, and agriculture was conducted to assess who and what is at-risk within the Trinity Regional Flood Plan. Existing development data leveraged for the Trinity Regional Flood Plan came from several data sources. The Homeland Infrastructure Foundation Level Data (HIFLD) and data from TWDB were the source of critical facilities data. The Texas Department of Transportation (TxDOT) bridge inventory and roadway data was also used. The TWDB provided building data in August 2021 with (associated) population and Social Vulnerability Index (SVI) estimates, which were confirmed and updated where additional information was available.

Figure 2.7: Existing Condition Floodplain Quilt Data Gaps



The 2021 TWDB building dataset was built on available Light Detection and Ranging (LiDAR) information (2010 to 2021), Microsoft Artificial Intelligence Version 2 data, and 2021 Open Street Map (OSM) buildings. The 2019 LandScan USA dataset from Oak Ridge National Laboratory (ORNL) was utilized to estimate population per building, for both day and night. The 2018 Center for Disease Control (CDC) SVI dataset was applied at the census tract level.

2020 Texas Cropland Data layer developed by the United States Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) and the bridge and roadway asset inventory data came from the 2020 TxDOT dataset. Communities and stakeholders within the Trinity Region also provided data via the online GIS-based data collection tool developed for the Trinity Region.

Results of the detailed analyses of exposure to development within the existing floodplain are presented in later in this chapter.

Current Mitigation Projects

Throughout the flood planning region, multiple projects are in various stages of a project lifecycle. As weather and development patterns change, it is crucial that such projects address the changing risks of future disasters. Communities that invest forward-looking projects will see fewer impacts and are more likely to recover quickly after severe events. Projects completed with the consideration of future conditions will minimize structures from being in the floodplain and reduce losses to life and property over time.

When asked what flood management strategies (FMS) or flood mitigation projects (FMP) are currently in progress or proposed, survey respondents indicated significant interest in participating in the NFIP, establishing and maintaining floodplain management ordinances, and in making improvements to existing roadways and water crossings. ***Figure 2.8*** summarizes the responses received regarding the types and counts of in-progress flood projects.

Per the survey responses, two projects were identified as in-progress with dedicated funding in place: (Each project is summarized in ***Table 2.4***.)

1. The College Street Drainage Improvements in the city of Waxahachie within Ellis County focuses on the building of local storm drainage systems and a tunnel. Due to holes that appeared in the parking lots of businesses on College Street in 2019, the decade-old infrastructure was deemed outdated and no longer serving its intended purpose.
2. Lynchburg Creek Flood Mitigation Grant in the City of Corinth in Denton County is improving and/or building regional dams, reservoirs, detention, and retention basins. The Lynchburg sub-basin is in the central and eastern portion of the city and contains most of the drainage problems in the city. The area is about 2.2 square miles and has mixed development with quite a bit of undeveloped land. The westernmost reach is in the Amity Village. Flooding in this basin has gotten progressively worse over the years.

Figure 2.8: Types of Flood Mitigation Strategies or Projects Currently in Progress or Proposed

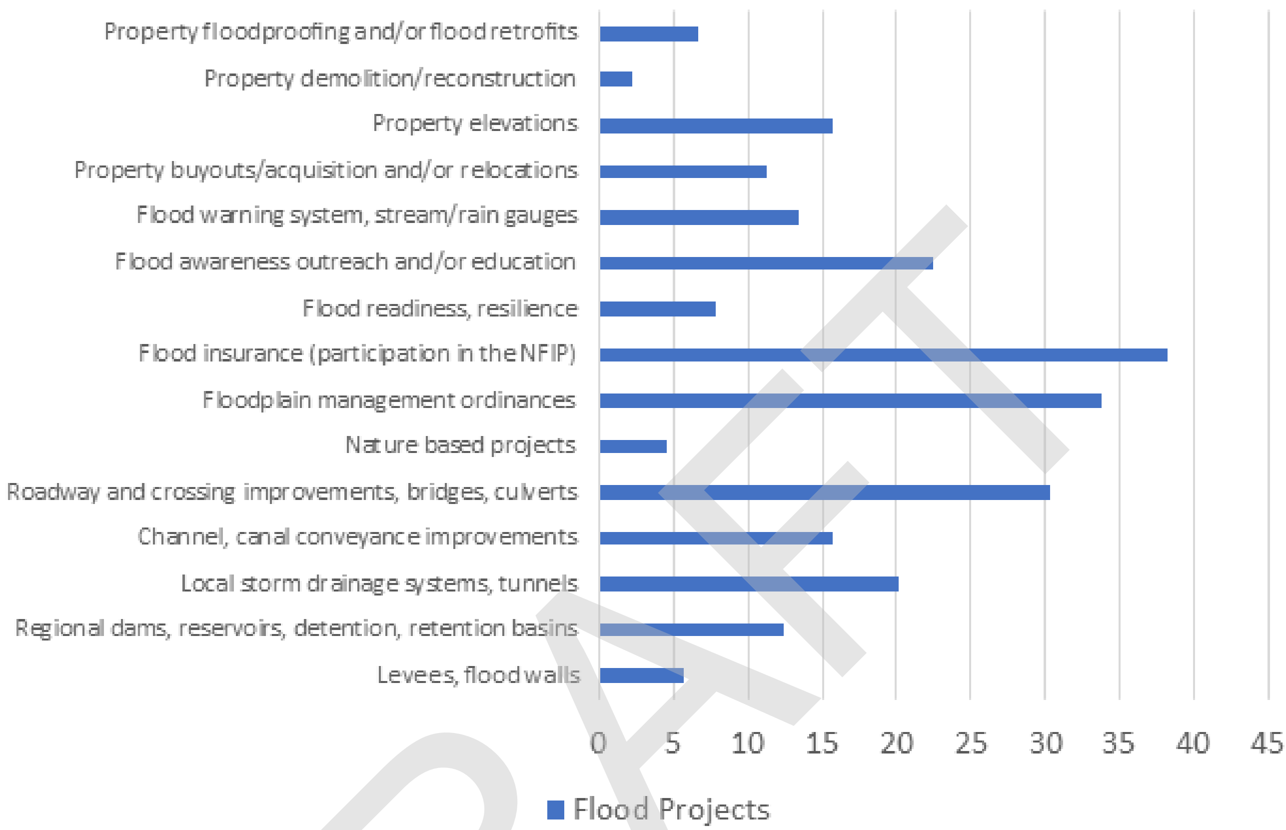


Table 2.4: Projects In-Progress with Dedicated Funding

Project Name	College Street Drainage Improvements	Lynchburg Creek Flood Mitigation Grant
Description	Local storm drainage systems, tunnels	Regional dams, reservoirs, detention, retention basins
Communities	City of Waxahachie, Ellis County	City of Corinth, Denton County
Project Status	In progress	In progress
Project Cost	$2,600,000	$3,000,000
Dedicated Funding for Construction (Yes/No)	YES	YES
Source of Funding	Not Identified	FEMA Grant
Expected Year of Completion	6/1/2022	6/30/2023

Flood Exposure Due to Existing Levees or Dams

Flood exposure is the identification of what is at risk due to extreme flooding. This refers to the people, buildings, businesses, infrastructure systems, and associated functions that could be lost to a flood hazard. Exposure also refers to the economic value of assets subjected to the flood hazard. This section discusses flood exposure due to levees and dams in the Trinity Region.

Levees in the Trinity Region

The USACE National Levee Database (NLD) identifies an estimated 101 levees within the 407-mile Trinity Region. Approximately 76 percent of the levees are maintained and owned by local entities. The remainder are overseen by USACE or another federal or state agency. These levees are built parallel to rivers, streams, creeks, lakes, and their tributaries. They are also built along the coast to provide protection from certain levels of flooding. Over 26 percent of levees in the Trinity Region are located along the Trinity River mainstem and 24 percent are located along the West Fork Trinity River. The remaining are scattered throughout the Trinity Region.

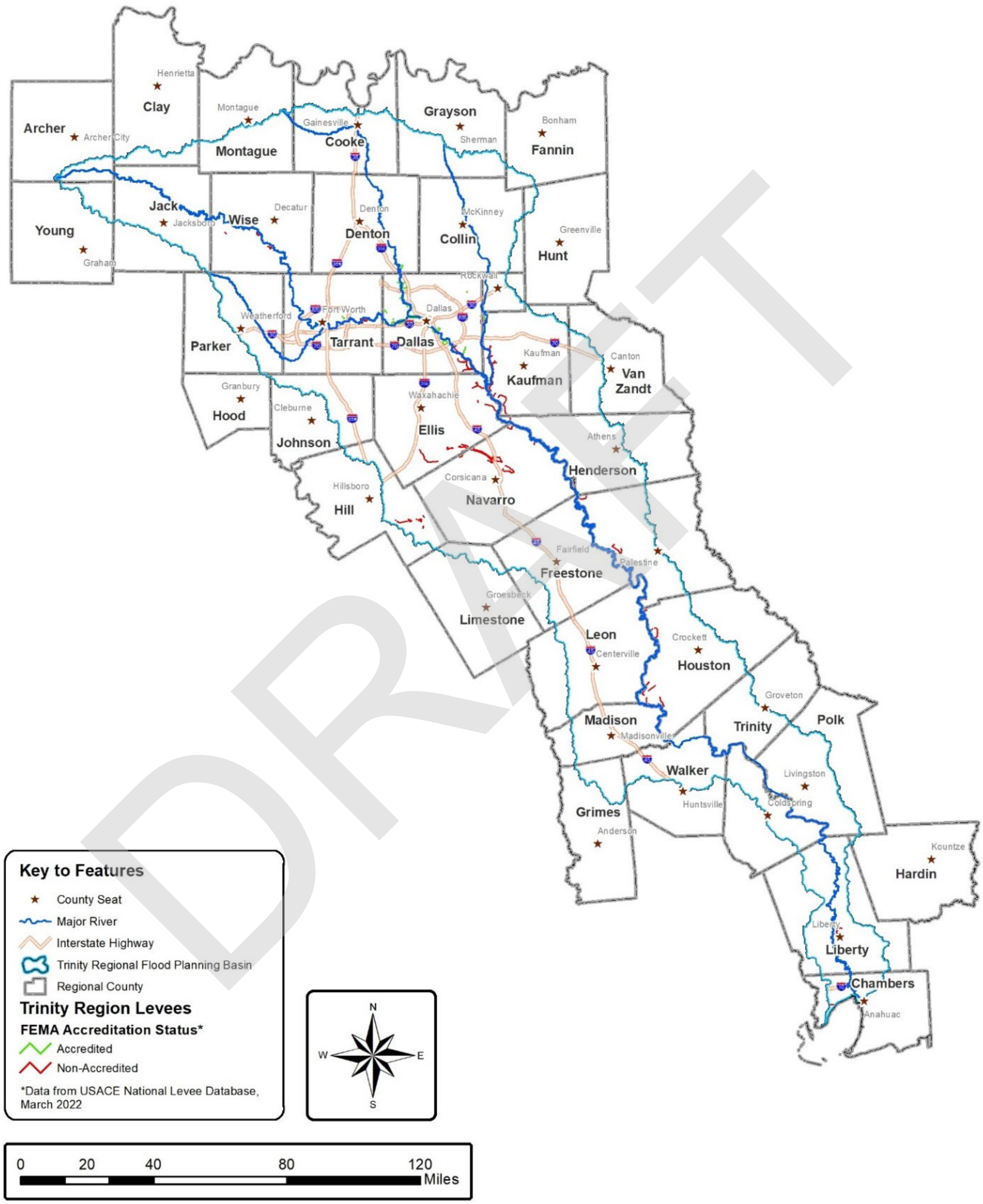
Levees can be breached during flood events due to overtopping, toe scour, seepage/piping, and foundation instability. The resulting torrent can quickly inundate a large area behind the failed levee with little or no warning, thereby exposing them to extreme flooding effects and consequences.

Levee accreditation is FEMA’s recognition that a levee is reasonably certain to contain the base (1-percent ACE, sometimes referred to as the 100-year flood) regulatory flood. To help communities understand their risk behind levee structures, FEMA applies levee accreditation information on FIRMs to show the locations with reduced risks from the regulatory flood event. Approximately 34 percent of the levees in the Trinity Region are accredited. See ***Figure 2.9*** for location of the levees and their FEMA accreditation status in the Trinity Region.

On FIRMs, FEMA shows areas mapped behind accredited levee as "Areas with Reduced Risk Due to Levee". These accredited levees protect several thousands of structures and people as well as several billion dollars of property from flood damage. When the levee is not accredited, the embankments are categorized as hydraulic significant structures and the area behind the landward side of the levee is not considered to be protected from any flood event, and consequently, exposed to flooding.

USACE leveed-area floodplain data and FEMA’s "Areas with Reduced Risk Due to Levee" datasets were incorporated into the existing floodplain quilt dataset for the Trinity Region as "Other Floodprone Areas”.

Figure 2.9: Levees and Federal Emergency Management Agency Accreditation Status



Levee Exposure Assessment

There are more than 13,000 people who live and work behind the non-accredited levees in the Trinity Region. See ***Table 2.5*** for levee exposure by county. The exposure summary was estimated by overlaying the leveed areas within the Trinity Region's existing floodplain quilt with building and population data. The exposure assessments include structure and population counts behind the non-accredited levees.

As shown in ***Table 2.5***, Chambers, Dallas, Kaufman, Liberty, and Tarrant counties have the most exposure with respect to levees.

Dams in the Trinity Region

In the Trinity Region, dams and their associated reservoirs are used for water supply, recreation, navigation, electric generation, irrigation, and flood control. According to the USACE National Inventory of Dams and Texas Commission on Environmental Quality (TCEQ), there are over 1,800 dams in the Trinity Region and most of these dams are used for flood control, water supply, recreation, or agriculture. Most dams are owned by local and private entities.

Dam-controlled reservoirs with flood storage capacities keep floodwaters impounded and either release floodwaters in controlled amounts downstream to the river below or store or divert water for other uses. As such, areas lying adjacent or downstream of dams are exposed to severe flooding and its associated consequences when a dam breaks or fails.

Dams suffer the same failure modes as levees. A dam failure causes an uncontrolled release of impounded water to adjacent or downstream areas. The recent dam failure of Lake Dunlap along the Guadalupe River, downstream of New Braunfels, is a good example; On May 14, 2019, the spillway unexpectedly collapsed due to structural defects. Homeowners experienced flooding with the resultant fear of decline in their property values. Because the area was an attraction for fishing, boating, and other recreational activities, the area experienced significant economic losses after the dam failure.

On average, the dams located in the Trinity Region are 66 years old and over, with 83% built before 1975. Typically, the dams that are owned and operated by large entities are well-maintained. However, dams owned and operated by smaller entities or private landowners may need inspections and/or rehabilitation as funding for such activities is often more costly than the property owners can afford.

Table 2.5: Levee Exposure by County

County	Number of Levees	Buildings Affected	Population Affected	Economic Value
Anderson	3	4	1	$750,708
Archer	0	0	0	$0
Chambers	2	836	2196	$173,038,800
Clay	0	0	0	$0
Collin	0	0	0	$0
Cooke	1	17	3	$2,731,340
Dallas	29	666	1472	$424,888,628
Denton	2	0	0	$0
Ellis	14	49	54	$4,567,667
Fannin	0	0	0	$0
Freestone	0	0	0	$0
Grayson	0	0	0	$0
Grimes	0	0	0	$0
Hardin	0	0	0	$0
Henderson	3	11	2	$1,228,710
Hill	12	2	3	$227,748
Hood	0	0	0	$0
Houston	6	52	102	$36,974,591
Hunt	0	0	0	$0
Jack	0	0	0	$0
Johnson	0	0	0	$0
Kaufman	11	125	185	$52,277,607
Leon	0	0	0	$0
Liberty	1	1651	8671	$516,187,086
Limestone	0	0	0	$0
Madison	0	0	0	$0
Montague	0	0	0	$0
Navarro	10	16	15	$2,610,125
Parker	0	0	0	$0
Polk	0	0	0	$0
Rockwall	0	0	0	$0
San Jacinto	0	0	0	$0
Tarrant	16	81	576	$404,067,033
Trinity	0	0	0	$0
Van Zandt	0	0	0	$0
Walker	0	0	0	$0
Wise	5	5	5	$1,876,655
Young	0	0	0	$0

While FEMA does not show downstream dam inundation extents on maps, such data may be available as non-regulatory products in some of its flood risk studies. TCEQ requires dam inundation mapping for certain dams. Recently, USACE developed dam inundation mapping for six high-hazard dams in the Trinity Region from the NHD dataset. The dam inundation areas were incorporated into the existing floodplain quilt for the Trinity Region as "Other Floodprone Areas". These “Other Floodprone Areas” do not have the same probability of occurrence as the 1-percent ACE and 0.2-percent ACE.

Dam Flowage Easement

Flowage easements are perpetual rights typical of a government agency such as the USACE. The dam flowage easements grant them the rights to essentially flood privately owned land to properly operate a reservoir. Flowage easements also grant entities the rights to prohibit construction of, or maintenance to, any improvement(s) for human habitation, and the right to approve any other structures constructed on such property. The purpose of establishing these lines is to protect personal property in the event of a flood exposure since they are flood prone. These boundaries, therefore, assist in estimating buildings and population affected in areas subject to dam inundation within the Trinity Region. FEMA identifies these flowage easements lying along reservoirs on its FIRMs. ***Figure 2.10*** shows a typical dam and associated flowage easement on a FEMA FIRM.

Dam Exposure Assessment

For the purposes of the Trinity Region dam exposure analysis, areas subject to flooding from dams were overlaid on buildings, critical facilities, and population to estimate the associated hazard potential. ***Figure 2.11*** shows location of dams in the Trinity Region. There are over 300, 000 people living in these exposure areas. These areas are mostly located around dams with no Emergency Action Plans. In populated areas, residents may not be aware of this risk, especially when flooding occurs. According to ***Table 2.6***, high dam exposures are prevalent in Collin, Denton, Ellis, and Tarrant counties, with a few scattered exposures throughout the region.

It must be emphasized that the State of Texas does not regulate development in high hazard areas immediately adjacent to or downstream of dams. While flooding from high precipitation or dam failure impact dams, human activity must also be considered when analyzing the risks posed by dams. In Texas, the hazard classification of dams is based on the potential for loss of life and economic loss in the area downstream of the dam, not on its structural safety. Thus, dams that may be of very sound construction are labeled “high hazard” if failure could result in catastrophic loss of life. In other words, if people have settled in the potential inundation zone. The “high hazard” designation does not imply structural weakness or an unsafe dam (Texas Commission on Environmental Quality, 2006).

Figure 2.10: Flowage Easement Area on Federal Emergency Management Agency Flood Insurance Rate Maps

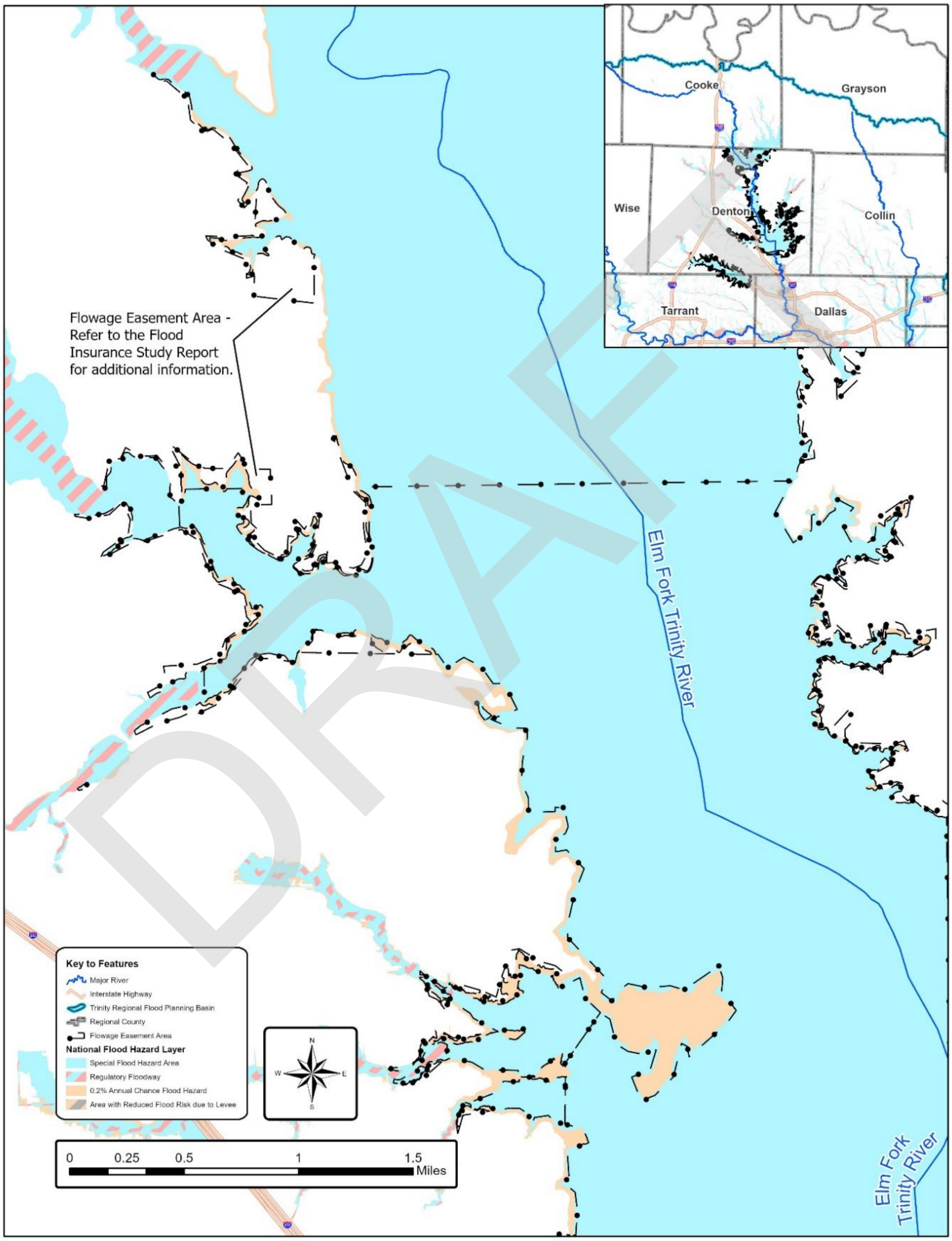


Figure 2.11: Dams in the Trinity Region

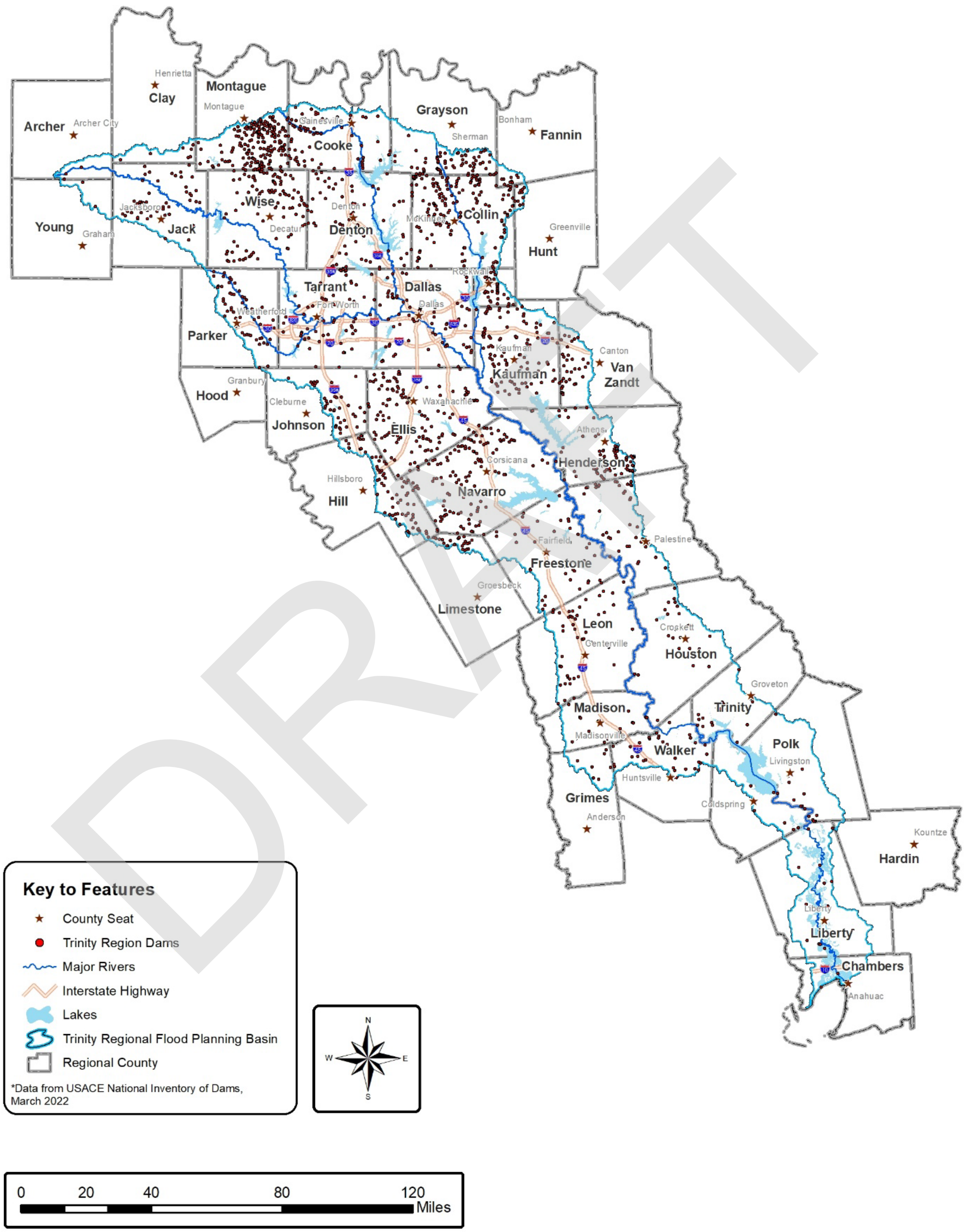


Table 2.6: Dam Exposure by County

County	Dams	Buildings Affected	Population Affected	Economic Value
Anderson	40	2	-	$749,379
Archer	3	-	-	$0
Chambers	4	-	-	$0
Clay	7	-	-	$0
Collin*	162	153	661	$142,688,363
Cooke	68	40	23	$2,116,653
Dallas	74	28	66	$11,247,803
Denton*	71	236	280,538	$29,698,167,896
Ellis*	123	39	10,648	$413,563,584
Fannin	10	-	-	$0
Freestone	46	-	-	$0
Grayson	64	4	2	$460,154
Grimes	7	-	-	$0
Hardin	-	-	-	$0
Henderson	79	1	-	$40,674
Hill	72	11	13	$2,105,550
Hood	-	-	-	$0
Houston	26	2	-	$61,950
Hunt	11	-	-	$0
Jack	51	2	1	$150,137
Johnson	38	19	41	$5,400,036
Kaufman	108	54	122	$6,949,515
Leon	44	-	-	$0
Liberty	16	-	-	$0
Limestone	24	3	2	$64,500
Madison	21	2	2	$20,820
Montague	189	99	81	$9,939,365
Navarro*	117	17	19	$2,091,873
Parker	54	265	338	$19,730,381
Polk	18	91	137	$11,728,800
Rockwall	33	69	298	$17,046,170
San Jacinto	7	88	89	$10,181,303
Tarrant*	70	609	20,368	$661,530,080
Trinity	22	150	233	$21,168,894
Van Zandt	32	-	-	$0
Walker	33	53	63	$35,645,933
Wise	99	647	996	$139,327,119
Young	2	-	-	$0

**Includes data from the 2017 USACE Dam Risk Assessment*

Many developers are purchasing property with small livestock dams and developing property around lakes and downstream of the dams, creating additional risk. Continued growth in rural areas will result in changes to hazard classifications of dams that current residents may not be aware of.

Existing Conditions Flood Exposure

This section of the Trinity Regional Flood Plan discusses and summarizes the results of the existing condition flood exposure to existing development. The existing conditions flood exposure analysis considered buildings, population, public infrastructure, critical facilities, roadway crossings, and agricultural areas exposed to the compiled existing conditions floodplain quilt. This section excludes flood exposure for levees and dams and only applies the existing conditions 1-percent ACE and 0.2-percent ACE mapping extents in the Trinity Region floodplain quilt.

Buildings, Critical Facilities, Infrastructure, and Agriculture Exposure Totals by County

For this planning cycle, flood exposure analysis estimated the structure count of buildings, critical facilities, LWCs, roadway segments, and agriculture areas potentially exposed to existing flooding by overlaying these items with the existing conditions floodplain quilt developed for the Trinity Region. ***Figure 2.12*** shows the total number of buildings, critical facilities, LWCs, and agriculture areas exposed to the existing condition floodplain quilt. The highest counts are in the populated areas of Dallas and Tarrant counties, in the Upper Subregion. Collin County, as well as coastal Chambers County, show significant counts. Most of the Trinity Region shows moderate exposure counts with a few overall county totals interspersed between.

Population Totals by County

Population data (day and night) attributed to the buildings and critical facilities data was used to summarize countywide population exposed to the existing conditions floodplain quilt. The higher of the day or night population attributes was used for the exposure population estimates according to guidance received from the TWDB. ***Figure 2.13*** shows the percent population exposure to the existing condition floodplain quilt by county. As shown in ***Figure 2.13***, high population exposures occur in the Dallas-Fort Worth-Arlington area, Collin, Dallas, Denton, and Tarrant counties in the Upper Subregion, as well as coastal Liberty County in the Lower Subregion. It must be noted that because the population count is the higher of the day or night numbers, this assumes the worst possible scenario where the maximum number of people present are exposed to the existing condition floodplain quilt.

Figure 2.12: Existing Condition Flood Exposure Total Numbers by County

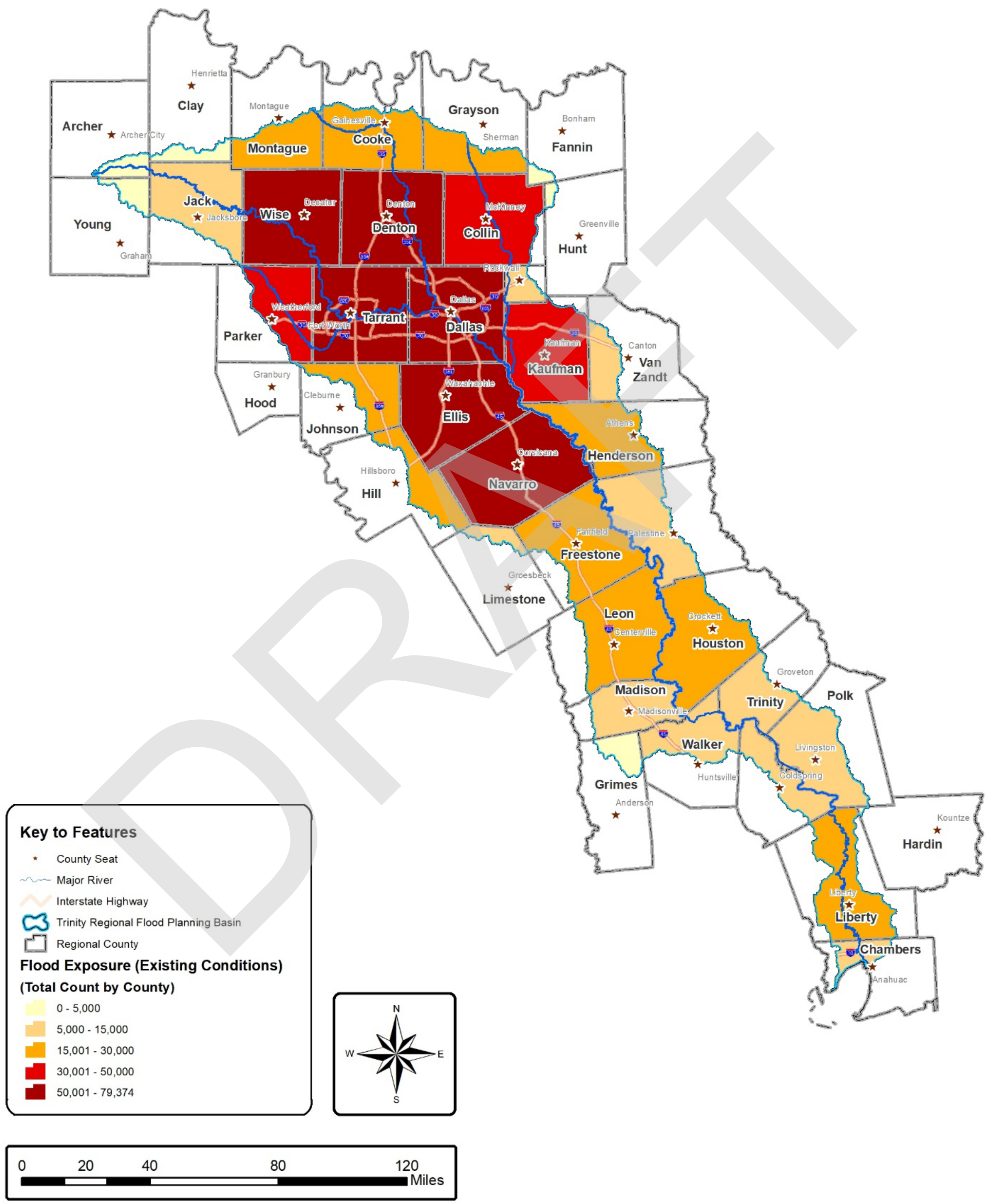
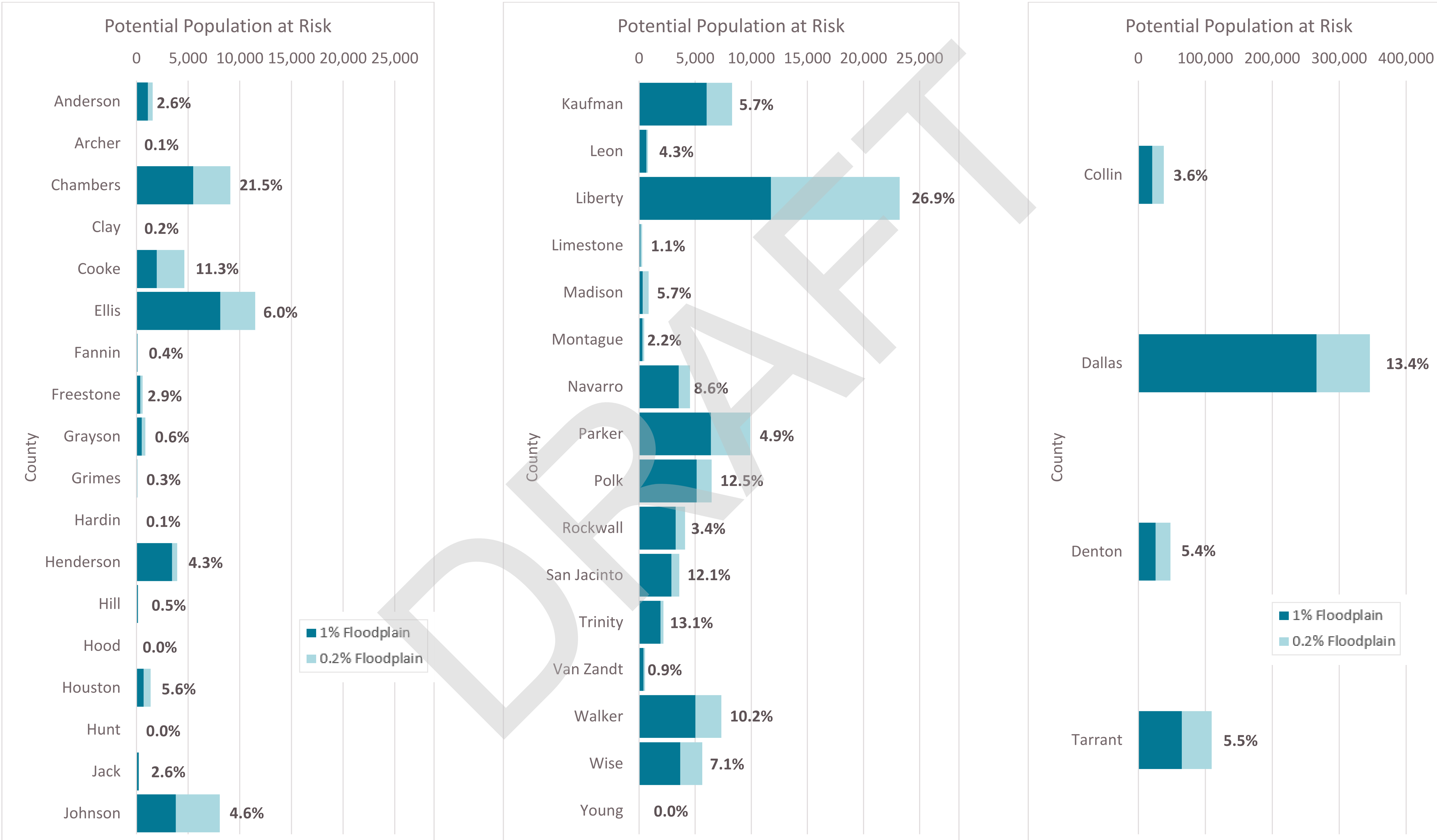
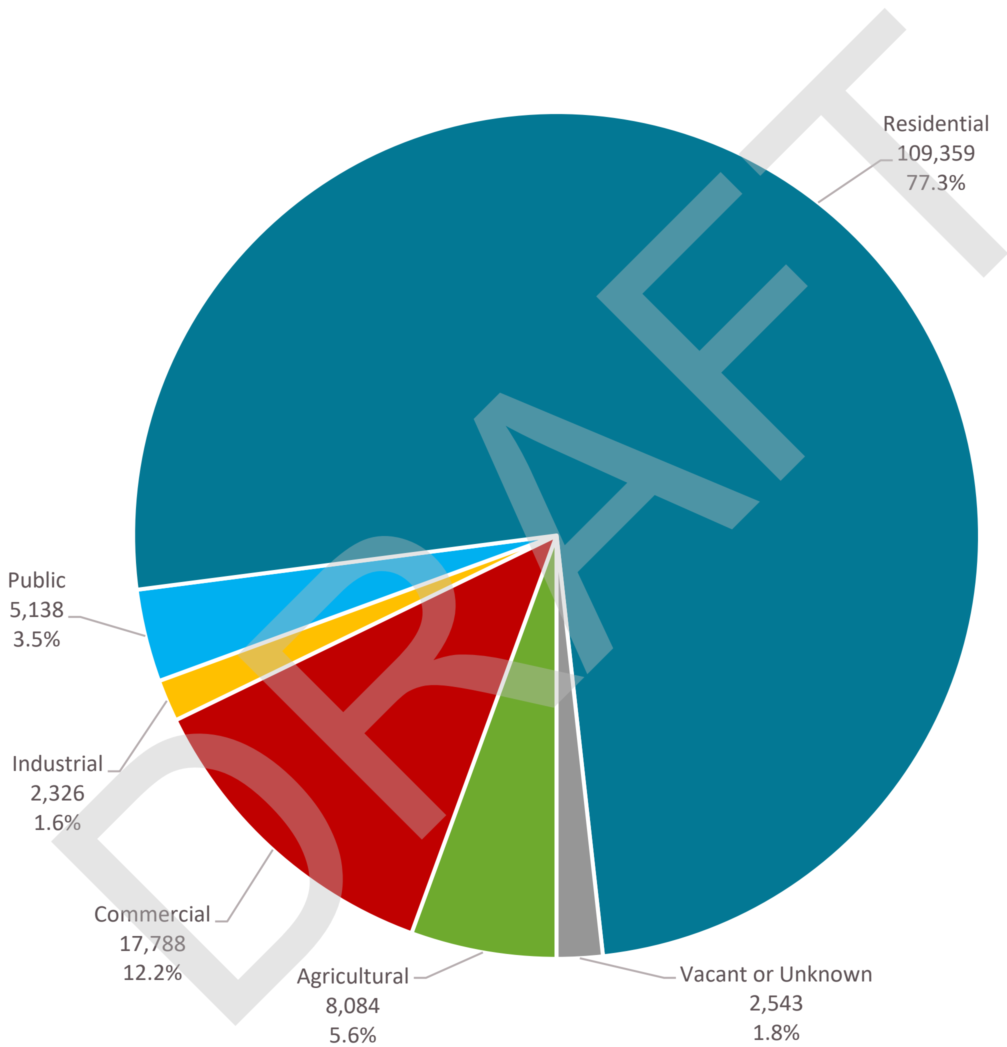


Figure 2.13: Population at Risk in Existing Condition Flood Hazard by County



Regional building data collected for the Trinity Region were classified into two main categories: residential and non-residential. As shown in ***Figure 2.14***, approximately 7 percent of buildings within the Trinity Region are within the existing floodplain. Of those, an estimated 77 percent are residential and 12 percent are commercial. Buildings classified as vacant are structures for which the building type and/or use could not be determined.

Figure 2.14: Building Type Distribution in the Existing Condition Floodplain Quilt



Residential Properties

Residential structure data used in the Trinity Regional Flood Plan included single-family homes, town homes, mobile homes, as well as multi-family residences like apartments and condominiums. Over 2,060,131 residential building footprints were gathered for the Trinity Region and an estimated 6.9 percent of these buildings were found to be exposed to flooding. An associated population of over 661,496 is estimated of being at risk to flooding.

Figure 2.15 shows the total estimated number of residential structures by county exposed to the existing floodplain quilt. Dallas, Denton, and Tarrant counties (all in the Upper Subregion) and the coastal Liberty County (in the Lower Subregion) have the highest number of residential buildings in the existing floodplain. Archer, Clay, Hardin, Hill, Hood, Hunt, Leon, Limestone, and Young counties show very little residential building exposure because only a very small portion of these counties are in the Trinity Region, most of which are their respective unincorporated areas.

Non-Residential Properties

Non-Residential inventory data also included agricultural, commercial, industrial, and public buildings. Over 406,409 non-residential building footprints were gathered for the Trinity Region and an estimated 8 percent of these buildings are exposed to flooding. An associated population of over 52,484 is estimated of being at risk to flooding. ***Figure 2.16*** shows the total estimated number of non-residential structures by county exposed to the existing condition floodplain quilt.

Ellis County (in the Upper Subregion) and coastal Chambers County (in the Lower Subregion) have the highest number of agricultural buildings in the existing floodplain. Collin, Dallas, Denton, and Tarrant counties (in the Upper Subregion) showed the highest number of commercial buildings in the existing condition floodplain. Archer, Clay, Hardin, Hill, Hood, Hunt, Limestone, and Young counties show very little residential building exposure because only a very small portion of these counties are in the Trinity Region, most of which are their respective unincorporated areas.

Critical Facilities and Public Infrastructure

A critical facility provides services and functions essential to a community, especially during and after a disaster. Critical infrastructure includes all public or private assets, systems, and functions vital to the security, governance, public health and safety, economy, or morale of the state or the nation (TWDB Flood Planning Frequently Asked Questions, 2021). Critical facilities data gathered for the Trinity Region included fire stations, hospitals, nursing homes, police stations, emergency shelters, schools (kindergarten through 12^{th} grade), water and wastewater treatment facilities, TCEQ wastewater outfalls, water supply systems (well sites), and Superfund sites. Lifeline utility systems data, such as petrol storage tanks, power generating plants, as well as natural gas and electric transmission lines, were collected for exposure analysis. Critical facilities data was from TWDB, TCEQ, Railroad Commission (RRC) of Texas, HIFLD, as well as data from Trinity Region area communities.

The existing floodplain quilt was overlaid on the data gathered for critical facilities to estimate the flood exposures. ***Figure 2.17*** shows the total counts of exposed critical facilities to the existing floodplain quilt in the Trinity Region.

Figure 2.15: Residential Structure Counts in Existing Condition Floodplain Quilt

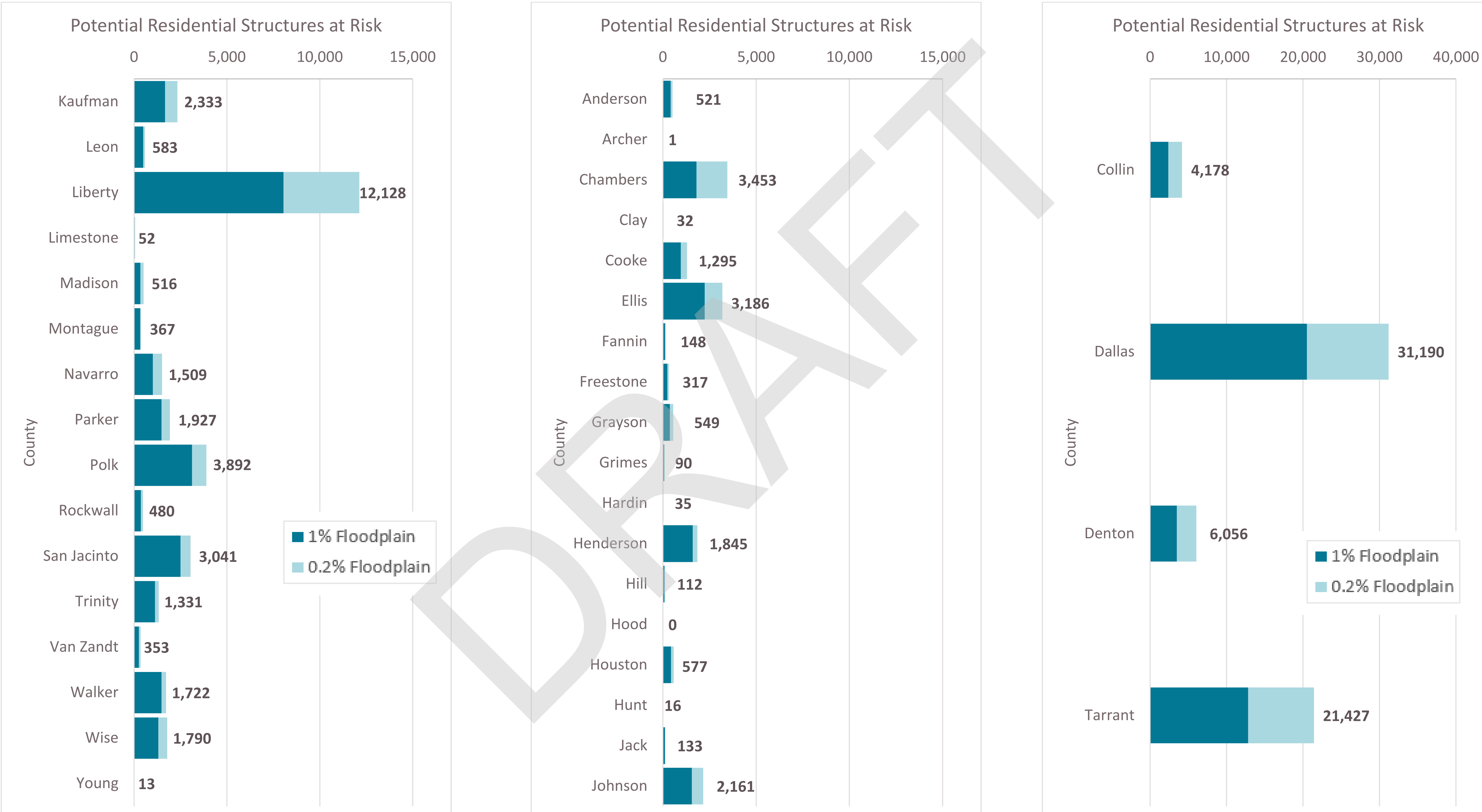


Figure 2.16: Non-Residential Structure Counts in Existing Condition Floodplain Quilt

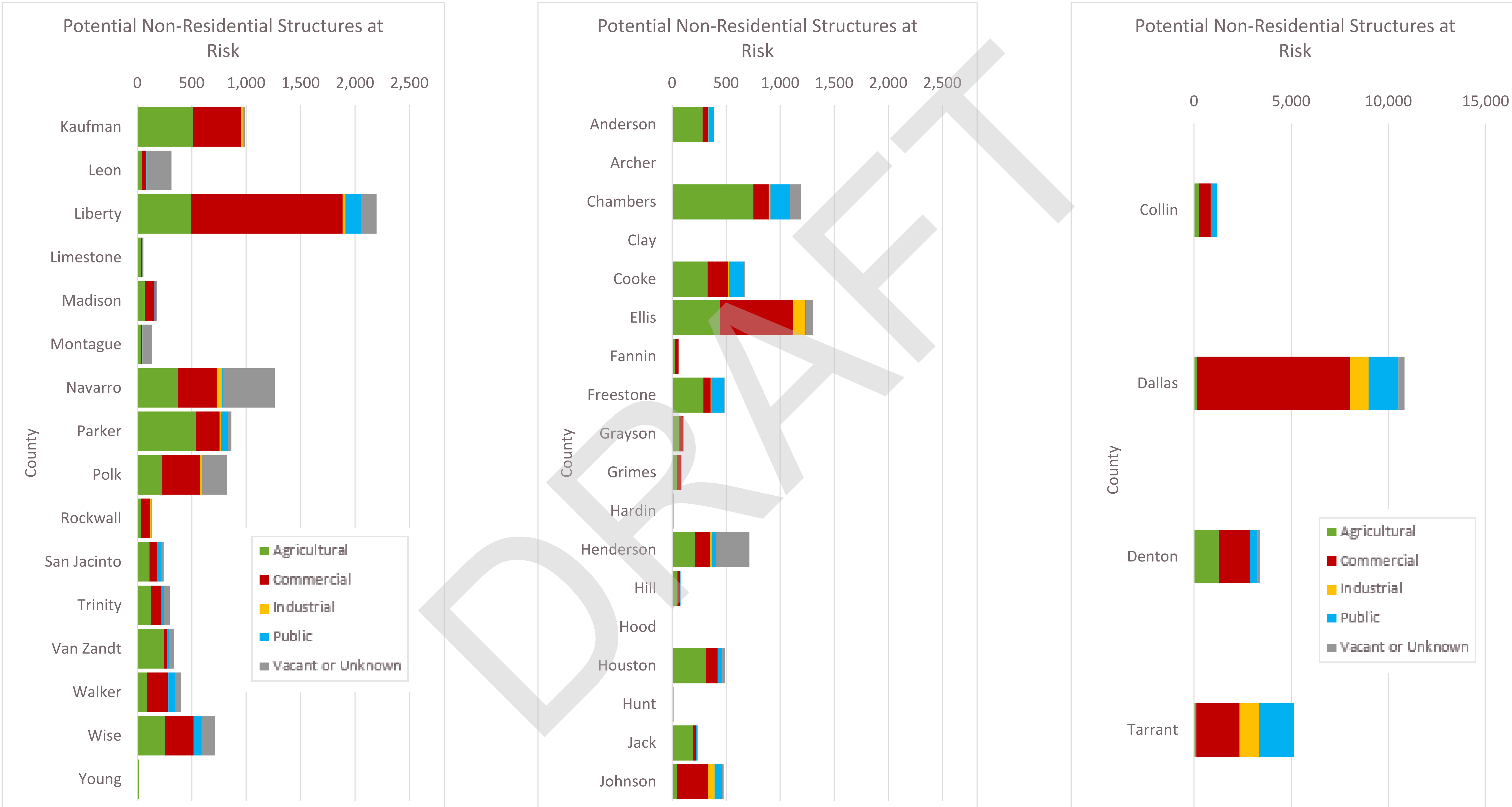
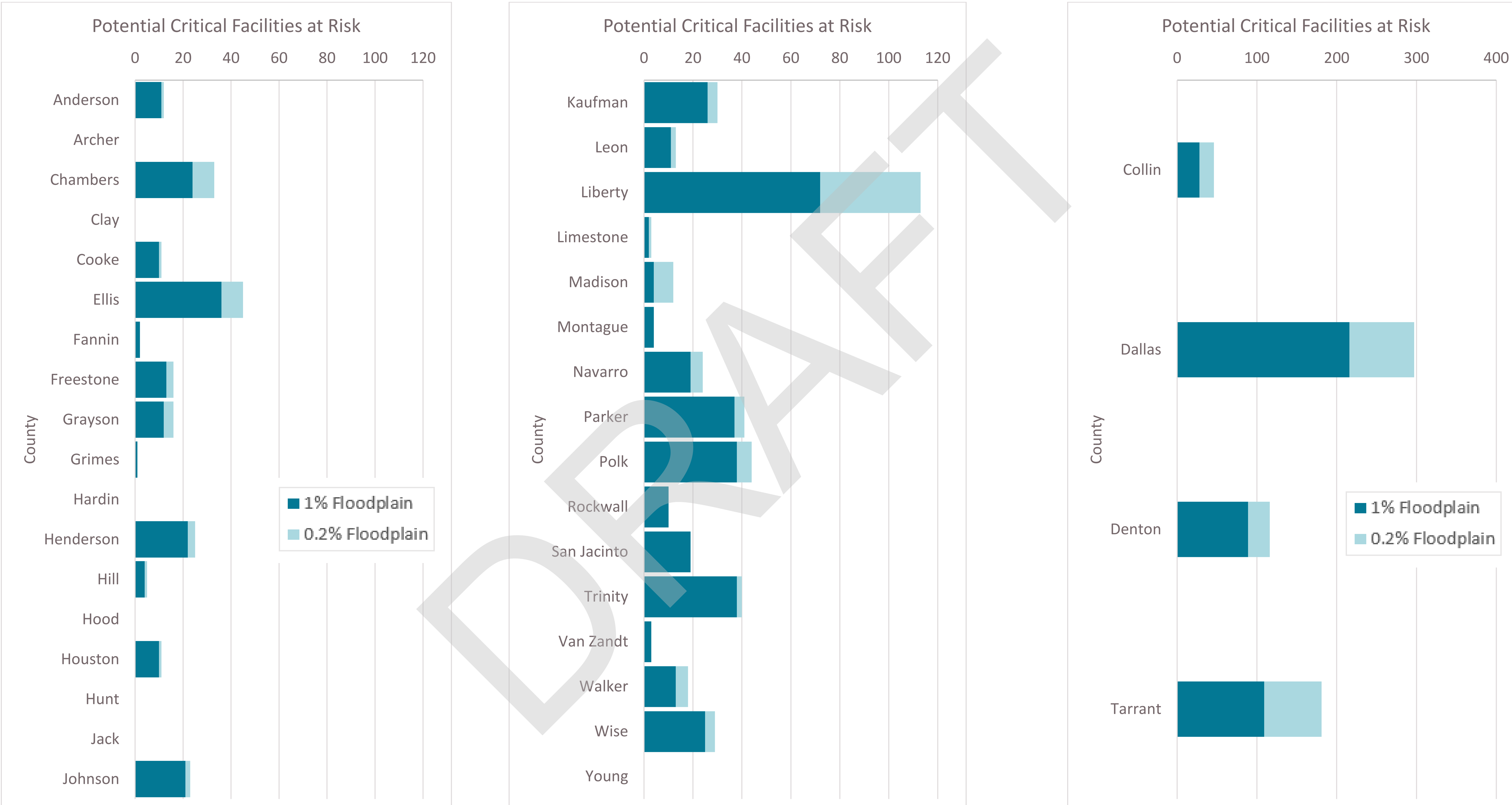


Figure 2.17: Critical Facilities in Existing Condition Floodplain Quilt by County



Over 10,662 critical facilities were identified for the Trinity Region and an estimated 11.9 percent of these facilities are exposed to flooding.

The Trinity Region's Upper Subregion counties have the most critical exposure counts to the existing floodplain quilt, with the Dallas/Fort Worth (DFW) area counties having the highest exposures of people and structures. Archer, Clay, Hardin, Hood, and Hunt counties showed very little to no exposure of critical facilities to the existing floodplain quilt.

Roadway Crossings and Roadway Segments

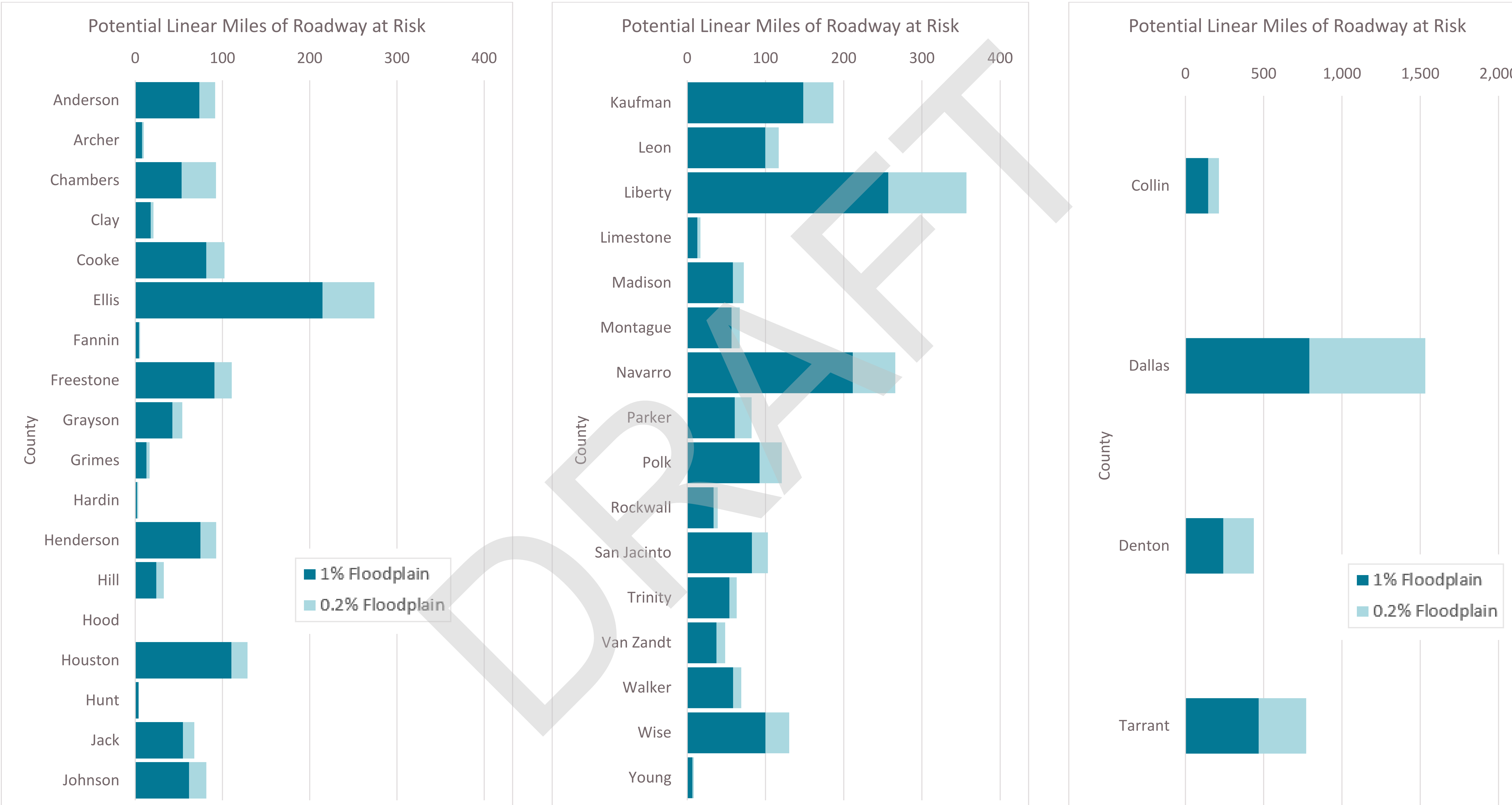
Transportation line data (roadways and railroads) from TxDOT was used to estimate road and railway crossings at-risk to flooding. A combination of available flood depth information from BLE and Fathom data, as well as bridge deck elevation from LiDAR data was used to estimate flood exposure of road and railroad bridges at stream crossings. LWC data, provided by Trinity Region area communities and the TWDB, was also used to identify exposed road and railway crossings. The Tarrant Regional Water District (TRWD) also provided information on bridges that are inundated during flood events.

There are approximately 2,415 LWCs in the Trinity Region and several bridges inundated by flooding in the Trinity Region. ***Table 2.7*** shows the LWC and bridge exposure totals per county. ***Figure 2.18*** shows the miles of road segment exposed to the existing floodplains. The highest mileage exposures are seen in Dallas and Tarrant counties in the Upper Subregion and in the coastal Chambers County in the Lower Subregion.

Table 2.7: Exposed Bridge and Low Water Crossings in Existing Condition Floodplain Quilt

County	Number of LWCs	County	Number of LWCs	County	Number of LWCs
Anderson	39	Henderson	26	Navarro	163
Chambers	6	Hill	32	Parker	59
Collin	108	Houston	46	Polk	22
Cooke	85	Hunt	1	Rockwall	20
Dallas	565	Jack	6	San Jacinto	3
Denton	204	Johnson	427	Tarrant	746
Ellis	194	Kaufman	50	Trinity	6
Fannin	6	Leon	43	Van Zandt	26
Freestone	38	Liberty	26	Walker	20
Grayson	60	Limestone	14	Wise	62
Grimes	11	Madison	22	Young	4

Figure 2.18: Linear Miles of Roadway at Risk in Existing Condition Floodplain Quilt



Agricultural Area

Crop and livestock data used in the Trinity Region was obtained from the 2020 Texas Cropland Data layer developed by the USDA NASS. In the Trinity Region, increasing population continues to have a significant influence on the continued loss of working lands, changing ownership sizes, and land values. This is occurring particularly within or in surrounding urban centers like DFW in of the Upper Subregion. Large sections of the Lower Subregion are facing similar challenges because of development from the neighboring Houston-Galveston area. (Texas A&M Natural Resources Institute, 2020). ***Figure 2.19*** shows the distribution of Farming (crops) and Ranching (livestock) areas in the Trinity Region.

Crops and livestock exposed (dollar exposure from production) to flooding are documented in ***Table 2.8***, which summarizes estimated exposure values in dollars to the existing floodplain quilt by county. The 2020 FEMA National Risk Index (NRI) data was leveraged to show the value of crops and livestock exposed to flooding. The FEMA NRI uses data from the 2017 USDA CropScape and the Census of Agriculture to document value of exposed crops and livestock. The CropScape data in dollars was used to calculate crop and livestock production value density per county. The county value is divided by the total crop and livestock land area of the county to find its dollar value density as shown below.

$$AgValueDen_{Co} = \frac{AgValue_{Co}}{AgArea_{Co}}$$

$AgValueDen_{co}$ is the crop and livestock value density calculated at the county level (in dollars per square mile; $AgValue_{co}$ is the is the total crop and livestock production value of the county, as reported in the 2017 Census of Agriculture (in dollars); and $AgArea_{co}$ is the total crop and livestock production area of the county (in square miles).

Each county's crop and livestock value losses were then calculated as the product of the crop and livestock production value density per county and the associated crop and livestock areas exposed to flooding from the existing conditions floodplain. ***Table 2.8*** shows the value of crop and livestock (production) areas in dollars and square miles of exposed areas to the existing floodplain quilt in the Trinity Region. Denton, Ellis, Hill, Houston, Kaufman, Leon, Limestone, Navarro, and Van Zandt counties have high agricultural exposure values. Hardin County had no agricultural exposure in the Trinity Region; however, (less than one percent of the land area is in the Trinity Region. Even though Madison County showed a large agriculture area exposure to the existing conditions mapping (a little more than Anderson County), there was no data available from the 2017 USDA crop and livestock production summaries. ***Figure 2.20*** shows the exposed agricultural areas in square miles.

Figure 2.19: Agricultural Land Distribution in the Trinity Region

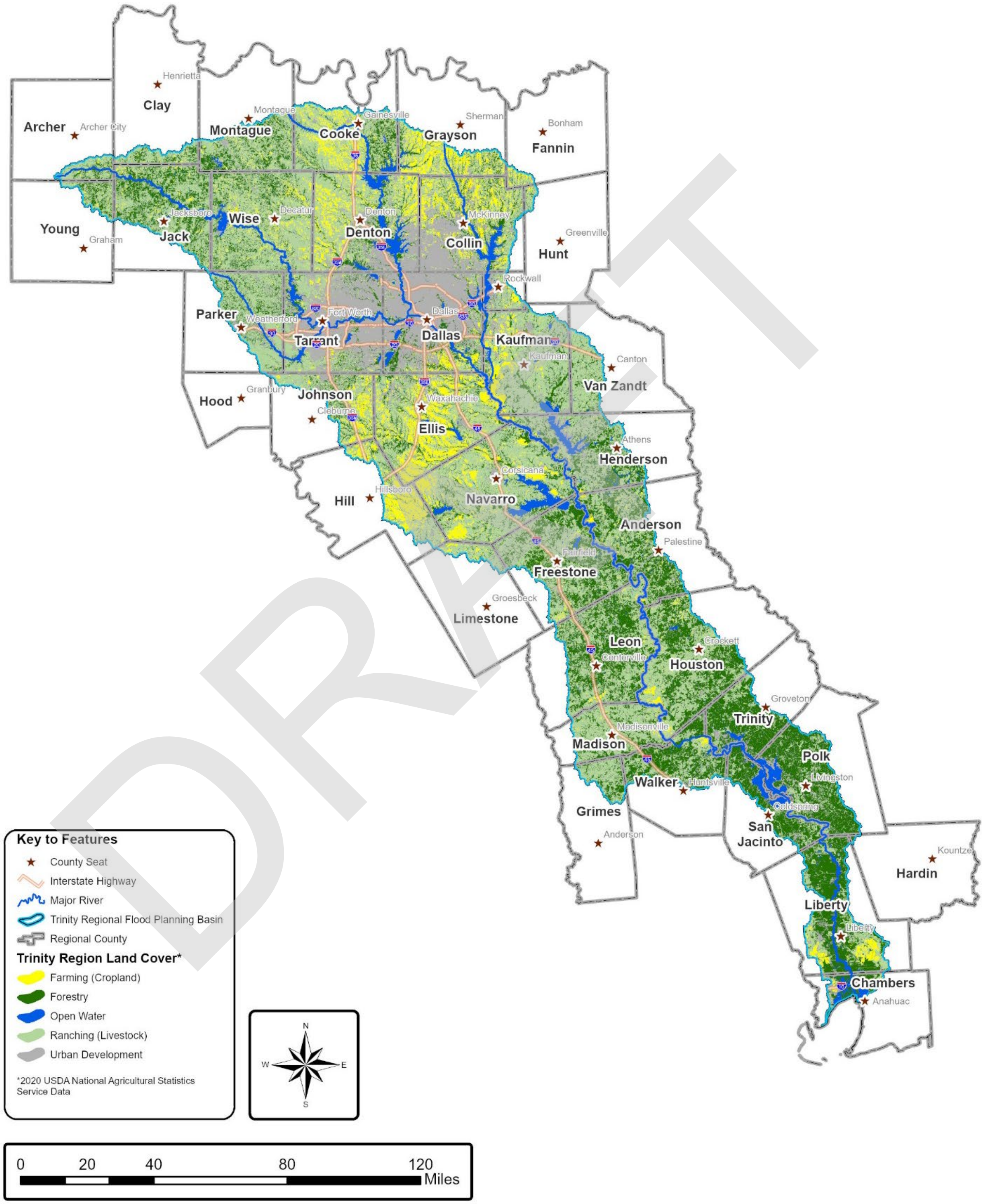
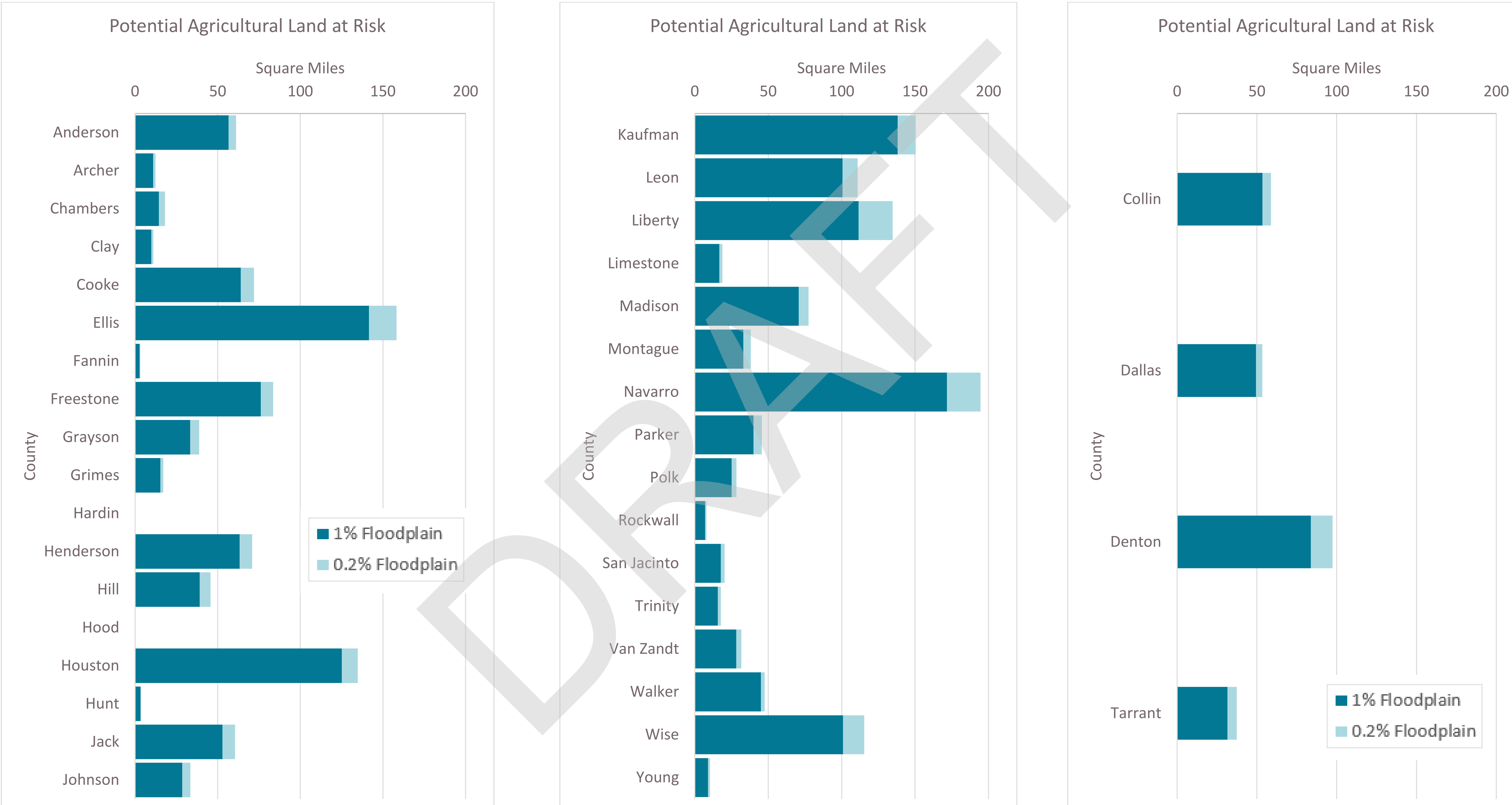


Table 2.8: Exposed Crop and Livestock Production Dollar Losses in Existing Condition Floodplain Quilt

County	$ Losses in Existing 100-Year	$ Losses in Existing 500-Year	Total $ Losses
Anderson	$6,585,859.53	$347,619.85	$92,943,000.00
Archer	$3,148,048.84	$339,605.55	$72,439,000.00
Chambers	$727,548.59	$244,637.68	$19,252,000.00
Clay	$4,299,671.53	$511,919.68	$55,650,000.00
Collin*	$3,307,738.71	$208,575.84	$66,829,000.00
Cooke	$3,281,843.65	$101,341.85	$53,830,000.00
Dallas	$1,417,685.55	$338,534.67	$29,781,000.00
Denton*	$8,843,880.47	$631,898.15	$123,209,000.00
Ellis*	$8,063,277.01	$614,192.58	$73,146,000.00
Fannin	$3,620,884.57	$385,973.64	$86,292,000.00
Freestone	$4,487,436.34	$404,559.94	$68,131,000.00
Grayson	$3,305,320.58	$111,452.65	$66,171,000.00
Grimes	$3,306,876.11	$380,657.27	$47,509,000.00
Hardin	$ -	$ -	$4,694,000.00
Henderson	$2,976,802.24	$151,672.36	$40,183,000.00
Hill	$7,938,240.43	$1,488,228.21	$114,001,000.00
Hood	$160,458.00	$ -	$18,944,000.00
Houston	$7,599,549.20	$394,697.63	$64,518,000.00
Hunt	$3,619,615.91	$17,574.35	$55,313,000.00
Jack	$1,008,118.84	$147,747.69	$23,176,000.00
Johnson	$2,836,202.32	$230,236.26	$57,850,000.00
Kaufman	$8,104,418.94	$455,727.57	$57,063,000.00
Leon	$15,144,547.66	$1,366,972.36	$169,404,000.00
Liberty	$2,711,802.52	$725,267.08	$29,950,000.00
Limestone	$7,318,238.96	$1,007,766.25	$66,257,000.00
Madison	$ -	$ -	$ -
Montague	$1,193,327.74	$108,082.32	$33,416,000.00
Navarro*	$7,898,495.75	$620,323.08	$73,306,000.00
Parker	$2,865,510.02	$65,937.53	$65,043,000.00
Polk	$241,555.50	$31,328.54	$6,831,000.00
Rockwall	$368,691.54	$27,043.07	$7,830,000.00
San Jacinto	$352,333.29	$48,355.78	$7,190,000.00
Tarrant*	$869,004.49	$144,186.79	$29,393,000.00
Trinity	$214,144.08	$26,658.37	$8,228,000.00
Van Zandt	$9,306,683.99	$1,045,426.77	$104,603,000.00
Walker	$3,224,082.01	$152,300.54	$33,795,000.00
Wise	$3,175,505.89	$128,129.87	$46,269,000.00
Young	$672,112.77	$20.21	$21,694,000.00

Figure 2.20: Agricultural Land Exposure (in Square Miles) to Existing Condition Floodplain Quilt



Expected Loss of Function

Severe flooding can cause a loss of function for a community's residential and critical infrastructure, which has an impact on the socio-economic systems supported by them. These impacts include disruptions to life, business, and public services. Some public services are essential to a community during and after a flood event. Flood inundation depth and duration are typically considered the best flood characteristics in predicting expected functionality losses. Inundated structures and critical facilities are often not functional during the flood event and through the recovery process. Closure length is dependent on the severity of damage to the structure, interrupted access, and lingering health hazards.

Inundated Structures

FEMA's Hazus Program was used to generate quantitate estimates of expected loss of functions for counties in the Trinity Region. Note that the Hazus analysis assumes that a flood event covers the entire county or river basin. The Hazus analysis is also based on the default inventory data and future similar assessments will benefit from updated inventory data. The total exposure value of buildings in the Trinity Region is $636.83 billion. Hazus estimates the total direct and indirect losses for a 1-percent ACE to be $13.12 billion and $12.33 billion, respectively. Direct losses account for building, content, and inventory losses, while indirect losses include relocation, capital, wages, and rental income losses. The total loss is estimated at $24.45 billion or four percent of the total exposure value of buildings in the Trinity Region. ***Table 2.9*** summarizes direct, indirect, and total building losses by county in the Trinity Region. Liberty County is anticipated to have the highest loss ratio, while no losses are predicted for Chambers County.

The Hazus analysis predicts that approximately 1,021 million tons of debris will be generated from finishes (drywall, flooring, insulation, etc.), structures (framing, walls, exterior cladding), and foundation weight (concrete slab, concrete block, or other foundation) from a 1-percent ACE. ***Table 2.10*** summarizes Hazus' estimated debris generation by county in the Trinity Region. Dallas County is estimated to generate the highest amounts of debris and would account for approximately 35 percent of the total debris generated in the Trinity Region.

Hazus predicts that 1.32 million people would be displaced during 1-percent ACE and approximately 170,000 people would require short-term shelter. ***Table 2.11*** summarizes Hazus' estimated displacement and shelter requirements by county in the Trinity Region. Dallas and Denton counties are estimated to account for 79 percent of the displaced population, and 65 percent of the people requiring short-term shelter.

Table 2.9: Direct, Indirect, and Total Building Losses by County

County	Direct Loss ($ million)	Indirect Loss ($ million)	Total Loss ($ million)	Total Loss Ratio (%)
Anderson	57.92	34.24	92.16	4.0%
Archer	21.89	9.73	31.62	4.5%
Chambers	0.00	0.00	0.00	0.0%
Clay	0.77	0.16	0.93	2.2%
Collin	1,073.89	754.75	1,828.64	2.3%
Cooke	115.37	78.11	193.49	2.0%
Dallas	5,207.52	6,822.67	12,030.19	3.5%
Denton	1,040.23	599.10	1,639.33	1.4%
Ellis	227.22	151.28	378.50	2.4%
Fannin	4.57	1.27	5.84	1.4%
Freestone	38.06	20.93	58.99	3.5%
Grayson	23.93	8.86	32.79	1.3%
Grimes	4.92	7.01	11.93	3.6%
Hardin	0.76	0.23	0.99	2.7%
Henderson	54.24	47.21	101.44	1.7%
Hill	4.67	1.79	6.46	1.7%
Hood	0.00	0.00	0.00	0.0%
Houston	35.66	13.52	49.17	3.3%
Hunt	1.49	0.27	1.76	2.4%
Jack	9.21	5.05	14.26	2.5%
Johnson	28.42	14.47	42.89	2.6%
Kaufman	172.61	101.70	274.31	2.8%
Leon	48.97	27.75	76.72	4.8%
Liberty	39.07	18.71	57.78	29.3%
Limestone	1.65	0.87	2.52	1.8%
Madison	28.06	26.72	54.78	6.1%
Montague	41.03	19.04	60.07	5.7%
Navarro	92.05	83.82	175.87	4.2%
Parker	40.78	27.91	68.69	3.5%
Polk	190.26	91.15	281.40	8.3%
Rockwall	146.05	56.74	202.79	3.5%
San Jacinto	161.48	82.87	244.35	14.2%
Tarrant	237.29	129.79	367.08	3.7%
Trinity	88.59	36.21	124.79	11.4%
Van Zandt	16.77	14.75	31.52	2.4%
Walker	146.41	59.24	205.66	10.7%
Wise	168.50	85.95	254.45	5.0%
Young	0.26	0.08	0.34	0.9%

Table 2.10: Debris Generation by County

County	Finishes (tons)	Structures (tons)	Foundations (tons)	Total (tons)
Anderson	1,953	1,856	2,914	6,722
Archer	1,366	717	1,048	3,131
Chambers	0	0	0	0
Clay	72	19	35	126
Collin	40,205	11,218	14,144	65,566
Cooke	5,794	1,432	2,274	9,499
Dallas	192,258	62,640	70,061	324,959
Denton	32,371	13,635	18,077	64,083
Ellis	8,450	3,280	5,318	17,049
Fannin	232	57	103	392
Freestone	2,041	1,020	1,764	4,824
Grayson	1,180	454	809	2,442
Grimes	440	104	225	769
Hardin	61	25	53	139
Henderson	3,885	1,598	3,494	8,975
Hill	368	136	255	760
Hood	0	0	0	0
Houston	2,870	1,847	2,898	7,615
Hunt	92	35	70	197
Jack	733	233	424	1,390
Johnson	1,449	729	1,364	3,542
Kaufman	6,732	2,060	4,058	12,849
Leon	2,956	1,996	3,094	8,044
Liberty	2,009	3,083	4,325	9,417
Limestone	100	35	73	209
Madison	2,013	1,131	2,039	5,183
Montague	2,093	2,107	3,367	7,565
Navarro	4,855	1,433	2,691	8,981
Parker	2,385	1,094	2,100	5,579
Polk	13,349	9,510	14,392	37,252
Rockwall	3,984	651	722	5,358
San Jacinto	9,973	8,110	13,111	31,193
Tarrant	7,110	5,839	6,057	19,007
Trinity	6,387	6,630	10,746	23,763
Van Zandt	1,236	523	1,074	2,832
Walker	8,975	9,268	13,817	32,061
Wise	7,751	5,340	8,713	21,804
Young	35	7	14	56

Table 2.11: Displacement and Shelter Requirements by County

County	Number of Displaced People	Number of People Needing Short-Term Shelter
Anderson	2,778	535
Archer	478	105
Chambers	0	0
Clay	36	3
Collin	91,846	16,267
Cooke	36,706	2,190
Dallas	430,161	88,251
Denton	601,551	44,812
Ellis	5,772	2,657
Fannin	150	63
Freestone	800	346
Grayson	9,364	435
Grimes	198	108
Hardin	39	8
Henderson	2,211	1,328
Hill	180	50
Hood	0	0
Houston	842	319
Hunt	57	9
Jack	262	48
Johnson	796	414
Kaufman	5,156	2,116
Leon	831	319
Liberty	331	60
Limestone	47	16
Madison	783	343
Montague	2,633	188
Navarro	2,780	870
Parker	1,432	543
Polk	3,692	1,334
Rockwall	2,776	1,142
San Jacinto	2,460	583
Tarrant	3,655	1,640
Trinity	1,376	421
Van Zandt	827	394
Walker	4,067	806
Wise	4,117	1,038
Young	15	3

Transportation

Hazus estimates the total highway bridge damage to be $3.49 million in the Trinity Region for a 1-percent ACE. An average damage of 2.6 percent for a 100-year flooding event is estimated for the 599 highway bridges in the Trinity Region. Other than the nine bridges identified by TRWD, none of the highway bridges are estimated to be non-functional. ***Table 2.12*** summarizes Hazus' estimated highway bridge damage by county in the Trinity Region. The highest damages are estimated for Collin and Dallas counties. Hazus estimates total daytime and nighttime vehicle losses at $1.97 billion and $2.14 billion, respectively for a 1-percent ACE. ***Table 2.13*** summarizes Hazus' estimated vehicles losses by county in the Trinity Region. The highest loss is estimated for Dallas County (approximately $900 million) and accounts for more than 45 percent of the total vehicle losses predicted for the Trinity Region.

Health and Human Services

The Hazus analysis does not predict any losses to small, medium, and large hospitals in the Trinity Region for a 1-percent ACE. There are no predicted losses to the number of available beds, no building or content losses are predicted, and none of the hospitals are expected to be non-functional based on the results of the Hazus analysis.

Water Supply

Floods can contaminate water supply sources such as wells, springs, and lakes/ponds through polluted runoff laden with sediment, bacteria, animal waste, pesticides, and industrial waste and chemicals. Drinking water wells have the potential to become contaminated during major flooding events, requiring disinfection and cleanup. Based on TCEQ's Public Water Supply dataset, there are 2,391 public water supply wells in the Trinity Region with 127 in the 100-year floodplain. Therefore, five percent of the public water supply wells in the Trinity Region are potentially exposed to flood risk. The Hazus analysis predicts damage to one potable water facility in the Trinity Region (as discussed shortly), however, does not estimate any damages to potable water pipelines.

Water Treatment

Failure of water treatment systems due to flooding may consist of direct losses, such as equipment damage and contamination of pipes, as well as indirect impacts, such as disruption of clean water supply (Arrighi, Tarani, Vicario, & Castelli, 2017). Floods have the potential to impact operations at water treatment facilities resulting in poorer potable water quality. Hazus predicts that one potable water system in Kaufman County will be non-functional due to damages from a 11-percent ACE. The potable water facility is estimated to sustain an average damage of 40 percent and a total loss of $11.86 million.

Table 2.12: Highway Bridge Damages by County

County	Number of Highway Bridges	Average Damage (%)	Total Loss ($)
Anderson	15	3.8%	61,000
Archer	1	0.3%	2,000
Chambers	0	0.0%	0
Clay	0	0.0%	0
Collin	56	3.3%	576,000
Cooke	0	0.0%	0
Dallas	30	0.6%	534,000
Denton	21	3.4%	180,000
Ellis	82	3.2%	352,000
Fannin	3	3.8%	12,000
Freestone	32	3.3%	143,000
Grayson	32	3.5%	165,000
Grimes	15	4.0%	66,000
Hardin	0	0.0%	0
Henderson	5	2.0%	17,000
Hill	2	0.3%	25,000
Hood	0	0.0%	0
Houston	57	2.9%	173,000
Hunt	3	3.4%	17,000
Jack	1	0.5%	1,000
Johnson	17	4.1%	178,000
Kaufman	31	2.2%	172,000
Leon	25	3.1%	95,000
Liberty	2	1.3%	6,000
Limestone	7	2.9%	28,000
Madison	19	2.2%	59,000
Montague	1	5.0%	4,000
Navarro	21	2.5%	110,000
Parker	0	0.0%	0
Polk	32	1.0%	52,000
Rockwall	3	1.3%	5,000
San Jacinto	6	1.5%	15,000
Tarrant	5	0.9%	15,000
Trinity	3	1.3%	14,000
Van Zandt	29	2.1%	56,000
Walker	8	4.1%	75,000
Wise	6	2.1%	37,000
Young	0	0.0%	0

Table 2.13: Vehicle Losses by County

County	Daytime Loss ($ million)	Nighttime Loss ($ million)
Anderson	10.51	10.99
Archer	2.06	4.08
Chambers	0.00	0.00
Clay	0.07	0.15
Collin	137.28	151.65
Cooke	17.41	19.27
Dallas	838.47	888.81
Denton	114.03	127.59
Ellis	54.47	32.37
Fannin	0.48	0.65
Freestone	8.10	7.10
Grayson	2.63	4.02
Grimes	0.93	1.42
Hardin	0.04	0.07
Henderson	9.87	15.34
Hill	0.53	1.08
Hood	0.00	0.00
Houston	7.84	11.79
Hunt	0.12	0.26
Jack	1.06	1.73
Johnson	4.34	6.15
Kaufman	24.53	29.81
Leon	7.28	11.08
Liberty	4.50	6.61
Limestone	0.30	0.31
Madison	8.81	9.82
Montague	4.26	7.85
Navarro	15.75	18.79
Parker	6.68	8.47
Polk	30.06	49.51
Rockwall	12.70	14.17
San Jacinto	18.91	35.01
Tarrant	27.46	25.94
Trinity	11.43	21.58
Van Zandt	2.24	3.98
Walker	21.54	28.22
Wise	23.12	29.26
Young	0.04	0.08

The Hazus analysis estimates a total loss of $1.33 billion to wastewater treatment facilities in the Trinity Region. The average predicted damage is approximately 18 percent. Thirty-five of the 38 facilities are predicted to be non-operational due to damages from a 1-percent ACE. ***Table 2.14*** summarizes Hazus' predicted wastewater facility losses by county in the Trinity Region. The highest loss is predicted for Wise County with 10 out of 12 facilities estimated to be non-functional.

Utilities

The Hazus analysis estimates damages to potable water and wastewater facilities amounting to $11.86 million and $1.46 billion, respectively. The analysis estimates no losses to communication systems in the Trinity Region for a 1-percent ACE. Predicted utility losses at the county level for the Trinity Region are summarized in ***Table 2.15***.

Energy Generation

The Hazus analysis estimates no losses to oil systems, natural gas, and electric power systems in the Trinity Region.

Emergency Services

Flooding has the potential to cause disruption to emergency services by causing delays in response times. The Hazus analysis for the Trinity Region quantifies damages and expected loss of use associated with essential facilities including emergency operation centers, fire stations, and police stations. For a 1-percent ACE, the Hazus analysis estimates total building and content damages amounting to $3.75 million and $10.52 million, respectively. One emergency operation center each in Dallas County and one emergency operation center in Liberty County are estimated to be non-functional. A total of 14 fire stations are estimated to be non-functional in the event of a 1-percent ACE.

Total building and content damages to fire stations are predicted at $2.83 million and $8.76 million, respectively. Total building and content damages to police stations are estimated at $588,000 and $1.14 million, respectively. ***Table 2.16*** summarizes Hazus estimated losses to emergency services by county in the Trinity Region for a 1-percent ACE.

Table 2.14: Wastewater Facility Losses by County

County	Number of Wastewater Facilities	Average Damage (%)	Total Loss ($)	Number of Non-Functional Facilities
Anderson	2	7.1%	8,406	0
Archer	0	0.0%	0	0
Chambers	0	0.0%	0	0
Clay	0	0.0%	0	0
Collin	1	40.0%	23,710	1
Cooke	0	0.0%	0	0
Dallas	0	0.0%	0	0
Denton	1	30.0%	17,782	1
Ellis	5	33.6%	146,666	4
Fannin	1	7.9%	4,696	0
Freestone	3	9.4%	16,803	0
Grayson	0	0.0%	0	0
Grimes	0	0.0%	0	0
Hardin	0	0.0%	0	0
Henderson	0	0.0%	0	0
Hill	4	6.2%	29,432	0
Hood	0	0.0%	0	0
Houston	2	4.9%	5,808	0
Hunt	0	0.0%	0	0
Jack	0	0.0%	0	0
Johnson	2	20.6%	24,378	1
Kaufman	4	14.2%	33,609	1
Leon	0	0.0%	0	0
Liberty	0	0.0%	0	0
Limestone	0	0.0%	0	0
Madison	1	30.0%	17,782	1
Montague	0	0.0%	0	0
Navarro	10	18.7%	202,365	7
Parker	0	0.0%	0	0
Polk	2	19.0%	22,524	1
Rockwall	4	20.6%	48,861	3
San Jacinto	2	19.6%	23,235	1
Tarrant	1	40.0%	23,710	1
Trinity	4	22.1%	52,457	3
Van Zandt	0	0.0%	0	0
Walker	0	0.0%	0	0
Wise	12	25.8%	364,869	10
Young	0	0.0%	0	0

Table 2.15: Utility Losses by County

County	Potable Water ($ million)	Wastewater ($ million)	Oil Systems ($ million)	Natural Gas ($ million)	Electric Power ($ million)	Communication ($ million)	Total ($ million)
Anderson	0.00	8.41	0.00	0.00	0.00	0.00	8.41
Archer	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chambers	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Clay	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Collin	0.00	23.71	0.00	0.00	0.00	0.00	23.71
Cooke	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dallas	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Denton	0.00	17.78	0.00	0.00	0.00	0.00	17.78
Ellis	0.00	146.67	0.00	0.00	0.00	0.00	146.67
Fannin	0.00	4.70	0.00	0.00	0.00	0.00	4.70
Freestone	0.00	16.80	0.00	0.00	0.00	0.00	16.80
Grayson	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Grimes	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hardin	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Henderson	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hill	0.00	29.43	0.00	0.00	0.00	0.00	29.43
Hood	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Houston	0.00	5.81	0.00	0.00	0.00	0.00	5.81
Hunt	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Jack	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Johnson	0.00	24.38	0.00	0.00	0.00	0.00	24.38
Kaufman	11.85	33.61	0.00	0.00	0.00	0.00	45.46
Leon	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Liberty	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Limestone	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Madison	0.00	17.78	0.00	0.00	0.00	0.00	17.78
Montague	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Navarro	0.00	334.83	0.00	0.00	0.00	0.00	334.83
Parker	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Polk	0.00	22.52	0.00	0.00	0.00	0.00	22.52
Rockwall	0.00	48.86	0.00	0.00	0.00	0.00	48.86
San Jacinto	0.00	23.24	0.00	0.00	0.00	0.00	23.24
Tarrant	0.00	23.71	0.00	0.00	0.00	0.00	23.71
Trinity	0.00	52.46	0.00	0.00	0.00	0.00	52.46
Van Zandt	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Walker	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wise	0.00	364.87	0.00	0.00	0.00	0.00	364.87
Young	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 2.16: Emergency Services Losses by County

		County				
		Anderson	Dallas	Liberty	Tarrant	Wise
Emergency Operation Centers	Building Damage ($ thousand)	0	147	180	0	0
	Content Damage ($ thousand)	0	253	372	0	0
	Non-Functional	0	1	1	0	0
Fire Stations	Building Damage ($ thousand)	190	867	1038	207	533
	Content Damage ($ thousand)	452	3364	2834	546	1559
	Non-Functional	1	4	5	1	3
Police Stations	Building Damage ($ thousand)	0	229	359	0	0
	Content Damage ($ thousand)	0	393	745	0	0
	Non-Functional	0	2	2	0	0

Note: Only counties for which the HAZUS analysis reported losses are summarized.

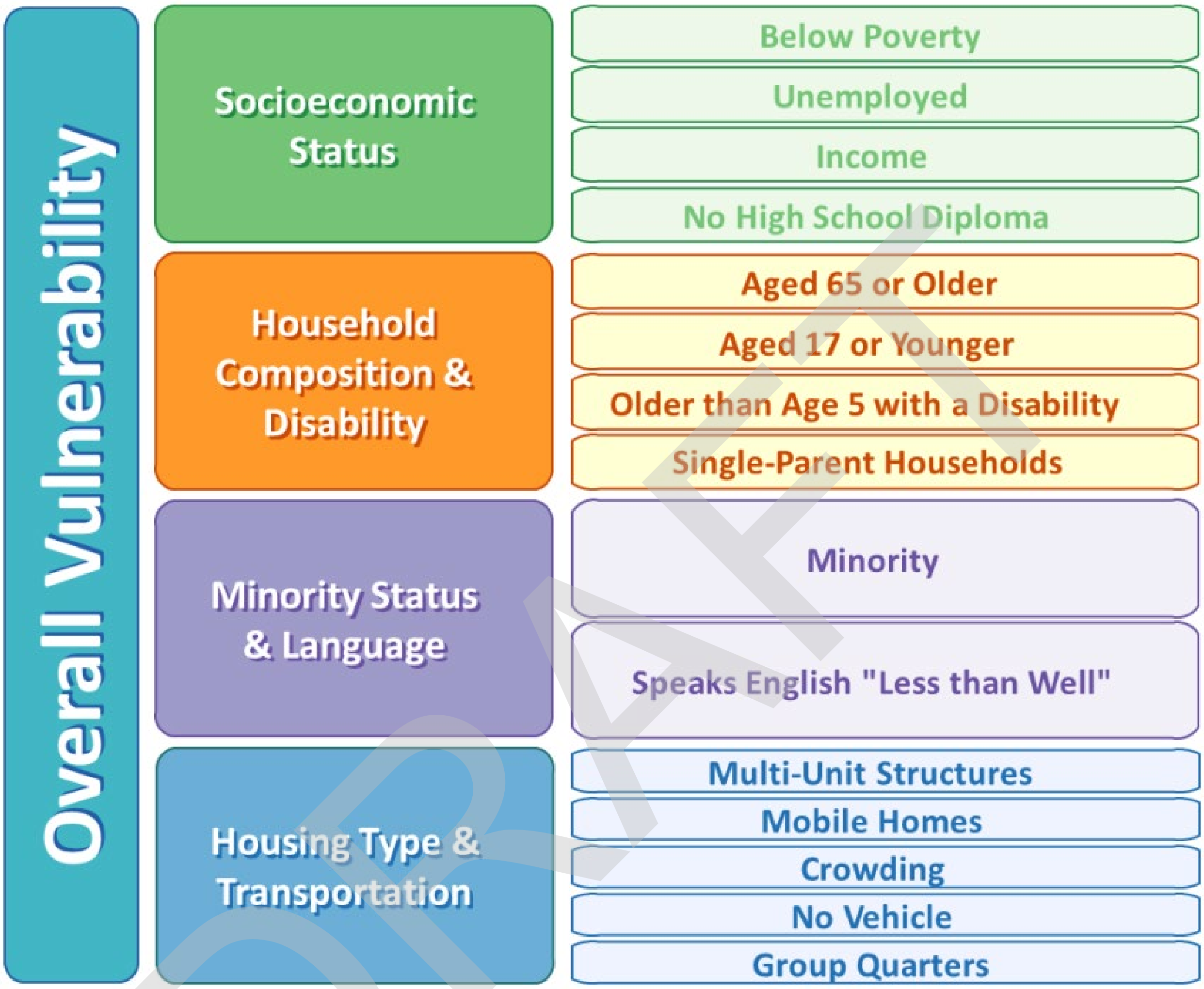
Existing Condition Vulnerability Analysis

Vulnerability is an assessment of the potential negative impact of the flood hazard to communities and a description of the impacts. The existing condition vulnerability analysis uses the 2018 SVI data developed by the CDC. The CDC calculates the SVI at the census tract level within a specified county using 15 sociable factors including poverty, housing, ethnicity, and vehicle access. It then groups them into four related themes: Socioeconomic Status, Household Composition, Race/Ethnicity/Language, and Housing/Transportation. ***Figure 2.21*** shows the CDC themes used for SVI calculation. Each census tract receives a separate ranking for each of the four themes, as well as an overall ranking.

Vulnerabilities of Structures, Agricultural Areas, Bridges, Low Water Crossings, and Critical Facilities

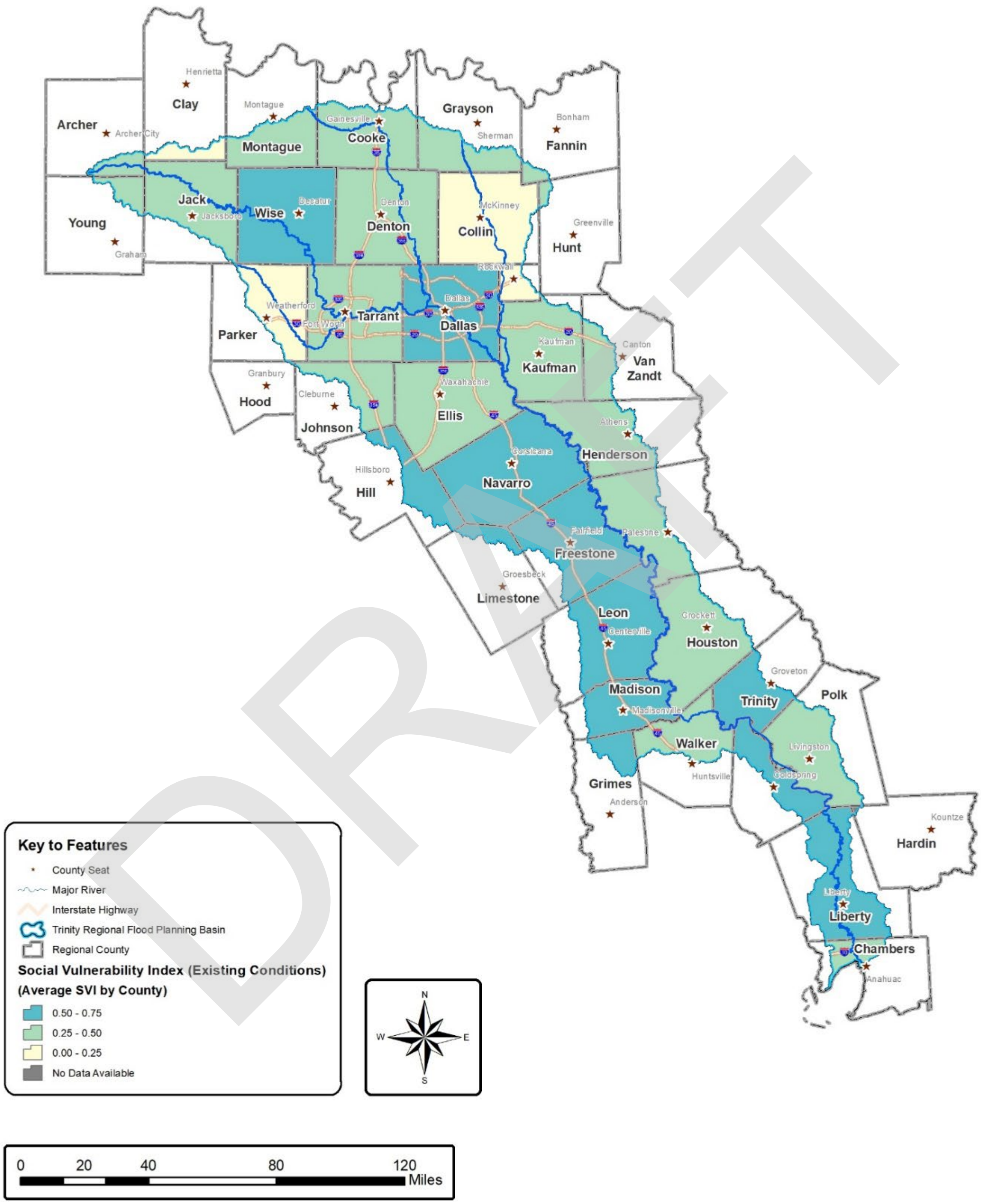
The 2018 CDC SVI data was overlaid with the Trinity Region's buildings, critical facilities, bridges, LWCs, and agricultural areas. The SVI values for all the buildings, critical facilities, agricultural areas, bridges, and LWCs exposed to the existing conditions floodplain quilt are summarized by county averages and shown in ***Figure 2.22***.

Figure 2.21: Center for Disease Control Themes



Source: U.S. CDC (U.S. Center for Disease Control, 2018)

Figure 2.22: Existing Condition Exposure and Social Vulnerability Index by County



A community's social vulnerability score is proportional to a community's risk. Social vulnerability is a consequence enhancing risk component and community risk factor that represents the susceptibility of social groups to the adverse effects of natural hazards like floods, including disproportionate death, injury, loss, or disruption of livelihood (U.S. Center for Disease Control, 2018). An SVI score and rating represent the relative level of a community's social vulnerability compared to all other communities, with a higher SVI score resulting in a higher risk index score (U.S. Center for Disease Control, 2018).

Figure 2.22 shows Clay, Collin, and Parker counties as being the least vulnerable with respect to the existing exposure of buildings, critical facilities, agricultural areas, bridges, and LWCs. TWDB considers a threshold of 0.75 as an indicator for highly vulnerable areas. At the county level, none of the counties reached this threshold. ***Figure 2.23*** shows the countywide average distribution of SVI with regards to the exposed buildings, critical facilities, agricultural areas, bridges, and LWCs in the Trinity Region. Leon, Liberty, and Navarro counties had the largest SVI countywide values. Large, detailed maps for the vulnerability assessment are shown in ***Appendix B***.

Resiliency of Communities

Community resilience is a measure of the sustained ability of a community to prepare for anticipated natural hazards, adapt to changing conditions, and withstand and recover rapidly from disruptions. It refers to the ability of a community to survive and thrive when confronted by external stresses, such as natural or human-caused disasters like floods. A community resilience score is inversely proportional to a community's risk.

FEMA's 2021 Resilience Analysis and Planning Tool (RAPT) was leveraged to assess the resilience readiness of communities in the Trinity Region. RAPT uses 20 commonly used community resilience indicators from peer-reviewed published methodologies, infrastructure, and hazard data that informs strategies for preparedness, response, and recovery. Example indicators include median household income, disability (percent of population with disabilities and hospital capacity (number of hospitals per 10,000 people), and NFIP policy penetration rates. ***Table 2.17*** illustrates a summary community resilience indicator used by RAPT. The data is aggregated at the census tract and county levels and then aggregated into bins for visualization using all the indicators combined. ***Figure 2.24*** shows the resiliency ratings of the counties in the Trinity Region. Community resilience is a consequence reduction risk component, and a community resilience score is inversely proportional to a community's risk. A higher community resilience score results in a lower risk index score.

Figure 2.23: Social Vulnerability Index Averages by County

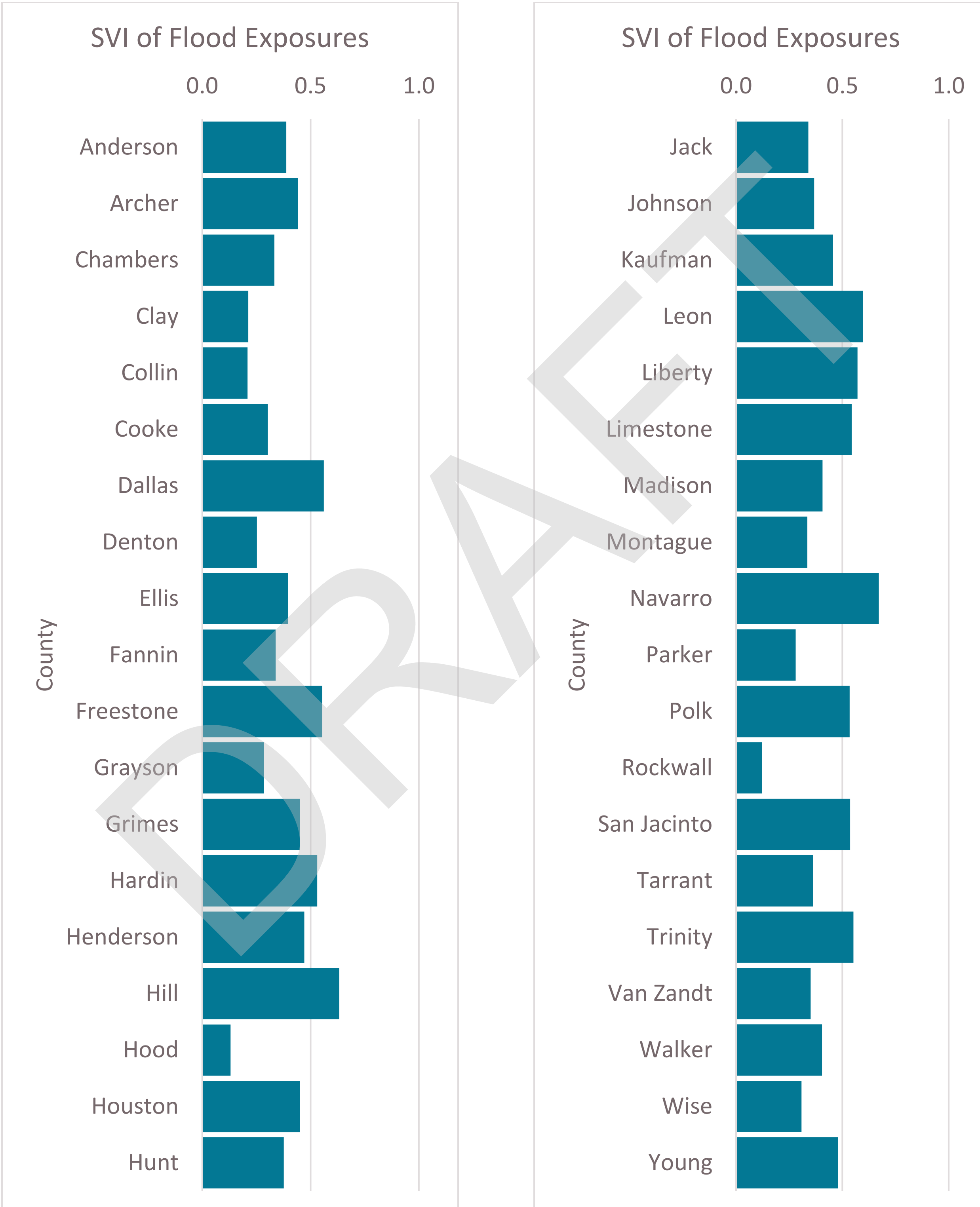
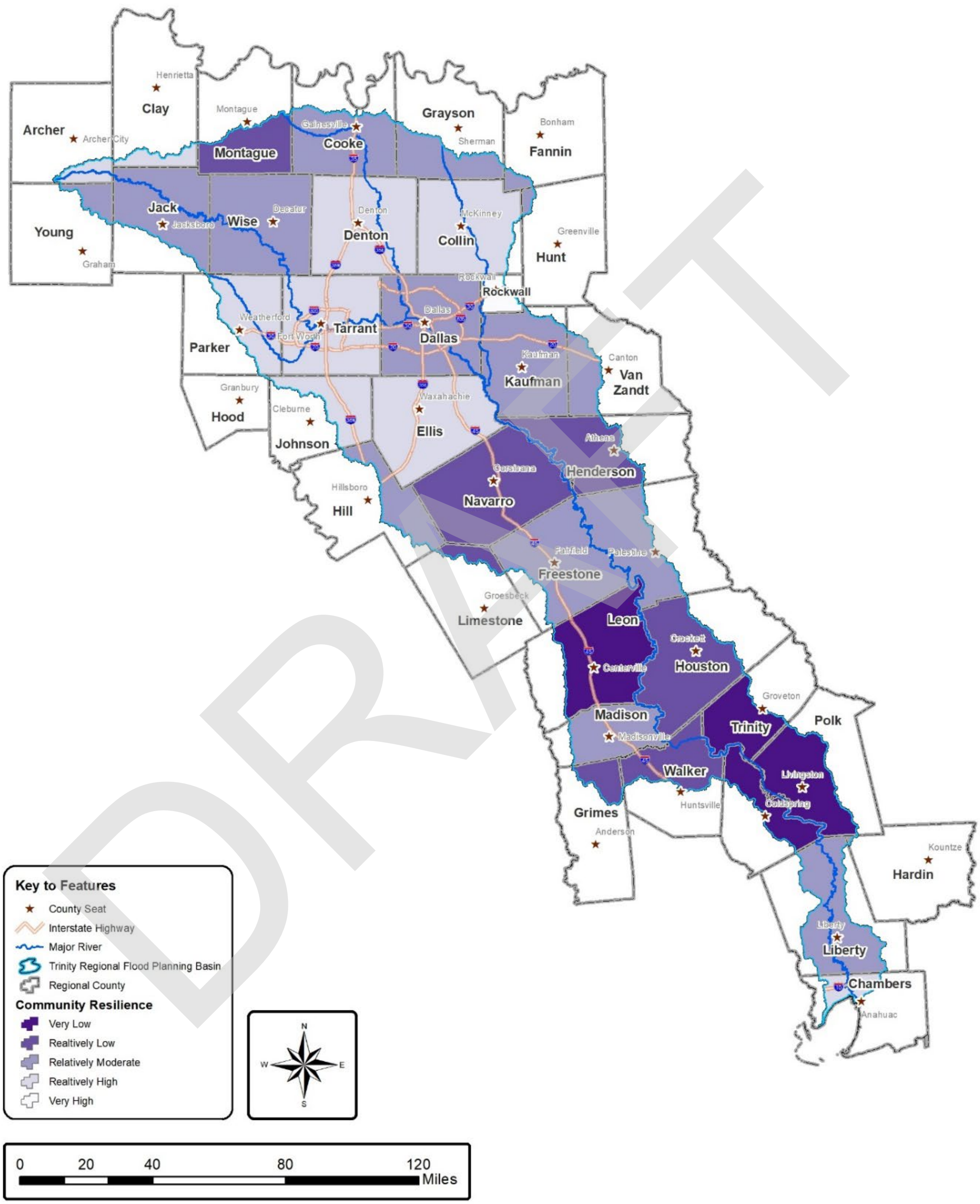


Table 2.17: Commonly Used Resilience Analysis and Planning Tool Indicators and Datasets

Population-Focused Indicators	Community-Focused Indicators	Infrastructure Data	Hazard Data
• % Population without Health Insurance • % Population Unemployed • % Population without a High School Education • % Population with a Disability • % Population without Access to a Vehicle • % Population with Home Ownership • % Population over 65 • % Population Single-Parent Households • % Population with Limited English Proficiency • Median Household Income • Gini Index: Income Inequality • At-risk electricity-dependent Medicare beneficiaries • Tribal Populations • Households without Internet Subscriptions • Power-dependent Devices for Medicare beneficiaries	• Connection to Civic/Social Organizations • Hospital Capacity • Medical Professional Capacity • Affiliation with a Religion • Presence of Mobile Homes • Public School Capacity • Population Change • Hotel/Motel Capacity • Rental Property Capacity • NFIP policy penetration rates (residential) • National Flood Insurance Program policy penetration rates (residential)	• Nursing Homes • Hospitals • Urgent Care Facilities • Public Health Depts. • Fire Stations • Emergency Medical Services (EMS) stations • Local Law Enforcement locations • 911 Service Area Boundaries • Mobile Home Parks • Places of Worship • Public Schools • Private Schools • Colleges and Universities • Prison Boundaries • Transmission Lines • Electric Power Plants • Solid Waste Landfills • Wastewater Treatment Plants • Pharmacies (Rx Open) • Dialysis Centers • High Hazard Dams	• Flood Hazard Zones • Tornado Paths • Tropical Storms • Seismic Hazards • Wildfire • Current Watches/Warnings • Hurricane Outlook: Atlantic • Severe Weather Outlook • Excessive Rainfall Outlook • River Flood Outlook

Figure 2.24 shows that Rockwall County has the highest resiliency rating in the Trinity Region. Leon, Polk, and Trinity counties show the lowest overall resiliency readings. In general, the Trinity Region Upper Subregion shows relatively higher resiliency ratings than the Middle and Lower Subregions.

Figure 2.24: Resiliency Rating by County



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Summary of Existing Conditions Flood Exposure and Vulnerability Analyses

Based on exceedance probability for a period of years, and not just one year, there is a 26 percent chance that a 100-year flood will occur over the next 30 years. There are over 140,000 buildings in the Trinity Region that have greater than a 26 percent chance of being severely affected by flooding over the next 30 years. This represents 2.2 percent of all buildings in the region.

While population estimates are valuable for defining the general severity of flood exposure, as documented in the upcoming Existing Conditions Flood Exposure section, such aggregated measures inform only how many people are exposed, but not who. Disaggregating the exposed populations according to SVI helps inform who lives in the floodplain and where. Questions about flood risk, exposure, vulnerability, and resilience are fundamentally questions of where. Hence the for the Trinity Region, spatial autocorrelation techniques using the values from the existing flood exposure and social vulnerability were used to map to map and identify hotspots (most vulnerable areas).

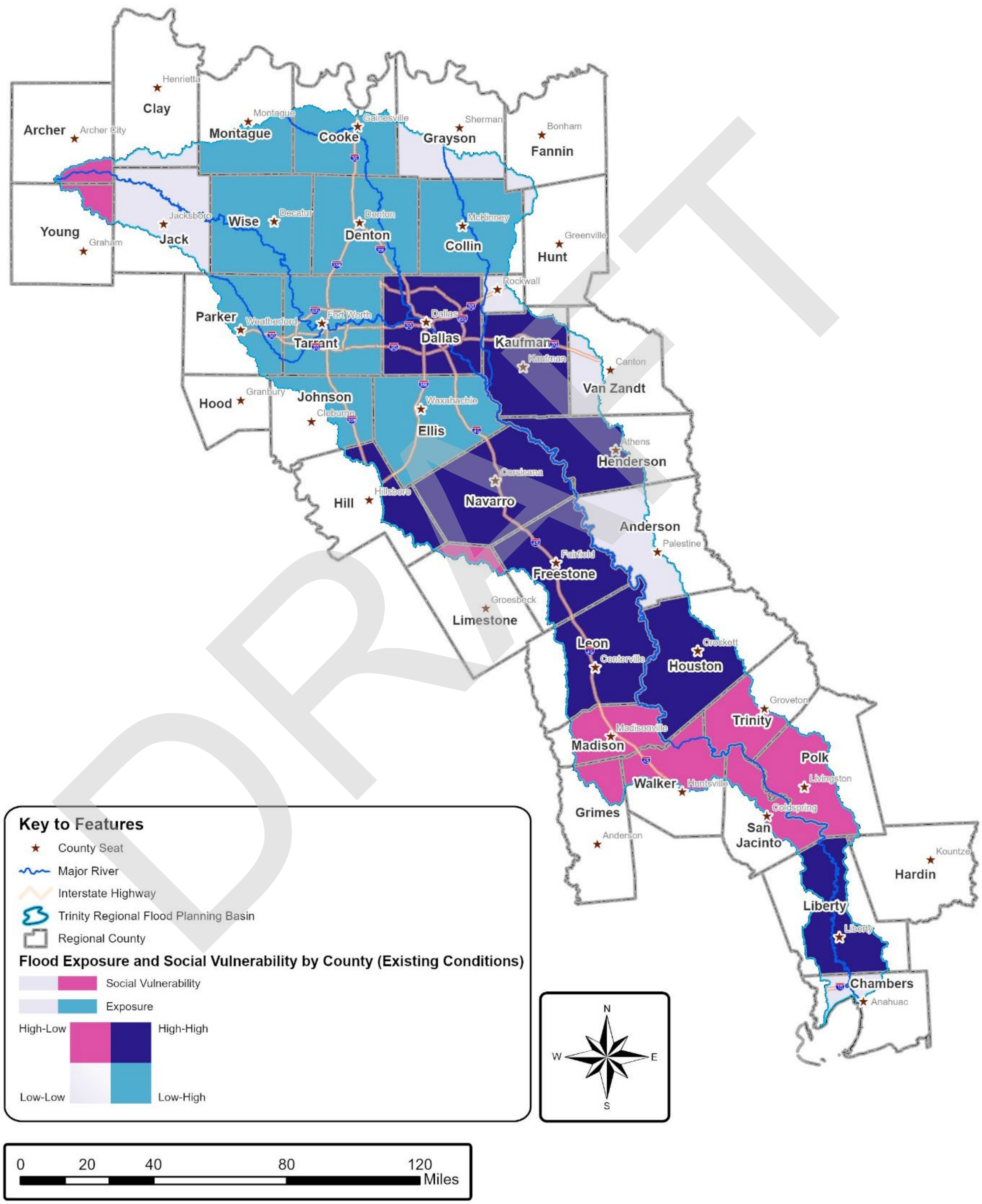
As shown in ***Figure 2.25***, the High-High (HH) hotspots (purple) are counties with higher-than-average flood exposure and are surrounded by areas with higher-than-average social vulnerability. The majority occur in the upper region (Dallas, Henderson, Hill, Kaufman, and Navarro counties). There are also three hotspots in the middle region (Freestone, Houston, and Leon counties) and one in the lower region (Liberty County). These HH counties are home to approximately 3,060,000 people.

The High-Low (HL) counties are in pink, representing counties with high social vulnerability with neighboring low flood exposure. These areas are mostly in the middle region (Grimes, Limestone, Madison, Trinity, and Walker counties), and then two in the lower region (Hardin and San Jacinto counties), and two clusters in the upper region (Archer and Young counties). In total the HL clusters are populated by approximately 275,000 people. Extreme flood events have the probability of high adverse impacts due to the high population susceptibility.

The Low-High (LH) counties in blue, represent counties with low social vulnerability and high flood exposure, and are home to approximately 4,650,000 people. The areas are all in urbanized upper region.

The Low-Low (LL) counties are the least in the Trinity Region and are interspersed throughout the region. These LL counties are Anderson, Chambers, Clay, Fannin, Grayson, Hood, Hunt, Jack, Rockwall, and Van Zandt counties. These counties have the lowest levels of flood exposure and social vulnerability and require less attention from the perspective of flood vulnerability.

Figure 2.25: Flood Exposure and Social Vulnerability Index by County to Existing Condition Floodplain Quilt



A larger version of ***Figure 2.25***, as well as a more detailed exposure and vulnerability relationship at the census tract level, is shown in ***Appendix B***.

The hotspot area can be used to help identify and justify priority locations for interventions like FMPs that can mitigate both physical and social aspects of flood vulnerability (Tate, Asif, Emrich, & Sampson, 2021). FMPs are discussed in ***Chapter 4***. For example, LH areas (Low vulnerability and High exposure) can become areas where exposure reduction projects like levees, detention basins, and other natural based solutions can be prioritized. If an FMP goal is to optimize both reduction in physical risk and address socially vulnerable populations, then areas can be prioritized.

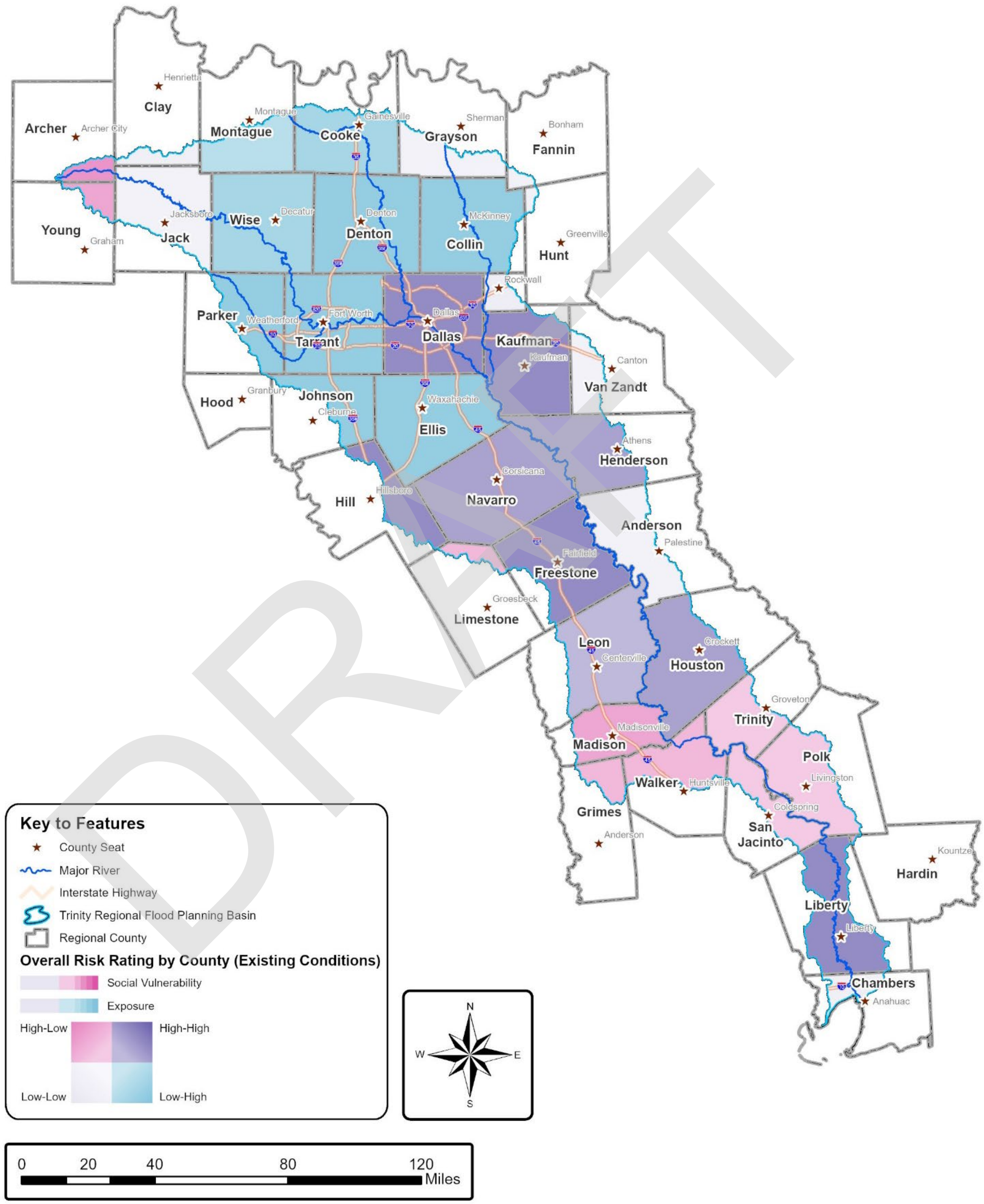
While the product of exposure and vulnerability paints a picture of risk in an area, weighing this against resilience helps to map an overall risk rating for a community. The bivariate map in ***Figure 2.26*** that shows exposure and vulnerability is weighted against the resiliency factors discussed previously in the Resiliency of Communities section. This results in trivariate choropleth map with varying color intensities to maps and display the overall ratings by county.

As shown in ***Figure 2.26***, with the addition of the third variable (resiliency), counties like Henderson, Houston, Leon, and Navarro counties are now in a slightly lower risk rating than Dallas, Freestone, Hill, Kaufman, and Liberty counties. In the previous ***Figure 2.25***, the counties all used to be in the same High Exposure and High vulnerability category (HH). A more detailed-level, larger map of the overall risk rating based on census tract levels for the Trinity Region is shown in ***Appendix B***. Higher intensity colors show higher risk levels within the same category. For example, Limestone, Polk, San Jacinto, and Trinity counties now show a lower risk rating than Archer, Hardin, Madison, and Young counties, even though they all fit in the High-Low category.

The existing flood risk, exposure, and vulnerability for the Trinity Basin are summarized in ***TWDB-Required Table 3***. The TWDB ***Table 3*** provides the results per county of the existing flood exposure and vulnerability analysis as outlined in the Technical Guidelines for Regional Flood Planning. This table is included in ***Appendix A***.

A geodatabase with applicable layers, as well as associated ***TWDB-Required Maps 1*** through ***22*** are provided in ***Appendix B*** as digital data. ***Table 2.1***, included in ***Appendix B***, outlines the geodatabase deliverables included in this Technical Memorandum, as well as spatial files and tables. These deliverables align with the TWDB's Exhibit D: Data Submittal Guidelines for Regional Flood Planning located on the web at www.twdb.texas.gov/flood/planning/planningdocu/2023/index.asp.

Figure 2.26: Overall Risk Rating by County to Existing Condition Floodplain Quilt



Task 2B – Future Condition Flood Risk Analyses

Future Condition Flood Hazard Analysis

The future flood risk assessment begins by estimating the increased extent of the future flood hazard. The future flood risk mapping extent is commonly determined under fully developed watershed conditions, which is the anticipated condition of the watershed after the watershed has undergone ultimate land use development. The determination of the general magnitude of potential increases in the Trinity Region's future 1-percent ACE and 0.2-percent ACE is based on a "do-nothing" or "no-action" scenario of approximately 30 years of continued development and population growth under current development trends and patterns, and existing flood regulations and policies.

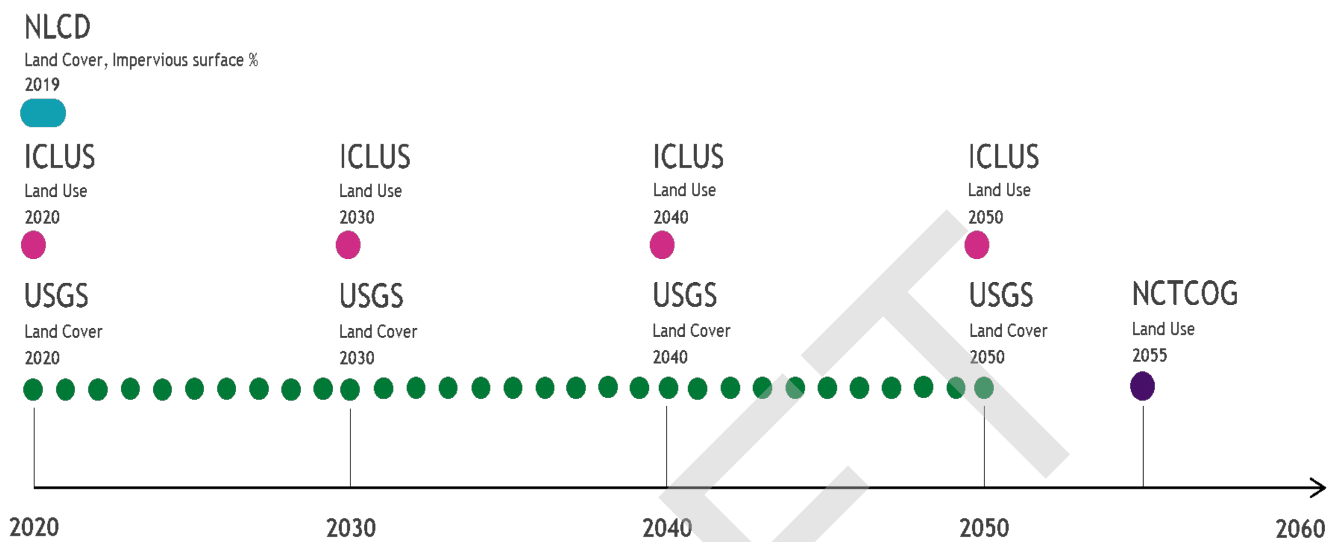
Future Conditions Based on "No Action" Scenario

Land Use and Development Trends

Land use and land cover (LULC) data provides a valuable method for determining the current and future extents of various land types in a floodplain. The LULC datasets are typically derived from the results of classifying satellite images. For the Trinity Region, the open-sourced datasets of current LULC conditions and future projections can be retrieved from the National Land Cover Dataset (NLCD), Environmental Protection Agency (EPA) Integrated Climate and Land Use Scenarios (ICLUS) land use projections, USGS conterminous United States land cover projections, and North Central Texas Council of Governments (NCTCOG) land use projection as shown in the ***Figure 2.27***.

The NLCD provides the latest LULC dataset (Year 2019) for the Trinity Region, which is considered as a credible data source with a 30-meter spatial resolution. The current LULC condition can also be estimated based on the projections from the ICLUS and USGS datasets for the year of 2020, which can be consistently compared with the respective projections for the year of 2050. The ICLUS dataset provides decadal land use projections (Years 2020, 2030, 2040, and 2050) at a 90-meter spatial resolution, while USGS provides annual land cover projections (every year from 2020 to 2050) at a 250-meter spatial resolution. The NCTCOG also provides a localized land use projection for North Central Texas for the year of 2055. The following sections will include detailed descriptions for each dataset and show how the datasets can be used to investigate future LULC changes in the Trinity Region.

Figure 2.27: Summary of the Current and Future Land Use and Land Cover Datasets



Future Land Use and Land Cover Conditions

Future land use conditions are available from three LULC datasets:

- EPA ICLUS land use projections
- USGS conterminous United States land cover projections
- NCTCOG land use projection

The ICLUS is based on the EPA demographic and spatial allocation models to produce land use changes according to different scenarios. The dataset includes land use classifications of the contiguous United States at a spatial resolution of 90 meters. A demographic model generates population estimates that are distributed by a spatial allocation model (SERGoM v3) (Bierwagen, Theobald, Pyke, & Morefield, 2010) into housing density (HD) across the landscape. In the initial version (1), land-use outputs were developed for the four main Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) (A1, A2, B1, and B2) and a baseline. The land use outputs are available for each scenario by decade from 2010 to 2100.

Two of the new Shared Socioeconomic Pathways (SSPs) (SSP2 and SSP5) and two Representative Concentration Pathways (RCPs) (RCP 4.5 and RCP 8.5) were added in the recent version 2. (U.S. Environmental Protection Agency, 2016). The details of the selected pathways are shown below:

- SSP2 is a "middle-of-the-road" projection, where social, economic, and technological trends do not shift markedly from historical patterns, resulting in a United States population of 455 million people by 2100. Domestic migration trends remain largely consistent with the recent past.
- SSP5 describes a rapidly growing and flourishing global economy that remains heavily dependent on fossil fuels, and a United States population that exceeds 730 million by 2100. ICLUS v2.1 land use projections under SSP5 result in a considerably larger expansion of developed lands relative to SSP2.
- RCP4.5 assumes that global greenhouse gas emissions increase into the latter part of the century, before leveling off and eventually stabilizing by 2100 because of various climate change policies.
- RCP8.5 assumes that global greenhouse gas emissions increase through the year 2100.

Figure 2.28 and ***Figure 2.29*** illustrate the land use conditions of the Trinity Region based on the ICLUS dataset of the years of 2020 and 2050.

Another LULC projection dataset for the contiguous United States is produced by USGS. The year 1992 was used by USGS as the baseline for the landscape modeling while other datasets such as NLCD, USGS Land Cover Trends, and USDA's Census of Agriculture were used to guide the recreation of historical land cover information for the 1992 to 2005 period. The forecasting scenarios of land use (FORE-SCE) model were used to produce landscape projections for the 2006 to 2100 period as future projection. The FORE-SCE model also considers four IPCC SRES scenarios (A1/A1B, A2, B1, and B2) corresponding to the four storylines (Shukla, et al., 2019). The details of each storyline are shown below:

- The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. As one of A1 scenario family, A1B is selected in the USGS land cover model to represent balanced use across fossil and non-fossil energy sources.
- The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.

Figure 2.28: Integrated Climate and Land Use Scenarios Land Use Projections of 2020

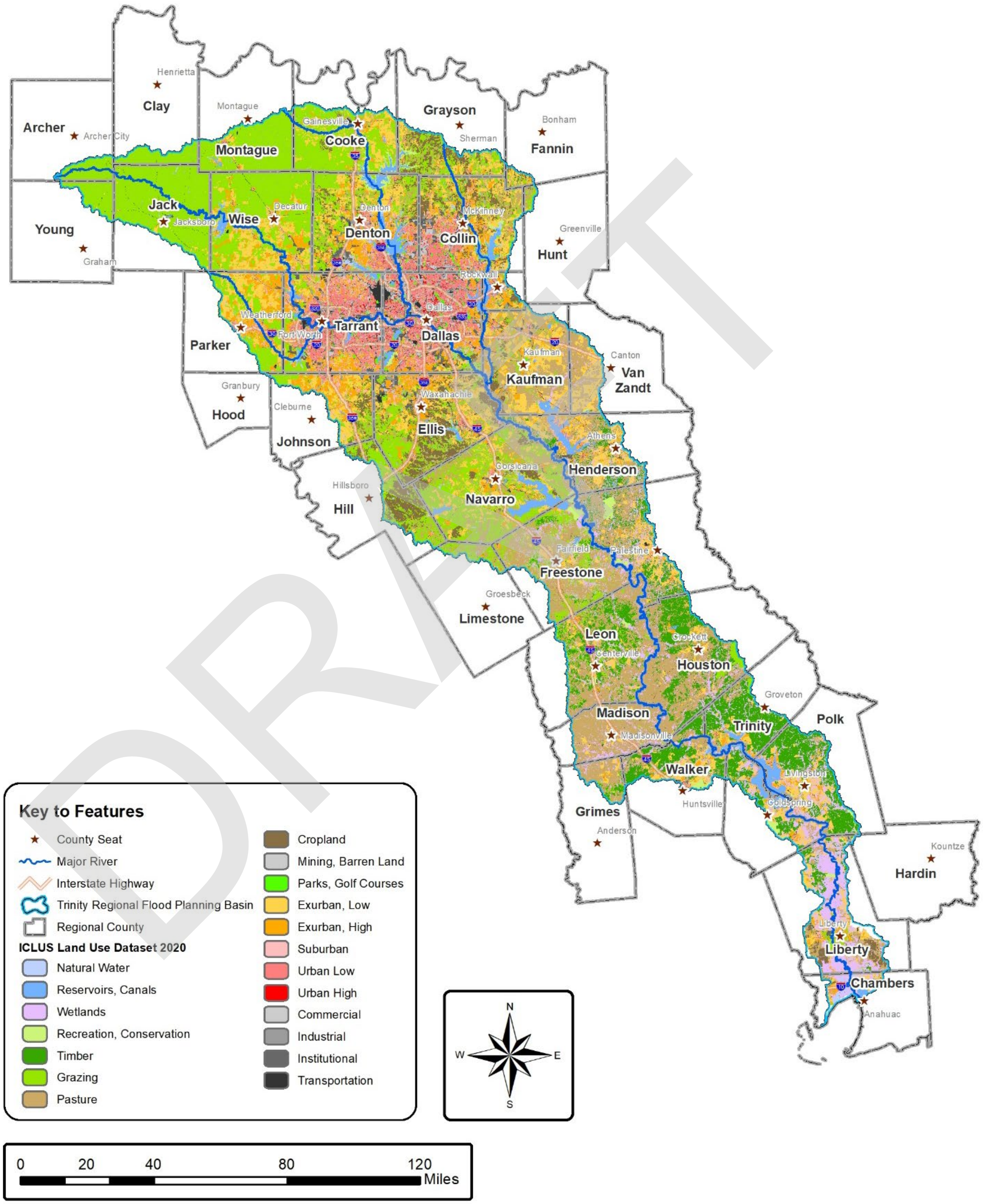
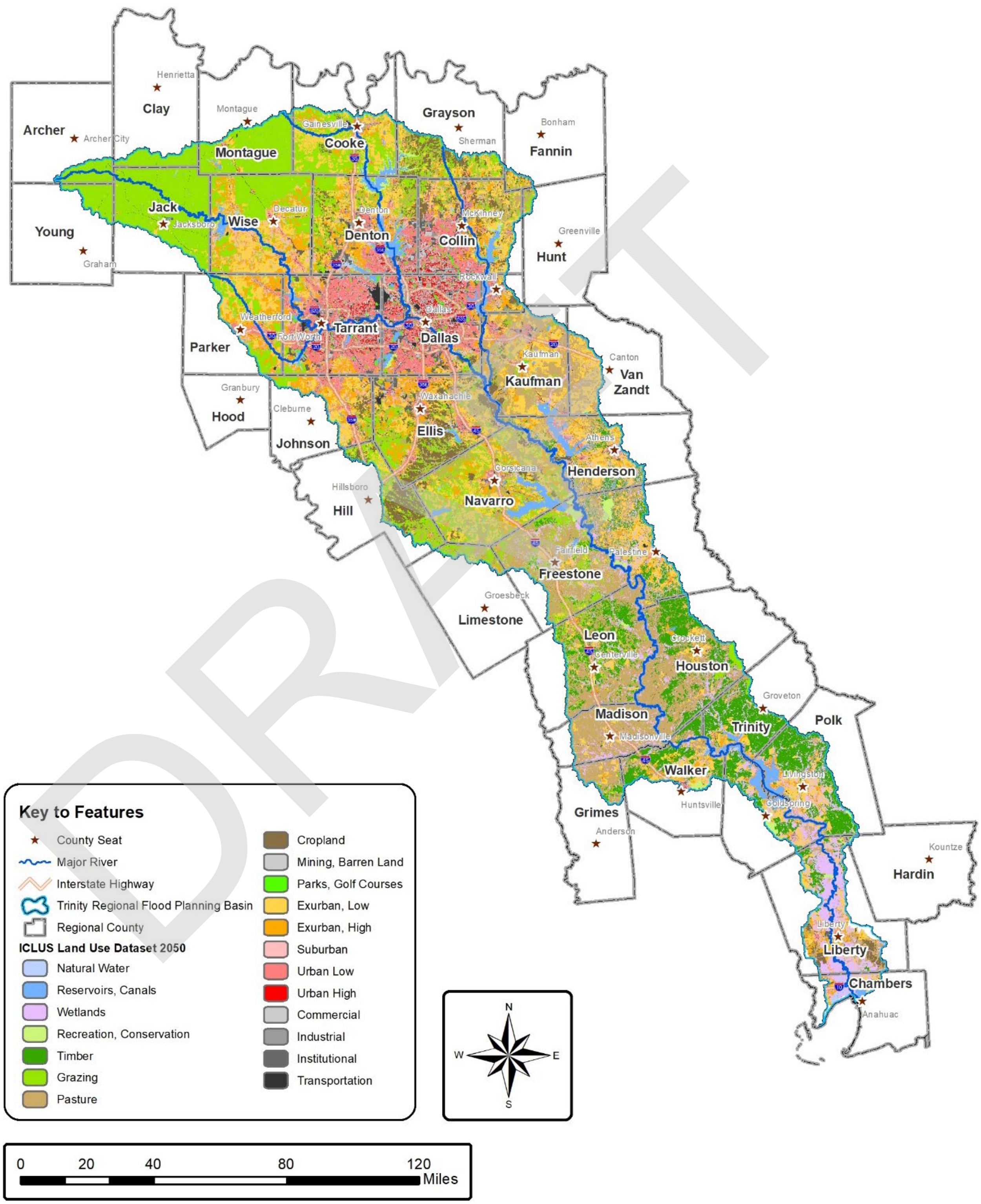


Figure 2.29: Integrated Climate and Land Use Scenarios Land Use Projections of 2050



- The B1 storyline and scenario family describes a convergent world with the same global population that peaks in midcentury and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.
- The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

This USGS LULC projection dataset has been used for a wide variety of studies, including topics of regional weather and climate, landscape change on biodiversity, and water quality (Sohl, 2018). ***Figure 2.30*** and ***Figure 2.31*** illustrate the land cover conditions of Trinity Region from the USGS dataset of the years of 2020 and 2050.

From both the LULC projections from ICLUS and USGS datasets, rapid land development is found to occur in the Upper Subregion from 2020 to 2050, indicated by increased coverage of the “Suburban”, “Urban Low” and “Urban High” (***Figure 2.30***) and “Developed” (***Figure 2.31***) areas in the DFW metroplex and its suburbs. Rapid land use changes will increase the flood risks for the communities in this region if no proactive flood planning and mitigation measures are taken. On the contrary, areas in the Trinity Region don’t show significant changes in the future land use. The comparative analysis between the LULC data suggests that further studies (e.g., hydrologic/hydraulic analyses) should be conducted to provide more detailed information related to impacts from changes of LULC.

For the Upper Subregion, the NCTCOG collects the future land use planning data from individual cities (e.g., Plano, Dallas, Arlington, etc.) and integrates it into a regional future land use planning dataset (as shown by the land use conditions of 2055 in ***Figure 2.32***). This dataset provides a future land use condition scenario for the Upper Subregion and will be compared with the datasets from ICLUS and USGS for future flood risk analyses. In summary, the current and future projection of land cover and land use datasets suggest that the upper basin will experience rapid urban development with significant land use changes. It is highly recommended for stakeholders to consider land use planning and projections in the future flood mitigation and planning to help communities mitigate their current and future vulnerability to floods.

Figure 2.30: United States Geological Survey 2020 Land Cover Projection

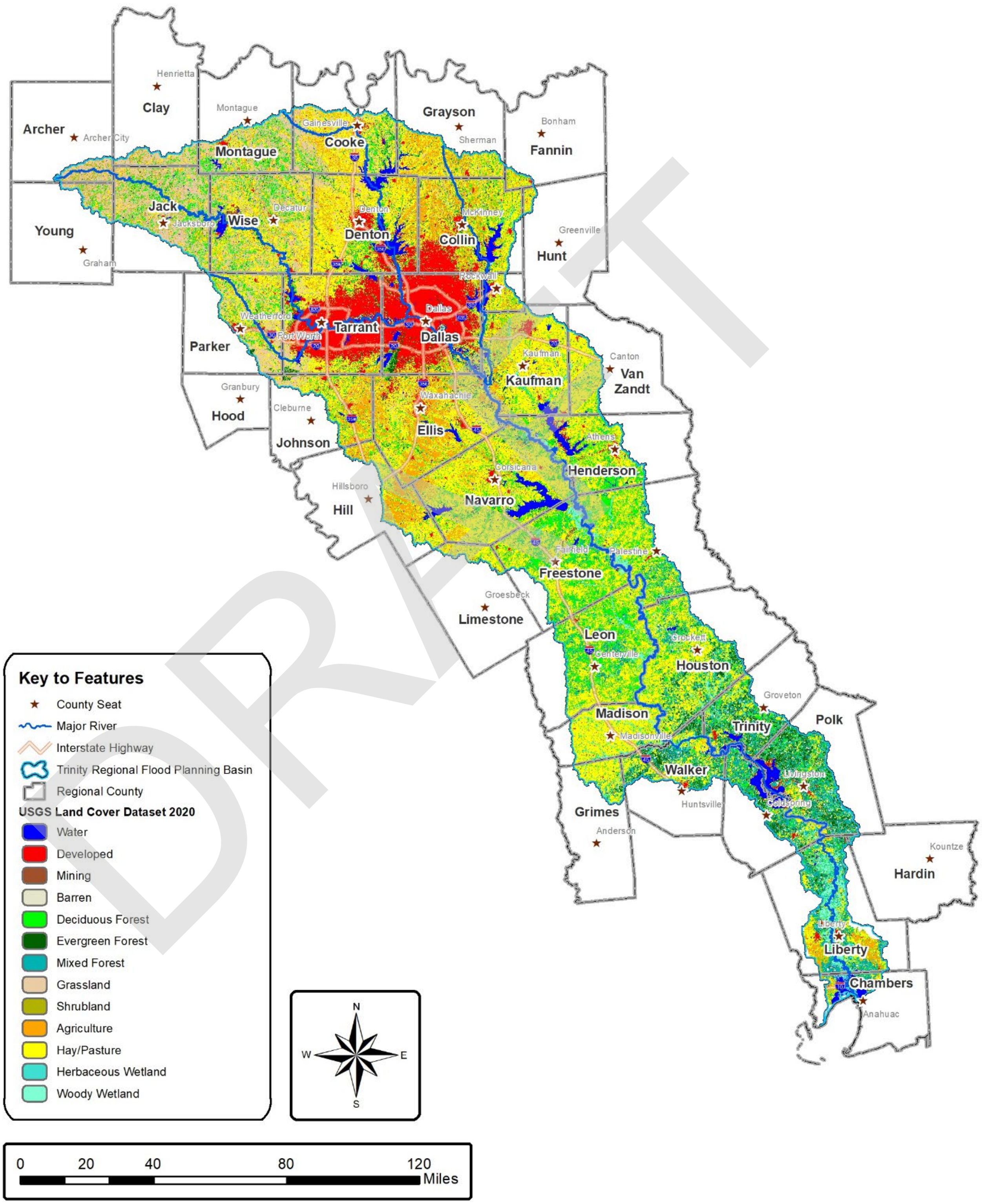


Figure 2.31: United States Geological Survey 2050 Land Cover Projection

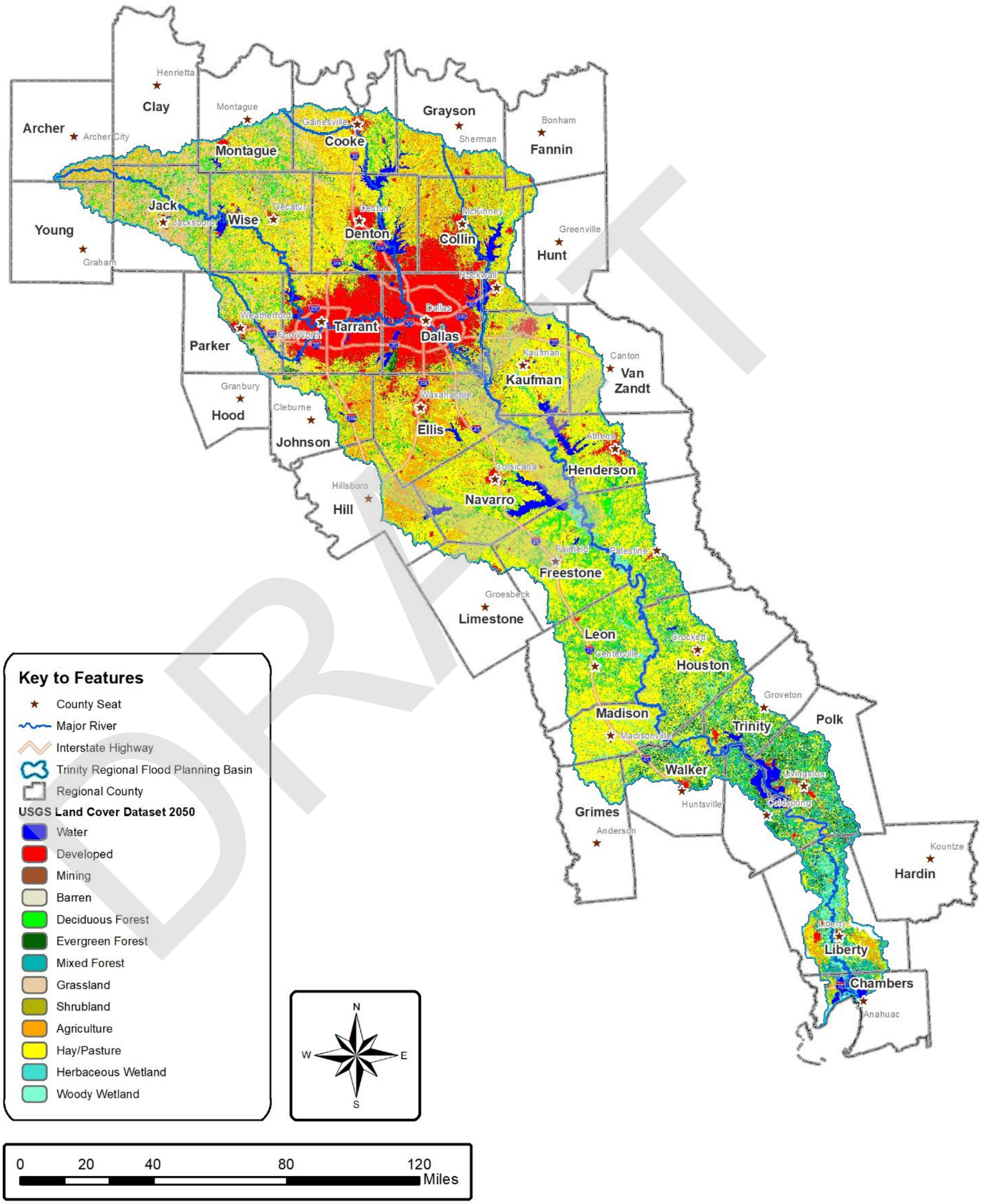
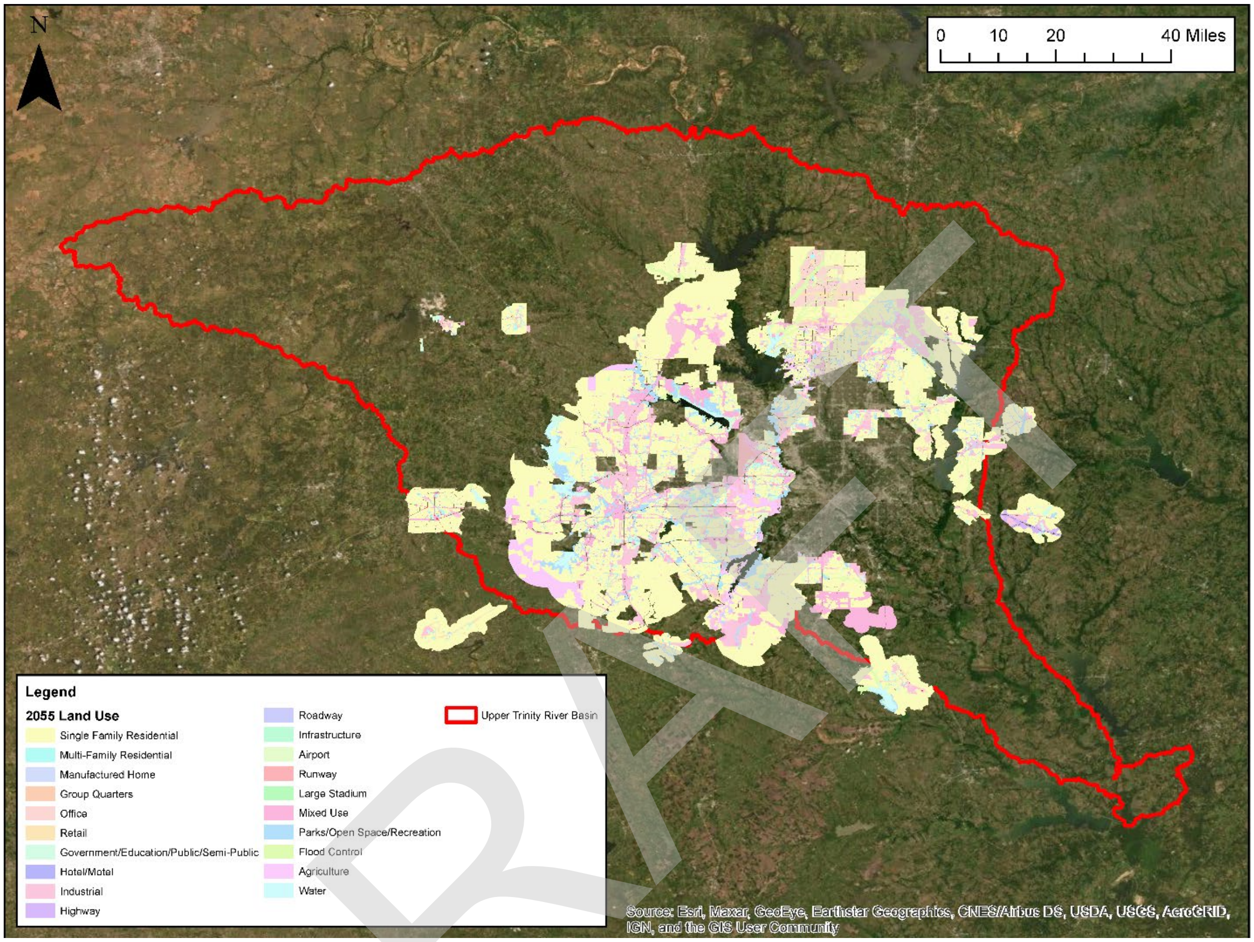


Figure 2.32: North Central Texas Council of Governments Land Use Projection in 2055



It is noted that the future land use and development trends discussed in the section were not used in determining future flood risk for this first regional flood plan due to uncertainties in the model projections and lack of local information. Further investigation is needed to evaluate the impact of LULC change in great details during future cycles of planning.

Population Growth

According to World Bank, 2.2 billion people, or around 29 percent of the world population, live in the areas that experience various levels of inundation during 100-year flood event (Rentschler & Salhab, 2020). FEMA estimates that 13 million Americans live within a 100-year flood zone. Recent research argues that the real number is about 41 million (Wing, et al., 2018). On one hand, the future flood conditions will significantly affect the people exposed to flood risks, leading to higher flood vulnerability over the areas with rapid population growth in the United States (Swain, et al., 2020).

On the other hand, the population dynamics, which show how and why populations change in structure and size over time, also has important interrelationships with the changes of land cover and land use, as well as water demands for all uses (National Academies of Science, Engineering, and Medicine, 1994). Rapid population growth results in expansion of urban and industrial lands, and depletion of wetlands, floodplains, and waterbodies, which can potentially impact the flood dynamics (Rahman, Tharzhiansyah, Rizky, & Vita, 2021). Identifying future growth, composition, and distribution of a population is crucial for flood planning.

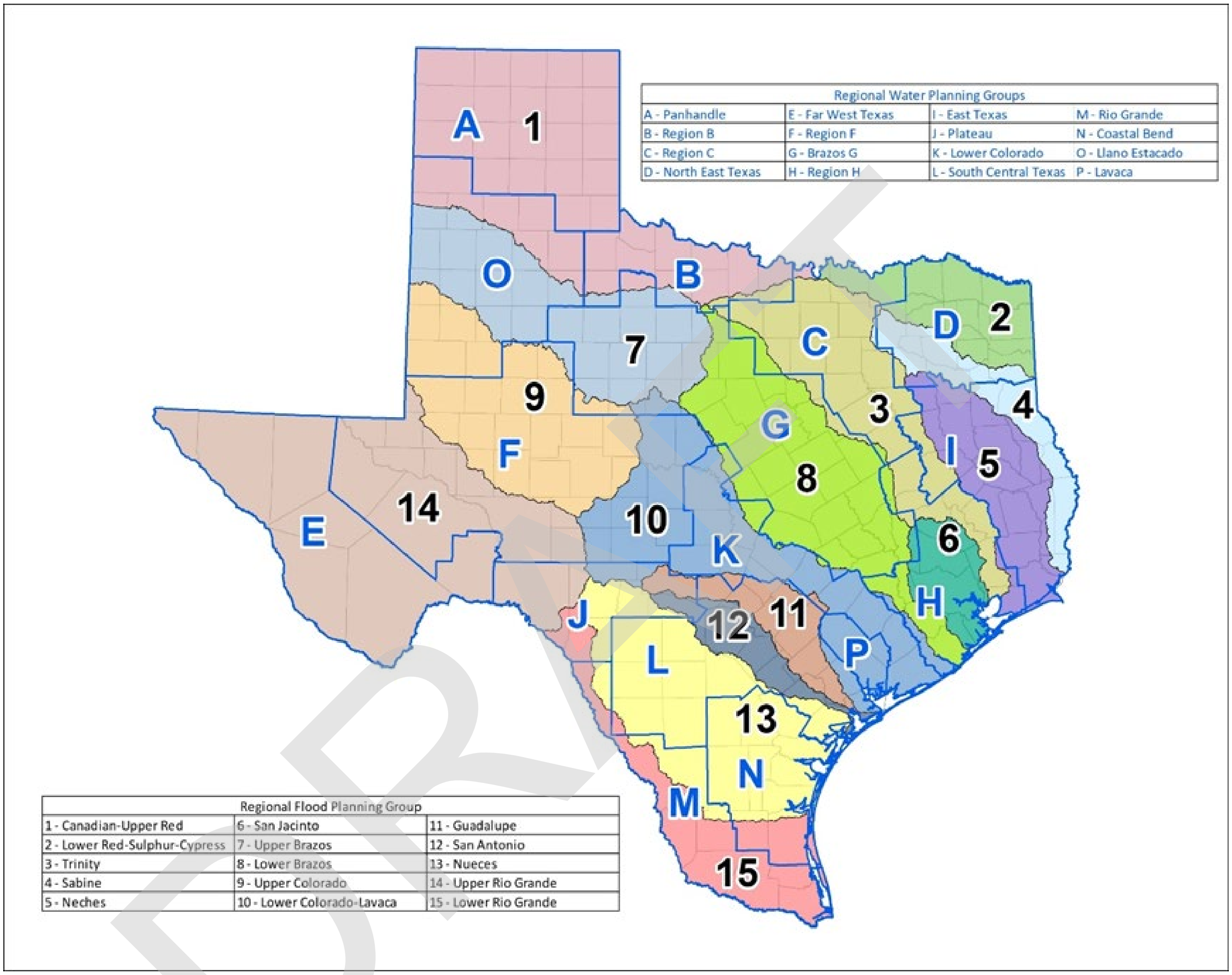
The population in Texas is expected to increase 42 percent between 2020 and 2050, from 29.7 million to 42.3 million people (Texas Water Development Board, 2021). The projection was made based on a standard demographic methodology known as a cohort-component model, which uses different cohorts (combinations of age, gender, and racial-ethnic groups) and components of cohort change (birth, survival, and migration rates) to estimate future population in a county level. The Texas State Data Center provided the TWDB with the initial 30-year population projections for each county. The TWDB then extended these 30-year projections to the state water plan's 50-year planning horizon. In the State Water Plan, the state is divided into 16 RFPGs (***Figure 2.33***). Rapid population growth (over 35 percent) between 2020 and 2050 is expected to occur within Regions C (which includes the Dallas-Fort Worth metropolitan area) and H (which includes the Houston metropolitan area) as shown in ***Table 2.18***. It is noted that the majority of Region C and portions of Region H are contained in the Trinity Region (***Figure 2.33***).

Table 2.18: Decadal Population Growth for Regions C and H Water Planning Areas from 2020 to 2050

Region	2020	2030	2040	2050	Percent Growth from 2020 to 2050
C	7,504,000	8,649,000	9,909,000	11,260,000	50%
H	7,325,000	8,208,000	9,025,000	9,868,000	35%

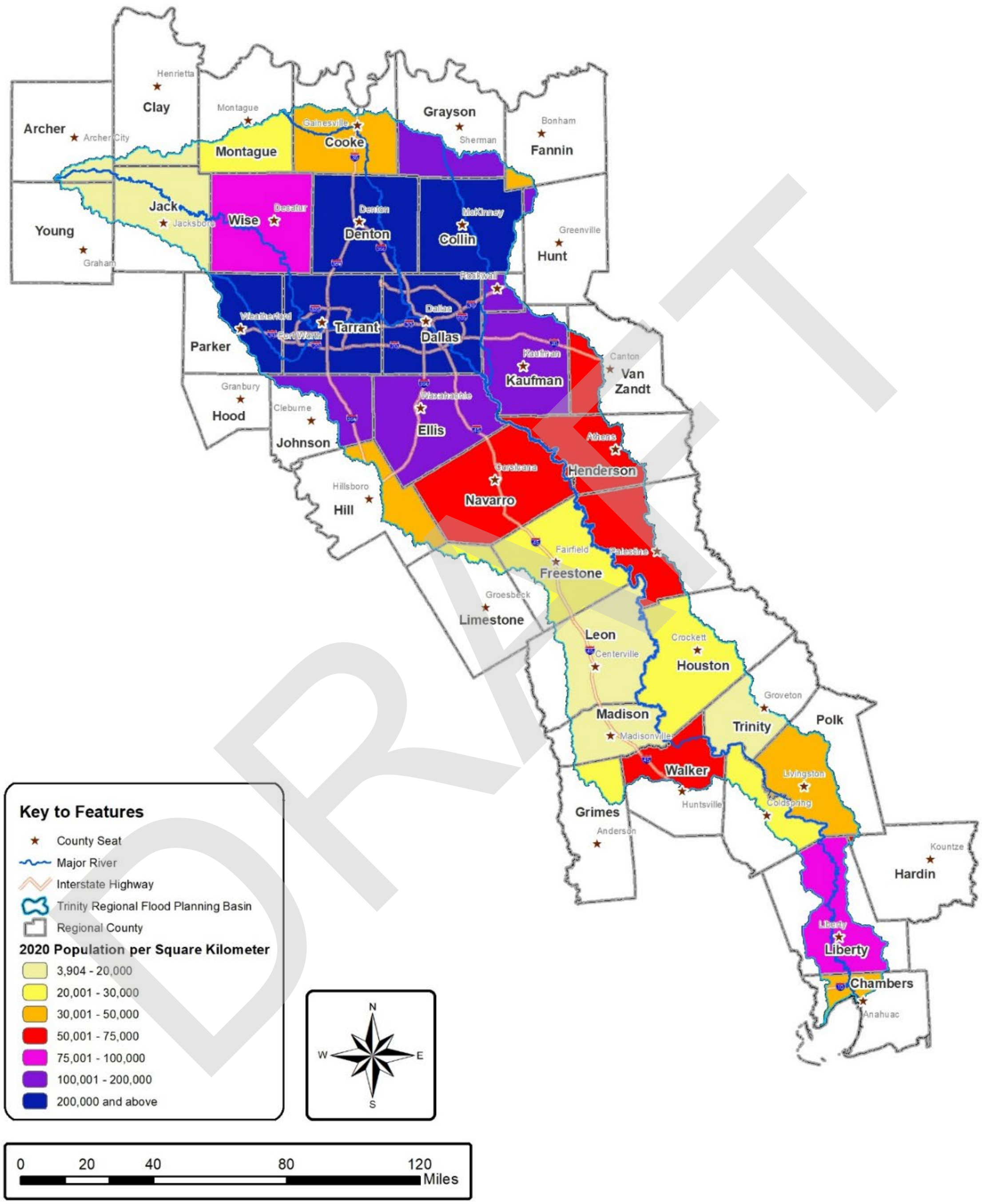
The population of the Trinity Region is estimated to be 7,853,969 by 2019 (Texas Water Development Board, 2021), where higher population density is presented in the Trinity Region's upper reaches (***Figure 2.34***). As an example, the projected population for each county in Region C and Region H in the Trinity Region is listed in ***Table 2.18***. Kaufman County and Rockwall County are projected to more than double their current population by 2050 as shown in ***Table 2.19***. The counties with over one million population, such as Collin, Dallas, and Tarrant counties, will also have rapid growth (over 30 percent) by 2050. Not only will the population growth demand for significant higher water supply, but also will change regional land cover and land use conditions that could alter the floodplain and increase flood risks in these areas.

Figure 2.33: Texas Water Development Board Regional Water Planning Areas and the Trinity Region



Source: TWDB, 2016

Figure 2.34: Population Density of the Trinity River in 2020



Source: TWDB County Population Projections in Texas: 2020-2070 population projections by county (Texas Water Development Board, 2021)

Table 2.19: Decadal Population Growth for all the Counties in the Region C and Region H Water Planning Areas from 2020 to 2050

Region	County	2020	2030	2040	2050	Percent Growth (from 2020 to 2050)
C	Collin	1,050,506	1,239,303	1,497,921	1,807,279	72%
C	Cooke	40,903	44,035	46,984	52,427	28%
C	Dallas	2,587,960	2,871,662	3,180,529	3,429,783	33%
C	Denton	891,063	1,115,119	1,329,551	1,584,015	78%
C	Ellis	191,638	241,778	280,745	360,584	88%
C	Fannin	38,330	43,084	52,891	69,328	81%
C	Freestone	20,437	21,077	22,947	31,142	52%
C	Grayson	135,311	149,527	159,610	178,907	32%
C	Henderson	67,579	72,592	78,504	85,901	27%
C	Jack	9,751	10,409	10,817	11,033	13%
C	Kaufman	146,389	195,107	242,354	306,833	110%
C	Navarro	52,505	59,556	65,958	74,213	41%
C	Parker	201,491	260,194	276,979	360,125	79%
C	Rockwall	119,410	160,315	213,619	246,938	107%
C	Tarrant	2,004,609	2,279,113	2,580,325	2,799,127	40%
C	Wise	79,882	95,086	110,343	135,797	70%
H	Chambers	42,162	50,543	59,210	68,541	63%
H	Leon	18,211	19,536	20,603	22,071	21%
H	Liberty	86,303	97,227	107,618	118,048	37%
H	Madison	14,753	15,817	16,786	17,872	21%
H	Polk	42,911	47,935	51,888	55,259	29%
H	San Jacinto	29,610	32,627	34,996	37,614	27%
H	Trinity	12,754	13,793	13,897	13,504	6%
H	Walker	71,800	75,243	77,724	80,050	11%

Note: Regions C and H cover most area in the Trinity Region; and they are the most populated water planning regions in Texas

Consequently, an integrated assessment of linkage between population dynamics and future flood planning is highly recommended for the Trinity Region.

Sea Level Change

Global mean sea level (MSL) has risen by about 0.2 meters (or eight inches) at a rate of 1.7 millimeters per year since reliable record keeping began in 1880 (Church & White, A 20th Century Acceleration in Global Sea-Level Rise, 2006). Research shows that rising sea levels can affect coastal regions in many ways including shoreline erosion, loss of land, tidal flooding, and saltwater intrusion into groundwater (Anthoff, Nicholls, Tol, & Vafeidis, 2006), (Nicholls & Tol, Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century, 2006), (Nicholls & Cazenave, Sea-Level Rise and Its Impact on Coastal Zones, 2010), (Church & White, Sea-Level Rise from the Late 19th to the Early 21st Century, 2011). The contributions to sea level rise come primarily from two factors related to global warming — increases in water mass from melting ice and glaciers, and thermal expansion of seawater (Church & White, A 20th Century Acceleration in Global Sea-Level Rise, 2006) (Nicholls & Cazenave, Sea-Level Rise and Its Impact on Coastal Zones, 2010) (Church & White, Sea-Level Rise from the Late 19th to the Early 21st Century, 2011).

The rapid changes observed in polar regions suggest that the ice sheets melt faster than previously anticipated due to global warming (Masson-Delmotte, et al., 2021) , and many studies show that the sea level is projected to rise another 0.3 to 1.8 meters (one to four feet) by 2100 as global warming continues (Rahmstorf, 2007), (Vermeer & Rahmstorf, 2009), (Jevrejeva, Moore, & Grinsted, 2010), (Nicholls & Cazenave, Sea-Level Rise and Its Impact on Coastal Zones, 2010), (Walsh, et al., 2014). Climate-induced sea level rise will affect a large fraction of the cities located along the coastline by the end of the 21st century (Church, et al., 2013). Meanwhile, high-tide flooding is increasingly common due to years of sea level increases. High tide flooding occurs when tides reach anywhere from 0.53 to 0.61 meters (1.75 to two feet) above the daily average high tide, and inundate low-lying streets (National Oceanic and Atmospheric Administration, 2021). Being one of the largest coastal communities in the world, the Houston-Galveston region is highly susceptible to coastal and inland flooding from hurricanes (storm surge and rainfall), high tides, and other extreme storms. Because the Trinity River drains into Galveston Bay, the change of sea level inevitably affects the riverine hydraulics and ecology of the watershed. Thus, the sea level rise near the outlet of the Trinity River must be evaluated by analyzing the MSL measured at tide gauges to help us understand sea level trends and potential hydrodynamic changes to the Trinity River.

Because sea level rise varies around the globe, relative sea level measured locally provides more insights to engineering practices in coastal resilience and flood mitigation for the study area. Five NOAA tide gauges located along the Gulf Coast and near the Trinity River outlet were identified to provide water elevation records: Sabine Pass (8770570), Galveston Pier 21 (8771450), Galveston Pleasure Pier (8771510), Freeport (8772440), and Freeport (8772447) (***Figure 2.35***). All five gauges have monthly data have more than 50 years of records available from NOAA (2013a); in particular, the Galveston Pier 21 gauge has the longest time series, data ranging from January of 1904 to April of 2021. ***Table 2.20*** summarizes location and period of record for each gauge. Available tidal records are referenced to MSL vertical datum.

Figure 2.35: Locations of the Five Selected National Oceanic and Atmospheric Administration Tide Gauges

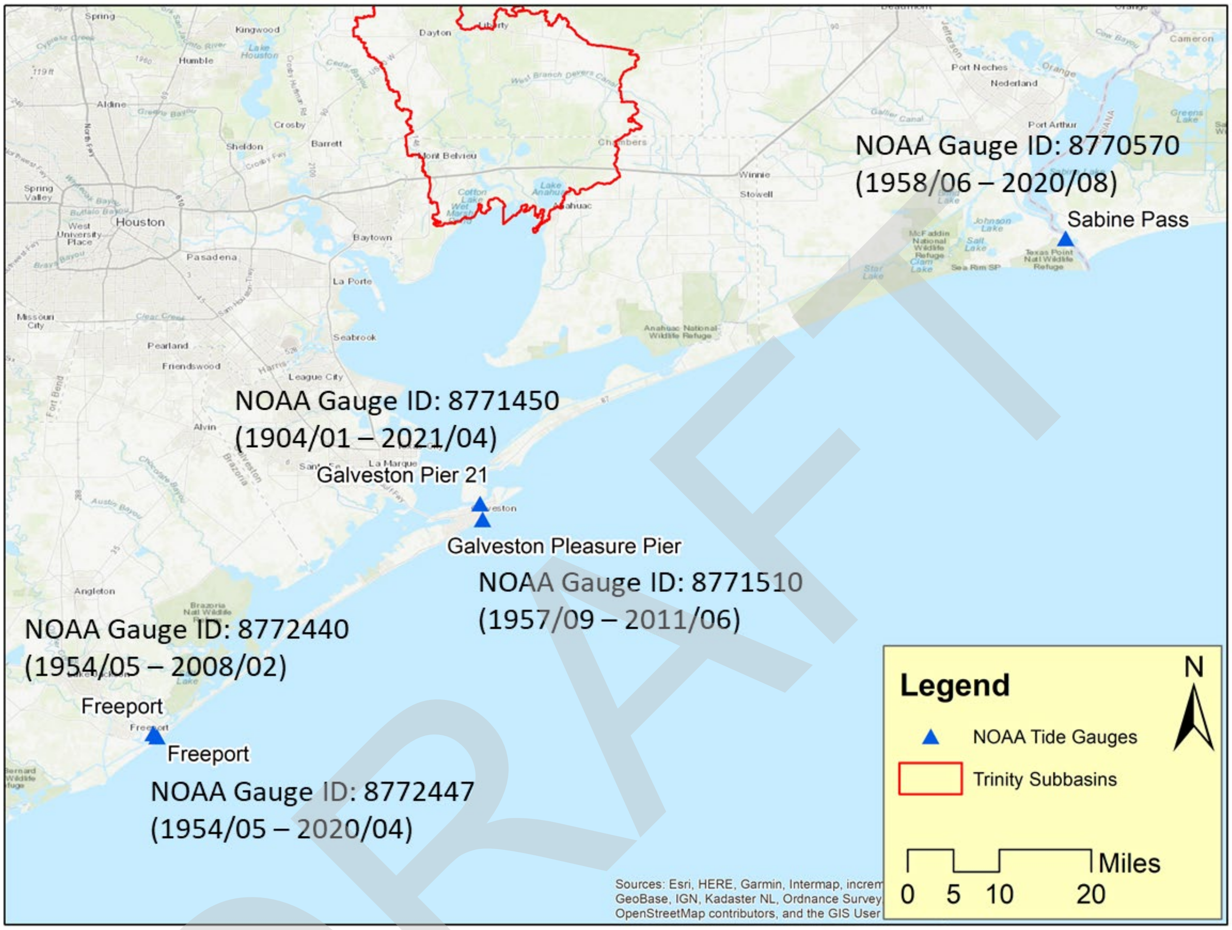


Table 2.20: Tide Gauges Along the Gulf Coast

Gauge ID	Gauge Name	Latitude & Longitude Coordinates	Data Availability Period
8770570	Sabine Pass	29.7284, -93.8701	1958/06 – 2020/08
8771450	Galveston Pier 21	29.3100, -94.7933	1904/01 – 2021/04
8771510	Galveston Pleasure Pier	29.2853, -94.7894	1957/09 – 2011/06
8772440	Freeport	28.9483, -95.3083	1954/05 – 2008/02
8772447	Freeport	28.9433, -95.3025	1954/05 – 2020/04

To examine the trend of MSL along the Galveston Gulf Coast, historical data from the five selected tide gauges is plotted together with a fitted regression line as shown in ***Figure 2.36***. All five gauges show a similar rise in MSL trend between 1980 and 2021. The slope (0.0068) of the regression equation implies the rate (6.8 millimeter per year) of the relative sea level rise for these five locations. As previously noted, the Galveston Pier 21 gauge has the longest time series data and is located closest to the outlet of the Trinity River Estuary. Linear regression is used to simply demonstrate an average change rate of the sea level to date based on available data. The linear trendline of the Galveston Pier 21 gauge is similar to the other four nearby tide gauges, as shown in ***Figure 2.37***.

The trend analysis shows that the MSL at the Galveston Pier 21 gauge has risen 0.167 meter (0.547 feet) between 1904 and 2021. If the trend continues at the current rate (6.6 millimeters per year), the MSL at the Galveston Pier 21 gauge in 2050 will result in an additional MSL increase of 0.19 meter (0.627 feet), or a total increase of 0.358 meter (1.175 feet) since 1904.

Figure 2.36: Plot of the Mean Sea Level at the Five Tide Gauges

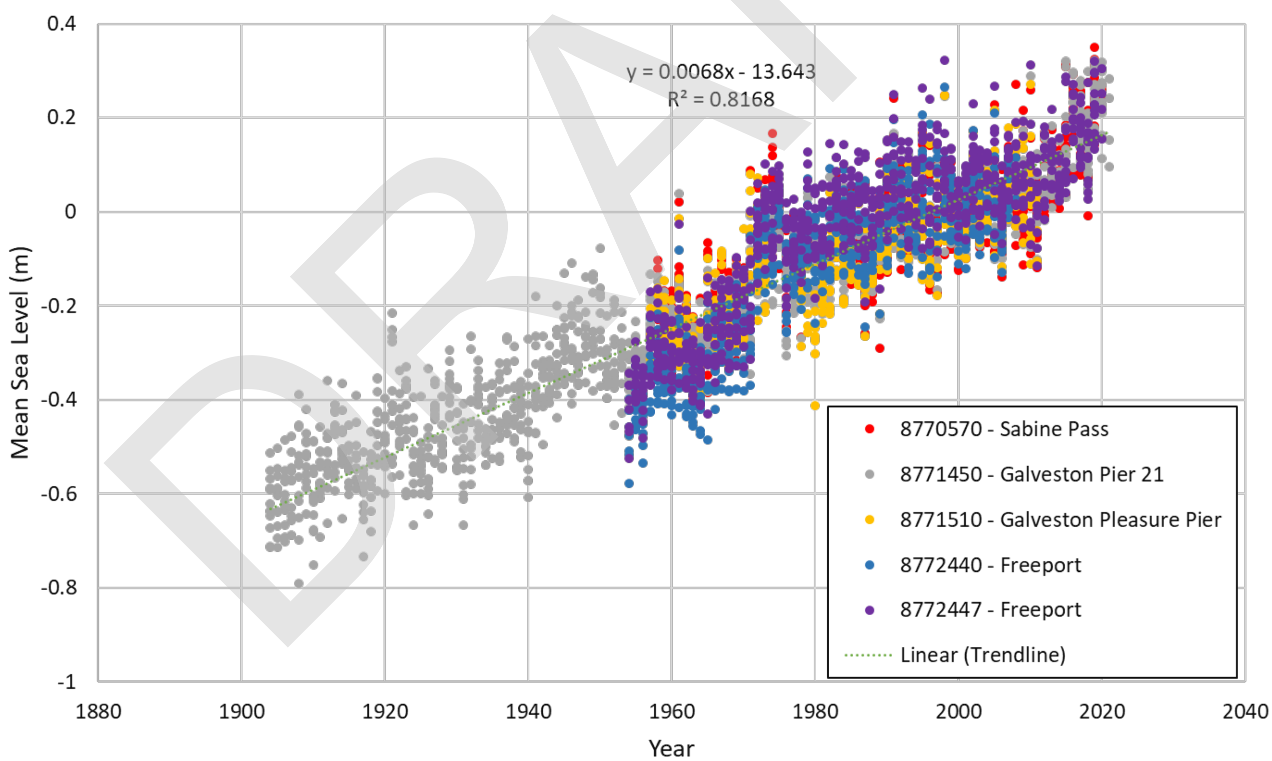
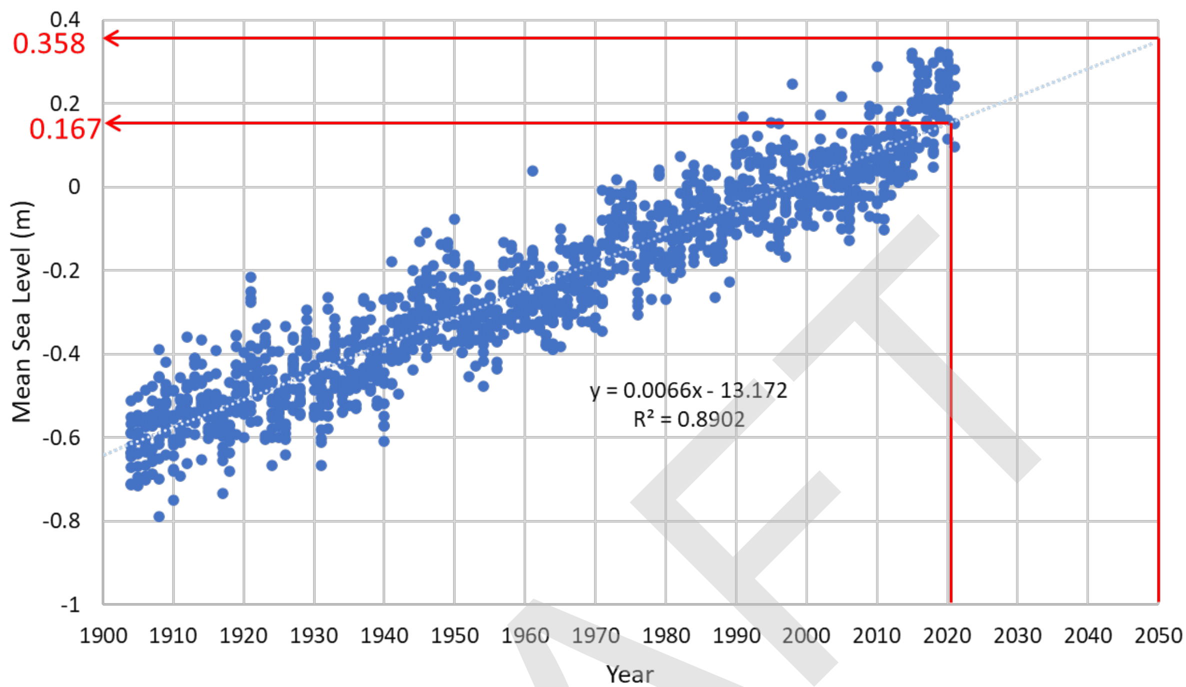


Figure 2.37: Plot of the Mean Sea Level at Gauge Galveston Pier 21 (8771510)



To account for the uncertainty from the expected ice melting volume and ocean temperatures, researchers and engineers from the NOAA and USACE have made predictions based on ranges from low to high (Huber & White, 2017). The governing equations for calculating the sea level change are shown below:

Global Sea Level Change: $E(t) = 0.0017t + bt^2$

In the above equation, *t* refers to the number of years starting in 1992 (NOAA considers 1992 as the center year of the NOAA National Tidal Datum Epoch (NTDE) ranging from 1983–2001), 0.0017 is the global sea level rise rate (1.7 millimeters per year) and *b* is a constant parameter.

Relative (Regional) Sea Level Change: $E(t) = Mt + bt^2$

In the above equation, *M* is the combination of the global sea level rise rate (1.7 millimeters per year) plus the local Vertical Land Movement (VLM). *M* can be obtained from NOAA's Sea Level trends website (National Oceanic and Atmospheric Administration, 2022) and NOAA Technical Report NOS CO-OPS 65 (Zervas, Gill, & Sweet, 2013).

To visualize different sea level scenarios for any NOAA tide gauge, the data from an online Sea Level Change Curve Calculator (U.S. Army Corps of Engineers, 2022) can be used. This online tool was developed under the USACE Comprehensive Evaluation of Projects with respect to Sea Level Change in support of vulnerability assessments for USACE coastal projects. The USACE Sea Level Change Curve Calculator includes the datasets from four studies, namely: the NOAA

Technical Report OAR CPO-1 titled Global Sea Level Rise Scenarios for the United States National Climate Assessment (Parris, et al., 2012), the USACE Incorporating Sea Level Changes in Civil Works Programs (Department of the Army, 2013), the Region Sea Level Scenarios for Coastal Risk Management Report by the Coastal Assessment Regional Scenario Working (Hall, et al., 2016), and the United States Global Change Research Program 2017 (Wuebbles, et al., 2017). Different parameters of *b* were utilized to represent different sea level scenarios among the four studies.

Figures 2.38 through ***2.41*** show the ranges of estimated relative sea level change at the Galveston Pier 21 gauge from (Parris, et al., 2012), (Huber & White, 2017), (Department of the Army, 2013), and (Hall, et al., 2016) for the period of 1992–2050 (Note: (Huber & White, 2017) only shows a ranger from 2000 to 2050). As summarized in ***Table 2.21***, three studies unanimously show the lowest projected sea level is approximately 0.37 meter (1.214 feet) by 2050 (Parris, et al., 2012), (Department of the Army, 2013), (Hall, et al., 2016), and their results are consistent with the historical records by assuming that the sea level rises at the current rate of 6.6 millimeters per year. In other words, the lowest sea level rise scenarios conducted by (Parris, et al., 2012), (Department of the Army, 2013), (Hall, et al., 2016), all produce a rate (6.3 millimeters per year) similar to the average rise rate (6.6 millimeters per year) from 1904 to 2021 at Galveston Pier 21.

Figure 2.38: Estimated Relative Sea Level Change Projections – Gauge: 8771450, Galveston Pier 21, TX (Parris, et al., 2012)

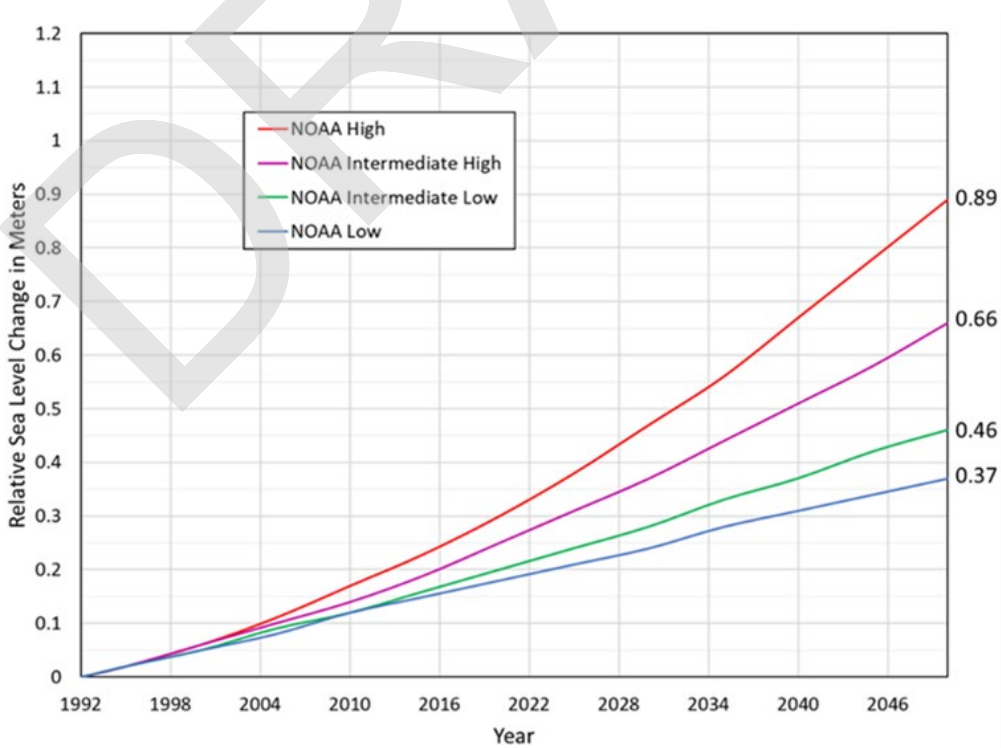


Figure 2.39: Estimated Relative Sea Level Change Projections – Gauge: 8771450, Galveston Pier 21, TX (Department of the Army, 2013)

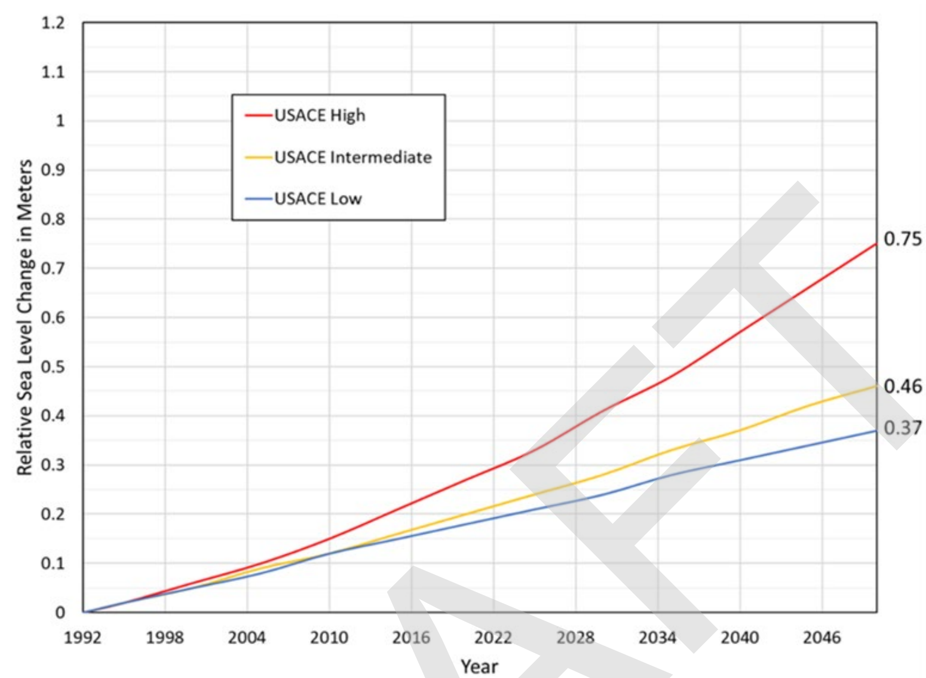


Figure 2.40: Estimated Relative Sea Level Change Projections – Gauge: 8771450, Galveston Pier 21, TX (Hall, et al., 2016)

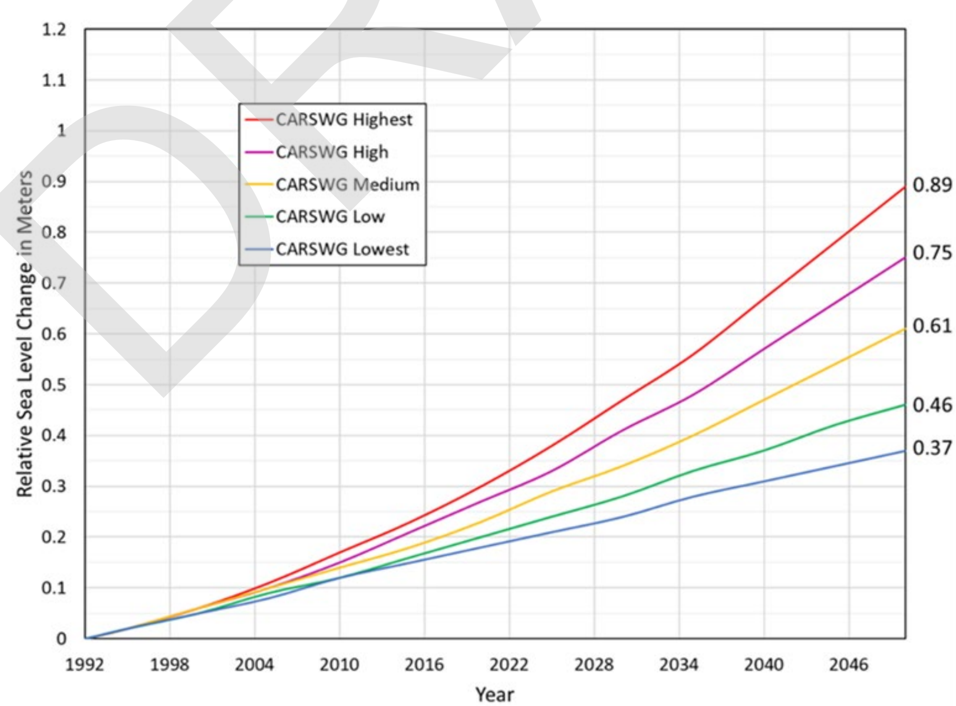


Figure 2.41: Estimated Relative Sea Level Change Projections - Gauge: 8771450, Galveston Pier 21, TX (Huber & White, 2017)

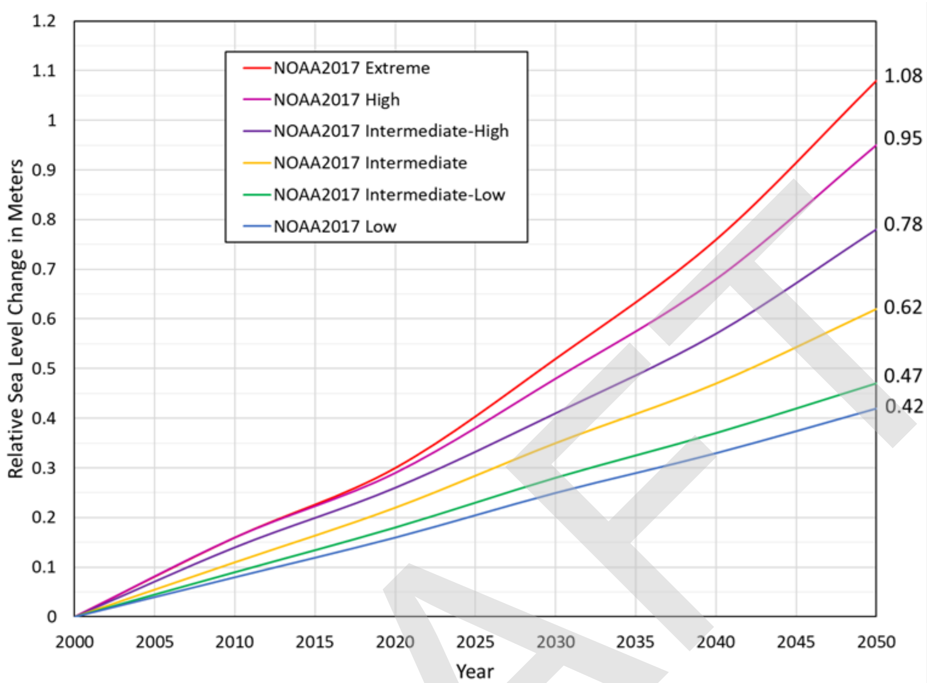


Table 2.21: Estimated Relative Sea Level in Meters for 2020 and 2050 from Various Studies

Study	2020		2050		Delta (Δ) Between 2020 and 2050	
	Lowest (m)	Highest (m)	Lowest (m)	Highest (m)	Lowest (Δ)	Highest (Δ)
NOAA 2012	0.18	0.3	0.37	0.89	0.19	0.59
USACE 2013	0.18	0.27	0.37	0.75	0.19	0.48
CARSWG 2016	0.18	0.3	0.37	0.89	0.19	0.59
NOAA 2017*	0.16	0.3	0.42	1.08	0.26	0.78

**Note:* (Huber & White, 2017) *projects relative sea level changes from 2000 and other three studies* (Parris, et al., 2012)*;* (Department of the Army, 2013)*; and* (Hall, et al., 2016) *project relative sea level changes from 1992.*

The NOAA 2017's extreme scenario forecasts a sea level rise of 1.11 meter (3.642 feet) in 2050. Under the extreme scenario, an increase of 0.78 meter (2.560 feet) sea level would be expected to occur from 2020 to 2050. The delta values of the estimated sea levels between 2020 to 2050 (***Table 2.21***) from various scenarios indicate that the estimated sea level in 2050 range from 0.19 meter to 0.78 meter.

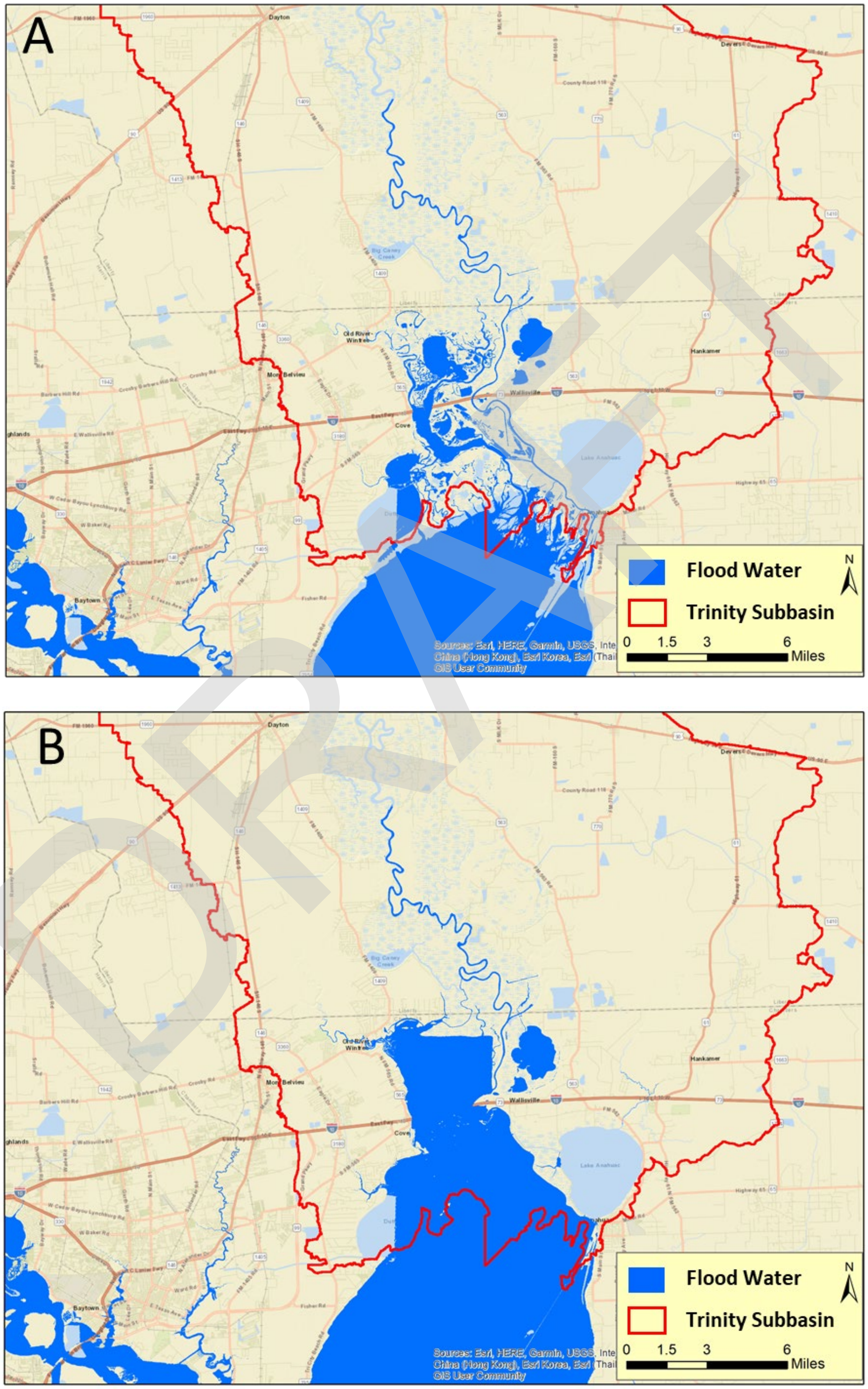
Dr. Nick Fang at the University of Texas at Arlington performed a GIS exercise applying increase of sea level from both low and high scenarios to the study area, as a demonstration of the potential land that would be inundated. ***Figure 2.42*** shows the flooded area (blue) in the Trinity Region caused by a rise of 0.19 meter (Lowest Scenarios from (Parris, et al., 2012), (Department of the Army, 2013), and (Hall, et al., 2016) studies) and 0.78 meter (Highest Scenario from (Huber & White, 2017)) respectively by 2050. While the additional area inundated by sea level rise is limited to the outlet of the Trinity River, the impacts from sea level rise on the Trinity Region cannot be neglected. For more information, Sea Level Rise Viewer from NOAA (https://coast.noaa.gov/slr/) can be utilized to visualize the sea level rise along with potential coastal flooding impact areas and relative depths. Meanwhile, Dr. Fang highly recommends continued monitoring of the local sea level through the tide gauges and/or buoys along the coastline for future flood mitigation and planning.

Land Subsidence

Land subsidence, as a sudden sinking or a gradual settling of the Earth's surface on account of the subsurface movement of earth materials, is regarded as a worldwide problem leading to numerous adverse impacts on infrastructure and the environment (Galloway, Jones, & Ingebritsen, Land Subsidence in the United States, 1999). The natural and human-induced causes of land subsidence include tectonic motion; aquifer-system compaction associated with groundwater use, soil, and gas withdrawals; underground mining; etc. ((Galloway, Jones, & Ingebritsen, Land Subsidence in the United States, 1999); (Xue, Zhang, Ye, Wu, & Li, 2005); (Braun & Ramage, 2020); (Herrera-García, et al., 2021)). During the past century, land subsidence caused by the groundwater depletion occurred at approximately 200 locations in 34 countries (Herrera-García, et al., 2021).

In the United States, more than 17,000 square miles in 45 states have been directly affected by land subsidence (Galloway, Jones, & Ingebritsen, Land Subsidence in the United States, 1999). Land subsidence is of particular concern, especially in flat coastal areas such as the Houston-Galveston Region, since land subsidence in conjunction with the sea level rise would exacerbate the severity of flooding in the neighboring watersheds (Galloway & Coplin, Managing Coastal Subsidence, 1999).

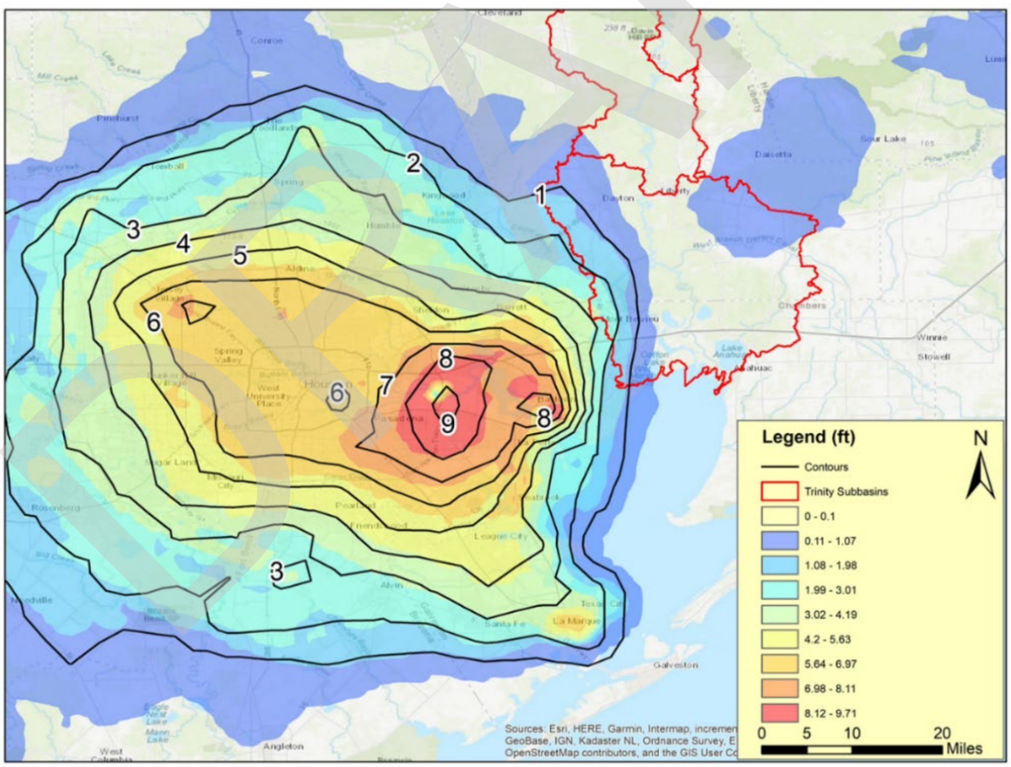
Figure 2.42: Potentially Impacted Area in the Trinity Region Caused by the Increase of (A) 0.19 Meter Sea Level Rise, (B) 0.78 Meter Sea Level Rise by 2050



According to a report produced by the USGS, land subsidence in the Houston-Galveston region continues to occur throughout the 20th century (Stork & Sneed, 2002). Two additional studies by (Kasmarek & Johnson, 2013) and (Liu, Li, Fasullo, & Galloway, 2020) have been completed for investigating the land subsidence in the Houston-Galveston region. Given that the downstream portion of the Trinity River is close to the Houston region, the expansion of land subsidence impacts the H&H of the watershed. Thus, potential impact needs to be understood for the area subject to land subsidence in the Trinity Region.

(Kasmarek & Johnson, 2013) simulated and measured land subsidence between 1900s to 2000 for the Houston-Galveston region. To better illustrate the land subsidence conditions in the Trinity Region, the boundary of the Trinity River is overlaid with the simulated land subsidence data as shown in ***Figure 2.43***. The highest land subsidence (9.7 feet) areas can be found in southeastern Harris County.

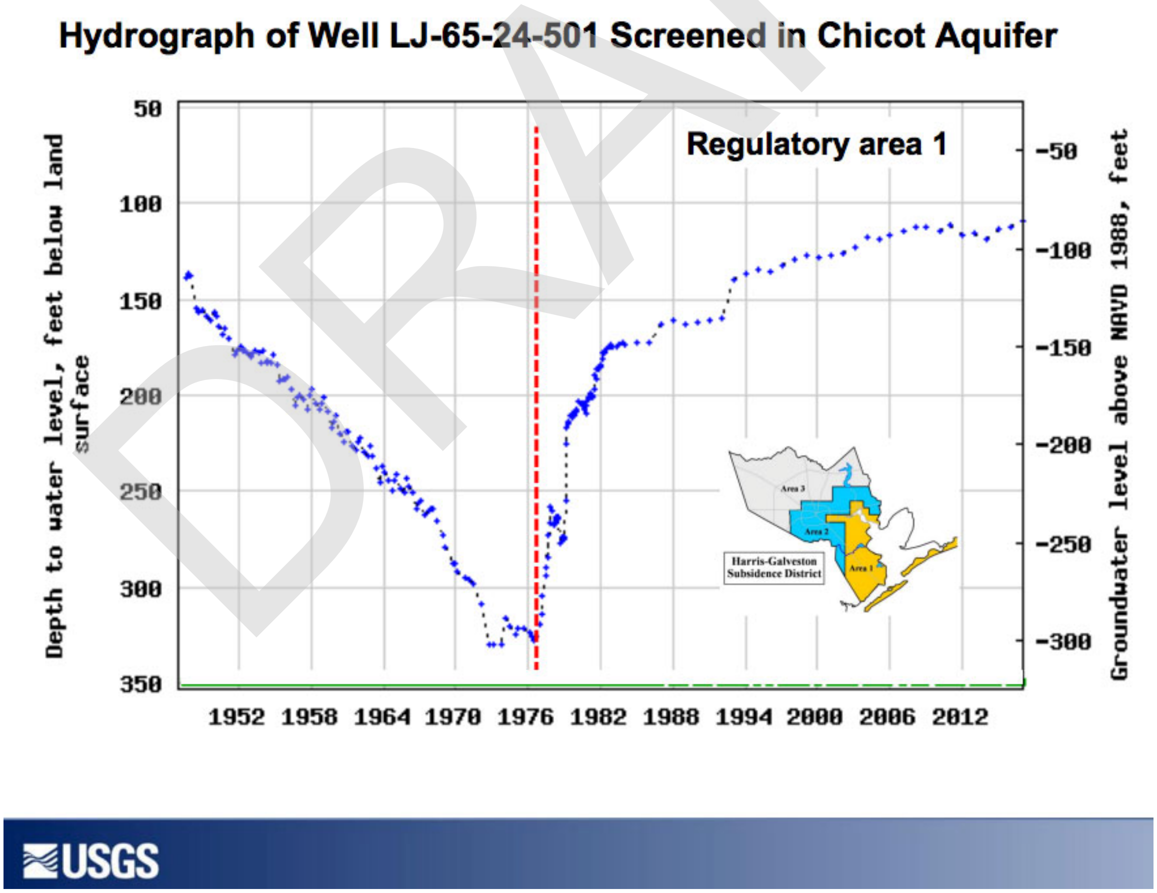
Figure 2.43: Land Subsidence Simulated by the Houston Area Groundwater Model (Liu, Li, Fasullo, & Galloway, 2020)



Since the 1970s, several subsidence regulatory entities (Harris-Galveston Coastal Subsidence District, Fort Bend Subsidence District, Lone Star Groundwater Conservation District, and Brazoria County Groundwater Conservation District) have established various policies to manage groundwater pumping activities and enforce groundwater regulations. The well monitoring data from USGS shows that groundwater levels in the region rose significantly once subsidence districts were established, thereby mitigating subsidence issues in the region (Texas Living Water Project, 2017).

Figure 2.43 shows that when the Harris-Galveston Coastal Subsidence District was created around 1976 (red line), groundwater levels in the Chicot Aquifer rose substantially and have remained relatively constant since 2006, suggesting that the rate of land subsidence should not change significantly compared to the current condition. In other words, the future impact of land subsidence to the Trinity Region in 2050 will not increase, but rather remain the same as 2020 (***Figure 2.44***). The current regional flood plan did not consider land subsidence in determining future flood risk due to its insignificant changes as observed and projected. While the impacted area by land subsidence is considered minimal for the Trinity Region, the Trinity RFPG supports long-term monitoring and management of the groundwater resources for future planning cycles.

Figure 2.44: Chicot Aquifer Hydrograph



Source: USGS Presentation: Connecting Groundwater level altitudes, Compaction and Growth

Changes in Floodplain

Future rainfall patterns are also considered regarding potential impacts to the floodplains in this plan. To aid the regional planning groups, the Office of the Texas State Climatologist provided TWDB with guidance on how to incorporate future rainfall in its April 16, 2021 report, titled “Climate Change Recommendations for Regional Flood Planning.” (Nielsen-Gammon & Jorgensen, 2021) The report states that 24-hour, 100-year rainfall amounts increased by approximately 15 percent between 1960 and 2020. The climatologist coupled historic rainfall data with results from climate models to develop a relationship between extreme rainfall amounts and future increases in global temperature. Percent increase in future precipitation was developed for both urbanized and rural watershed conditions. Due to the uncertainty of predicting weather patterns for extreme rainfall events, the climatologist provided a minimum and maximum range for estimating future rainfall increases. The climatologist found even more uncertainty when analyzing rural and large river catchments due to future decreases in soil moisture. This uncertainty resulted in the climatologist developing a range of future rainfall increases as shown in ***Table 2.22***.

Table 2.22: Trinity Region Range of Potential Future Rainfall Increase 2050-2060

Location	Range - Minimum	Range - Maximum
Urban Areas	12%	20%
Rural Areas/River	-5%	10%

Sedimentation and Major Geomorphic Changes

Anticipated Impacts of Sedimentation in Flood Control Structures

Flood control structures prevent floodwaters, either stormwater or coastal water, from inundating vast amounts of land and property. Hydraulic works (levees, flood walls, dams, river diversions, etc.) represent the most important single form of human adaptation to the flood hazard. In the Trinity Region, the most prominent flood control structures at a regional scale are levees, dams, and their associated reservoirs. In general reservoirs are the flood control facilities that are most susceptible to the impacts of sediment deposition over time within this watershed. While sedimentation in reservoirs is a directly measurable impact and is typically accounted for in the design, the plan needs to recognize the reduction in conveyance capacities due to sedimentation in channels, and floodplain fringes, and ultimately bays and estuaries.

Historically, reservoirs have been designed with relatively large storage capacities to offset sediment deposition and achieve the desired reservoir life. In general, reservoir design includes a sedimentation pool, commonly known as “dead storage”, which is a portion of its storage capacity that is essentially set aside for sediment deposition during the design life of the structure. It could be argued that the operation of the reservoir for authorized purposes, such as municipal water supply, flood control, hydropower generation, and recreation, is not significantly impacted if sediment accumulation does not exceed the dead storage capacity. However, large flood events will carry relatively large loads of sediment that can be deposited in portions of the reservoir that are outside of the designated dead storage areas. Thus, provisions need to be taken for sediment management in order to achieve a sustainable long-term use of the facility.

Within the framework of this regional flood plan for the Trinity Region, the loss of flood storage is considered the primary impact of sedimentation in terms of increasing future flood risk. Reservoir flood operations can be severely impacted by the time 50 percent of the sedimentation volume has been filled with sediment, but operational issues may arise even when smaller percentages of flood storage are lost. The intent of this section is to provide a high-level assessment of the expected loss of flood storage capacity due to sedimentation in the region's flood control facilities and determine if these losses would result in a significant increase to flooding risks. Data for this assessment was obtained from Natural Resources Conservation Service (NRCS) historical documents, TWDB volumetric and sedimentation surveys, and recent NRCS basis of design reports. The assessment was subdivided into two main groups: major reservoirs and NRCS floodwater retarding structures.

It is recognized, however, that sediment transport within a river system is a complex phenomenon with substantial geographic and temporal variability. The assessment and information provided in this section is based on a series of simplifying assumptions and are only intended to serve as a general indicator of the potential impacts of sedimentation in future flood risk at a regional scale within a 30-year planning horizon.

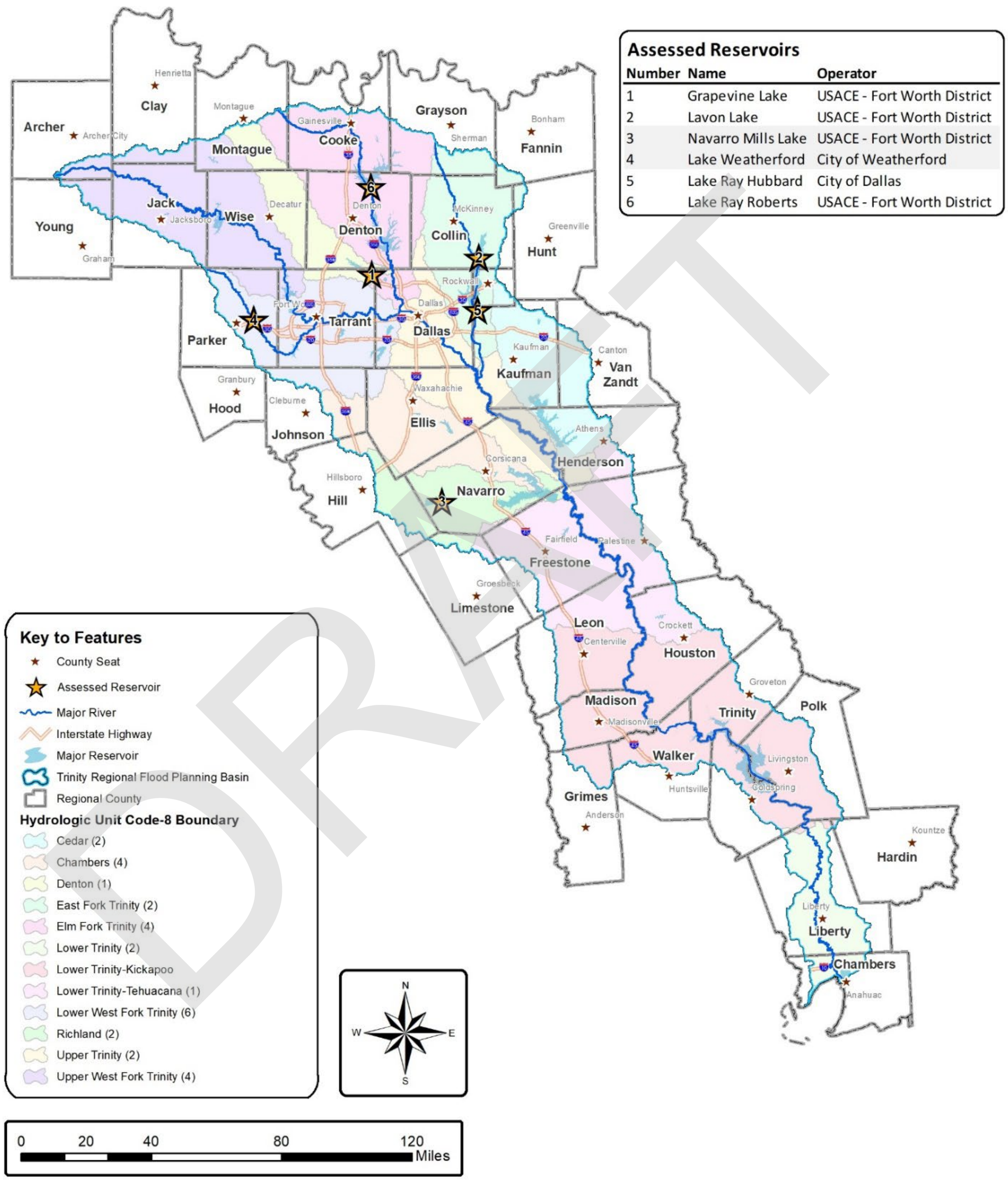
Major Reservoirs Assessment

The TWDB recognizes 34 major lakes and reservoirs within the Trinity Region. A body of water that contains at least 5,000 acre-feet of storage capacity at its normal operating level is considered a major reservoir, according to the TWDB. Some of the operators of these reservoirs include the USACE, TRWD, Trinity River Authority (TRA), and local municipalities. These facilities may serve multiple purposes including municipal water supply, irrigation, flood control, and/or recreation. Not all reservoirs are designed with flood control capacity. Six of these reservoirs were selected for this high-level assessment as a representative sample for the watershed (see ***Figure 2.45***).

Design and Operation of Multipurpose Reservoirs

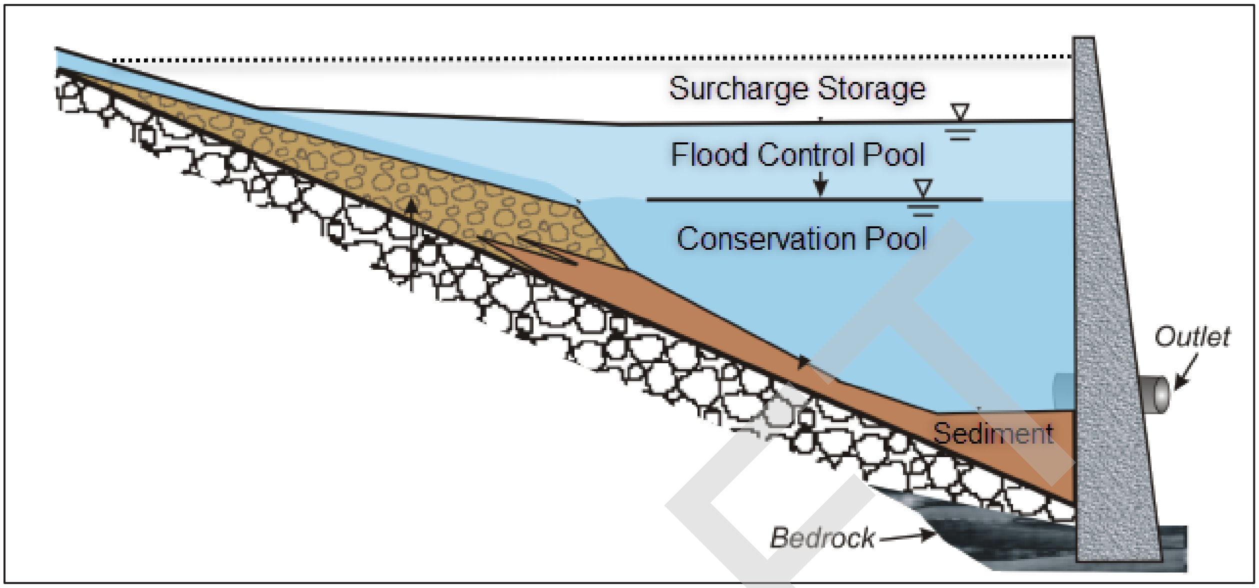
The design and operation of reservoirs includes allocating volumes of reservoir storage (typically referred to as "pools") for each purpose. There are three broad categories of pools (***Figure 2.46***): flood control, conservation (also referred to as multi-purpose), and sediment (also referred to as inactive or dead storage). In ***Figure 2.46***, these water storage areas are depicted. Each reservoir is designed with specific capacity limits for each pool.

Figure 2.45: Locations of Major Reservoirs Analyzed



Number	Name	Operator
1	Grapevine Lake	USACE - Fort Worth District
2	Lavon Lake	USACE - Fort Worth District
3	Navarro Mills Lake	USACE - Fort Worth District
4	Lake Weatherford	City of Weatherford
5	Lake Ray Hubbard	City of Dallas
6	Lake Ray Roberts	USACE - Fort Worth District

Figure 2.46: Typical Multipurpose Reservoir Design



Source: Modified from https://acwi.gov/sos/faqs_2017-05-30.pdf

The conservation pool is generally the largest layer, with the greatest capacity. The top of the conservation pool is typically varied based on seasonal patterns. Reservoir operators attempt to maintain this pool at the highest possible level. On top of the conservation pool is the zone reserved for flood control, which is also influenced by seasonal variations. Major reservoirs that provide flood control benefits are designed to capture upstream runoff, store it, and then release it at a controlled rate to minimize the flooding downstream.

Sediment Deposition

The amount of sediment accumulation in a reservoir depends on the sediment yield to the reservoir and the trap efficiency. Trap efficiency is the amount (percentage) of the sediment delivered to a reservoir that remains in it. How the accumulated sediment is distributed within the reservoir pools depends on the character of the inflowing sediment, the operation of the reservoir, detention time, and other factors. The incoming sediment that is deposited under water is called “submerged sediment”. The sediment deposited above the conservation pool elevation is referred to as “aerated sediment” (U.S. Soil Conservation Service, 1983).

The distinction between submerged and aerated sediment is important in determining the capacity that each will displace within a reservoir. The high-level assessment presented in the following sections assumes that 80 percent of the incoming sediment will be submerged and 20 percent aerated. This assumption is based on guidelines established on the SCS National Engineering Handbook, Section 3 (U.S. Soil Conservation Service, 1983) and a study performed by (Strand & Pemberton, 1987) for 11 reservoirs in the US Great Plains region. In this study, the reported percent of aerated sediment deposited in the flood control pool for Lavon Lake was approximately 20 percent, and this same value was adopted for all other reservoirs included in this assessment. Due to the complexity in determining the trap efficiency for each reservoir, a conservative assumption of 100 percent trap efficiency was adopted for the purposes of this assessment. A 100 percent trap efficiency indicates that all sediment delivered to a given reservoir remains in it and there are no sedimentation management practices being implemented.

Flood Control Capacity Loss Assessment

The TWDB in conjunction with the USACE-Fort Worth District, TRWD, and TRA, developed Volumetric and Sedimentation Surveys for several major reservoirs within the Trinity Region (Texas Water Development Board, 1993-2020). Six reservoirs were identified as a representative sample of all the major reservoirs in the watershed for this high-level assessment (see ***Figure 2.45***).

In the sedimentation surveys, a range of values is provided for the annual sedimentation rates of each reservoir. The reported high and low annual sedimentation rate estimates are reflected in ***Table 2.23***. These sedimentation rates are generally determined based on a comparison of storage capacity from volumetric surveys over time. In addition to the TWDB Volumetric and Sedimentation Surveys, the TWDB's Water Data for Texas website, and the USACE – Fort Worth District website were used to collect pertinent reservoir data. The flood control storage volume was not provided as part of the TWDB surveys; however, those volumes were collected from multiple sources including data sheets from the USACE – Fort Worth District website (U.S. Army Corps of Engineers, 2021), interpolation of rating curves from TRWD, and original reservoir/dam design documents from Freese and Nichols, Inc. (FNI).

The objective of this assessment is to estimate the potential loss of flood control storage capacity for the selected reservoirs over a 30-year planning horizon. Sediment accumulation was calculated from the year of the latest volumetric survey for each reservoir until year 2053. The percent of reservoir capacity lost from the conservation and flood pools by year 2053 was determined using both the high and low annual sedimentation rates. This calculation assumes that the annual sedimentation rate will be constant over time and that, as stated in the previous section, 80 percent of the annual sediment load will deposit in the conservation pool and 20 percent in the flood control pool. A conservative 100 percent trap efficiency assumption was adopted for this assessment. It was also assumed that the conservation storage included any additional volume designated as dead pool storage.

Table 2.23: Estimate of Flood Control Storage Capacity Remaining by 2053 – Representative Reservoirs

Reservoir Name	Reservoir Operator	Drainage Area (square miles)	Conservation Storage (acre-feet)	Flood Control Storage (acre-feet)	Annual Sedimentation Rate (acre-feet/year)		Remaining Flood Control Capacity (%) by 2053	
					Low	High	Low	High
Lavon Lake	USACE – Fort Worth District	770	409,360	338,840	1,212	1,310	97.1%	96.9%
Lake Ray Roberts	USACE – Fort Worth District	692	788,490	276,110	180	483	99.4%	98.5%
Navarro Mills Lake	USACE – Fort Worth District	320	49,827	149,403	124	124	99.3%	99.3%
Lake Weatherford	City of Weatherford	109	17,812	11,188	37	37	97.1%	97.1%
Grapevine Lake	USACE – Fort Worth District	695	163,064	235,136	392	426	98.6%	98.5%
Lake Ray Hubbard	City of Dallas	1,074	439,559	44,224	719	1,097	88.0%	81.6%

A summary of analysis results is presented in ***Table 2.23*** and ***Figure 2.47***. Detailed calculations are provided in ***Table 2.24***. Analysis results suggest that, overall, sedimentation will have a minor impact in the flood control function of the major reservoirs in the Trinity Region, as nearly all reservoirs resulted in over 90 percent of their flood control storage capacity still available by the end of the 30-year planning horizon.

Natural Resources Conservation Service Floodwater Retarding Structures

The NRCS, formerly known as the SCS, has a long history of designing and building dams and reservoirs with the primary purpose of serving rural/agricultural areas. Based on a combination of data from the (U.S. Army Corps of Engineers, 2020) and the Texas State Soil and Water Conservation Board's (TSSWCB) Local Dams Inventory (Texas State Soil and Water Conservation Board, 2021), there are 1,128 NRCS dams within the Trinity Region (see ***Figure 2.48***), most of which were designed and built during the early 1950s and 1960s. These dams are one of the elements that comprise what is known as a Watershed Work Plan (WWP), developed by the NRCS. The typical goals of a WWP are to improve agricultural practices, apply land treatment practices that will reduce upland erosion, and implement structural measures to reduce flood damages and provide for sediment control.

The WWPs refer to their dams and reservoirs as “Floodwater Retarding Structures”. Their intent is to reduce flood-related damages to both private property and agricultural crops. Reduction of floodplain scour and capturing excess sediment is also a typical goal for these facilities. A section of a typical floodwater retarding structure is shown in ***Figure 2.49***. It is important to note that the design of these structures includes a sediment pool and a sediment reserve. Thus, sedimentation may be considered to have an adverse impact to the structure’s flood control performance only when the sediment pool capacity has been depleted and sediment starts to accumulate in the detention pool. However, as stated earlier, large flood events may carry relatively large loads of sediment that can be deposited in portions of the reservoir that are outside of the designated sediment pool, which results in some loss of detention storage prior to filling the entire sediment pool.

Figure 2.47: Estimate of Flood Control Storage Capacity Remaining by 2053 – Representative Reservoirs

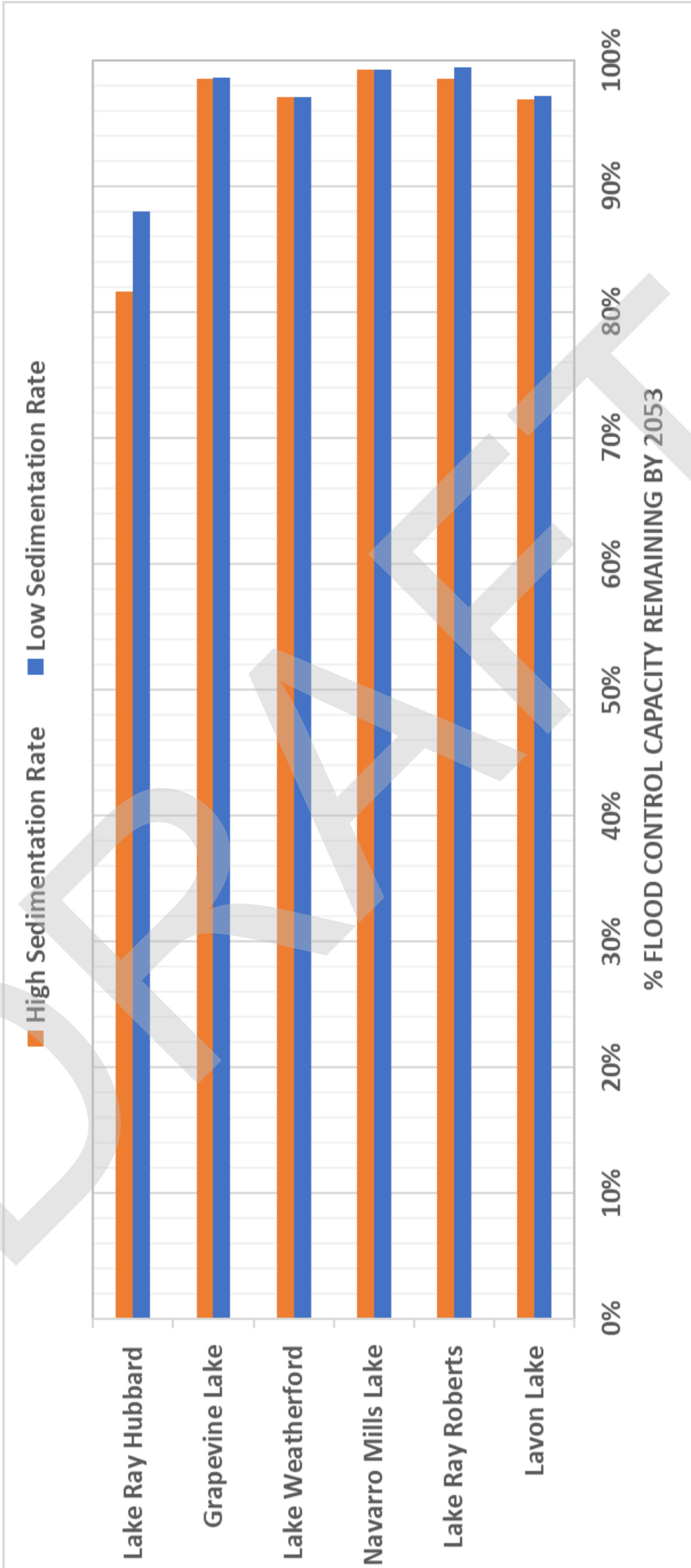
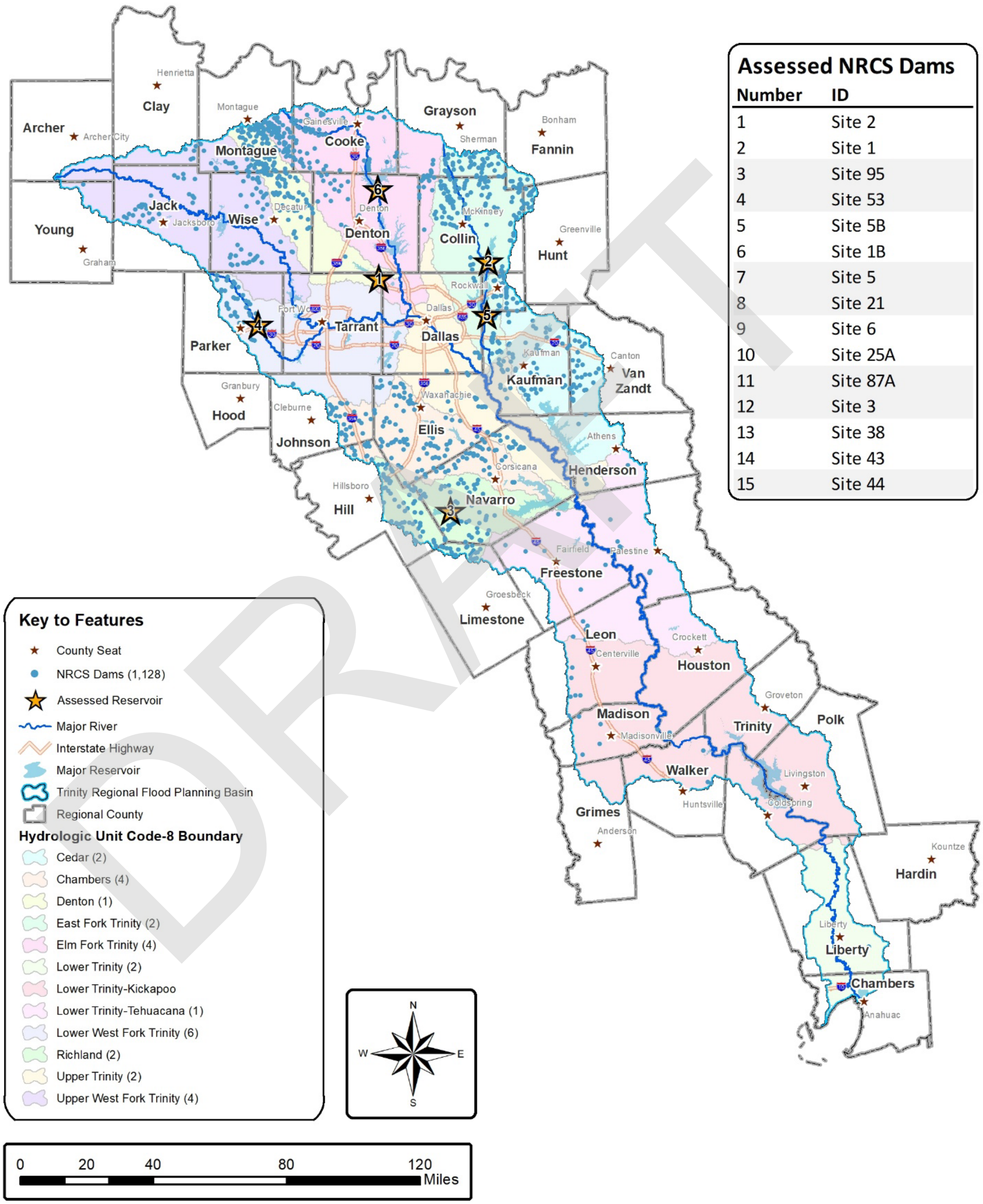


Table 2.24: Estimated loss of Conservation Pool and Flood Control Pool Capacity due to Sedimentation – Detailed Calculations

Reservoir Name	Reservoir Operator	Drainage Area (square miles)	Survey Year	Years to 2053	Conservation Storage (acre-feet)	Flood Control Storage (acre-feet)	Annual Sedimentation Rate (acre-feet/year)		Average Annual Sedimentation Rate (acre-feet/year)	% Capacity Lost from Conservation Pool by 2053		% Capacity Lost from Flood Control Pool by 2053		Average % Capacity Lost from Flood Control Pool by 2053	Remaining Flood Control Capacity (%) by 2053	
							Low	High		Low	High	Low	High		Low	High
Lavon Lake	USACE – Fort Worth District	770	2013	40	409,360	338,840	1,212	1,310	1,261	9.5%	10.2%	2.9%	3.1%	3.0%	97.1%	96.9%
Lake Ray Roberts	USACE – Fort Worth District	692	2010	43	788,490	276,110	180	483	332	0.8%	2.1%	0.6%	1.5%	1.0%	99.4%	98.5%
Navarro Mills Lake	USACE – Fort Worth District	320	2009	44	49,827	149,403	124	124	124	8.8%	8.8%	0.7%	0.7%	0.7%	99.3%	99.3%
Lake Weatherford	City of Weatherford	109	2009	44	17,812	11,188	37	37	37	7.3%	7.3%	2.9%	2.9%	2.9%	97.1%	97.1%
Grapevine Lake	USACE – Fort Worth District	695	2012	41	163,064	235,136	392	426	409	7.9%	8.6%	1.4%	1.5%	1.4%	98.6%	98.5%
Lake Ray Hubbard	City of Dallas	1,074	2016	37	439,559	44,224	719	1,097	908	4.8%	7.4%	12.0%	18.4%	15.2%	88.0%	81.6%

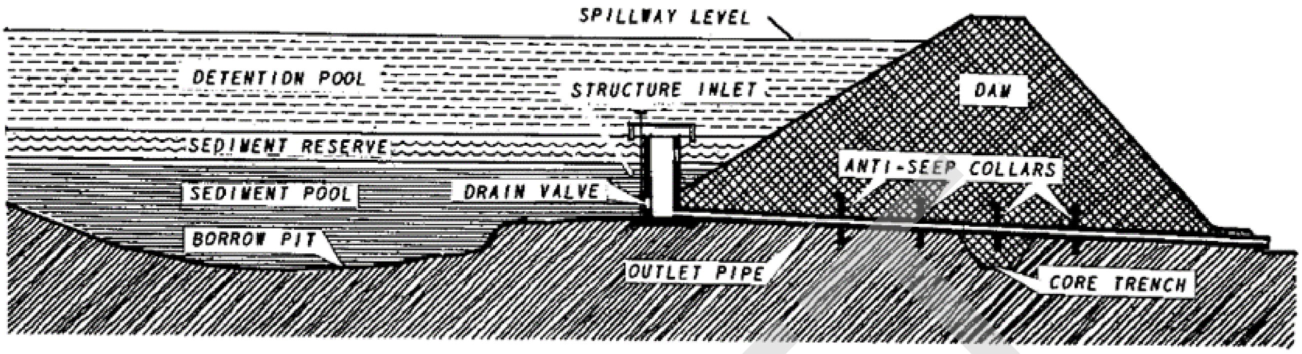
Figure 2.48: Locations of Natural Resources Conservation Service Dams



Assessed NRCS Dams

Number	ID
1	Site 2
2	Site 1
3	Site 95
4	Site 53
5	Site 5B
6	Site 1B
7	Site 5
8	Site 21
9	Site 6
10	Site 25A
11	Site 87A
12	Site 3
13	Site 38
14	Site 43
15	Site 44

Figure 2.49: Section of a Typical Natural Resources Conservation Service Floodwater Retarding Structure



Source: Big Sandy Creek WWP, SCS, 1955 (U.S. Department of Agriculture, 1955)

Flood Storage Loss Assessment

A high-level assessment of the loss of flood storage capacity due to sedimentation in the region's NRCS facilities was conducted as part of this regional flood plan. A total of 30 WWPs were reviewed for this plan. The watershed areas included in these WWPs are scattered throughout the Trinity Region and represent areas that are within 10 of its 12 sub-basins. No WWPs were available for floodwater retarding structures located within the Lower Trinity-Kickapoo and Lower Trinity sub-basins. WWPs can be downloaded from the following NRCS website: www.nrcs.usda.gov/wps/portal/nrcs/detail/tx/programs/planning/wpfp/?cid=stelprdb1186445.

The WWPs include relevant data about each of the floodwater retarding structures, including sedimentation pool storage, detention storage, drainage area, and the year the facility was built. Most WWPs include a "Sedimentation Investigation" section or similar that provides an average annual rate per area of sediment deposition into the floodwater retarding structures. This data was used to perform approximate calculations of the time it would take to fill the sedimentation pool and the time it would take to fill a given percentage of the detention or flood control storage. For the purposes of this high-level assessment, it is assumed that the performance of the structure in terms of reducing flooding risk begins to be significantly affected once 15 percent of the flood control pool is lost due to sedimentation.

Given the large number of NRCS floodwater retarding structures in the region and other limitations, the assessment was limited to 15 representative structures. At least one structure was included in each Trinity Region sub-basin (see ***Figure 2.48***). Structures that were analyzed by FNI in 2021 (four sites) were also included to supplement the assessment (Freese and Nichols, Inc., 2021).

Based on the sedimentation rates reported in the above-mentioned references, an average rate was calculated for each structure except for those that were analyzed by FNI in 2021. In these four cases, the sedimentation rate that was calculated as part of those investigations was adopted for the analysis. To calculate the time it would take to fill 100 percent of the sediment pool and 15 percent of the flood control pool, it was assumed that 80 percent of the annual sediment deposition would occur within the sediment pool and 20 percent within the flood pool. Once the sediment pool was filled, the entire sediment accumulation would occur within the flood pool. A conservative 100 percent trap efficiency assumption was adopted for this assessment. The results of these calculations are presented graphically in ***Figure 2.50*** and summarized in ***Table 2.25***. Further details on the data used and calculations are presented in ***Table 2.26***.

Figure 2.50 shows a series of bar graphs representing each site. The first point on the bar represents the year the structure was built. The segment between the first and second points represents the time it would take to fill the sedimentation pool. At that point, the facility would no longer perform its sediment control purpose as designed. The segment between the second and third points represents the additional time it would take to fill 15 percent of the flood control pool. This point represents a conservative assumption of when flood control benefits could start to be significantly reduced due to loss of storage capacity. The red dashed line that marks year 2053 depicts the long-term planning horizon for this first regional flood plan. Based on these calculations, flood control operations would not be significantly affected for most of the selected sites within the next 30 years. Ten sites would still have residual capacity in their sedimentation pool to continue accumulating sediment beyond 2053. In some instances, the bars extend beyond the limits of the time axis, indicating extensive time frames to reach the set storage losses.

Figure 2.50: Estimate of Time to Lose Sediment Pool and Flood Control Pool Capacity due to Sedimentation – Representative National Resources Conservation Services Structures

Table 2.25: Estimate of Time to Lose Sediment Pool and Flood Control Pool Capacity due to Sedimentation – Representative Natural Resources Conservation Service Structures

Trinity Region Sub-basin	Creek	NRCS Dam ID	Average or *FNI 2021 Sedimentation Rate (ac-ft/yr)	Year Built	Estimated Year Sediment Pool is Filled	Estimated Year Flood Pool is Filled 15%
Upper West Fork Trinity	Blue Creek	Site 43	0.07*	1981	3963	5242
Upper West Fork Trinity	Blue Creek	Site 44	0.09*	1981	3050	3660
Denton Creek	Denton Creek	Site 25A	12.42	1961	1971	1976
Elm Fork Trinity	Clear Creek	Site 53	2.50	1963	2085	2128
East Fork Trinity	Buffalo Creek	Site 3	2.26*	1953	2048	2070
East Fork Trinity	Buffalo Creek	Site 5B	1.77*	1955	2172	2245
East Fork Trinity	Rutherford Branch	Site 1B	4.10	1957	2010	2020
Lower West Fork Trinity	Clear Fork	Site 21	1.79	1956	2059	2093
Upper Trinity	Turkey Creek	Site 1	0.80	1954	2139	2291
Upper Trinity	Grays Creek	Site 5	13.92	1954	1982	1987
Upper Trinity	Village Walker Creek	Site 6	1.59	1963	1988	1993
Cedar Creek	Muddy Cedar Creek	Site 87A	4.80	1955	2082	2212
Chambers	Boss Branch	Site 38	0.55	1960	2407	2702
Richland	Post Oak Creek	Site 95	1.81	1956	2083	2135
Lower Trinity Tehuacana	Lake Creek	Site 2	1.36	1954	2354	2384

*Note: * Sedimentation Rates from FNI 2021 Basis of Design Reports for NRCS*

Table 2.26: Estimated Loss of Sediment Pool and Flood Control Pool Capacity due to Sedimentation – Detailed Calculations

Trinity Region Sub-basin	Creek	NRCS Dam ID	Year Built	Drainage Area (square miles)	Sediment Pool Storage (acre-feet)	Flood Pool Storage (acre-feet)	Total Capacity (acre-feet)	Sediment Rate Estimate (acre-feet/square miles/year)		Sediment Rate Estimate (acre-feet/year)		FNI 2021 Sedimentation Rate Estimate (acre-feet/year)	Average or FNI 2021 Sedimentation Rate (acre-feet/year)	Estimated Years to Fill Sediment Pool	Estimated Year when Sediment Pool is Filled	Additional Years to fill 15% of Flood Pool	Estimated Year when 15% of Flood Pool is Lost
								High	Low	Low	High						
Upper West Fork Trinity	Blue Creek	Big Sandy Creek Site 43	1981	3.2	111	782	893	–	–	–	–	0.07	0.07	1982	3963	1,279	5242
Upper West Fork Trinity	Blue Creek	Big Sandy Creek Site 44	1981	2.0	77	494	571	–	–	–	–	0.09	0.09	1069	3050	609	3660
Denton Creek	Denton Creek	Site 25A	1961	2.2	103	575	678	10	1.5	21.6	3.2	–	12.42	10	1971	5	1976
Elm Fork Trinity	Clear Creek	Site 53	1963	4.4	243	1,129	1,372	0.76	0.37	3.4	1.6	–	2.50	122	2085	43	2128
East Fork Trinity	Buffalo Creek	LEF Site No. 3	1953	2.0	172	623	795	4	2	7.9	4.0	2.26	2.26	95	2048	22	2070
East Fork Trinity	Buffalo Creek	UEFL Site No. 5B	1955	4.8	307	1,376	1,683	–	–	–	–	1.77	1.77	217	2172	73	2245
East Fork Trinity	Rutherford Branch	Site 1B	1957	2.1	175	568	743	3	1	6.2	2.1	–	4.10	53	2010	10	2020
Lower West Fork Trinity	Clear Fork	Site 21	1956	2.8	148	645	793	1	0.3	2.8	0.8	–	1.79	103	2059	33	2093
Upper Trinity	Turkey Creek	Site 1	1954	3.2	118	1,006	1,124	0.4	0.1	1.3	0.3	–	0.80	185	2139	152	2291
Upper Trinity	Grays Creek	Site 5	1954	3.2	308	983	1,291	6	2.7	19.2	8.6	–	13.92	28	1982	5	1987
Upper Trinity	Village Walker Creek	Site 6	1963	0.4	32	105	137	7.68	1.13	2.8	0.4	–	1.59	25	1988	5	1993
Cedar Creek	Muddy Cedar Creek	87A (New Terrell City Lake)	1955	14.3	488	4,968	5,456	0.45	0.22	6.4	3.2	–	4.80	127	2082	130	2212
Chambers	Boss Branch	Site 38	1960	3.4	197	1,411	1,608	0.22	0.11	0.7	0.4	–	0.55	447	2407	295	2702
Richland	Post Oak Creek	Site 95	1956	4.3	184	934	1,118	0.43	0.40	1.9	1.7	–	1.81	127	2083	52	2135
Lower Trinity Tehuacana	Lake Creek	Site 2	1954	3.4	435	1,000	1,435	0.5	0.3	1.7	1.0	–	1.36	400	2354	30	2384

Results also show that there are four sites that should theoretically be experiencing a significant reduction in their flood control effectiveness. However, sedimentation rates do change significantly over time, and more recent sedimentation rate estimates are typically much lower due to significant improvements in agricultural practices and the implementation of erosion control policies among other factors. FNI's long term experience with NRCS ponds and results from recent FNI detailed assessments suggest that sedimentation rates reported in these early documents can be quite conservative and not representative of current rates. For example, the sedimentation rates estimated in the early documents for Site 3 in the East Fork Trinity sub-basin range from four to 7.9 acre-feet per year, while the most recent estimates calculated by FNI (2021) resulted in a rate of 2.26 acre-feet. This is a 44 percent reduction from the low estimate indicated in the early documentation.

The results of this high-level assessment suggest that at a regional scale, sedimentation will not pose a significant limitation to achieving flood control benefits from these structures within the 30-year planning horizon. However, it is recognized that 15 structures is a relatively small sample size, and that further analysis is required to comprehensively assess the impacts of sedimentation on these structures, especially at the local scale. Sedimentation was not used in determining future flood risk for the this first regional flood plan due to the minimal effect at the regional scale. Reduction in reservoir capacity may be looked at in greater detail by local entities and in future planning cycles.

Anticipated Impacts of Major Geomorphic Changes in Flood Risk

Geomorphic changes in fluvial systems have a clear relationship with flood hazard protection. Fluvial systems are a series complex feedback loops where many interrelated variables influence both flood hazards and changes in a river condition. In short, the geometry of river systems changes when the influencing variables, such as hydrology (caused by things such as climate change, land use changes, stormwater infrastructure, etc.) and sediment dynamics such as erosion, sediment deposition, and sediment transport change. This ultimately relates back to flood hazards because of increases or decreases in flood conveyance inherent to changes in river geometry.

Most flood hazard assessments assume the capacity of river channels to convey flood flows is stationary, with the thought that changes in flood frequency are primarily driven by hydrology. However, several studies have shown that while hydrology has a greater influence on flood hazards and flood variability, identifying potential geomorphic changes are important because flood hazards and flood variability is not driven by hydrology alone.

Predicting Geomorphic Changes

Effectively predicting geomorphic channel changes quantitatively requires intense data collection and modeling. These requirements are further magnified at larger scales because the factors that control the geomorphology of a system are variable throughout a watershed. At the regional scale, there is significant heterogeneity within a river system. As such, geomorphic channel changes and sediment dynamics are difficult to quantify at the regional scale because of the lack of available data, number of interrelated influential variables, and differences in the local conditions within a watershed.

Including predicted geomorphic changes into flood assessment is often not appropriate or feasible at the regional scale. This is because the uncertainty of predictions become exceedingly high with the introduction of additional variables/complexity, which can lead to erroneous flood predictions (Stanzel & Natchnebel, 2009). However, this does not mean that general effects of geomorphic channel changes on flood risks should not be considered.

Effects of Geomorphic Changes on Flood Risks

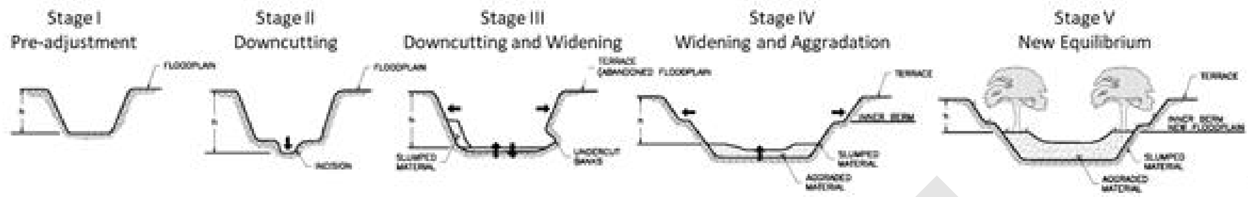
While major geomorphic changes can occur at the regional scale, their effect on flood risks are most apparent at the local level. This is because of the variability of geomorphic conditions within a river. Local changes in the channel geometry and sediment dynamics of the system can have profound effects on flood inundation extents at smaller scales. This section provides high-level descriptions of how geomorphic changes can affect flood risks.

Hydrology and Channel Changes

River geometry changes to accommodate the amount of flow it receives. Both increases and decreases in flow regime can initiate these changes. Common causes of hydrologic changes include urbanization/land-use changes, implementation of stormwater infrastructure (such as detention/retention ponds), climate change, and reservoir release schedules.

Increased flow often occurs when a watershed urbanizes or has land-use changes. Flow in streams become flashier because surface runoff reaches streams more quickly and in greater magnitude due to increased smooth impermeable surfaces that prevent infiltration of water into the ground. While this gets floodwaters downstream more quickly, stream geometries will enlarge via erosion to accommodate the additional flow. This is manifested by channel downcutting until the stream slope can accommodate the discharge without scouring the channel bed; and by channel widening caused by overly steepened stream banks following downcutting. ***Figure 2.51*** shows the processes involved in the channel evolution model.

Figure 2.51: Diagram of Channel Downcutting and Channel Widening (Adapted from Schumm et al, 1984)



Channel enlargement is a gradual process that migrates from downstream to upstream between local baselevels or hardpoints. Local baselevels are features that prevent the channel from downcutting. Examples may include tributary confluences, bedrock outcrops, concrete-lined channels, and culvert crossings. Geometric changes to the channel (i.e., channel enlargement) typically affect flood levels within these bounded local baselevels.

Locally, channel enlargement may increase the flow capacity and reduce flood risks. This effect scales with river size/drainage area. Flood capacity is less impacted by erosion in larger streams than in smaller streams because the amount of material removed relative to the channel size is less in larger streams. In smaller streams it is common for erosion to create enough capacity to completely remove overbank flows during flood events. Likewise, significant amounts of erosion in larger streams may only have a marginal effect on flood inundation levels.

This does not mean that erosion is solely beneficial to flood risks. There are adverse impacts of erosion brought about by increased hydrology including:

- Direct erosion impacts to homes, infrastructure (e.g., stormwater outfalls, waterlines, sewer lines, roads, bridges, culverts, etc.), and private property adjacent to the stream
- Channel geometry used in flood assessment analyses becoming outdated
- Excess sediment yields sourced from channel erosion and subsequent downstream effects

Decreased flow in the stream can also occur due to the presence of detention/retention ponds, lakes/reservoirs, and other factors. This can cause channels to aggrade because flows no longer have enough stream power to carry the sediment in the system. As a result, channel capacity will decrease as sediment aggrades in the channel and flood levels can rise for a given storm event. In addition to aggradation, erosion can also occur on stream banks caused by deposition patters/sediment bars directing flow into stream banks.

Changes to Sediment Dynamics and Culvert Sedimentation

Sediment transport is a fundamental function of stream systems. However, changes in sediment dynamics can affect flood risk. These changes are often interrelated with hydrologic changes, the presence of man-made structures, or local disturbances to channel geomorphology. Upstream channel change/erosion can account for as much as 90 percent of sediment yield volumes. When sediment yields increase, the resulting excess sediment typically has one of three fates:

1. Sediment can be redeposited downstream within the channel or floodplain. This reduces flood capacity in locations where the stream no longer has the sediment transport capacity to move the sediment through the system. This can happen in locations where the channel has become overly wide as a result of historic channel downcutting and widening.
2. Sediment can be transported and stored within reservoirs or retention/detention ponds. This can reduce flood storage if not properly addressed by maintenance (as discussed in previous sections). This then becomes a maintenance responsibility for the owner of the reservoir.
3. Sediment is effectively transported out of the watershed over time.

Sedimentation within culverts or stormwater infrastructure is also a common source of increased local flood risk. Culvert designs are typically based on maximum expected flood events. However, culvert designs have traditionally not considered lower-level flood events or sediment transport. As such, many culverts are oversized for more frequent storm events. Flows entering culverts spread out laterally, increasing the channel width and decreasing the channel depth. This reduces the stream power through the culvert. The result is a loss in sediment transport capacity and deposition within the culvert. As deposition continues, culverts lose capacity. This can cause increased flood risks as water stacks up behind filled in culverts and road crossings. This phenomenon is often not accounted for in flood risk analysis.

There are two primary solutions to local sedimentation at culverts and road crossings: ongoing monitoring and maintenance by the owner of the culvert to make certain that sedimentation is not reducing culvert capacities that could lead to local increases in flood risks and considering sediment transport and stream geomorphology during culvert design.

One example of culverts that accounts for sediment transport is tiered culverts or staged culverts. These have shown to be considerably more effective at reducing sedimentation, while still maintaining flood capacity, than the traditional practice of oversizing of culverts. A tiered culvert set-up has a primary culvert that accommodates more frequent flow events and maintains the stream channels width-depth ratio and sediment transport capacity. Adjacent culverts are placed at higher flow elevations and become activated during larger flood events. This allows flood capacity to be maintained while reducing sedimentation within culverts. An example of a staged culvert is shown in ***Figure 2.52***.

Figure 2.52: Staged or Tiered Culvert Design Used in North Texas with Multiple Culvert Sizes and Flow Elevations

Other Considerations

It is often not feasible to evaluate region scale geomorphic changes and their potential effects on flood hazards because of the significant uncertainties introduced into flood hazard assessment without accounting for the intensive data requirements, extensive analysis of interrelated variables, and system heterogeneity. Major geomorphic changes and their effects of flood hazards are most prominently experienced at the local level and can be accounted for at this scale.

The above sections provide high-level examples of the connection between geomorphic changes and flood hazards at specific locations due to local sediment dynamics or bank erosion. As such, mitigation of flood hazards is often a maintenance concern located at specific areas or pieces of infrastructure (such as easements, culverts, retention/detention ponds, reservoirs, etc.). The maintenance responsibilities of these areas, and therefore much of flood hazard mitigation practices, falls onto the owners of these assets.

One method used by numerous cities and regulatory bodies to account for uncertainty in geomorphic changes at a high level includes erosion hazard setbacks (also known as erosion clear zone, stream buffer area, etc.). This consists of a buffer area around the stream system that is not allowed to be disturbed without prior investigation. Multiple methods of creating this setback distance have been developed in design criteria manuals and local flood plans as a means of accounting for the uncertainty in future geomorphic changes without intense data requirements. Maintaining a buffer around streams provides numerous benefits including:

- Allowing for geomorphic channel adjustments to occur within an allotted lateral extent without significantly affecting flood inundation extents
- Reducing hydrologic changes in the stream by slowing overland flow via riparian vegetation
- Improving water quality via riparian vegetation filtering surface runoff
- Reduction of bank erosion and subsequent excess sediment due to streambanks increased resistance to bank erosion from the roots of established riparian vegetation (i.e., bank vegetation reduces stream bank erosion)
- Prevention of erosion impacts to homes, infrastructure, and property adjacent to the stream

In larger drainage area streams with more thorough flood inundation mapping, these setbacks may not be as effective at reducing flood risk due to their relatively small buffer distances from streams compared to mapped floodplains. However, in smaller watersheds with limited flood analysis, these can be an effective means of providing an extra layer of protection with relatively low effort.

Future Conditions H&H Model Availability

Table 2.27 includes a list of projects that include H&H models with future conditions. Details for two of the projects follows:

- **The Interagency Flood Risk Management (InFRM) Watershed Hydrology Assessment for the Trinity Region:** A watershed model was built for the Trinity Region with input parameters that represented the physical characteristics of the watershed. The rainfall-runoff model for the basin was completed using the basin-wide Hydrologic Engineering Center – Hydrologic Modeling System (HEC HMS) model developed for the 2015 Trinity Basin Corps Water Management System (CWMS) implementation as a starting point. This model was further refined by adding additional detailed data, updating the land use, and calibrating the model to multiple recent flood events. Through calibration, the updated HEC-HMS model was verified to accurately reproduce the response of the watershed to multiple, recently observed storm events, including those similar in magnitude to a 1-percent ACE. Finally, frequency storms were built using the depth area analysis in HEC-HMS and the latest published frequency rainfall depths from NOAA Atlas 14 (National Oceanic and Atmospheric Administration, 2018). These frequency storms were run through the verified model, yielding consistent estimates of the 1-percent ACE and other frequency peak flows at various locations throughout the basin.

Table 2.27: Hydrology and Hydraulic Models by Project

Project	Model Name	Date Created	Stream Section	HEC RAS version	Steady or Unsteady state	Model Developer
Interagency Flood Risk Management (InFRM) Watershed Hydrology Assessment for the Trinity River Basin	AP_Freq_002yr AP_Freq_005yr_NOAA AP_Freq_025yr AP_Freq_050yr AP_Freq_250yr	09/17/2018	Trinity Bay, Lewisville Lake, Lavon Lake, Grapevine Lake, Ray Roberts Lake, Benbrook Lake, Joe Pool Lake	HEC-HMS 4.3	Steady Flow	USACE
Interagency Flood Risk Management (InFRM) Watershed Hydrology Assessment for the Trinity River Basin	AP_Freq_002yr_NOAA AP_Freq_200yr_NOAA_WF	01/18/2021	Trinity Bay, Lewisville Lake, Lavon Lake, Grapevine Lake, Ray Roberts Lake, Benbrook Lake, Joe Pool Lake	HEC-HMS 4.3	Steady Flow	USACE
Interagency Flood Risk Management (InFRM) Watershed Hydrology Assessment for the Trinity River Basin	AP_Freq_002yr_NOAA_WF AP_Freq_005yr AP_Freq_005yr_NOAA_WF AP_Freq_010yr AP_Freq_010yr_NOAA_WF AP_Freq_025yr_NOAA_WF AP_Freq_050yr_NOAA AP_Freq_050yr_NOAA_WF AP_Freq_100yr_NOAA AP_Freq_100yr_NOAA_WF AP_Freq_200yr AP_Freq_500yr_NOAA_WF	05/7/2021	Trinity Bay, Lewisville Lake, Lavon Lake, Grapevine Lake, Ray Roberts Lake, Benbrook Lake, Joe Pool Lake	HEC-HMS 4.3	Steady Flow	USACE
Interagency Flood Risk Management (InFRM) Watershed Hydrology Assessment for the Trinity River Basin	AP_Freq_010yr_NOAA	01/11/2019	Trinity Bay, Lewisville Lake, Lavon Lake, Grapevine Lake, Ray Roberts Lake, Benbrook Lake, Joe Pool Lake	HEC-HMS 4.3	Steady Flow	USACE
Interagency Flood Risk Management (InFRM) Watershed Hydrology Assessment for the Trinity River Basin	AP_Freq_100yr AP_Freq_500yr	12/10/2018	Trinity Bay, Lewisville Lake, Lavon Lake, Grapevine Lake, Ray Roberts Lake, Benbrook Lake, Joe Pool Lake	HEC-HMS 4.3	Steady Flow	USACE
Interagency Flood Risk Management (InFRM) Watershed Hydrology Assessment for the Trinity River Basin	AP_Freq_500yr_NOAA	01/14/2019	Trinity Bay, Lewisville Lake, Lavon Lake, Grapevine Lake, Ray Roberts Lake, Benbrook Lake, Joe Pool Lake	HEC-HMS 4.3	Steady Flow	USACE
Marine and Cement Creek Frequency and Probability Maximum Flood Study	002_Year_AMC_II 005_Year_AMC_II 010_Year_AMC_II 025_Year_AMC_II 050_Year_AMC_II 100_Year_AMC_II 500_Year_AMC_II	04/9/2020	Marine and Cement Creeks	HEC-HMS 3.5	Steady Flow	USACE
Marine and Cement Creek Frequency and Probability Maximum Flood Study	AMC_II_002_Freq AMC_II_005_Freq AMC_II_100_Freq AMC_II_500_Freq	04/9/2020	Marine and Cement Creeks	HEC-HMS 3.5	Steady Flow	USACE
Marine and Cement Creek Frequency and Probability Maximum Flood Study	Marine_CementCreek	03/1/2008	Marine and Cement Creeks	HEC-HMS 4.0	Steady Flow	USACE

- **Marine and Cement Creek Frequency and Probability Maximum Flood Study:** Marine Creek is in the northwest portion of Tarrant County. The headwater of Marine Creek is approximately 3.5 miles northwest of Saginaw, Texas, and the flow is in a general southeasterly direction. The Marine Creek confluence with the West Fork of the Trinity River is just downstream of the Fort Worth Stockyards near Samuel Avenue north of downtown Fort Worth. Total drainage area of the Marine Creek watershed is approximately 22.2 square miles, including portions of the City of Saginaw, Fort Worth, Lake Worth, Sansom Park, and unincorporated Tarrant County. H&H models for the study were developed using HEC-HMS Version 3.4 and HEC-RAS Version 4.0, as well as GIS applications.

Best Available Data

Even though there were some models with future conditions in the Trinity Region as identified previously, these models did not have corresponding mapping data available; therefore, the methodology described next was developed to delineate consistent seamless future conditions floodplain extents for the Trinity Region.

Hydrology and Hydraulic Models Without Future Conditions

The methodology to leverage existing conditions modeling and mapping to produce the future conditions floodplain extents for the Trinity Region was approved by the TWDB on January 21, 2022 and described in the following narrative.

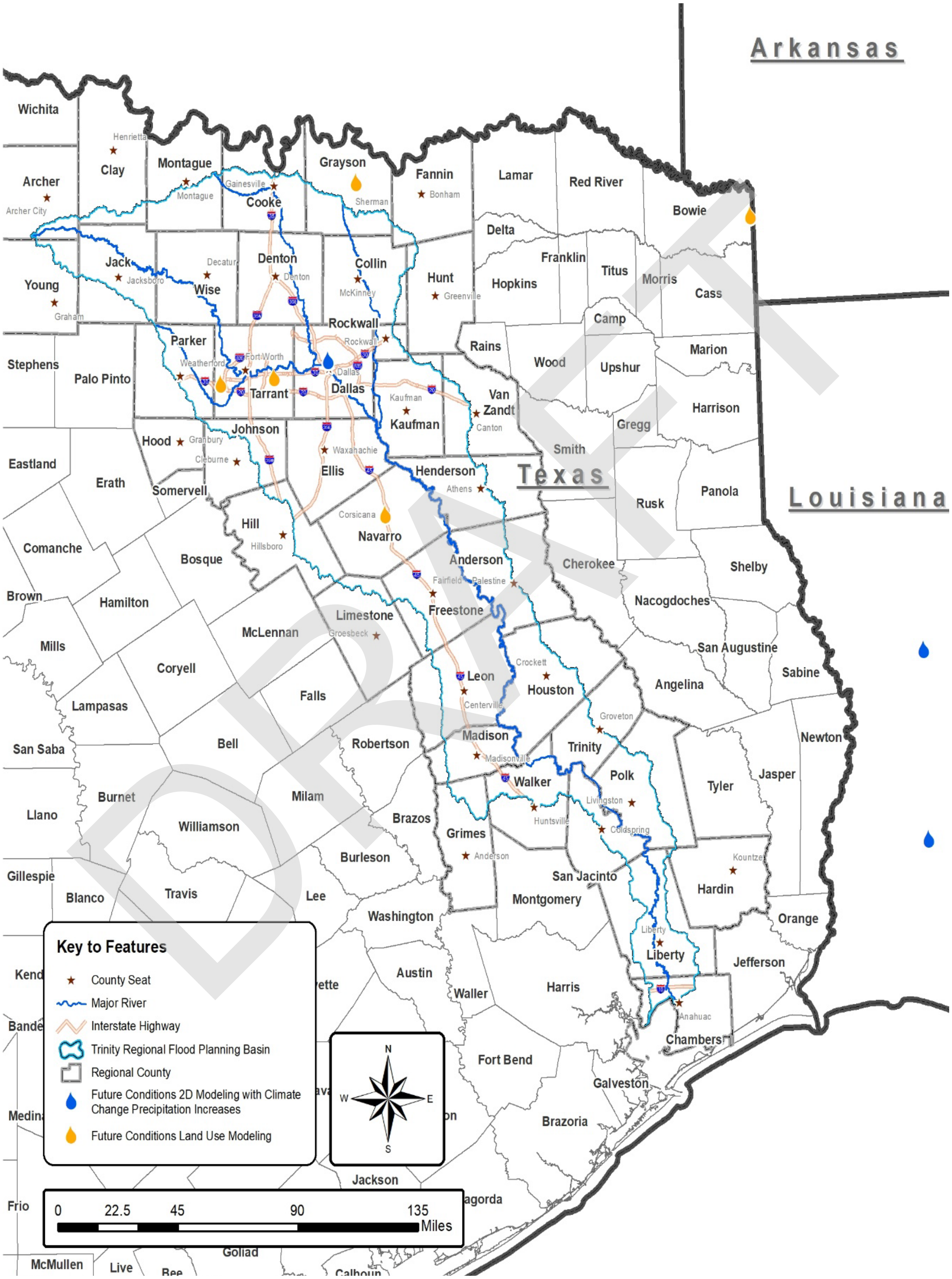
1-percent and 0.2-percent Annual Chance Exceedance Floodplains

When developing a predictive assessment for future conditions flood risk, two major factors were considered: unmitigated population increase and projected future rainfall.

Case Studies – Future Conditions Flood Risk

To obtain a better understanding of how future conditions affect extreme rainfall flood risk within the Trinity Region, pre-existing H&H models containing future flood risk data were analyzed. Results from these studies served as an estimation of how future land use and climate change impact floodplain elevations and widths when compared to existing conditions. Comparable studies were chosen based on availability, location, and similar H&H parameters. ***Figure 2.53*** provides a location for the existing studies collected for this assessment.

Figure 2.53: Case Study Locations



Future Conditions – Land Use Studies

Five drainage/floodplain master plans were utilized to assess potential flood risk increases due to future fully developed land use conditions. The future conditions analysis for these studies did not consider potential increases to rainfall data and are, therefore, based on land use changes only. A comparison was made between the existing and future conditions 100-year flood elevations. In addition to the future 100-year comparison, a flood elevation comparison was made between the existing 100-year and 500-year storm events to analyze the viability of utilizing the existing 500-year floodplain to represent future 100-year flood hazard data for this planning cycle. Results of the comparisons are provided in ***Table 2.28***.

Table 2.28: Future Condition Land Use Water Surface Elevation Comparison

Location	Flooding Source	Average WSEL Change Existing vs. Future 100-year (feet)	Average WSEL Change Existing 100-year vs. 500-year (feet)
Parker County	Marys Creek	0.1	0.8
Grand Prairie	Fish, Kirby, Rush, Prairie Creek	0.2	1.4
Sherman	Post Oak, EF Post Oak, Sand Creek	0.7	1.0
Texarkana	Wagner, Swampoodle, Corral Creek	0.6	1.8
Corsicana	Post Oak, SF Post Oak, Mesquite Creek	0.2	1.0
	Average	**0.4**	**1.2**

Future Conditions – Projected Future Rainfall

During the data collection phase, the Trinity RFPG team was unable to obtain studies that analyzed future flood risk based on potential future rainfall predictions. As a substitute, two large scale rain on grid studies were obtained: Dallas City-Wide Watershed Masterplan and the FEMA Louisiana Upper Calcasieu BLE Analysis. The modeling methodology of these studies allowed for rainfall data to be quickly modified in accordance with the recommendations from the state climatologists. The 100-year storm event rainfall was increased by 15 percent for both studies and the flood elevation results were compared to the present-day conditions. The increase of 15 percent was chosen because it fell into the high range of rainfall increases and matched the historic period of record increase. The existing 100-year and 500-year flood elevations were also compared. Results of the comparisons are provided in ***Table 2.29***.

Table 2.29: Trinity Region Future Rainfall Increase Water Surface Elevation Comparison

Location	Average WSEL Change Existing vs. Future 100-year (feet)	Average WSEL Change Existing 100-year vs. 500-year (feet)
Dallas	0.2	Unavailable*
Upper Calcasieu	0.4	1.7
Average	**0.3**	**N/A**

** Dallas Watershed Master Plan only considered the 100-year storm event*

Future Conditions Flood Hazard Approach

Potential Future 100-year Flood Hazard Methodology

Due to the relatively large coverage of adequate existing 500-year floodplain data within the region, utilizing the existing 500-year floodplain quilt to represent potential future 100-year flood hazard was considered the most reasonable approach. Results from the comparison showed that using this methodology would be considered a more conservative approach.

From the future conditions land use case study results, the average change in potential future 100-year WSEL compared to existing conditions was only 0.4 feet, while the comparison between the existing 100-year and existing 500-year WSEL yielded an average 1.2 feet change. By increasing the average change in WSEL between existing and potential future conditions from ***Table 2.28*** by the average taken from ***Table 2.29*** to account for future rainfall projections, the results generally yielded a comparison less than that of the differences between the existing 100-year and existing 500-year WSEL. This evaluation, taken from detailed future conditions hydraulic studies, demonstrated that the future 100-year floodplain is generally located between the existing 100-year and 500-year floodplain limits, with its location lying closer to the existing 100-year boundary.

Entities mistakenly using this data for regulatory purposes was evaluated as a potential concern. As a solution to this concern, the potential future 100-year floodplain was presented in this planning cycle as a range between the existing 100-year and the existing 500-year (zone of potential expanded risk). The methodology covers the uncertainty and variability resulting from the case study analysis. The exposure and vulnerability assessment data would be extracted from the maximum potential future 100-year floodplain limit.

Potential Future 500-year Flood Hazard Methodology

Under Method 2 in the TWDB Technical Guidelines, an excerpt regarding the determination of the future 500-year flood hazard states:

"RFPGs will have to utilize an alternate approach to develop a proxy for the 0.2 percent annual chance future condition floodplain, such as adding freeboard (vertical) or buffer (horizontal) estimates. The decision on what specific approach or values to use, which may vary within the region (e.g., for urban vs. rural areas), for these estimates will be up to the RFPGs, but technical justification should be provided to explain how the estimates were developed. This method cannot be applied to flood risk areas that do not already have a delineated existing condition 0.2 percent annual chance floodplain, (i.e., flood-prone areas)."

Based on this statement, reasonable buffer limits were researched based on the difference in existing top widths between the 100-year and 500-year floodplain quilt within the Trinity Region. It is reasonable to assume that the difference between top widths for the existing conditions, will be similar for potential future conditions. To establish a reasonable buffer zone to represent potential future 500-year flood risk, BLE data previously collected for the plan was analyzed. Nine large-scale studies were selected to form the basis for the buffering analysis. ***Figure 2.54*** shows the general location and coverage of the nine studies selected.

The nine studies collected represent over 25,000 miles of floodplain, with over 300,000 cross-sections. Using automated means, 600,000 individual distance measurements were collected along these cross-sections between the existing 100-year and 500-year floodplains. ***Figure 2.55*** shows an example of measurement locations. The measurements were then averaged for each of the nine study locations. The average distance measurement along the right or left overbank of the floodplain ranged from 30 feet to 50 feet. The total average overbank measurement of all nine studies was determined to be approximately 40 feet, representing an 80-foot total change in top width. Similar to the future 100-year flood risk boundary, the future 500-year will be presented as a range between the existing 500-year flood risk boundary and the 40-foot buffer. ***Table 2.30*** provides the average measurement results of the analysis.

Summarization of Potential Flood Hazard Methodology

A procedure for generating potential future 100-year and 500-year flood risk data that generally follows the TWDB's Technical Guidance was developed for the Trinity Region. The existing 500-year floodplain was selected to serve as a proxy for the potential maximum 100-year flood hazard. A 40-foot buffering of the existing 500-year flood hazard boundary was selected to serve as the potential maximum future 500-year flood hazard. Using the previously described buffering methodology for potential future 500-year conditions allows for rapid development of estimated expanded risk within the constraints of the flood plan timeline and lack of future 500-year detailed data throughout the planning area.

Figure 2.54: Future Condition 500-year Case Study Locations

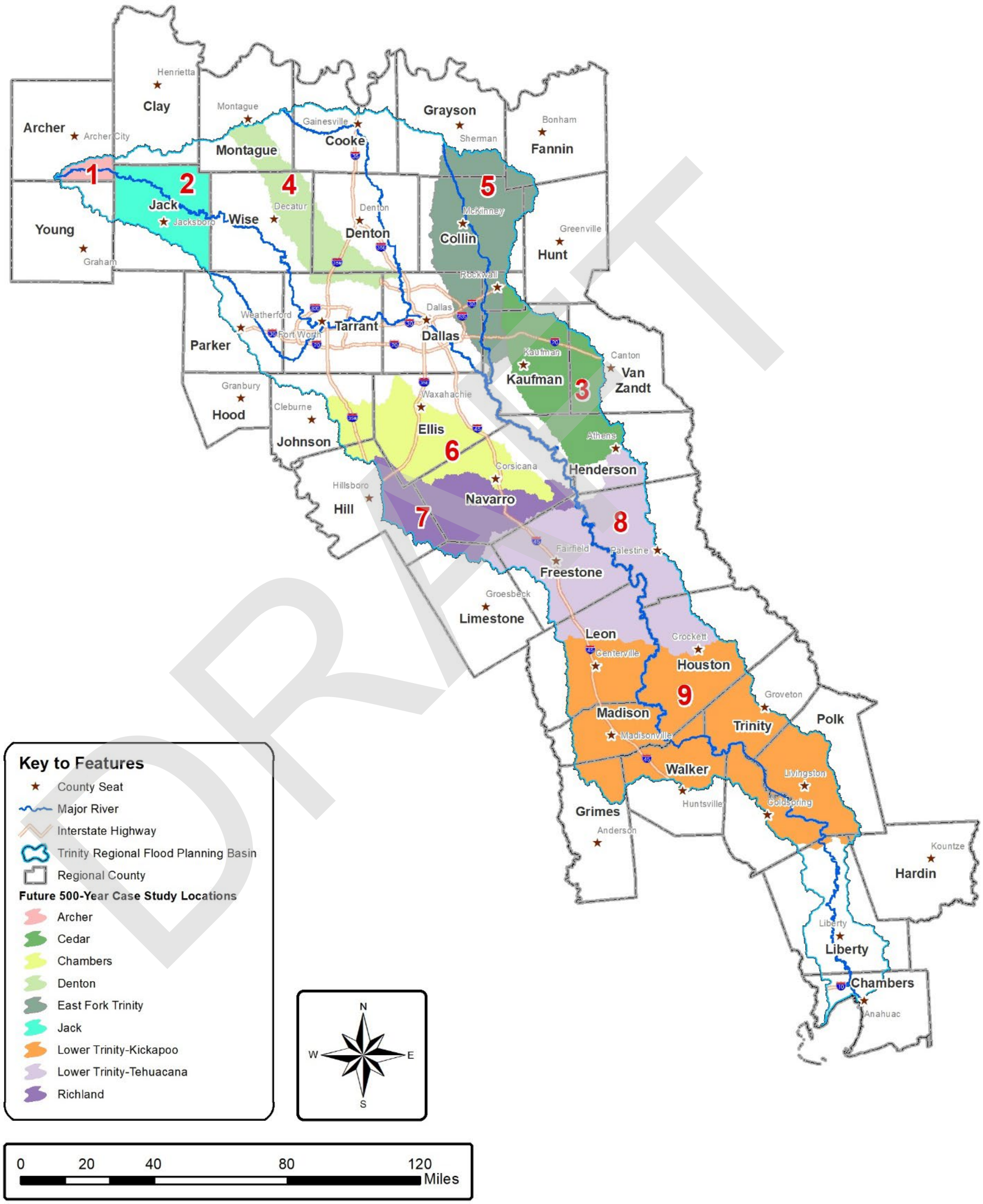


Figure 2.55: Measurement Locations to Develop Potential Future Condition 500-year Flood Risk Buffer

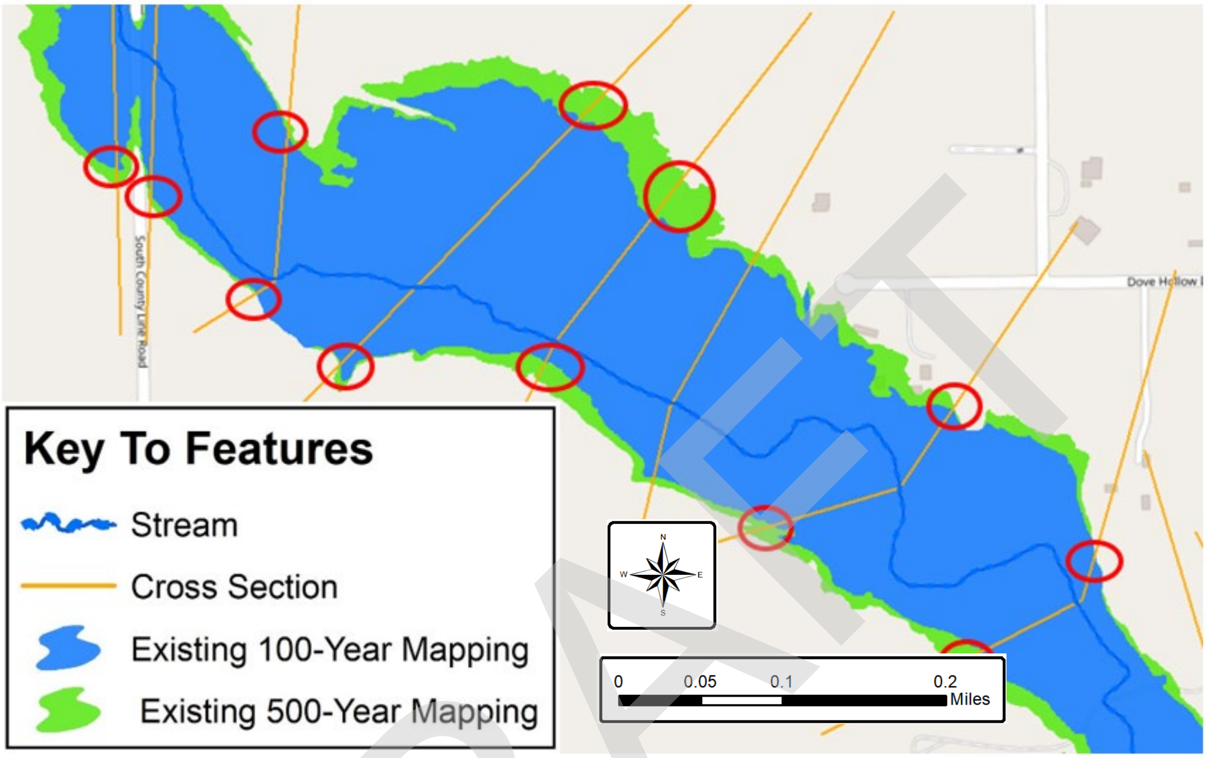


Table 2.30: Average Change in Horizontal Distance

Location	Average Width Change (Left or Right Overbank) Existing 100yr vs 500yr (ft)
1. Archer	30.8
2. Jack	32.2
3. Denton	32.6
4. Cedar	30.8
5. East Fork Trinity	42.6
6. Chambers	37.2
7. Richland	44.5
8. Lower Trinity Tehuacana	36.3
9. Lower Trinity Kickapoo	47.6
Rounded Average	**40**

A disadvantage of this approach is that average buffering is performed independent of topographic or WSEL changes. For areas with relatively flat terrain, the potential 500-year flood risk limit based on buffering may underestimate the expanded urban exposure risk. This disadvantage may be less impactful on rural floodplains whose exposure risks are large tracts of agricultural land. ***Table 2.31*** shows the existing and range of potential future conditions flood risk approach summary. ***Figure 2.56*** presents an example of the range of potential future flood risk.

Large maps showing the future conditions floodplain extents developed for the Trinity Region are included in ***Appendix B***.

Data Gaps

Future conditions mapping data gaps include that of the existing conditions data gaps in addition to the unavailability of extensive future flood models and associated mapping data in the Trinity Region.

Future Condition Flood Exposure Analysis

Existing Development within the Existing Conditions Floodplains

To assist with flood risk analysis, TWDB was provided statewide coverage of building footprints along with improvement value, land use, population estimate, and SVI values at the census tract level. This dataset formed the basis for determination of existing development within the existing conditions floodplains in the Trinity Region. According to this database, there are approximately three million buildings in the counties intersected by the Trinity Region. Approximately 65,000 buildings in the Trinity Region are partially or completely within the 100-year floodplains. ***Table 2.32*** summarizes existing development in existing conditions floodplains. Note that these estimates are based on a GIS analysis that accounts for the area of impact without necessarily considering the finished floor elevations of structures.

Existing and Future Developments within the Future Conditions Floodplains

Assuming that the 100-year future conditions floodplains are limited to the existing conditions 500-year floodplains, approximately 275,000 buildings in the TWDB database are partially or completely within the future conditions floodplains.

Table 2.31: Existing and Future Condition Flood Hazard Analysis Approach

	Best Available		→		→		→		Most Approximate	
	Local Floodplain (if determined current)		NFHL AE		BLE		NFHL A / FAFDS		No FEMA or Better than Quilt	
	100YR	500YR	100YR	500YR	100YR	500YR	100YR	500YR	100YR	500YR
Existing	Local Study (if provided)	Local Study (if provided)	Floodplain quilt 100YR	Floodplain quilt 500YR	BLE 100YR	BLE 500YR	Replaced with Fathom 100YR	Replaced with Fathom 500YR	Fathom 100YR	Fathom 500YR
Future	Local Study (if provided)	Local Study (if provided)	Range between Existing 100-year and 500-year	40-foot buffer of the existing 500YR	Range between BLE Existing 100-year and 500-year	40-foot buffer of the existing 500YR	Range between Fathom Existing 100-year and 500-year	40-foot buffer of the existing 500YR	Range between Fathom Existing 100-year and 500-year	40-foot buffer of the existing 500YR

Figure 2.56: Example of 2020-2023 Planning Cycle Range of Potential Future Condition Flood Risk Data

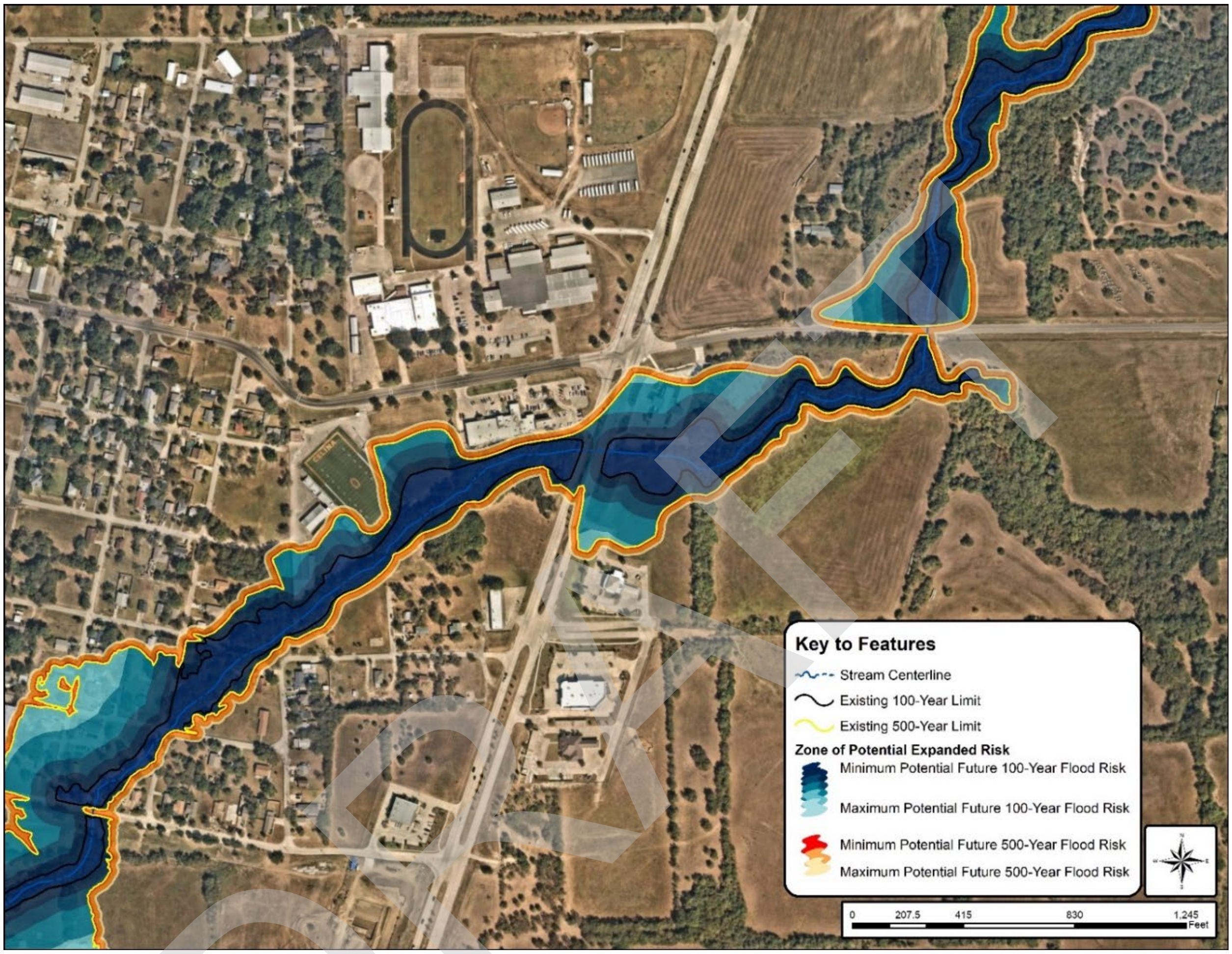


Table 2.32: Existing Development in Existing Condition Floodplain Quilt

County	Number of Structures within Existing Conditions Floodplains	County	Number of Structures within Existing Conditions Floodplains
Anderson	164	Jack	156
Archer	1	Johnson	1,465
Chambers	551	Kaufman	1,214
Clay	32	Leon	408
Collin	2,283	Liberty	4,740
Cooke	1,382	Limestone	32
Dallas	13,532	Madison	329
Denton	4,292	Montague	348
Ellis	1,637	Navarro	1,373
Fannin	129	Parker	1,164
Freestone	370	Polk	4,142
Grayson	312	Rockwall	485
Grimes	100	San Jacinto	2,701
Hardin	0	Tarrant	13,984
Henderson	2,481	Trinity	1,302
Hill	42	Van Zandt	256
Hood	0	Walker	1,398
Houston	435	Wise	1,370
Hunt	15	Young	11

Current development trends, combined with future population projections were used to estimate future developments within future condition floodplains. The United States Census Bureau's county level annual building permits survey data from 1991 to 2019 (30 years) along with TWDB's population projections were used to determine the average number of new building permits per unit change in population for each county in the Trinity Region. The number of new permits were divided by the change in population for each year from 1991 to 2019 and the average over the 30-year period is reported as the average # permits per unit population change.

The county specific number of permits per unit change in population were multiplied by the respective county level change in population between existing and future conditions to estimate the potential number of new buildings in the future. The TWDB's county level population data for 2020 and 2050 was used to determine the county change in population between existing and future conditions.

Table 2.33 summarizes the county level number of permits per unit change in population (as determined from United States Census data), existing and future populations, and existing and future estimated buildings in the Trinity Region.

Future Flood Mitigation Project with Dedicated Funding

Future FMPs with dedicated construction funding scheduled for completion within the next 30 years are included inin the Current Mitigation Projects section of this plan. Typically, funding committed for FMPs is within a shorter timeframe than the 30-year TWDB planning period. Once the funding is committed, the project moves forward as the funding must often be spent within a specified timeframe, which is often less than two years.

Future Conditions Flood Exposure

The potential future conditions mapping methodology (also discussed in the previous Best Available Data section) for the Trinity Region was accepted by the TWDB on January 21, 2022. This methodology was used to develop the 30-year potential future conditions floodplain quilt for the Trinity Region. For this planning cycle, the potential future flood exposure and vulnerability analysis consisted of two scenarios:

1. Estimated the structure count of buildings, critical facilities, infrastructure systems, population, and agriculture potentially exposed to flooding by overlaying the future conditions floodplain quilt developed for the Trinity Region
2. Estimated additional exposure and vulnerability by identifying of areas of existing and known flood hazard and future flood hazard areas where development might occur within the next 30 years if the current land development practices in the Trinity Region continues

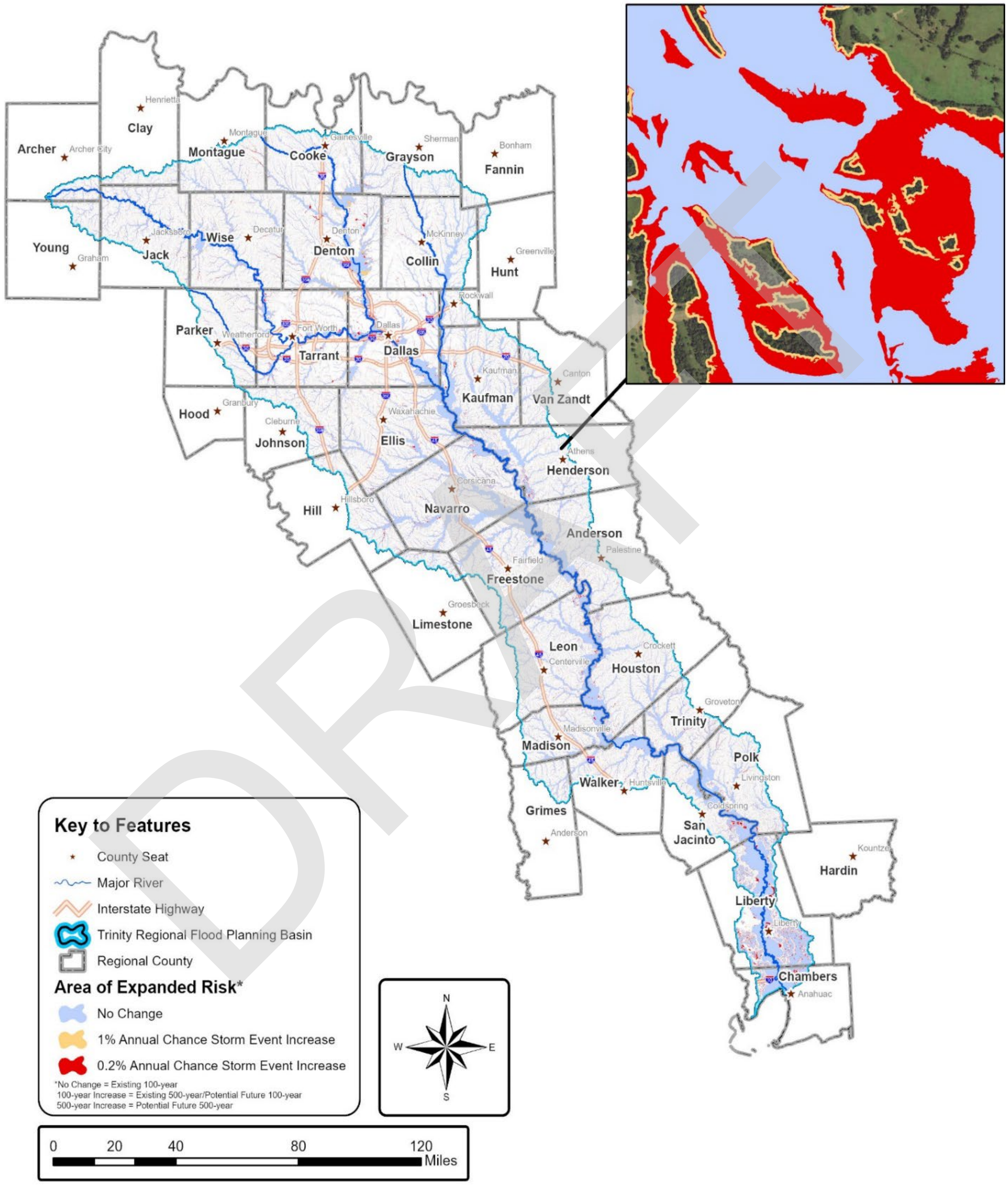
Potential Future Floodplain Changes

The potential 30-year future conditions floodplain quilt generally resulted in larger mapping extents when compared to the existing conditions floodplain quilt. ***Figure 2.57*** (See ***Appendix B*** for a larger version map) shows the areas of expanded risk between the existing and future conditions mapping.

Table 2.33: Estimated Future Development per County

County	Average # Permits per Unit Population Change	Existing Buildings (TWDB 2021)	Existing County Population (TWDB 2020)	Future County Population (TWDB 2050)	Future Additional Buildings (Estimated 2050)	Future Total Buildings (Estimated 2050)
Anderson	0.089	26,693	61,016	63,746	244	26,937
Archer	0.551	8,030	9,409	9,960	304	8,334
Chambers	0.432	26,162	42,162	68,541	11,395	37,557
Clay	0.771	10,078	11,154	11,503	269	10,347
Collin	0.281	269,530	1,050,506	1,807,279	212,791	482,321
Cooke	0.238	28,628	40,903	52,427	2,742	31,370
Dallas	0.629	674,024	2,587,960	3,429,783	529,228	1,203,252
Denton	0.185	231,182	891,063	1,584,015	128,532	359,714
Ellis	0.248	69,578	191,638	360,584	41,838	111,416
Fannin	0.120	23,852	38,330	69,328	3,718	27,570
Freestone	0.131	15,685	20,437	31,142	1,408	17,093
Grayson	0.228	67,409	135,311	178,907	9,957	77,366
Grimes	0.118	23,976	29,441	36,454	829	24,805
Hardin	0.260	30,186	59,477	69,560	2,626	32,812
Henderson	0.182	54,344	92,383	116,100	4,318	58,662
Hill	0.125	24,540	37,828	43,643	728	25,268
Hood	0.095	32,259	61,316	84,147	2,169	34,428
Hunt	0.229	58,373	104,894	207,929	23,554	81,927
Jack	0.069	7,867	9,751	11,033	89	7,956
Johnson	0.275	76,028	173,835	258,414	23,258	99,286
Kaufman	0.123	57,781	146,389	306,833	19,680	77,461
Leon	0.017	20,298	18,211	22,071	65	20,363
Liberty	0.961	53,494	86,303	118,048	30,513	84,007
Limestone	0.272	16,635	25,136	29,134	1,088	17,723
Madison	0.106	10,574	14,753	17,872	330	10,904
Montague	0.048	17,326	20,507	21,979	71	17,397
Navarro	0.191	31,296	52,505	74,213	4,154	35,450
Parker	0.144	67,342	201,491	360,125	22,812	90,154
Polk	2.458	29,354	51,870	66,796	36,692	66,046
Rockwall	0.292	30,887	119,410	246,938	37,239	68,126
San Jacinto	0.252	22,719	29,610	37,614	2,017	24,736
Tarrant	0.258	606,697	2,004,609	2,799,127	205,307	812,004
Trinity	0.069	10,819	16,502	17,473	67	10,886
Van Zandt	0.049	52,369	58,455	72,817	699	53,068
Walker	0.184	34,518	71,800	80,050	1,516	36,034
Wise	0.075	39,611	79,882	135,797	4,197	43,808
Young	0.183	13,485	19,336	21,972	484	13,969

Figure 2.57: Potential Expanded Risk between Existing and Future Conditions Floodplain Quilt



The largest increases in the potential future 100-year floodplain are seen in Collin, Dallas, Denton, Ellis, Navarro, and Tarrant counties. While Chambers County shows minimal increase from existing to future conditions, it must be noted that Chambers County has a high percent of the land areas in the Trinity Region within the potential future floodplain (63 percent). This is because Chambers is a coastal county located along the Trinity Bay and East Bay with relatively flat terrain and inundated with coastal flooding coupled with riverine flooding from the Trinity River. Hardin and Hood counties have less than 20 percent of their land area in the Trinity Region and, therefore, exhibit small floodplain area percentages. ***Table 2.34*** shows the floodplain area increases between the existing and future conditions mapping, in addition to the percent county area in the potential future mapping.

Per the future conditions mapping methodology in previous Future FMPs with Dedicated Funding section and ***Figure 2.58***, the horizontal increases in potential future mapping extents are shown as a range of potential minimum and maximum extents.

Scenario 1

The 30-year potential future conditions floodplain quilt was overlaid with all the same GIS exposure layers (buildings, critical facilities, agricultural areas, bridges, and LWCs) as in ***Task 2A*** to get an estimation of exposure to the future mapping based on existing development. For population estimates, the higher of the day or night population attributes was used for the exposure population estimates per guidance received from the TWDB.

Buildings, Critical Facilities, Infrastructure and Agriculture Exposure Totals by County

Figure 2.59 shows the total exposure counts of buildings, critical facilities, infrastructure, and agriculture by county of existing development to the future floodplains. The highest counts are in the populated areas of Collins, Dallas, Denton, and Tarrant counties in the Upper Subregion. Chambers, Henderson, and Liberty counties also show significant counts.

Population Totals by County

Figure 2.60 shows the population exposure to the existing floodplain quilt by county. As shown in ***Figure 2.13***, high populations exposures occur in the Collin, Dallas, Denton, and Tarrant counties in the Upper Subregion, as well as the coastal Liberty County in the Lower Subregion. Because the population count is the higher of the day or night numbers, the worst possible scenario was assumed where the maximum number of people present are exposed to the future condition floodplain quilt.

Table 2.34: Percentage of County in Future Condition Floodplain Quilt

County	Existing 1% Flood Hazard Areas in Trinity Region (Square Mile.)	Future 1% Flood Hazard Area in Trinity Region (Square Mile.)	Difference	Percentage of County in Region in 1% and 0.2% Flood Hazard Area
Anderson	143.4	151.8	8.4	26%
Archer	15.3	16.8	1.5	16%
Chambers	86.1	89	2.9	63%
Clay	21.4	28.1	6.7	23%
Collin	152.8	167.1	14.3	20%
Cooke	87.1	93.8	6.7	16%
Dallas	245.4	260.5	15.1	29%
Denton	235	250	15	26%
Ellis	194.7	208.4	13.7	22%
Fannin	4.9	5.9	1	13%
Freestone	183	193.3	10.3	25%
Grayson	46.4	51.7	5.3	15%
Grimes	26	28.7	2.7	21%
Hardin	0	0.01	0.01	0%
Henderson	153.8	163.3	9.5	29%
Hill	44.2	49.9	5.7	16%
Hood	0.03	0.04	0.01	2%
Houston	184.7	195.6	10.9	24%
Hunt	4.32	4.9	0.58	17%
Jack	84	95	11	14%
Johnson	41.9	47.8	5.9	13%
Kaufman	220.2	230.6	10.4	30%
Leon	176.3	186.2	9.9	23%
Liberty	326.7	334.5	7.8	51%
Limestone	17.7	19.3	1.6	20%
Madison	104.3	109.6	5.3	27%
Montague	33.2	37.8	4.6	9%
Navarro	292.8	309.4	16.6	29%
Parker	40.4	46.4	6	10%
Polk	149	157.7	8.7	28%
Rockwall	32.5	35	2.5	30%
San Jacinto	120.5	125	4.5	41%
Tarrant	159.2	33.1	17.9	4%
Trinity	83.6	89.6	6	24%
Van Zandt	40.3	45.4	5.1	21%
Walker	109.4	116	6.6	29%
Wise	125.9	137.8	11.9	15%
Young	9.6	11.3	1.7	10%

Figure 2.58: Future Condition Flood Hazard Areas (in Square Miles) by County

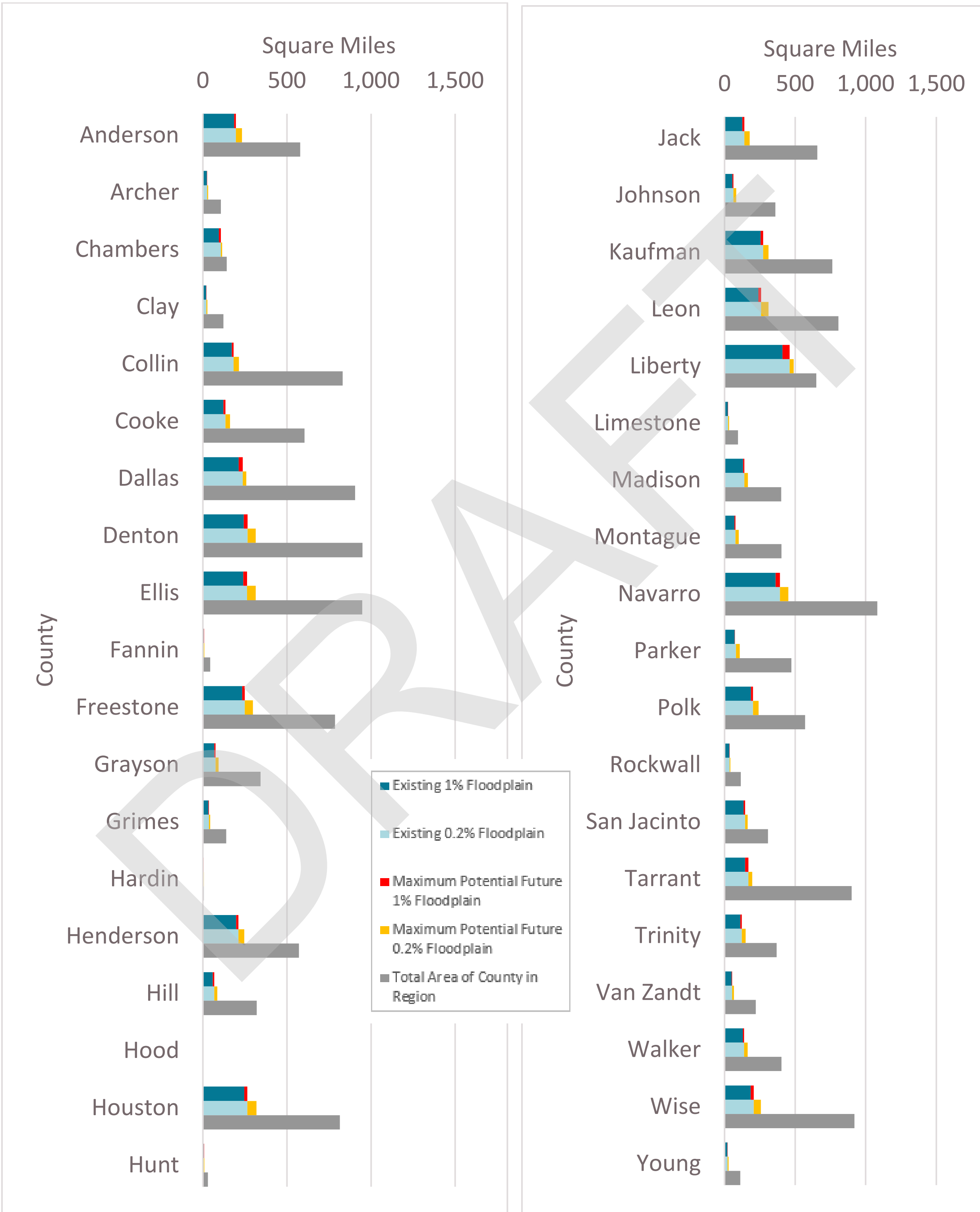


Figure 2.59: Potential Future Condition Flood Exposure by County

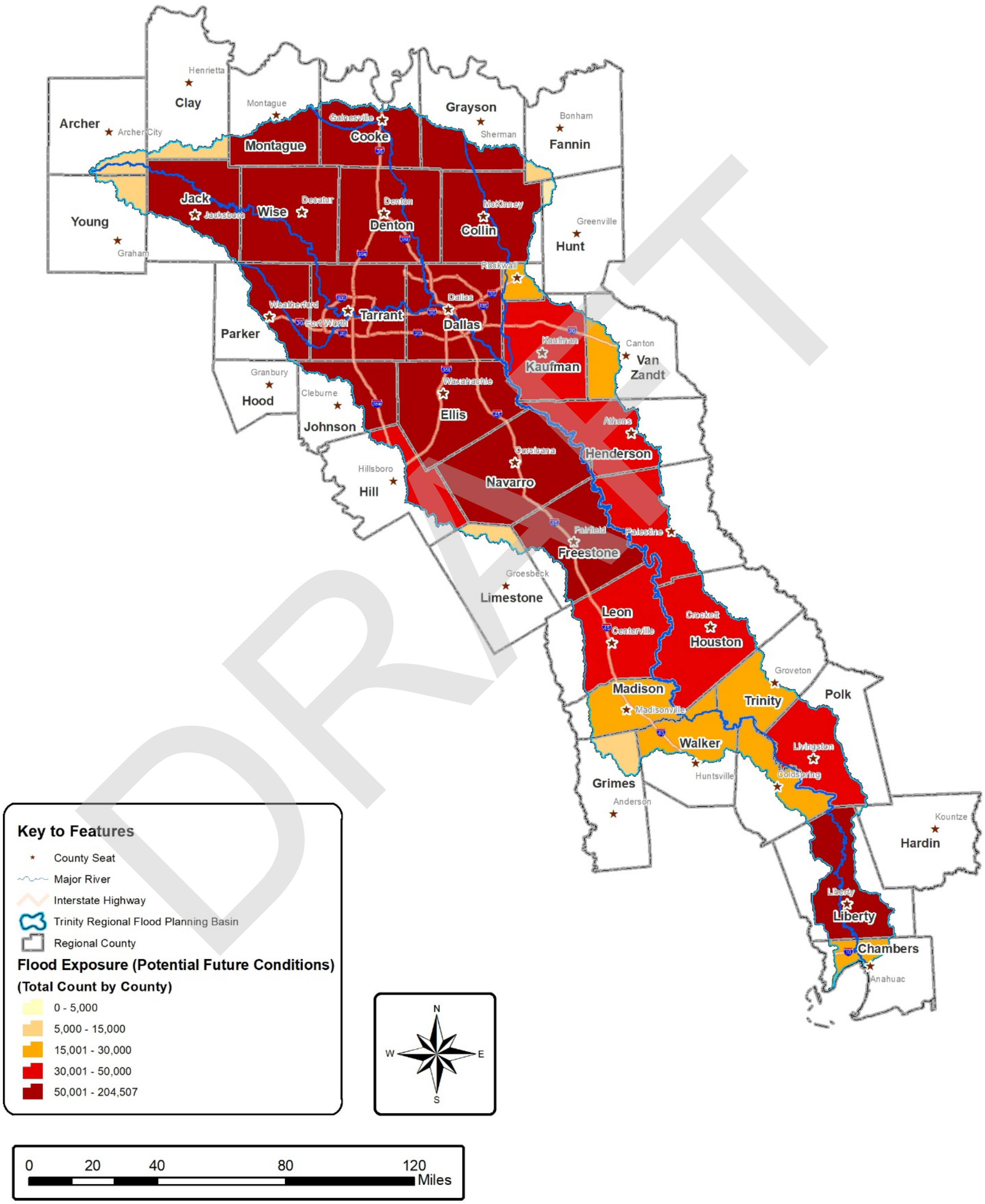
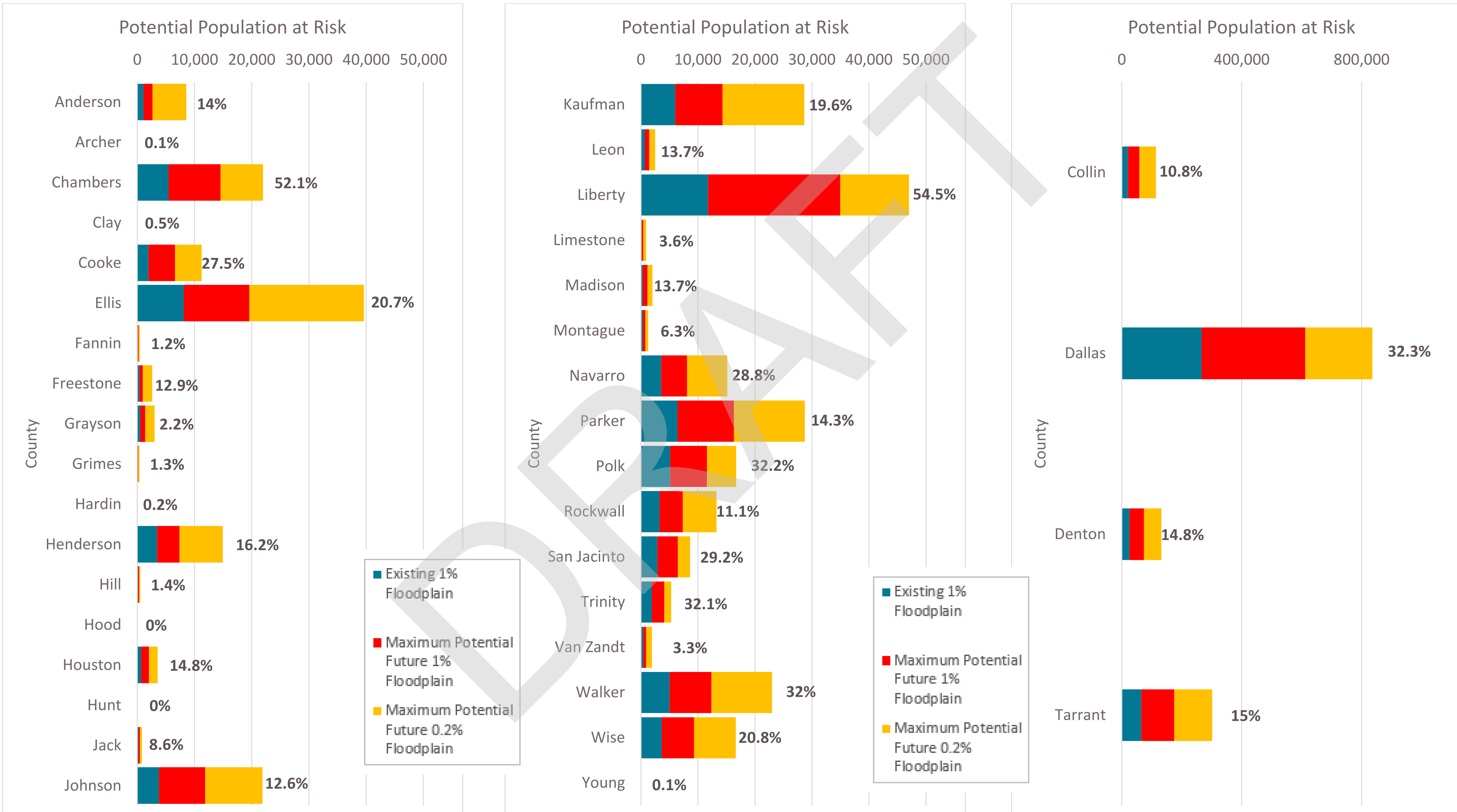


Figure 2.60: Potential Population at Risk in Future Condition Floodplain Quilt



Building Exposure Totals by County

Figure 2.61 shows the existing building type exposure distribution in the Trinity Region with the future condition's floodplain quilt.

Residential Properties

Figure 2.62 was made to show the maximum exposure additions to the existing conditions floodplain quilt exposure estimates, that results in the exposure counts for the potential future conditions 100-year and 500-year mapping. The largest increases occur in Collin, Dallas, Denton, and Tarrant counties. Ellis, Henderson, Johnson, Kaufman, Polk, and San Jacinto counties also showed significant increases in exposure to the future floodplain.

Non-Residential Properties

Figure 2.63 shows the total exposure counts by county of existing non-residential buildings to the future floodplains. In addition, ***Figure 2.64*** included a comparison exposure to existing conditions. The upper chart in ***Figure 2.64*** refers to existing conditions exposure while the lower chart applies to future conditions exposure. Overall, there were increase in exposure to the future floodplains for all non-residential buildings, with the largest increases in Collin, Dallas, Denton, and Tarrant counties. Tarrant County has very little agricultural exposure to floodplains. Dallas, Ellis, and Tarrant counties show industrial buildings in the floodplain with increases in exposures from existing to the future floodplains. The comparison chart also reveals that agriculture sector is a very small percentage of the non-residentials structures, flood exposure can be extensive across several counties and significant.

Critical Facilities Exposure Totals by County

The Trinity Region's existing critical facilities exposure to the potential future conditions mapping is shown in ***Figure 2.65***. The largest increases occur in Collin, Dallas, Denton, and Tarrant counties. Ellis, Kaufman, and Navarro counties also showed significant increases.

Roadway Crossings and Roadway Segments

Road and railroad crossing in the Trinity Region at risk of flooding to future conditions mapping are shown in ***Figure 2.66***.

Agricultural Area

Crop and livestock production dollar losses due to the 30-year future conditions mapping are summarized in ***Table 2.35*** and ***Figure 2.67***. Denton, Ellis, Hill, Houston, Kaufman, Leon, Limestone, Navarro, and Van Zandt counties have high agriculture exposure values to the future conditions mapping. The largest increases from existing conditions to future conditions were seen in Clay, Denton, Ellis, Fannin, Hill, Hunt, Leon, Limestone, and Van Zandt counties.

Figure 2.61: Building Type Distribution in the Future Condition Floodplain Quilt

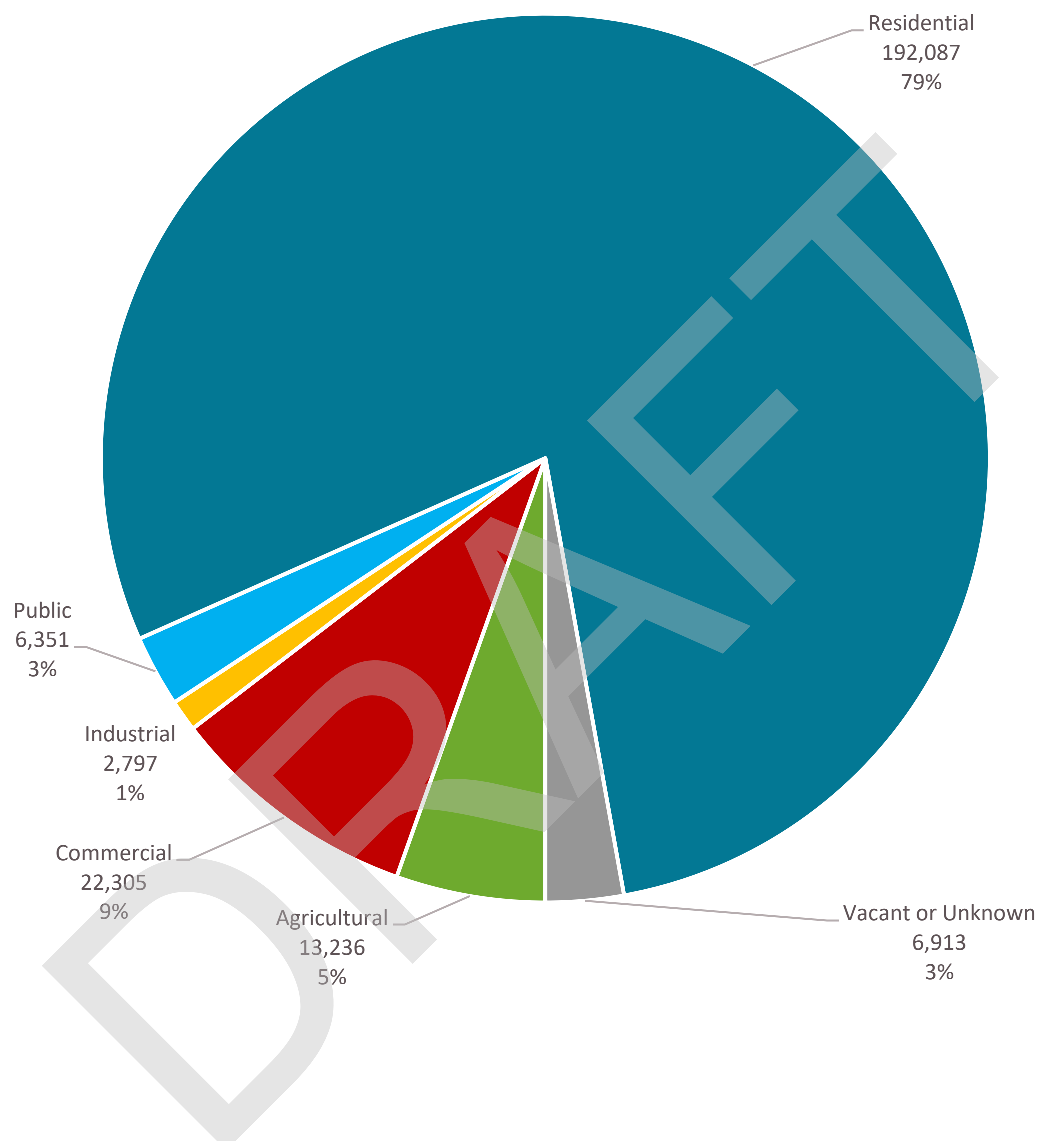


Figure 2.62: Potential Residential Structures at Risk in Future Condition Floodplain Quilt

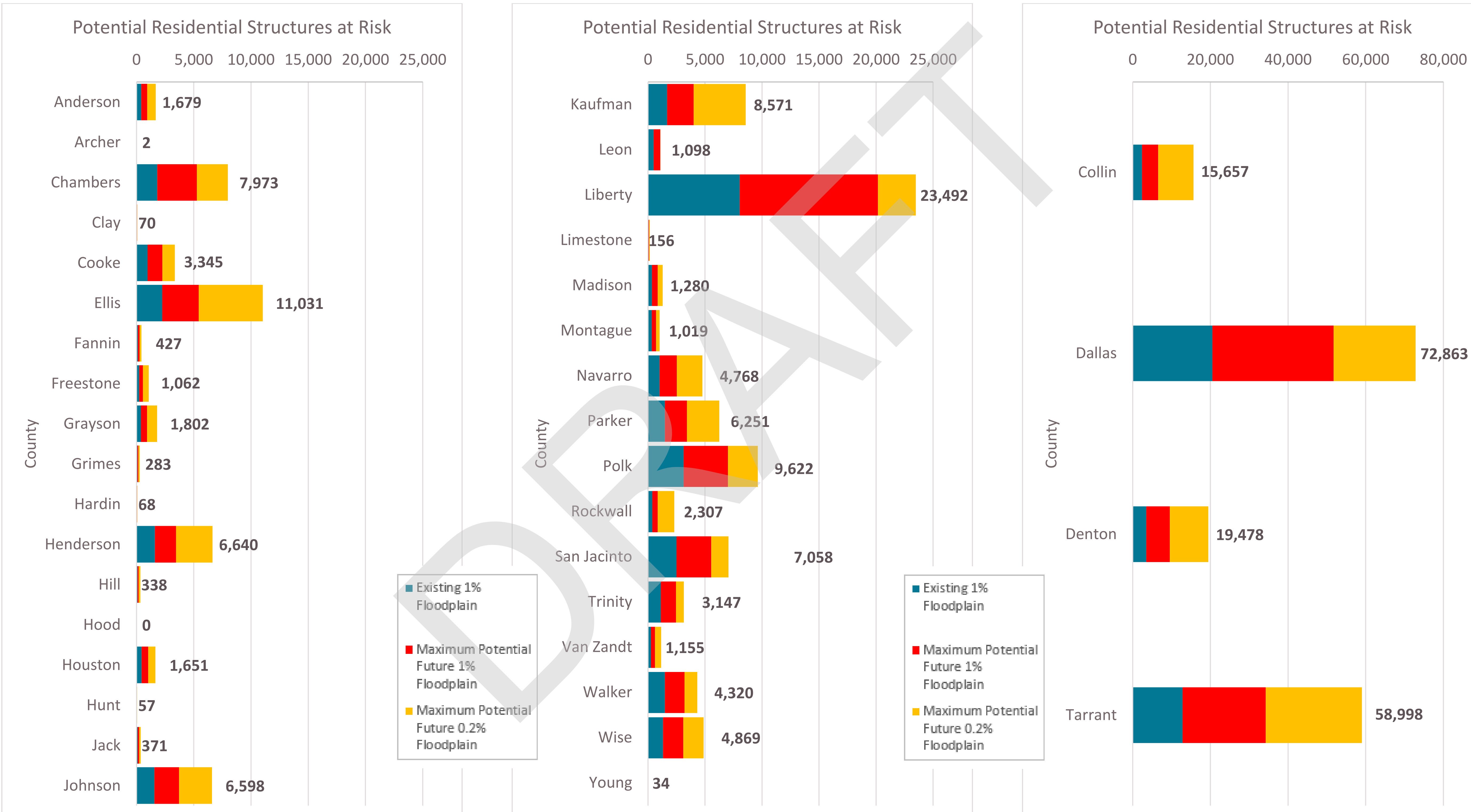


Figure 2.63: Potential Non-Residential Structures at Risk in Future Condition Floodplain Quilt

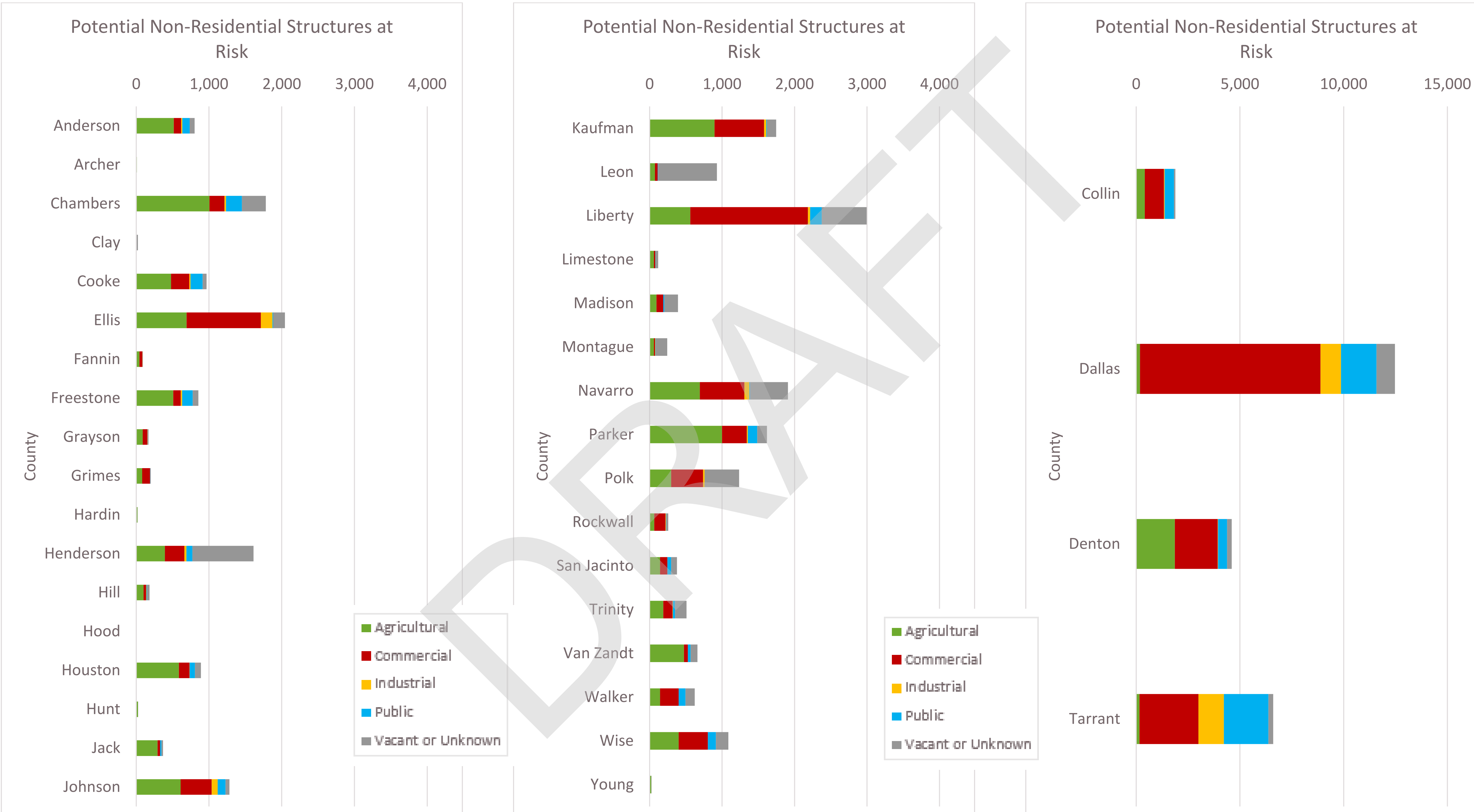


Figure 2.64: Potential Non-Residential Structures at Risk in Future Condition Floodplain Quilt

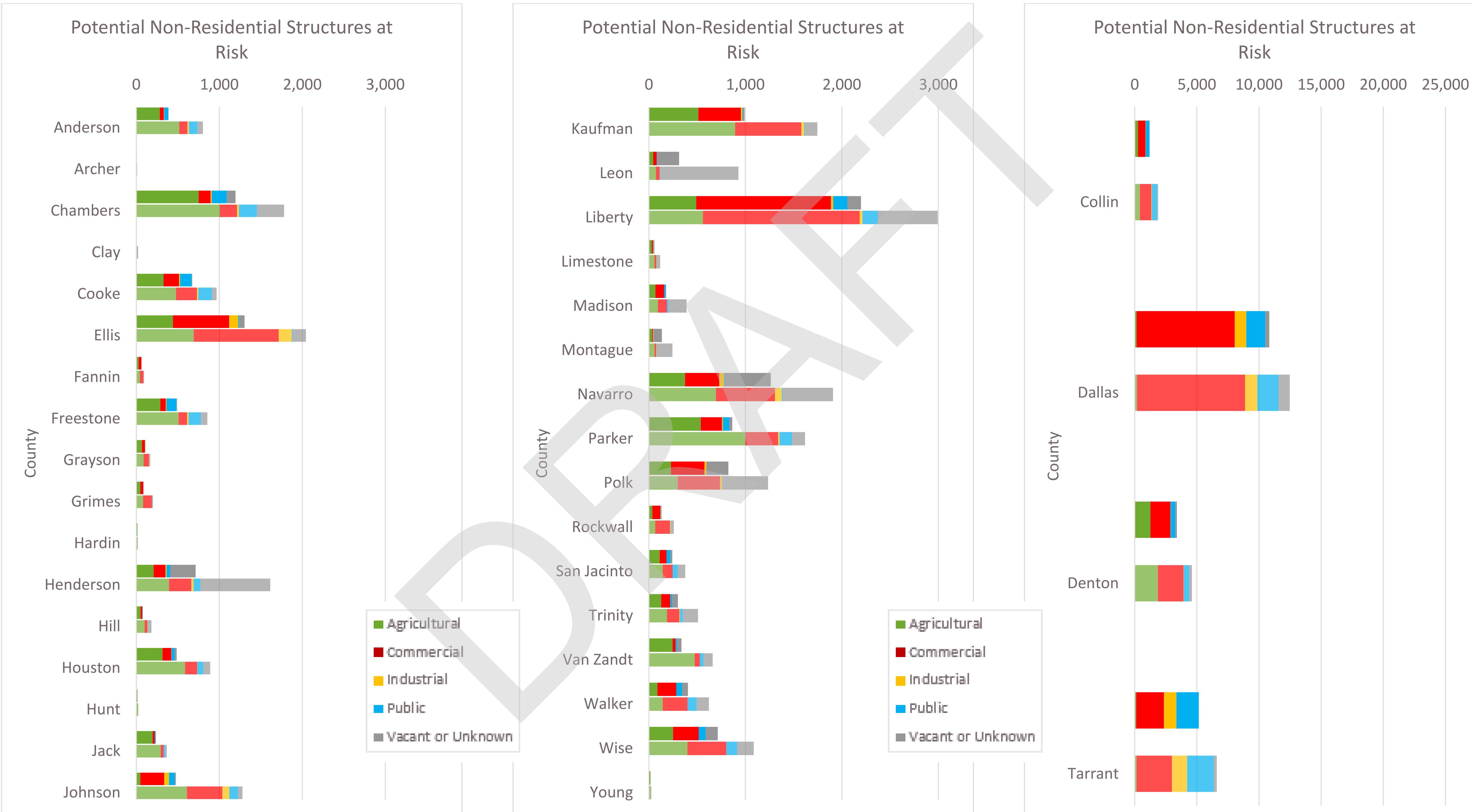


Figure 2.65: Potential Critical Facilities at Risk in Future Conditions Floodplain Quilt

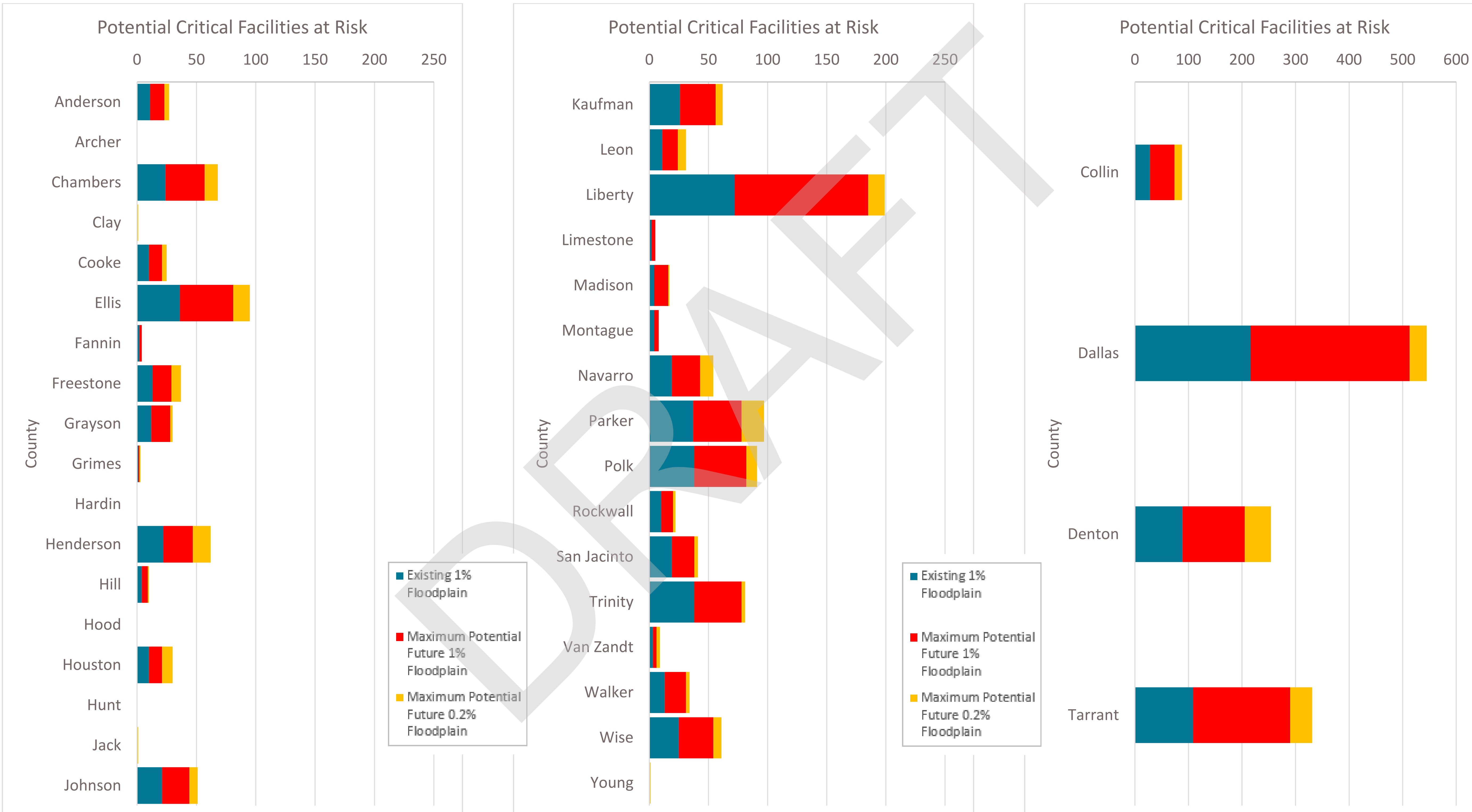


Figure 2.66: Linear Miles of Roadway at Risk in Future Condition Floodplain Quilt

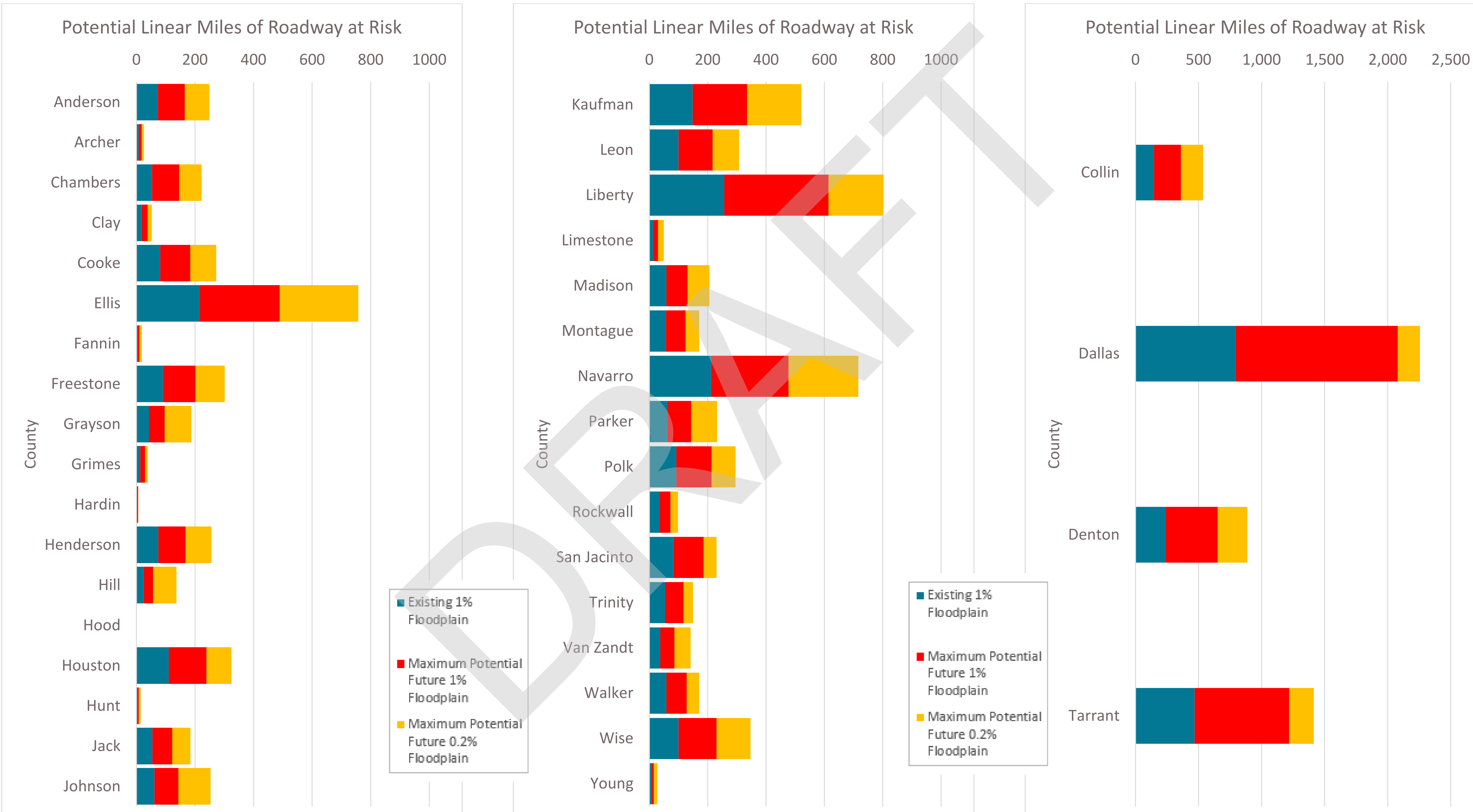


Figure 2.67: Agricultural Land at Risk in Future Condition Floodplain Quilt

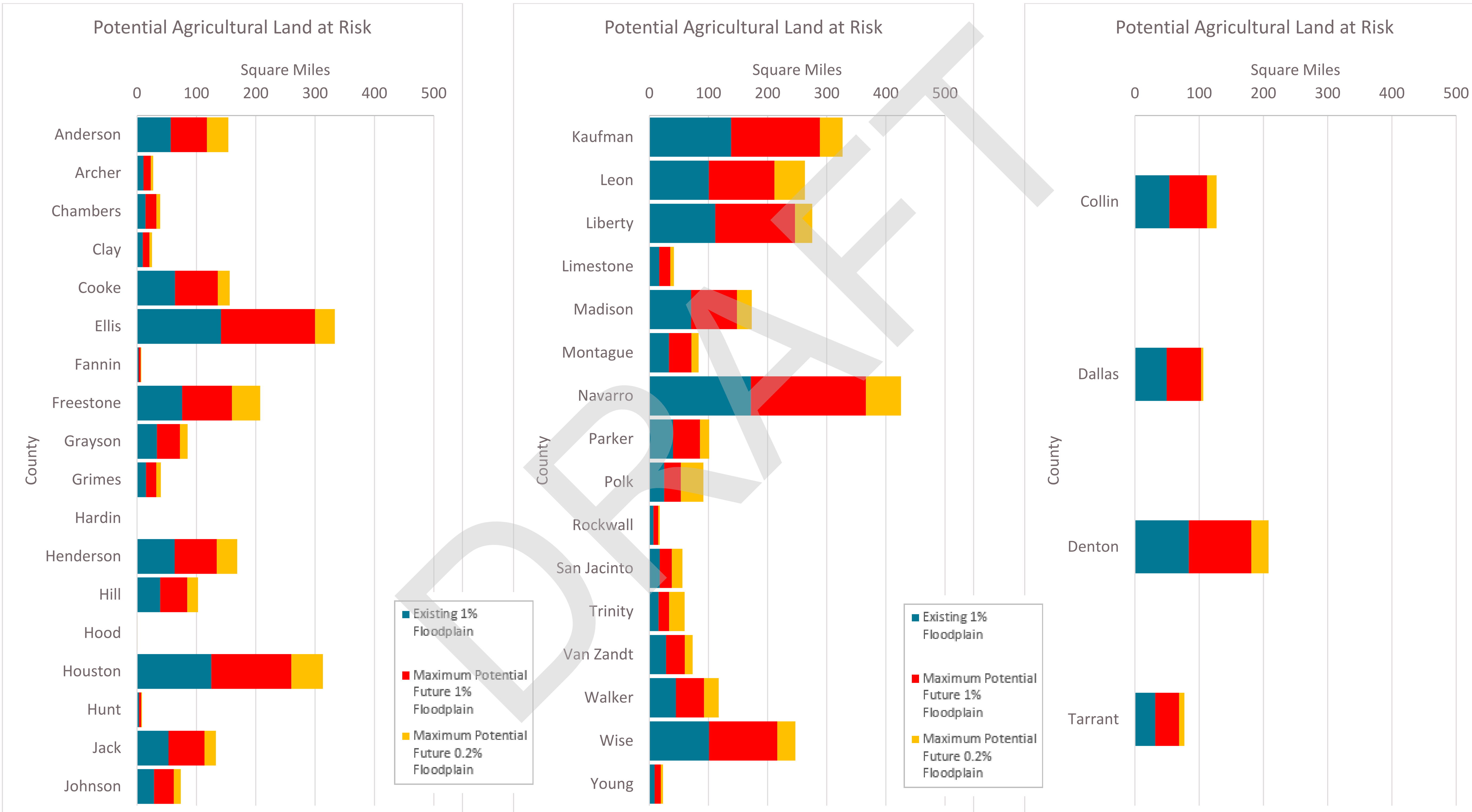


Table 2.35: Exposed Crop and Livestock Production Dollar Losses in Future Condition Floodplain Quilt

County	$ Losses in Future 100-Year	$ Losses in Future 500-Year	Total $ Losses
Anderson	$6,933,056.25	$329,595.67	$92,943,000.00
Archer	$3,487,654.41	$516,719.61	$72,439,000.00
Chambers	$972,186.27	$70,603.11	$19,252,000.00
Clay	$4,811,591.40	$1,886,621.70	$55,650,000.00
Collin*	$3,516,314.55	$419,353.94	$66,829,000.00
Cooke	$3,383,185.51	$350,675.41	$53,830,000.00
Dallas	$1,756,219.92	$56,726.37	$29,781,000.00
Denton*	$9,475,769.71	$986,697.79	$123,209,000.00
Ellis*	$8,677,428.14	$641,173.10	$73,146,000.00
Fannin	$4,006,858.18	$1,092,588.99	$86,292,000.00
Freestone	$4,891,996.29	$349,169.62	$68,131,000.00
Grayson	$3,416,773.23	$553,606.39	$66,171,000.00
Grimes	$3,687,533.40	$490,804.55	$47,509,000.00
Hardin	$--	$68.32	$4,694,000.00
Henderson	$3,128,474.60	$231,677.19	$40,183,000.00
Hill	$9,426,468.51	$1,338,331.75	$114,001,000.00
Hood	$160,458.00	$74,998.70	$18,944,000.00
Houston	$7,994,246.64	$310,070.56	$64,518,000.00
Hunt	$3,637,190.25	$703,591.84	$55,313,000.00
Jack	$1,155,866.53	$173,822.95	$23,176,000.00
Johnson	$3,066,438.54	$500,354.92	$57,850,000.00
Kaufman	$8,560,146.51	$496,540.81	$57,063,000.00
Leon	$16,511,520.00	$760,037.63	$169,404,000.00
Liberty	$3,437,069.60	$126,008.68	$29,950,000.00
Limestone	$8,319,202.35	$841,658.54	$66,257,000.00
Madison	$--	$--	$ -
Montague	$1,301,410.06	$183,664.94	$33,416,000.00
Navarro*	$8,518,046.01	$679,552.53	$73,306,000.00
Parker	$2,931,447.55	$432,336.44	$65,043,000.00
Polk	$272,884.03	$12,169.33	$6,831,000.00
Rockwall	$395,734.62	$79,496.59	$7,830,000.00
San Jacinto	$400,689.07	$10,333.99	$7,190,000.00
Tarrant*	$1,013,186.99	$132,237.72	$29,393,000.00
Trinity	$240,802.44	$17,127.24	$8,228,000.00
Van Zandt	$10,352,110.78	$1,552,989.99	$104,603,000.00
Walker	$3,376,382.55	$112,157.41	$33,795,000.00
Wise	$3,303,635.76	$322,882.43	$46,269,000.00
Young	$672,132.99	$141,323.64	$21,694,000.00

Hardin County had no agricultural exposure in the Trinity Region (less than one percent of the land area is in the Trinity Region). Even though Madison County showed a large agriculture area exposure to the future conditions mapping (a little more than Anderson County), there was no data available from the 2017 USDA crop and livestock production summaries.

Scenario 2

The Existing and Future Developments within Future Conditions Floodplains section discussed existing and future developments in the floodplain and estimated number of potential buildings per county in 2050 using the number of permits per unit change in population. However, the number of permits per unit change in population in the future condition floodplains are not expected to be the same as the county level values since development in future condition floodplains are likely to be regulated by floodplain regulations (assuming existing floodplain management practices will not change). Therefore, four criteria were used to determine weighting factors for development in the future condition floodplains:

- FEMA's Community Rating System (CRS)
- Participation in the NFIP
- Adoption of higher standards
- Presence or absence of a Hazard Mitigation Plan (HMP)

Figures showing spatial distribution of these factors in the Trinity Region are included in ***Appendix B***. CRS applicable discount ranging from 0 to 45 percent were converted to normalized scores ranging from 0 to 1. For example, a community with a CRS rating of 5 (or 25 percent discount) received a score of 0.56. Each community was given a score of 1 or 0 depending on participation or non-participation in NFIP. Similarly, a score of 1 was assigned to communities adopting higher standards and 0 for others. Communities with a HMP were assigned a score of 1 and 0 for others. The community level scores for each criterion were averaged at the county level. Each county level criterion was assigned an equal weight of 0.25 and summed to generate one weighted score for each county. A higher score implies more rigorous regulations associated with floodplain development. Therefore, a county with a weighted score of 1 implies that the likelihood of floodplain development is close to 0. The floodplain number of permits per unit change in population for such instance is 0 or county level number of permits per unit change in population multiplied 1 minus the weighted score. The weighting factors were determined as 1 minus the weighted scores and were subsequently multiplied by the county level number of permits per unit change in population to determine floodplain number of permits per unit change in population. ***Table 2.36*** summarizes the scores for each criterion, weighting factor, and floodplain number of permits per unit change in population by county in the Trinity Region.

Table 2.36: Development Factor Per Unit Change in Population

County	Average # Permits per Unit Population Change	NFIP Score	CRS Score	HMP Score	Higher Standards Score	Weighting Factor	Floodplain # Permits per Unit Population Change
Anderson	0.089	1.00	0.00	0.00	0.67	0.58	0.052
Archer	0.551	1.00	0.00	0.00	0.00	0.75	0.413
Chambers	0.432	1.00	0.03	0.00	0.86	0.53	0.228
Clay	0.771	1.00	0.00	0.00	1.00	0.50	0.386
Collin	0.281	0.96	0.00	0.88	0.79	0.34	0.096
Cooke	0.238	0.88	0.00	0.00	0.63	0.62	0.148
Dallas	0.629	1.00	0.04	0.08	0.96	0.48	0.302
Denton	0.185	0.91	0.01	0.67	0.85	0.39	0.072
Ellis	0.248	0.88	0.00	0.94	0.75	0.36	0.089
Fannin	0.120	1.00	0.00	1.00	0.67	0.33	0.040
Freestone	0.131	0.67	0.00	0.00	0.00	0.83	0.109
Grayson	0.228	0.70	0.00	1.00	0.80	0.38	0.086
Grimes	0.118	0.33	0.00	1.00	0.00	0.67	0.079
Hardin	0.260	1.00	0.00	0.00	1.00	0.50	0.130
Henderson	0.182	1.00	0.00	0.00	0.92	0.52	0.095
Hill	0.125	0.63	0.00	0.00	0.63	0.69	0.086
Hood	0.095	1.00	0.00	0.00	0.50	0.63	0.059
Houston	0.075	0.80	0.00	1.00	0.40	0.45	0.034
Hunt	0.229	1.00	0.00	1.00	1.00	0.25	0.057
Jack	0.069	1.00	0.00	0.00	0.00	0.75	0.052
Johnson	0.275	0.90	0.00	0.10	0.50	0.63	0.172
Kaufman	0.123	0.63	0.00	0.38	0.63	0.59	0.072
Leon	0.017	0.86	0.00	0.00	0.57	0.64	0.011
Liberty	0.961	1.00	0.00	0.00	0.50	0.63	0.601
Limestone	0.272	0.75	0.00	0.25	0.00	0.75	0.204
Madison	0.106	0.67	0.00	0.33	0.67	0.58	0.062
Montague	0.048	1.00	0.00	0.00	0.67	0.58	0.028
Navarro	0.191	0.63	0.00	0.16	0.47	0.69	0.131
Parker	0.144	0.91	0.00	0.09	0.64	0.59	0.085
Polk	2.458	0.80	0.00	0.00	0.60	0.65	1.598
Rockwall	0.292	0.83	0.00	0.00	0.67	0.63	0.183
San Jacinto	0.252	1.00	0.00	0.00	0.75	0.56	0.142
Tarrant	0.258	1.00	0.03	0.00	0.94	0.51	0.131
Trinity	0.069	1.00	0.00	0.00	0.33	0.67	0.046
Van Zandt	0.049	1.00	0.00	0.00	1.00	0.50	0.024
Walker	0.184	1.00	0.00	0.00	0.33	0.67	0.123
Wise	0.075	0.85	0.00	0.38	0.62	0.54	0.040
Young	0.183	1.00	0.00	0.00	1.00	0.50	0.092

The 2021 TWDB buildings dataset was used to determine the existing structure and exposed population in the existing and future 100-year and 500-year floodplains. The exposed population in the floodplains at the county level divided by the existing population provides as estimate of the percent of the county population exposed to flood risk. Assuming that the percent of exposed population at the county level in the future conditions floodplains remains unchanged from existing conditions, the existing percent exposed population multiplied by the future county population provides the future exposed population in the future condition floodplains. The additional future population in the future condition floodplains multiplied by the floodplain number of permits per unit population change provides an estimate of additional future buildings in future conditions floodplains. ***Table 2.37*** and ***Table 2.38*** summarize the existing buildings and population in the existing conditions floodplains, and future estimated buildings and population in future condition floodplains.

Future Condition Vulnerability Analysis

Resiliency of Communities

The resiliency ratings of communities in the Trinity Region, previously discussed in the Resiliency of Communities section, helps predict a community's ability and readiness to recover quickly from disruptions such as flood-related disasters. This means that the current resiliency rating in the Trinity Region is a measure of the communities' abilities within the region to prepare for future threats, absorb impacts, and to recover and adapt after disruptive event such as a flood.

Recent developments in flood data science and data development such as FEMA's planned shift from binary in/out floodplain mapping to graduated risk analysis and Risk rating 2.0 will help create better risk-informed communities. Local communities, regional entities, state, and federal authorities, as well as floodplain-related organizations continue to encourage and advocate for higher standards and No Adverse Impacts (NAI).

These and many other floodplain management practices will create plans and systems that future-proof communities in the Trinity Region.

Vulnerabilities of Structures, Low Water Crossings, and Critical Facilities

The 2018 CDC SVI data was used to estimate community vulnerability in the context of the potential future conditions flood quilt. The SVI values for all the structures, critical facilities, and LWCs exposed to the future condition floodplain quilt are summarized by county average and shown in ***Figure 2.68***.

Table 2.37: Estimated Building and Population in Existing and Future Floodplain (100-Year)

County	Existing Buildings in Existing Floodplain	Existing Population in Existing Floodplain	Existing Buildings in Future Floodplain	Future Buildings in Future Floodplain	Future Population in Future Floodplain
Anderson	164	74	192	192	77
Archer	1	5	2	2	5
Chambers	551	547	1,317	1,395	889
Clay	32	13	35	35	13
Collin	2,283	16,526	4,011	5,158	28,431
Cooke	1,382	1,764	1,697	1,771	2,261
Dallas	13,532	114,007	38,910	50,101	151,092
Denton	4,292	11,530	8,384	9,033	20,497
Ellis	1,637	3,369	2,197	2,460	6,339
Fannin	129	75	168	170	136
Freestone	370	212	458	470	323
Grayson	312	393	339	350	520
Grimes	100	55	132	133	68
Hardin	0	0	0	0	0
Henderson	2,481	2,601	2,540	2,603	3,269
Hill	42	86	67	68	99
Hood	0	0	0	0	0
Houston	435	334	562	562	336
Hunt	15	6	15	15	12
Jack	156	85	210	211	96
Johnson	1,465	2,821	1,788	2,024	4,194
Kaufman	1,214	1,893	1,525	1,675	3,968
Leon	408	229	484	485	278
Liberty	4,740	4,841	8,152	9,222	6,622
Limestone	32	29	50	51	34
Madison	329	367	412	417	445
Montague	348	229	355	355	245
Navarro	1,373	2,318	1,702	1,828	3,276
Parker	1,164	2,300	1,253	1,407	4,111
Polk	4,142	5,028	4,832	7,144	6,475
Rockwall	485	1,047	508	712	2,165
San Jacinto	2,701	2,507	3,234	3,330	3,185
Tarrant	13,984	61,398	24,511	27,702	85,733
Trinity	1,302	1,669	1,489	1,494	1,767
Van Zandt	256	195	340	341	243
Walker	1,398	3,654	1,650	1,702	4,074
Wise	1,370	1,521	1,429	1,472	2,586
Young	11	0	11	11	0

Table 2.38: Estimated Building and Population in Existing and Future Floodplain (500-Year)

County	Existing Buildings in Existing Floodplain	Existing Population in Existing Floodplain	Exiting Buildings in Future Floodplain	Future Buildings in Future Floodplain	Future Population in Future Floodplain
Anderson	28	38	90	90	40
Archer	1	0	2	2	0
Chambers	766	1,142	503	666	1,857
Clay	3	1	32	32	1
Collin	1,728	12,331	4,805	5,660	21,214
Cooke	315	2,526	347	452	3,238
Dallas	25,378	232,851	12,083	34,939	308,594
Denton	4,092	33,060	3,744	5,604	58,770
Ellis	560	1,190	904	997	2,239
Fannin	39	45	83	84	81
Freestone	88	60	209	212	91
Grayson	27	62	144	146	82
Grimes	32	17	34	34	21
Hardin	0	0	0	0	0
Henderson	59	43	1,562	1,563	54
Hill	25	22	50	50	25
Hood	0	0	0	0	0
Houston	127	184	156	156	185
Hunt	0	0	12	12	0
Jack	54	27	85	85	31
Johnson	323	1,778	723	872	2,643
Kaufman	311	404	656	688	847
Leon	76	50	176	176	61
Liberty	3,412	8,324	538	2,377	11,386
Limestone	18	26	25	26	30
Madison	83	53	100	101	64
Montague	7	3	65	65	3
Navarro	329	384	588	609	543
Parker	89	711	478	526	1,271
Polk	690	1,092	847	1,349	1,406
Rockwall	23	52	477	487	108
San Jacinto	533	618	561	585	785
Tarrant	10,527	43,205	14,471	16,717	60,329
Trinity	187	196	188	189	208
Van Zandt	84	63	213	213	78
Walker	252	1,382	267	287	1,541
Wise	59	86	550	552	146
Young	0	0	3	3	0

Figure 2.68: Future Condition Exposures Averaged by County

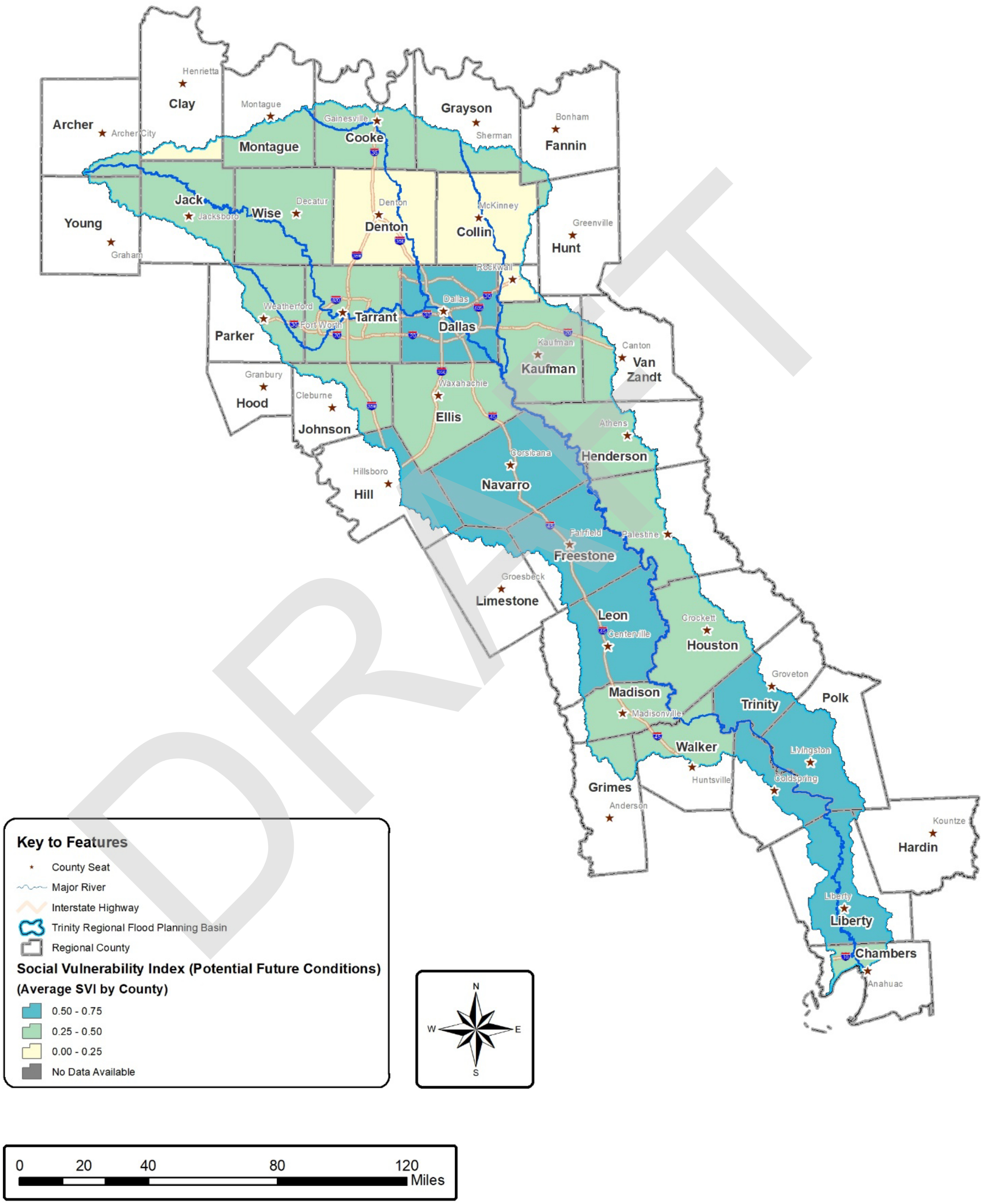


Figure 2.69 shows the countywide average distribution of SVI with regards to the exposed structures, critical facilities, and LWCs in the Trinity Region. ***Figure 2.68*** shows Clay, Collin, Denton, Parker, and Rockwall counties as being the least vulnerable with respect to the future condition exposure of structures, critical facilities, and LWCs. TWDB has a threshold of 0.75 as an indicator for highly vulnerable areas. At the county level, none of the counties reached this threshold. Large, detailed maps for the vulnerability assessment are shown in ***Appendix B***.

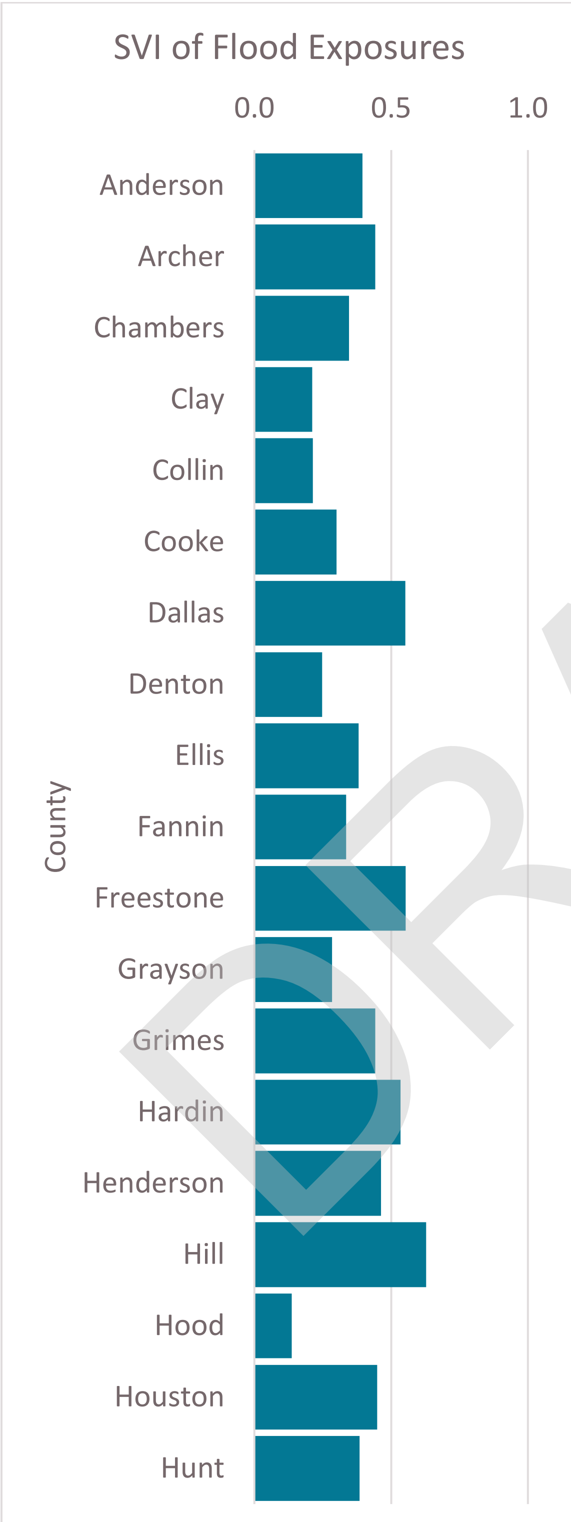
Summary of Future Conditions Flood Exposure and Vulnerability Analyses

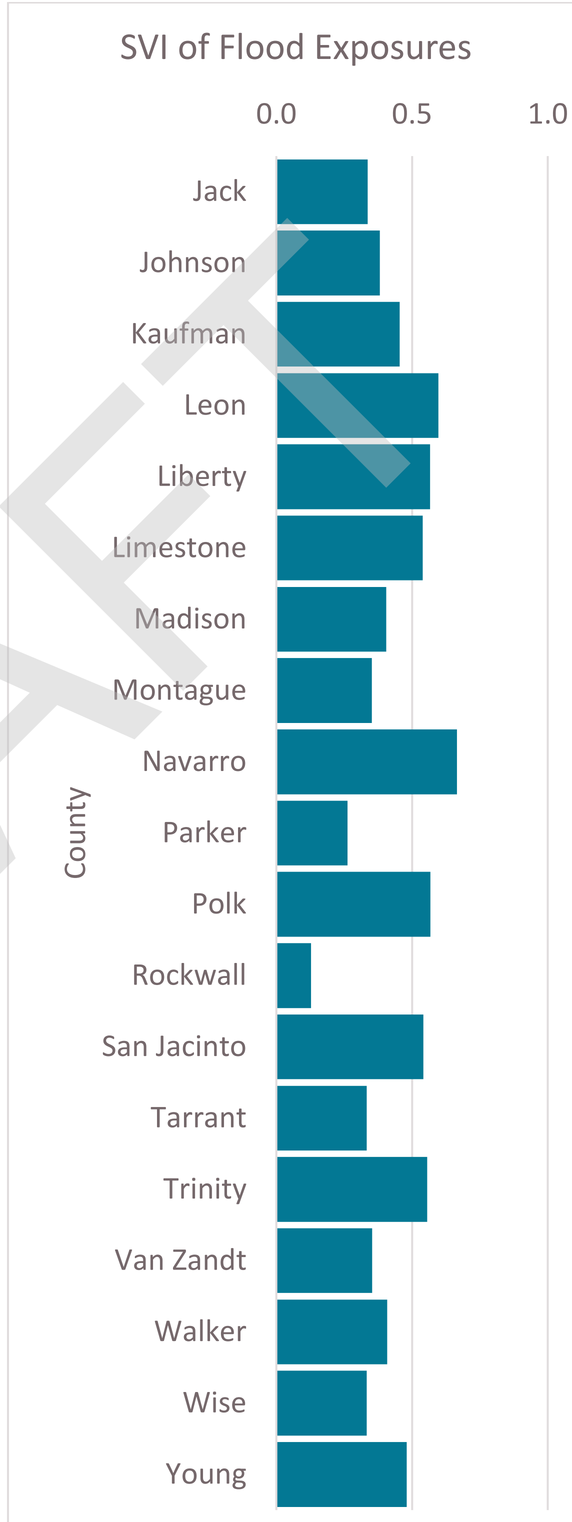
The future condition floodplain anticipates that there will be 51 percent more structures and 52 percent more people potentially impacted than under current conditions.

The future flood risk, exposure, and vulnerability assessment for the Trinity Region are summarized in ***TWDB-Required Table 5*** located in ***Appendix A***. The ***TWDB-Required Table 5*** provides the results per county of the future flood exposure and vulnerability analysis as outlined in the Technical Guidelines for Regional Flood Planning.

A geodatabase with applicable layers as well as associated ***TWDB-Required Maps 1*** through ***22*** are provided in ***Appendix B*** as digital data. ***TWDB-Required Table 2.2***, included in ***Appendix A***, outlines the geodatabase deliverables included in this Technical Memorandum as well as spatial files and tables.

Figure 2.69: Future Condition Flood Exposures by County





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