Appendix A – Hydrology and Hydraulic Engineering

Lower Guadalupe Feasibility Study
(Guadalupe and Blanco Rivers), TX
Integrated Draft Feasibility Report and Environmental Impact Assessment

December 2019

US Army Corps
of Engineers®
Fort Worth District

(NOTE: This page intentionally left blank.)

Table of Contents

1 Background

1.1 Study Purpose

The purpose of Lower Guadalupe Interim Feasibility Study is to develop alternatives that reduce flood risk within the Lower Guadalupe River Basin. The non-federal sponsor of the study is the Guadalupe – Blanco River Authority (GBRA). The scope of the study is to investigate the hydrologic and hydraulic conditions of the Blanco and Guadalupe Rivers within the study area, and to determine if there is a federal interest in implementing alternatives to address flood risk. This appendix will describe the hydrologic and hydraulic (H&H) analyses that were undertaken within the scope of this study.

1.2 Study Area

The Lower Guadalupe Basin study area is comprised of the portions of the Guadalupe and Blanco River Basins in Texas that are under the stewardship of the GBRA. The study area includes the Guadalupe River from Canyon Lake Dam downstream to Victoria, Texas, the San Marcos River from the headwaters to its confluence with the Guadalupe River near Gonzales, Texas, and the Blanco River from the confluence with the San Marcos River upstream through Blanco County, as shown in Figure 1.1.

The study area covers approximately 4,530 square miles of contributing drainage area from Canyon Dam and the confluence of the Guadalupe and San Antonio Rivers and drains a large portion of the following 7 Texas counties: Comal, Guadalupe, Hays, and Caldwell, Gonzales, DeWitt, and Victoria. Three large urban areas lie within the study area including San Marcos, New Braunfels, and Victoria. Two Interstate Highways, I-35 and I-10, traverse the northern portion of the study area. I-35 runs north and south between San Antonio and Austin, and crosses the Blanco and San Marcos Rivers in San Marcos, multiple tributaries of the San Marcos River in between San Marcos and New Braunfels, and the Guadalupe River at New Braunfels. The I-35 corridor has seen substantial residential and commercial development. The study area's population is estimated at 397,000, or approximately 71% of the total population of the seven counties.

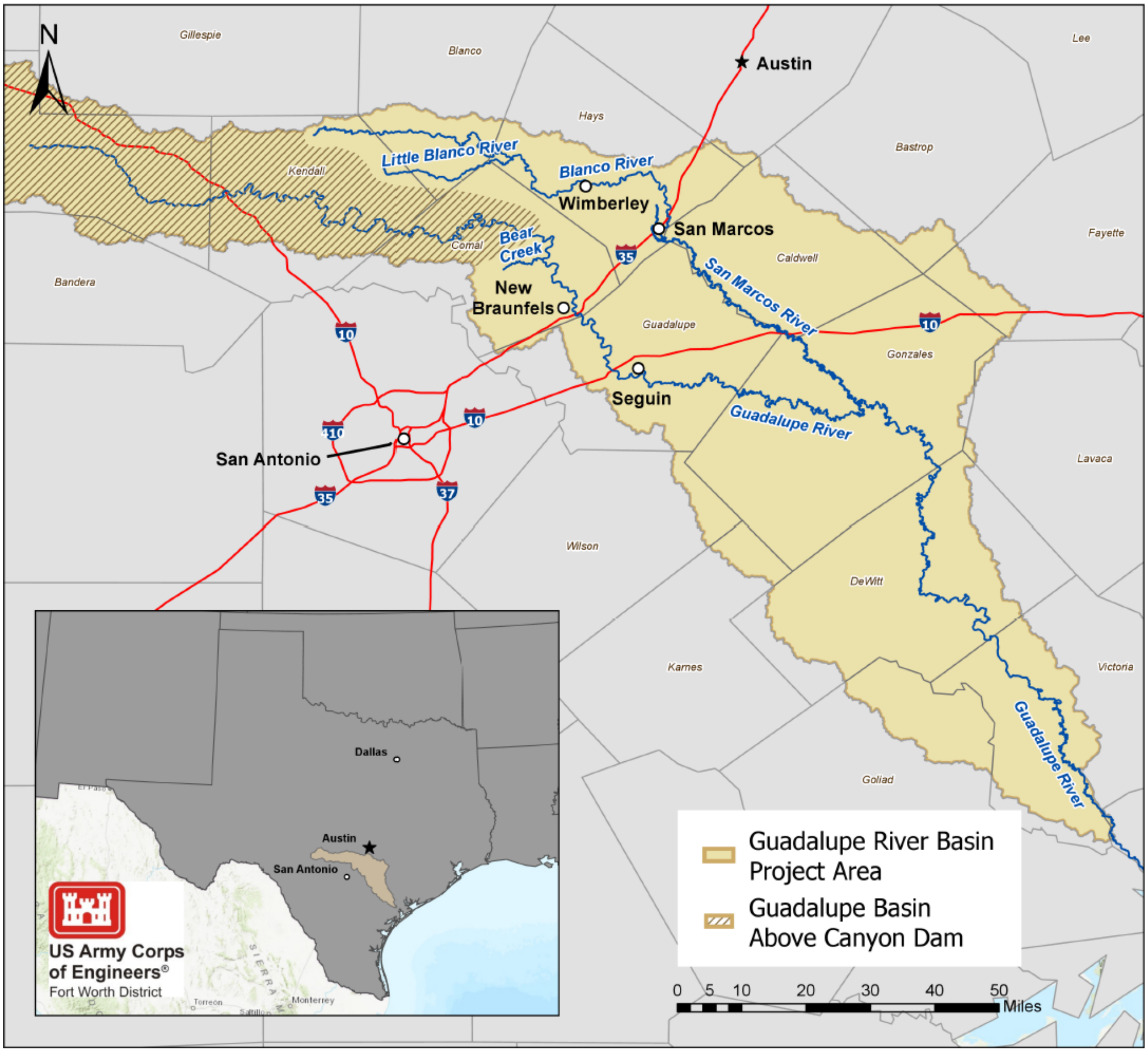

Figure 1.1: Lower Guadalupe Study Area

2 Lower Guadalupe River Basin

2.1 Watershed Description

The Guadalupe River Basin is located in south Texas, stretching from its headwaters, which are approximately 65 miles northwest of San Antonio, to its confluence with San Antonio Bay, which is 30 miles southeast of Victoria, Texas. The Lower Guadalupe River basin has a drainage area of approximately 4,530 square miles between Canyon Dam and the confluence of the Guadalupe and San Antonio Rivers. The watershed spans the counties of Kerr, Kendall, Comal, Hays, Caldwell, Guadalupe, Gonzales, Dewitt and Victoria in Texas. The general elevation of the watershed increases from sea level at the mouth to an elevation of approximately 1,700 feet at its headwater area. The Guadalupe River is formed by the confluence of the North and South Forks of the Guadalupe River at a point approximately ten miles west of Kerrville, Texas. From its source, the Guadalupe River flows in an easterly direction for a distance of approximately

184 miles to the Balcones Escarpment near the city of New Braunfels. From there, the river turns southeasterly and flows 280 miles to San Antonio Bay, an estuary of the Gulf of Mexico.

The Edwards Plateau above New Braunfels is a region of rugged hills and narrow valleys and is strikingly accentuated at its eastern edge by steep hills and limestone bluffs that form the Balcones Escarpment, the boundary between the plateau area and the coastal plains. In the plateau area the Guadalupe River is deeply entrenched, flowing for the greater part of its course through narrow canyons 200 to 300 feet deep. Below New Braunfels, in the coastal plains, the river flows through an area of rolling hills and broad plains, changing to flat prairies along the Gulf Coast. The river follows a winding course throughout its length which is about twice the length of the valley axis. The principal tributaries of the Guadalupe River, all of which enter the main stem below Canyon Dam are the San Marcos River with its major tributary, the Blanco River, the Comal River, Peach Creek, Sandies Creek, and Coleto Creek.

Canyon Dam, which is the only major flood control reservoir in the basin, is located on the Guadalupe River 12 miles northwest of New Braunfels, Texas. Six hydropower dams are located on the Guadalupe River downstream of New Braunfels. These hydropower dams are operated by the Guadalupe-Blanco River Authority and do not contain any significant flood storage.

The Blanco River Basin encompasses approximately 436 square miles in the counties of Gillespie, Kendall, Blanco, Comal, and Hays in south Texas. The general elevation of the watershed increases from 540 feet at the confluence with the San Marcos River to an elevation of roughly 1720 feet at its headwater area. It joins the San Marcos River in the City of San Marcos. From its source, the Blanco River flows in an easterly direction until it turns to the south near the city of Kyle, Texas.

The principal land uses of Guadalupe River Basin are farming and ranching. The mean annual precipitation over the Guadalupe River Basin is 32.7 inches, and varies from approximately 36 inches near the mouth to about 29 inches at the headwaters. Approximately 18 operational United States Geological Survey (USGS) stream flow gages and 11 National Weather Service (NWS) forecast points are located within the Lower Guadalupe River Basin.

2.2 Canyon Lake

Canyon Lake is an existing USACE reservoir that was authorized by the Rivers and Harbors Act of 1945, PL 79-14, as modified by the Flood Control Act of 1954, PL 83-780. Canyon Lake is located in Comal County, Texas 12 miles northwest of New Braunfels, Texas, on the Guadalupe River. The project consists of a rolled earth-fill dam (6,830 feet long by 224 feet high); an uncontrolled spillway (1,260 feet wide in the saddle); and, one 10-foot diameter conduit controlled by two slide gates (5-foot, 8-inch by 10-foot). The flood control storage is 354,600 acre-feet. USACE Fort Worth District owns and operates the dam. The GBRA is the sponsor for water supply storage and non-federal hydropower.

2.3 GBRA Hydropower Dams

Below Canyon Dam, six hydropower dams are located along the Guadalupe River between New Braunfels and Gonzales. These hydropower dams were built in the 1920s and early 1930s and are operated by the Guadalupe Blanco River Authority (GBRA). While these dams do not have significant flood control storage, they do have an effect on the way a flood wave attenuates as it moves downstream. The floodplain around these lakes is also a significant source of economic damages, as the homes built around the lakes have experienced significant damage during flood events. The lakes that are impounded by these dams are known as Lake Dunlap, Lake McQueeney, Lake Nolte, Lake Placid, Lake Gonzales, and Lake Wood. One of the constraints of this study was that the proposed project alternatives cannot negatively impact the existing hydropower dams.

2.4 Major Floods in the Basin

Available stream flow records show that major floods have been experienced over nearly all sections of the Guadalupe River Basin. While the highest average monthly flows usually occur in May, June, July, and September, flood flows may occur during any month of the year. Communities in the Lower Guadalupe basin have suffered from several major floods over the last 25 years. Approximately 27 lives have been lost, and over a billion dollars-worth of flood damages have occurred within this basin in just the past 25 years.

2.4.1 The 1998 Flood on the Lower Guadalupe River

Severe flooding in parts of south-central Texas resulted from a major storm during October 17–18, 1998. The meteorologic conditions that produced the storm rainfall were dominated by Hurricane Madeline in the Eastern Pacific near the tip of Baja California, and Hurricane Lester in the Eastern Pacific near Acapulco, Mexico. The hurricanes, coupled with an atmospheric trough of low pressure over the western United States, forced a very deep layer of air with high water-vapor content across Mexico and into Texas. Meanwhile, an atmospheric ridge of high pressure to the east, extending from the North Atlantic to the Yucatan Peninsula of Mexico, confined the surface and mid-level water-vapor plumes to south-central Texas. During the morning of October 17, 1998, a strong low-level inflow of moist air traveling 23 to 35 miles per hour flowed from the Gulf of Mexico across Texas into Bexar County. An upper-level divergent wind pattern over south-central Texas lifted the extremely moist air mass from lower levels. Early thunderstorms slowly pushed eastward throughout the day into the prevailing moisture-rich flow. In the early morning hours of October 17, extreme atmospheric instability over western Bexar County extending northward to Kendall County caused rapid uplift of low-level moisture, forming heavy thunderstorms. By 6 a.m., the area from western Comal County to eastern Medina County had received 4 to 6 inches of rain. By 8 a.m., 6 to 10 inches had fallen; and by late morning, this area had received about 15 inches. By late morning on October 17, the rains extended into Hays and Travis Counties. The NWS rain gage at Wimberley (Hays County) indicated that intense rainfall began by 8 a.m. and recorded 4.5 inches by 11 a.m., 6 inches by 1 p.m., 9 inches by 4 p.m., and 11.25 inches by 8 p.m. At 11:30 p.m., the 12-inch rain collector overflowed. Finally, by mid-day October 18, the tropical plume and intense rainfall shifted eastward to the upper Texas Coastal Plain and extended into Louisiana. During the Oct 1998 flood event, approximately 22 inches of rain fell in western Comal County, near the city of New Braunfels over a two day period. 30 inches of rain was also recorded in parts of the San Marcos River basin.

The volume of runoff for the USGS gage, Guadalupe River at Cuero, was computed for the period October 17–31, 1998, at about 1,840,000 acre-feet. The total outflow from Canyon Lake during October 18–31 was only about 2,600 acre-feet; thus, almost all runoff at the Cuero station originated from the basin downstream of the reservoir. The rainfall volume in the drainage basin upstream of the Cuero station and downstream of Canyon Lake is about 2,580,000 acre-feet, which represents a mean depth of about 15.0 inches over almost 3,500 square miles of drainage area. (U.S. Geological Survey, Floods in the Guadalupe and San Antonio River Basins in Texas, October 1998.)

The October 1998 flood event resulted in record flooding along much of the lower Guadalupe River and in record flood stages at several gages on the Comal, San Marcos and Guadalupe Rivers. The recorded peak flows for the Guadalupe River at Cuero and Victoria in October 1998, which were 473,000 and 466,000 cfs respectively, have never even been approached anywhere else the basin. This one flood event resulted in the deaths of 15 people and approximately $750 million in property damage in the Guadalupe River Basin.

2.4.2 The 2002 Flood in the Upper Guadalupe Basin and at Canyon Dam

In late June 2002, a low-pressure system migrated west from Florida to Texas and eventually stalled over South Central Texas. From 29 June to 6 July, tropical moisture was pulled inland from the Gulf of Mexico and the orographic lift provided by the Balcones Escarpment caused widespread heavy rainfall. Rains moved from south to north repeatedly causing tremendous rainfall accumulations on an area from southwest of San Antonio to the northern Hill Country. The low-pressure system moved north on 5 July, only to stall again in Central Texas. The system again produced heavy rains in this area on 6 July. The low-pressure system finally moved northwest and weakened, ending the period of heavy rain in the Hill Country.

The main part of the storm event, between 29 June and 6 July, was concentrated in Kendall County and surrounding counties. The heaviest rainfall occurred between early morning and noon of 30 June. Rainfall intensities of 3 inches per hour were common. In the first week of July, a pattern of afternoon heating led to explosive evening and overnight thunderstorms. These evening thunderstorms also produced heavy rainfall. Several precipitation stations recorded more than 30 inches of rain during this eight day period.

Widespread rainfall across Kerr County and Kendall County sent five flood waves down the Guadalupe River into Canyon Lake in the first week of July. The highest inflow peak, of approximately 110,000 cfs, occurred on 5 July. During the first nine days in July, the total inflow into Canyon Lake was about 700,000 acre-feet of floodwater. The capacity of the flood pool is approximately 355,000 acre-feet.

Between 30 June and 31 July, the computed inflow totaled 872,000 acre-feet. This volume of water is equal to 11.5 inches of runoff over the entire basin, which is enough to have more than filled the flood control pool twice. Due to saturation of the watershed, the Guadalupe River and its tributaries continued to run at well above normal stages for several months.

On 28 June, before the flooding began, Canyon Lake was at elevation 908.38 feet NGVD or 0.62 feet below the top of the conservation pool. The heavy rains and high inflow filled the lake to the top of the flood pool, elevation 943.0 feet NGVD, at 1530 hours on 4 July. The continuing waves of flood water raised the lake level above the emergency spillway crest. The lake peaked on 6 July at elevation 950.32 feet NGVD. At this elevation, the lake level was 7.32 feet above the spillway crest, having risen nearly 42 feet in just over a week. The maximum discharge over the spillway was about 66,800 cfs, whereas the controlling capacity of the downstream channel at New Braunfels, Texas was 12,000 cfs. The 2002 flood is the flood of record at Canyon Lake.

The torrential rains of 2002 caused flooding of historic proportions on south Texas rivers. Major to record flooding occurred along portions of all the rivers in the Hill Country. Extensive damage occurred from flash flooding and headwater flooding in Wimberley on the Blanco River and in Kerrville on the Guadalupe River. Some communities were isolated by the flood waters in the upper Guadalupe River for a day or more. Damage on the Guadalupe River below Canyon Dam was catastrophic in some locations.

2.4.3 The 2015 Floods in the Blanco and San Marcos Watersheds

The steep gradients of the streams, the thin layer of topsoil with frequent outcroppings of rock, and the narrow valleys in the Blanco watershed produce rapid runoff and sharp crested floods of short duration during storm periods. Extreme and rapid variations in the flow, ranging from a few cubic feet per second (cfs) to over a hundred thousand cfs, have been experienced in the vicinity of the cities of Wimberley and San Marcos due to flooding from the Blanco River.

In 2015, back-to-back large flood events occurred in the Blanco River and San Marcos River basins in May and October of that year. In May 2015, heavy rainfalls produced devastating floods throughout the state of Texas. The Blanco River experienced some of the most severe flooding as a result of an intense rain event that occurred during 6-hour period in the evening of May 23, 2015. During that flash flood event, the Blanco River rose more than 20 feet in one hour and peaked at a stage of almost 45 feet. The high velocity nature of the flooding uprooted thousands of large cypress trees, destroyed bridges and damaged or destroyed over 350 homes, some of which were washed completely off of their foundations and carried down river. The flood also resulted in 12 deaths, including two children. Property damage in the city of Wimberley was estimated at more than $30 million.

On both the Lower Guadalupe River and the Blanco River, there are numerous road and railroad bridges, utility crossings, and other critical public infrastructure that are highly susceptible to flooding. Shown are two examples of public infrastructure that were impacted or even destroyed in the May 2015 flood event. The first photo is of Fischer Store Bridge, which was totally destroyed. The second shows Interstate 35 in San Marcos, Texas, which was completely impassable in both directions for hours. Note that the 6-lane Interstate Highway was completely underwater during the event.

Fischer Store Road Bridge destroyed during May 2015 Flood on the Blanco River

Flooded Interstate 35 at the Blanco River in May 2015

During that event, both the Kyle and Wimberley USGS stream gages on the Blanco River were damaged and ceased to operate. The May 2015 event was estimated to be the highest flood of record for the Blanco River gages at Wimberley and near Kyle. The May 2015 peak streamflow at Wimberley has been estimated by the USGS as 175,000 cfs with a peak stage of 44.90 feet. The peak near Kyle was also estimated by the USGS as 180,000 cfs. Many of the homes that were damaged in this flood event were outside of the existing FEMA 1% floodplain, and some of the high water marks that were collected after the flood were 5 to 10 feet higher than the existing base flood elevations (BFEs).

A second major flood occurred in October 2015. The estimated peak flows for that event were 71,000 cfs at Wimberley and 115,000 cfs near Kyle. Extensive property damage occurred once again in both Wimberley and San Marcos, with over 1,000 structures flooded in the city of San Marcos alone.

Other major floods that have occurred in the Guadalupe River basin, along with their peak flow estimates, are listed in Table 2.1. From this table one may observe that since 1998, there have been several major flood events that have equaled or exceeded historic flooding within the basin.

Table 2.1: Major Floods in the Guadalupe River Basin

Date of Flood	Observed Peak Flow (cfs)		
	Guadalupe River abv Comal River at New Braunfels	Blanco River at Wimberley	Guadalupe River at Victoria
Jul-1869	38 ft	25 ft	-
Dec-1913	38 ft	-	28.3 ft
May-Jun-1929	-	113,000	30.2 ft
Jul-1932	95,200	-	-
Jun-1935	101,000	-	38,500
Jul-1936	-	-	179,000

Sep-1936	52,800	-	-
Sep-1952	72,900	95,000	-
Apr-1957	26,900	62,600	35,300
Feb-1958	-	-	58,300
May-1958	47,900	96,400	-
Oct-1959	35,700	40,100	-
Jun-1961	-	-	55,800
Sep-1967	-	-	70,000
May-1972	92,600	-	58,500
Sep-1981	-	-	105,000
Jun-1987	-	-	83,400
Dec-1991	-	32,900	61,500
Oct-1998	90,000	88,500	466,000
Nov-2001	-	108,000	-
Jul-2002	73,200	82,500	71,700
Nov-2002	-	-	58,500
Nov-2004	17,000	34,000	102,000
Mar-2007	-	36,900	-
Jun-2010	69,000	-	-
Oct-2013	25,500	75,800	-
May-2015	-	175,000	49,100
Oct-2015	39,000	71,000	-
Aug-2017	-	-	86,500

2.5 Previous H&H Studies

Although historical floods have indicated that many of the watercourses of the basin are inadequate for conveying the flows of significant storm events, the coverage of existing hydrologic and hydraulic data across the watershed was scattered and usually limited to the urban areas. Table 2.1 below details the dates and extents of the previous Flood Insurance Studies, which included hydraulic and hydrologic analyses.

Table 2.1: Previous Hydrologic & Hydraulic Studies in the Lower Guadalupe River Basin

Study Name	River Extents
Comal County Flood Insurance Study 2009	Guadalupe River below Canyon Dam
Guadalupe County Flood Insurance Study 2007	Guadalupe River from the County Line down through the City Seguin
Guadalupe County Flood Insurance Study 2007	Guadalupe River below Seguin
Gonzales County Flood Insurance Study 2010	Guadalupe River within Gonzales County and the City of Gonzales
DeWitt County Flood Insurance Study 2011	Guadalupe River within DeWitt County
Victoria County Flood Insurance Study 1998	Guadalupe River through the County and the City of Victoria

Study Name	River Extents
Comal County Flood Insurance Study 2006	Comal River within New Braunfels
Hays County Draft Flood Insurance Study by USACE 1988	Blanco and San Marcos Rivers
Hays County Effective Flood Insurance Study 1996 and 2005	Blanco and San Marcos Rivers in Hays County
Guadalupe County Flood Insurance Study 1998	San Marcos River at Luling

3 Existing Conditions

To address the scattered nature of the existing hydraulic and hydrologic data in the basin, the decision was made to develop basin wide hydrologic and hydraulic models to a level of detail such that they could be used to adequate assess the existing conditions.

3.1 Terrain Data used in the H&H Analyses

High resolution LiDAR data was available for most of the basin, including Hays, Caldwell, Comal, Fayette, Guadalupe, and Gonzales counties. This LiDAR data was processed into the form of a basin wide terrain dataset created by Halff Associates for this study (Halff, Mar 2014). The final terrain dataset utilized the best available LiDAR data from various sources with collection dates varying from 2008 to 2012. The final terrain dataset was in State Plane Texas South Central 4204 projection, North American Datum (NAD) 1983 horizontal datum, and with elevations in North American Vertical Datum (NAVD) 1988. This terrain dataset was further processed into 3-foot by 3-foot DEMs for hydraulic modeling and into a 30-ft by 30-ft DEM for hydrologic subbasin delineations. Additional details on the LiDAR data and the terrain processing can be found in Appendix A-1.

3.2 Existing Conditions Hydrology

3.2.1 Lower Guadalupe River Basin Hydrology

The Lower Guadalupe River watershed was modeled, under contract with Halff, to determine the existing conditions standard frequency flows for use in determination of potential damage centers within the watershed. A new basin-wide hydrologic model was developed in HEC-HMS. New subbasins were delineated in HEC-GeoHMS using the 30-ft DEM processed from the LiDAR data. Subbasins were sized as large as possible to support an accurate analysis for both the main stems and tributary streams. The Lower Guadalupe River basin was divided into 50 sub-basins ranging in size from 17 to 175 square miles. The smaller sub-basins were created to accommodate important confluences and USGS gages. The larger sub-basins were created in areas not affecting hydraulic study reaches. The final subbasin layout for the basin-wide Lower Guadalupe HEC-HMS model is shown in Figure 3.1.

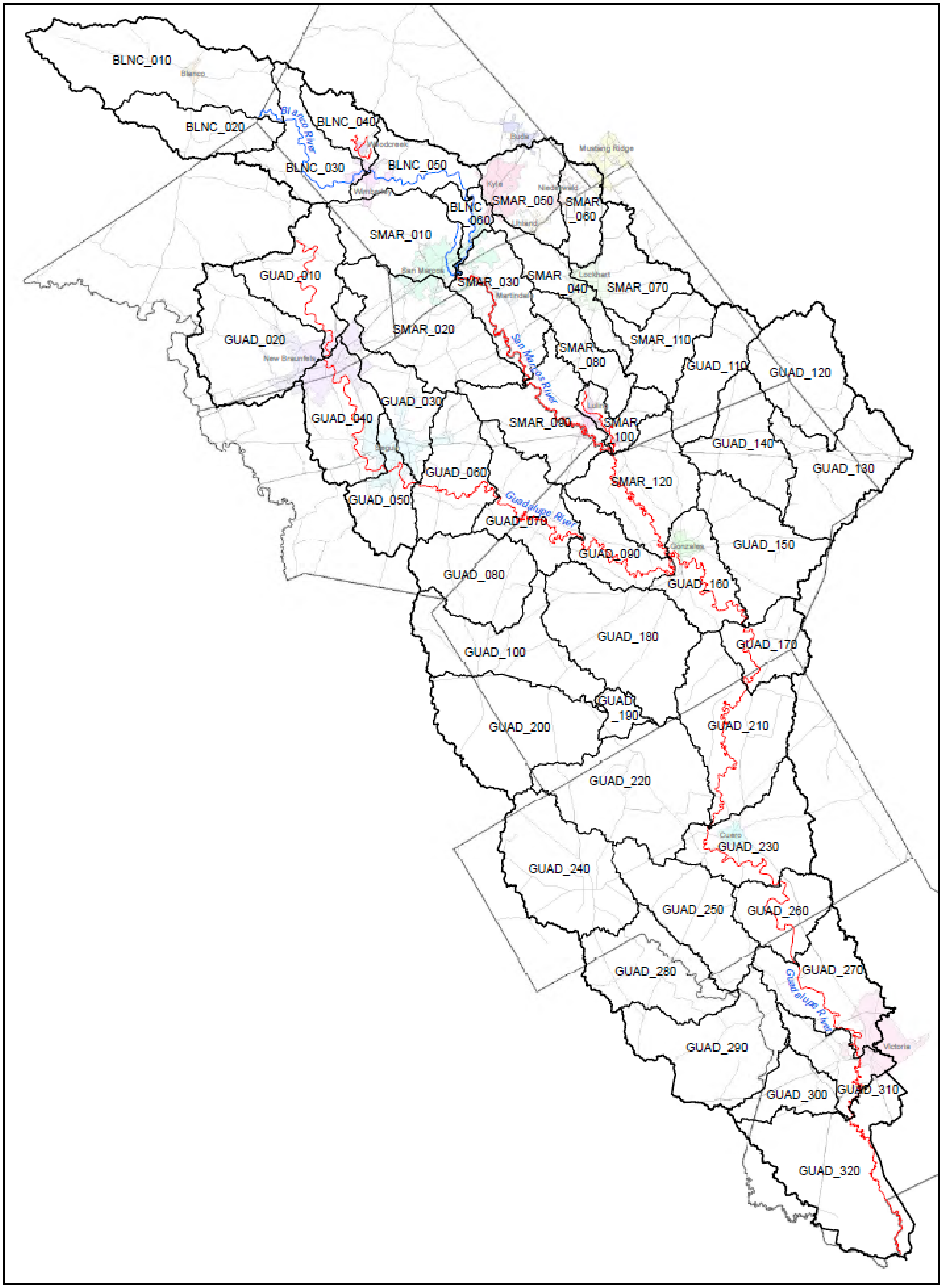

Figure 3.1: Final Subbasins for the Lower Guadalupe Basin-wide HEC-HMS model

The methods used in the HEC-HMS model included initial and constant loss rates, Snyder's lag times and peaking coefficients, which were developed according to the Corps of Engineers Fort Worth method, and Modified Puls routing. HEC-GeoHMS was utilized to extract spatial variables utilized in the development of the HEC-HMS model. The sources of the initial estimates for these parameters are described below.

- Initial Loss and Constant Loss Rate – The USACE Fort Worth District method for calculating frequency losses was used. These equations utilize estimates of Percent Sand in the soil to develop initial deficit and constant loss rates for different frequency storm events, as shown in Table 3.1. Percent Sand estimates are related to the permeability of the soil and were obtained from the NRCS SSURGO soil data. The Percent Sand value that is calculated for each subbasin was then used to interpolate between the 0% and 100% Sand loss values in Table 3.1. More information on these calculations is included in Appendix A-1.

Table 3.1: Frequency Loss Rates by Percent Sand

Annual Exceedance Probability (AEP) %	Initial Abstraction (inches) for Soil with 0% Sand	Infiltration Rate (inches per hour) for Soil with 0% Sand	Initial Abstraction (inches) for Soil with 100% Sand	Infiltration Rate (inches per hour) for Soil with 100% Sand
50%	1.50	0.20	2.10	0.26
20%	1.30	0.16	1.80	0.21
10%	1.12	0.14	1.50	0.18
4%	0.95	0.12	1.30	0.15
2%	0.84	0.10	1.10	0.13
1%	0.75	0.07	0.90	0.10
0.4%	0.61	0.06	0.73	0.09
0.2%	0.50	0.05	0.60	0.08

- Percent Impervious – The percent impervious values were developed based on land use data. Impervious % for all developed low, medium, and high density land uses was increased to 47%, 70%, and 100% respectively to better represent the impact of developed areas, the effects of which tend to be dampened in large scale hydrology models.
- Snyder Transform Parameters – The time to peak and peaking coefficients were developed from the USACE Fort Worth District urban curves based on length and slope watershed characteristics extracted from HEC-GeoHMS, Percent Urban values taken from the 2011 NLCD, and Percent Sand values taken from the NRCS SSURGO soils data. From this data, the following regional equation, which was developed as part of the Fort Worth District urban studies (Nelson, 1979) (Rodman, 1977) (USACE, 1989), was used to calculate lag time:

  log (tp) = .383log (L*Lca/(Sst ^ .5))+(Sand*(log1.81-log.92)+log.92)-(BW*Urban./100)

  where:

tp = Snyder's lag time (hours)

L = longest flow path within the subbasin (miles)

Lca = distance along the stream from the subbasin centroid to outlet (miles)

Sst = stream slope over reach between 10% and 85% of L (feet per mile)

Sand = percentage of sand factor as related to the permeability of the soils

(0% Sand = low permeability, 100% Sand = high permeability)

BW = log(tp) bandwidth between 0% and 100% urbanization = 0.266 (log hours)

Urban. = percentage urbanization factor

- Routing Parameters (Modified Puls) – Storage-discharge curves for the Modified Puls routing were extracted from the best available detailed hydraulic and hydrologic models. Initial subreach values were estimated based on an average travel time through the reach.

Historical storms occurring in October 1998, July 2002, and November 2004 were used in the calibration of the Lower Guadalupe basin-wide HEC-HMS model. National Weather Service (NWS) gridded precipitation data was used for calibration of the hydrologic model to these storm events. The precipitation data consists of hourly rainfall grids for the period before, during, and after each storm event. Snyder’s peaking coefficients and routing parameters were adjusted during calibration. In some cases, switching to Muskingum-Cunge routing yielded better calibration results.

Resultant standard frequency rainfall events from the 2004 USGS published Atlas of Depth-Duration Frequency (DDF) of precipitation for Texas were then used to build frequency storms in the HEC-HMS model (Asquith, 2004). Figure 15 of NWS Technical Paper 40 was used for aerial reduction of the point rainfall depths. This reduction was applied through depth-area analyses in HEC-HMS. Discharges were computed for 2-, 5-, 10-, 25-, 50-, 100-, 250-, and 500 year recurrence intervals for existing conditions.

As part of the Lower Guadalupe Feasibility Study, a gage analysis was performed for all stream flow gages within the Lower Guadalupe River basin with sufficient period of record using standard Bulletin 17B methodologies. The six gages listed in Table 3.1 were used to develop frequency flows for the Guadalupe River. The “Guadalupe at FM 1117 near Seguin” gage was not analyzed by the Corps since it is a relatively new gage and the systematic record was too short. The “Guadalupe at Sattler” gage is highly affected by Canyon Dam outflows and did not produce very good gage analysis results. Therefore, a set of Canyon Dam outflows for the different frequencies was provided by the Water Management Section of the Fort Worth District USACE.

Table 3.1: Gage Analysis Results for the Guadalupe River with Canyon Dam Outflows

Summary of Gage Analysis Results								
Location	Frequency Flows (CFS)							
	50% ACE	20% ACE	10% ACE	4% ACE	2% ACE	1% ACE	0.4% ACE	0.2% ACE
Canyon Dam Outflows	1770	4510	5000	5000	5000	15300	101325	130000
Guadalupe Above Comal River at New Braunfels (ACD)	4150	12300	21800	40100	59500	85000	130000	175000
Guadalupe River at New Braunfels	6040	16300	27900	50400	74400	106000	164000	222000
Guadalupe River at Gonzales	16500	43000	71700	124000	178000	247000	365000	480000
Guadalupe River at Cuero	16900	42500	70100	121000	174000	242000	362000	481000
Guadalupe River below Cuero	17800	45000	72300	119000	165000	219000	308000	389000
Guadalupe River at Victoria - Full Systematic Record	18000	41900	65700	105000	145000	192000	259000	347000

Table 3.1 contains the Guadalupe River gage analysis results used to interpolate the set of frequency flows to be used in the final hydraulic modeling. The basin-wide HEC-HMS model was used to proportion peak flows between the gages. The final adopted frequency flows for the Lower Guadalupe were taken as a combination of the statistical gage analyses and the HEC-HMS model results. A full listing of the final adopted frequency flows for the Lower Guadalupe River, and additional details on the basin-wide hydrology, can be found in in Appendix A-1.

3.2.2 Blanco and San Marcos Rivers Watershed Hydrology

After completion of the basin-wide hydrology for this study, the hydrology for the Blanco and San Marcos River basin was updated to include additional calibrations for the May and October 2015 flood events and to add additional detail near the cities of Wimberley and San Marcos. This hydrology was updated as part of a separate study for FEMA (InFRM, 2016).

To better define the hydrology of the San Marcos River Basin, additional subbasin breaks were added to the original basin-wide delineation. The total number of subbasins was increased from 19 to 47. Additional subbasins were added in two areas: the Blanco River and Sink Creek. These areas were selected for additional detail due to their locations just upstream of the developed areas of Wimberley and San Marcos.

The Blanco River is an important part of the basin as it tends to be the primary source of flooding for the cities of Wimberley and San Marcos, Texas. Additional subbasins were added to the Blanco River basin in order to give better definition to the rainfall patterns and the timing of the tributaries entering the Blanco River. In total, the number of subbasins in the Blanco River basin was increased from 6 to 29. The new subbasin break points were chosen based on several factors which include: the locations of significant tributaries, the locations of the new USGS stream flow gages that were installed after the flood events of 2015, and the locations of developed areas or major road crossings.

Sink Creek is a tributary to the San Marcos River just upstream of the city of San Marcos. Flood flows from the Sink Creek Watershed are significantly attenuated by the presence of three NRCS dams in the watershed. In order to better account for the effects of these dams, subbasin breaks were added at the locations of the dams. The physical data for these NRCS dams, including elevation-capacity curves, spillway and outlet structures, were also added to the HEC-HMS model. In total the number of subbasins on Sink Creek was increased from one subbasin to six.

The final subbasin map for the San Marcos River Basin HEC-HMS model, including 47 subbasins and 1,359 square miles, is shown in Figure 3.2.

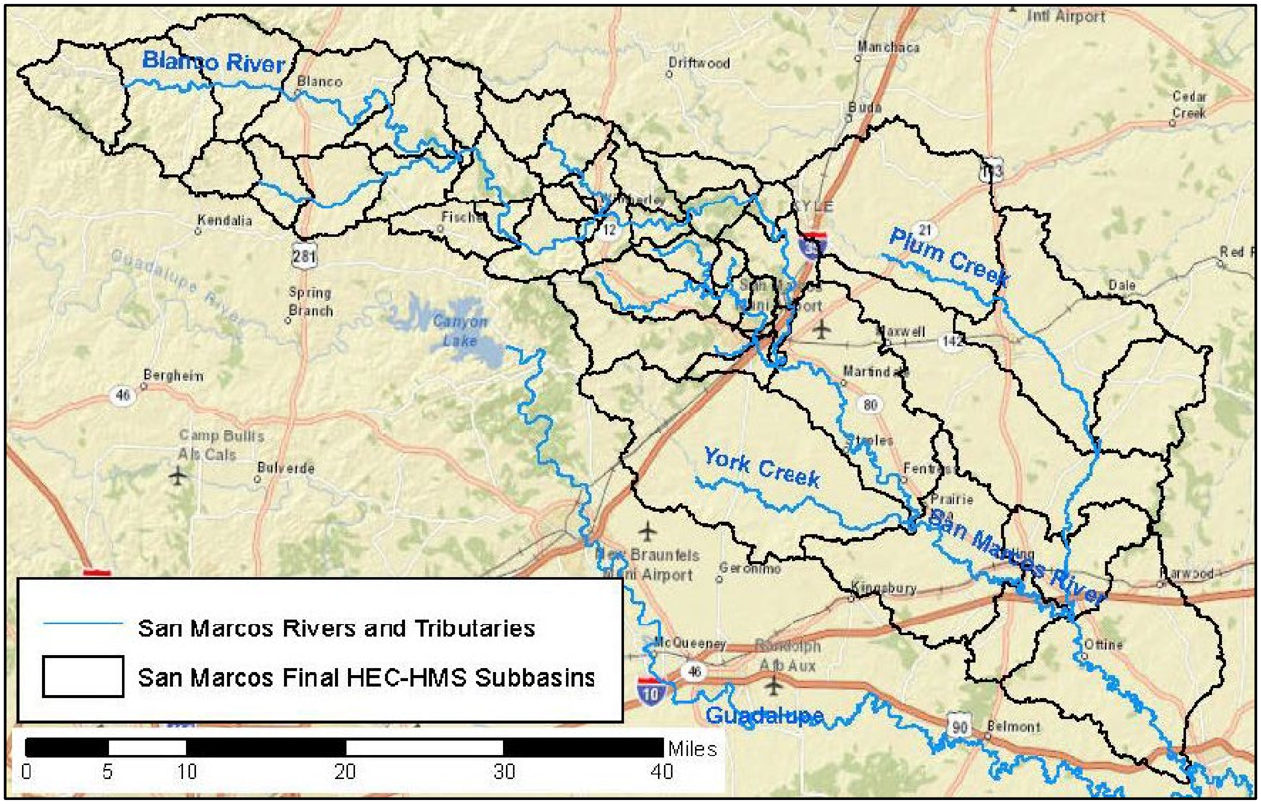

Figure 3.2: Final HEC-HMS Subbasins for the San Marcos River Basin

The San Marcos River HEC-HMS model used the same methods and data sources for initial parameters as the Lower Guadalupe basin-wide HEC-HMS model, which included initial and constant losses, Snyder unit hydrograph transform parameters, and Modified Puls routing. The percent impervious values were developed based on the 2011 NLCD percent developed impervious dataset.

After breaking out the additional subbasins, detailed routing data was added to the HEC-HMS model for the associated new river reaches and for other reaches where detailed hydraulic modeling was available. The Modified Puls routing method was used for all of the reaches throughout the basin model. Modified Puls is a routing method that calculates the change in flow through the reach based on the volume of floodplain storage through that reach. For the San Marcos River basin, the necessary storage-discharge curves for the Modified Puls routing were extracted from the best available detailed hydraulic models, which included detailed HEC-RAS models of the Blanco River, San Marcos River, Plum Creek and Sink Creek from the Lower Guadalupe Feasibility Study. These HEC-RAS models were built off of detailed LiDAR topographic data and included other detailed information such as bridge and channel surveys.

Modified Puls routing data for other reaches, such as the Blanco River and Little Blanco River in Blanco County, which were not included in the Lower Guadalupe Feasibility study area, were extracted from existing detailed HEC-1 hydrologic models from the 1988 draft Hays County Flood Insurance Study.

After building the HEC-HMS model, the InFRM team calibrated the model to verify it was accurately simulating the response of the watershed to a range of observed flood events, including large events similar to a 1% annual chance (100-yr) flood. A total of eight recent storm events were used to fine tune the model, as shown in Table 3.1.

Table 3.1: Observed Flood Events Simulated in the San Marcos Watershed Model

Date of Flood	Recorded Peak Flow (cfs)		
	Blanco River at Wimberley	Blanco River near Kyle	San Marcos River at Luling
Oct-1998	88,500	105,000	206,000
Nov-2001	108,000	87,300	43,700
Nov-2004	34,000	31,600	84,800
Mar-2007	36,900	34,500	25,900
Jan-2012	-	-	34,700
Oct-2013	75,800	101,000	48,200
May-2015	175,000	180,000	74,800
Oct-2015	71,000	115,000	71,000

For these storms, the National Weather Service (NWS) hourly rainfall radar data allowed the team to fine tune the watershed model through detailed calibration. For each storm event, the model's calculated flow hydrographs were compared to the observed USGS stream flow data at the gages. The model's parameters were then adjusted to improve the match between the simulated and observed hydrographs for the observed events. The final model results accurately simulated the expected response of the watershed, as it reproduced the timing, shape, and magnitudes of the observed floods very well. Additional detail on the model calibration process can be found in InFRM's San Marcos Hydrology report (InFRM, 2016).

After the calibration process was completed, the final parameters were established. The final lag times, peaking coefficients, and Mod Puls subreaches were developed by taking a weighted average of the adjusted parameters from the calibration events. The full listing of final model parameters can be found in the San Marcos Hydrology report (InFRM, 2016).

Existing conditions frequency flow values were then calculated in HEC-HMS by applying frequency rainfall depths to the final watershed model through a depth-area analysis. Frequency point rainfall depths of various durations and recurrence intervals were collected for the Blanco and San Marcos River basins from the 2004 Atlas of DDF of precipitation for Texas published by the USGS (Asquith, 2004). The point rainfall depths for the Blanco River subbasins were taken from a point near Wimberley, Texas, as shown in Table 6.20. The point rainfall depths for the rest of the San Marcos subbasins were taken from a point near the lower basin's centroid. These also happened to be the same point rainfall depths as were used in the Lower Guadalupe basin-wide hydrology.

The calculated 1% annual chance (100-yr) peak discharges at the Wimberley and Kyle gages on the Blanco River were 152,600 and 153,900 cfs, respectively. The 1% annual chance (100-yr) peak discharges for the San Marcos River at San Marcos and Luling were 7,860 cfs and

142,400 cfs, respectively, and for Plum Creek, the 1% annual chance (100-yr) peak discharges were 48,900 cfs and 78,600 cfs at Lockhart and Luling, respectively. The final HEC-HMS frequency flows for significant locations throughout the watershed model can be seen in Table 3.2.

In some cases, one may observe that the simulated discharge decreases in the downstream direction. It is not uncommon to see decreasing frequency peak discharges for some river reaches as flood waters spread out into the floodplain and the hydrograph becomes dampened as it moves downstream. This can be due to a combination of peak attenuation due to river routing as well as the difference in timing between the peak of the main stem river versus the runoff from the local tributaries and subbasins.

Table 3.2: Summary of Discharges (cfs) Results for the Blanco and San Marcos Rivers

Location Description	50%	20%	10%	4%	2%	1%	0.40%	0.20%
	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR	250-YR	500-YR
Blanco River below Little Blanco	9,100	31,800	51,900	86,500	111,800	141,300	178,700	213,300
Blanco River at Wimberley	8,900	31,000	51,600	88,600	116,600	152,600	196,800	238,500
Blanco River near Kyle	8,600	30,300	50,700	88,100	116,300	153,900	199,300	244,900
Blanco River above San Marcos	7,900	28,300	46,000	79,000	106,300	142,900	188,300	232,800
San Marcos River at San Marcos	310	1,380	2,530	4,100	5,160	7,860	14,800	21,100
San Marcos River below Purgatory	950	2,720	6,640	12,000	17,200	23,100	31,400	40,300
San Marcos River above Blanco	2,640	5,210	7,000	11,800	17,200	23,500	32,300	40,900
San Marcos River below Blanco	8,800	29,900	48,500	82,400	110,500	153,600	205,500	255,900
San Marcos River above York Creek	8,400	27,600	45,800	75,900	100,200	136,500	182,200	237,900
San Marcos River below York Creek	8,800	29,400	49,000	80,100	105,500	144,100	194,000	257,100
San Marcos River at Luling	10,400	28,300	47,400	78,400	103,900	142,400	193,100	253,100
San Marcos River above Plum Creek	10,100	27,300	44,800	74,200	100,600	138,300	185,400	241,300
San Marcos River below Plum Creek	16,700	42,600	65,900	101,700	139,100	189,200	252,300	331,700
San Marcos Riv above Guadalupe R	13,900	38,000	56,700	91,000	128,000	178,200	239,700	304,600

3.3 Existing Conditions Hydraulics

New hydraulic models were developed in HEC-RAS for the Guadalupe, San Marcos, and Blanco Rivers. Hydraulic analyses were developed for approximately 450 miles of stream including about 270 miles of detailed study that required field surveys to be incorporated into the hydraulic models, 50 miles of limited detail study without surveys, and 130 miles of incorporated existing detailed models from FEMA’s Map Mod program in Comal, Guadalupe, and Victoria Counties. These models were built under contract with Halff, as described in Appendix A-1.

The primary source of topographic data used in the hydraulic modeling was developed from the 2007-2008 CAPCOG and TNRIS LiDAR data. 3 ft. by 3 ft. digital DEMs were generated from the LiDAR data for use in the hydraulic modeling. The HEC-GeoRAS extension was used to cut cross sections from the 3-ft DEMs and to geo-reference existing models. Some channel sections were modified to match field measurements, as built drawings and survey data.

Manning's roughness values were developed based on land use maps, aerial photography, and site visits.

Field surveys of open channel sections and bridges/culverts along the detailed study reaches of the Guadalupe and San Marcos Rivers were conducted April 2013 through July 2013. Some channel section surveys were collected using boat-mounted sonar equipment where the water was too deep for standard survey methods. The survey data was collected using surveying standards set by FEMA as specified in the current version of Guidelines and Specifications for Flood Hazard Mapping Partners.

Cross-sections were evaluated for natural grade breaks for bank station placement. Bank stations were placed as near as possible to the natural grade breaks so that the streams maintained a smooth channel depth that may slightly increase as they move downstream along the profile. Ineffective areas and blocked obstructions were set following the standard practice as outlined in the HEC-RAS Hydraulic Reference Manual.

Available bridges/culverts for all streams were modeled using field measurements, "as-built" plans, or bridge/culvert data from the current effective USACE models. Where available, survey data was incorporated in the final hydraulic models as well.

Storm and high water mark data was obtained through coordination with the Local Sponsor for use in calibration of the models. The models were reasonably calibrated to USGS gage rating curves and recorded gage heights for historic flood events and any established high water marks. Existing high water mark elevations were available on the Guadalupe, San Marcos and Blanco Rivers for the 1998 flood event.

The frequency discharges from the hydrologic analysis were run through the models in steady flow analysis to compute water surface elevations for the standard frequency flood events (the 50%, 20%, 10%, 4%, 2%, 1%, 0.4%, and 0.2% annual chance exceedance events). The only exception to this steady state methodology was in the area of the City of San Marcos, which is described in a later section. Figure 3. 3 illustrates the hydraulic model extents and the resulting 1% annual chance floodplains from these models. Additional details on the development of the hydraulic models and the resulting water surface profiles are available in Appendix A-1.

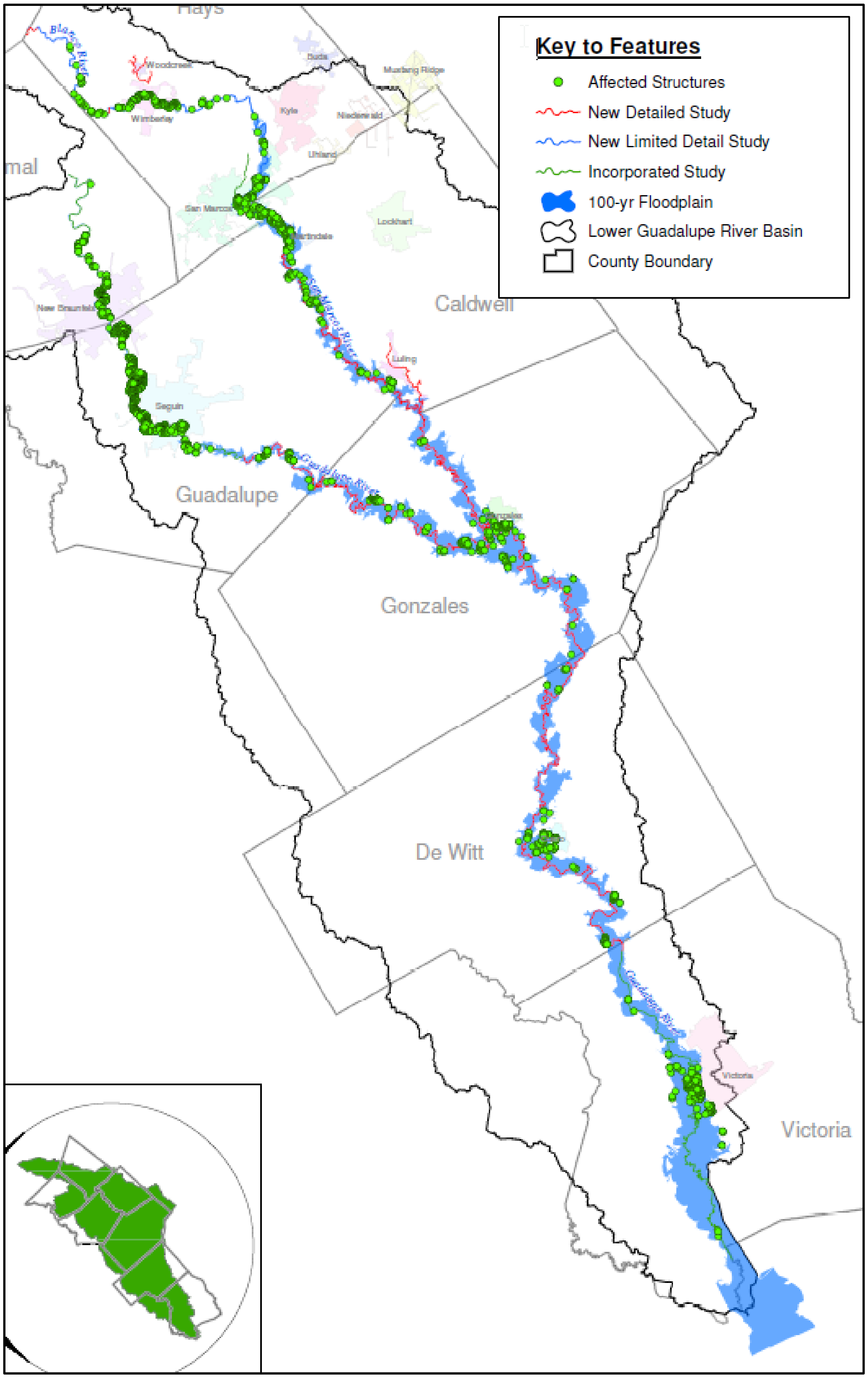

Figure 3.3: Hydraulic Model Extents and 1% ACE Floodplain

3.3.1 Guadalupe River Hydraulic Model

The Guadalupe River was studied for 296.1 miles with surveyed sections and structures from Canyon Dam downstream to the Victoria/Calhoun County Boundary near the Town of Tivoli, TX. The study was broken up into six models: (1) Victoria, (2) Dewitt, (3) Gonzalez, (4) Lower Guadalupe, (5) 23248, and (6) Upper Guadalupe. Sections 1, 4, 5 and 6 are incorporated existing studies and sections 2 and 3 are new models.

The four Guadalupe River reaches that incorporated existing hydraulic models were created during the recent FEMA Map Mod effort in Comal, Guadalupe, and Victoria Counties. Technical modeling details for the incorporated reaches can be found in the Comal County Effective Flood Insurance Study (FIS) (2009), Guadalupe County Effective FIS (2007), and Victoria County Preliminary FIS (upcoming).

Minimal changes were made to the incorporated model geometries since they have already been reviewed and accepted by FEMA. The main update of note to the incorporated models was to use frequency discharges derived from this study's hydrologic analysis rather than those from the existing hydrologic studies.

3.3.2 Blanco River 1D Hydraulic Model

The Blanco River was studied in limited detail for 47.8 miles without surveyed sections and structures from the Blanco/Hays County line to its confluence with the San Marcos River near the City of San Marcos.

3.3.3 San Marcos River 1D Hydraulic Model

The San Marcos River was studied for 76.9 miles with surveyed sections and structures from its confluence with the Blanco River near the City of San Marcos downstream to its confluence with the Guadalupe River near the City of Gonzales.

3.3.4 2D Hydraulic Modeling in the City of San Marcos

The Blanco River is the primary source of flooding for the City of San Marcos, which is located at the confluence of the Blanco River with the San Marcos River. The San Marcos River above San Marcos has a drainage area of only 50 square miles and is a spring fed stream that is largely controlled by NRCS flood detention structures. The Blanco River, on the other hand, is 436 square miles and flows through narrow canyons and steep stream beds until it approaches the City of San Marcos. Near San Marcos, the valley widens and the stream bed flattens. Rapidly rising floodwaters from the Blanco River tend to spread out when they reach San Marcos, flowing in multiple directions through city neighborhoods and over the drainage divides into the neighboring watersheds, as shown in Figure 3.4. As a result, the city experiences substantial flood damages when the Blanco River exceeds its banks, most recently in May and October of 2015.

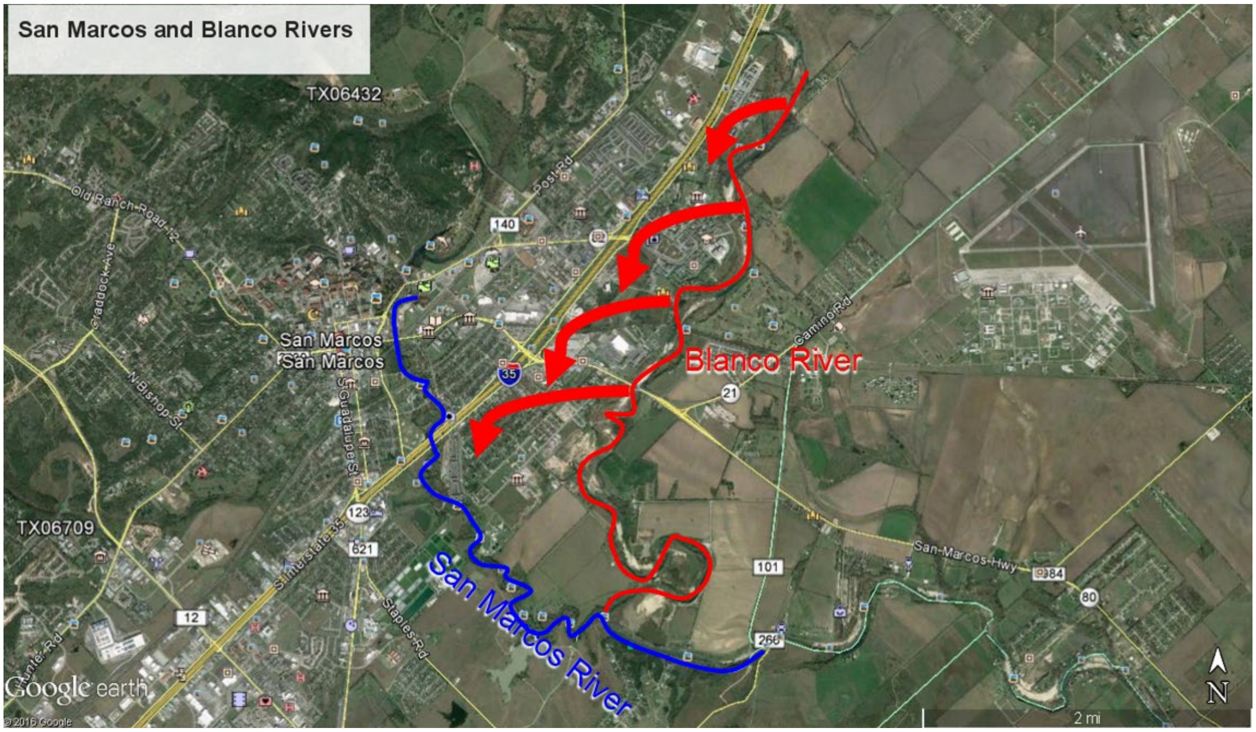

Figure 3.4: Blanco River Overflows through the City of San Marcos

For water surface elevations in the City of San Marcos, an existing InfoWorks ICM 2-Dimensional (2D) model of the floodplain in the City of San Marcos was used. This model was developed by Halff under a contract with the Guadalupe-Blanco River Authority (GBRA) unrelated to the feasibility study. The 2D hydraulic analysis of the confluence and overflow areas was developed to better model the complex multi-directional flow patterns occurring in the overflow area that were observed in the 2015 flood events.

The Innovyze Integrated Catchment Modeling (ICM) version 6.5.9 platform was utilized to complete the requested 2D simulations in Infoworks. The 1D hydraulic models of the Blanco and San Marcos Rivers were truncated to represent the 1D portions of those rivers while an overland mesh was formed using the Hays County 2008 LiDAR. The main stems of the Blanco River, San Marcos River, and Bypass Creek were modeled as 1D channel flow between channel bank stations. Overflow from each of these creeks was modeled as 2D overland flow which allows the flow to travel in multiple directions between mesh points. The result was a 1D / 2D coupled model in ICM.

The 2D model extends from just west of I-35 down to the confluence of the San Marcos River and Bypass Creek and can be seen in the figure below. The red line represents the 2D modeling extents and the blue shaded area is the preliminary FEMA 1% annual chance event (ACE) floodplain.

The Infoworks ICM platform was selected for the 2D simulations due to the model's stability with large datasets, ability to simulate underground conveyance systems, and time efficiency to execute multiple 2D simulations. Given the study's need for expedited alternatives analysis of this complex area, it was recommended that the City's available Infoworks ICM model be utilized to advance the Tentatively Selected Plan (TSP) analysis. A 2D simulation is preferred rather than utilizing multiple 1D HEC-RAS simulations to observe overall risk. Time constraints did not allow for the model to be converted and re-calibrated to a USACE approved platform such as HEC-RAS 5.0. Additionally, HEC-RAS 5.0 does not allow for the simulation of underground conveyance systems or complex alternatives analyses in the overland 2D mesh.

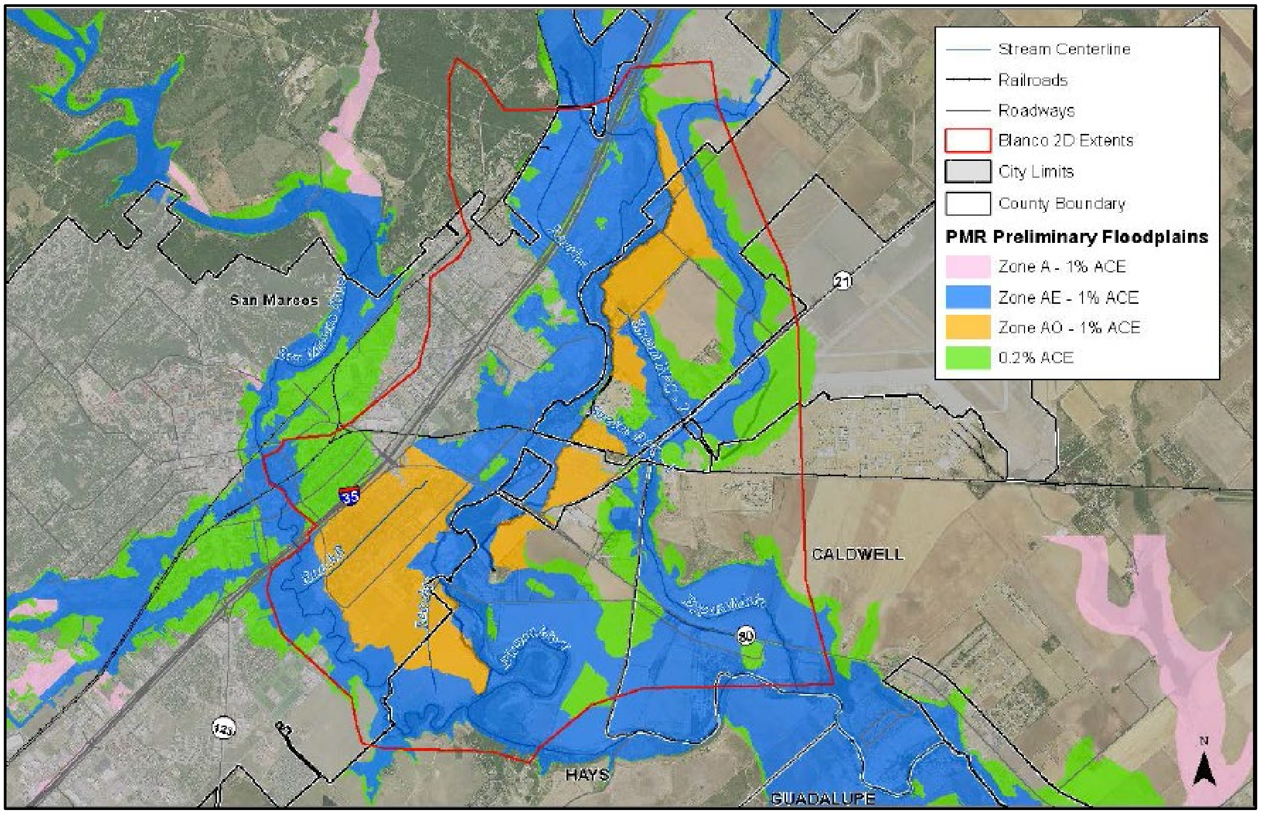

Figure 3.5: 2D Hydraulic Model Extents in the City of San Marcos

ICM utilizes mesh triangles to distribute flow through the overland 2D extents. The mesh triangles are assigned elevations from the 2008 LiDAR that was confirmed with 2016 field survey spot shots in the Blanco Gardens area. Roughness values are based on the assigned land use type. Manning's roughness values used for the 2D mesh ranged from 0.03 - 0.08 with buildings and homes being modeled as voids in the mesh.

The 2D model was calibrated to the observed high water marks, flood photos, and known damages from the May flood event in San Marcos. The model was calibrated to surveyed high water marks (provided by GBRA), a stage hydrograph at State Highway 80, and estimated high water marks in the Blanco Gardens neighborhood. The calibrated 2D model was found to accurately represent the depth of flooding at structures within the City of San Marcos, within a reasonable margin of error. At Highway 80, the peak stage of the model results were within 0.1 feet of the observed stage.

After calibration, the frequency flow hydrographs from the InFRM San Marcos HEC-HMS model were applied to the upstream boundaries of the 2D InfoWorks model. The frequency storm events analyzed included the 2-, 5-, 10-, 25-, 50-, 100-, 250-, and 500-year storms. For the 10-yr and smaller storm events, there was no ponding in the areas of interest. For the 25-yr and larger storm events, water from the Blanco River spilled outside of the banks downstream of the

Highway 80 bridge, inundating the Blanco Gardens area and overflowed just upstream of West Uhland Road into a low lying area through Bogie St. The large storm events such as the 100-yr and higher show more inundation upstream of Highway 80 and begin to flood the apartment complexes located along the Blanco River.

The resulting gridded 2D water surface elevations were then applied to the structure inventory to calculate existing conditions economic damages in the City of San Marcos. Additional details on the 2D hydraulic model development and results are available in Appendix A-1.

4 Future Without-Project Conditions

The principal land uses of the Lower Guadalupe River Basin are farming and ranching with residential and commercial development centered in cities such as New Braunfels, San Marcos, Wimberley, Seguin, Gonzales, and Victoria. Future development is anticipated to occur primarily along the Interstate corridor of I-35, which includes the cities of New Braunfels and San Marcos. The percentage of the basin that is actually subject to increased runoff due to changing land uses is very low. Future development in other areas of the basin is anticipated to primarily consist of scattered low density residential development on large lots which will have minimal effects on runoff.

Hays, Comal, and Guadalupe counties, as well as the rest of the basin counties, are participants in the National Flood Insurance Program (NFIP). As such, local ordinances are in effect that require the construction of new structures within the 1% ACE floodplain to be above the 1% ACE water surface elevation. The floodplain regulation combined with the predicted stable peak discharges should limit increasing future without project damages. Therefore, the future conditions discharges are not projected to increase substantially.

The projected future conditions were tested by utilizing the existing conditions HEC-HMS model with revised variables sensitive to development. Variables that typically change due to future development in a watershed are percent urbanization, percent impervious, and resultant Snyder's lag. Available future land-use maps from cities and counties in the watershed were utilized to estimate future hydrologic parameters. The following sections describe the future conditions impacts to the hydrology of the three damage centers that were carried forward in plan formulation, which were New Braunfels, San Marcos and Wimberley, Texas.

4.1 New Braunfels, Texas

The City of New Braunfels' future land use from their 2015 Comprehensive Plan shows future development as primarily low density residential expanding from the city center with designated sectors for commercial and industrial development, as shown in the following figure.

This future development in New Braunfels could increase future flood property damages within the city, but it is expected to have minimal effect on frequency peak discharges on the Guadalupe River at New Braunfels. The Guadalupe River discharges through New Braunfels are driven by runoff from further upstream which includes potential releases from Canyon Dam and local runoff from areas of Comal County which are downstream of the dam. The area upstream of Canyon Dam is expected to remain primarily rural, so releases from the dam are not anticipated to increase in the future. Outside of the city limits, the areas downstream of the dam are expected to experience scattered low density residential development on large lots which will have minimal effects on runoff. Therefore, future conditions discharges in New Braunfels are projected to remain essentially the same as existing conditions.

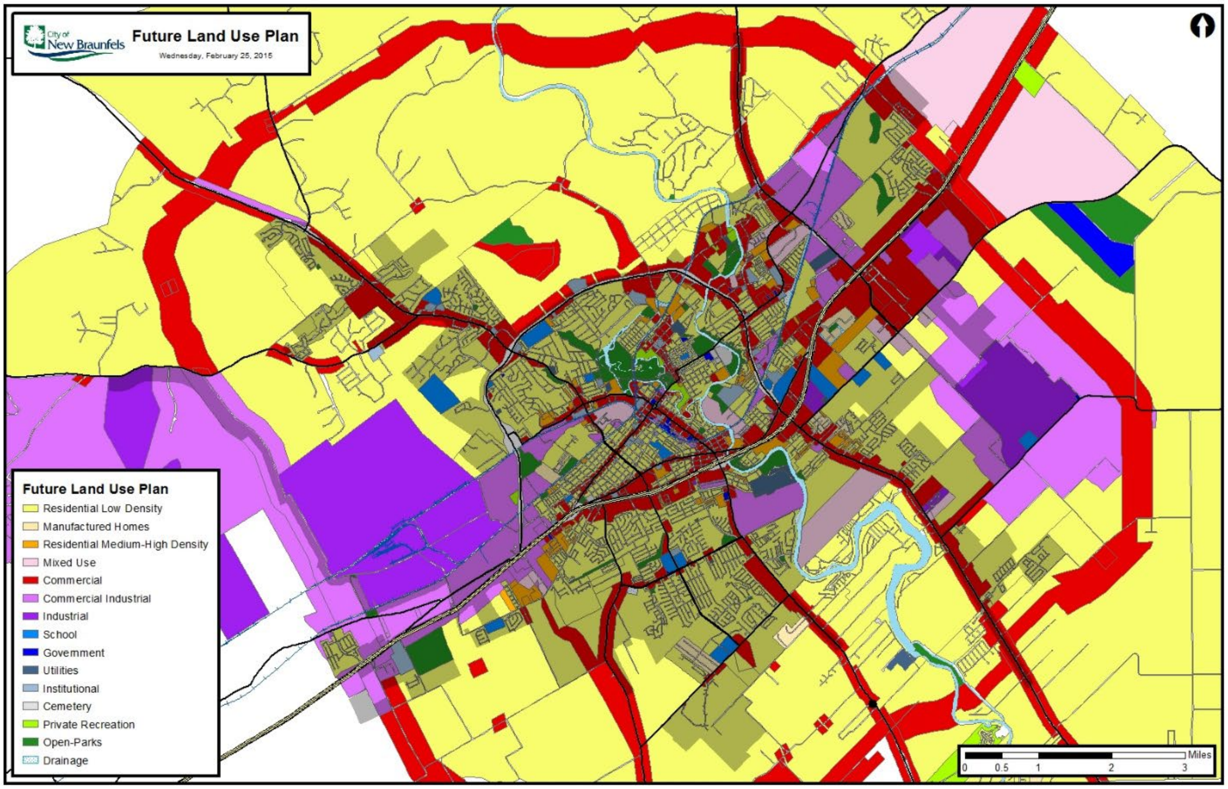

Figure 4.1: Future Land Use for the City of New Braunfels, Texas

4.2 San Marcos, Texas

The city of San Marcos' 2010 future land use map shows additional low density residential and industrial development on the east side of the Blanco River and very low density residential along the northwest and southwest edges of the city, as shown in the following Figure.

Similar to the situation described for New Braunfels, frequency flood flows through the City of San Marcos are primarily driven by discharges from the upper Blanco watershed which is not expected to experience significant future development. Future development in San Marcos could increase future flood property damages within the city, but it is expected to have minimal effect on frequency peak discharges from the Blanco River and the San Marcos River at San Marcos. The flood discharges through San Marcos tend to be driven by runoff from the steep channel slopes and narrow valleys of the upper Blanco watershed which are expected to remain the same in the future. Therefore, future conditions discharges in San Marcos are projected to remain essentially the same as existing conditions.

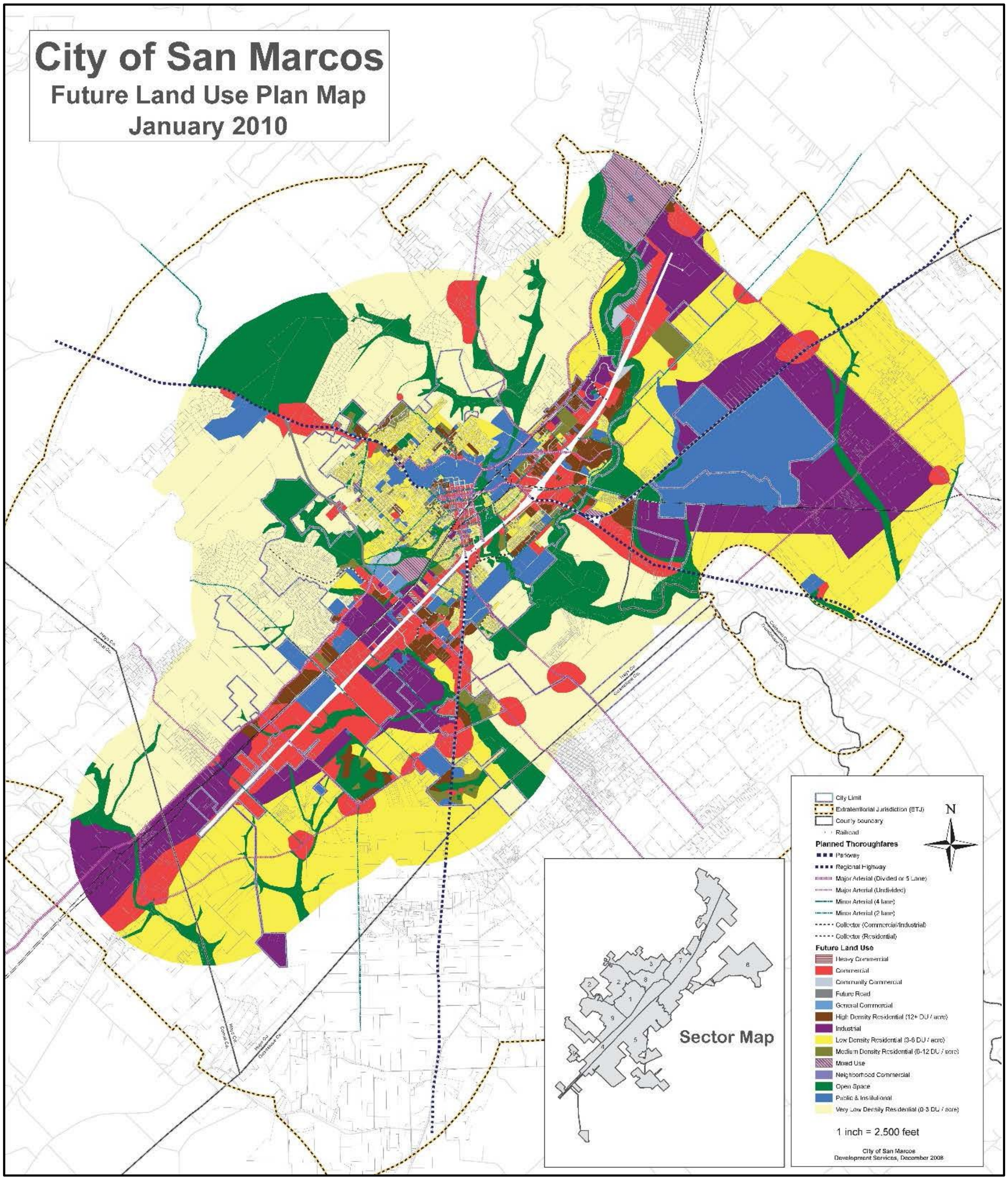

Figure 4.2: Future Land Use Map for the City of San Marcos, Texas

4.3 Wimberley, Texas

The Blanco watershed upstream of the city of Wimberley consists primarily of rural portions of Blanco and Hays County. Principal land uses in the Blanco watershed are farming and ranching. Future development is not expected to be significant, consisting of scattered low density residential development. Peak flood flows through Wimberley are driven by the steep channel slopes and narrow valleys of the watershed, and those conditions are expected to remain the same in the future. Therefore, future conditions discharges in Wimberley are projected to remain essentially the same as existing conditions.

5 Future With-Project Conditions

Flooding and associated damages occur throughout the Lower Guadalupe Basin in numerous locations. The planning approach for this study has been to narrow the focus of the plan formulation to those damage areas appropriate to be carried forward where a potential solution could rise to the level justifying congressional approval for implementation. The narrative that follows provides information on the approach by the study team to narrow from the large basin level to those specific damage centers appropriate for formulation under this General Investigation study.

5.1 Initial Screening of Damage Centers

Utilizing mapping and aerial imagery with the existing conditions 1% annual chance exceedance (ACE) floodplain from Figure 3.3 overlaid, potential damage centers were identified within the basin using structure counts (concentration of structures) within the 1% ACE floodplain (commonly referred to as the 100-year event). This effort resulted in the identification of 11 separate damage centers with a total of 9,021 structures identified in the 100-year floodplain (during the screening level). During the Basin level screening phase, the damage centers identified included: Kyle, Lockhart, Seguin, Victoria, San Marcos, New Braunfels, Wimberley, Luling, Cuero, Gonzales and Woodcreek.

The 11 damage centers were then further screened based upon available information. Items taken into account include the frequency and extent of past flooding events, the estimated frequency at which flooding starts to occur, the concentration of structures, and probable structure values. Costs based on best engineering judgment in combination with a very preliminary list of potential measures was applied within the remaining damage centers. Altogether, this information was used to screen the damage centers down to those with the highest potential for being economically justifiable within the parameters of this feasibility study. As a result, three damage centers were identified to be carried forward in a more detailed plan formulation process within this existing study. The three damage centers identified are known as New Braunfels-Seguin, San Marcos and Wimberley, Texas.

5.2 Alternatives Evaluated for Future With-Project Conditions

After the Alternatives Milestone Meeting (AMM), the three structural alternatives that remained for further evaluation were:

1. Bear Creek Detention upstream of New Braunfels.
2. Blanco River Detentions upstream of Wimberley, Texas

3. Blanco River and Bypass Creek Alternatives at San Marcos, Texas.

The following sections will describe the hydrologic and hydraulic analyses that were undertaken to evaluate the future with project conditions associated with these alternatives.

5.3 Bear Creek Detention

The Bear Creek watershed is a 16.7 square mile watershed that empties into the Guadalupe River about 9 river miles downstream of Canyon Dam and about 15 river miles upstream of New Braunfels, TX. Bear Creek was chosen for alternative analysis because it is the largest tributary that is not regulated by a detention dam and is located upstream of New Braunfels and Seguin, which have approximately 1,982 structures located in the 1% ACE floodplain, according to the initial screening of damage centers. Figure 5.1 illustrates the locations of the structures that could potentially receive flood risk reduction benefits from a detention project on Bear Creek.

The Bear Creek detention was one of many alternatives identified by Halff in their preliminary alternatives analysis, but Halff's preliminary economic analysis showed that the Bear Creek detention had the highest preliminary benefit-cost ratio of any other alternative (see Appendix A-1). Therefore, the Bear Creek detention was carried forward for further analysis in plan formulation.

The Bear Creek detention provides benefits by controlling the runoff from the Bear Creek portion of the uncontrolled Guadalupe watershed below Canyon Dam. Releases from Canyon Dam and the runoff from the other uncontrolled portions of the Guadalupe watershed were assumed to remain the same.

In Halff's analysis, the proposed Bear Creek dam was located 1.5 miles east of Farm to Market road 2722 and Bear Creek Trail. The dam extends across Bear Creek with a proposed top of dam elevation of 850 feet NAVD88, which is approximately 85 ft above the invert of the channel, and an approximate dam length of 680 ft. The maximum storage capacity of the dam would be approximately 3,375 ac-ft. The dam size and location were chosen to minimize impacts on existing structures while minimizing construction cost and maximizing flood reduction benefits. A storage-elevation curve was created based upon 2007-2008 TNRIS LiDAR data. The outlet structures in Halff's preliminary analysis were sized to pass the 1% ACE with at least one foot of freeboard and to contain the 0.2% ACE event without overtopping the dam. The outlet structure was composed of a reinforced concrete box culvert designed to pass the low flows. The overflow spillway for the dam was set at an elevation of 845 ft. The exact dimensions of the dam and outlet structures were expected to be refined through the feasibility level design. Figure 5.2 shows the location of the proposed detention dam on Bear Creek.

The benefits associated with the Bear Creek detention were determined through HEC-HMS, HEC-RAS and HEC-FDA models. For with-project conditions for the Bear Creek detention, the study team assumed the same dam configuration as was initially proposed by Halff. The with-project hydrology was modeled by splitting the Bear Creek subbasin at the location of the dam, and adding a reservoir element to the HEC-HMS model at the location of the proposed detention dam. The computed storage-elevation curve from the LiDAR data was entered into the with-project HEC-HMS model along with the rest of the proposed dam's properties. Figure 5.3 shows the Bear Creek 1% ACE (100-yr) flows for with-project versus existing conditions, as calculated in HEC-HMS.

The With Project HEC-HMS model quantified the reduction in flow on the Guadalupe River due to the proposed dam on Bear Creek. Since the final existing conditions frequency flows for the

Guadalupe River used a combination of gage analysis and HEC-HMS model results, the percent reduction in peak flow from the hydrology model for the pre- and post-project conditions was applied to the gage analysis flows used in the final hydraulic model. These post-project flows were then entered into the Guadalupe River hydraulic model, which included the reaches through New Braunfels and Seguin, to determine the reduction in the water surface profiles for with project conditions.

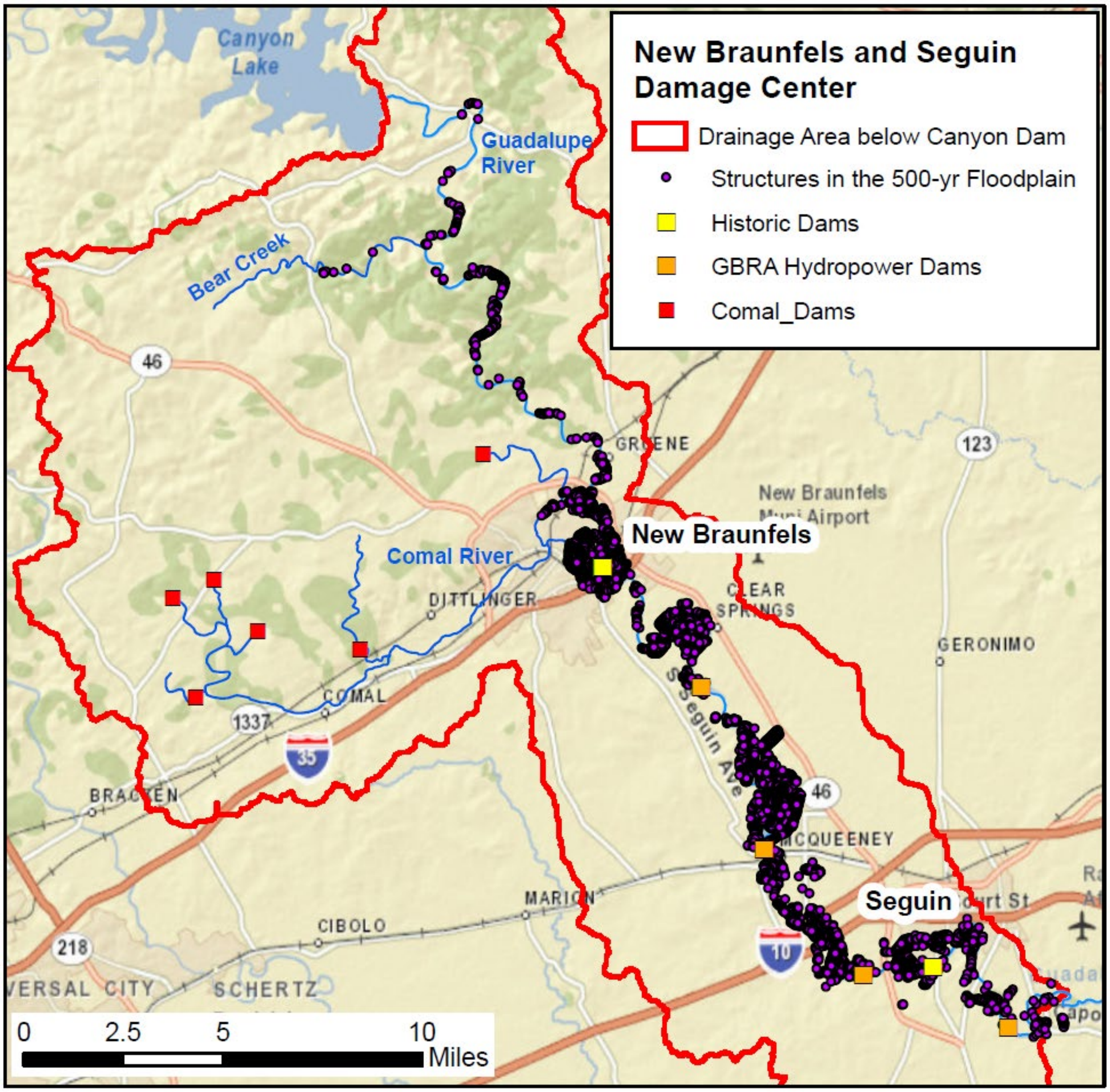

Figure 5.1: Structures in New Braunfels and Seguin downstream of Bear Creek

Figure 5.2: Bear Creek Detention Location

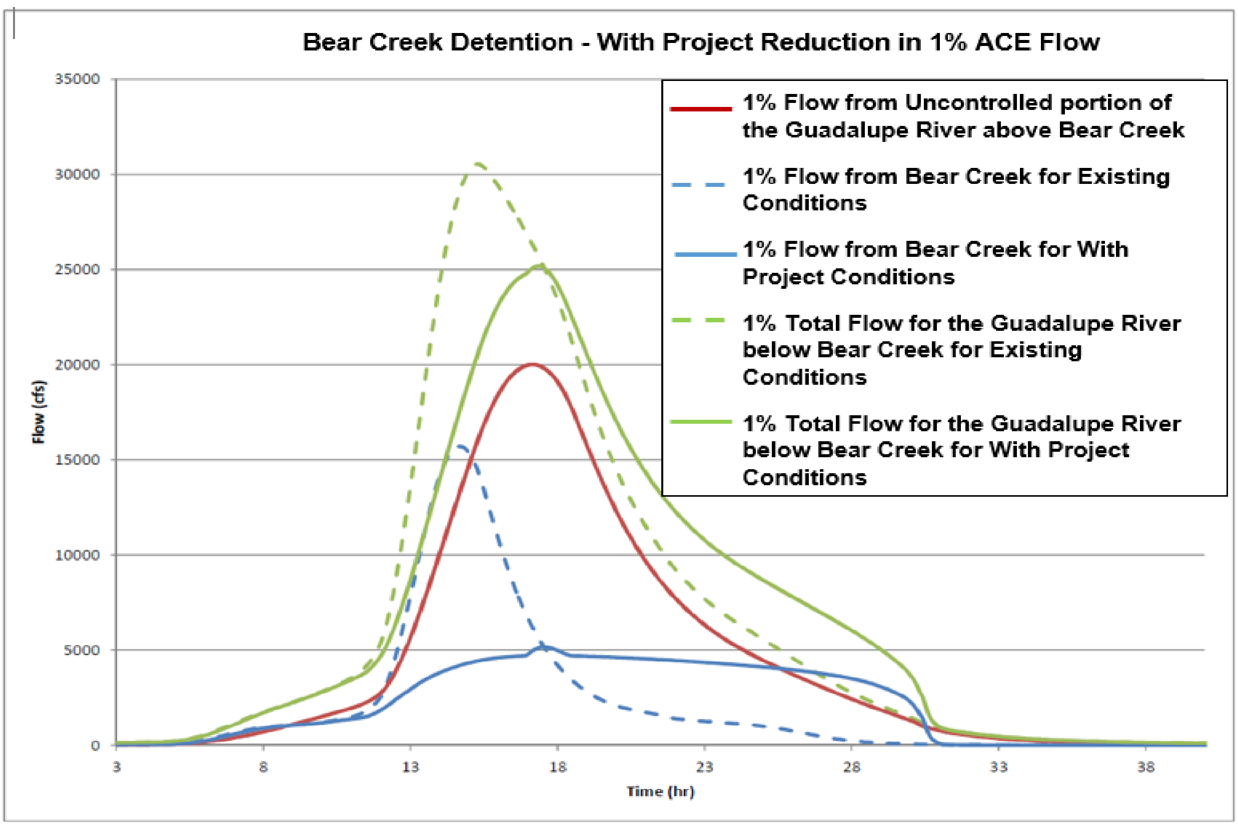

Figure 5.3: Existing and With Project 100-yr Hydrographs on Bear Creek.

The largest reduction in flow and water surface occurred within the City of New Braunfels. The post-project hydrology model showed an 8% reduction in peak flow for the 1% ACE event at New Braunfels, and the with-project hydraulic model showed a water surface reduction of over 2 ft. The detention on Bear Creek also reduced the 1% ACE peak flow in the City of Seguin by 4% and reduced the water surface by more than 0.5 ft. The final with project flow frequency curves and water surface profiles, along with their respective uncertainties, were then input into HEC-FDA for economic analysis. See the Economics Appendix for more information.

5.4 Blanco River Detention Alternatives Upstream of Wimberley, Texas

Following the flood events of May and October 2015, detention upstream of Wimberley, Texas was identified as a potential alternative to help alleviate flood risk in both the Wimberley and San Marcos damage centers.

5.4.1 Identification of Potential Detention Sites

Potential detention sites upstream of Wimberley were identified by visual examination of the topographic and aerial imagery data or by input from the Local Sponsor. Once potential detention sites were identified, basic information such as potential storage volume, maximum dam height, approximate dam length, and drainage area were gathered and analyzed for each site. A total of seven detention sites upstream of Wimberley were identified through this process, as shown on Figure 5.4 below.

5.4.2 Screening of the Potential Detention Sites

The seven identified dam sites were then ranked based on several factors including (1) their potential storage volume per square mile of drainage area, (2) their storage volume per foot of dam height, and (3) the percent of the drainage area upstream of the Wimberley damage center that they would control. The results of that ranking are shown in Table 5.1 and Figure 5.5 below.

Further screening of the potential dam sites was then performed by examining aerial imagery against the maximum inundation area of each site to identify any significant real estate or transportation impacts associated with each site.

Upon completion of this screening process, the PDT decided that only the highest ranked site would be carried forward for further analysis. This approach allowed the PDT to focus on the site that should have the highest potential of becoming an economically feasible project. Therefore, the Blanco2 detention site was carried forward for further hydrologic and economic analysis. At the request of the Local Sponsor, an additional site in Hays County, just downstream of the confluence of confluence of the Little Blanco River with the Blanco River was also added to the analysis.

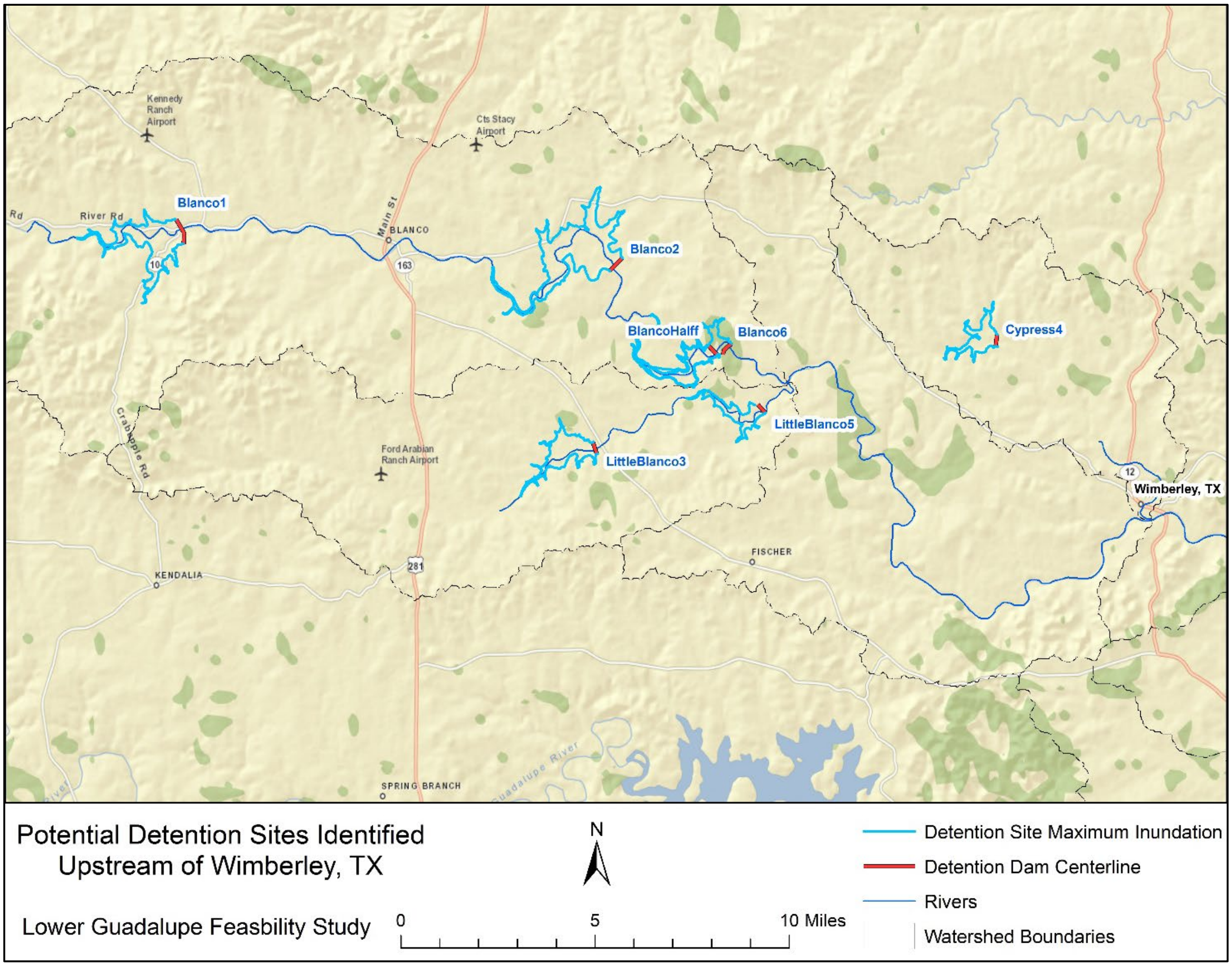

Figure 5.4: Potential Detention Sites Identified Upstream of Wimberley, Texas

Table 5.1: Ranking of Detention Sites upstream of Wimberley by Storage Volume and Drainage Area

Site Name	Stream Location	Drainage Area (DA) (sq mi)	Dam Length (ft)	Stream Elev (ft)	Maximum Pool Elevation (ft)	Maximum Height (ft)	Volume at Maximum Elevation (ac-ft)	Volume/DA (ac-ft/sqmi)	Percent of Wimberley DA Controlled by Site	Ranking Factor (product of previous two columns)
Blanco2	Blanco River	146.69	2510	1172	1245	73	43690	298	41%	123
Blanco1	Blanco River	67.23	3720	1377	1470	93	25441	378	19%	72
Blanco6	Blanco River	166.97	1970	1014	1120	106	12360	74	47%	35
BlancoHalff	Blanco River	163	1840	1026	1128	102	11614	71	46%	33
Cypress4	Cypress Creek	15.00	2520	1022	1082	60	7112	474	4%	20
LittleBlanco3	Little Blanco	50.13	1725	1159	1200	41	7037	140	14%	20
LittleBlanco5	Little Blanco	67.55	1550	1025	1100	75	5596	83	19%	16

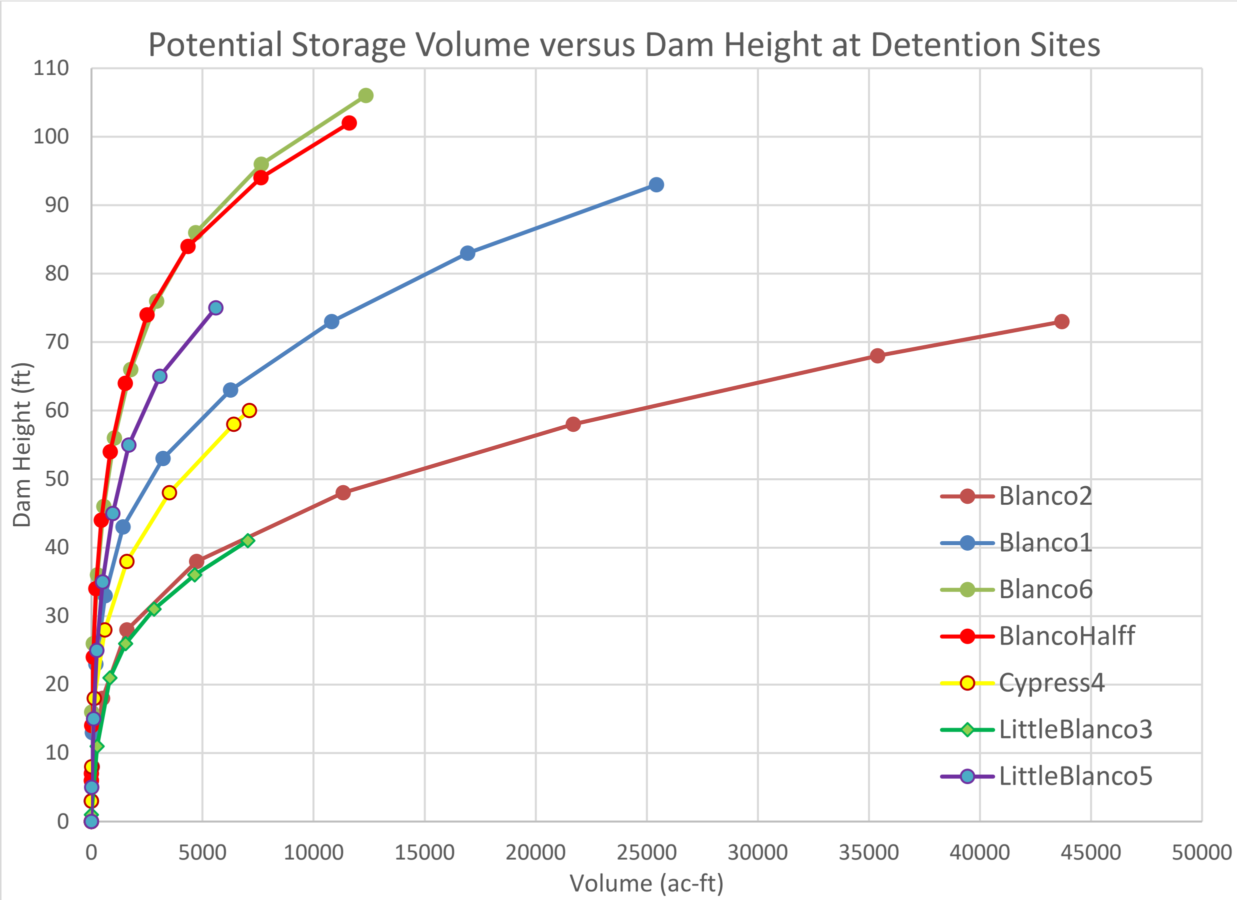

Figure 5.5: Detention Sites Storage Volume versus Dam Height

5.4.3 Hydrologic Analysis of the Blanco2 and Hays Co Detention Sites

The Blanco2 dam site extends across the Blanco River in tree covered ranch land with some open pasture in Blanco County, Texas. Chimney Valley Road (County Road 407), an asphalt paved road extends through the center of the proposed dam site 2 and crosses the Blanco River near the proposed dam site. The Hays Co dam site is in the western corner of Hays County, just downstream of the confluence of the Blanco with the Little Blanco River. Figure 5.6 shows the locations of the proposed Blanco2 and Hays Co detention sites.

Once these detention sites were selected for further analysis, the potential hydrologic impacts of the structures were analyzed by creating a with-project basin model in HEC-HMS. This with-project model was created by adding a few new elements to the basin model. First, a new subbasin break was added at the location of the detention site. Second, a new routing reach was added from the detention site to the next downstream subbasin break. Third, a new reservoir element was added to the basin model to represent the detention structure.

Three potential dam heights were analyzed for the Blanco2 detention site: 60 feet, 65 feet, and a maximum dam height of 73 feet. For the Hays Co dam site, only the maximum dam height was analyzed, as only the maximum height had adequate flood storage volume.

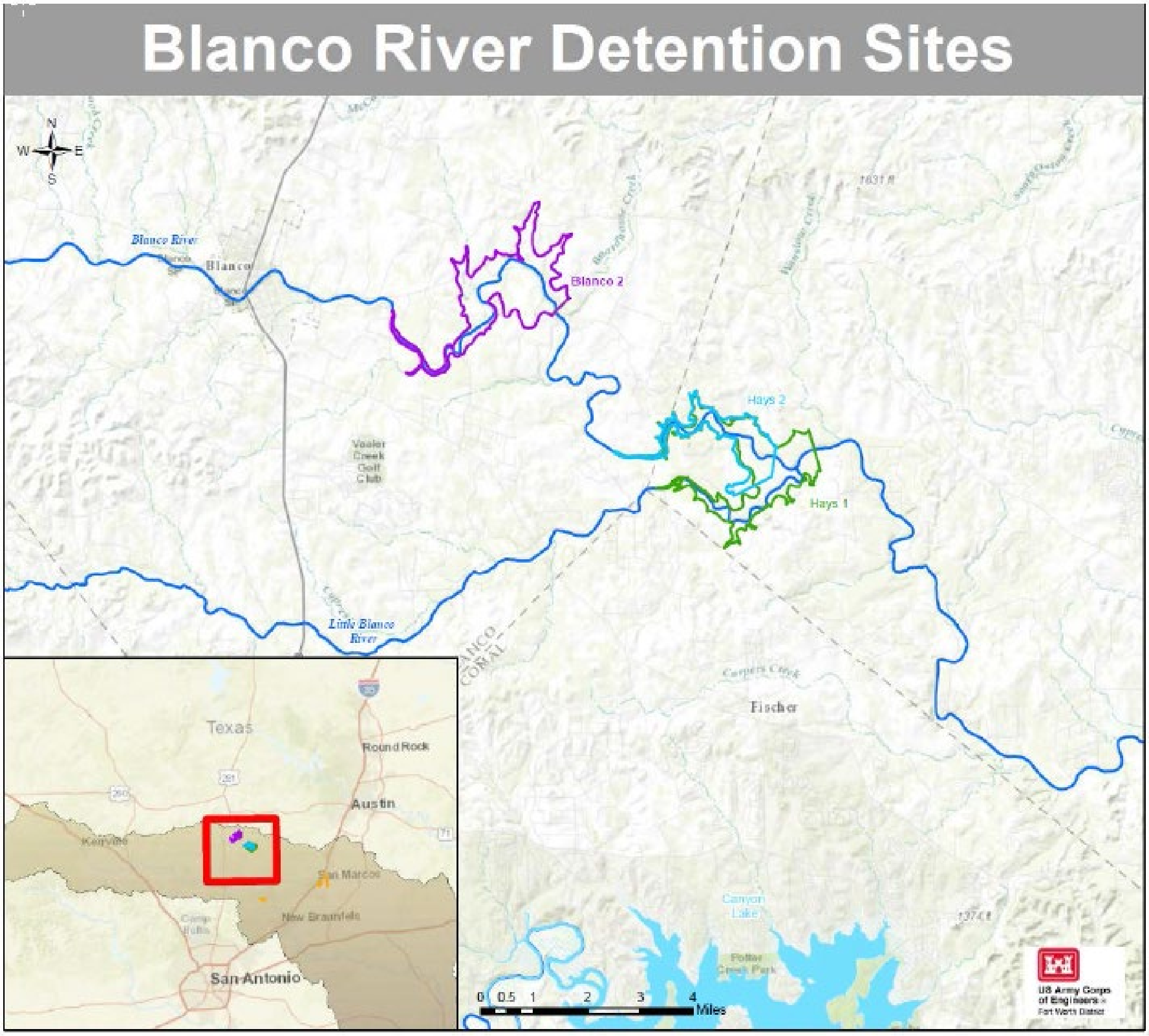

Figure 5.6: Location of the Blanco2 and Hays Co Detention Sites

In order to the model the detention structures, some assumptions had to be made. The assumptions that were made regarding dam height, outlet configuration, and spillway elevation and width are shown in Table 5.2 and Figures 5.7 and 5.8 below. The dam height was assumed to be the same as or up to the maximum dam height determined during the screening phase. The outlets were sized in order to pass inflows up to the downstream channel capacity and were placed at the channel invert elevation. The spillway was sized in order to pass the 500-yr (0.2% AEP) flood without overtopping the dam and with a reasonable amount of freeboard (4 feet or more). It was also assumed that the dam would be designed to overtop during extreme flood events, such as the Probable Maximum Flood (PMF). All of these assumptions were expected to be further refined later in the study in order to find the optimum dam configuration that produces the largest benefit-to-cost ratio.

Table 5.2: Assumed Configurations for the Blanco2 and Hays Co Detention Sites

Site Name	Dam Length (ft)	Stream Elev (ft)	Top of Dam Elev (ft)	Max Dam Height (ft)	Spillway Crest (ft)	Spillway Width (ft)
Blanco2 Small Dam	1990	1172	1232	60	1172	90
Blanco2 Medium Dam	2150	1172	1237	65	1172	65
Blanco2 Dam at Max Height	2510	1172	1245	73	1172	40
Hays Co Dam Site	4350	982	1092	110	982	52

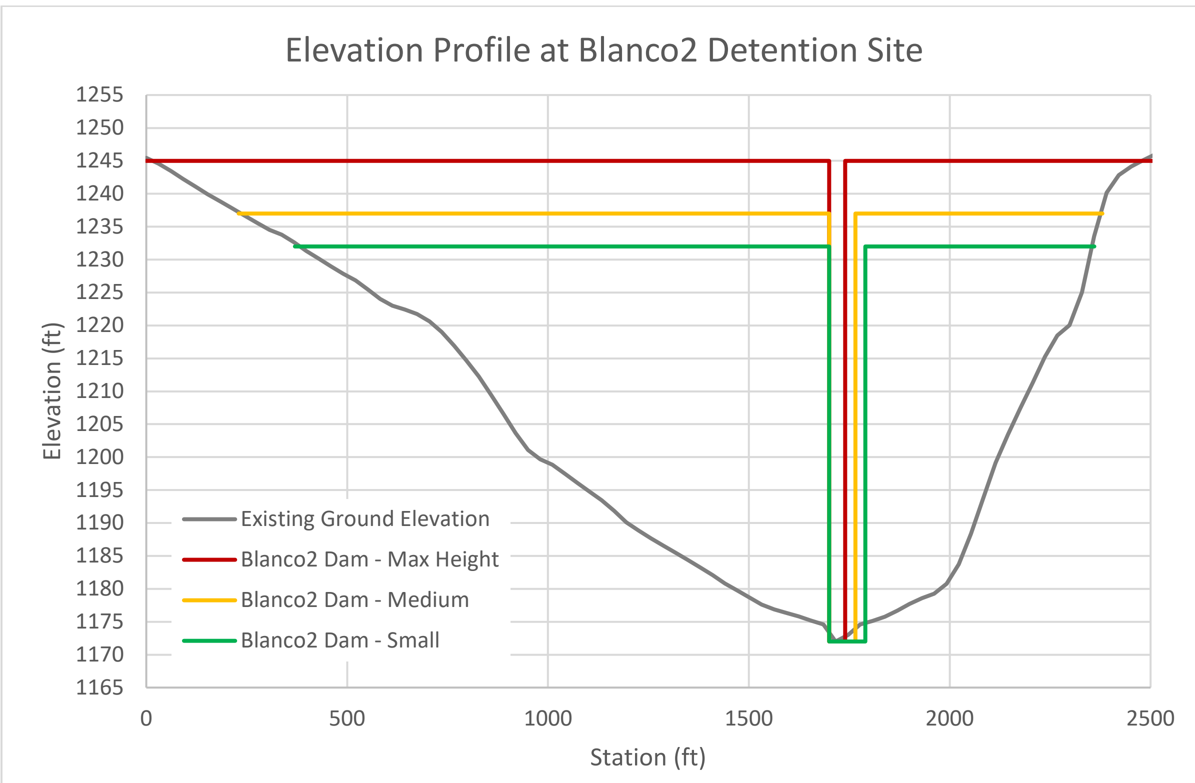

Figure 5.7: Blanco2 Detention Elevation Profile

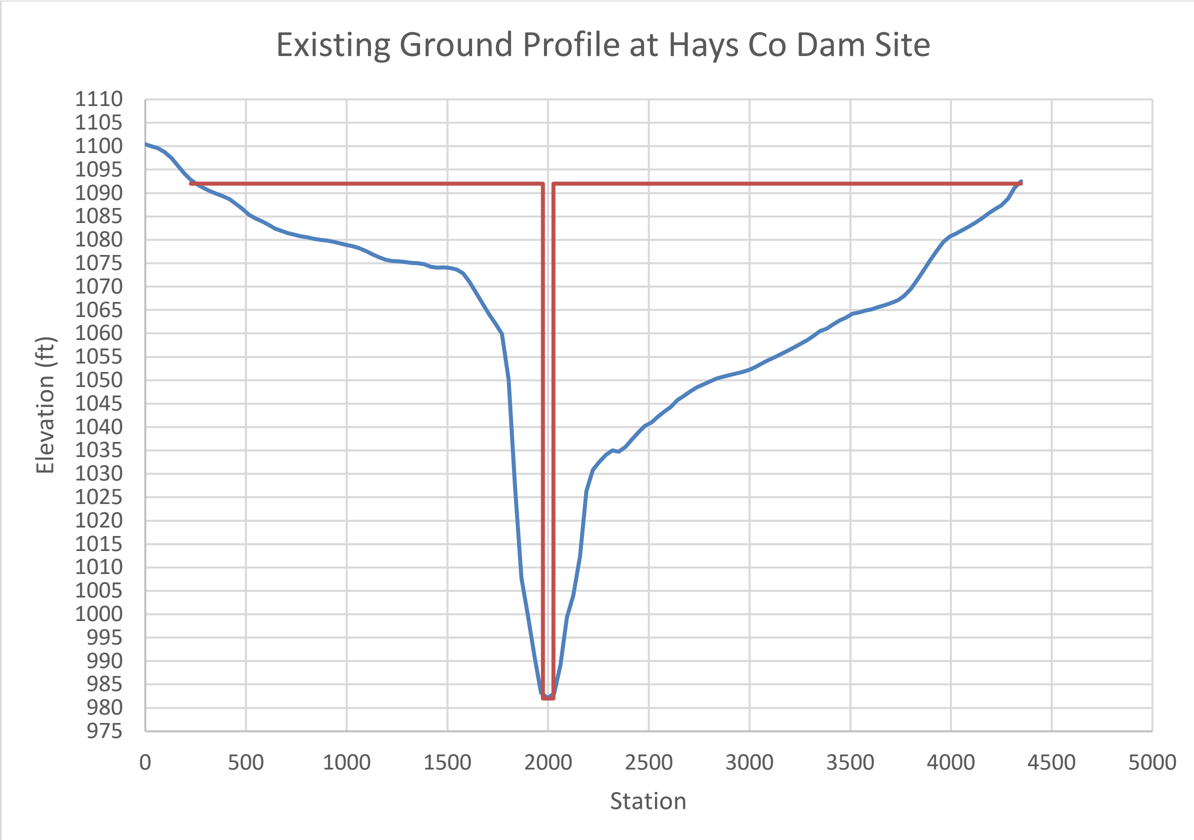

Figure 5.8: Hays Co Detention Elevation Profile

The elevation-storage volume relationships, which were calculated during the screening phase of the alternatives, was also entered into HEC-HMS as shown in Figures 5.9 and 5.10. These storage volumes were calculated from the LiDAR terrain data using the 3D analyst tools in ArcGIS.

After configuring the with-project basin models in HEC-HMS, the same eight standard frequency storms were run in HEC-HMS for with-project conditions as were run for existing conditions. The with-project peak flows that were calculated in the HEC-HMS model were then input into the applicable hydraulic models to calculate their impact on the water surface elevations through the damage centers of Wimberley and San Marcos.

The resulting reductions in frequency peak discharges for with project conditions are shown in Figures 5.11 to 5.13. The resulting reductions in flood depth at Wimberley and San Marcos are illustrated in Figures 5.14 and 5.15.

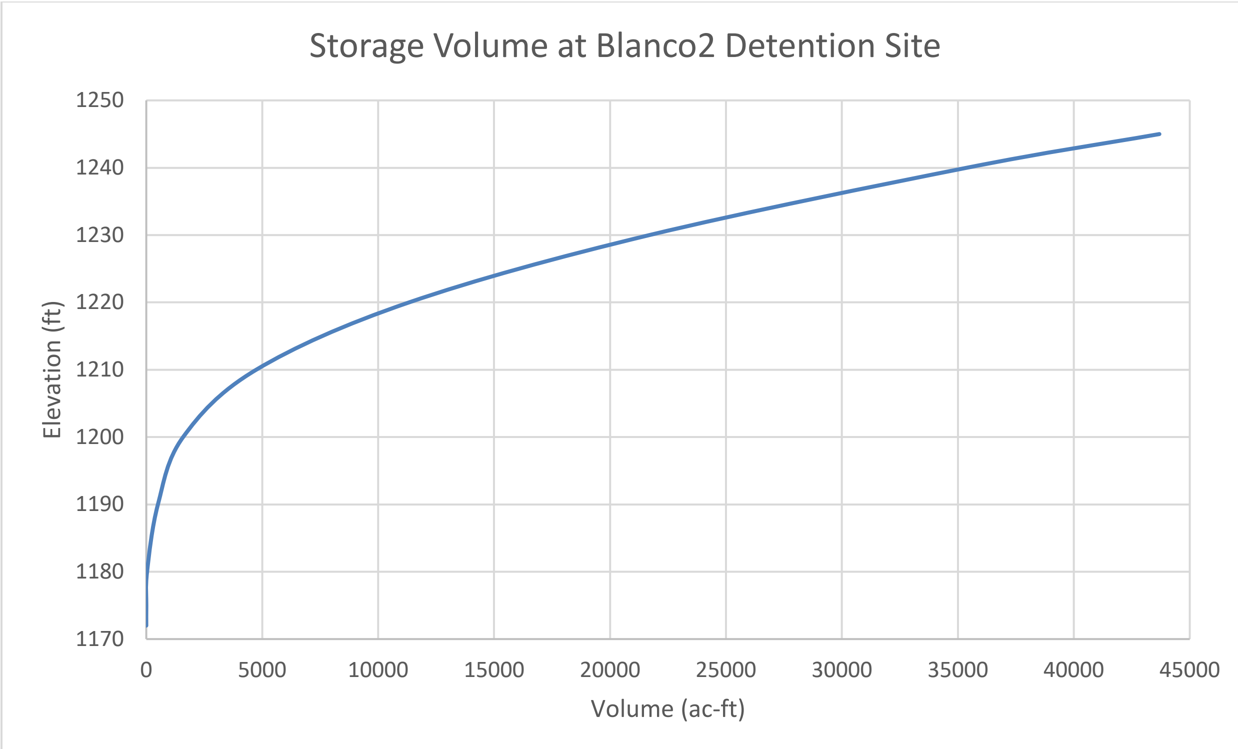

Figure 5.9: Elevation-Storage Volume Relationship at the Blanco2 Detention Site

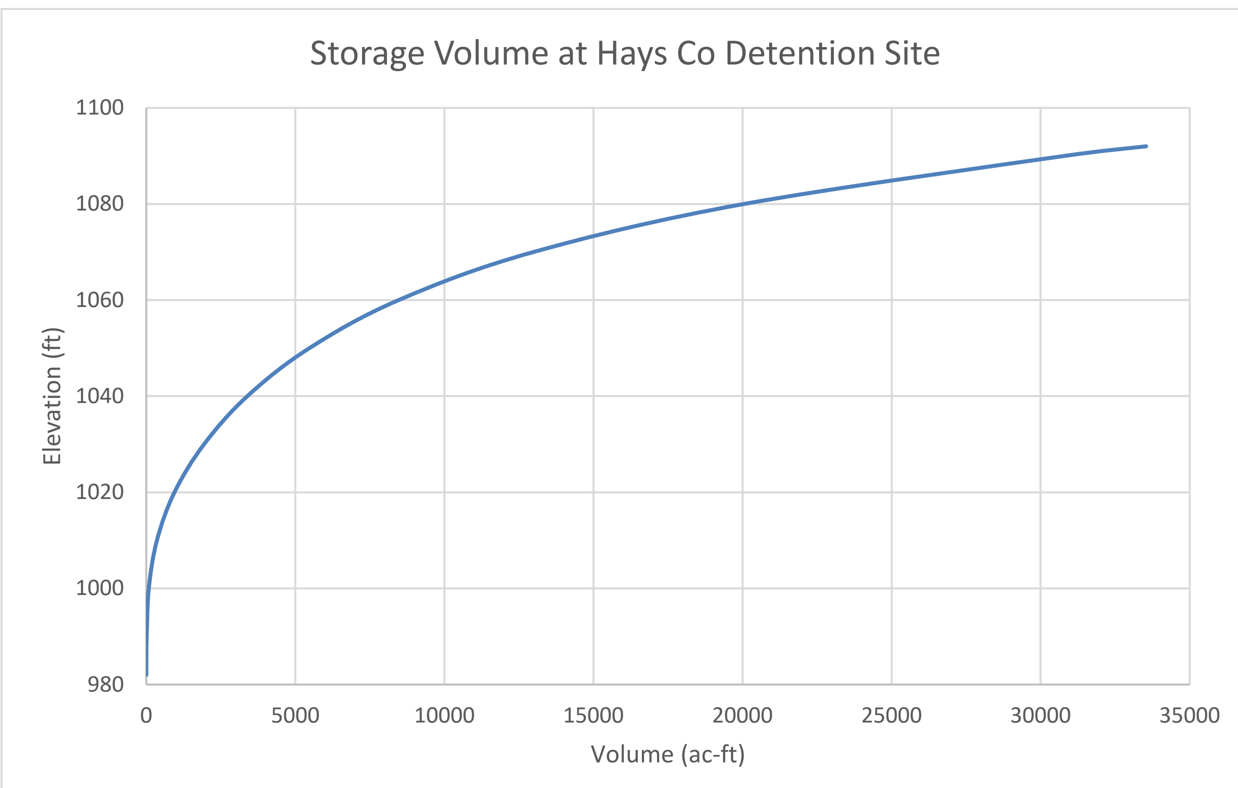

Figure 5.10: Elevation-Storage Volume Relationship at the Hays Co Detention Site

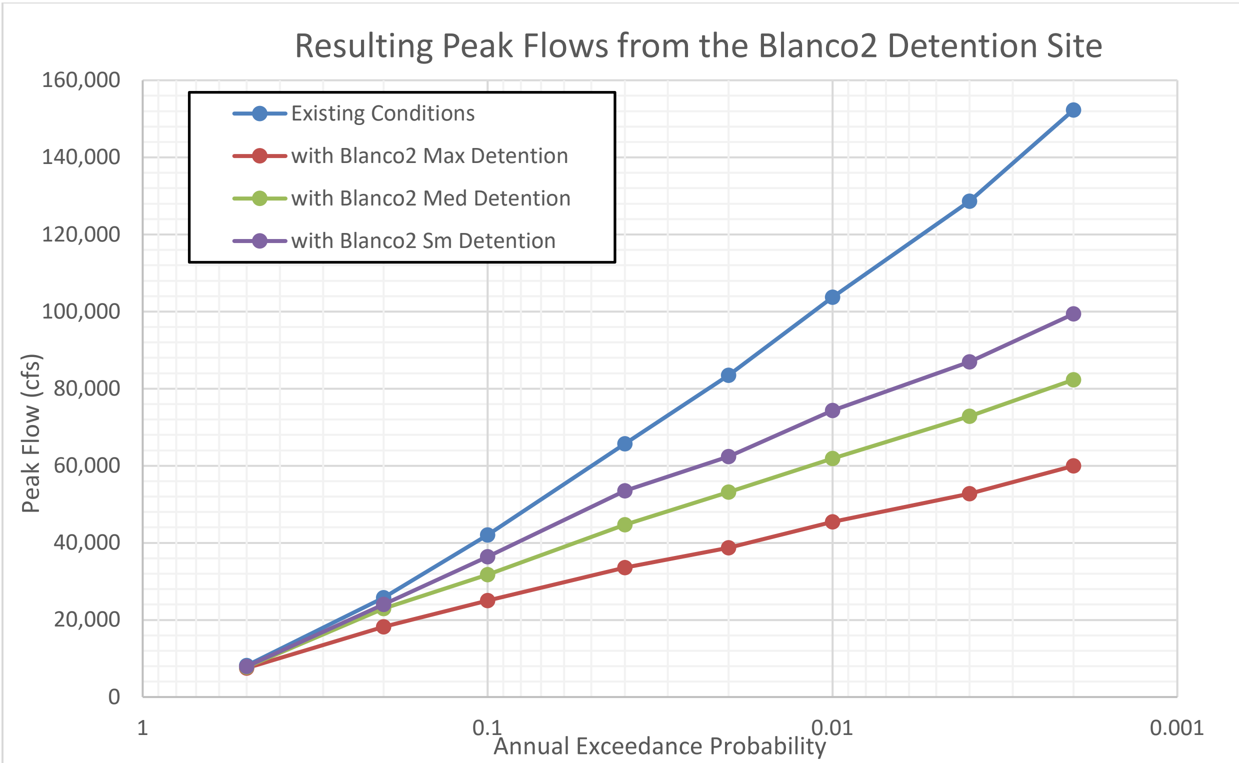

Figure 5.11: With and Without Project Peak Flows at Blanco2 Detention site.

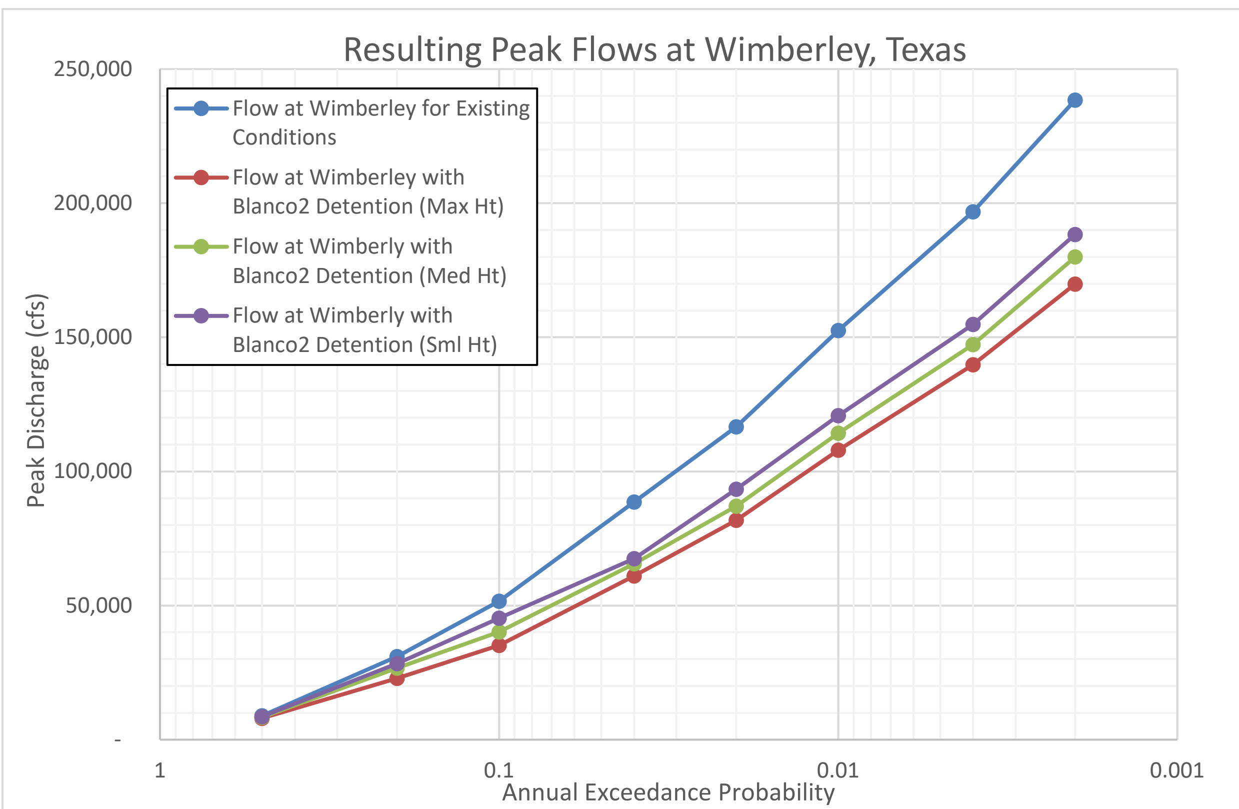

Figure 5.12: With and Without Project Peak Flows at Wimberley for Blanco2 Detention.

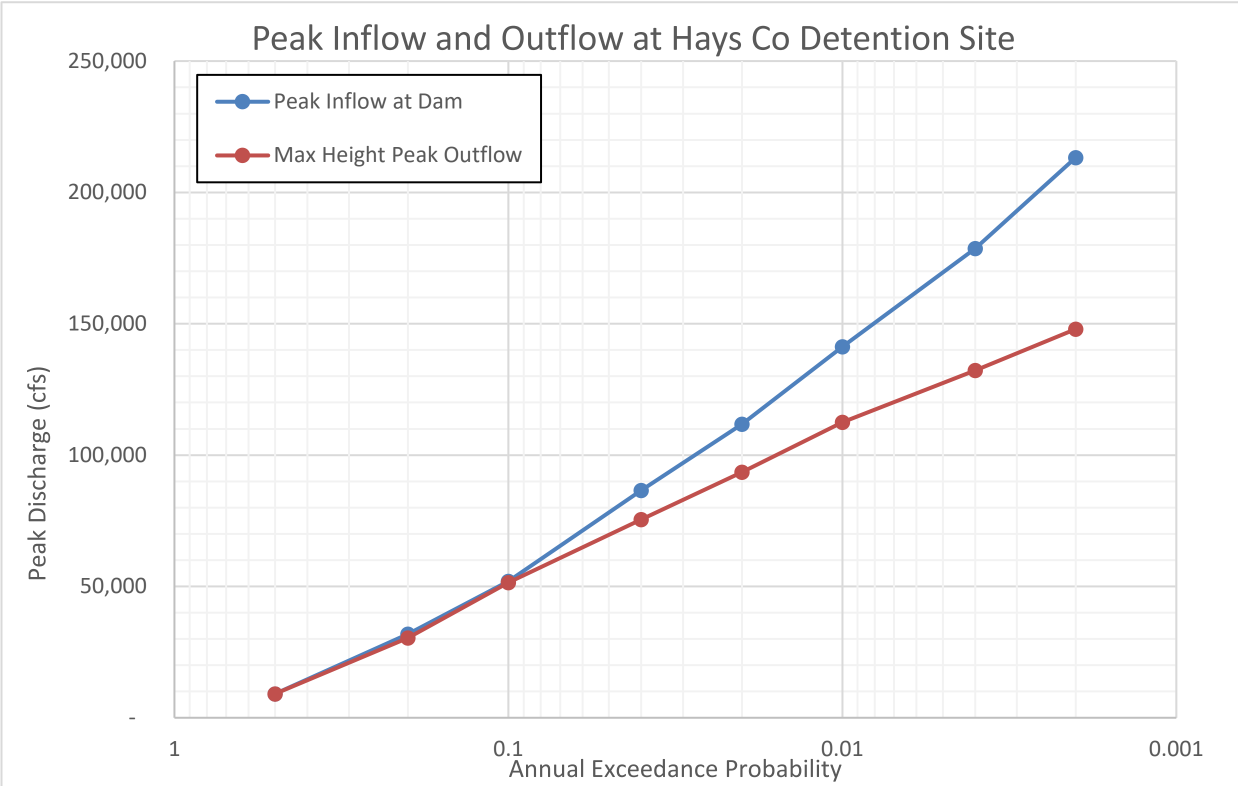

Figure 5.13: With and Without Project Peak Flows at Hays Co Detention site.

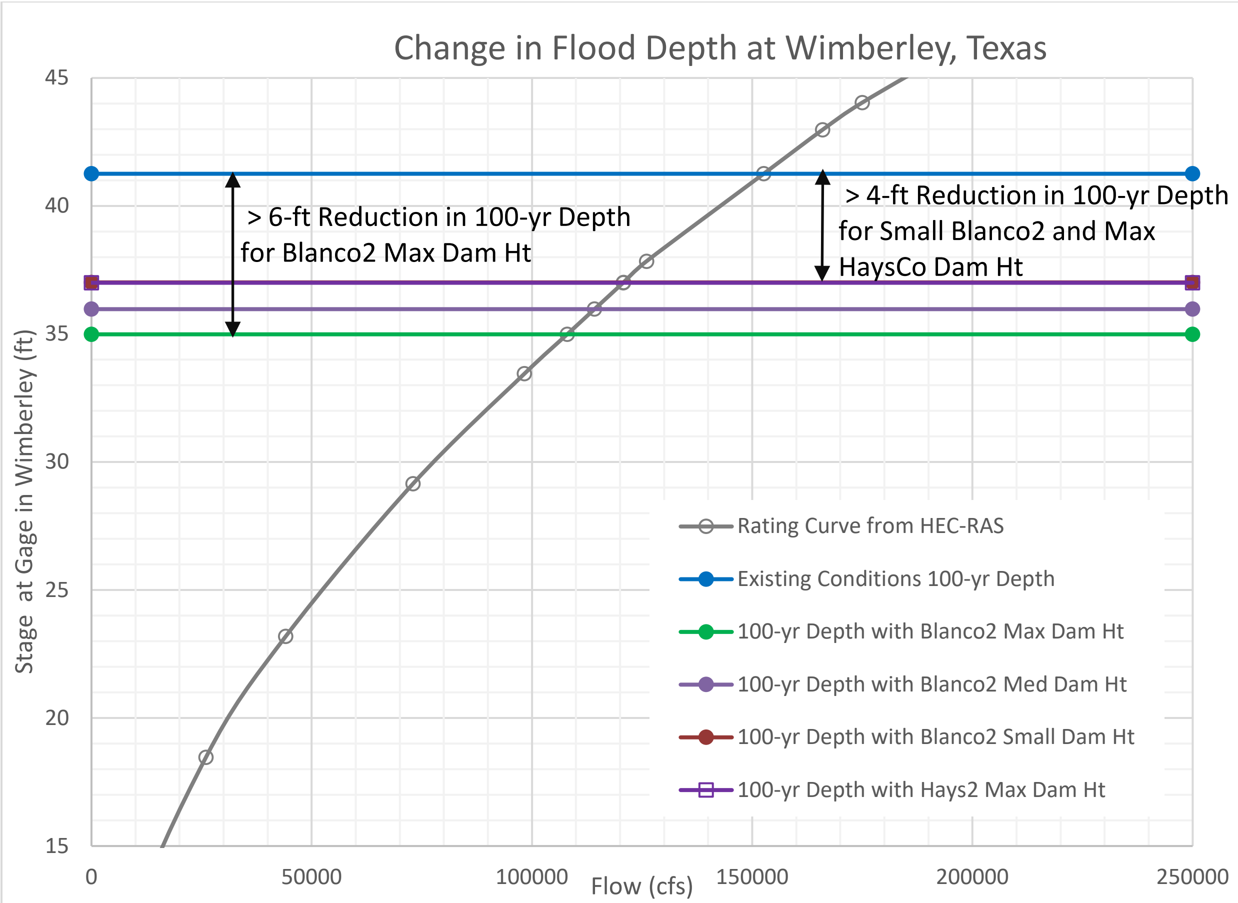

Figure 5.14: With Project Reduction in 1% ACE Water Surface at Wimberley, Texas

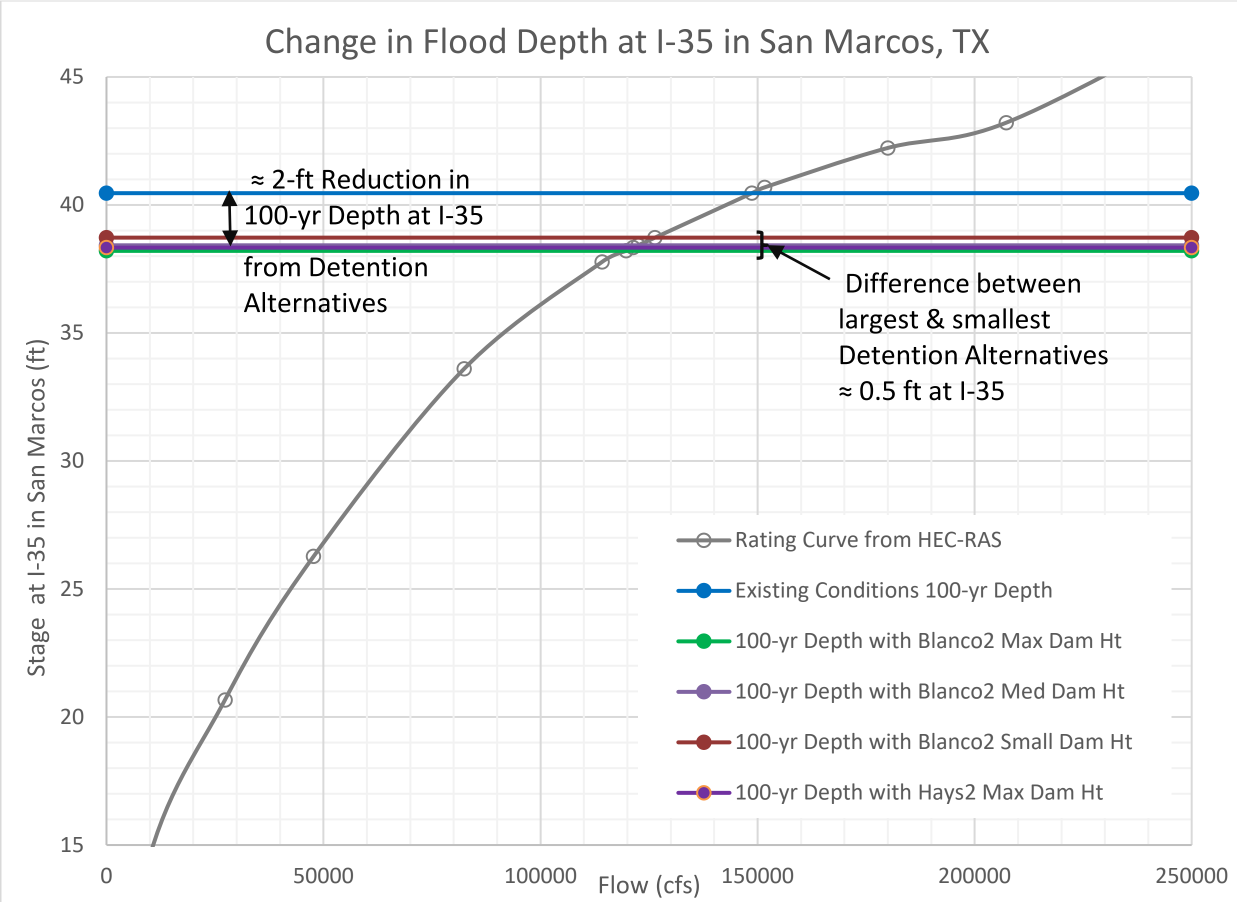

Figure 5.15: With Project Reduction in 1% ACE Water Surface at San Marcos, Texas

As one can see from the preceding figures, the addition of the maximum height Blanco 2 detention site produced the largest benefits at Wimberley, with a 6-ft reduction in the 1% ACE (100-yr) water surface elevation. However, all of the detention alternatives produced significant flood risk reduction benefits that carried through Wimberley and all the way to the city of San Marcos.

5.5 Blanco River and Bypass Creek Alternatives at San Marcos, Texas

The confluence of the Blanco and San Marcos Rivers has been the focus of repeated historical flooding. The largest recorded flood event to date on the Blanco River occurred on Memorial Day weekend in May 2015, inundating many buildings and homes in the overflow areas between the Blanco and San Marcos Rivers. The proposed alternatives in San Marcos, Texas focus on reducing flood risk to the structures in those overflow areas. The 2D hydraulic model of the overflows in the city of San Marcos served as the baseline hydraulic model for evaluating alternatives in and around the city of San Marcos.

For this study, various measures were analyzed to potentially mitigate the flooding impacts in the Blanco / San Marcos confluence area. The modeled with-project results were compared with the existing condition results to determine the preferred alternative based on feasibility of implementation and flood reduction benefits to the community. The location of the flood risk measures analyzed are displayed in Figure 5.16.

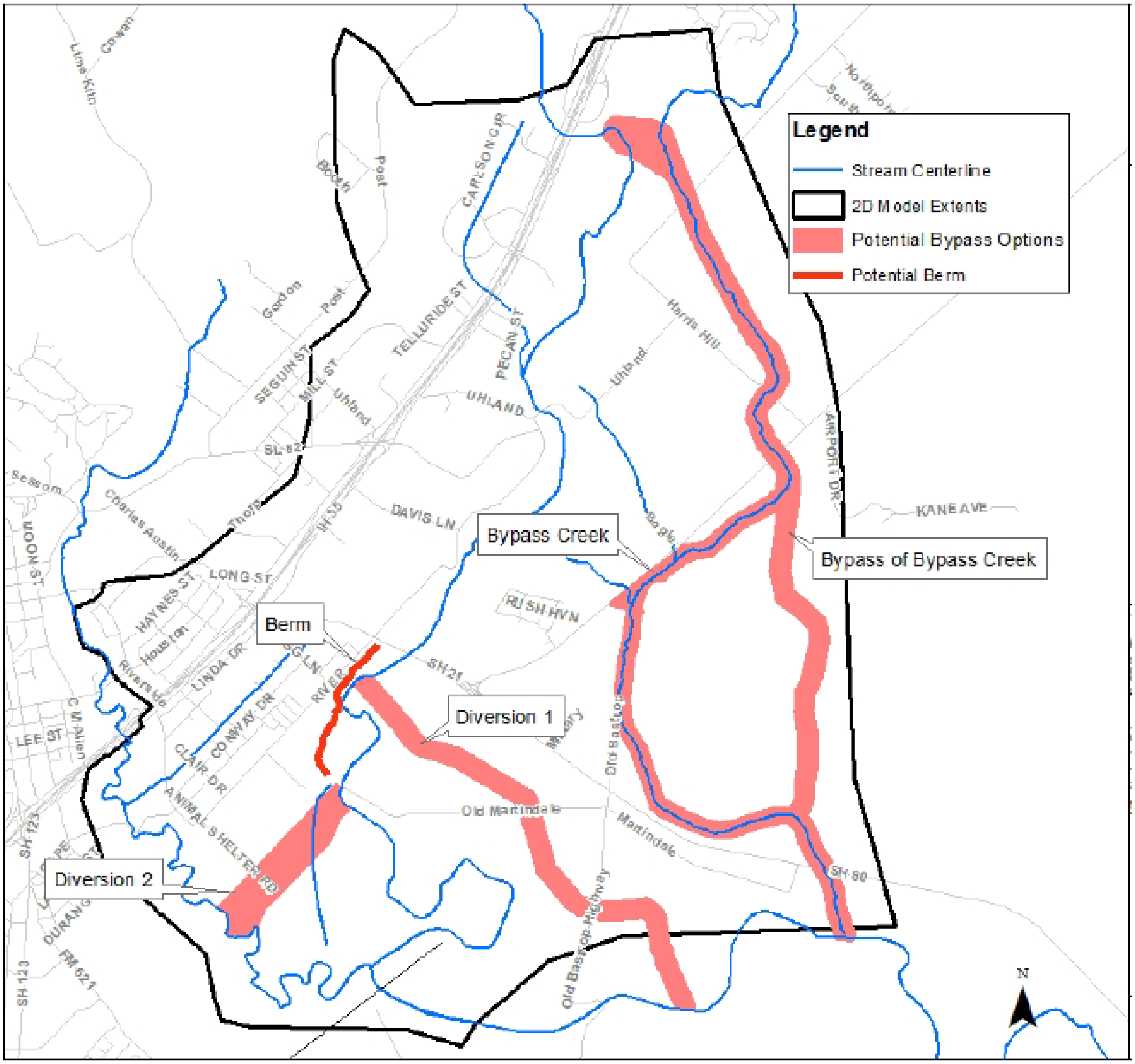

Figure 5.16: Flood Risk Measures Analyzed in San Marcos, Texas

Descriptions of the analyzed flood risk measures are provided as follows.

• Channelization of Bypass Creek: Channelizing Bypass Creek from the Blanco overflow near IH-35 to the confluence with the San Marcos River increases the capacity of Bypass Creek allowing more overflow from the Blanco River into the improved channel while avoiding heavily populated areas. The conceptual diversion consisted of a 125-foot, 20-feet deep channel. In addition to the channel improvements, this alternative also requires lowering the topography between the Blanco River and Bypass Creek upstream of County Road 160 to allow more flow to divert into Bypass Creek. Channel improvements will also require each of the crossing structures to be removed and reconstructed as bridges that span the channel. The bridges were not included in the hydraulic modeling as it was assumed the bridges would be designed to generate minimal headloss.

• Bypass of Bypass Creek: Channelization of Bypass Creek from the Blanco overflow near IH-35 and rerouting the channel to the confluence with the San Marcos River increases the capacity of Bypass Creek and the Bypass of Bypass Creek allowing more overflow from the Blanco River into the improved channel while avoiding heavily populated areas. This alternative reroutes Bypass Creek between Airport Highway and Highway 80 creating a shorter channel with less crossings, development, and constraints. Two conceptual channel options were investigated: 1) 125-foot, 20-feet deep channel and 2) 200-ft, 20-feet deep channel. Similar to channelization of Bypass Creek, this alternative also requires lowering the topography between the Blanco River and Bypass Creek and construction of bridges.

• Diversion 1: Diverting water from the Blanco River downstream of the Highway 80 bridge crossing to the San Marcos River downstream of the Old Bastrop Highway efficiently transfers flow to the San Marcos River allowing for water surface elevation reductions along the Blanco River downstream of Highway 80. The conceptual diversion consisted of a 125-foot, 20-feet deep channel. Similar to channelization of Bypass Creek, this alternative also requires each of the roadway crossings to be constructed as bridges that span the channel generating minimal headloss.

• Diversion 2: Diverting water from the Blanco River near Old Martindale Road to the San Marcos River between Cape Street and Scrutchin Lake efficiently transfers flow to the San Marcos River allowing for water surface elevation reductions along the Blanco River downstream of Highway 80. This diversion is primarily located on the City of San Marcos property in between the Blanco and San Marcos Rivers. The conceptual diversion consisted of a 300-foot, 10-feet deep channel. Similar to channelization of Bypass Creek, this alternative also requires each of the roadway crossings to be constructed as bridges that span the channel generating minimal headloss.

• Blanco Gardens Berm: A berm located on the west side of the Blanco River near the Blanco Gardens Neighborhood in San Marcos decreases overflows from the Blanco River. A berm with an elevation of the 50-year existing condition Blanco River water surface elevations was used to reduce the neighborhood's flood risk for more frequent storm events.

• Upstream Detention: The USACE provided the hydrologic results from the simulated Blanco2 regional detention site in Blanco County that was previously discussed. The post-detention flow rates were applied to the 2D model to evaluate flood mitigation benefit. The Blanco2 detention conceptually reduced the 100-yr flow in the Blanco River to near the 50-year flow levels under existing conditions.

These measures include the construction of diversion channels, detention and berms in order to reduce the computed 100-year water surface elevations on the at-risk structures in San Marcos, Texas. For this analysis, it was assumed that any downstream adverse impacts or increases in water surface elevation associated with the alternatives would be evaluated and mitigated during a later phase of the study.

The with-project simulations were modeled using the boundary condition from the existing conditions analysis with the exception of Bypass Creek. For alternatives which included the channelized or rerouted Bypass Creek, additional tailwater hydrographs were developed to include the altered downstream boundary condition of the San

Marcos River. Tailwater hydrographs were established using a rating curve of the hydraulic cross section nearest to the outfall from the San Marcos River 1D HEC-RAS model and the flow hydrograph from the junction at the Blanco and San Marcos River confluence in the HEC-HMS model. These tailwater conditions were derived for each simulated storm event.

Using the results from the initial analyses, the study team was able to identify favorable combination alternatives for evaluation. Table 5.3 lists each combination alternative that was simulated for these analyses.

Table 5.3 Combination Alternatives Analyzed in San Marcos, Texas

Alternative	Bypass Creek Channel	Rerouted Bypass Creek Channel	Diversion 1 Channel	Diversion 2 Channel	Larger Rerouted Bypass Creek Channel	Blanco Gardens Berm	Upstream Detention
Alternative 1	✓						
Alternative 1A	✓			✓			
Alternative 2		✓					
Alternative 2A		✓		✓			
Alternative 2B		✓	✓				
Alternative 2C		✓	✓			✓	
Alternative 2D		✓				✓	
Alternative 3			✓				
Alternative 3A			✓	✓			
Alternative 4					✓		
Alternative 4A					✓	✓	
Alternative 5						✓	✓
Alternative 6				✓		✓	

Once all of the alternatives were developed in the 2D Infoworks ICM model, each alternative was simulated to observe the 100-year storm event impacts. With-project flow rates and water surface elevations varied depending on what improvements were used for the specific alternative. Certain improvements had more hydraulic impact based on the location of the improvement relative to the watershed, the size of the proposed channels, and the reduction in flow through the Blanco River. Additional information on the results of these alternative simulations is available in Appendix A-1.

After reviewing the results of the 100-yr with-project 2D simulations and comparing them to the high-level project cost estimates, the two best alternatives, Alternative 2D and Alternative 6, were selected for further evaluation and were simulated for the 2-, 5-, 10-, 25-, 50-, 100-, 250-, and 500-year events in the 2D hydraulic model. The results of the simulations were then provided to the economist to estimate economic benefits in HEC-FDA.

5.5.1 Alternative 2D: Bypass of Bypass Creek with Blanco Gardens Berm

This alternative includes the combination of the Bypass of Bypass Creek and the Blanco Gardens Berm. This alternative provides flood mitigation benefits for all analysis points since flows in the Blanco River are decreased from near I-35 to the confluence with the San Marcos River. A schematic of the alternative is displayed in Figure 5.17.

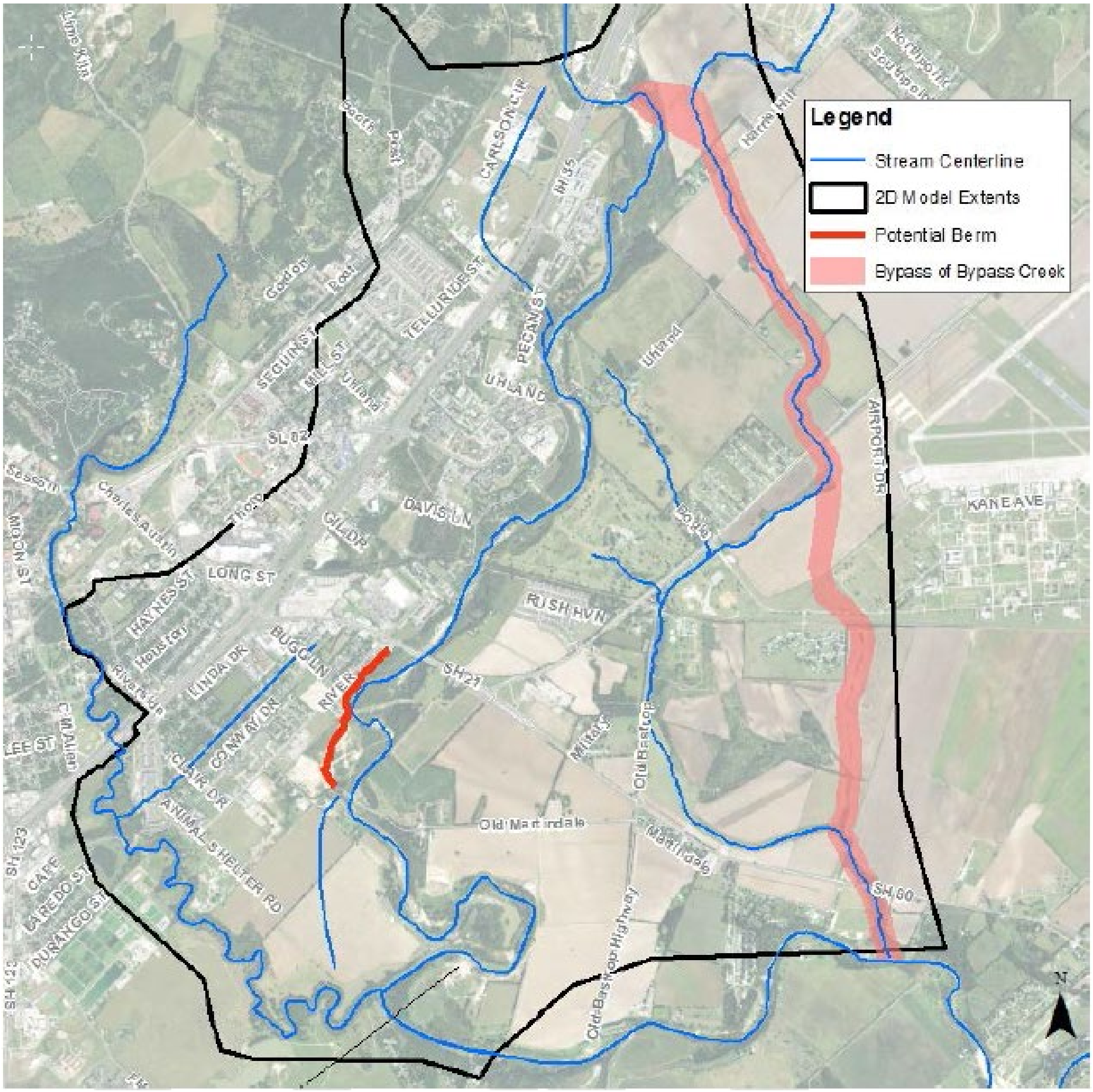

Figure 5.17: Schematic of Alternative 2D in San Marcos, Texas

This alternative lowers the topography between the Blanco River and Bypass Creek upstream of County Road 160 to allow approximately 33,000 cfs to flow from the Blanco River into Bypass Creek. The conceptual diversion consists of a 125-foot, 20-feet deep channel that follows the Bypass Creek alignment to Airport Highway then flows south ultimately rejoining the Bypass Creek alignment near Highway 80. This alignment is preferred over the Bypass Creek alignment creating a shorter channel with less crossings, development, and constraints. The proposed channel improvements will require each of the crossing structures to be removed and reconstructed as bridges that span the channel. The bridges were not included in the hydraulic modeling as it was assumed the bridges would be designed to generate minimal headloss. As noted above, the Bypass of Bypass Creek reduces flows along the main stem of the Blanco River. The lower flow rates combined with the Blanco Gardens Berm significantly reduce overflows into the Blanco Gardens neighborhood. The conceptual berm is located on the western bank of the Blanco River downstream of Highway 80. The berm is simulated at the 50-year existing condition Blanco River water surface elevations protecting the neighborhood from the more frequent storm events.

This flood mitigation alternative results in an average 100-year water surface depth reduction of approximately 1.5 feet upstream of Highway 80, 1.1 feet in the Blanco Gardens area, and 4.0 feet along Bogie Drive. This flood mitigation alternative provides flood reduction benefits to the entire 2D study area. Not only does this alternative reduce water surface elevations along the Blanco River, this alternative significantly reduces overflows and associated flood depths from I-35 to Highway 80 toward Bypass Creek, Blanco Gardens overflows, and overtopping of I-35.

5.5.2 Alternative 6: Blanco Gardens Berm combined with Diversion 2

This alternative includes the combination of the Blanco Gardens Berm and Diversion 2 from Old Martindale Road to the San Marcos River. This alternative only provides flood mitigation benefits for the Blanco Gardens neighborhood. A schematic of the alternative is displayed in Figure 5.18.

This alternative raises the topography of the western Blanco River bank from Highway 80 to Old Martindale Road. This elevation of the bank reduces the overflow from the Blanco River into the Blanco Gardens neighborhood. The berm is simulated at the 50-year existing condition Blanco River water surface elevations protecting the neighborhood from the more frequent storm events. Reduction of overflow into the neighborhood increases flows in the Blanco River causing a slight increase in the water surface. A diversion from near Old Martindale Road to the San Marcos River is used to mitigate that rise. The conceptual diversion consists of a 300-foot wide, 10-feet deep channel. Additionally this alignment significantly reduces the required property acquisition because the majority of the land along this alignment is owned by the City of San Marcos. This flood mitigation alternative results in an average 100-year water surface depth reduction of approximately 0.8 feet in the Blanco Gardens area.

Subsequent economic analyses revealed that Alternative 6 had the highest net economic benefits for the San Marcos damage center. Additional information on the with-project 2D simulations can be found in Appendix A-1.

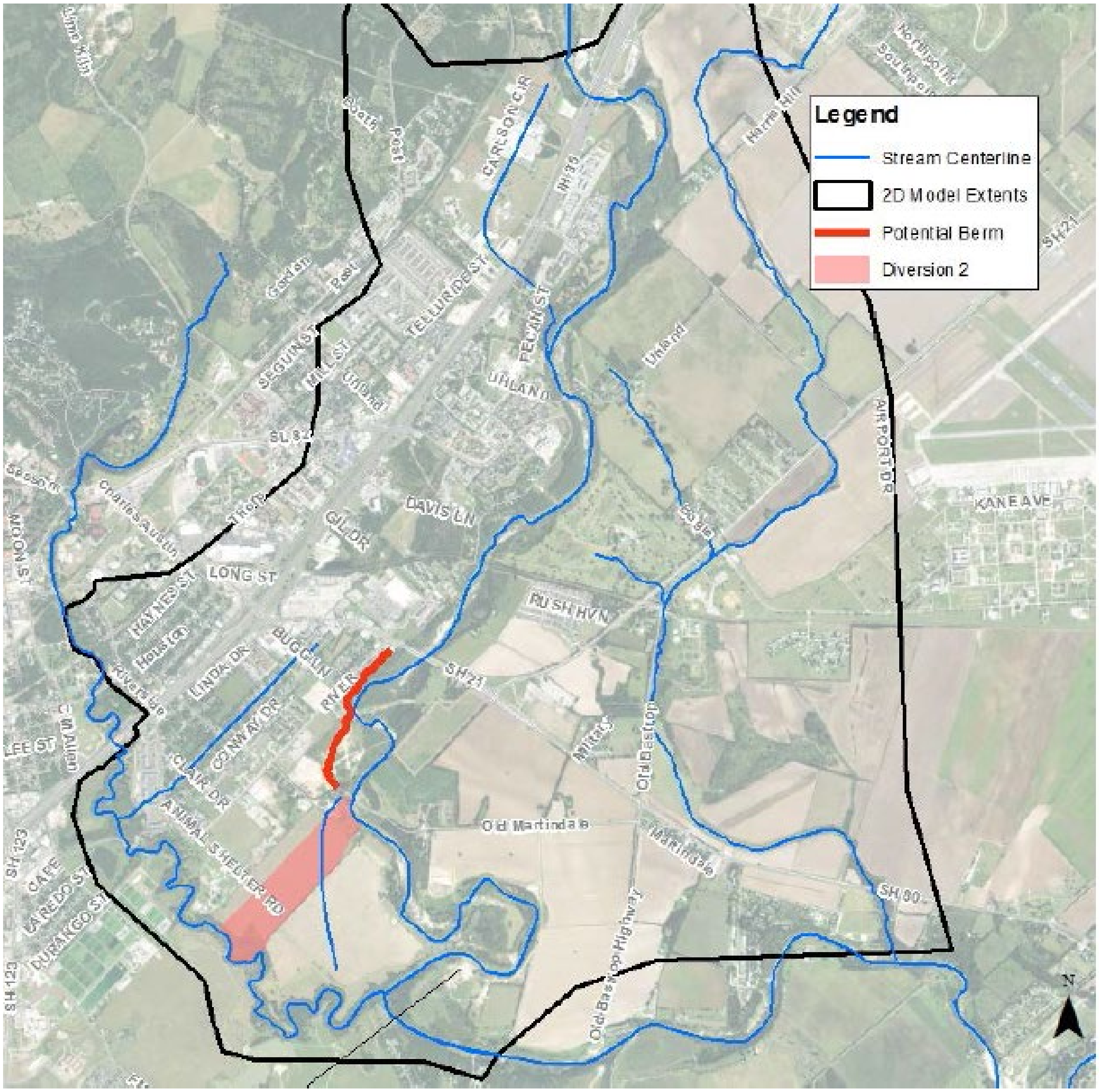

Figure 5.18: Schematic of Alternative 6 in San Marcos, Texas

6 Conclusions

Subsequent economic analyses of the alternatives described in this study revealed that only the Bear Creek detention and Alternative 6 in San Marcos had positive net benefits. As of the writing of this appendix, the Local Sponsor began implementation of Alternative 6 independent of the federal study. Therefore, only the Bear Creek detention alternative was still in consideration for the tentatively selected plan (TSP). However, after the TSP meeting, the preliminary Bear Creek detention design was updated to include recommended features from USACE dam safety experts, and the cost of those features caused the benefit cost ratio of the Bear Creek detention to drop well below one. Therefore, the final outcome of this feasibility study is a “no action” recommendation. Ultimately, the study team was unable to find structural flood risk solutions in the Guadalupe-Blanco River basin that met the required criteria of economic justification.

7 References

Asquith, W.H., Roussel, M.C., *Atlas of Depth-Duration Frequency of Precipitation Annual Maxima for Texas*; U.S. Geological Survey Scientific Investigations Report 2004-5041; 2004.

Halff. *Lower Guadalupe River Basin Interim Feasibility Study – Phase 1, Technical Report Notebook (TRN) Appendix A - Topographic Data Development,* March 2014.

Halff. *Lower Guadalupe River Basin Interim Feasibility Study – Phase 1, Technical Report Notebook (TRN) Appendix B.1 Engineering Analysis – Hydrology, Lower Guadalupe, Blanco, and San Marcos Watersheds. September 2013.*

Halff. *Lower Guadalupe River Basin Interim Feasibility Study – Phase 1, Technical Report Notebook (TRN) Appendix D.1 Engineering Analysis –Hydraulics, Guadalupe, Blanco and San Marcos River Watersheds.* March 2014.

Halff. *Lower Guadalupe River Basin Interim Feasibility Study – Phase 1, Technical Report Notebook (TRN) Appendix E - Preliminary Alternative Development and Benefit-Cost Analysis.* March 2014.

Halff. *Lower Guadalupe River Basin Interim Feasibility Study - Technical Report Notebook (TRN) Alternatives Development – Blanco and San Marcos River Confluence. November 2017.*

Interagency Flood Risk Management (InFRM). *Hydrology Report for the San Marcos River Basin.* Sept 2016.