CHOCOLATE BAYOU WATERSHED FLOOD CONTROL STUDY

Volume 1 of 2

Prepared For

Brazoria County

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EXECUTIVE SUMMARY

ES.1 Background and Study Purpose

Flooding is frequent and severe in the 155 square-mile Chocolate Bayou Watershed (CBW) located predominately in Brazoria County, Texas. Approximate locations of repetitive losses across the CBW are shown in Exhibit ES-1. Reported repetitive loss damages to residential structures in the cities of the CBW average about ½ million dollars per year.

This planning Study identifies, broadly describes, and evaluates major flood control projects that can significantly reduce flooding in the CBW. The Study provides a set of projects that when individually implemented can reduce repetitive losses in a coordinated and economically efficient manner.

ES.2 Modeling, Potential Projects, and Damage Reduction

Updated hydrologic and hydraulic flood models are developed for the primary watercourses in the CBW to determine the flood reduction impacts of potential flood control projects. Potential projects consist of conveyance improvements by widening and/or deepening a channel; construction of diversion ponds to temporarily store flood waters; diversion of portions of flood flows from one channel to another; improvement of the capacity of hydraulic structures; and selected combinations of these different types of projects. Mitigation is included in projects that would increase flood flows to downstream points (e.g., channel widening projects). Comparison of flooding depths with and without a proposed flood control project for different flood frequencies statistically summed across all structures subject to flooding is used to determine the expected reduction in flood damages achieved by a particular project.

ES.3 Basis for Project Costing

Potential flood control project costs are evaluated using a cost model for estimated commercial construction costs ("EDDC"), which include excavation, bridge replacement (when required), and hydraulic structure (e.g., siphons and culverts) improvement costs. Supplementary costs for engineering, survey, geotechnical investigation, environmental assessment, and permitting; land acquisition costs; and contingency costs are also estimated and included in estimated total project costs ("ETPC"). To facilitate total project implementation over time, projects can be constructed in phases to reduce initial costs while still achieving flood reduction benefits. Some projects or project phases may have costs actually lower than the ETPC because portions of the projects can be constructed by the County and county drainage districts.

ES.4 Project Identification and Selection

A benefit-cost ratio (B/C) > 1 criterion is used to initially identify some 58 economically preferred projects. The initial project list is further refined by examining the trade-off of individual project costs with project benefits. Other considerations of environmental impact, hurricane evacuation (an important consideration for projects near State Highway 6 [SH 6] in the Manvel area), overall project cost, impacts of project phasing, and potentials for county or drainage district construction are recognized to further refine the selection of projects. The final six recommended projects along with their estimated costs and recommended sequence for phased construction are described in the following.

ES.5 Recommended Projects and Project Phasing

The projects recommended in this Study can be implemented in phases to facilitate their construction over time at a rate commensurate with available funding. A total project provides the roadmap for construction of individual, phased projects that will individually and collectively contribute to reduction of repetitive flooding and flood damages as each phase is implemented. The potential need for mitigation of downstream impacts from the individual phases of a project needs to be always recognized.

Project CV-28: West Fork Conveyance Improvements

Project CV-28 is a conveyance improvement (i.e., channel widening and deepening) project along the West Fork of Chocolate Bayou from the Brazoria-Fort Bend County line downstream to the confluence with the East Fork of Chocolate Bayou; see Exhibit ES-2. This project has an overall B/C value of 2.21; see Table ES-1. The project will raise the capacity of the West Fork to a full 2-year flood level. The ETPC is $36.54 million.

As listed in Table ES-1, the EPTC per mile for conveyance improvements, including mitigation, along the West Fork is approximately $4.2 million per mile. Project CV-28 is particular suitable for decomposition into a series of smaller projects that can be implemented in phases along various short reaches of the West Fork as right-of-way can be acquired and funding becomes available.

Project CV-28-Phase 1: The recommended first phase project along the West Fork is Project CV-28-Phase 1. The project is approximately 3 miles (hence with an ETPC of $12.6 million) of conveyance improvement along the West Fork immediately above the confluence with the East Fork; see Exhibit ES-3. This channel improvement would lie in a zone of relatively high repetitive losses (see Exhibit ES-1) and thus have significant near-term benefits.

Project CV-28-Phase 2: The next project phase would be an approximately 2-mile extension of Project CV-28 into Arcola in Fort Bend County; see Exhibit

ES-3. This project phase would reduce flooding in one of the most concentrated areas of flood losses in the CBW (see Exhibit ES-1). Development of this particular phase would require additional technical evaluation (because of data-limited hydraulic evaluation in the Arcola area in the present Study); the costs for such additional evaluation should be borne by Fort Bend County.

Project CV-28-Phase 3: Additional projects along the West Fork that increase the conveyance of a segment of the West Fork to a 2-year flood flow capacity.

Projects DP-18 and DP-12: Diversion Ponds along Ditch C-12

Diversion ponds along Ditch C-12 south of SH 6 in the vicinity of Manvel (see Exhibits ES-2 and ES-3 for the general location of the diversion ponds) where repetitive losses are severe could be constructed in phases at low incremental costs to partially detain flood waters and significantly reduce flooding impacts.

First Phase-DP-18: This first set of ponds, with a B/C = 1.82, would be designed to fully capture relatively small storm event flood volumes in the range of 5- to 10-year flood events (see Table ES-1); larger floods would be only partially captured. This first phase of ponds would collectively have an ETPC of $1.78 million. Detailed engineering would determine the specific number and locations of individual ponds along Ditch C-12.

Second Phase-DP-12: This second phase of ponds would expand the first phase of ponds to fully capture floods as small as a 2-year flood, with large floods still being only partially captured. By expanding the first phase ponds, the second phase ponds would have an ETPC of only $1.05 million but a high B/C value of 13.53.

Project CV-16: Chocolate Bayou and the East Fork Conveyance Improvements

Project CV-16 is a conveyance improvement project along the East Fork and the mainstem of Chocolate Bayou (see Exhibit ES-2). Environmental concerns will likely limit the rapid construction of the project even if all funds were available for construction. Consequently, Project CV-16-Mod, a scaled down version of CV-16, is proposed. This project would extend only from the upper end of the East Fork of Chocolate Bayou in the vicinity of Iowa Colony downstream to the vicinity of the confluence of the East Fork and the South Hayes Creek (see Exhibit ES-3). The estimated B/C value of 2.65 for Project CV-16-Phase 1 would be similar to that of the original Project CV-16 but its ETPC would be reduced to approximately $24.46 million (see Table ES-1), representing an average cost of approximately $3.3 million per mile.

CV-16-Mod-Phase 1: As with the conveyance improvements for the West Fork, incremental improvements to the East Fork could be constructed. In particular, Project CV-16-Phase 1 would compliment the West Fork CV-28-Phase 1 project by raising the capacity of the East Fork to a 2-year flood level for the approximately first two miles along the East Fork upstream of its confluence with the West Fork (see Exhibit ES-3). The ETPC for this first phase would be approximately $6.6 million. Because this project is located near a concentration of repetitive losses (see Exhibit ES-1) benefits from this project phase would be significant.

Project CV-16-Mod-Phase 2: This phase represents additional projects along the East Fork which would increase the conveyance of a segment of the East Fork to a 2-year flood flow capacity.

Brunner Ditch Projects BR-2B and BR-3B

A variety of Brunner Ditch options were considered, but the two most promising in terms of B/C values are Brunner Ditch Project BR-3B and Brunner Ditch Project-BR-2B. Construction of Project BR-3B before BR-2B will allow an effective phasing of the Brunner Ditch Projects, which will overall achieve a B/C value of approximately 1.8 (see Table ES-1). Individual phased projects should be ordered so that the increased capacity of Brunner Ditch is provided in a downstream to upstream order. While basic design features for both projects should be generally determined before construction of any phase, the recommended construction phasing is as follows (see Exhibit ES-3):

Brunner Ditch Project BR-3B

Brunner Ditch Project BR-3B, recommended for constructed before Project BR-2B, would widen the existing Brunner Ditch from its downstream tie-in with Chocolate Bayou to the vicinity of the Savannah Plantation subdivision and then extend the ditch towards Chocolate Bayou to connect with an existing Chocolate tributary north of Alvin; see Exhibits ES-2 and ES-3. The existing tributary would be widened and re-graded to reverse flow direction and allow for diversion of Chocolate Bayou flood flow to the widened downstream Brunner Ditch. Particular beneficiaries of this project would include Alvin and subdivisions between Alvin, where flood damages are large, and the existing saltwater barrier near Liverpool. The design level of the project would generally be a 100-year flood condition in order to facilitate project use for not only Project BR-3B but also Project BR-2B.

Overall, the project would have an ETPC of $93.74 million and a B/C = 1.86. Because this project would also provide some of the same flood reduction benefits as Project CV-16 along the mainstem of Chocolate Bayou but without the environmental impacts of Project CV-16, Project BR-3B would be recommended over the Chocolate Bayou portion of Project CV-16 (but Project CV-16-Mod would still be recommended).

Project BR-3B-Phase 1: Widen the existing Brunner Ditch-northeast-to-southwest-leg from Chocolate Bayou near the existing Saltwater Barrier to he west boundary of the CBW where Brunner Ditch turns northward. The target design level would be that for a 100-year flow from upstream reaches of both Project BR-3B and Project BR-2B, but the full capacity expansion could be delayed until Project BR-2B is initiated.

Project BR-3B-Phase 2: This phase would expand and extend the existing Brunner Ditch from the upstream end of Project BR-3B-Phase 1 northward to the southern end of the reverse-grade ditch near FM 1462. Of special interest in this phase is the currently proposed future location of the Grand Parkway in the general vicinity of the existing Brunner Ditch along the western boundary of the CBW. Use of excavated material from the Brunner Ditch widening could be used in the construction of the parkway, potentially yielding considerable net savings to both projects.

Project BR-3B-Phase 3: Widening and reversing the grade of the existing tributary to Chocolate Bayou near FM 1462 to allow flows to be diverted from Chocolate Bayou to Brunner Ditch. The maximum diversion would be dictated by the right-of-way that could be acquired for the reversed grade tributary.

Brunner Ditch Project BR-2B

Project BR-2B envisions extending Brunner Ditch from the vicinity of the Brunner Ditch Project BR-3-Phase 2 northward along an alignment which intersects the downstream ends of the North and South Hayes Creeks and the

West Fork of Chocolate Bayou (see Exhibit ES-3). This project would capitalize on the already constructed elements of Project BR-3B. This project would also increase the conveyance capacity of the West Fork and the North and South Hayes Creeks to a 100-year design level. The entire Brunner Ditch Project BR-2B, assuming the prior construction Brunner Ditch Project BR-3B, would have an estimate cost of $177.6 million and a B/C = 1.68.

Project BR-2B-Phase 1: This first phase would extend and widen as necessary Brunner Ditch from the existing Brunner Ditch widening of Project BR-2B-Phase 2 northward to intersect the North and South Hayes Creeks and the West Fork of Chocolate Bayou. Flows coming down the extended Brunner Ditch would be added to the diverted flows from Chocolate Bayou that Project BR-3B would generate.

Project BR-2B-Phase 2: This phase would expand the capacity of much of the West Fork to a 100-year flood level, upstream to the vicinity of Iowa Colony. The prior expansion of portions of the West Fork done as part of Project CV-28 would reduce the costs for this phase 2 work.

Project BR-2B-Phase 3: This phase would increase the capacity of the North and South Hayes Creeks to a 100-year level. This phase could be delayed until North and South Hayes watershed development necessitated significant flood control.

Projects SI-1, SI-2, SI-3, SI-4, SI-5: Siphons along West Fork Tributaries

Siphon improvement projects along the West Fork Tributaries A and B and Ditch C-12 are proposed (see Exhibit ES-2). The projects would increase the capacity to convey flood flows under the Gulf Coast Water Authority Canal raw water canal in the Manvel area where the canal generally parallels SH 6. This area is a heavily populated area with historically severe flooding; thus the projects are recommended because of their significant flood reduction benefits. The projects would include channel improvements upstream of SH 6 to provide for more hydraulically efficient removal of 100-year storm event flood waters from regions upstream of the siphons (and, as well, upstream of SH 6) and consequently reduce flooding in the general area of the tributaries above the GCWA canal. To avoid downstream impacts, mitigation ponds would have to be constructed near the siphons. In view of the B/C values and the benefits to reduced flooding of SH 6 that these projects have (see Table ES-1), the following phasing is recommended:

Phase 1: Siphon Project SI-4. Construct the following elements in the following order along the East Fork Tributary B (see Exhibit ES-3): Mitigation pond for mitigation of upstream improvements; construction of the siphon improvements to carry the 100-year flood event; and conveyance improvements of Tributary B upstream of the siphon sufficient to carry the 100-year flood runoff from areas north of SH 6. This project has an estimate cost of $8.3 million and a B/C value of 1.06. While not having the highest B/C value for the siphon projects, the project has the lowest cost of all the siphon projects.

Phase 2: Siphon Project SI-2. Construct mitigation pond, siphon improvement, and upstream conveyance improvements along West Fork Tributary B in sequence similar to Phase 1. This project has an estimate cost of $21.0 million and a B/C value of 1.19.

Phase 3: Siphon Project SI-1. Construct mitigation pond, siphon improvement, and upstream conveyance improvements along West Fork Tributary B in sequence similar to Phase 1. This project has an estimate cost of $21.0 million and a B/C value of 1.19 upstream of the GCWA canal siphons.

Phase 4: Siphon Project SI-3: Construct mitigation pond, siphon improvement, and upstream conveyance improvements along East Fork Tributary A in sequence similar to Phase 1. This project has an estimate cost of $24.7 million and a B/C value of 0.56. This particular project is recommended for construction despite its low B/C value because of its importance (along with the other siphon projects) to eliminating flooding of both Manvel and of SH 6.

Phase 5: Siphon Project SI-5: Construct mitigation pond, siphon improvement, and upstream conveyance improvements along Ditch C12 in sequence similar to Phase 1. This project has an estimate cost of $52.8 million and a B/C value of 0.88. As with the Phase 4 siphon, the project has a low B/C value, but it is recommended because it contributes to the general elimination of flooding in the heavily populated Manvel area north of SH 6. However, this low B/C ratio for this siphon improvement project could be improved by combining it with Projects DP-18 and/or DP-13, using some of the storage of these two latter projects to provide some of the mitigation storage required by the siphon projects; the B/C value of the combined project would be 1.06.

ES.6 Final Observations

Anticipatory Land Acquisition and Right-of-Way Requirements: Land requirements for preferred projects should be undertaken in a timely fashion to avoid conversion of currently available land to uses which would preclude or increase the difficulty of their acquisition at future times. Data in this Study provide estimated land acquisition and right-of-way requirements.

Inclusion of Mitigation: This has been a planning study. In detailed design of particular projects, mitigation needs should be not overlooked. Each individual project (regardless of size) must be assessed as to its particular impacts and each project must incorporate adequate mitigation. Cost estimates for the recommended projects include estimated mitigation costs.

Funding Options: Additional sources of funding, such as the Texas Water Development Board or the Texas Department of Transportation (the latter in regard to channel crossings) should be considered to reduce project costs.

Cooperation an Essential Ingredient to Success: The projects identified in this Study, even when implemented in a phased manner with focus upon the most beneficial elements, are significant in their cost. The cooperative effort of all entities in the Chocolate Bayou Watershed is essential to maximizing the utility of the resources available for implementing various projects.

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SECTION 1

STUDY PURPOSE AND SCOPE

1.1 Authorization and Sponsorship

The development and preparation of this Chocolate Bayou Watershed Flood Protection Plan (Study) was authorized by Brazoria County, Texas under Purchase Order 0000900377 dated October 9, 2008, pursuant to contract between Klotz Associates, Inc. (Klotz Associates) and Brazoria County dated February 10, 2009 and performed under Texas Water Development Board Grant G218 9/TWDB Flood Protection Planning. This Study was conducted by Klotz Associates as a consultant to Brazoria County. The issuance of the Brazoria County purchase order served as official notice to proceed.

This Study was sponsored by the Texas Water Development Board, Brazoria County, Brazoria County Conservation and Reclamation District No. 3, Brazoria County Drainage District No. 4, Brazoria County Drainage District No. 5, and the Brazoria County cities of Manvel, Alvin, and Iowa Colony.

1.2 Study Purpose

The Chocolate Bayou Watershed (CBW) lies almost entirely in Brazoria County, Texas (see Exhibit 1-1). The county and the Chocolate Bayou Watershed (CBW) are characteristically flat, with low lying topography, meandering natural channels, rather straight man-made canals, and sometimes ill-defined watershed boundaries (see Appendix B for selected watershed photographs and Exhibit 1-2 for aerial imagery). These features, coupled with historically severe rainfall events (e.g., the City of Alvin has the highest recorded 24-hour rainfall in United States history, some 43 inches [Texas Almanac, 2008-09; see References]), are highly conducive to drainage problems and significant and frequent flooding throughout the county, including the CBW. Indeed, major portions of the CBW lie in Federal Emergency Management Agency (FEMA) designated 100-year floodplains (see Exhibit 1-3).

Flood related damages are common in Brazoria County. Many of these flooding losses have occurred in the cities of the CBW. Manvel, which lies at the heart of the floodplain areas in the northern portion of the watershed, has suffered more than 200 loss incidents since 1978. The communities of Manvel, Iowa Colony and Liverpool have had, collectively, nearly 300 reported loss incidents since 1978 [FEMA, 2007]. The City of Alvin, which has recently expanded its boundaries into and across the Chocolate Bayou watershed in response to residential land development, may experience significant damage from Chocolate Bayou flooding in the future if effective control measures are not instituted.

This Study has been undertaken because

- Flooding is severe and frequent in the CBW
- Repetitive losses to residential structures are extensive in the CBW
- Emergency evacuation routes in the CBW are adversely impacted by flooding
- Upgrade of modeling tools is needed to support flood evaluation activities
- Comprehensive identification of flood control remedies is needed

Objectives for this Study are identification, description, assessment, and recommendation of potential flood control options that will address flooding problems in the CBW, with particular focus directed toward reduction in residential structure flooding-induced damages. Flood control projects identified in this Study are of a planning level character; their actual implementation will require additional detailed engineering study and design.

1.3 Study Area

The CBW is a 154.5 square-mile (sq-mi) watershed lying predominately in northern and central Brazoria County, Texas (see Exhibit 1-1). The watershed generally trends and drains from northwest to southeast (see Exhibit 1-4). Brazoria County is one of seven counties surrounding the Houston-Harris County, Texas metropolitan area. The far northwestern portion of the CBW, approximately 8.7 sq-mi, lies in Fort Bend County; the remaining portion of the CBW lies in Brazoria County. The watershed has an overall point-to-point length and maximum width of approximately 30 and 10 miles (mi), respectively.

The CBW drains all or portions of several cities, including Alvin, Arcola, Iowa Colony, Liverpool and Manvel (see Exhibit 1-1). The 2008 combined population of these cities is approximately 35,000.

Residential, light commercial, agricultural, and ranching land use dominates the northern and central portions of the watershed, while petrochemical and related industrial facilities are located in the far downstream reaches of the watershed where Chocolate Bayou outfalls to Chocolate Bay and the Galveston Bay estuary system. The southern portions of the CBW are a mixture of rural residential, agricultural, ranching, and undeveloped and forested land. The lands along the upper reaches of the CBW are seeing increasing pressures from urban development moving southward from the cities of Houston, Pearland, and Friendswood.

1.3.1 Transportation Corridors for Hurricane Evacuation

The CBW has four major state transportation corridors: the north-south corridor of State Highway (SH) 288, the northeast to southwest SH 35, the generally northwest to southeast corridor of SH 6, and the generally east-west corridor of FM 2004 (see Exhibit 1-1). The Texas Department of Transportation (TxDOT) has designated SH 6 as a primary hurricane evacuation route, while SH 288, FM 2004, and SH 35 have been designated as secondary evacuation routes [NOAA, 2009] for Galveston Island and coastal mainland areas north and west of the island, as well as some coastal communities south of Houston. Other primary transportation routes in the watershed are a mixture of farm-to-market roads, county roads, and urban streets.

1.3.2 Grand Parkway

Proposals have been also made for extension of the Grand Parkway, a major thoroughfare already partially constructed in some counties not including Brazoria County; the parkway is planned to encircle the City of Houston and connect various suburban areas. Proposals call for the Grand Parkway to enter into and cut across the CBW in the general area of Alvin (see Exhibit 1-5 for the currently proposed alignment of the parkway and its relation to Brunner Ditch; Brunner Ditch is discussed in the following section). While not yet constructed in the CBW, the parkway alignment parallels Brunner Ditch along a significant length of the ditch in the Alvin area.

1.3.3 Key Watercourses and Their Management

Exhibit 1-6 shows major and minor watercourses in the CBW. The primary watercourses are Chocolate Bayou and four major tributaries (see Exhibit 1-6): the East Fork of Chocolate Bayou, the West Fork of Chocolate Bayou (both of which are more simply referred as to as, respectively, the East Fork and the West Fork), the North Hayes Creek, and the South Hayes Creek (both of which are, likewise, more simply referred to as, respectively, the North Hayes and the South Hayes). The East Fork has traditionally been referred to as part of the upstream lengths of Chocolate Bayou; but Brazoria County floodplain managers have more recently begun to refer to the reaches of Chocolate Bayou above the confluence of Chocolate Bayou with the West Fork as the East Fork of Chocolate Bayou.

The upper end of the East Fork breaks has two primary branches: East Fork Tributary A (EF Trib A) and the West Fork Tributary B (EF Trib B) (see Exhibit 1-2); the EF Trib B is also sometimes identified as the upper end of the East Fork.

The upper end of the West Fork has three primary branches: West Fork Tributary A (WF Trib A), West Fork Tributary B (WF Trib B), and the West Fork. WF Trib A and WF Trib B extend to the north and lie in Brazoria County west of the Manvel. The West Fork upstream of its confluence with the WF Trib A continues westward into the Arcola area of Fort Bend County.

Chocolate Bayou and its four primary tributaries are distinguished by the fact that they have FEMA-approved flood models based upon FEMA Flood Insurance Studies (FIS) [FEMA, 1999]. While there are numerous flood models which have been developed by various parties covering sub-reaches or extensions of these FEMA-approved models, there are no current FEMA-approved hydraulic models for watercourses in the CBW other than those for Chocolate Bayou and its four primary tributaries of the East and West Forks and the North and South Hayes Creeks. These five watercourses are used as the skeleton for the hydraulic modeling developed and applied in this Study and the development of flood control options.

Two other watercourses are judged, because of their location, extent and drainage management agency interest in them, as particularly significant to evaluation of flooding and development of flood control options in the CBW: Ditch C-12, a tributary to the East Fork, and Brunner Ditch, which currently connects North Hayes Creek with Chocolate Bayou (see Exhibit 1-6). These two additional watercourses are included among the watercourses for which hydraulic models are developed in this Study.

Chocolate Bayou also receives additional flow from beyond the limits of the CBW boundaries via a channel diversion from New Bayou, which lies adjacent to the east side of the CBW in the New Bayou Watershed (see Exhibits 1-6 and 1-7). There are also anecdotal verbal reports of additional minor withdrawals and diversion from Chocolate Bayou south of the FM 1462.

Both natural and manmade waterways which in combination serve as the main drainage system in the county are under the management of Brazoria County Conservation and Reclamation District No. 3, Brazoria County Drainage District No. 4, Brazoria County Drainage District No. 5, and in the limited areas without drainage district responsibilities, Brazoria County; see Exhibit 1-1 for district boundaries lying in the CBW. Drainage management in the small portion of the CBW lying in Fort Bend County is the responsibility of the Fort Bend County Drainage District.

1.4 Study Scope

This Study has the following major elements:

- Data Collection and Assessment, consisting of:
    - Existing data collection and information development
    - Development of topographic data
    - Environmental review
    - Flooding problem identification
- Watershed Characterization and Modeling, consisting of:
    - Drainage Basin Description and HEC-HMS (Hydrologic Engineering Center Hydrologic Modeling System) modeling
    - HEC-RAS (Hydrologic Engineering Center River Analysis System) modeling
- Development of Flood Relief Options, consisting of
    - Problem identification and characterization
    - Development of options
    - Assessment of the benefits of options
    - Cost of options
    - Recommendations for project implementation
- Public Meetings for Development of Citizen Input

This Study report (Report) documents the accomplishment of these various study elements and makes recommendations for flood control projects in the CBW.

In broad overview, this study identifies and characterizes significant flooding concerns as indicated by repetitive losses to residential structures, flooding reports by citizens, and reports on major roadway flooding; and develops flood control alternatives to address these concerns. Data are developed from various sources to construct or update hydrologic and hydraulic models using HEC-HMS and HEC-RAS software and to use this software to analyze existing flooding conditions and assess the effectiveness of possible future flood control options in reducing flooding conditions.

For options addressing large scale flooding issues and considered to be sufficiently effective, both costs and benefits of the options are evaluated. Costs are based upon estimated commercial construction and right-of-way costs, while the value of benefits recognizes the randomness of flooding events and the impacts of different flood levels on structural flooding. Based upon the character of the benefits and costs, as described in terms of a benefit-cost ratio, recommended projects are identified and prioritized for implementation.

1.4.1 Study Intent

This Study is a planning study, not a detailed engineering study or a preliminary engineering study. This Study is intended to identify and assess in broad perspective potentials for large-scale projects throughout the CBW to cost-effectively reduce flooding across the CBW. As such, approximations and professional judgment are incorporated into the development and assessment of potential flood control projects. Projects are described and evaluated only in broad terms, with the full intention that detailed engineering study will be required before any one project or portion of any one project developed in this Study can actually be implemented.

The projects identified and broadly described in this Study are intended to be used as the skeletons for defining and fleshing out particular, individual projects and project features that can be implemented over the years to reduce flooding damages in the CBW. The results of this Study can serve as a roadmap for implementation of projects which will have long-term cost effectiveness in reducing flooding in the CBW.

1.4.2 Public Meetings

Three public meetings were held as part of the Study to collect information, receive comments from citizens, and to inform citizens about Study activities and results. Appendices C, D, and E provide documentation of the public meetings.

1.5 Flood Control Options and Their Purposes

The flood control options identified in this Study are intended to address primarily repetitive losses for residential structures. Flooding of critical evacuation routes at points of or near points of watercourse crossings is also addressed.

The flood control options recommended by this Study are just that: options, not alternatives. One or more of the options could be implemented to address flooding in various areas; options are not meant to be alternatives which inherently rule out the development of another option.

The options identified in this Study focus upon structurally oriented flood control projects. The structurally oriented flood control options initially considered in developing a focused list of recommended options are of the following character:

- *Diversion Ponds*: Construction of new ponds or reservoirs to capture flood waters to reduce flood flow magnitudes at downstream locations by temporarily detaining flood waters in the pond or reservoir.
- *Conveyance Improvements*: Modification of existing channels to increase flow capacities in order to keep more flood waters within channel banks and/or convey flood waters more rapidly downstream and away from the areas where out-of-bank flooding occurs.

- *Mitigation Ponds:* Construction of new ponds to mitigate the adverse downstream impacts of conveyance improvements.
- *In-line Channel Detention*: Construction of new or modification of existing channels to increase the size of the channel above minimal size in order to increase the capability of the channel to store more flood water, and thereby function not only as a conveyance device but also as a storage device, much like a detention pond, to mitigate adverse downstream impacts of conveyance improvements.
- *New Channels and Diversions:* Construction of new channels or channel extensions, to which flood waters can be redirected from a watercourse with limited capacity and thereby convey flood waters to downstream points via an alternative path, thus reducing flooding in the overtaxed watercourse.
- *Use of pumping* to divert flow from under-capacity watercourses to watercourses with excess capacity.
- *Retrofit, upgrade, or replacement of bridges, culverts, or siphons:* New or modifications to bridges and other drainage structures at roadway, channel, or railway crossings to significantly reduce the constriction the existing structures cause for the flow of flood waters, thereby reducing flood levels at points upstream of the crossing.
- *Construction of levees or dikes*: Levees or dikes can be used to keep flood waters from spreading to areas behind the levee or dike.

Among the techniques commonly viewed as non-structural (or minor structural) flood control methods which are potentially available to address apparent flooding not specifically identified in this Study are the following:

- *Localized drainage improvements:* Improving storm sewer drainage by modifying drainage ditches or sewers to provide more effective drainage.
- *Ponding relief:* Use of ditches or swales to drain low areas where runoff waters tend to pond because of the absence of a pathway by which runoff water can drain away.

- *Flooding proofing:* Different measures can be taken to prevent damage to individual structures from flooding or limit the damage from flooding.
- *Raising of affected structures:* Raising a building to a level which puts the first floor level above flood levels.
- *Buy-out*: Purchase and subsequent demolition of a structure to prevent its future flooding.

Specifically excluded from consideration in this Study are out-of-watershed transfers (i.e., diversion of flood flow out of the CBW) or increases in flood flows purposely delivered to adjacent watersheds. Modifications or special features of flood control facilities for water quality control or improvement purposes are not considered in this Study, though some flood control projects could be adapted to incorporate water quality features. (For example, a diversion pond might be constructed with a wet bottom to provide a permanent pool for storm water quality improvement). Note, however, environmental considerations related to potential adverse impacts of flood control options are recognized.

The flood control alternatives evaluated in this Study are intended to deal with control of major flooding events (i.e., floods of sufficient size to commonly produce structure flooding) and the consequent damages they cause. Flooding situations caused by inadequate storm water drainage capacity of a community or subdivision storm sewer system (whether a sewer pipe or ditch system) is not addressed in this study, except in the context of such causes possibly being a reason for reported flood losses beyond recognized floodplain limits.

1.6 Existing vs. Future Flooding Problems

The flood control options evaluated in this Study are intended to address existing flooding problems or future flooding problems which can be fully expected because of current conditions not being rectified. The flood control options are not intended to address flooding problems arising from future land development (i.e., conversion of land to residential, commercial or industrial use). The term "land development" is used here not in a pejorative manner, but merely to identify land use changes made for the purpose of construction of residences and residential subdivisions, commercial or industrial facilities, roadways, and similar development.

Increased runoff from future land development activities associated with urban growth (e.g., residential subdivisions, commercial properties, state highways) is required by county [Brazoria County, 2003] or state drainage criteria to be mitigated, i.e., controlled in such a way that increases in runoff are not discharged to receiving waters. While certainly mitigation activities are not always fully effective, it must be presumed that regulatory requirements are generally satisfied; development of major flood control works cannot be predicated upon the assumption that regulatory-based drainage requirements will not be followed in some undeterminable fashion. Thus, the runoff consequences of future land development in the watershed are expected and presumed to be mitigated. Consequently, facilities such as detention ponds and the channels carrying flow to them are assumed, if they are proposed as a flood control measure as a consequence of this Study, not to be designed (even in a very preliminary fashion) to provide migration of future land development impacts

In particular, detention as proposed in this Study is designed to remedy existing flooding problems, not mitigation of future land development impacts, which is the responsibility of the land developer, either through onsite mitigation or use of regional facilities designed, all or in part, to provide mitigation of land development with costs being borne at least in part (in some fashion) by the developer. That is, detention as proposed in this Study is for reduction of existing flooding or for mitigation of impacts of flood control works which themselves are constructed for reduction of existing flooding.

This is not to say that a detention facility or a channel could not be constructed for purposes in addition to flood control to address current flooding; a channel or detention facility could be oversized (from the standpoint of flood control) in its design to provide mitigation of development-induced runoff, with the anticipation that the additional cost of the increased storage or channel capacity (above flood control needs) would be a cost not assigned to the flood control purposes of the storage facility or modified channel, but rather a cost which would be recovered in some fashion by the parties constructing the detention facility or channel modification for flood control purposes. The storage or channel capacity provided for mitigation of land development runoff would be in *excess* of that proposed in this Study for remedy of current flooding problems. Over-sizing of a pond or channel for mitigation of land development runoff is not addressed in this Study, though in some situations a detention pond site or drainage ditch expansion might be, as part of its detailed design developed in subsequent studies, of such size as to allow its use to meet undefined needs for mitigation of future land development runoff.

SECTION 2

CHOCOLATE BAYOU WATERSHED

2.1 Watershed Overview

The CBW is a 154.5 square-mile (sq-mi) watershed lying in the Gulf Coast Prairies Major Land Resource Area. The lower (more downstream) portion of the watershed is in the Gulf Coast Marsh Resource Area. The land is of very limited slope and elevation, generally sloping from northwest to the southeast, with highest land elevations about 60 feet (ft) in the northwest part of the watershed [SCS, 1981; see also Exhibit 1-4]. From its highest elevation in the northwest part of the watershed to Chocolate Bay at the southeast end of the watershed, the overall land surface elevation falls from about 63 ft to approximately zero feet over a point-to-point distance of about 22 miles (i.e., a slope of 0.05%).

Based upon current floodplain delineations developed for FEMA studies, about 47 sq-mi of the watershed is covered by regulatory-defined 100-year floodplains [Brazoria County, 2007]; flooding is known to also occur in areas not lying in the regulatory floodplain defined by FEMA.

2.1.1 Watershed Meteorology

Average annual temperature in Brazoria County is 68.5 degrees Fahrenheit (deg. F), with average daily maximum and minimum ranging from 91.7 deg. F to 42.5 deg. F. Average annual rainfall is 52.12 inches (in.), with monthly average ranging from 2.85 in. to 5.63 in. Rainfall occurs throughout the year, although about 60% of the rainfall occurs in the months of April through September [SCS, 1981].

Brazoria County data are used to describe the intensity-duration-frequency rainfall characteristics; intensity-duration-frequency data for Brazoria County are shown in Exhibit 2-1 [Brazoria County 2003].

2.1.2 Severe Storm Events

The CBW is subject to severe storm events, often associated with tropical storms and hurricanes. The largest 24-hour (24-hr) rainfall in U.S. history occurred on July 24, 1979, as a consequence of Tropical Storm Claudette; 43 inches of rainfall fell in the 24 hour July 24 period. The following table lists the more damaging documented storm events in Brazoria County area [Texas Almanac, 2008-09]:

Table 2.1.2 Severe Storms Events in the Brazoria County Area

Year of Storm	Storm Description (Data Source: National Oceanic and Atmospheric Administration; United States Geological Survey)	Maximum Precipitation
1919	The storm was centered over Brazoria in Brazoria County where 13.5 in. of rainfall was recorded. 12.83 in. of rainfall was recorded at Hitchcock in Galveston County	13.5 inches
1922	The largest amounts of rain fell in Matagorda and Brazoria Counties. The largest amount recorded in the 3-day period was 11.84 in. in the city of Matagorda in Matagorda County	11.84 inches
1922	The largest amounts of rain fell on Brazoria and Galveston Counties. In Brazoria County, a range of 8 to 13 in. fell over the 3-day period	13 inches
1933	A weak tropical disturbance moved inland over the Texas coast and then interacted with a cold front during the night of July 23. The maximum storm rainfall of 21.3 in. was recorded at Logansport, La., 7:00 a.m. July 22 to 7:00 a.m. July 25. The largest recorded maximum rainfall in Texas of 12.8 in. was recorded in Port Arthur, Jefferson County and Freeport, Brazoria County.	12.8 inches
1979	Continuous, torrential rains fell in the eastern upper coast and southeastern Texas for almost 48 hours causing major flooding that closed streets and highways and forced hundreds of residents from their homes. Rainfall totals of 10-20 in. for 2 and 3 days were common. Alvin in Brazoria County recorded the maximum 24-hour rainfall on record for the United States of 43 in.	43 inches
1979	Three-day rainfall totals throughout the upper coast were 8-27 in. Freeport in Brazoria County recorded 27 in. of rain	27 inches
1995	Flash Flooding developed across the coastal counties (Harris, Brazoria, Galveston and Chambers) in the overnight hours when 3 to 7 inches of rain swamped the area. Widespread street flooding was reported throughout the counties, and damage was estimated around $40,000.	7 inches
1998	In Brazoria County Chocolate Bayou near Alvin exceeded its banks in the channel above FM 1462 to the mouth at Chocolate Bay. Several minor roads were impacted by this flooding.	24 inches

2.1.2 Watershed Soils

The CBW lies in the West Gulf Coast subdivision of the Atlantic and Gulf Coastal Plains geomorphic province of the United States [SCS, 1981]. Soils are predominately clayey and loamy. Nonsaline clayey soils of the Lake Charles formation are found primarily along the floodplain areas of Chocolate Bayou while nonsaline clayey soils of the Bernard-Edna formation lie predominately along the more outer edges of the watershed more or less parallel to the Chocolate Bayou. The Lake Charles formation soils are poorly drained, with very low permeability (upper layer soils are in the 0.6 to 2.0 in./hr permeability range) while the Bernard-Edna formation soils are loamy and moderate to poorly drained, also with very low permeability (upper layer soils are also in the 0.6 to 2.0 in./hr permeability range) [SCS, 1981].

2.2 Watercourses and Sub-watersheds

The primary watercourses in the CBW are Chocolate Bayou, with an approximate length of approximately 29.2 mi and representative flow line slope (ft/ft) of 0.00066; the West Fork of Chocolate Bayou, with length of 9.9 mi and representative flow line slope of 0.00089, the East Fork of Chocolate Bayou with length of 8.1 mi and representative flow line slope of 0.00117, South Hayes Creek, with length of 7.7 mi and representative flow line slope of 0.00299, the North Hayes Creek with length of 5.9 mi and representative flow line slope of 0.00039, Ditch C12, with length of 4.3 mi and representative flow line slope of 0.00206, and the existing Brunner Ditch with length of 11.8 mi and representative flow line slope of 0.00039. These watercourses are shown in Exhibit 2-2.

Sub-watersheds used in hydrologic analyses for this Study were determined with Arc-Hydro Geographic Information System (GIS) software tools in conjunction with Light Detection and Ranging (LiDAR) data (additional discussion is provided in Section 3). Sub-watershed boundaries are shown in Exhibit 1-7. These watersheds do not agree in precise detail with watersheds delineated in prior studies [e.g., FEMA, 1999; Klotz Associates, 2003; Klotz Associates and Baker & Lawson, 2002; Snowden, 1989] because the delineation of watershed boundaries in prior studies for the CBW did not have the LiDAR elevation data available to this Study. Table 2-1 summarizes basic characteristics of the sub-watersheds defined for this Study as determined by calculations of this Study (the hydrologic parameters listed in this table are defined in the Nomenclature list at the beginning of this Report).

2.2.1 Raw Water Canals

Major hydraulic features in the Chocolate Bayou watershed are the several raw water canals owned and operated by the Gulf Coast Water Authority (GCWA). These canals do not carry (except in cases where a canal berm may be in disrepair) local surface runoff but rather raw water that has been pumped from the Brazos River some 30 to 40 miles to the west of the CBW. GCWA canal locations in the CBW are shown in Exhibit 1-6. The primary importance of these canals in evaluating flooding conditions in the CBW is that these canals sometimes act as barriers to overland flow and the spread of floodwaters.

2.2.2 Salt water Barrier in Chocolate Bayou

Chocolate Bayou is divided by the State of Texas into two classified segments (as identified in the Texas Administrative Code)

- Segment 1107: Chocolate Bayou Tidal, extending from the confluence with Chocolate Bay 0.9 miles downstream of FM 2004 to the salt water barrier (immediately downstream of the Chocolate Bayou Rice Canal; see Exhibit 1-6) 3.2 miles downstream of SH 35 and about 11.8 mi upstream of Chocolate Bay; the downstream end of the Chocolate Bayou Tidal segment begins at the upstream end of Chocolate Bay (Segment 2432).
- Segment 1108: Chocolate Bayou above Tidal, extending from upper end of Segment 1107 to SH 6.

The salt water barrier prevents salt waters from Chocolate Bay intruding far upstream into Chocolate Bayou. Because the lower reaches of Chocolate Bayou are directly connected to Chocolate Bay and subject to tidal influences, Chocolate Bay seawaters can advance up the lower reaches of Chocolate Bay. During low tide levels in Chocolate Bay, the intruding seawater does not extend far up Chocolate Bayou, but during the larger high tide levels saline water can be forced up Chocolate Bayou until blocked by the submerged barrier.

Exhibit 2-3 shows a profile of Chocolate Bayou and the location of the barrier as determined in prior studies [Klotz Associates and Baker & Lawson, 2002]. The limit of 100-year tidal flooding (i.e., flooding induced by 100-year tide levels in Chocolate Bay) is approximately 9.9 miles upstream of FM 2004, while the salt water barrier and SH 35 are about 11.0 miles and 15.9 mi, respectively, above FM 2004 [pg. 24, FEMA, 1999; Klotz Associates and Baker & Lawson, 2002]

2.3 Prior Studies

FEMA flood insurance studies [FEMA, 1999] define the current FEMA-recognized floodplain boundaries. Other watershed wide studies have been conducted to refine or revise floodplain descriptions [Klotz Associates and Baker & Lawson, 2002], but none have yet to be used to formally redefine the FEMA-recognized floodplain boundaries. Appendix 1 provides a copy of various documents relating to prior studies or works pertinent to this Study which were reviewed and/or used in the development of this Study and which are judged to be not readily available from public sources.

2.3.1 FEMA Recognized Regulatory Floodplains

Flood Insurance Rate Maps (FIRMs) have been developed by FEMA for some of the watercourses in the CBW; the floodplain map panels are 48039C0020H, 48039C0105H, 48039C0110H, 48039C0115H, 48039C0120H, 48039C0130H, 48039C0140H, 48039C0145H, 48039C0275H, 48039C0280H, 48039C0285H, 48039C0295H, 48039C0305H, 48039C0315H, 48039C0460H, and 48039C0480H, all of which have an effective date of June 5, 1989. The datum upon which these maps are based is the National Geodetic Vertical Datum of 1929 (NGVD 1929). The floodplains depicted by these floodplain map panels are shown on Exhibit 1-3. Review of the FIRMs shows that major portions of the CBW lie in the 100-year floodplain, with the majority of the floodplains occurring in the mid and upper portions of the CBW.

2.3.2 Watershed Wide and Regional Studies

In addition to the flood insurance studies upon which current regulatory floodplain delineations are based, the following watershed wide studies have been done.

2.3.2.1 Snowden Study

Snowden Engineering prepared a Master Drainage Plan Report for different watersheds in Brazoria County [Snowden, 1989; see also Appendix A] which lay within the jurisdiction of Conservation and Reclamation District No. 3. The CBW was among the watersheds studied. HEC-1 (Hydrologic Engineering Center Hydrology Model) and HEC-2 (Hydrologic Engineering Center Hydraulic Model) of flooding for the 25- and 100-year flood events was conducted and flood control options were identified. Reasons identified for flooding in the CBW were 1) upstream flow from contributing areas in Fort Bend County, 2) the continuous meandering of Chocolate Bayou, and 3) tidal flooding.

Recommendations for projects in the CBW included establishment of an automated rainfall measurement and flood warning system (to be developed for the entire Conservation and Reclamation District No. 3 area), and, specific to the CBW, construction of three detention ponds (of 250 acres, 150 acres, and 200 acres) in the upper reaches of the watershed and Chocolate Bayou channel widening from what is referred to as the BRA Canal (now part of the GCWA canal system) downstream to approximately FM 2004 (with different amounts of widening along various segments of the widened bayou).

In the present study, a variety of detention ponds are considered, including some similar to those recommended in the Snowden Study. Channel widening, some of which is similar to the Snowden proposals, is also considered

2.3.2.2 2002 Brazoria County Master Drainage Plan (BCMDP)

The Brazoria County Master Drainage Plan Report (BCMDP) [Klotz Associates, 2002] was completed in 2002 by Klotz Associates with support from Brazoria County, the seven drainage districts in the county, and grant funding support from the TWDB. The BCMDP report revised many of the FEMA hydrologic and hydraulic models for various watersheds in the county. The report also recommended remedies to address some of the drainage problems being faced in the County, with emphasis on remedies within the financial capabilities of the county and the drainage districts to construct. Many of the recommendations from this MDP, such as de-snagging and general channel clearing as well as rainfall and discharge monitoring, have been or are being implemented by the drainage districts.

The CBW is among the watersheds addressed in the BCMDP. Hydraulic models for the BCMDP were adapted from the Snowden Study [Snowden, 1989] with updating to reflect new watershed conditions in the county; model topography consequently reflected States Geological Survey (USGS) Quadrangle Sheets published in the time period of 1977 to 1982. The modeling in BCMDP study also did not extend far enough upstream to cover all the repetitive loss properties identified in the present Study. Methods for evaluating hydrologic parameters were more approximate than those used in the present Study as well.

For the CBW, the BCMDP proposed 1) a 90-acre pond on Chocolate Bayou near FM 1462; 2) hydraulic structure replacement at the CR 48 crossing of Chocolate Bayou; 3) cleaning of North Hayes Creek from its confluence with Chocolate Bayou to CR 121 to restore channel capacity; and 4) realignment of the existing Brunner Ditch so as to change its current point of downstream confluence with Chocolate Bayou near Liverpool to a more downstream confluence with Cottonwood Bayou, a tributary to Chocolate Bayou near SH 2004. Exhibit 2-4 shows the approximate locations of these particular proposed projects. Selected portions of the BCMDP Report are provided in Appendix 1.

2.3.2.3 Brazoria County Drainage District No. 5 Studies

A series of improvements to the Chocolate Bayou and its tributaries was proposed in a study done for Brazoria County Drainage District in 2003 [Klotz Associates, 2003; see also Appendix 1]. These proposed improvements consisted of the following: 1) a series of channel improvements (widening and deepening) along Chocolate Bayou, from the mouth of Chocolate Bayou to SH 6; 2) channel improvements along South Hayes Creek from SH 288 to Chocolate Bayou; 3) channel improvements along North Hayes Creek from SH 288 to Chocolate Bayou; and 4) channel improvement along the West Fork of Chocolate Bayou from SH 288 to its confluence with Chocolate Bayou.

In addition, a sequence of three basic improvements to Brunner Ditch was proposed: 1) enlargement of the existing Brunner to convey the 100-yr flow; 2) extension and enlargement of the Brunner Ditch northward about 10,000 ft to intersect the West Fork of the Chocolate Bayou; and 3) extension and enlargement of the Brunner Ditch farther northward about 19,000 ft to CR 67.

In addition, informal studies conducted by Klotz Associates in 2000 identified potential detention pond sites in the upper portions for the Chocolate Bayou watershed which might serve as either mitigation storage sites or diversion pond sites to reduce flows to downstream points; these pond locations are recognized in the identification of potential pond sites discussed in connection with diversion pond projects in Section 5.

2.3.3 Brunner Ditch Studies

Studies were undertaken by Klotz Associates [Klotz Associates, 2008a; Klotz Associates, 2009a; see also Appendix A] for Brazoria County Drainage District No. 5 and the

Chocolate Bayou Steering Committee (an ad-hoc committee composed of representatives of drainage districts in the County and some cities in the CBW) to examine the potentials for lessen of flooding by modifying the existing Brunner Ditch by widening and extending the existing Brunner Ditch to the north and/or south. These studies provided a more extensive look at the utility of using Brunner Ditch for flood reduction than was provided by the Brazoria County Drainage District study of 2003 [Klotz Associates, 2003, discussed above]. The focus of these 2008 and 2009 Brunner Ditch studies was estimation of necessary right-of-way (ROW) to carry the 100-yr flows intercepted by an extended Brunner Ditch.

The 2008 and 2009 Brunner Ditch studies proposed extension and lengthened, along with widening and deepening, of Brunner Ditch so that in addition to intercepting North and South Hayes Creeks, Brunner Ditch could possibly intercept the West Fork and, in one option, the East Fork of Chocolate Bayou. Also considered was possible lengthened of the southern end of Brunner Ditch to return the ditch to Chocolate Bayou not at its current location near Liverpool but farther south near FM 2004. While not exactly the same as the options proposed in the present Study, the proposed Brunner Ditch realignments in these 2008 and 2009 studies are similar to some of the options considered in this Study.

The results of the floodplain evaluation in these 2008 and 2009 studies for the proposed Brunner Ditch modifications showed little improvements to the extent of flooding in the four watercourses intercepted by Brunner Ditch. As a consequence, it was suggested that channel conveyance improvements in the four watercourses might be considered as well, but no evaluation of the potential flooding reduction benefits was made for these possible improvements.

2.3.4 Land Development Studies

There have been numerous drainage studies dealing with proposed land development in the CBW along primary watercourses. These studies have typically not addressed definition of flood flows in the primary watercourse, but rather use flow data from prior studies to develop necessary mitigation to avoid impacts to the receiving watercourses. To the extent these studies may have altered the land configuration along watercourses or in areas of structure construction, such changes are captured in the LiDAR data used in this study if made before 2007 (the date for the LiDAR used in this Study). Changes to land elevation data after that point would not be captured in the elevation data used in this study.

A recent study [HCRA, 2009, currently underway] has undertaken a reevaluation of flooding along the West Fork of Chocolate Bayou as part of a proposed land development project (referred to as the "Seven Oaks" subdivision), preparing, as part of the reevaluation, a Letter of Map Revision (LOMR) request; this LOMR study has not been accepted by FEMA at the current time (i.e., the time of preparation of this Study). The Seven Oaks study incorporated information from prior flood studies as well as using the same LiDAR data as used in this Study and new land survey data collected for the LOMR study (to provide greater detail of channel configuration in some areas); the draft Seven Oaks LOMR study proposes a revision to the regulatory-defined floodplain along the West Fork of Chocolate Bayou.

Some of the data used in Seven Oaks LOMR study was incorporated into the present Study to provide greater definition to channel cross section shape and some of the LiDAR data used in this Study was incorporated into the Seven Oaks LOMR study.

2.3.5 Grand Parkway Development

The currently proposed Grand Parkway alignment parallels Brunner Ditch along a significant length of the ditch in the Alvin area (see Exhibit 1-5). As discussed in subsequent sections, widening of the Brunner Ditch is a potential project for alleviating flooding in the CBW; implementation of the Brunner Ditch projects evaluated in this Study or the Grand Parkway in the vicinity of Brunner Ditch will require coordination between those parties involved in flood control project development and parkway development. While the two projects are potentially in conflict, there is also opportunity for cost savings by joint use of right-of-way (i.e., the width of one combined right-of-way for both projects might be significant less for the two individual rights-of-way).

2.4 Land Use and Topography

2.4.1 Land Use

The aerial photographs of Exhibit 1-2 show land use and land features in the CBW. All aerial photographs in this Report (unless specifically noted otherwise) were obtained from the Houston-Galveston Area Council (HGAC) and are identified with a date of 2006; these area photos were released to the public in January 2008. These aerial photographs were relied upon, in conjunction with site inspection and previously conducted studies, to generally identify and clarify watershed conditions and assist in identifying potential locations for future detention or diversion ponds.

2.4.2 Horizontal Control

The coordinate system used for this project is the NAD83 State Plane Texas South Central FIPS Zone 4204

The horizontal datum of the data of this Study is the North American Datum of 1983 (NAD83) based on the Texas Universal Transverse Mercator coordinate system (Zone 14 and 15). All georeferenced spatial data are referenced to this horizontal datum unless specifically noted otherwise.

2.4.3 Elevation Data and Vertical Datum

The vertical datum used in this Study, unless specifically noted otherwise, is the North American Vertical Datum of 1988 (NAVD88), with 2001 Datum Adjustment. Elevation-based data from sources not using this datum were adjusted to this Study datum when appropriate to the proper use and understanding of the data.

To provide more accurate land elevation data for this Study, recent LiDAR topographic data were obtained from the Texas Natural Resources Information System (TNRIS) for Brazoria County as part of the data collection activities for this Study. TNRIS in coordination with FEMA Region VI have been recently (2007-8) produced high-resolution digital terrain data along the Texas Gulf Coast, including Brazoria County. These data are being used by FEMA to update Digital Flood Insurance Rate Maps (DFIRMs) for the coastal areas.

Recently (2008) flow LiDAR data for Fort Bend County was obtained directly from Fort Bend County.

The LiDAR data for Brazoria and Fort Bend Counties were used to define the surface topography of the CBW except when detailed local survey data from other reports were used to supplement the LiDAR data with more detailed elevation data for channel cross section configurations. The horizontal accuracy of the LiDAR data is 2.4 ft, while the vertical accuracy is 1.2 ft.

These topographic data were used for the following purposes: 1) describing elevation contours for the watershed (see e.g., Exhibit 1-4); 2) delineating and sizing watershed drainage areas; 3) identifying potential areas of significant ponding; 4) estimating hydrologic parameters (such as sub-basin slopes) where necessary; 5) developing geometric data for hydraulic models to reflect current conditions; and 6) locating floodplains for various flood events.

2.4.4 Ponding

Ponding in the CBW can result from localized low spots from which drainage is absent or impeded due to surrounding topography. Localized flooding problems distinct from flooding due to river and bayou overflows can sometimes be identified when ponding areas can be distinguished from flooding adjacent to rivers and channels. These latter areas can become isolated areas of storm water accumulation contributing to localized flooding of structures if located near structures.

Locations of ponding areas can be identified using GIS tools in combination with LiDAR data; the depths of low areas can be determined and plotted as shown in Exhibits 2-5, 2-6, and 2-7. As can be seen in these exhibits, ponding areas in the CBW are widespread. Clearly evident are the low areas forming channels, bayous, and drainage ditches. Other areas appear to be ponds, detention areas (natural or manmade; e.g., see the oxbow lake area about a mile east of Liverpool in Exhibit 2-7), and agricultural fields. The extensive and widespread nature of these ponding areas across the CBW precludes detailed investigation and assessment of their individual characteristics and potential need, desirability, or means to eliminate them.

2.5 Environmental and Historical Review

Flood control alternatives developed as a consequence of this Study should avoid impacting wetlands and historical sites. If a flood control remedy is located or is of such character as to adversely impact wetlands or historical sites, mitigation of impacts will be necessary. However, with proper detailed design, flood control alternatives can enhance natural habitat and encourage preservation of wildlife. All proposed flood control measures for the CBW should undergo detailed environmental review as part of the detailed design of the flood control project. For any proposed project, there should be review and coordination of the proposed project in the early phases of project development with state and federal environmental agencies, including but not limited to the U.S. Army Corps of Engineers (USACE), the Texas Parks and Wildlife Department, and the U.S. Fish and Wildlife Service. Depending upon the character of the potential impact, involvement of the Texas Commission on Environmental Quality may also be desirable or required.

The Galveston District of the USACE should be initially contacted to initiate review of particular proposals; the District will typically serve as the coordinating agency for environmental review by various different state and federal agencies as may be required. Issue of permits for channel modifications or wetland mitigation will be through the Galveston District of the USACE.

2.5.1 Wetlands

The U.S. Department of Interior National Wetland Inventory (NWI) was accessed online to identify approximate potential locations of jurisdictional wetlands (i.e., under the legal jurisdiction of the United States Government). Exhibit 2-8 shows the approximate location of known jurisdictional wetlands in the CBW as given by the NWI. Based upon the NWI data there are approximately 6500 acres (ac) of wetlands in the CBW. The existence and precise location of these wetlands will require on-the-ground confirmation for development of any project which might impact these wetlands.

Also to be recognized is that recent (2009) changes to regulatory definition and determination of jurisdictional wetlands [USACE, 2008] might well add wetlands areas to those shown in the current National Wetland Inventory. These new regulations are commonly expected to increase the number and size of jurisdictional wetlands.

2.5.2 Modifications to Natural Channels

Modification of natural channels resulting in cut or fill (e.g., widening of a natural channel) or vegetative impacts (e.g., cutting of trees) carrying waters of the United States (which would include all natural channels in the CBW, or man-made channels with natural channel segments) cannot occur at levels at or below the ordinary high water mark without USACE permit. Location of the ordinary high water mark may, as well, require USACE determination or concurrence in the determination of such level by other parties.

2.5.3 Historical and Archeological Sites

According to the Texas Historical Commission, there are no known historical sites located in the Chocolate Bayou Watershed (see correspondence of Appendix F). There are also no known archeological sites in the CBW. No objections to the preliminary project proposals considered in this Study have been raised by the Commission (see Appendix F).

SECTION 3

FLOODING PROBLEMS AND ISSUES

3.1 Historical Perspective

Flooding is frequent and widespread in the CBW. Based on NFIP Statistics, approximately 560 properties in the CBW suffered flood losses from January 1, 1978 to October 31, 2007. The City of Manvel, which lies at the heart of the largest floodplain areas in the watershed, has suffered more than 200 loss incidents since 1978. The combined communities of Manvel, Iowa Colony and Liverpool have had nearly 300 loss incidents [FEMA, 2007].

Brazoria County has been identified by FEMA as a county with severe repetitive losses (SRL). Since 1978, Brazoria County has had nearly 5,500 repetitive loss incidents, totaling more than $62 million dollars in claims [FEMA, 2007]. Properties within cities of the CBW have, likewise, suffered significant losses, as evidenced by the data of the following table:

Table 3.1 Summary of Historical Flood Losses in Cities in CBW

City	Number of losses in City from January 1, 1978 to October 31, 2007	Total amount paid by FEMA for losses during the period of January 1, 1978 to October 31, 2007
Manvel	239	$3,259,602
Iowa Colony	23	$434,723
Liverpool	37	$409,737
Alvin	1,130	$11,200,478
Total	1,429	$15,307,540

Source: FEMA, 2007

Flooding of hurricane evacuation routes roadways is also a critical flooding concern in the CBW. Hwy 6 has seen significant flooding in the past decade, even with improvements to the highway. Flooding along the highway has become sufficiently severe to sometimes cause roadway overtopping.

The most recently documented overtopping event (see Exhibit 3-1) occurred during a heavy rainfall period in October of 2006. The roadway was overtopped in the area of the West Fork of Chocolate Bayou in and near the City of Manvel. It is recognized by TxDOT and local officials that flooding of HW 6 is problematic and presents significant concerns for effective emergency evacuation of Galveston County, Brazoria County and southern Harris County.

3.2 Types of Flood Loss Data

This Study seeks to identify potential remedies for residential structural flooding resulting from overflow of watercourses in the CBW and (to a lesser extent) recognized problematic flooding of critical hurricane evacuation routes. Information about or related to such flooding for this Study comes from the following:

3.2.1 Repetitive Loss Data

Repetitive loss data identifies locations of residential structure losses reported to FEMA for a property location suffering at least two reported (to FEMA) occurrences of flood damage. Losses which may have occurred to residential structures near the reported loss but not reported are not included in these data.

Repetitive loss information was obtained from the Floodplain Administrator for Brazoria County. The data received from the Floodplain Administrator was in the form of an Excel spreadsheet listing data for the entire county. The data provided included the following:

- Physical locations (based on street address) of repetitive losses, along with the dates and number of repetitive losses at each location; these locations could be precisely located in a geo-referenced framework.
- Repetitive losses with only mailing (non-physical) addresses, along with the dates and numbers of repetitive losses at the mailing address; these data could only be located

within a ZIP code zone, assuming the ZIP code of the mailing address was the same as the ZIP for the physical address of the loss location.

Since the repetitive loss data was for the entire county, it was necessary to determine to the extent possible which loss data corresponded to locations in the CBW. There were 1,433 repetitive losses incidences in the database supplied by the county. All loss data not having a ZIP code within (part or all) the CBW were eliminated from the database. Adjustment of data items were made when obvious errors could be identified (e.g., when the repetitive loss was listed as $99 billion)

To locate loss locations within the CBW (for which a physical address was given in the county data), a Brazoria County road database in the form of a GIS shape file was obtained from commercially available databases to identify roadways in the CBW (or near the CBW, when a roadway might cross the CBW boundary). A geo-coding address locator within ArcMap GIS was used to compare the physical addresses of the repetitive loss data base to the road data file to develop a geo-referenced address along the roadway. There were found to be 99 repetitive losses (with each loss being counted) for which loss locations could be determined to lie within the CBW.

The remaining loss data (those without physical addresses but having a post office box address or a rural route number) lie within (as based upon their ZIP code) cities within (all or in part) in the CBW. Within each city lying totally within the CBW, the losses were randomly distributed across the city. For cities lying only partially lying in the CBW (e.g., Alvin), the losses were assigned to be lying within or outside of the CBW in proportion to the area of the city within or outside of the CBW. The losses lying within the CBW within a particular zip code were then distributed randomly across the zip code. These randomly distributed loss locations lying within the CBW represented 37 repetitive losses.

3.2.2 Citizen Reports

Information on incidences of structural flooding, property (non structure) and street flooding, and roadway and bridge overflow data was collected as part of the first public meeting conducted as part of this Study. Appendix C documents this meeting. Information collected from the public meeting activities was incorporated into the Study database on flooding problems; if a loss, based upon the information provided, appeared to be a structural flooding loss and was identified with an address not already among those identify from the county database, it was included in the repetitive loss database.

3.2.3 Summary of Repetitive Loss Data

The following summarizes the repetitive losses (each repetition of a loss is counted)

Table 3.2.3 Summary of Structure Loss Data in CBW

Type of Loss (Data reported to FEMA were provided to this Study by Brazoria County over period of approximately 1979 to 2008)	# of Loss Locations in CBW	# of Losses in CBW
Reported to FEMA with physical address	68	184
Reported to FEMA but without physical address *	37	100
Estimated from Public Meeting reports	24	24
Total	129	308

* # of losses estimated from ratio of losses to loss location for locations with physical address

Exhibit 3-2 plots the structure loss information (distinguish by types). Shown for reference is the current 100-yr floodplain (as computed in this Study). The following is noted:

- Loss locations are rather widely distributed up and down (i.e., northwest to southeast) the watershed, but (not unexpectedly) concentrated along the general locations of creeks and bayous.
- Loss locations are more common in the vicinity of population centers (also not unexpected)

- Some loss locations are sometime located beyond the existing 100-yr floodplain

Loss locations outside the 100-yr floodplain (as shown in the Exhibit 3-2) can be the result of possibly the following:

- There are channels, creeks, and major drainage ditches which can overflow during a severe storm event which are not among the modeled waterways and which, therefore, do not have a defined and known current floodplain which is depicted on a floodplain map.
- The reported loss may not be the result of an overflowing channel or creek, but due to a localized drainage problem such as an under-capacity roadside ditch, sewer, or subdivision drainage ditch.
- The reported loss may be a result of a high tailwater from a flooding channel or creek which inhibits drainage from a residence or subdivision

In the first instance, the reported loss is properly a loss, which if it has occurred more than once, is a repetitive loss. In the second instance, it is a loss which is not directly a loss associated with an overflowing channel, while the third instance is a hybrid of the two extremes: something that is not the result of overflowing channel banks but a result of high receiving waters, which may or may not be overflowing channel banks. The distinction between these three types of losses cannot be made in this planning level study; thus no attempt was made to exclude loss data merely because it was located outside the modeled 100-yr existing floodplain.

3.2.4 Unreported Losses

All flooding of residential properties is not reported for various reasons. Common reasons for non reporting could include 1) concern that a report could affect insurance rates (such a concern was actually voiced by some citizens in the second Public Meeting);

2) the amount of damage was sufficiently small that it did not exceed deductible limits and thus deemed not necessary to be reported; 3) the loss was the first time that a loss occurred for a particular location and the affected party did not realize or care that possible loss reimbursement could be obtained; 4) the party affected by a loss considered the level of effort required to seek loss reimbursement was not worth the reimbursement that might be obtained; 5) the property owner suffering the loss did not want a public record of the loss; and 6) the flooded structure was not covered by insurance and thus not reported for reimbursement. Thus it is concluded that, in general, the repetitive loss data underestimates in unknown amount the actual number of structure losses.

3.3 TxDOT and Evacuation Route Flooding

SH 6, a TxDOT designated evacuation route, has experienced documented flooding (i.e., overtopping) in the area of the City of Manvel. SH 6 has seen overtopping or partial pavement inundation, resulting in not only reduced capacity but also dangerous conditions. The most recently documented overtopping event occurred during a heavy rainfall period in October 15-16, 2006 period (see photographs of Exhibit 3-1).

The roadway was overtopped on at least at two different locations in the area of the West Fork east of Hwy 288 and west of the SH 6 crossing of Ditch C12. While not yet fully identified nor understood as to its full causes, the overtopping is believed by many to be in significant amount due to inadequate downstream infrastructure and infrastructure deficiencies in the Manvel area. Overtopping of CR 48 in the Manvel area also occurred during the same October 16, 2006 flood event [Houston Chronicle, 2006]. It is generally recognized by TxDOT that flooding of SH 6 is problematic.

3.4 Generalization of Loss Data

It has been noted above that reported losses are likely less than the actual number of losses. But the extent of potential under-reporting is unknown. However, it could be reasonably expected that where losses are reported, the potential amount of under-reporting is likely more than where few reported losses occur. Flood control improvements can thus be expected to benefit not only locations were repetitive losses are reported but nearby locations as well. More generally, areas where structures occur can be expected to benefit in varying amounts even if no specific data on losses in such areas are known or available. As the number of structures in an area subject to flooding increases, the more likely it is that a reduction in structural flooding and consequent benefits will be obtained.

To capture these likely benefits of both reported and unreported repetitive structure losses, a generalized repetitive loss map was prepared to estimate the number of potential repetitive losses throughout the CBW. The map was created in a GIS format so that GIS tools could be used to combine the flood loss data with modeling results to determine the level of losses for various flooding conditions; the use of the generalized loss data is described in subsequent sections of this Report. The following describes the development of this generalized loss data map.

The initial step was to derive a raster coverage which represents the density of structures within the CBW (in layman's terms, the raster is simply an image composed of individual pixels, spread uniformly across the watershed, each pixel representing a very small area of land within the watershed, and describing some characteristic as it occurs across the watershed). 2008 census tract data were used to estimate the number of households in each census tract. It was assumed that each household in the census tract actually represents a residential structure with flooding potential. Without specific address point information, these structures were randomly distributed within each census tract.

A density map of structures was then generated using a GIS spatial analysis tool which defines a raster grid of cells or pixels (i.e., the raster is formed by the collection of grid cells or pixels) of a specified size (30-ft x 30-ft in this Study), with each cell determining the number of structures within a specified search radius. (With each grid cell covering an area of 900-sq-ft, a total of approximately 5 million grid cells were thus used to cover the entire 155 square-mile watershed). The density value computed for each cell is the number of structures within each as estimated from the average number of structures per area covered by the search radius. Consequently the number of structures for any given area could then be deduced by simply summing the cell values in that area.

By using raster calculations (i.e., cell by cell calculations), the evaluation of flood control benefits was simplified since the depth of flooding in each cell could be directly determined from the HEC-RAS flood model computations (discussed in Section 4). Flood depth raster coverages are produced by HEC-GeoRAS as a byproduct of generating floodplain depths and boundaries. Assuming that all structures start to be inundated at flood depths greater than zero, one can use raster calculations to develop a structure loss raster coverage in terms of dollars. The flood depth-damage is given by generic U.S. Army Corps of Engineers data as discussed above (see Table 6-1). The structure and damage coverages can then be simply multiplied together (i.e., in layman's terms, the "number of structures in a cell x depth of flooding in a cell x % damage per structure for the flood depth x the value of a typical structure") to generate a loss coverage which represents the losses incurred by the structures (on a cell by cell basis) in the watershed based for the flood depth in the cell for each particular flood event of interest.

This above described data model assumes that all structures are inundated when they are in a floodplain, and that they all have an equal chance (for the same flood event) of being damaged. This is not the case in reality as many different factors determine a structure's flood potential and resulting losses. Consequently, the repetitive flood loss data were used to weight the flooding potential of all structures within the watershed.

To account for the relative density of reported repetitive flood losses, a repetitive loss density map was generated using methods as described above for the number of structures subject to potential flooding. That is, the repetitive loss density map was created by generating for each cell the number of repetitive losses per cell by counting the number of repetitive losses with a specified search radius about the cell in question to determine the losses per unit area in the search area and converting that to the number of losses in a cell using the area of the cell. The search radius (which was the same for all cells) was taken as ½ of the total area of the FEMA 100-year floodplains in the model watercourses divided by the length of the modeled watercourse; the resulting radius is in effect ½ of the average floodplain width for the modeled rivers. This computed width was approximately 7000 feet resulting in a search radius of 3500 feet.

This repetitive flood loss density map was then reclassified to generate a structure weighting map, to account for the fact that losses are more likely in areas where reported-repetitive losses are numerous. The reclassification was based on the ratio of households in the 100-yr floodplain (1396) to the number of reported repetitive losses (238). Where the repetitive loss density was zero a weighting of 1 was given; conversely, the maximum repetitive flood loss density was given a weighting of 5.87 (1396/238). Weights were assigned on a pro-rata basis for all values of repetitive flood loss density between zero and the maximum. That is, the lowest density value for cell was assigned a value of 1 and the highest density value for a cell was assigned a value of 5.87. A density value between the highest and lowest density was assigned a value prorated on the basis of actual density in comparison to the high and low values.

The weighting raster was then multiplied by the structure raster to develop a weighted structure dataset, i.e., a weighted number of structures subject to possible loss for each cell in the watershed. All weighted structure numbers were scaled so that when the potential structures which might be flooded were summed across the entire watershed (on a cell by cell basis), the total number of potential structures losses equaled the total number of structures in the watershed (i.e., 7233). The resulting weighted structure raster is shown in Exhibit 3-3. (Exhibits 5-123, 5-124, and 5-125 in Appendix J show key steps in the weighting process leading to Exhibit 3-3.)

The value of this generalized mapping for flood losses is several:

- It accounts for the potential number of structures which could be flooded throughout the entire watershed
- It recognizes that in areas of high repetitive loss reports, the potential for structural flooding increases
- It accounts for variation in the density of residential structures irrespective of whether flood reports in the area have historically occurred
- It is scaled so that the total number of structures which could ever be flooded throughout the watershed does not exceed that actual total number of structures
- It is readily implemented with GIS tools to compute actual flood damages using hydraulic modeling results and depth-damage curves

And, most importantly, it is a forward looking methodology; the information provided by the generalized flood loss map that focuses upon potential future flood damages, not just what has happened in the past.

Furthermore, it is noted that flood losses beyond the limits of a defined floodplains as determined by modeling could be significant in estimating benefits and costs, in part because about ½ of the CBW is located outside of the 100-year floodplain (see Section 2.1). However, by including loss data (as is done in defining the loss distribution as discussed in Section 3.4 above) beyond the 100-year floodplains in the generalized loss distribution methodology used in this Study (see Exhibit 3-3), the impact of losses beyond the defined floodplain are recognized in determining the relative importance (i.e., mathematical weighting) that is assigned to loss locations within the floodplain but near concentrations of losses beyond the floodplain. Thus, while not fully and only approximately accounting for losses outside the floodplain, the methodology used does incorporate some of the impacts of losses beyond the floodplain in evaluating damages, thus reducing the imprecision in the estimate of benefit-cost ratios for potential flood control projects that losses beyond the floodplain might cause"

SECTION 4

HYDROLOGIC AND HYDRAULIC MODELING

4.1 Purposes

Hydrologic and hydraulic models were generated for the primary watercourses in the CBW. These models are based upon or adapted from existing hydrologic and hydraulic models or modeling parameters to varying degrees, depending upon the particular watercourse of interest and available data. These updated models are used for the following purposes:

- To provide description of existing CBW flooding for selected storm events
- To provide a basis for assessment of reported flooding problems by comparison of problem locations to floodwater inundation for selected storm events
- To provide insights to identification of potential flood control options to reduce flooding
- To describe the reduction in flood inundation that selected flood control options will achieve by modification of the existing condition models to reflect the control option of interest
- To assess the effectiveness and benefits of selected flood control options

This section address 1) the development of the hydrologic and hydraulic models used in this Study, 2) special considerations in the application of the models, and 3) comparisons of flood predictions by others to the predictions of the models of this Study.

4.1.2 New Model Development

Available models from which new models could be constructed for this Study were original 1989 FEMA models [FEMA, 1999] that define the current regulatory floodplains and the models developed for the Brazoria County Master Drainage Plan [Klotz

Associates and Baker & Lawson, 2002]. The Brazoria County Master Drainage Plan (BCMDP) models utilized much of the same data as the earlier FEMA models, the primary distinction between the two sets of models being 1) the significant differences in the discharges used in the models for similar points along a channel (the FEMA model use regional regression curves while the BCMDP used a HEC-1 model for discharge prediction), 2) the cross sections between the top of channel banks (the BCMDP models used survey data), and 3) the floodplain elevation data of the BCMDP (floodplain limits were adjusted in the BCMDP to provide a wider possibly floodplain than the FEMA models). On the other hand, the FEMA modeling work focused only on the CBW, while the BCMDP was a broader-based, less detailed countywide modeling program. These differences suggested a need to consider a major upgrade of the FEMA models and BCMDP models.

In addition, the following considerations were important to the strategy selected for model development:

- Earlier models utilized the hydrologic HEC-1 model and hydraulic HEC-2 model software. Modeling by regulatory agencies is relying more and more upon hydrologic HEC-HMS model and hydraulic HEC-RAS model software. HEC-1 and HEC-2 models are receiving little or no software support by regulatory agencies and their consultants. In addition, HEC-1 and HEC-2 input files could be exported to HEC-HMS and HEC-RAS software with limited fixes to remove data inconsistencies.
- The existing hydraulic models for the CBW are not geo-referenced. By using HEC-GeoRAS to develop the model alignment and cross section data, the HEC-RAS model is spatially consistent and tied to real-world location. Model output can be combined with digital terrain models developed from LiDAR to locate floodplain boundaries with high precision, reproducibility, and consistency with computed and plotted floodplain widths.
- The 2006 LiDAR data available for elevation determination is more up-to-date and more accurate than the elevation data used in the earlier FEMA and BCMDP studies.

Because of Geographical Information System (GIS) tools now available, these newer elevation data can be more readily incorporated into the database used to describe model geometry. Therefore, for example, the sub-watersheds and flow path lengths used in hydrologic modeling can be more accurately estimated.

As a consequence, new HEC-HMS and HEC-RAS models were developed, but with the data incorporated into the models being drawn from both new information (when considered more accurate than older data used in prior modeling) and prior models (when the data from the prior models were considered to be more accurate or just as accurate as new data). Thus, for example, cross section information for channel areas between bank lines was considered to be more accurate as given in prior models because the prior models used survey data to describe channel configuration between bank lines, while LiDAR data would tend to overly smooth the channel depth information with a resulting channel depth not as deep as the actual channel. Conversely, elevation data for areas beyond channel banks in the floodplain zones will be more accurately described by LiDAR data because of the high level of detail that LiDAR provides as opposed to the typically very few surveyed elevation points defining floodplain elevations used in prior models.

For this Study, HEC-HMS version 3.3 and HEC-RAS version 4.1 were used as the software platforms for model development and application.

4.2 Modeling Features and Assumptions

Assumptions made and features incorporated in developing the models are as follows.

4.2.1 Existing Conditions Only

Models were developed assuming existing conditions as best could be determined from available data and as reflected in LiDAR, 2008 aerial photography, limited site inspection, and some limited field survey of existing condition reflected in computer models for LOMR application development currently underway for the West Fork of Chocolate Bayou in the vicinity of the Seven Oaks Subdivision [EHRA, 2009].

Model changes to reflect potential flood control projects described changes only to existing conditions that the project would create; no changes in model characteristics were made to reflect possible future development of the watershed.

4.2.2 Riverine vs. Storm Surge Modeling

Modeling is done under the general assumption that flooding is the result of storm events occurring in the watershed, not the result of tropical storms and storm surge in Galveston Bay or Chocolate Bay. That is, flooding is assumed to be riverine flooding, and not storm surge induced flooding. This focus is assumed because storm surge flooding effects are limited to near coastal areas and are not the cause of the repetitive losses that are seen throughout the CBW.

4.2.3 Sub-Watershed Model Approach

Separate models, to facilitate modeling work and allow for isolation of the impacts of various possible flood control projects, were created for various sub-watersheds as follows: West Fork, North Hayes Creek, South Hayes Creek, Ditch C-12, and Brunner Ditch. The East Fork and the main stem of Chocolate Bayou were developed as a single model. When necessary and appropriate, the water level in the East Fork-Main Stem Chocolate Bayou model was used to define the tailwater level in the sub-watershed models.

4.3 Drainage Areas and Patterns

4.3.1 Drainage Area Definition and Network Structure

With the availability of high quality LiDAR data it was determined that the Chocolate Bayou Watershed sub-drainage areas and drainage network structure should be redefined in order to provide the most accurate hydrologic model. LiDAR provided through the TNRIS coastal program were obtained from Brazoria County and combined with similar quality data collected for Fort Bend County; these data represent watershed conditions during the 2006-2008 timeframe.

The LiDAR data for individual geographic quadrants were combined into one database for the entire watershed. Resulting elevation data were reviewed by visual inspection of plotted contour maps generated by the LiDAR using GIS software. Review of the data indicated that additional processing of the LiDAR data to account for drainage through bridges and culverts was first needed before definition of watersheds was completed.

4.3.1.1 Agree Stream Delineation

The LiDAR data were processed to include "Agree" stream delineation. This was done because a bare-earth LiDAR grid, which is that which is provided by basic processing of LiDAR data, is essentially a continuous surface which has been interpolated over a sub-set of the raw LiDAR points. This sub-set contains only those points which represent the bare-earth and is devoid of any readings from vegetation and structures. This "mowing" of the raw LiDAR, however, cannot identify small hydraulic structures such as culverts. Consequently, the bare earth LiDAR, although a good representation of surface conditions, cannot be used "as is" for hydrologic analysis.

The most important part of preparing the LiDAR for use is to develop what is termed an "Agree Stream." This is a vector representation of the known flow paths within the watershed to be analyzed. Creation of this vector representation is done by digitizing the flow paths by hand using the best available data in concert with visual inspection of the LiDAR generated surface. For the CBW, the major flow paths were defined for the Chocolate Bayou watershed with reference to the bare-earth LiDAR as well as previously defined channel data from the BCMDP and supplementary data from Brazoria County Drainage District No. 5.

4.3.1.2 Drainage Area Definition

The GIS ArcHydro v1.3 tool was used to develop the drainage areas and other topographic-based parameters (discussed below) necessary for describing the hydrology of the CBW. Nominal drainage area size was selected to be approximately 3 sq-mi; this size was selected as an appropriate compromise for providing a reasonable level of detail for hydrologic analysis and limiting the amount of computation necessary to describe flow and runoff conditions across the entire CBW.

A contour map of the CBW with drainage area delineations and primary flow paths determined from the LiDAR data and the ArcHydro analysis is provided in Exhibit 4-1.

4.4 Hydrology

Key features of the hydrologic model building process are as follows.

4.4.1 Storm Event Rainfall Behavior

Because of the size of drainage areas being evaluated and the need to examine rainfall impacts for major rainfall events, rainfall events of 24-hour duration were simulated for evaluating flood control project effectiveness. Rainfall intensities as a function of rainfall event frequency are given by data in the Brazoria County Drainage Criteria Manual [Brazoria County, 2003] (see Exhibit 2-1).

However, during a storm, rainfall is unlikely to be distributed uniformly across a watershed the size of the CBW; consequently, care needs to be taken in applying a hypothetical or design storm based upon such data to model runoff behavior.

Applying a single uniform storm across the entire watershed is the simplest method to implement; however, it is unlikely to reflect what would happen in the real world. The single uniform storm stresses all of the reaches at the same time while, in reality, a storm tends to move across a watershed, stressing river reaches in a sequential or cumulative manner.

Varying the rainfall across the catchment would certainly provide a more realistic description of rainfall impacts; however, it is extremely difficult to determine how possible temporal and spatial rainfall variations should be applied. Each watershed behaves differently so there is no standard method of variation. Some watersheds flood due to short, sharp storms in the upper reaches, while others become inundated due to prolonged storms of a more average intensity. Usually it is a combination of these types of behaviors that give rise to flooding. In the final analysis, there would simply be too many permutations of temporal and spatial patterns to analyze in a planning level study in order to find the combination of frequency, duration and spatial variation that gives the worst case scenario. Consequently, the traditional approach of using a single, uniform storm event as the basis of analysis was used.

Precipitation estimates derived from depth-duration-frequency studies (such as TP-40 [Hershfield, 1961]) are generally point estimates; these point estimates are those values used to describe the depth-duration-frequency behavior of rainfall in various drainage criteria documents, such as the Brazoria County Drainage Criteria Manual [Brazoria County, 2003], which is used to describe rainfall behavior in this Study. Studies [Hershfield, 1961; Eagleson, 1976] have shown that for a specified frequency and duration the average rainfall depth over an area is less than the depth at a single point; as the area covered by rainfall event becomes larger, the average rainfall becomes less than that estimated by point rainfall data. To account for this effect HEC-HMS can apply an “Areal Correction Factor” derived from the U.S. Weather Bureau [Hershfield, 1961]; these correction factors reflect the average rainfall behavior illustrated by the figure. Use of this correction factor was incorporated into the hydrologic modeling using the area of the CBW. Thus, with an area of approximately 155 sq-mi, the point rainfall for a 24-hour storm event is reduced by approximately 6% when applied to a particular modeling scenario.

4.4.2 Infiltration Parameters

Rainfall infiltration was modeled in HEC-HMS using the "Initial and Constant" loss method. This method uses an initial abstraction parameter, which represents the watersheds reflects antecedent conditions, and a constant loss rate, which represents the watersheds ultimate infiltration capacity. These parameters are assumed to be the same as those previously used in the modeling for the BCMDP [Klotz Associates and Baker & Lawson, 2002].

4.4.3 Runoff Hydrographs

Runoff hydrographs are described by the Clark Tc & R hydrograph model [Maidment, 1992]. This model uses two primary parameters: time of concentration (Tc) and Clark's storage coefficient (R). These primary parameters were computed from modified Tc & R equations developed by the Harris County Flood Control District [HCFCD, 1988] and adopted by Brazoria County [Brazoria County, 2003].

<u>Tc & R Equation Parameters</u>

The Tc & R equations use land use, channel improvement and conveyance parameters as well as key physical watershed parameters such as average slope, overland slope and watercourse length.

The land use parameters were estimated from a review of land use depicted by aerial photography and land cover data developed by the United States Geological Survey (USGS). Channel development and conveyance parameters previously used in the BCMDP [Klotz Associates and Baker & Lawson, 2002] were adopted for this Study.

The physical watershed parameters were derived using GIS. The longest flow paths were determined using ArcHydro. These flow paths were used to determine the watercourse length (L) and the length to centroid (Lca) of the drainage area. The elevations of each of the flow paths were extracted from the LiDAR surface using the GIS Spatial Analyst extension. An average slope (S) calculated in Microsoft Excel by manually creating a best-fit line through the middle 75% of the extracted profile. The overland slope (So) for each sub-watershed was determined by finding the mathematical computed maximum slope of the best-fit plane of the LiDAR grid describing the topography of the sub-watershed in question.

4.4.4 Hydrologic Routing to Determine Peak Discharges

Hydrologic routing was used to determine flood wave movement and peak discharge in a channel reach. Existing condition channel geometry was used to determine stage-storage-discharge relations for flow in existing watercourses. When a proposed flood control project envisioned change in channel geometry, new stage-storage-discharge relations were determined using the proposed channel geometry.

4.4.5 Inflows from New Bayou

Ditch C-1 was originally a man-made tributary of Chocolate Bayou with its confluence with Chocolate Bayou approximately midway between Highway 35 and CR 171 (see Exhibits 1-6 and 1-7). The New Bayou is a relief channel for Ditch C-1 and extends from the split, north of Mustang-Chocolate Bayou Road and Stuart Road, to its outfall into Chocolate Bay. Analysis determined that the flow splits relatively evenly with 48% directed to Chocolate Bayou via Ditch C-1 and 52% directed to Chocolate Bay along New Bayou. This was calculated by an area-conveyance correlation based upon assumed uniform flow in the channels and flow line slopes estimated from LiDAR data. This relationship was modeled in HEC-HMS using an "Inflow Function" diversion element.

4.4.6 Water Gains or Losses along Raw Water Canals

For hydrologic modeling purposes, raw water canals at natural ground or elevated levels (the latter within levees) were assumed not to capture or release water to adjacent lands, and thus not affect the estimated runoff using hydrologic models.

4.5 Hydraulic Model Development

This sub section discusses various key features of the hydraulic model building process.

4.5.1 Model Structure and Formation

Hydraulic models were generally developed from new alignments determined using a GIS evaluation of aerial photography and LiDAR to obtain a geo-referenced channel centerline. Cross section locations were selected to be similar to the original base models; more cross sections were then added to ensure that the cross section spacing was in the order of 500 to 1000 ft (Exhibit 4-2 shows the locations of the cross section developed for the various sub-watersheds). Spacing of sections in the vicinity of bridges and culverts followed HEC-RAS documentation guidance.

Where the new models and old models shared common cross section locations, the interior section between top-of-bank lines was taken directly from the old model cross section profiles (generally from the BCMPD [Klotz Associates and Baker & Lawson, 2002]). Ground surface profiles beyond the channel banks were determined from LiDAR data using HEC-GeoRAS to cut sections and then HEC-RAS to merge the sections with the interior section data.

Cross section data had to be generated when the new models had cross sections where the old models did not. To do this, the old models were imported into HEC-RAS and the cross section interpolation function used to generate new sections at similar locations to the new model. Once this was done the interior and exterior cross section profiles were generated in a similar manner to that described above.

In general, bridge and culvert geometry from prior models was used to define the needed bridge and culvert geometry for the models developed in study. Where more detail was needed, or when bridges or culverts were missing from the model, field inspection was used to clarify or confirm bridge geometry features.

4.5.2 Datum Adjustment

Prior model data are based upon a datum different than the datum of this Study. An approximate datum shift was applied to prior model data to adjust channel geometry data to the datum of this Study. This shift was obtained by comparing the top-of-bank elevations as predicted by the LiDAR data of this Study to the top-of-bank elevations of the prior study being used on a section by section basis for the length of the subwatershed reach being modeled. The average shift in elevation over the length of the modeling reach necessary to bring the top-of-bank elevations into close agreement over the length of the watershed reach defined the datum shift.

4.5.3 Lateral Boundaries of Hydraulic Models

LiDAR data were used to extend floodplain elevation data to the full width of the sub-watershed for which a model was being developed. This was done to avoid apparent limitations of earlier modeling studies which terminated sections at distances less than the full width of the subwatershed, and which, therefore, often limited the spreading of floodwaters across the rather flat floodplain areas common to the CBW, with the consequent result that flood depths would tend to be higher than likely actually occurs.

Allowing extension of cross section data to the full width of the sub-watershed sometimes resulted in, because of the changing alignment of the channel and cross sections being oriented perpendicular to the expected flood flow direction in the floodplain, overlapping of cross sections from an adjacent subwatershed. When this occurred, blocking out of overlapping segments of sections was used to prevent overlap of sections and assure that floodplains did not extend across sub-watershed boundaries.

4.5.4 Channel Geometry for the West Fork, East Fork, and Ditch C-12 Upstream of Hwy 6

Edminster, Hinshaw, Russ and Associates (EHRA), as part of LOMR application for the Seven Oaks Subdivision, recently (2008) developed field survey data to describe the upper reaches of the West Fork, the East Fork and Ditch C-12 upstream of Hwy 6.

EHRA supplied this Study with HEC-RAS geometry models for the West Fork of Chocolate Bayou, the East Fork of Chocolate Bayou, and Ditch C-12 above Hwy 6 [EHRA, 2009]. The supplied geometry cross section locations in the EHRA models were used in this Study. Prior to their use, the geometric cross section data provided were reviewed; the locations of the cross sections were reasonable and were retained. If it were judged cross sections were spaced too far apart, additional cross sections between the existing cross section were added. The supplied cross sections were extended in the locations that did not go to the watershed boundaries. The EHRA channel cross section geometry was used since EHRA indicated that these data were based upon some field surveyed data. As necessary, the EHRA data were merged with the LiDAR floodplain data (i.e., data beyond the top of bank locations) of this Study.

Obstructed areas, ineffective areas, and levee areas in the EHRA data were revised and sometimes actually eliminated (levees assumed in the EHRA model were removed because they were considered unrealistic representations of actual conditions) in accord with the professional judgment of the modelers of this Study. EHRA bridge and culvert geometry data were retained. EHRA cross section data were extended to the boundaries of the subwatershed when considered appropriate.

4.5.5 Siphon Geometry under GCWA Raw Water Canal

Five siphons convey West Fork, East Fork and Ditch C-12 flows under the Gulf Coast Water Authority (GCWA) raw water canal. The canal generally parallels SH 6 (see Exhibit 5-19). These siphons are generally considered to constrict the flow of water southward and cause flooding problems along SH 6 in the Manvel area. Due to the limits of previous FEMA flood studies, the effect of these constrictions on the downstream flow had not been considered. Extending the hydraulic models of West Fork, East Fork and Ditch C-12 farther north in this Study allowed the storage behind the GCWA canal to be incorporated into the hydrologic modeling via new storage-discharge relationships. As part of a LOMR application for the Seven Oaks Subdivision, EHRA had surveyed the siphons and provided the geometry to Klotz Associates for inclusion in this study.

4.5.6 Obstructions Due to Canals, Levees and Roads

Levees, raised raw water canals, and roadways across floodplains above natural adjacent natural ground levels act as barriers to flow across a floodplain. When LiDAR or other information indicated the presence of such barriers, the blockage to flow that they cause was recognized in the geometry of hydraulic models by appropriately raised ground level elevations in cross sections defining the model geometry.

Raw water canals at ground level were assumed to not block the flow of runoff waters across the area traversed by a canal.

4.5.7 Channel Roughness and n Values

Initial estimates of channel roughness, as quantified by the Manning n value, were based on prior model data. Revisions to these initial estimates was made by review of aerial photographs to identify different land cover conditions, such as open areas, wooded lands, developed areas, etc.

Manning n values in the overbank areas were developed using GIS and land cover data obtained from USGS National Land Cover Database (NLCD). Adjustments to the land cover data were made with reference to more recent (2008) aerial photographs. The land cover data is in raster format and describes the land cover using NLCD Land Cover Class Definitions. The land cover classes were given a representative Manning n value in order to reclassify the land cover database as a Manning n value database. This database was then used in conjunction with HEC-GeoRAS to develop representative roughness values over an entire reach of a modeled watercourse.

4.5.8 Salt Water Intrusion and Barrier

A salt water barrier to prevent intrusion of Chocolate Bay sea waters up Chocolate Bayou is located approximately 3.2 miles downstream of Hwy 35 (see Exhibit 1-6) and 11.8 miles from Chocolate Bay. Depending upon conditions, salt water may or may not actually intrude upstream to this point. Hydraulic modeling assumes the barrier only modifies the geometry of the channel in the vicinity of the barrier. Fresh water flow is assumed to extend the entire length of the Chocolate Bayou mainstem flood model. This assumption becomes more realistic the greater the discharge in Chocolate Bayou since large flows will push saline waters farther downstream. Consequently, possible salt water intrusion has less and less impact on the hydraulic modeling the larger the flood flow being modeled.

4.6 Flood Modeling

This following discusses special features of the actual flood modeling using the hydrologic and hydraulic models described above.

4.6.1 Steady State Modeling

All HEC-RAS modeling assumed steady state conditions with flows equal to peak values predicted by the hydrologic modeling. Unsteady behavior was incorporated by using the hydrologic model to describe flood hydrographs (see Sections 4.4.3 and 4.4.4 above).

4.6.2 Tailwater Conditions

The Chocolate Bayou subwatershed model used a tailwater equal to those currently used Harris County Flood Control District models for tailwater conditions in Galveston Bay opposite Clear Creek (approximately 30 miles point to point) north of Chocolate Bay).

Tailwater conditions for the East Fork, North Hayes, South Hayes, and Ditch C-12 subwatershed models were based upon either 1) existing condition tailwater levels as given by existing condition models (these levels being used for describing existing conditions); 2) normal depth conditions at the tailwater location, or 3) water levels at the confluence of the tributary in question and Chocolate Bayou. Generally, these three levels were different but similar to one another.

Numerical testing of the impact of such different levels on flood levels using the West Fork and Ditch C-12 as prototypes for testing was done. The numerical testing showed small differences in computed floodplain acreage between different but reasonably similar tailwater levels of magnitude actually existing for various flow conditions. While the various tributary subwatershed reaches have different confluence-based tailwaters (i.e., Chocolate Bayou-based tailwater levels) and normal depth tailwaters (i.e., normal depth conditions at the downstream end of the tributary in question), the differences in floodplain areas behaved in a similar way in both test subwatershed tributaries

A comparison was made of the difference in floodplain area resulted from changing the confluence-based tailwater level versus the normal depth tailwater in the test subwatershed tributaries. The floodplain area was calculated for the confluence-based tailwater and normal depth tailwater. The differences in the confluence tailwater and normal depth tailwater were in the range of 1.5 ft to 2.0 ft. This seems substantial but for the low frequency storms (i.e., 50- and 100-yr floods), the percent difference of floodplain areas is rather small, confluence-based tailwater increased the floodplain area only approximately 1% over that for a normal depth tailwater. For the higher frequency storms (i.e., the 2- and 5-yr events), the percent difference in floodplain area was in the range of 10% to 30%. However, since the primary concern for flood prevention is with the lower frequency storm event and examination of worse case scenario impacts, the confluence-based tailwater level was used for modeling of all five tributaries (East and West Fork, C-12, North and South Hayes). Appendix I provides a comparison of the impacts of the tailwater variation on floodplain area.

4.6.3 Modeling Frequencies

The storm events selected for evaluation in floodplain determinations are the 2-, 5-, 10-, 25-, 50-, and 100-yr storm events, these particular event frequencies being selected because they 1) collectively cover a broad range of frequencies and consequently provide a broad-based insight into the behavior of major floods, 2) are sufficient to generally characterize the impact of the dependence of flood damage on the randomness of large storm events, and 3) are the standard frequencies used in FEMA flood insurance studies. These same frequencies also include (except for the 500-yr flood) frequencies regularly used in FEMA flood studies and the BCMDP [Klotz Associates and Baker & Lawson, 2002].

The 500-yr storm event was not simulated because, as discussed in Section 7, it was estimated for the CBW that the impact of a 500-yr storm upon evaluation of the benefit of a flood control alternative is not significant for the level of benefit that is estimated using 100-yr and smaller event sizes.

Floodways were also not evaluated since they do not affect the level of flood impact or benefit of flood level reductions.

4.6.4 Comparisons of Modeling Results

Exhibit 4-3 compares the 100-yr floodplain for the CBW predicted by the models of this Study to prior FEMA floodplains. Floodplains are roughly similar but the floodplains predicted by the models of this Study are generally more extensive than those predicted by the FEMA models. The following are potential reasons for the differences:

- The models of this Study actually extend farther upstream in some locations than the FEMA models
- Different elevations define the topography of FEMA models and the models of this Study
- There is more accurate representation of cross sections and floodplain elevations because of the availability of LiDAR data for this Study
- The use of more extensive floodplain widths defined by the width of a sub-watershed in this Study as compared to the restricted, somewhat arbitrary limitations to the width of cross sections used in the FEMA models
- Inaccurate representation or unrepresentative flood blockages in the FEMA models
- Different flood flow magnitudes for floods of similar frequency; the FEMA models rely on hydrologic correlations for flow predictions while actual hydrologic models are used in this Study. Also diverted flows from New Bayou were not included in the FEMA models but are included in the models of this Study.
- Differences in hydraulic roughness; this Study adjusted roughness values to reflect variations in land cover in floodplain areas
- Different rainfall magnitudes because of the use of different areal adjustment factors
- Different tailwaters; all the FEMA models assume a normal depth tailwater condition

4.7 Modeling of Proposed Flood Control Projects

To model flooding conditions for potential flood control projects, both hydrologic and hydraulic modifications to the existing condition models were, in general, necessary.

Hydrologic modifications were necessary if the stage-storage-discharge behavior of a watercourse were altered by a potential project. When the stage-storage-discharge behavior changed, the hydraulic model with the effects of the potential project was executed to re-define the stage-storage-discharge relation; the revised relation would be inserted into the appropriate hydrologic model element and the revised hydrologic model would be run to determine peak discharges for the necessary flood frequencies.

Specific modifications to the hydraulic or hydrologic models or methods used to simulate potential flood control projects varied with the type of project under consideration, as follows:

4.7.1 Conveyance Improvements

Potential flood control projects using conveyance improvements involve widening and/or deepening a channel to convey, without bank overflow, a particular frequency of flood flow for which the channel improvement is to be designed. That is, the conveyance improvement level is defined by a flood frequency which the channel can carry without bank overflow. In general, the magnitude of the discharge for the specified frequency will decrease as one moves upstream.

These types of projects assume the existing channel is modified to form a trapezoidal channel of specified side slopes. Trial and error, which is assisted using channel design tools in HEC-RAS, is used to increase the bottom width of the trapezoidal channel and deepen the channel sufficiently to convey the specified flood flow without bank overflow along the entire length of the reach under study. Backwater computations are made by the HEC-RAS model to determine water levels in the channel. Each sub-reach between channel cross section is modified progressively as the HEC-RAS backwater computations are made as one moves upstream until the entire reach is covered. The computation is made so that, by the end of the trial and error process, the channel is not larger than absolutely necessary to carry the design discharge.

HEC-RAS computes the amount of excavation and fill that is necessary to create the modified channel. Increasing channel width will not only require excavation but additional right-of-way.

In the development of conveyance improvements for potential projects in this Study, the improvement, in so far as computational issues are concerned, is made for the entire channel reach under consideration; while the necessary widening may vary along the channel reach under consideration, the improvements are determined for the entire length of channel.

4.7.2 Mitigation of Conveyance Improvements

Improvements which increase the capacity of a channel will in general require mitigation somewhere along and generally near the end of the channel to prevent increased discharges being sent downstream with consequent adverse impacts to flooding conditions downstream of the improved channel reach. Mitigation is considered to be provided by one of two means: off-line detention ponds or in-line mitigation.

4.7.2.1 Off-Line Detention Ponds

Off-line detention envisions a detention pond or collection of several detention ponds to which part of the flow in the channel can be diverted in sufficient amounts such that flow conveyed to points downstream of the improved channel do not exceed the flow that existed prior to the improvements. As a result of the detention, no adverse flooding impacts are created downstream by the upstream channel improvements. In the present Study, only the necessary amount of detention is estimated. The precise locations of the detention pond or the several detention ponds to be used to provide the necessary storage is not specified, except that it would be expected to be in the general vicinity of the more downstream end of the improved channel reach. Identification of specific sites for off-line detention is beyond the scope of this Study and would require detailed engineering to select and develop a potential detention site or sites.

However, since the development of a detention pond would, in general, require excavation and incur additional cost beyond that required for the channel improvement, the storage volume of the detention pond (or collection of ponds) is estimated as a volume equal to the amount of excavation required for the conveyance improvement. In concept the volume of excavation in the channel is removed and replaced with a volume of waters drawn from the flood flow. Approximate generic calculations, based upon uniform flow assumptions, can be made to demonstrate that this excavation volume is approximately that required to achieve the necessary storage to return the increased flow in the improved channel to its pre-improvement levels.

Use of a mitigation pond (or ponds) will also require acquisition of land to construct the pond. For planning purposes, a typical pond is assumed to estimate land requirements. This typical pond is assumed to have vertical side walls and to be 5-ft deep; the area of this pond times the five foot depth must yield the required mitigation storage. Actual ponds will likely be somewhat deeper but have sloped side walls with side slopes on the order of 4 to 1 horizontal to vertical. Thus, the assumption of a pond with a 5-ft depth but with vertical side walls is considered to provide a reasonable estimate of the actual pond area required.

4.7.2.2 In-line Detention

Mitigation using in-line detention is achieved by widening the improved channel beyond that required for the improved capacity. The required extra widening is approximated as the same storage volume that would be required if off-line detention storage were used for mitigation.

The required channel width to provide the necessary in-line detention volume is determined by calculating the extra cross sectional channel area (assuming the same channel slide slope and depth for the improved channel) multiplied by the channel length which yields the necessary storage volume. The increase width will not only require extra channel excavation but also increased right-of-way.

4.7.3 Diversion Ponds

Diversion ponds are like mitigation detention ponds except they are intended to reduce the flow in a channel at points generally downstream of the point of flow diversion to the pond and are not intended to provide mitigation of upstream conveyance improvements. In the present study, as with mitigation ponds, *the precise location of a diversion pond is not prescribed; it is merely located in the general proximity of its eventual location, with the precise location to be determined by detailed engineering studies.* Furthermore, as with detention ponds, the diversion pond does not have to be constructed as one pond, but can be a series of smaller ponds which collectively have the desired total storage of the single diversion pond which provides the necessary storage volume. This flexibility to provide the desired diversion pond storage using multiple ponds is an important one in the present Study since diversion pond volume requirements are found to be generally quite large, and the need to acquire sufficient land for their construction may be a significant challenge.

In contrast to a mitigation pond, diversion ponds are not sized on the basis of mitigation of increased flow. Their size is determined by the degree of flood protection sought. This level of flood protection is described in terms of two parameters for the diversion pond: 1) the "level of service" (also referred to as the "target flow," "channel design flow," or the "bypass flow"), and 2) the pond design level. Both parameters are quantified in terms of flood frequency. The diversion pond is designed to provide a particular downstream level of service (or bypassing) at a particular design frequency and a particular level of pond storage.

The level of service defines the size of the flow (expressed in terms of flood frequency) at which diversion of flood flow to the pond begins. Flow less than the level of service magnitude are not diverted, but bypassed, i.e., continue to flow downstream unabated. The pond design frequency specifies the largest flood flow, as described in terms of flood frequency, for which the pond can store the flood flow.

Thus, for example, a diversion pond with a 10-year pond design and a 5-year level of service would function so that any flow passing the pond site that is less than a 5-year frequency flow would not be diverted to the pond but any flood flow in excess of that frequency would be diverted to the pond. A flow equal to a 10-year or less flood flow magnitude would be contained in the in the pond. Floods in excess of the 10-year flow magnitude would fill the pond and cause some overflow of the pond which would be returned to the watercourse. Thus, flooding for flows less than a 5year flow would produce the same downstream flooding as currently occurs but floods in the 5- to 10-year range would have less flooding than currently occurs. Thus, the diversion pond seeks to reduce flooding for a reduced range of frequencies so that the costs of construction of a very large pond to, say, capture a 100-year flood can be avoided.

To determine the size of the pond to provide the necessary storage for a particular design frequency, the design frequency storm event is modeled with the HEC-HMS model assuming a pond of infinite size is available to capture the design storm. Execution of the model results in a maximum accumulation of volume in the pond over the course of the storm event. This maximum volume is the diversion pond design volume for the storm frequency modeled. Different model runs for different storm events can be used to determine the necessary design volume for different flood frequencies. For computational and costing purpose, the pond is assumed, as with mitigation ponds, to have vertical side walls and an effective depth of 5 ft. Consequent pond volume and surface area are used to determine the construction costs for the pond. For computation purposes, the pond is assumed to be of square shape.

Once the necessary pond size for the pond design frequency of interest is determined, the pond of that size is modeled for various potential floods (i.e., 2-, 5-, 10-, 25-, 50-, and 100-yr floods). To account for flood flows entering the pond after the pond is filled by diversions during the early portion of the rising hydrograph for the storm event in question, the pond is assumed to have a broad crested weir along the entire length of one side of the pond. Once flood waters fill the pond, additional waters flow over the weir and are returned to the channel from which they were diverted at approximately the same point as the initial diversion.

4.7.4 Structural Improvements

Structural improvements are changes (or possibly new) hydraulic conveyance structures such as culverts and siphons. The impacts of such structural improvements are modeled by increasing the size the culvert or siphon until it can convey the design flow for the channel in which the structure is located. The proposed structure is incorporated into the HEC-RAS model using the options available in HEC-RAS to describe culverts; siphons are modeled like fully submerged culverts. The size and length of the culvert modeled is the basis for determining the cost of the structure.

4.7.5 Diversion Channels

Diversion channels are simply channels breaking away from a primary channel, thereby reducing the flow in the primary channel and adverse flooding impacts in the downstream reaches of the primary channel. For planning purposes, the size of the diversion channel is determined by one of two methods.

In the first method a flow of know amount (based upon flood frequency) is computed in the primary channel and presumed diverted to the diversion channel. The diversion channel is sized assuming a uniform flow, a trapezoidal channel shape with representative side slopes and bottom slope. The bottom slope is determined by the depth of the primary channel at the beginning of the diversion and the depth of the receiving channel or water body to which the diversion channel reconnects at its terminal point. Local runoff is presumed to be able to flow to the diversion channel along the length of the diversion channel.

In the second method, the upstream and downstream flowline elevations are determined for the diversion channel. The upstream elevation determined by the primary channel flowline elevation at the point of diversion. The downstream elevation is determined at the point of confluence or at the diversion channel outfall. The length of the proposed diversion thus determines the available channel slope; a minimum slope of approximately 0.05% is desirable for a viable channel. A maximum reasonable top width of channel is estimated in light of land use conditions and general considerations of constructability. Based upon the maximum slope and the maximum channel width, a channel is configured. The capacity of this diversion channel is then determined assuming a uniform flow condition.

Depending upon where the diversion channel reconnects, if it does at all, to the primary channel and the magnitude of the discharge it produces in the recombined channel, mitigation of the flow in the diversion channel may or may not be required. Mitigation volume is estimated in a manner similar to channel conveyance improvements for those segments of the diversion channel where flow magnitudes will be expected to increase the flow being delivered to downstream points and/or returned to the channel from which the diversion was originally made. In the case of Brunner Ditch diversions, a comparison of approximate Brunner Ditch channel lengths to Chocolate Bayou channel lengths was made to estimate the additional volume of channel length that the Brunner Ditch diversion would create; the volume of additional length defined the necessary mitigation volume. Either off-line detention ponds or in-line detention is considered for mitigation.

SECTION 5

FLOOD CONTROL OPTIONS

5.1 Development of Options

The development of flood control options was a three-step process:

- Step 1: Identification of conceptual options. This was a high level view of potential ways to remedy flooding problems in the CBW.
- Step 2: Screening and refining of conceptual options. Professionally based review supported by limited computations were used to screen out those conceptual options which for various reasons were not considered feasible or realistic and further define the features of realistic options.
- Step 3: Evaluation of screened options: The screened options were given focused evaluation and technical assessment to assess their feasibility, effectiveness and utility for significant lessen of flood problems in the CBW.

The options identified as a result of this process are indeed options, not alternatives for which one alternative rules out other alternatives. The options developed are, in general, just that: options. One option does not inherently rule out the use of another option.

5.2 Identification of Conceptual Options

Potential types of flood control and flood mitigation options were conceptually identified in Section 1. Identification of practical options from these types of options for possible implementation was accomplished by the following:

- Review of prior reports and proposals on flood control projects in the CBW (see discussion in Section 2.3).
- Suggestions by Study sponsors and other interested parties, including members of the Chocolate Bayou Steering Committee

- Comments by the public in or as a consequence of public meetings
- Review of floodplain modeling results for current conditions and professionally based judgment as to ways to address reduce areas of significant flooding.
- General brainstorming during the course of the Study by the Study team

Section 1 identified broad categories of potential flood control options, as follows:

- *Ponds or Reservoirs*, which could be used to capture and temporarily store excess flood waters or mitigate increased discharge from upstream channel improvements. (The distinction between pond or reservoir is a distinction of semantics, not function).
- *Channel Improvements*: Modification of existing channels to increase flow capacities in order to keep more flood waters within channel banks and/or convey flood waters more rapidly downstream and away from the areas where out-of-bank flooding occurs.
- *In-line Channel Detention*: Over-sizing of channels to increase the ability to slow the rate of the rate of drainage in the channel and thus increase the amount of water in the channel and delay the movement of that water to downstream points.
- *New Channels and Diversions:* Construction of new channels or channel extensions, to which flood waters can be redirected from a watercourse with limited capacity and to a location better able to convey or store runoff waters.
- *Pumped Withdrawals*: Pumping of flood waters from an under capacity watercourse to another location where it can be stored or conveyed without flooding.
- *Retrofit, upgrade, or replacement of bridges or major culverts:* Construction of new bridges and culverts or modifications of bridges and culverts at roadway, railway or canal crossings may be considered to increase the capacity of the waterway and reduce flood levels at points upstream of the crossing.
- *Construction of levees or dikes*: Levees or dikes can be used to keep flood waters from spreading to areas behind the levee or dike.

- *Use of Flow Constrictions.* Reduction (but not full elimination) of flood flows to downstream can be accomplished by using restricting flow devices, such as culverts with relatively small capacity, which cause waters to backup upstream of the device if such backup would not produce adverse impacts.

Techniques to address flooding problems not directly arising from overflowing watercourses are addressed separately below as a distinctly different type of flooding problem.

5.3 Screening of Potential Options

The screening process ruled out some conceptual options as well as suggesting potential refinements to conceptual options.

5.3.1 Preliminary Screening Observations

Features identified as particularly significant in the review of floodplain modeling results for current conditions and likely important to development of projects for reduction of flooding are as follows:

- Flooding is particularly extensive (i.e., floodplains are very wide) in the northern half of the CBW, particular in the area of the confluences of the East and West Forks of the Chocolate Bayou, North and South Hayes Bayou, and Ditch C-12 with Chocolate Bayou. Review of the 100-year existing condition hydrographs at the confluence of these watercourses with the Chocolate Bayou indicates that the West Fork of Chocolate Bayou and Ditch C-12 peak at very similar times during a watershed wide storm event. Some significant non-peak levels of the North and South Hayes Bayous occur also occur at this same time, but Ditch C-12 and the West Fork are particular significant in adverse peak coincidence. Peak-on-peak and peak-on-near-peak flood flows from upstream tributaries occur at the confluence of these tributaries and Chocolate Bayou, thus contributing to large total peak flows in the vicinity of the confluence. These large peak flows cause out-of-bank flooding. Large scale detention along some tributaries may be an important solution for not only reducing peak flows but also affecting the timing of peak flows at Chocolate Bayou confluences. On the other hand, increasing the speed of runoff to affect coincident peaking by improving upstream conveyance of channels (and thus speed of flow in the channels) might also be a component of a flood control option.

- The bank-full capacity of Chocolate Bayou near the confluences with the East and West Forks all the way down to the vicinity of the Chocolate Bayou to the vicinity of FM 1462 is quite limited. Using the current condition CBW model for Chocolate Bayou to make a series of simulations with different discharges, the existing bank-full capacity of Chocolate Bayou in this generally reach of Chocolate Bayou is often less than a 10-yr frequency flood and sometimes less than a 2-yr frequency flood (see Exhibit 5-1). This, combined with coinciding peak flows discussed in the preceding paragraph, suggests that if the extensive flooding found in the upper portions of Chocolate Bayou is to be effectively addressed, the extensive flooding conditions in the confluence areas of Chocolate Bayou with its major upstream tributaries will need to be addressed.
- The extent of flooding at the 25- and 100-year flood frequencies is generally not radically different; that is, once out-of-bank conditions develop, flooding is rather extensive for all flood frequencies which cause out-of-bank flooding. This suggests that flood control projects may have to be focused on reducing the impacts of smaller floods (of magnitude less than the 25-yr flood) and accepting flood damages for larger floods.
- In many areas of the CBW, repetitive losses are reported for areas outside of the 100-yr floodplain. The flooding in these areas may be the result of localized ponding. Thus, flood control options which deal with lessening the extent of floodplains along Chocolate Bayou may not be effective in impacting structural flooding for areas beyond the current floodplain, except through tailwater reductions in drainages

leading to the major watercourses. Option remedies for reducing localized ponding may be necessary.

Other considerations (developed from general information developed during this Study or as part of past Klotz Associates experience in flood control projects and proposals in and near the Study Area) that could adversely affect the viability of flood control remedies for the CBW are the following:

- Ditch C-12 appears, based upon its width, to have large capacity downstream of Hwy 6 and limited capacity upstream of Hwy 6. Upstream conveyance improvements might significantly affect the timing of peak flows down the ditch.
- Straightened of Chocolate Bayou (a very sinuous bayou) using high flow bypasses has been previously proposed [Klotz Associates, 2008a] but environmental impacts arising from channel straightened are concluded to be significant and likely meet with significant regulatory (and possible community) resistance.
- A variety of detention pond sites have been previously proposed [Klotz Associates, 2003] in the Manvel and consideration could be given to possible use of these previously selected sites.
- Many flooding problems in city areas not subject to frequent inundation from Chocolate Bayou or its major tributaries may be rooted in drainage criteria which are insufficient in requirement or enforcement for achieving effective local drainage.
- In the case of bypassing using new or widened ditches, reasonable availability of open land for a bypass route (with maintenance berm) will be required.
- In the case of ponds, reasonable availability of open land for a pond site of estimated size as needed for effective detention will be required.
- In the case of channel widening or other channel reconfiguration, availability of land adjacent to the existing channel for widening or other channel reconfiguration will be required.

- Limitations imposed by known significant wetland areas, obvious adverse impacts to existing natural habitats, or modifications affecting natural watercourse conditions below the ordinary high water mark must be recognized.
- The possibility of significant adverse impact upon future residential and/or commercial development should be recognized.
- Impediments presented by existing known pipelines and utilities may be present, but such impediments are not evaluated in the present Study.
- Possible significant community resistance to some options because of potential impacts on individual citizens in the watershed.

5.3.2 Screening Based upon Option Features

Options with the following features were eliminated from detailed evaluation:

- Options requiring pumping, because of 1) the extremely large and unrealistic amount of pumping capacity that would be needed to make them effective; and 2) the substantial maintenance that would be required for reliable operation of pumping systems for flood control
- Options requiring significant lengths of levees because of 1) environmental impacts of levee construction, such as loss of wetlands, and 2) the requirements of long term maintenance, inspection, and repair of levee structures and consequent safety concerns
- Major drainage structures under major highways and railways because of the expensive difficulties of constructing not only the drainage structure but the rebuilding of the highway or railway.
- Options requiring straightening of natural channels because of adverse impacts on wetlands and natural habitats
- Use of cutoffs (across channel meanders) for high flows cause of impacts to natural habitats

- Options utilizing flow constrictions because of 1) the inherent potential consequences on upstream flooding, particularly if flooding is already significant in upstream areas, 2) the need to acquire dedicated land for flooding caused by the restriction, and 3) the inherent contradictory approach of controlling flooding by increasing flooding
- Options which might require extreme widening of channels (beyond several hundred feet)
- Options which would be clearly maintenance intensive for continue effective function
- Options which not be expected to be function for long periods of time (greater than 50 years) with ordinary maintenance before retrofit might be necessary.

Options were not screened from possible consideration due to potential construction cost; issues of cost and associated benefits are discussed in Sections 6 and 7.

5.4 Options Selected for Detailed Evaluation and Possible Implementation

Options selected for detailed evaluation and possible recommendation for implementation, depending upon their costs and benefits (discussed in Sections 6 and 7), fall into several broad categories: Channel conveyance improvements, diversion ponds, diversion channels, realignment and extension of existing channels, hydraulic structure improvements, and combinations of these options.

In developing and evaluating these options, each option (as described by its various features) is considered as a separate option. That is, its effect on flooding and the resulting reduction in floodplain extent and depth assumes, unless otherwise specifically noted, that only the option in question is implemented.

This approach is taken because construction of all options more or less simultaneously is unrealistic (because of, if nothing else, cost) and that the implementation of various options will, in fact, tend to occur more nearly like individual project implementation. Thus the beneficial impact of another option cannot be assumed in assessing the benefit of the option in question.

Because of the voluminous number of options and the number of flood event scenarios necessary to evaluate various options (more than 500), the floodplains resulting from various and options and storm event conditions were not all plotted for visual review. The geographic and depth information describing a flood event for a particular flood control option as computed by the HEC-RAS modeling was retained in GIS format (as a raster image) and recovered as needed for visual review on a computer screen and computation of flooding characteristics. Only a limited number of floodplain scenarios were actually printed out on hard copy; these illustrative printouts are identified in the following discussion and presented in the exhibits of this Report.

In the following presentation of options, the order of presentation does not reflect any preference for implementation of an option.

5.4.1 Conveyance Improvement Options

Conveyance improvements are obtained by widening and some deepening of a watercourse (whether a natural channel or man-made canal) between a defined upstream and downstream point along the watercourse. It is assumed that the improvement is made in amounts as necessary to the goal of the improvement; the extent of the widening and deepening will vary along the length of the improved watercourse. The widening and deepening will result in removal of all vegetation except grass within the widened channel (between banks). As a consequence, not only will the channel be bigger, but also smoother, with a smaller Manning's n roughness. Vegetation removal in the typical 30-ft wide maintenance berm on each side of the channel is accounted for in selection of the hydraulic roughness. The amount of excavation necessary for the widening and depending is determined from channel cross sections (using automated calculations available in the HEC-RAS software used for hydraulic calculations).

Increase conveyance will result in increases in peak discharge to downstream points, with potential adverse impact. Use of mitigation storage near the downstream end of the channel improvement is used to combat these potential adverse impacts. The amount of mitigation storage required is estimated as being approximately equal to the excavation required from the conveyance improvement.

Different amounts of conveyance improvement for a channel can be considered. The level of conveyance improve is described in terms of the flood magnitude, expressed in terms of flood frequency, that the channel can carry without overflow of its banks. Thus a 2-yr channel improvement design would widen and deepen the channel along its improvement length sufficiently such that at no point along the improved channel would the flood flow from a 2-yr storm event exceed the capacity of the channel (i.e., flow over the channel banks). A 10-yr channel improvement design would widen and deepen the channel along its improvement length such that a 10-yr flood event would not cause flood waters to flow over the channel banks. Because a 10-yr flood flow is larger than a 2-yr flood flow, the channel improvement for a 10-yr flood would have, in general, have more widening and deepening than a 2-yr improvement design.

Screening indicated that for existing channels, improvements to convey a flood flow larger than a 10-yr flood flow would result in a quite wide channel (for those locations where improvements were being considered) when these improvements were considered as individual projects of and by themselves. Thus channel conveyance improvement options are considered only for a 2-, 5-, and 10-yr flood flows, as follows:

- 2-, 5- or 10-year South Hayes Conveyance Improvement Options
- 2-, 5- or 10-year North Hayes Conveyance Improvement Options
- 2-, 5- or 10-year West Fork Conveyance Improvement Options
- 2-, 5- or 10-year Ditch C-12 Conveyance Improvement Options
- 2-, 5- or 10-year Chocolate Bayou Conveyance Improvement Options

For each watercourse, only one level of improvement would actually be implemented; the level selected for implementation would depend upon costs and benefits (but staging issues, discussed in Section 9, may suggest some sequential project development).

Exhibit 5-3 shown where the channel improvements for each of the above watercourse are considered; locations for mitigation ponds for these options would be in the general vicinity of the lower end of the improvement reach or distributed along the improvement reach; detailed engineering would be required to identify the most appropriate locations, although the opportunities for pond locations in view of undeveloped land parcel sizes and locations are, based upon these two parameters only, rather numerous, as illustrated by Exhibits 5-3, 5-4, and 5-5.

Table 5-1 summarizes the characteristics of the conveyance options. While a channel can be improved to convey a particular level of storm event, the actual storm event which occurs may be different than the design storm event. If the actual storm event is less than the design storm event, then the flood flow will be contained in the channel; if larger, than some flooding beyond the channel banks will occur. Exhibits 5-6 to 5-9 illustrate the floodplains for selected improvement options and flood events; these particular exhibits are intended only for illustration, not as a comprehensive depiction of all floodplain conditions.

Exhibits 5-6 and 5-7 compare floodplain conditions when the West Fork is upgraded to a 2-yr level of conveyance capacity and the 2-yr and the 100-yr storm events occur. For the 2-yr storm event (Exhibit 5-6), virtually all of the flood flow is contained in the channel by the improvement as compared to the 2-yr storm condition without the improvement for which significant flooding occurs. Exhibit 5-7 shows a very expansive existing 100-yr floodplain and a much reduced (but not totally reduced) 100-yr floodplain after the conveyance improvement. Exhibits 5-8 and 5-9 make a similar comparison for the North and South Hayes Creeks. Appendix 10 provides additional examples of floodplain conditions for various waterways in the CBW for various levels of conveyance improvement.

Two mitigation options are evaluated for each conveyance improvement option: mitigation with detention ponds, and mitigation using in-line detention. The conveyance options with these two alternative mitigation alternatives are summarized in Table 5-2. Thus, for example, the table shows that for Ditch C-12, channel widening to convey a 10-yr storm event using an off-line detention pond would require a channel with an estimated total average top width 77-ft (in comparison to an existing average top width of 49-ft) and a detention pond of area of 31 acres and a volume equal to 5 x 31 = 155 ac-ft. On the other hand, if in-line detention were used, the required average top width would be 126-ft.

5.4.2 Diversion Ponds

Diversion ponds are small to large sized ponds (some of the larger sizes perhaps being more appropriately characterized as a lake) which are placed along side or near a watercourse so that flood waters from the watercourse will, during the course of a storm event, flow into the pond. The computed diversion pond volume may be provided by a series of ponds which collectively have the total computed volume.

The operational features of a diversion pond have been discussed in Section 4.6.3. Detailed design is used to develop the geometry of the inlet and outlet structures to capture the proper levels of flow. The diversion pond allows small flood flows to occur unabated and exert only limited control on very large floods; the primary benefits from flood reduction occur for intermediate size floods. Thus, diversion pond options considered are the following:

- 2-, 5- or 10-year LOS with either 5-,10-, 25-, 50-, or 100-yr pond size for flood capture and detention along South Hayes
- 2-, 5- or 10-year LOS with either 5-,10-, 25-, 50-, or 100-yr pond size for flood capture and detention along North Hayes
- 2-, 5- or 10-year LOS with either 5-,10-, 25-, 50-, or 100-yr pond size for flood capture and detention along the West Fork

- 2-, 5- or 10-year LOS with either 5-,10-, 25-, 50-, or 100-yr pond size for flood capture and detention along Chocolate Bayou and the East Fork
- 2-, 5- or 10-year LOS with either 5-,10-, 25-, 50-, or 100-yr pond size for flood capture and detention along Ditch C-12

Exhibit 5-10 illustrates approximate pond locations used for determining the total volumes for pond storage for diversion pond projects in the various sub-watersheds; Table 5-3 summarizes pond volumes assuming the number of ponds developed is the number depicted in Exhibit 5-10. The ponds shown in Exhibit 5-10 correspond to a 2-yr channel target flow and a 100-yr pond design frequency. The locations of the diversion pond sites illustrated in Exhibit 5-6 are only for the purpose of showing the general size of total detention area needed for the selected design. Actual pond locations would require detailed engineering to locate. In developing the pond requirements, the following assumptions (similar to sizing ponds for mitigation storage) are made:

- The pond is square in its configuration
- The pond volume available for storage is computed assuming a 5-ft effective storage depth and vertical side walls to the pond.

Generally the pond requirements listed in Table 5-3 are large, with, as to be expected, pond size becoming larger the smaller the level of service. For example, diversion ponds along the combined Chocolate Bayou and the East Fork with a 5-yr level of service and a 50-yr pond size require a total pond area of 3877 ac (about 6 sq-mi) and pond volume of 5 x 3877 = 19385 ac-ft. However, it is to be remembered that the volumes listed are gross volumes; a series of ponds with cumulative volume could be, and most probably would be, used in place of a single diversion pond.

Exhibits 5-11 through 5-14 provide examples of particular designs of diversion pond projects in comparison to potential areas available for pond development. Again, pond numbers and locations are conceptual; detailed engineering would select numbers and locations of diversion ponds. Appendix 10 provides additional examples of floodplain conditions for various waterways in the CBW for various levels of diversion pond development.

Exhibits 5-11 and 5-12 shown potential ponds in the upper and lower portions of the Chocolate Bayou watershed, respectively, assuming the ponds are sized to bypass a 2-yr flood flow but capture and store flood waters up to a 25-year flood. Note that pond size requirements generally increase as one moves father down the CBW because flow become larger. Exhibits 5-13 and 5-14 show similar information for diversion ponds in the East Fork and Ditch C-12 sub-watersheds for bypass of a 2-yr flood flow when the ponds are sized to capture up to a 5-yr flood flow (Exhibit 5-13) or a 25-year flood flow (Exhibit 5-14). Note that 25-yr pond design requires larger pond volumes.

5.4.3 Potential Pond Sites

To illustrate the flexibility in developing potential pond sites, actual potential pond sites for possible diversion ponds are shown in Exhibits 5-3 to 5-5; for comparison, the required pond sizes are also shown for some pond designs.

Available pond site areas tend to be smaller in the more northern portions of the CBW, but as one moves down the watershed, agricultural and open undeveloped land areas increase, and opportunities for large pond sites increase in number. The potential pond sites identified in Exhibits 5-3 to 5-6 in the East and West Forks tend to be smaller; some of these sites are based upon previous studies [Klotz Associates, 2003]. More generally, the sites shown in the East and West Fork area were identified on basis of apparent effectiveness, availability of undeveloped (generally non-agricultural land); and close proximity to a watercourse of sufficient size to enable capture of significant amounts of runoff. Specifically, the following criteria were used to identify potential sites upstream of FM 1462 (Exhibit 5-4) in addition to those sites identified in earlier studies:

- Detention sites must be located on undeveloped or agricultural lands.

- Potential sites must be (based upon available data) a lot or parcel of land under the ownership of one party.
- No buildings are located on the potential site.
- Local detention is considered at locations only north of Hwy 35. Because of the availability of open lands, potential impoundments south of Hwy 35 need not be as restricted in size as they need to possible be in areas north of Hwy 35. Local detention sites will generally be relatively small (when compared to the sites discussed below).
- Local detention sites are to be located only on significant tributaries to Chocolate Bayou (north of Hwy 35) or on Chocolate Bayou itself in Chocolate Bayou reaches north of FM 1462.
- Local detention sites must be within 30 ft of Chocolate Bayou or a tributary to Chocolate Bayou. The 30-ft buffer distance is selected since maintenance berms along maintained watercourse are commonly 15 to 30 ft.
- The local detention site must have a minimum size of 7 ac. Previously identified sites had a minimum size of 10 ac [Klotz Associates, 2003]; a 7-ac criterion is similar to the 10-ac criteria but allows for some uncertainty in an effective minimum size.
- Sites of 10-ac or less immediately adjacent to FM 1462 or Hwy 35 are excluded as possible sites because of anticipated urban growth patterns of the City of Alvin.

Potential sites downstream of Hwy 35 (Exhibit 5-5) tend to become larger. Possible sites generally downstream of Hwy 35 were selected on the basis of the following criteria:

- The detention site must be located on undeveloped and/or agricultural lands.
- No buildings can be located on the potential site.
- A reservoir site cannot be located all or in part within the limits of a city.
- The parcels or lots in the collection of parcels and lots forming the detention site must be contiguous.

- The smallest parcel or lot in the collection of the parcels and lots forming the site can be no smaller than 7 ac.
- No detention site can be formed by parcels or lots such that any one parcel or lot adjacent to FM 1462 or Hwy 35 is less than 10 ac.
- No detention site can be formed by parcels or lots such that any one parcel or lot is farther than 1000-ft from a defined watercourse which is judged to be of sufficient size to significant impact flooding downstream of the reservoir site.
- Because of tidal influences and lack of population centers south of Snug Harbor (just upstream of Hwy 2004 on Chocolate Bayou) potential detention sites south of the confluence of Pleasant Bayou with Chocolate Bayou are excluded.

5.4.4 Combined Conveyance Improvement and Diversion Pond Options

In light of the effectiveness of conveyance options (when examined in light of cost and benefits discussed in Section 8 below), a group of options was created by combining conveyance improvements with diversion ponds. Each option was formed by taking a mitigation option with a particular design level and combining it with a diversion pond with a level of service equal to the design level of the diversion pond. Thus a conveyance improvement option of, say, a 5-yr design level was formed by combining the 5-yr conveyance improvement with a diversion pond with a 5-yr level of service equal and possible pond design levels of 10-yr, 25-yr, 50-yr, or 100-yr (i.e., pond design levels in excess of the level of service. Thus the following combinations were considered:

- 2-, 5- or 10-year conveyance improvement with a 2-,5-, or 10-yr level of service, respectively, and either 5-,10-, 25-, 50-, or 100-yr pond size for flood capture and detention along South Hayes Creek
- 2-, 5- or 10-year conveyance improvement with a 2-,5-, or 10-yr level of service, respectively, and either 5-,10-, 25-, 50-, or 100-yr pond size for flood capture and detention along North Hayes Creek

- 2-, 5- or 10-year conveyance improvement with a 2-,5-, or 10-yr level of service, respectively, and either 5-,10-, 25-, 50-, or 100-yr pond size for flood capture and detention along West Fork of Chocolate Bayou
- 2-, 5- or 10-year conveyance improvement with a 2-,5-, or 10-yr level of service, respectively, and either 5-,10-, 25-, 50-, or 100-yr pond size for flood capture and detention along Chocolate Bayou
- 2-, 5- or 10-year conveyance improvement with a 2-,5-, or 10-yr level of service, respectively, and either 5-,10-, 25-, 50-, or 100-yr pond size for flood capture and detention along Ditch C-12

The storage for mitigation of conveyance improvements is assumed to be included in the diversion pond volume. Because mitigation volume is included in the detention pond, in-line detention is not considered for these options.

These options are summarized in Table 5-4. Thus, for example, the option for the North Hayes creek with 10-yr conveyance improvements, 10-yr level of service, and a 25-yr pond design widens North Hayes Creek to an average top width of 138-ft and requires approximately 116 ac-ft for diversion ponds storage.

5.4.5 Brunner Ditch Options

Prior studies [Klotz Associates, 2008; 2009] have examined in concept the possibilities of widening and extending the length of Brunner Ditch. Brunner Ditch current lies on the west side of the CBW, connecting South Hayes Creek with Chocolate Bayou in the vicinity of Ditch C-1 (see Exhibit 1-5). Brunner Ditch also currently extends northward from its junction with South Hayes Creek to North Hayes Creek, but the Brunner Ditch channel between North Hayes and South Hayes is extremely limited in size, and not much more than a roadside ditch along much of this distance (see photographs in Appendix B).

Various combinations of ditch extension were examined in these prior studies [Klotz Associates 2003, 2008a, 2009]; these studies concluded the most effective extension likely to be an extension from the upstream end of Brunner Ditch across South and North Hayes Creeks, the West Fork, and to the East Fork. This Study, in light of the findings of these prior Brunner Ditch studies, identified three Brunner Ditch options; locations are shown in Exhibits 5-14, 5-15, and 5-16. (Exhibits 5-120, 5-121, and 5-122 in Appendix J show the effect on the 100-yr flood of the options.).

Each of the 6 Brunner Ditch options considered here have the lower end of the Brunner connecting to Chocolate Bayou at the existing point of connection in the vicinity of Ditch C-1 (see Exhibits 1-5 and 1-6). Mitigation requirements for these options would be located in the general vicinity of the more downstream southern leg of Brunner Ditch before it turns eastward to connect to Chocolate Bayou (see Exhibit 5-15) or use in-line detention.

An alternative to the existing reconnection of Brunner Ditch to Chocolate Bayou at its current location is to extend Brunner Ditch to the south and reconnect to Chocolate Bayou just upstream of FM 2004, as shown in Exhibit 5-18. Potential reasons for pursuing this latter option include:

- Relatively inexpensive or possibly even donated land for the extension
- Smaller flows in Chocolate Bayou north of the return point for Brunner Ditch (generally north of the Snug Harbor community to the vicinity of Liverpool) and consequent flood benefits.
- More area for mitigation storage at farther points south along the extension where land might be acquired more easily. Note that mitigation storage should still be expected to be required because without it the flow entering Chocolate Bayou from Brunner Ditch could cause backwater water impacts in the vicinity of Snug Harbor and the industrial areas north and near FM 2004.

However, there are significant disadvantages to a downstream extension of Bruner Ditch:

- There would be considerable more excavation required for extension of Brunner Ditch to the south to the vicinity of FM 2004
- Potentials for backwater impacts in the vicinity of Snug Harbor and industrial areas between Snug Harbor and FM 2204 could be considerable.
- The opening of a new channel north of FM 2004 would open another pathway for intrusion of salt water into lands which are currently dominated by freshwater conditions, with potential adverse impacts on soils and habitat.

The potential value of extending Brunner Ditch to the vicinity of FM 2004 relies considerably upon the availability of relative free or very low cost land for construction of the extended channel. However, as discussed at greater length in Section 6, costs are considered comprehensively in evaluation of the cost and benefits of a particular project; disregard of costs because of some ill-defined possibility of free or near-free land for ditch construction is not appropriate to consistent and comprehensive evaluation of costs and benefits for flood control projects throughout the CBW. With additional land and excavation costs to extend a Brunner Ditch option to the south of its current return point to Chocolate Bayou, an extension option will cost considerably more than options which return flow at its current location and place a southward extension option at a distinctly less competitive position that the option which returns Brunner Ditch flow to Chocolate Bayou its it current location.

Consequently, while a Brunner Ditch alternative of extending Brunner Ditch southward to the vicinity of FM 2004 is a possibility; such an alternative is not evaluated in detail in the present Study. Should more definitive information or conditions develop which would either significant lower costs or increase the benefits of extending Brunner Ditch farther to the south, this Brunner Ditch alternative could be reconsidered at that time.

5.4.6 Brunner Ditch Options 1A and 1B

Brunner Ditch Options 1A and 1B, two of the six options considered for Brunner Ditch, extend, similar to prior studies, the ditch northward from its current confluence (which currently has only very limited capacity to capture flow from either the South or North Hayes Creeks) to intercept the West and East Forks; see Exhibit 5-149. This option (which recognizes the intent and deliberations of prior studies) proposes widening the existing ditch and constructing the extended ditch to convey a 100-yr flood event.

For this widening and extension to function effectively, it is necessary that flow from the intercepted channels be efficiently delivered to the ditch. Consequently, the North and South Hayes and the East and West Forks above Brunner Ditch are also proposed to be widened to provide a 100-yr capacity in each of these channels. This widening is considered more than the widening envisioned in the conveyance improvement options of Section 5.4.1, but if a 100-yr capacity is not provided in these upstream tributaries, the increasing the capacity of Brunner Ditch to a 100-yr level serves little purpose. At ultimate design conditions, the capacities, in terms of storm event frequency, of Brunner Ditch and the tributaries draining to the ditch should be of the same magnitude.

Two options to this basic plan are considered: Option 1A uses mitigation ponds to mitigate the increased flows in the tributaries and the ditch that the conveyance improvements would produce, so that when the Brunner Ditch flow enters Chocolate Bayou an increase in flow in Chocolate Bayou itself downstream of the return point does not occur. In Option 1A, the necessary mitigation is achieved by in-line detention in the tributaries. Exhibit 5-15 summarizes the two options.

5.4.7 Brunner Ditch Options 2A and 2B

Brunner Ditch Option 2 is similar in concept to Brunner Ditch Option 1, except that the Brunner Ditch interception point for the tributaries is moved farther downstream along the tributaries almost to their confluence with Chocolate Bayou; see Exhibit 5-16. Option

2A mitigates the increased flow return to Chocolate Bayou using detention ponds while Option 2B mitigates using in-line detention.

5.4.8 Brunner Ditch Options 3A and 3B

In this option, a new cross connecting channel would be constructed from Chocolate Bayou to the existing Brunner Ditch (see Exhibit 5-17). The point of diversion along Chocolate Bayou would be downstream of the confluence of Chocolate Bayou with the South Hayes Creek and upstream of FM 1462. An existing unnamed creek which currently flows from the southwest to the northeast to discharge to Chocolate Bayou at the point of proposed diversion would be used to define the alignment of the diversion. The existing unnamed creek would be re-graded and extended to the southwest to reverse the existing flow line and connect Chocolate Bayou to Brunner Ditch. Detailed engineering would be required to size a diversion structure, but the structure would be designed to divert a large portion of the 100-yr flow in Chocolate Bayou at the diversion point (preliminary evaluation estimates a flow diversion on the order of a 75-yr flow in the diversion.

Flood benefits would be realized at points downstream of the diversion point and reduced tailwaters at upstream points which, in turn, would beneficially impact upstream flooding. Mitigation of the increased flow along Brunner Ditch resulting from the diversion would be provided along Brunner Ditch by either a mitigation pond (Option 3A) or by in-line detention (Option 3B).

5.4.9 Manvel Siphon Improvements

Five siphon systems are located in the Manvel area to convey flow under the GCWA Briscoe Canal (see Exhibits 2-6 and 4-3); the siphons are along the West Fork Tributary A and West Tributary B, the East Fork Tributary A and East Tributary B, and Ditch C-12. These siphons have insufficient capacity to convey large flood flows and as a result of the constriction they produce cause flooding upstream of the siphons, including the developed area of the City of Manvel north of SH 6. Constrictions offered by culverts under the existing railroad and SH 6 are estimated, based upon general information currently known [e.g., 2007b], to be nearly as significant as the constrictions of the siphons.

This overall project, i.e., the Manvel Siphon Improvement Project, consists of the five subprojects: SI-1, SI-2, SI-3, SI-4, and SI-5 corresponding to siphons for the West Fork tributaries, the East Fork Tributaries, and Ditch C-12. The number or order of individual siphon projects which would be constructed is addressed in Section 6 where project benefits are evaluated. Actual determination of how the improvements of the existing siphons will be accomplished will require detailed engineering study; improvements could be replacement of existing siphons or addition of new siphons near the existing siphons.

To reduce the flooding upstream of the improved siphons, improved drainage of flood waters must be provided. Improvements to channel capacity, by widening or deepening the existing channel will have to accompany the siphon improvements if flooding upstream of the siphons is to be reduced. The siphon and upstream channel improvements are proposed to eliminate flooding for the 100-yr storm event.

The construction of the siphons, because of the increased capacity they provide, will increase discharges to downstream unless the increases are mitigated. Mitigation ponds are therefore included in the proposed projects; locations of the ponds are shown in Exhibit 5-29.

The reduced flooding that the siphons will achieve will also reduce flooding over SH 6 in the Manvel area; the benefits from elimination of flooding over SH 6 are discussed in Section 6.

5.4.9.1 Manvel Siphon Improvements vs. Diversion Pond for Ditch C-12

A potential variant to the Manvel Siphon Improvement project is a project combining a diversion pond project for Ditch C-12 with the siphon improvement of Ditch C-12. Comparing Exhibits 5-10 and 5-19, it is apparent that the diversion pond for Ditch C-12 could be combined with the mitigation pond for Ditch C-12 siphon improvement. While detailed engineering would be required to locate and size a pond (or series) of ponds which could serve both projects, the opportunity does exist for combining the storage for the two projects.

In addition, it would appear that a large diversion pond, i.e., one designed to store the 100-yr flood event with a 2-yr channel target flow (thus assuring the capacity of the siphons is sufficient), if located upstream of the siphon, would be sufficient to reduce the 100-yr flood flow coming down the conveyance-improved Ditch C-12 channel and eliminate the need for improvement of the Ditch C-12 siphon.

Such a project would thus consist of upstream channel conveyance improvement to a 100-yr capacity and diversion pond with a 100-yr pond and a 2-yr bypass flow.

5.5 Improvement Options for Loss Sites beyond the 100-Yr Floodplain

It has already been noted in Section 3 that some reported flood losses are beyond the 100-yr floodplains for those watercourses which are modeled in this Study. Different reasons for this been discussed (see Section 3.2.3). In some cases, these losses may be due to localized conditions not directly the result of major flooding along watercourses. Whether particular losses are the result of localized conditions or more general flooding along watercourses cannot be determined in this present Study. However, if apparent flooding or drainage losses are due to localized conditions that will not be resolved by flood control improvements along channels, bayous, canals and other larger watercourses, the following are possible options to consider for addressing such flooding or drainage losses:

- *Localized drainage improvements*: Detailed, localized review of the drainage conditions to determine whether the problem arises from localized subdivision (or similar) sewer or drainage ditch capacity limitations, in which case, improvements to the subdivision drainage system need to be identified and remedied.
- *Ponding relief:* Identification of ponding areas and use of ditches or swales to drain the low lying ponding areas where runoff waters tend to accumulate because of the absence of a pathway by which runoff water can drain away.
- *Flooding proofing:* Prevention of damage to structures by use of various means to either prevent intrusion of waters into structures and/or limit the degree of damage when intrusion occurs. Such measures can include flood doors, isolating levees around structures, break-away walls, waterproofing of outside walls, specialized construction to raise sensitive building materials (e.g., sheet rock) above flood levels, and raising or removing low level openings (e.g., doors and full height windows).
- *Raising of affected structures:* Raising a building to a level which puts the first floor level above flood levels. Note that under Brazoria County regulations, flood slabs must be at least 2-ft above the natural ground level or the 100-yr flood level, whichever is higher.
- *Buy-out*: Purchase and subsequent demolition of a structure to prevent its future flooding. This option is typically an option of last resort, and other options need to be fully evaluated before this option is pursued.

It is to be recognized that while measures such as these may be required to address such localized flooding problems, the potential damages arising from such flooding have been recognized in evaluating repetitive flood damages because the loss representation has been extended across the entire CBW though the use of the generalized repetitive loss map described in Section 3.4

SECTION 6

FLOOD CONTROL BENEFITS

6.1 Definition of Benefit

Ultimately, the benefit of a potential flood control project should be balanced against the cost of implementing the project. The value of a project and thus its priority for implementation depends, at least in significant part, upon both benefit and cost. This section address flood control project benefits.

6.1.1 Types of Flood Control Benefits

In this Study, benefits are measured in terms of reduction of flood damages. Thus, for example, if a flood rises to three feet in a structure before a flood control project is instituted but the *same* flood would cause only one foot of rise in the flood level after institution of the flood control project, the benefit would be the difference in the damages resulting from three feet of flooding less the damages resulting from one foot of flooding.

Flood damages in absent of remedy to reduce such damages are assumed to continue to occur in the future in amount, frequency, and location as they currently do. No attempt in this Study is made to account for new development or other watershed changes which might alter flooding occurrences across the CBW.

There are a variety of potential direct and indirect damages that a flood can produce, including not only damages to residential structures but such diverse things as damage to industrial property, loss of revenue due to loss business during and after a flood, disruption to the use of public facilities such as sewerage treatment plants, loss of personal property (e.g., automobiles), loss of wages due to commercial inactivity, damage to transportation facilities (e.g., destruction of a bridge), and loss of life [e.g., USACE, 2009]. Consequent benefits resulting from reduction of flood damages could include an increase in property revenue because of increased property value (because a property is subject to less flooding), improved transportation and emergency access (reduction in the frequency of flooding in an area will lessen the likelihood of street flooding, including during times of emergency), improved stream water quality (because of less likelihood of flooding of sewage treatment facilities), and greater community value (because of less flooding, a community becomes a more desirable place to live). Such comprehensive views of damages are beyond the scope of this Study, which is focused upon repetitive losses to residential structures

Two types of flood situations resulting in flood damages or situations of damage avoidance are recognized in this Study:

- *Residential Structural Flooding*: Flooding of residential structures in floodplains resulting from 100-yr or smaller floods. Structural flooding of commercial, industrial, or other non-residential structures is not specifically addressed. The benefits of reduced flooding of non-residential structures are assumed to be adequately reflected by the reduction of flooding of residential structures. The methodology for quantifying flood damage includes estimates of damage from floods greater then the 100-yr flood, but the location of where damage is evaluated is restricted to areas of inundation by the 100-yr or smaller floods. (Note that areas of inundation for the 100-yr flood are often so large in the CBW that they are often limited only by the boundaries of the 100-yr flood; flood boundaries for floods larger than the 100-yr flood would not exceed those of the 100-yr flood.)
- *Flooding or Significant Drainage Problems beyond the Computed 100-yr Floodplain:* This is residential flooding based upon flooding reports for locations beyond the 100-yr floodplain but not believed due to a flood larger than a 100-yr flood. These flooding or drainage problems have various potential causes which are either 1) not believed to be a direct result of floodplain inundation, or 2) are a result of floodplain inundation which is not reflected in the floodplain locations computed in the present

Study. In the case of the former situation, general guidance on potential ways to address flooding problems is identified in Sections 1.5 and 5.5. In the latter case, it has already been noted in Section 3 that there are different potential reasons (beyond inaccurate flood reporting data) why flooding outside the computed 100-yr floodplain may occur, including 1) flooding can occur along watercourses which are not among those modeled; and 2) reported flooding may be a result of a high tailwater from a flooding channel or creek which inhibits drainage from a residence or subdivision. However, the use of the generalized watershed wide loss map (discussed in Section 3) allows for incorporation, albeit approximately, of such losses in the same computational manner as those losses occurring within the computed 100-yr floodplain.

Other benefits not addressed in this Study but which might be of interest in evaluation of project benefits are reductions in the inundation of agricultural, undeveloped, or otherwise generally open lands. These benefit measures are not explicitly considered because they are considered not to be within with the intent or purpose of this Study; however, changes in the amount of inundated acreage is identified for both use in computing structure damage and as a matter of general information for projects for which structural flooding is also evaluated.

6.1.2 Monetary vs. Non-Monetary Damage and Benefit

Benefits can be diverse, but fall into two broad categories: those directly described in monetary terms, and those not so described. In the former category are reductions in flood damages which can be remedied by refurbishment, repair, replacement, disposal or improvements and which therefore require expenditure of funds. For example, new carpet in a damaged residence can be purchased to replace water-soaked carpet, or if the damage is so great as to require a very large amount of money to repair the structure, the structure might be torn down and the owner reimbursed for the market value of the house.

As another example, avoidance of bridge overtopping (to reduce impediment to traffic flow during floods) can require modification of the bridge to increase its non-overtopping capacity.

Non-monetary damages include such things as the reduction in the *number* of structures flooded or acres of land inundated by flooding. In the present Study, the damage and benefit indicator is measured in monetary terms as described in terms of flood damage reduction (although some special consideration is given to the estimated monetary value of keeping evacuation routes open during flooding periods).

6.2 Residential Structure and Land Values

Flooding causes damage to structures. To evaluate benefits of flood reduction, the values of structures subject to flooding needs to be known. The estimated average value of a housing unit in Brazoria County, based upon census and similar statistical data [Wolfram Alpha, 2009], is $88,500. Housing unit values in the CBW were assumed to be the same as this countywide value; this value was used in flood damage reduction calculations.

This estimated value is consistent with repetitive loss data for Brazoria County provided to this Study by Brazoria County. The building values for single family residential structures, based upon 1287 structures, averaged $90,594.

A random sampling of 2008 assessed value of properties in Brazoria County (using county property tax records) was made of properties in the CBW both within incorporated areas and external to incorporated areas. Forty different properties were randomly sampled across the CBW. Reducing the appraised value of each sampled property by the typical value of a residential structure and accounting for the size of the lot on which the structure occurred yielded an average property value (exclusive of structure value) of $11,262 per acre.

6.3 Determining Amount of Structure Damage

Residential structure damage results from inundation of a structure. Different floods can be produce different levels of damage to a particular structure, and many different structures at different locations may be affected by the same flood. Thus number, location, and depth of flooding enter into the estimate of damage and consequent benefit from a flood potential flood control project.

The effective number of losses at various locations throughout the CBW is determined by the generalized repetitive loss map; the creation of this map has been described in Section 3. At any point of flooding, the map provides the number of structures to be flooded in a particular computational cell, the collection of all cells forming the entire flooding map. When summed overall acres of flooded cells, the total number of structures flooded by a particular flood event can be determined.

However, depth of flooding affects flood damage, so it is not only the fact that flooding may occur, but also the depth of flooding at a particular point that impacts the level of damages. Representative flood damage data as a percentage of total value of a structure and its contents (e.g., furniture) have been developed by the USACE [USACE, 2000].

Generic depth-damage curves for one-story, two-story, and split-level houses have been developed by the USACE [USACE, 2000]. Recommended procedures for using these curves incorporate not only structural damage but representative damage to structure contents (e.g., furniture). These generic depth damage curves for one-story, two-story, and split-level houses are shown in Exhibit 6-1.

Since the distribution of the type of residential structure in the CBW is not known, the generic depth damage curves for one-story, two-story, and split-level houses are averaged (with equal weight given to each) to generate the general depth-damage curve shown in

Table 6-1. Table 6-1 tabulates the percent of damage as a function of depth. Note, also, that as shown in Table 6-1, combining the average structure value of $88,500 with the value for contents yields a total value of a structure and its contents of approximately $144,000.

The data of Table 6-1 are used to estimate the level of damage at any point in the watershed as function of flood depth at that point and the full value of the structure and its contents. The data were fitted with a smooth curve and the smoothed curves values were used in the damage calculations. The data was approximated to yield zero damage with zero depth.

6.4 Losses from Different Frequency of Floods

Floods of different frequency (e.g., a 100-yr and a 10-yr) flood will have different levels of flooding and consequent different levels of potential damage at similar points. Consequently, two temporal effects need to be recognized in estimating benefits: 1) floods are random and the same frequency of flood does not occur every year, and 2) the benefits of flood control are distributed over many years while construction costs occur over a very (in a relative sense) short time. The following address these issues.

6.4.1 Equivalent Annual Benefits of Randomly Occurring Floods

The benefits of a flood control project will be realized only over an extended period of time as floods of different magnitudes occur from time to time. The randomly occurring benefits of various particular floods with particular frequencies can be transformed to an equivalent annual benefit by weighting the particular benefit associated with a particular frequency by the probability of the flood event occurring [Goodman, 1983, p. 216ff; Walesh, 1988, p. 203ff]. The resulting benefit is analogous to the average annual monetary damage (AAMD) except that the benefit here is the net reduction in damages

[Walesh, 1988, p. 203ff]. Thus, if the benefit varies with the annual flood exceedence probability P (P is the inverse of the return period, e.g., a 50-year flood has an exceedence probability of 1/50 = 0.02) such that benefit B = function of probability, i.e., B = f(probability = P), then the equivalent average annual benefit ("EAAB") is

$$\text{EAAB} = \int_0^1 f(P)dP \qquad (1)$$

Conceptually, equation 1 merely states that the area under a curve which plots probability (on a horizontal axis) against benefit dollars, or other similar measure (on a vertical axis), is the EAAB.

For calculation purposes, we can use the following to approximate the mathematically precise but computationally inconvenient equation given immediately above: Let the benefit associated with a particular frequency of flooding f_i be B_i, i = 1, 2, 3 … N, where N is the number of discrete frequencies at which flood benefits are evaluated (e.g., at f = 1/10, 1/25, 1/50, 100, for the 10-, 25-, 50-, and 100-year flood events, and for which N = 4). Then

$$\text{EAAB} \approx \sum_{i=1}^{N} B_i \, \Delta p_i \qquad (2)$$

in which B_i is the benefit associate with storm event i with probability p_i (the inverse of the return period); N (i = 1, 2… N) is the number of storm events of different frequencies; Δp_i is the interval of probability over which the benefit is approximately B_i ; and Δp_i = 0.5 ($p_i - p_{i-1} + p_{i+1} - p_i$) for i = 2, 3, …N, .$\Delta p_1$ = 0.5 ($p_2 - p_1$)+ p_1 and Δp_{N+1}= 0.5 ($p_N - p_{N-1}$) +(1 − p_N). Exhibit 6-2 illustrates a typical damage-probability curve and computation of the expected annual damage reduction.

Note the following:

- Benefits as described by equations 1 and 2 are annual benefits; these represent a time stream annual benefits over the life of a proposed project.
- Benefits will typically decrease with higher probability, i.e., the benefit of reduction of damages from small floods will typically and almost assuredly be less than the benefits of reduction of flood damages from a large flood.
- No benefits occur for floods with a probability greater than 1 since probabilities are based upon annual exceedences and the minimal number of annual exceedences is 1 (i.e., probability of 100%). However, some benefits may actually occur for floods of small magnitude which occur more frequently than annually. The methodology for conversion of randomly distributed floods of different frequencies is not intended to address the value of such very small floods. Indeed, when compared to flood damages with probabilities less than 1, such flood damages become (for the type of flooding issues addressed in this Study) of very minor or negligible benefit.
- The benefit is not specifically evaluated for flood events of greater magnitude the 100-year flood event. The 500-year benefit is approximated by the 100-year flood benefit. Benefits from larger floods are expected to change little because the 100-year flood is so expansive and will encompass virtually all structures potentially subject to flooding in numbers which could be counted in this Study. The benefits, therefore, of flood protection for floods of magnitude greater then the 100-year flood can be approximated merely as the benefits from a 100-year flood.

6.4.2 Equivalent Present Worth of Benefits

Costs for flood control projects are assumed to occur at one time and not be distributed over time. The EAAB described above is an equivalent annual cost recurring every year.

For comparison of costs to benefits, time streams of costs and benefits must reflect the time value of money and be compared on a similar basis. Because of the anticipate audience for this Study, costs and benefits are evaluated in terms of economic present worth.

In converting a future time series to its equivalent present worth, two parameters must be selected: duration (in years) of the stream of benefits and the time value of money, i.e., discount rate, or as commonly called, interest.

Duration of major public works projects are commonly in the time frame of 50 to 100 years. Sewers systems, for example, may begin to see significant deterioration in the 30 to 50 year range, while some sewers may last 70 or more; sewer system life varies significantly with materials, location, and quality of construction. Manmade canals and channels may last a century if properly maintained. Reservoirs may last a century or more, if sediments do not fill the reservoir. For the Study, a 75 year project life span is assumed. At the end of the 75 year period, it would be anticipated, if the project is still needed, the project would, in effect, be refurbished and continue to serve the same purpose as the initial project does.

To convert the annual time stream of benefits (for 75 years), an annuity factor is used. The annuity factor converts an annual stream of money to an equivalent present worth. The value of the annuity factor depends upon the discount rate, which reflects the time value of money, in the present Study, to the sponsoring entity. The discount rate is not the interest paid to borrow money, but rather a measure of how a public entity discounts benefits to be realized in the future. Low discount rates are usually associated with public projects because public entities put relatively high value on benefits even if they occur far in the future because public projects are intended to serve not only the current population but also future populations.

Public works projects use low discount rates, commonly well less than 6%, to reflect the long term societal view of project impacts on future citizens. If a zero percent discount rate is used, future benefits are considered to be equal to benefits realized at the current time; such a view might be considered fully appropriate for public projects. However, discounting is also used to reflect the uncertainties that might exist in realizing future benefits. While a plan calls a project to yield benefits not only in the near term but also the long term, the plan may not come to full fruition as anticipated; there is uncertainty that future benefits will be realized as anticipated, and discounting helps account for that uncertainty.

The annuity factor for $1 of average annual benefits occurring over each of 75 years is $75.00, $52.59, $38.68, $23.68, and $16.46 for an interest rate (i.e., the discount rate) of 0%, 1%, 2%, 4% and 6%. Note that 0% discount results in no discount; the present value is just the sum of the annual benefits (i.e., future benefits are just as valuable as current benefits).

6.4.2.1 Independence of Relative Value on Project Duration and Interest Rate

The uncertainty as to the most appropriate choice of project period over which benefits are received and the rate at which future benefits are discounted is not critical when comparing the relative value of two different projects (assuming they have the same project duration and are discounted at the same rate) if the measure of value is properly selected so that discounting is in effect merely a multiplier of the computed value. The same can be said of the project duration and its effect on discounted benefits. As discussed below, the benefit-cost ratio is such a measure of value.

On the other hand, if one seeks a monetary value indicative of the benefit only (as opposed to the relative merit of one project compared to another), the choice of project duration and interest rate is raised in importance. The 75-year choice of project duration made above is a compromise of representative durations for public works projects.

Discount rates in the 6% range discount future benefits by almost of a factor of five (compare \$16.36 to \$75.00), while, on the other hand, a 1% rate reduces the current value of the future stream of benefits to about $2/3^{ths}$ of the sum of the annual benefits (compare \$52.59 to \$75.00). Rather than discounting future benefits, one can interpret the discounting as a measure of the uncertainty of the future benefits, as discussed above. But, exactly how does one assess the uncertainty? A practical reinterpretation of this uncertainty can be used to assist in selecting a reasonable discount rate for project evaluation.

If a zero discount rate gives full credit to all future benefits over the entire time horizon of the proposed project, then a 1% discounting could be interpreted, from a practical perspective, as indicating that the full benefits of the proposed project are realized only each year for the first (approximately) 53 years of the project; after the first 53 years of benefits, no benefit is received. That is, the discounting says we give full weight to all future benefits as long as they are realized, with the uncertainty being shifted to the issue of how long benefits will be received. Considering the range of project durations for public works projects and the issue of project maintenance to assure continued effective operation, it might be reasonable to assume that receipt of benefits after about 50 years would be very unreliable. If we were to say, as we do for this Study, benefits can be relied upon, at least for the purpose of evaluating the effective economic value of those benefits, with certainty for only 53 years over the 75-year project life, then the effective discount rate is approximately 1%. That is, after 53 years (or, more approximately, 50 years), the benefits of the 75-year project become more tenuous, more uncertain.

6.5 Benefits of Proposed Projects

6.5.1 Damage Costs for Particular Storm Events for Particular Projects

The extent and depth of flooding throughout the watershed arising from the implementation of a particular flood control project (the existing condition for which no project is implemented is treated in the same manner as an actual project) was determined by either by 1) direct computation using the flood models discussed in Section 4, or 2) interpolation of actual modeling results spanning the interpolated condition of interest.

Interpolation was used to reduce the number of flood model event executions because of the large number potential projects which required evaluation: Each general project typically had more than one possible design level; and each design level required evaluation of flooding extent over the suite of 2-, 5-, 10-, 25-, 50-, and 100-year frequencies so that expected annual average damages could be computed. Collectively, more than approximately 500 different combinations of projects (including existing conditions), design levels, and flood frequencies required evaluation. Of this total, approximately 100 actual model executions were used to determine flood damages.

In estimating flood damages from a particular storm event for a particular project with a particular design level using flood modeling, the impacts of different effects had to be recognized and combined using the various models for the main stem of Chocolate Bayou and the different tributaries to Chocolate Bayou. That is, benefits for a particular project can extent beyond the boundaries of a particular watershed in which a project might be implemented; a project can have "coincident" or "ancillary" benefits in addition to direct benefits for the following reasons.

Consider a project, say a diversion pond along the West Fork. The project will reduce flooding along the West Fork downstream of the diversion pond; these reductions produces less flood damage in the West Fork watershed and are direct benefits. However, the project will also reduce discharges to Chocolate Bayou which will have coincident benefits. The reduced discharges in Chocolate Bayou will reduce flooding along Chocolate Bayou (which will also require re-computation of flood levels along Chocolate Bayou). Furthermore, the reduced discharges in Chocolate Bayou will lower tailwaters for the other tributaries to Chocolate Bayou (i.e., the East Fork, North and South Hayes, and Ditch C-12) which will also reduce flood levels in the individual watersheds of these tributaries; thus additional re-evaluation of the flood levels in these tributaries is also required. An additional benefit will also be derived by the reduction of the tailwater in the West Fork itself. These are coincident benefits and were found to be, in general, not insignificant.

While some approximations of such coincident benefits can reasonable be made in some cases, addition computation to account for coincident benefits is in general required; computational levels become significant and interpolation of flood damages becomes essential to reducing computation requirements to reasonable levels in light of the number of flood control options considered.

6.5.2 Present Worth of Expected Annual Average Flood Reduction Benefits

The present worth of the expected annual average flood damage benefits for the various potential projects identified in Section 5 are listed in Tables 6-3 and 6-5. Computation of these present worth benefits for a particular project with a particular design level consisted of the following steps: 1) using modeling or interpolation of modeling results to determine the flood damage for the entire watershed for a particular storm event by applying the depth damage curve to flooding at all points in the watershed (so that both direct and coincident damage levels are determined); 2) determining the flood damage for the full suite of flooding events, i.e., 2-, 5-, 10-, 25-, 50-, and 100-yr flood events; 3) weighting damages for various flood frequencies by their probability of occurrence to determined expected annual damage; 4) determining the present worth of the time stream of expected annual damages; and 5) computing the difference in annual damages with and without project implementation to determine damage reduction benefit.

Table 6-3 lists the computed expected annual average flood damage reduction benefits for conveyance projects, diversion pond projects, and combined conveyance and diversion pond projects for the various sub-watersheds (in this table, the Chocolate Bayou sub-watershed includes both the mainstem and the East Fork of Chocolate Bayou). For a particular sub-watershed, the benefits include not only the benefits occurring from reducing flooding in the sub-watershed but reduced flooding in other sub-watersheds due to downstream flow reductions and consequent tailwater reductions when they are expected to occur (see discussion in Section 6.5.1). Note that flood reduction benefits for diversion ponds occur only when the flood frequency exceeds the bypass flow for the pond in question since no change in flow conditions occur when the flood frequency is below the level at which diversion to the pond occurs.

Table 8-1 lists the estimated expected annual average flood damage reduction benefits for the siphon improvement projects in the Manvel area. Project benefits are broken down by the five individual siphon systems (East Fork Tributaries A and B, West Fork Tributaries A and B, and Ditch C-12) that compose the full set of siphon improvements. In evaluated these benefits, the only flood reduction benefits that obtain are reductions in flooding upstream of SH 6 because the mitigation ponds near the downstream end of the siphons return flows downstream of the siphons to their pre-project levels so that adverse downstream impacts are not created in the increased capacity that the siphon improvements yield.

Table 8-1 also lists the expected annual average flood damager reduction benefits from the three Brunner Ditch Options (Options A, B, and C); no difference in the benefits obtain when in-line detention vs. off-line detention ponds are used to mitigate the impacts of flow increases. The benefits that the Bruner Ditch options produce account for, if any, flood reductions along the existing Brunner Ditch alignment and upstream reaches of tributaries intersected by the existing and extended length of Brunner Ditch; both Brunner Ditch Options 1 and 2 improve conveyance in the West Fork and North and South Hayes Creeks. Brunner Ditch Option 3 reduces flooding along the existing Brunner Ditch alignment and along portions of the mainstem of Chocolate Bayou.

Table 6-4 converts the expected annual average flood damage reduction benefit for the various projects listed in Table 6-3 to an equivalent present worth assuming a project life of 75-years and a 1% social discount rate.

6.5.3 Reduction of Flooded Acreage

Flood control projects will also yield a reduction in flooded lands, irrespective of whether structural flooding is reduced. Table 6-5 lists for the conveyance improvement projects, the diversion pond projects, and the combined conveyance improvements and diversion projects the reduction in the 100-yr floodplain lands that the various potential projects would produce, irrespective of the presence of structures and irrespective of the depth of flooding. The reductions in flooded acreage were computed from modeling or interpolation of modeling results; the values listed are the difference in the flooded acreage without (i.e., existing conditions) and with a project in place. Thus, for example, if a diversion project with a 5-year bypass flow and a 50-yr pond design volume is developed for the West Fork, the computed reduction in the 100-yr floodplain acreage in the West Fork sub-watershed is 906 acres. By comparison, a similar project in the Chocolate Bayou sub-watershed (which includes both the mainstem and the East Fork) would yield across the total sub-watershed a reduction of 2130 acres for the 100-yr storm event, the larger value obtaining generally because of the larger size of the Chocolate Bayou sub-watershed.

SECTION 7

COSTS OF OPTIONS

7.1 Cost Types and Limitations

The costs of a flood project can be direct and tangible, indirect, or intangible. Costs for construction of a flood control facility would be direct and tangible. An indirect cost could be, e.g., costs for construction of public infrastructure for increased development encouraged by lessening of flood problems. An intangible cost might be loss of existing habitat due to construction of a flood control project. In this Study, only direct and tangible costs quantified in monetary terms are considered.

In estimating and using monetary costs for a project, it is assumed, because of the planning nature of this Study, that all costs are a one time cost incurred more or less at the one time of project construction. Costs are assumed to be of short duration. That is, construction costs for a particular project are not distributed over time. These one time costs are assumed to occur at the present time, i.e., no discounting or inflation of costs is considered.

7.2 Cost Elements

The following costs are estimated for various potential projects; note that all costs are preliminary in nature and are based upon representative, typical features of a project of the type under consideration. Project construction costs include both labor and materials; land acquisition associated with projects are also estimated but are addressed as a separate cost item.

7.2.1 Construction of Channel Improvements

Direct costs for construction of a channel improvement (widening or deepening) project include not only excavation and excavation-related costs but also bridge improvements and necessary mitigation pond construction if such elements are part of the project in question.

Mitigation pond construction, a typical feature required in channel conveyance improvement projects, is based upon excavation and excavation-related costs.

Bridge improvements are potentially a significant component of total construction costs, and may be necessary because the width of the channel crossing has significantly increased and, as well, there may be many bridge crossings for a particular channel widening project. In the present study, bridge improvements costs are determined by assuming that a bridge is widened so that it can span the full width of the widened channel. However, this provides a conservative estimate of bridge improvement costs. Detailed design may identify options to full width widening (such as side channels or limited channel constriction) so that bridge improvements can be reduced in total expense.

7.2.2 Detention and Diversion Ponds

Costs for any pond, whether for detention mitigation or detention for diversion purposes, are included, with the basis of the cost estimate keyed to the volume of excavation. The costing includes approximate allowances for typical inlet and outlet structures and appurtenances.

7.2.3 Computation of Channel Improvement and Pond Construction Costs

A planning level computational model for channel improvements and detention pond construction developed by the Harris County Flood Control District as part of reconnaissance level watershed planning studies [HCFCD, 2008] was used to evaluate costs for channel widening and deepening and construction of detention ponds. The model includes costs for replacement of bridges if a channel is crossed by a bridge and, as a consequence, bridge replacement is required. The cost computation model is summarized in Appendix H

7.2.4 Special Hydraulic Structures

If a project involves special hydraulic structures, the construction costs of the special structures are specifically estimated. The project of particular interest in this regard is the siphon improvements under the GCWA canal in the Manvel area. Costs of hydraulic structures are based prior studies and bid-tabs of recent projects [Klotz Associates, 2008b].

7.2.5 Function of SH 6 as Evacuation Route

Designated evacuation routes in the CBW are SH 288, SH 35, and SH 6. FM 2004 is not considered for improvement since its evacuation capability is limited by its location adjacent to Chocolate Bay and associated impacts from Chocolate Bay surges. Note as well, that the FM 2004 bridge crossing of Chocolate Bayou is quite high because of requirements for passage of barges into the industrial areas immediately north of the bridge over Chocolate Bayou. While the bridge-approach roadways, which are quite long (several miles in length), may be inundated by riverine flooding, the potential for flooding of the bridge itself is virtually nil.

For the remaining bridges along SH 288, SH 35, and SH 6 evacuation routes, review of the existing condition flood levels as computed in this Study shows the 100-yr flood levels at SH 288 does not overtop the bridges at the modeled watercourses. Nor does flooding over SH 35 appear to be significant.

However, modeling done in this Study of the various crossings of SH 6 in the general vicinity of Manvel where the highway crosses the West Fork and the East Fork shows overtopping by some flood events does occur. This predicted overtopping is consistent with the observed problematic conditions along this segment of Hwy 6.

Major lengths of bridge improvements to carry the highway across the 100-yr floodplain or shorter lengths of bridge improvements coupled with raising of the roadway could be used to address SH 6 flooding if modifications to SH 6 crossing were not done in conjunction with other flood control projects. However, the siphon improvement projects proposed in the Manvel area will address flooding in this area; the siphon improvement projects are expected to eliminate flooding of SH 6 in the Manvel area (see Exhibit 5-19 for the location of the proposed siphon projects). Consequently, the cost of prevention or reduction of flooding of SH 6 is evaluated in this Study as part of the siphon improvement projects proposed for East and West Fork Tributaries.

7.2.6 Supplementary Project Construction Costs

In addition to actual construction, costs are estimated for engineering design, field survey, geotechnical investigation, construction contract administration, limited environmental (phase 1) assessment, and environmental permitting. A representative contingency cost is also included. These supplementary costs are determined as a fixed percentage of the direct total construction cost of a project (including bridge improvements if they are part of the project). The fixed percentage is selected for these various and collective supplemental costs in light of the character of the projects and prior experience. For channel improvements and detention pond construction, these supplementary costs are estimated to be 40%; for bridge replacement, supplementary costs are estimated at 30% of construction costs.

7.2.7 Land Acquisition Costs

All projects will require, in general, some land acquisition, whether it be for channel widening or pond development. Bridge widening for evacuation routes improvement and construction of special hydraulic structures are, however, presumed not to require additional land for their implementation; current ROW or easement is considered sufficient for such projects.

The amount of land to be acquired for widening is the additional width of the channel when channel widening is used. The current channel is assumed to have adequate maintenance berms of each side of the channel and so additional amounts of land for maintenance berms of a widened channel would not be required (because of the existing berm width).

The estimation of pond volume and consequent land surface area is sufficiently conservative (because of the assumption of only an effective 5-ft of pond depth) that the estimated surface area of a pond (based on volume for a 5-ft depth and the required storage volume) is considered a reasonable estimate of the total area land needed for pond construction.

Actual land acquisition costs are based upon evaluation of property and flood damages discussed in Section 6.2. Land is estimated to typically cost $11,262 per acre.

7.2.8 Maintenance Costs

Costs for maintenance of flood control projects, while they do exist, are not specifically accounted for in project cost estimates because of the following reasons:

- The amount of maintenance for the type of projects proposed will tend to vary with the construction cost, and thus be proportional to project costs. The effect on the relative comparison of benefit and costs would not, for the method of comparison used (i.e., benefit-cost ratio), be impacted by such proportional costs.
- Maintenance would be anticipated to be generally done by the county or a drainage district as part of general maintenance activities for county drainage facilities and not specifically associated with a particular project. (In the terminology of the following Section 7.4 below, maintenance coats are reassigned to a non sponsoring entity.)

7.3 Estimated Project Costs

7.3.1 Costs for Conveyance Improvements and Diversion Ponds

These projects involve 1) channel widening to increase the conveyance of a channel and thus move flood waters more rapidly downstream, 2) construction of diversion ponds to which flood waters can be diverted to reduce flood discharges in a channel, and 3) a combination of these two strategies. Tables 7-1 to Table 7-4 provide estimated costs for these types of flood control projects for Chocolate Bayou (mainstem and the East Work), the West Fork, and the North and South Hayes Creeks for various specific designs of each of these types of projects.

In general, the costs are broken down by various elements so that the various contributions to the total project cost can be seen. Each project is identified with a number, sub-watershed where it is to be constructed, and features of the design which distinguish the design and define the basic parameters for cost determination. Cost elements are 1) total construction costs exclusive of bridge replacement costs, 2) supplementary costs for engineering, contingency, etc. (as discussed above), 3) bridge replacement/upgrade costs 4) estimated land acquisition costs, and 4) summations of these various elements. The key figure, of course, is the total project cost; this cost is used in the benefit-cost evaluations provided in Section 8.

Tables 7-1 and 7-2 present costs for diversion pond projects to reduce flooding. The size of the project is based upon two parameters: the flow which is intention bypassed by the pond site without capture (which is the "Design Level" in the 3rd column of these two tables) and the size of the maximum storm event which can be diverted to the pond without pond overflow (which is the "Pond Design" value in the 5th column in these two tables). Thus the diversion pond Project 15 in Table 7-2 bypasses a 2-year flood but captures and retains floods in excess of a 2-yr flood up to a maximum of a 25-year flood. The total diversion pond size to provide this less of flood storage is (for Project 15) 84 acres, which would correspond to a total volume of 5 x 84 = 420 ac-ft.

Both Tables 7-1 and 7-2 provide cost data for potential diversion ponds. The difference between the two tables is the type of breakdown of the costs. In Table 7-2, the cost information is for all diversion ponds along the channel in question (in Table 7-2, the East Fork and the mainstem of Chocolate Bayou are also combined). In Table 7-1, the cost is decomposed into the estimated ponds for each of several ponds that might be constructed to provide the total necessary storage. (The choice of the actual number of ponds was for convenience based upon the number of drainage basins composing a sub-watershed; see Exhibit 1-7. For planning purposes, each drainage area was assumed to have one diversion pond). Thus, e.g., as seen in Table 7-1, the West Fork is presumed to have 2 drainage areas, Chocolate Bayou has 4.

Table 7-3 provides cost for conveyance improvement projects. Two types of conveyance improvement projects are considered: 1) those for which mitigation of downstream impacts is provided by an off-line detention pond (or ponds), and 2) those for which mitigation is provided by in-line detention. Projects within a particular sub-watershed (in this tabulation, the East Fork and the Chocolate Bayou mainstem are combined) are based upon the capacity to which the channel is improved, e.g., the storm of a specified frequency that could be carried by the channel without overtopping the banks anywhere along the channel in question. These projects typically have a significant bridge replacement/upgrade cost because the bridge over the current channel must be lengthened to span the new channel width.

Also listed in Table 7-3 are the average top widths of the existing and proposed channel after widening. The difference between these top widths times the length of the channel determines the estimate amount of land to be acquired for the widening. The mitigation pond area required is also listed; the estimate pond volume required is 5-ft x pond area.

Table 7-3 provides costs for projects which combine both conveyance improvements and diversion ponds. These projects combine conveyance improvements and diversion ponds into a single project. These projects assume that the mitigation volume for channel conveyance improvement is included in the diversion pond volume. The bypass volume for the pond is also the design level for the conveyance improvement. Thus, as opposed to diversion pond only projects, in which downstream flooding might occur when the bypass flow occurs, these combined projects would prevent downstream flooding for flows which are bypassed by a diversion pond. Because these combination projects involved channel widening, bridge replacement or upgrade is required at road crossings. These bridge costs are reflected in the total project cost.

7.3.1.1 Costs per Unit Project Length

Also listed in Tables 7-1 to 7-4 is an equivalent total project cost per mile, which is the total project cost divided by length of the channel section for which or along which the project is to be constructed. These particular unit length data may be useful in estimating the costs for a project which does not extend the full length of the channel in a sub-watershed. Thus, for example, if it were desired to provided channel conveyance improvements of only 5 miles of length, rather than the full length of approximately 8.8 miles, along the West Fork sufficient to increase the capacity of the channel to a 5-year capacity, the costs would be (see 14th project in project list in Table 7-3) would be only about 5 x 5,054,674 = $25 million rather than $44 million.

7.3.2 Siphon Improvement Projects

Siphon improvements are proposed for five different siphon systems under the GCWA Briscoe Canal in the Manvel area near SH 6; improvements are proposed for the West Fork Tributaries A and B, East Fork Tributaries A and B, and Ditch C-12 (see Exhibit 5-19). Estimated costs for replacement or substantial upgrade of the existing siphons are given in Table 7-5.

The replacement or upgrade is intended to increase the capacity of the siphon systems to convey the 100-year flood without backup of floodwaters upstream of the SH 6, where flooding currently occurs due to the constriction that the existing siphons cause.

In addition to siphon construction itself, the channels upstream of the siphons would be increased to a 100-yr capacity so that no limitation on draining the 100-yr flood would be introduced by the channel upstream of the siphons. Because the increased capacity of the siphons will allow greater discharges to be sent downstream, mitigation ponds in the vicinity of the siphons would be used to temporally detain the higher flows so that adverse impacts would not be created downstream.

The cost data of Table 7-5 provides the costs for each of the major elements of the siphon projects: 1) the siphons themselves, 2) the widen of channels to increase their conveyance, and 3) the construction of the mitigation ponds.

7.3.3 Brunner Ditch Projects

Six different Brunner Ditch projects are considered, three of which anticipate use of mitigation ponds (Options 1A, 2A, and 3A) and three of which (Options 1B, 2B, and 3B) proposed use of in-line detention to provide necessary detention. The costs for the six different options are given in Table 7-6.

Each of three basic projects (Options 1, 2, and 3; see Exhibits 5-15, 5-16, and 5-17) involves widening of the existing Brunner Ditch; the variants arise as to what realignment or channel extension is proposed. Option 1 extends the existing the Brunner Ditch northward to the West Fork; Option 2 realigns the extension to the West Fork to be near the confluences of the North Hayes, South Hayes, and the West Fork with Chocolate Bayou; and Option 3 creates a new channel from Chocolate Bayou to Brunner Ditch.

The common section of the existing channel in each of these options is shown in each of the Exhibits 5-15, 5-16, and 5-17. The common section extends from the point along Brunner Ditch from where the existing channel intersects the CBW boundary south of FM 1462 and then parallels along the watershed boundary in a southeastern direction (because of the presence of a GCWA canal which defines the watershed boundary) to the point where the channel turns to the northeast and reconnects to Chocolate Bayou.

The cost for construction of this common element is identified in Table 7-6, and is included in each for total costs for each of the three options, under the assumption that only one of the three options is actually constructed. However, when projects are actually identified for implementation in Section 9, only two of the three options are actually proposed for implementation. Consequently in estimating the project costs care must be taken not to double count the common element in the cost of the second of the two projects proposed for implementation.

7.4 Cost Recovery and Reassignment Considerations

This Study does not have as one of its purposes the identification of alternative methods by which costs for a potential project can be reduced either by cost recovery or by cost reassignment. Cost recovery is merely recouping of monies to partially defray the cost of project construction. Reassignment is the effective transfer of some project costs to a party not the same (from an economic perspective) as the party paying for the construction of the project, the latter party being the "sponsoring entity."

A "sponsoring entity" is the party (an individual party or consortium of individual parties) which is proposing the project in question and is responsible for providing the necessary funds for the project construction. A county, drainage district, municipality, or some combination of these entities would be a typical sponsoring entity. However, the party assuming the role of a sponsoring entity is, from a cost recovery or reassignment perspective, distinct from the party providing money or services for cost recovery or reassignment, even if the parties in question are, physically, one in the same. In simple terms, it is matter of whose budget pocket is being used to provide money or services for cost recovery or reassignment, and whose budget pocket is being relied upon to pay for the construction of a project.

Cost recovery is the obtaining of funds to cover all or part of the project construction costs so that the sponsoring entity (e.g., the county or a drainage district) does not have to pay the full cost of a project from it own funds. Common cost recovery strategies include grants (as, e.g., example, from TWDB), low interest loans (which reduce interest costs), or facility participation fees (e.g., fees paid by a developer to utilize portions of the storage volume in a regional detention pond). Once a particular party provides monies for cost recovery, that party in question may be called a member of the sponsoring entity for community or public recognition purposes. If so, the sponsoring entity makeup, in effect, becomes expanded. Cost recovery strategies are distinguished by the actual transfer of money from some party not, at least initially, to directly compensate (either at the current or some future time) the costs of project construction.

Cost reassignment is merely the reduction of costs directly attributable to a project by utilizing the services or contributions of some party other than the sponsoring entity so that certain costs do not have to be borne (i.e., paid) directly by the sponsoring entity. Examples include the following:

- *Donation of land for ROW*: For example, a property owner may give without monetary consideration land to the County for construction of a canal across the owner's property.
- *Construction of a Facility on Behalf of a Project*: An entity, typically a public one, may use its own funds to construct an element or component of the total project without charge to the sponsoring entity. For example, if a project requires the crossing of a state highway, TxDOT might reconstruct the affected roadway segment to allow the needed crossing if such reconstruction also benefited regional transportation needs beyond just continuance of existing traffic over the roadway crossing.
- *Incorporation into Larger Projects of Others (Subsumption):* The proposed project might be possibly made a part of a larger, more comprehensive project. Such incorporation might result in overall efficiencies in construction costs or the ability of the initially proposed project to use some of the facilities of the larger project, thus negating the need for the construction of the facilities in the smaller project.

- *Contributed Services*: Contributed services are a common form of cost reassignment. A party, frequently a public entity, may perform some of the necessary construction of the proposed project but not actually charge the costs for provision of such construction to the project, i.e., the entity contributes the construction activity to the project without seeking payment from the sponsoring entity. The costs of the contributed services, which are real costs, are reassigned to the contributor. The contributor absorbs, in some manner, the incurred costs into his operating costs.
- *Self-Contributed Services:* This is a variant of contributed services. The contributor is also a member of the sponsoring entity of the proposed project. Rather than pay for a commercial contractor to perform a needed construction activity, the contributor performs the needed construction without charge to the project itself and does not formally seek payment for such work from the sponsoring entity.

The distinguishing characteristics of cost reassignment are two: 1) the reassignment reduces the necessary monetary outlays for the proposed project by the project's sponsoring entity, and 2) the reassignment does not directly involve transfer of monies from one party to another as it does in cost recovery. Recognize, however, that reassignment does not say that someone does not have to pay for the service being provided; it merely says that the party paying for such service is not identified as sponsoring entity of the proposed project.

7.4.1 Costs Impacts from Contributed Services from Public Entity Participation

The estimated project costs provided in Tables 7-1 to 7-4 assume that all construction work is done by commercial contractors (as opposed to, possibly, county employees using county equipment). However, the characteristics of the proposed projects do in part generally lend themselves to participation in their actual construction by the county or a drainage district. Such participation can, as discussed above, reduce the project costs by reassignment of some costs to a party not the sponsoring entity. This in turn can make a project not only more economically attractive (i.e., to have high apparent benefit-cost ratio) but also possibly may make it feasible (i.e., costs do not exceed the sponsoring entity's available money for construction) where before it was not so.

7.5 Average Cost Breakdown

Project costs are large, but not all the costs are direct construction costs. As discussed previously, there are a variety of elements which contribute to the total potential cost of a project. Excavation costs are dominating in all projects; thus reduction of unit costs of excavation can have a significant impact on project costs. If the project costs are broken out for all the projects listed in Tables 7-2 to 7-6, the results of following table obtain.

Table 7.5 Average Cost Breakdown

Project Type	Construction (w/o bridge replacement)	Bridge replacement (note 1)	Supplemental Costs (note 2)	Land Acquisition	Total
Diversion Ponds	63%	0%	28%	9%	100%
Conveyance Improvements	53%	12%	26%	9%	100%
Combined Conveyance & Diversion Ponds	61%	3%	27%	9%	100%
Siphons	58%	3%	38%	1%	100%
Brunner Ditch	61%	6%	27%	6%	100%
All Types	62%	3%	26%	9%	100%

Note 1: Bridge replacement costs for Siphon Projects are primarily siphon costs
Note 2: Supplemental costs include: environmental assessment, surveying, geotechnical investigation, engineering, permitting, contract administration, and contingency

SECTION 8

BENEFIT-COST COMPARISON

8.1 Concepts of Cost, Benefits and Value

Implementation of flood control projects of the type identified in this CBW Study involves expenditure of public funds, and should, as a consequence, recognize the value of a proposed project. Value is determined by project benefits and project costs. As benefits become larger compared to costs, so does the value of a project.

Cost and benefits can be diverse; general issues in the diverse nature of benefits and costs have been discussed in Sections 6 and 7. For evaluation of project value in this Study, only monetary costs directly associated with flood control project construction and monetary benefits due to estimated reduction of residential structure flooding (except for the special situation arising from flooding of SH 6) are considered.

8.2 Comparing Benefits and Costs

Commonly used measures of value for comparison of dollars of cost to dollars of benefit include the following [Goodman, 1983, p. 22; Wikipedia, 2009]:

- Present values of benefits (PVB): The equivalent present worth of the equivalent average annual benefits resulting from reduced damages randomly occurring over the life of the proposed flood control project.
- Present values of costs (PVC): The immediately incurred construction cost of the proposed flood control project.
- Net Present Value (NPV): PVB-PVC
- Benefit Cost Ratio (B/C): PVB/PVC
- Net Benefit Cost Ratio: (NPV/PVC)

Of these above measures, the widely recognized benefit cost ratio (B/C) is used to estimate project value.

8.2.1 Watershed Wide vs. Sub-watershed Perspectives

Benefits are evaluated on the basis of a storm event of particular and various frequencies occurring across the entire watershed. Storm events are not presumed to be concentrated in one particular sub-watershed. The effects of watershed wide (i.e., across the entire CBW) storm events as compared to more localized but severe storm events is indirectly accounted for by two factors.

- Rainfall area-reduction factors (see discussion in Section 4.3) are incorporated in the rainfall computation for computing rainfall-runoff. The 100-year rainfall producing the 100-year storm event anywhere in the CBW is based upon the *total area* of the CBW (irrespective of what sub-watershed may be modeled); this rainfall is less than that for a storm event of the same frequency which is restricted to a smaller area. This perspective is taken 1) because this a watershed wide study, and 2) because of the resulting inconsistency in assessing coincident benefits (from beyond the boundaries of the sub-watershed for which a project might be implemented) from projects constructed in different sized sub-watersheds if a varying area-reduction factor were to be used.
- The storm event duration yielding a flood flow is assumed to be 24-hours, a time which is consistent with the large size of the watershed and occurrence of storm events having watershed wide impacts. Storm events of short duration with large peak flows may have significant impacts, but such impacts would be concentrated in the localized area of the sub-watershed where the storm event is presumed to occur. Short duration storm events are more subject to erratic location and severity. It is thus more difficult to account for their random occurrence over the lifespan of a project than it is to account for the random occurrence of larger scale, watershed wide storm events which are less subject to the impacts of spatial variability.

8.2.2 Computed B/Cs for Projects

Costs and benefits are used to compute B/Cs for defining potential priorities for proposed project construction. Computed B/Cs for various proposed project options are summarized in Table 8-1. Computed B/Cs vary widely, from as low as 0.2 to about 6.2. Because of this wide variation as well as the large number of projects, there is both a need and opportunity to eliminate a number of projects from consideration as part of a process to identify the most preferred projects.

8.3 Economically Efficient Projects

Economically efficient projects are those projects from among those evaluated for their B/C ratio for which the B/C ratio is above a critical level of approximately 1. Projects with a B/C ratio somewhat less than 1 may be considered among the economically efficient projects because of uncertainties in the estimated amounts of benefits and costs that obtain for a planning level study such as the current Study if the project has characteristics which on a case-by-case basis suggest reasons for its retention in the list of economically efficient projects.

Exhibits 8-1, 8-2, 8-3, and 8-4 display the B/C ratios for the various projects for which benefits and costs have been evaluated. Projects with B/C ratios above approximately 1 have a wide range of costs, as illustrated by these exhibits. These exhibits show the same information but for clarity limit the range of data listed. Exhibit 8-1 plots the B/C value against cost for all projects; all projects have a total cost of $1,200 million or less. For clarity, Exhibits 8-2, 8-3, and 8-4 plot the B/C value for projects with costs of $500 million or less, $100 million or less, and $25 million or less, respectively, with B/C values greater than approximately 0.6. For convenience, projects are also identified by the sub-watershed

Review of Exhibits 8-1 to 8-4 show a rather wide range of B/C and project costs; many projects of those evaluated have obviously low B/C ratios. Of particular note in these exhibits are the following features: 1) the high B/C values for projects in the C-12 watershed, a result which can be attributed to the relative high concentration of population in the C-12 watershed; 2) the obviously low B/C value for projects in the North Hayes watershed; and 3) the few projects for the South Hayes watershed which have B/C near or above 1. The low B/C ratios for the North and South Hayes watersheds can be attributed to the low population and limited number of repetitive losses in these watersheds (see Exhibit 3-2 in regard to the latter).

Economically efficient projects are identified in Table 8-2; there are 58 projects for which the B/C is greater than 1; another 20 projects fall in the 0.6 (approximately) to 1 range. Those projects with B/C values in the range of 0.6 to 1 which are included in the economically efficient list are included for the following reasons (see Table 9-2) in addition to the uncertainty in project costs and benefits:

- The project is part of a larger, overall project which is economically efficient; the economically efficient portion of the project would likely not be constructed in isolation of other project components.
- The project has a close similarity to another project which is economically efficient; the project is at least temporarily retained for consideration for comparison purposes.
- The project may be marginally efficient when considered as an add-on to a previously constructed economically efficient project. That is, the additional benefit obtained by the additional cost to achieve the addition may be economically efficient.

8.4 Structures Saved from Flooding

Among the benefits of various flood control projects is not only the reduction of flood damage, but also the reduction in the number of structures flooded (whether at shallow or deep depths). The reduction in the number of structures flooded may be an additional consideration for selection of a project from those with B/C value greater than 1. This criterion is not employed in this Study, but is presented because it does provide a distinguishing feature of various projects in addition to B/C.

An estimate of the average annual number structures removed from flooding was determined by estimating the statistical average annual depth of flooding. This estimate was made by determining the average annual depth of flooding from existing flooding conditions in the West Fork (using the existing flooding conditions removed the variation of average depth from one flood project to another). Flooding behavior in the West Fork was considered representative, from a statistical perspective. The flood event probability-weighted depth of flooding was found to correspond to an average annual depth of 2.5-ft, which corresponds to, using the generic depth-damage curve of Table 6-1, a structure value of $19,100. This average damage to a flooded structure was considered representative of the average damage to a structure in all sub-watersheds.

The estimated average annual number of structures removed from flooding by a particular project was computed as the average annual flood damage reduction benefit divided by the average damage to a flooded structure. Thus, if a project yielded an average annual flood damage reduction benefit of $286,500, the estimated annual number of structures removed from flooding would be $286,500/$19,100 = 15 houses.

Table 8-2 lists the computed average annual number of structures saved from flooding for the projects with B/C values greater than approximately 0.6. The numbers range 3 to 470. As a point of comparison, it is noted from the tabular data of Table 3.2.3 (in Section 3.2.3), the average number flood losses and complaints over a period of approximately 29 years for the CBW is approximately = 308/29 = 10.6. Thus, *on average*, to remove 10.6 houses from flooding each year, a project would have to generate an average annual benefit of $19,100 x 10.6 = $202,460, which corresponds to a present worth benefit of approximately $10 million. Except for Projects DP-18, DP-19, DP-22, DP-23, SI-4, and DP-24, all projects in Table 8-2 have present worth benefits which exceed this value.

SECTION 9

FINDINGS AND RECOMMENDATIONS

9.1 Findings

Potential projects to address on a watershed wide basis extensive riverine flooding in the CBW include channel conveyance improvements with either mitigation ponds or in-line detention to avoid adverse downstream impacts, diversion ponds, channel realignment, channel extension, improvements to hydraulic structures, and combinations of these types of these projects. Variants to these basic types of projects are generated by considering different levels of flood protection as described by the frequency of flood events. Approximately 160 different specific projects have been identified and evaluated for effectiveness and cost. The various projects do in fact achieve in varying amounts reductions in the estimated annual number of flooded residential structures, with numbers ranging from approximately 3 to as high as 470.

Project effectiveness has been evaluated in terms of reduction in the extent of flooding, the depth of flooding, and the frequency of flooding at different depths, using an estimated average value of a residential structure in the CBW of $88,500. Benefits are described in terms of expected average annual reduction in flood damage to residential structures and equivalent present worth of the annual reduction assuming a time horizon of 75 years and a social discount rate of 1 percent. The present worth of the reduction in flood damages to residential structures obtained by individual projects range from a low of $0.2 million to a high of $472 million.

Planning level project costs of the various identified projects have been estimated. These cost include direct construction costs (assuming commercial construction); costs for bridge upgrade or replacement when required by project features (e.g., channel widening); supplemental costs for such items as environmental assessment, engineering, special investigations (environmental and geotechnical), and permitting; and land acquisition. Land acquisition costs are based upon an estimated average cost of $11,262 per acre. Estimated total project costs for the various evaluated projects range from a low of $1.6 million to a high of approximately $1.1 billion.

Benefit-cost (B/C) ratios have been determined for the various identified projects in terms of the ratio of the present worth of flood reduction benefits to the estimated total project costs. Computed B/C ratios range from less than 1 to as high as 6.17. Of the various projects considered in detail, 58 projects have a B/C ratio of 1 or more. Benefit-costs and total projects costs have been used to identify a program of recommended projects; these recommended projects are described below.

9.2 Preferred Projects

Economically efficient projects (i.e., B/C >1) have been distinguished in Section 8. In selection of projects for actual implementation, total project cost is, in addition to B/C ratio, an important consideration. Other factors being equal (i.e., similar B/C values), projects of smaller costs are generally to be preferred. But the question is: How can the best choice of projects be made from among projects that have both high B/C and low cost values? The following provides an example of how this can be accomplished.

9.2.1 Distinguishing Superior and Inferior Projects

Examination of variation of B/C values and project costs in Exhibits 8-2, 8-3, and 8-4 show a tradeoff between B/C and project cost. This tradeoff is illustrated by the following example (the data for this example are given in Table 9-1):

Consider the Ditch C-12 watershed and the particular projects identified as Projects DP-13 to DP-24, i.e., 12 different diversion pond projects along Ditch C-12. These projects have been sorted by B/C in Table 9-1. Consider the relation between B/C ratios and costs: Project DP-13 has the highest B/C, and cost of $2.83 million. Projects DP-14, DP-15, DP-16, and DP-17 have a lower B/C and a higher cost; thus Project DP-13 is clearly better (i.e., “superior”) to DP-14, DP-15, DP-16, and DP-17. However, DP-18, while having a lower B/C also has a lower cost of $1.78 million. Thus DP-13 is not clearly superior to DP-18. Project DP-19 has higher costs than DP-13 and DP-18 but a lower B/C value; thus DP-19 is “inferior” to both DP-13 and DP-18. Considering Project DP-22, while having lower B/C ratio than either BP-13 or DP-18, it also has a lower cost than either DP-13 or DP-18; thus DP-13 and DP-18 are not superior to DP-22. The remaining projects (DP-20, -21, -23, -24) are inferior to DP-13, DP-18, and DP-22 because of both their B/C and their cost.

Thus, this sequential process results in, for this example, Projects DP-13, DP-18, and DP-22 being superior to the other nine Ditch C-12 diversion pond projects. From the perspective of B/C ratio and project cost, each of these project is equally good (these define what some refer to as the Pareto optimal solutions [Goodman, 1983, pg. 392]).

There is a remaining question: which of the three remaining options should be the preferred option? There are several choices: 1) the highest value for one of the two original criteria could be used; 2) other criteria could be considered, or 3) other factors might be considered, such as environmental issues, desires of political leaders, etc. In regard to the first option, the highest B/C is obtained with project DP-13, while the lowest cost project is obtained with Project DP-22, so this option still leaves one in a quandary.

Other criteria might be structures removed from flooding (in which case Project DP-13 would be preferred) but because of the way structures removed from flooding are estimated (see discussion of Section 8.4), the number of structures tracks the benefits and is not really an independent parameter. There is, however, another way to consider these last three projects: project sequencing and marginal benefit-cost. This procedure looks at a sequence of potential feasible project construction and examines the benefit-cost of each phase of addition project construction for a potential project sequencing plan. The following illustrates this by continuing the Ditch C-12 example.

The three projects identified by the superior/inferior analysis each involve construction of diversion storage (either as one pond or a series of ponds). Project DP-13 requires the largest amount of pond storage (hence its high cost), followed by Project DP-18, and then Project DP-22. Therefore, if a phasing-in of diversion ponds along Ditch C-12 were to be considered, Project DP-22 could first be constructed, and then later expanded to the pond size for Project DP-18, which could then even later be expanded to the larger size required for Project DP-13. From a diversion pond constructability perspective, sequential construction is possible. Thus, the sequence of project construction, costs, and benefits would be as illustrated in the following table:

Table 9.2.1 Example of Incremental Economic Analysis

Project	Cost	Benefit	Incremental Cost	Pond Size (ac-ft)	Incremental Benefit*	Incremental B/C
DP-22	$1.56M	$2.16M	$1.56M	42	$2.16M	1.38
DP-18	$1.78M	$3.24M	$1.14M	48	$1.08M	2.86
DP-13	$2.83M	$17.46M	$1.05M	76	$14.22M	13.54

*Note: For the first project, incremental values are also the total values

Thus sequential construction (when feasible) could ultimately achieve the final project but done with outlays of monies in smaller increments, with each outlay being worth the additional benefit, i.e., the incremental benefit achieved more than compensates for the incremental cost of construction. In performing this "marginal" benefit-cost analysis, it is assumed here for this planning Study that the incremental cost of construction is closely approximated by just the difference in costs of the two separate projects, but in fact if sequential construction is anticipated the true incremental cost may be smaller because the project design can incorporate features which will facilitate future expansion.

Note that if other factors (i.e., constructability issues) affect the proposed sequential construction, then they would have to be considered as well. Thus, in this example, each of the diversion ponds bypasses an initial amount of flow which is different than the other option (i.e., the bypassing flow is the 10-, 5-, and 2-yr frequency flow, respectively, for

DP-22, DP-18, and DP-13). Thus, the pond intake and outlet structures for each project would be different, but these differences, in this case, would be expected to be of minor effect in comparison to the change in pond size that each project requires.

If a project has no prior phasing, then the total cost and benefit are also the marginal cost and benefit. If the marginal B/C is not greater than 1 when phasing of a project is considered, then one would not usually consider phasing of the project in question.

9.2.2 Preferred Economically Efficient Projects for Sub-Watersheds

Preferred economically efficient projects are those projects which have a high B/C ratio and a relative low cost such that no project is superior to the other. In the example of Section 9.2.1, these projects were DP-13, DP-18, and DP-22.

Table 9-2 identifies preferred economically efficient projects for projects within one particular subwatershed and of one particular type of project as determined by the superior/inferior types of analysis described in the example of Section 9.2.1. (Projects excluded from the list of Table 8-2 as a result of the superior/inferior are shaded.) Thus for example, of Ditch C-12 projects which are to be designed to use a combination of diversion ponds and conveyance improvements (denoted by "CO" projects), there are 3 projects (CO-13, CO-18, and CO-22) out of a total of 12 CO projects which are neither inferior or superior in both B/C ratio and cost.

Reviewing Table 9-2, there are a variety of types of projects for the different sub-watersheds which for a particular sub-watershed and project type are considered preferred economically efficient projects. Excluding the siphon projects (discussed separately below), 16 projects are considered preferred economically efficient projects.

9.2.3 Preferred Projects for Individual Sub-Watersheds

When the constraint of project type is removed and all preferred economically efficient projects for a particular sub-watershed are compared in terms of B/C and cost, review of Table 9-2 yields the following: There are 5 siphon projects (which are discussed in detail below), 1 joint siphon and diversion pond project (SI-5/DP-13, a special project discussed at greater length below); 2 projects for the South Hayes Creek sub-watershed, no projects for the North Hayes Creek sub-watershed, 2 projects for the West Fork, 7 (non-siphon) projects for the Ditch C-12 sub-watershed, 2 projects for the Chocolate Bayou/East Fork sub-watersheds, and 3 projects for the Brunner Ditch system, thus yielding in all 22 potential projects.

These 22 projects are further culled by the following considerations.

Project BR-1B has a B/C value less than 1 and is also inferior in cost to BR-2B and BR-3B. It is thus eliminated from the preferred list.

The South Hayes Project CO-46 has a B/C less than 1. In addition, the South Hayes conveyance improvement project (CV-25) is in an area with only limited population, i.e., the South Hayes watershed and consequent benefits are limited (as reflected in the low B/C value of 1.08). While development in the watershed will occur in the future, the watershed is not currently a rapidly developing area. Consequently, this project is removed from the preferred list of projects.

The West Fork Project CO-58 has a lower B/C value and a higher cost than the West Fork Project CV-28; thus Project CO-58 is eliminated.

The Chocolate Bayou Project CV-16 has a higher B/C value than CO-10 as well as a lower cost; thus CO-10 is eliminated from the preferred list of projects.

Of the Ditch C-12 projects, Project DP-13 is superior in B/C and cost to Projects CO-13, CO-18, and CV-19; thus Projects CO-13, CO-18, and CV-19 are dropped from the preferred list of projects.

Examining the three remaining Ditch C-12 projects, DP-13, DP-18, and DP-22, it is seen that none is completely superior or inferior to the others. However, these three diversion projects along Ditch C-12 are readily suited for phased construction since a sequential increase in pond size can be accomplished over a period of time, the order of the projects based upon an increasing storage volume being DP-22, DP-18, and DP-13. However, the increase in storage volume for Project DP-18 is only an estimated 6 ac-ft more than Project DP-22 (see Table 9-3). This small increase is reflected in the small increase in project cost for Project DP-18 over DP-22. The small increase, furthermore, yields a project with a relatively large increase in B/C ratio (i.e., increasing the B/C value from 1.38 to 1.82). Since the overall cost for DP-18 is not significantly different than the cost for DP-22, it is concluded that if the diversion projects along Ditch C-12 were to be built, the first project in a phase construction program would be DP-18 rather than DP-22. Thus Project DP-22 is dropped from the preferred project list.

The remaining projects resulting from this superior/inferior and phasing analysis yields the 11 (unmodified) projects of Table 9-3 (the SI-5/DP-13 project is a special case discussed below). For reader convenience, the estimated number of structures removed from flooding each year by each project is listed; Section 8.3 has discussed how these numbers are estimated.

9.3 Recommended Master Program Projects

The recommended unmodified projects of Table 9-3 define a master set of recommended projects. Their proposed order of construction (1, 2, 3, etc.) is based upon B/C and construction phasing considerations. The projects listed are "ultimate" projects, i.e., the projects as they would be ultimately constructed if carried to full implementation. Collectively, they define a recommended long term program of watershed wide master projects. They are meant to guide the selection of individual projects which would be implemented over the long term to achieve the overall benefits estimated by this Study.

Because of their considerable cost, it is recognized that *full* implementation of all projects in the foreseeable future is highly unlikely; *recommendations and considerations for partial or modified construction are discussed below*. Consequently, these "ultimate" projects serve as targets by which interim projects can be identified, structured, engineered, and constructed so as to be consistent with a long term program of effective and beneficial flood control improvements.

General locations of the "ultimate" projects are shown in Exhibit 9-1. Economic features of the projects are summarized in Table 9-3. Key design-related parameters are summarized in Table 9-4. The following discusses the individual "ultimate" projects in their recommended order of implementation.

9.3.1 Project DP-18

This project is a diversion pond project on Ditch C-12 in the upper reaches of the CBW near the eastern boundary of the CBW (see Exhibits 9-2A and 9-3), where it is noted from Exhibit 3-3 that possible flood damages are severe. This is a mid-size diversion project which obtains its benefits by bypassing 5-yr and smaller floods without diversion but capturing larger floods, with the diversion ponds sized to retain flood volumes from flood events up to a 10-yr frequency. This range, while limited, significantly reduces flooding for more frequent events and provides a relatively low cost project (an estimated $1.78 million) to implement in the near term in the upper reaches of the CBW.

Exhibit 9-2A shows the predicted floodplain for a 10-yr flood event with and without the project. The extent of the 10-yr floodplain is somewhat reduced from the current 10-yr floodplain. What is not evident in this depiction of the flood conditions is that the depth of flooding with the project in place is less than the existing condition; this reduction of flood depth for storms of 5-yr and larger flood events is the primary source of the flood benefits yielded by this project. The differences between flooding conditions with and without the project decrease as the flood event becomes larger. At a 100-yr flood condition, little difference between the existing conditions and the proposed project occur (see Exhibit 9-3).

Project DP-18 has a benefit cost ratio of 1.82, which is not a project with the highest B/C. However, the priority for this project was selected because this project provides a comparatively low cost project which is the first step for another larger project (DP-13, discussed below) which has a significantly higher cost B/C but also a much larger cost.

The total diversion volume for DP-18 is an estimated 48 acre-feet (ac-ft), as listed in Table 9-4. This volume can be provided by one or, more likely, a series of ponds spread along the length of Ditch C-12 at locations of available land; the preliminary evaluation of the effectiveness of this diversion pond does not distinguish the precise location or number of the diversion ponds; location and pond numbers would be determined as part of the engineering design of the diversion pond system.

9.3.2 Project CV-16

This project is a conveyance improvement project along Chocolate Bayou (and the East Fork of Chocolate Bayou) from the upper reaches of the East Fork downstream to Chocolate Bayou and thence downstream along Chocolate Bayou to the saltwater barrier a short distance upstream of Liverpool (see Exhibits 9-5 and 9-6). This conveyance improvement would raise the capacity along the entire length of the project to a full 2-yr flood event capacity. Mitigation to prevent adverse downstream impacts to Liverpool and other residential areas like Snug Harbor (the latter is a small community a short distance upstream of FM 2004, which crosses Chocolate Bayou near the lower end of the CBW; see Exhibit ES-1) would be required, either with off-line mitigation ponds distributed along the channel, in-line mitigation by over-widening of the improved channel, or a combination of the these two mitigation methods. The widening would also remove much of the small and heavy vegetation along the current banks of Chocolate Bayou. The necessary widening assuming in-line mitigation is given in Table 9-4.

If this project were implemented, the cost, because of the long length of the project, would be an estimated $83.28 million, but its benefit would be large, more than $200 million (see Table 9-3), resulting in a B/C value of 2.65. The reduction in flooding due to the project is evident in Exhibits 9-5 and 9-6. For a 2-yr storm event, virtually all flooding along the East Fork and the main stem of Chocolate Bayou to the saltwater barrier is eliminated (see Exhibit 9-5). For the 100-yr flood event, the extent of flooding is still significantly reduced by the project (see Exhibit 9-6). Major beneficiaries of the reduced flooding would be the cities of Manvel and Alvin, and subdivisions along the Chocolate Bayou generally between these two cities. However, environmental impacts may make this project or major portions of it below the confluence of Chocolate Bayou and South Hayes Creek unlikely to be fully implemented. Even if it were feasible to fully implement, it would likely require the development of major environmental mitigation projects because of the impacts the project would have on natural habitat and wetlands along much of Chocolate Bayou (the cost for such environmental mitigation is not included in estimated project cost).

9.3.3 Project CV-28

This is a conveyance improvement project along the West Fork of Chocolate Bayou (see Exhibits 9-7 and 9-8). The project, as evaluated for its costs and benefits, extends the full length of the West Fork from the Brazoria-Fort Bend County line downstream to the confluence with Chocolate Bayou. The length and representative width of the channel widening is given in Table 9-4, and is based upon a 2-yr flood event frequency, i.e., the channel is widened to contain without overflow a 2-yr flood event. Mitigation is an essential feature of this project; for CV-28, the mitigation is presumed to be provided by in-line detention, but off-line detention, when examined in detailed engineering, may be as cost efficient as in-line detention.

While costly (the project has an estimated cost of $36.54 million; see Table 9-3), the project has a B/C of 2.27. Exhibits 9-7 and 9-8 show the beneficial effect of flood reduction the project will yield. For the 2-yr flood (Exhibit 9-7), virtually all flooding is eliminated along the West Fork. Even for the 100-yr flood (Exhibit 9-8) significant reductions in floodplain extent due to the project are achieved. Another aspect of this project is that it can be a precursor to a more extensive project (BR-2 discussed below) and the costs for this project can lessen the costs of other projects involving the West Fork.

9.3.4 Project BR-3B

This is a Brunner Ditch project which would achieve many of the same benefits of Project CV-16, but at a greater cost. Brunner Ditch is currently a small and largely man-made ditch extending from the vicinity of the South Hayes Creek (the precise upstream end of Brunner Ditch is difficult to define because of its small size) southward to the vicinity of the CBW boundary where it begins to parallel an existing GCWA raw water canal before turning to the northeast to intersect Chocolate Bayou near Liverpool but upstream of the saltwater barrier (see Exhibit 9-1).

Three projects, BR-1, BR-2, and BR-3, were initially considered for improvement of Brunner Ditch. (The notations of A and B after the 1, 2, or 3 designation, e.g. BR-2B, are merely used to distinguish the type of mitigation proposed for the project, either A off-line detention or B for in-line detention.) Project BR-1 envisioned extension and widening of Brunner Ditch northward more or less along its current alignment to the West Fork, and then possibly northeastward to the East Fork (see Exhibit 9-1). Project BR-2 envisioned extending Brunner Ditch from the vicinity of the GCWA raw water canal northward along an alignment which intersected the downstream ends of the North and South Hayes Creeks and the West Fork of Chocolate Bayou (see Exhibit 9-1). Project BR-3 envisioned the northward extension of Brunner Ditch beginning as in Projects BR-2 and BR-3 but veering off towards Chocolate Bayou and connecting with

Chocolate Bayou below the confluence of South Hayes Creek and Chocolate Bayou. Evaluation of costs and benefits led to the conclusion that Project BR-1 was inferior (in terms of B/C and cost) to both Projects BR-2 and BR-1. Of these two latter projects, it was concluded that implementation of Project BR-3 before Project BR-2 was preferred because 1) the lower cost of implementing BR-3, 2) the ability to use the improvements of BR-3 project as part of the BR-2 project, and 3) Project BR-3 achieves some of the same benefits that the environmentally impacting Project CV-16 provides. In regard to the latter, compare the areas of floodplain reduction for the 100-yr flood for Project BR-3B shown in Exhibit 9-5 to Exhibit 9-9; while different, both projects do have obvious benefits to the area from Alvin southward to area of the saltwater barrier.

Project BR-3 envisions the widen of the existing Brunner Ditch along the GCWA canal and its tie-in with Chocolate Bayou, the extension of Brunner Ditch towards Chocolate Bayou, and the widening and grade reversal of an existing Chocolate tributary north of Alvin (see Exhibit 9-9). The grade reversal would allow flood flows from Chocolate Bayou to flow to the widened Brunner Ditch. The widening of the existing Brunner Ditch would be sized to handle an approximately 100-yr flow (see Table 9-4); the existing ditch for which the grade is to be reversed might be widening to a level less than a 100-yr diverted flow (perhaps about a 75-yr frequency), depending upon the right-of-way needed vs. that which is actually available; some residential developments along the reversed grade ditch may limit right-of-way availability. Irrespective of the actual flood frequency flow diverted from Chocolate Bayou, the project would seek to increase the ultimate width of the existing Brunner Ditch channel to a 100-yr capacity to meet the needs of Project BR-2 (discussed below).

Project BR-3, assuming construction methods as for other projects considered in this Study (special issues related to construction of the Brunner Ditch Project are discussed below), would cost an estimated $93.74 million, but achieve a B/C value of 1.86. Particular beneficiaries of this project would include Alvin and subdivisions between Alvin and the saltwater barrier near Liverpool.

9.3.5 Project SI-1

This project is a siphon improvement project located on the West Fork Tributary A; see Exhibit 9-4. This project is only one of five different potential siphon improvement projects; other siphon improvement projects are separate projects discussed below. This project consists of improvement of the East Fork Tributary A siphon system under the Gulf Coast Water Authority (GCWA) Briscoe Canal and channel conveyance improvements upstream of the improved siphon. The conveyance improvements are intended to provide for more hydraulically efficient removal of flood waters from regions upstream of SH 6 and also consequently reduce flooding and overtopping of SH 6 in the general area of the West Fork Tributary A. This project is intended to provide protection from the 100-year flood level. The approximate size of the conveyance improved channel is given in Table 9-4.

In addition, to prevent adverse downstream the project includes as an essential component an approximately 1500 ac-ft downstream mitigation pond (see Exhibits 9-4 and 5-19) to prevent increased flows to downstream reaches of the tributary and the West Fork of Chocolate. The cost of this mitigation pond is included in the overall project costs.

The SI-1 Siphon improvement project of the West Fork Tributary A has an estimated cost of $37.6 million and a B/C of 1.64. These benefits derive from elimination of flooding along the West Fork Tributary A upstream of the siphon, as depicted in Exhibits 9-4 and 5-19. The flooding eliminated by this project along the tributary lies within one of highest areas of flood damages in the CBW (see Exhibit 3-3)

In addition, the estimated benefits of this project include partial elimination of flooding along SH 6; the other siphon projects (discussed below) will also contribute to eliminating SH 6 flooding. Based upon an a very approximate estimated $18.5 million dollars of benefit from elimination of flooding of SH 6 and allocation of ¼ of that total to the SI-1 project, the B/C ratio for this project increases to 1.76.

9.3.6 Project SI-2

This project increases the capacity of the siphon system along the West Fork Tributary B (see Exhibit 9-4). In concept, this project is similar to the siphon improvement along the West Fork Tributary A. The siphon capacity is increased to a 100-yr flow level and the conveyance of Tributary B upstream of the siphon is also increased to a 100-yr flood flow capacity. Mitigation storage downstream of the siphon improvement is also an integral part of the project (see Exhibits 9-4 and 5-19).

This project will generally eliminate the flooding upstream of West Fork Tributary B, but will cost an estimated $21.04 million, achieving a B/C value of 1.19. If the allocated estimated benefits of flood elimination along SH 6 in the West Fork Tributary B sub-watershed are included, the B/C rises to approximately 1.41.

9.3.7 Project BR-2B

This project (shown in Exhibit 9-9) builds upon Project BR-3B. The project envisions widening the existing Brunner Ditch (which would actually be accomplished as part of BR-3) and extension of Brunner Ditch northward to intersect the North and South Hayes Creeks and the West Fork of Chocolate near their confluences with Chocolate Bayou. In addition, conveyance improvements to the North and South Hayes Creeks and the West Fork would be made to bring the capacity of the improved and extended Brunner Ditch, the North and South Hayes Creeks, and the West Fork up to a 100-yr flood capacity level. An essential part of the conveyance improvements would include mitigation using either in-line detention or off-line storage detention ponds.

This project would not only make use of the improvements to Brunner Ditch made as part of Project BR-3, but also the improvements to the West Fork made as part of Project CV-28. This Brunner Ditch project assumes the prior construction of Project BR-3 (or other modifications to BR-3) and Project CV-28 as described under the constructability column of Table 9-3. The reduction in flooding achieved by this project would be significant, as illustrated by the reduction of the 100-yr floodplain shown in Exhibit 9-10. Project features are summarized in Table 9-4.

Assuming the entire BR-2 project is constructed (including the prior construction of Project BR-3 and CV-28), the incremental cost of the project would be (see Table 9-4) $97.12 million and provide an additional $297.50 flood reduction benefits to yield a B/C ratio for the incremental investment of 3.06.

A modification to either Project BR-2 or BR-3 could be made by extending the existing Brunner Ditch to the south so that it rejoins Chocolate Bayou near FM 2004 by discharging to the existing Cottonwood Creek, a tributary to Chocolate Bayou near the downstream end of Chocolate Bayou near the community of Snug Harbor (see Exhibit ES-3). The benefit of this route would be reduction of flood flows along Chocolate Bayou downstream of the saltwater barrier, thus potentially reducing flooding in the vicinity of Liverpool. However, this downstream segment of Chocolate Bayou is tidally affected, and the reduction in flood discharges is not readily evaluated using the riverine models of this Study since tidal effects will create backwater effects which will limit water surface elevation reductions arising from upstream flow reductions. More significantly, the extension of Brunner Ditch would entail considerable additional cost for excavation which would more than double the length of the existing Brunner Ditch. Without special considerations which might reduce these costs (as discussed below), the extension of Brunner Ditch to the south would not be expected to warrant the additional cost. Consequently, detailed cost and benefits of extending Brunner Ditch to the south of its current alignment were not evaluated in detail.

9.3.8 Project DP-13

This is a diversion pond project along Ditch C-12 (see Exhibits 9-2B and 9-3), similar to Project DP-18, but one which is larger and more effective than DP-18. DP-13 envisions diversion ponds along Ditch C-12, but lowers the bypass flow to a 2-yr flood frequency and capture flood volumes up to 5-yr flood event (because of the 10-yr capture frequency of the ponds for the DP-18 project, actual flood capture limits may be larger than the 5-yr flood level). The total diversion pond volume (see Table 9-4) will require an approximate doubling of the pond volume of Project DP-18, but as seen from Exhibit 9-2B, flood extent in addition to flood depth will be significantly reduced for intermediate size flood events.

The cost of the project can be reduced by utilizing the diversion storage already constructed for Project DP-18. The incremental cost of the construction for DP-13 thus becomes an estimated $1.05 million while the additional flood benefits become $14.2 million, yielding an extremely high B/C value of 13.53, which results from the low incremental cost that implementing this project if Project DP-18 has already been constructed.

9.3.9 Projects SI-3, SI-4, and SI-5

The remaining projects recommended for potential implementation are the siphon projects for the East Fork Tributaries A and B and Ditch C-12 (see Exhibit 9-4). These projects are similar in concept to siphon improvement Projects SI-1 and SI-2. Of these three projects, only Project SI-4 has a B/C greater than one (see Table 9-3) and is therefore the only project justified from purely economic grounds.

Even when the allocated benefits of reduced flooding along SH 6 are recognized, Projects SI-3 and SI-5 (SI-5 does not significantly affect flooding along SH 6) are not economically justified. Yet, if flooding upstream of the siphons is to be fully eliminated, all the siphon projects (in addition to Projects SI-1 and SI-2) will require implementation; if the evacuation capabilities of SH 6 are to be achieved, all four siphons (SI-1, SI-2, SI-3, and SI-4) will need to be constructed, despite the low B/C ratios for SI-3.

Thus, whether the three siphon improvement projects should be implemented must incorporate factors in addition to just economic merit. If elimination of SH 6 flooding is considered to be essential, then Projects SI-3 and SI-4 should be constructed. On the other hand, Project SI-5 (the siphon improvements for Ditch C-12) might be combined with Projects DP-18 or DP-13 to make it more attractive; this latter possibility is discussed below.

9.4 Practical Considerations for Refined Project Recommendations

Selection of the recommended projects described above assumes ultimate project implementation and an economic justification based largely upon B/C values using a consistent methodology for estimating costs and benefits. Refinement of recommended projects, however, recognizes the significant costs for the various projects in comparison to the available monies for construction and special factors which may change the cost and benefits. These factors are described in the following as the basis for developing a refined list of recommended master level projects.

9.4.1 Modification to Project CV-16 Because of Environmental Impacts

The potential environmental impacts and resulting difficulties in implementing this project in its entirety (i.e., along the full length of the East Fork and Chocolate Bayou downstream to the saltwater barrier) are considered sufficiently impeding that Project CV-16 is not recommended in its entirety. A modified project of channel conveyance improvement along only the East Fork above the confluence of the East Fork and the main stem of Chocolate Bayou would be recommended for consideration in place of the CV-16 project. The estimated B/C ratio of this modified project, identified as Project CV-16-Mod, would be similar to that of the original project but its expected cost (based upon the relative lengths of the total and modified project) would be reduced to an estimated $26 million, as listed in Table 9-3.

9.4.2 Reduced Excavation Costs for Bruner Ditch Projects

Because much of the length of the Brunner Ditch options (BR-2 and BR-3) is located in rather undeveloped areas, there exists a realistic opportunity for construction of major portions of the ditch by drainage districts and other local entities. In addition, in such rural areas modified construction techniques can be used; these techniques would allow excavated materials for ditch widening to be placed along the ditch rather than being disposed of at some off-site location. Excavation cost should therefore be considerably reduced. Furthermore, land for the widened ditch might be donated by land owners because excavated materials could be used to build up the land owner's property and further remove it from flooding.

While the specific reduction in costs that might be achieved by such techniques is not known without additional information about actual work and procedures that might be undertaken by local entities, an optimistic estimate of the impact on the construction costs would be to assume that project costs for the widening of the existing Brunner Ditch (as well as extensions to the south should the southward extension be included in the Brunner Ditch projects) would be borne by local entities through in-kind construction services. The cost for these services would correspond to approximately $88.3 million of equivalent direct commercial contractor costs determined by the cost modeling of this Study. However, of this amount, in-kind services would still incur, indirectly, costs. Assuming the commercial costs without profit and other commercial-only costs would be about 2/3rd of the total costs, the estimated true reduction in costs obtained by using in-kind services would be approximately 33% of $88.3 million, i.e., about $29 million. This would reduce the Brunner Ditch Project BR-3 to approximately $65 million. The overall project cost for such a modified project (i.e., with local entities providing in-kind excavation), designated as Project BR-3B-Mod, would considerably enhance the value of this project, raising the B/C value (as shown in Table 9-3) to approximately 2.7.

9.4.3 Brunner Ditch and the Grand Parkway

The future construction of the Grand Parkway in the general vicinity of the existing Brunner Ditch offers an opportunity for significant savings to both projects. Excavated material from the Brunner Ditch widening could be placed along the proposed alignment of the parkway and used for parkway construction, including the raising of the roadbed to levels above the 100-year flood level.

In addition, a related benefit of the Brunner Ditch project will be the lower of flood levels in the floodplain along Brunner Ditch. This lowering will lessen the required height of the parkway necessary to keep the roadway above the 100-yr flood level. This indirect benefit was not recognized in benefit evaluation for the Brunner Ditch projects, but like lessen of the flooding of SH 6, this benefit could be substantial for the Brunner Ditch projects.

9.4.4 Combining Siphon Project and Diversion Ponds for Ditch C-12

Siphon improvement project SI-5 is the second least cost effective of the recommended projects, including the other siphon projects. However, Project SI-5 is located on Ditch C-12 where diversion pond projects DP-18 and DP-13 are proposed. Modification of project DP-13 to incorporate mitigation storage for the SI-5 project could lower the overall cost of the two projects. Based upon a length prorating of the channel affected by the two individual projects, the benefits and costs for a combined project were determined in Section 8 (see Table 8-1). Accounting for the assumed prior construction of the diversion pond for DP-18, the combined project cost is approximately $52.9 million while the benefits (from Table 8-1) are approximately $58.2 million, yielding a B/C value of 1.10. Because of the approximations used in estimating the costs and benefits for this joint project, the B/C value should be considered only approximate; thus from a practical standpoint, combining the SI-5 and DP-13 projects yields a project which is only marginally acceptable from a B/C viewpoint.

9.4.5 Reduction of Siphon Project Design Frequency

The various siphon improvement projects have been evaluated on the basis of a 100-yr frequency event. That level of design requires major mitigation detention storage. To reduce costs, a lesser design frequency could be considered for all the siphons, but particularly for the siphon improvement projects SI-4 and SI-5, for which the B/C is considerably less than 1 (if not combined with other projects as discussed in the previous section).

To effect a project of lesser design but provide for the flexibility to meet potential future needs, the siphons improvements themselves could be designed for a 100-yr frequency flood but be restricted (with downstream restrictors at the outflow points from the siphons) so that the capacity of the restricted siphons matched the capacity of the channel improvements upstream of the siphon and mitigation storage capabilities of the detention ponds downstream of the siphons.

9.4.6 Elimination or Delay of Less Beneficial Project Elements

Elements of some projects are not as beneficial as other elements. In particular, the Brunner Ditch Project BR-2 envisions conveyance improvements to the North and South Hayes Creeks. In the long term, such improvements may be desirable, but the North and South Hayes watersheds currently have limited development, a fact which is reflected in the relatively low levels of potential flood damage shown in Exhibit 3-3 for these two watersheds. Consequently, the beneficial impact of flood reduction in these two watersheds is in, a relative sense, small. This in turn suggests a modification to Project BR-2 that would eliminate the conveyance improvements for the North and South Hayes watersheds from the project.

The revised project, Project BR-2-Mod 1, would have a smaller cost and smaller benefit, but with somewhat disproportionate reductions (because primarily of the disproportionate number of residential structures in the 100-yr floodplain areas within and without of the North and South Hayes watersheds) favoring a higher B/C. Removal of the conveyance improvements (along with necessary mitigation) would reduce project costs by approximately $53 million while the benefits would be reduced by an estimated $58 million. These changes would yield a B/C value for the Project BR-2-Mod 1 of 1.97 as compared to 1.68 based upon the marginal costs and benefits of construction of BR-2 after construction of the BR-3B project. Furthermore, if the in-kind services for excavation of BR-3 are used, the cost of BR-2 resulting in a Project BR-2B B/C value of 2.56 (see Table 9-3).

9.4.7 Incremental Frequency Design for Projects

Consideration should be given to incremental increases in project capacities rather than initial construction at the full capacity of the ultimate project. Projects DP-18 and DP-13 are in fact just such projects. The diversion storage of DP-18 is only approximately ½ of the ultimate diversion storage for Project DP-13. Use of constrictors on siphon projects is also an incremental approach to development of capacity so that less costly conveyance improvements and mitigation could be initially constructed with the siphon improvement projects.

The Brunner Ditch projects also represent projects for potential incremental development. With appropriate engineering which recognizes the ultimate capacity to be achieved by the project, ditch widening of the existing Brunner Ditch could be undertaken in stages which would provide for increasing capacity at each stage. If such staging is used, then, as well, appropriate staging of conveyance improvements in the tributaries intersected by the extended Brunner Ditch will have to be also done so that the possibly unmitigated discharges do not exceed the capacity of Brunner Ditch at the time the tributary conveyance improvements are completed.

Incremental frequency design appears to offer an important opportunity for achieving flood reductions along Chocolate Bayou between Alvin and Liverpool, an area where Project CV-16 in, in its unmodified form, would be difficult to implement because of environmental concerns. Project BR-3B will alleviate flooding along Chocolate Bayou in this Alvin-Liverpool reach. The level of flow diversion from Chocolate Bayou can be reduced below the ultimate level of diversion to a level consistent with the existing capacity of the existing Brunner Ditch; based upon the CV-16 project a target level of diversion would be on the order of a 2-yr flow. Such a diversion is expected to require only limited improvements to the existing Brunner Ditch.

9.4.8 In-line Detention and Off-Line Detention Ponds for Mitigation

The recommended projects requiring mitigation were found to be those which utilized in-line mitigation. However, the difference in costs of using in-line mitigation and off-line detention ponds are sufficiently small that these two mitigation options should always be examined on a project-by-project basis before final design of a project is undertaken.

9.4.9 Piecewise Conveyance Improvement and Mitigation

No project has to be built in its entirety at one time. In the case of conveyance improvements of a channel, selected reaches can be improved on a piecemeal basis *provided that appropriate mitigation* is incorporated with each element. Improvements along the West Fork appear to offer the greatest opportunity of piecewise implementation, with individual channel reaches being selected in light of right-of-way conditions, joint funding opportunities, and interaction with land development activities. The upper reaches of the West Fork appear highly suitable for initial development because of the high density of potential flood losses in this area (see Exhibit 3-3).

In addition, selection of reaches for improvement should avoid reaches encompassing bridges, so that bridge improvements costs can be kept to a minimum until such time that they must be incurred to continue improvements along particular reaches.

9.4.10 West Fork Conveyance Improvement in Arcola Area

While detailed models were not available for determining conveyance improvement needs along the West Fork of Chocolate Bayou in Arcola in Fort Bend County, the extension of Projects CV-28 and BR-2 into Fort Bend County and Arcola would have obviously high benefits because of the concentration of potential flood losses in Arcola (see Exhibit 3-3). Extension of Project CV-28 into Arcola is identified as Project CV-28-Mod in Table 9-3. Preliminary estimates based upon unit costs for Project CV-28 suggest that Project CV-28 could be extended into and across Arcola for a cost of about $8.4 million. The B/C ratio for this extension would be expected to be similar to that for Project CV-28 (i.e., about 2.2). More detailed evaluation of extension of CV-28 into Fort Bend County would need to be undertaken to refine the cost and benefit estimates for the extension, but such evaluation would be expected to yield a slightly higher B/C ratio due to the high level of flood damages in the Arcola area.

9.4.11 Refined List of Recommended Projects and Priorities

The above described practical considerations lead to a refinement, due to anticipated cost and benefit modifications, of project scale and priority. These revised projects and priorities are listed in Table 9-3 under the modified project priorities column.

Of the 11 initial projects, the siphon improvement SI-5 is combined with the diversion pond project to create the SI-5/DP-13 project. Project DP-13, by itself, is retained as a possible alternative, but a combined Project SI-5/DP-13 in place of Siphon SI-5 alone is considered as an alternative. Extension of West Fork improvements into Arcola, Project CV-28-Mod, is included as an additional project. Projects 3B-Mod and 2B-Mod 2 would be alternatives to Projects 3B and 2B-Mod 1 if in-kind services that Projects 3B-Mod and 2B-Mod 2 envision could in fact be obtained. Thus the number of projects in the list of potential projects increases to a total of 13.

The modified channel improvement project CV-28-Mod moves to the highest priority because of several factors: 1) The project has a relatively high B/C ratio (2.21); 2) this project can and would be expected to be expanded (in terms of flood capacity) in the future to become an integral part of the Brunner Ditch BR-2 project; and 3) the total project can be relatively easily decomposed into sub-projects which can be individually implemented.

In regard to the latter factor (project decomposition), it is noted that the estimated cost for project implementation is on the order (depending upon the number of bridge replacements required) of $4.2 million per mile. A mile or so long widening in the more critical stretches of the West Fork could therefore likely be accomplished for less than $5 million.

The first diversion pond project along Ditch C-12, Project DP-18, remains at a relatively high priority for several reasons: 1) it has a moderately large B/C value; 2) its overall cost is relatively small (less than $2 million), and 3) it is the initial phase of a more comprehensive project, DP-13 (or a combined SI-5/DP-13 project), which has a high B/C value because of its ability to capitalize on the initial construction accomplished for Project DP-18.

Brunner Ditch Project 3B (or 3B-Mod) project move ups in priority because of the potential for in-kind construction services to be provided by local entities for construction of the widening of the existing Brunner Ditch. In addition, the BR-3 project replaces many of the benefits along Chocolate Bayou downstream of the confluence with South Hayes Creek which are lost if the full length of Project CV-16 is not implemented (see discussion above Section 9.9.7).

Project CV-16 remains in the recommended projects in a modified form (i.e., CV-16-Mod). This project is the only project which focuses on the East Fork above the confluence with the West Fork. This project is also amendable to piecewise implementation.

Project DP-13 builds upon the assumed prior construction of Project DP-18. Because of the costs already absorbed in the DP-18 project and the relatively limited extent of the project, it requires only a relatively small incremental cost to implement and yields a very high B/C for this incremental investment. However, it might be jointly constructed with SI-5 in which, because the combined projects would have a low B/C, DP-13 project would be delayed if the SI-5/DP-13 were to be jointly constructed.

Siphon improvements Projects SI-1 and SI-2 on the West Fork are proposed for the next level of priority because of their moderately high B/C values, the high flood losses in the Arcola area, and the cost connection these projects have with West Fork improvements.

The estimated relatively high CV-28 Mod project (extension of the West Fork improvements into the Arcola area) puts this project moderately high on the priority list.

Brunner Ditch Project 2B-Mod 1 (or Project 2B-Mod 2, depending upon availability of in-kind services) is placed next in priority to capitalize not only on the prior construction of Project 3B, but also the benefits of improvements to the West Fork. This modified project would also capitalize on the cost reductions of removing (for the near future) the North and South Hayes Creek improvements from these projects.

The remaining siphon improvement projects round out the list of priorities. A higher priority for the siphon improvement projects would obtain if reduction in effective siphon capacity were considered so that mitigation requirements and costs were lowered.

9.5 Factors Affecting Project Implementation Recommendations

The recommended modified projects are selected using economic considerations based largely upon the economic efficiency of repetitive loss flood damage reduction. However, other practical factors can and will very likely enter into project choice and phasing plans. These factors include the following.

Environmental Impediments: Different projects can be expected to encountered different levels of environmental impact. Projects which require widening of Chocolate Bayou downstream of the confluence of the East and West Forks as far downstream as Liverpool are considered to be particularly environmentally sensitive and thus more difficult to implement. Project CV-16 is just such a project.

Aesthetic Features: Various projects envision channel conveyance improvements which involve widening of the channel. The analyses did not assume the channel alignment to be straightened; the natural channel alignment was maintained in project evaluation. Besides maintaining natural channel alignments, consideration should be given in detailed engineering design to creating a widening which is more environmentally friendly and aesthetically pleasing. This includes using benching along reaches or in curves to allow development of natural habitat on land which only occasionally floods. Aesthetically pleasing effects can also be created by allowing expected floodplain areas (i.e., areas not intended to be removed from flooding) to be maintained in a natural state rather than cleared. Some of these aesthetic features will require increased right-of-way beyond that estimated in this Study. However, if in-line detention is used for mitigation, the additional channel width could be combined with aesthetic features and/or replaced by aesthetic features in conjunction with mitigation ponds replacing the in-line mitigation.

Availability Land for Land Acquisition: The location and amount of land acquisition required easements or right-of-way for various projects may affect project preferences. Projects which required land acquisition in less developed portions of the county can be expected to be, all other factors being equal, more readily implemented. Furthermore, donation of lands for easements may be possible for some projects; such donation would significant enhance the B/C ratios as computed in this Study. Possibilities for such donation would have to be explored on a case-by-case basis.

Anticipatory Land Acquisitions: Land requirements for preferred projects should be undertaken in a timely fashion to avoid conversion of currently available land to uses which would preclude or increase the difficult of their acquisition at future times. Projects (e.g., the conveyance widening for Project BR-2B) along the West Fork are projects which would likely benefit from anticipatory land acquisitions.

Funding Options: All projects do not have to have their costs funded from local sources (i.e., the sponsoring entities of this Study). Use of additional sources of funding, such as TWDB grants, allows project costs to be less of a financial burden on local sources. Those projects which either have high B/C ratios and/or address flooding problems in densely populated areas where repetitive losses are high can be expected to be more favorably viewed by the TWDB. The results of this Study provide a basis for approaching the TWDB for grant funding and justifying the need for grant funds.

Also to be explored should be funding from TxDOT for the siphon improvement projects in Manvel because of their significant impact on flood reduction along Hwy 6; the siphon improvement projects will lessen potential traffic hazards along Hwy 6 in the Manvel area, and the costs for obtaining those benefits should be duly recognized.

In addition, the projects set out in this Study provide a basis for defining funding needs and opportunities which may come not only from public sources but private sources as part of land development activities in the Chocolate Bayou Watershed.

SECTION 10
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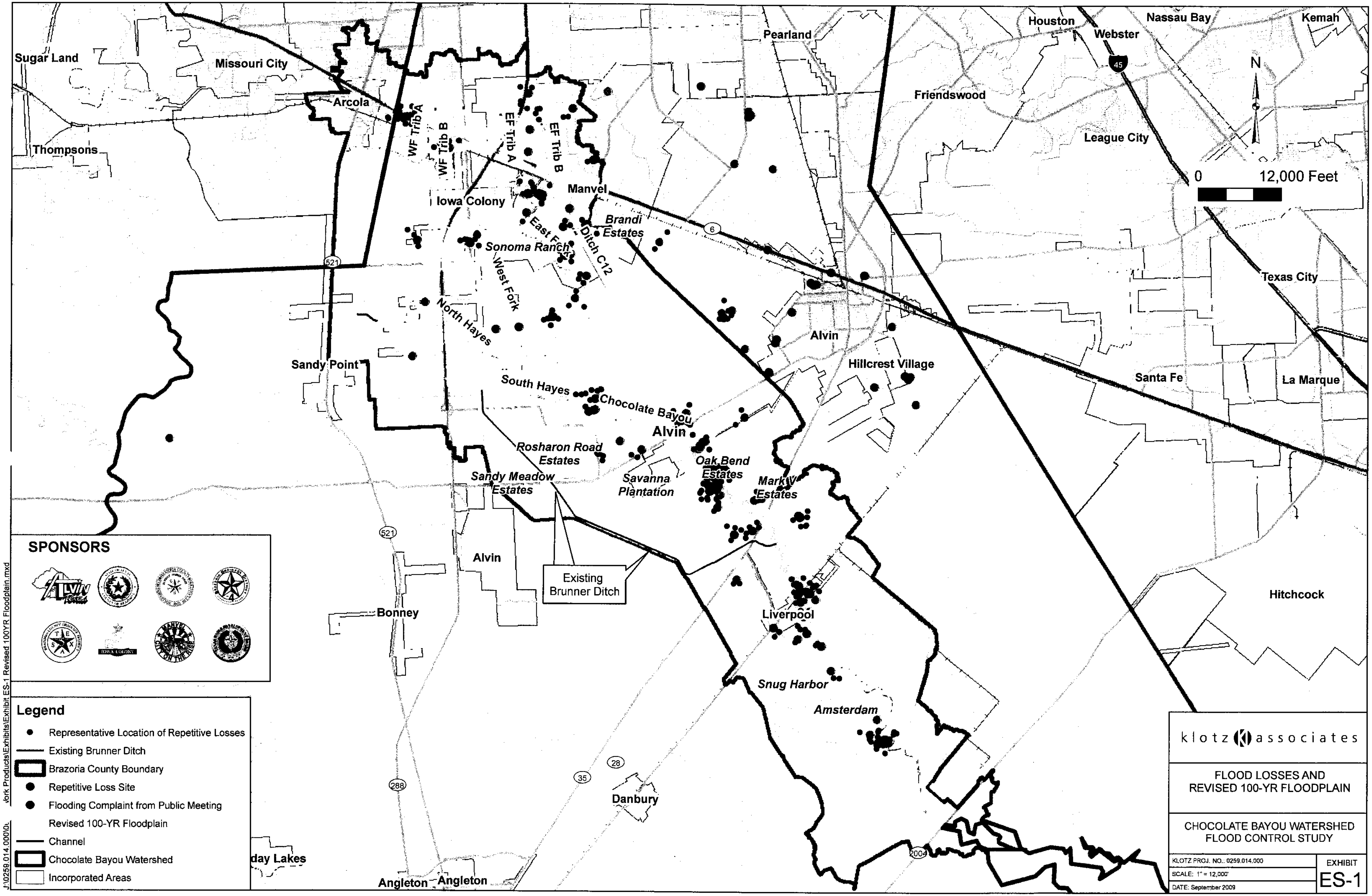

Sugar Land
Missouri City
Arcola
Thompsons
WF Trib A
WF Trib B
EF Trib A
EF Trib B
Iowa Colony
Manvel
Pearland
Houston
Webster
Nassau Bay
Kemah
Friendswood
League City
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Brandi Estates
Sonoma Ranch
West Fork
Ditch C12
North Hayes
Sandy Point
Alvin
Hillcrest Village
Texas City
Santa Fe
La Marque
South Hayes
Chocolate Bayou
Rosharon Road Estates
Sandy Meadow Estates
Savanna Plantation
Oak Bend Estates
Mark V Estates
Existing Brunner Ditch
Bonney
Liverpool
Snug Harbor
Amsterdam
Hitchcock
Danbury
day Lakes
Angleton
SPONSORS
Legend
Representative Location of Repetitive Losses
Existing Brunner Ditch
Brazoria County Boundary
Repetitive Loss Site
Flooding Complaint from Public Meeting
Revised 100-YR Floodplain
Channel
Chocolate Bayou Watershed
Incorporated Areas
klotz associates
FLOOD LOSSES AND
REVISED 100-YR FLOODPLAIN
CHOCOLATE BAYOU WATERSHED
FLOOD CONTROL STUDY
KLOTZ PROJ. NO.: 0259.014.000
SCALE: 1" = 12,000'
DATE: September 2009
EXHIBIT
ES-1
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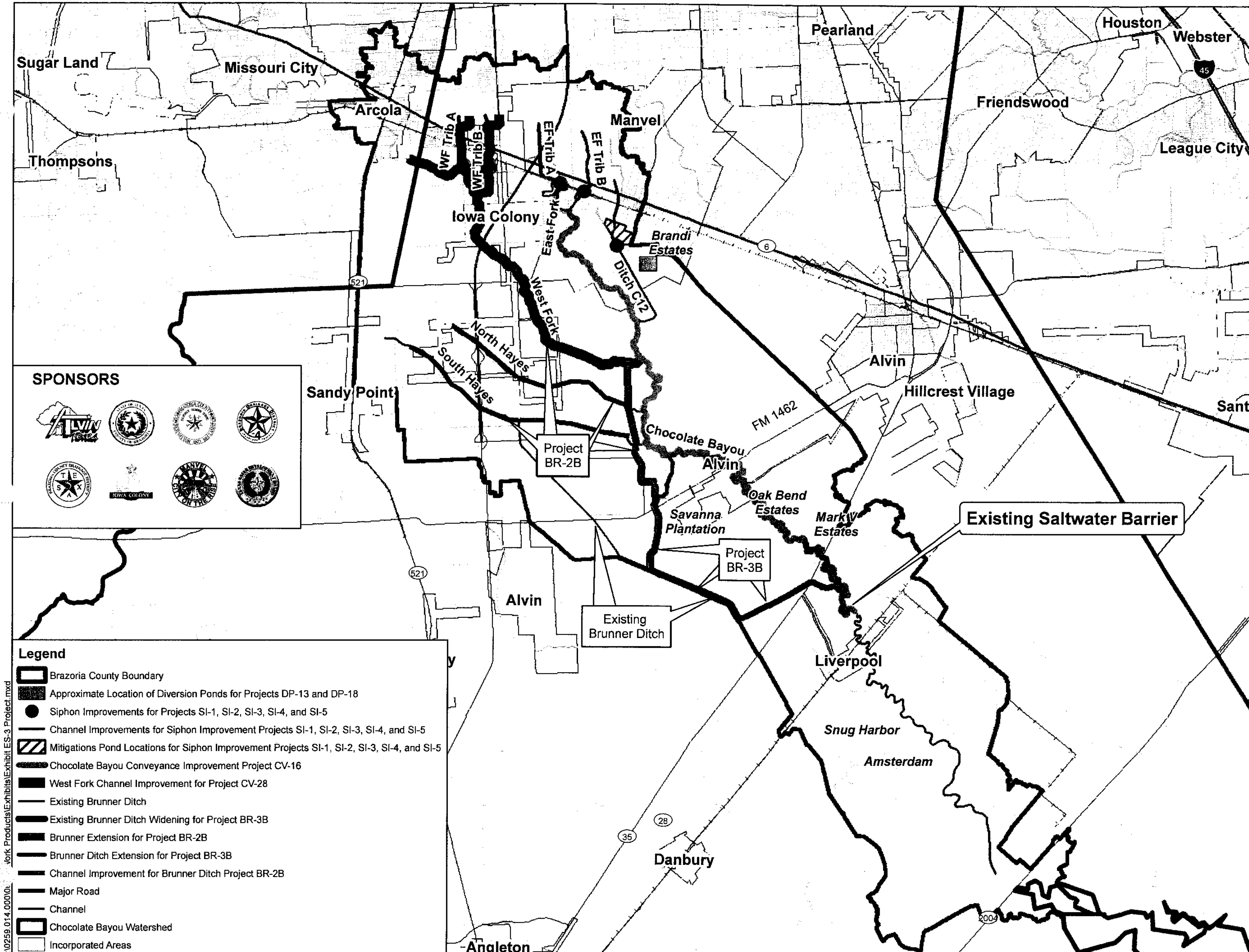

klotz associates

RECOMMENDED PROJECTS

CHOCOLATE BAYOU WATERSHED FLOOD CONTROL STUDY

KLOTZ PROJ. NO.: 0259.014.000
SCALE: 1" = 12,000'
DATE: September 2009

EXHIBIT
ES-2

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Table ES-1 Recommended Projects

Overall Project	Project Phase	Location	Description	Total Cost and Marginal Cost if Constructed After Indicated Project	B/C for Project and Phase
CV-28 West Fork Improvements		West Fork	Channel conveyance improvements by widening and deepening to raise West Fork capacity to 2-year flood level; total of 234 acres of ROW to be acquired	$36.5 Million Total Cost - equivalent to $4.2 million per mile	2.21 Based Upon Total Cost and Benefit
	CV-28-Phase 1	Three mile segement along West Fork at confluence and immediately upstream of confluence with East Fork	Localized conveyance improvements along West Fork to address flooding in vicinity of project phase by raising channel capacity to 2-year flood level; local inline or offline mitigation will be necessary. Approximately 230 of ROW would be required	$12.6 Million Total Cost - equivalent to $4.2 million per mile	2.21 Based Upon Total Cost and Benefit
	CV-28-Phase 2	Two mile segment at upper end of West Fork in Arcola area	Localized conveyance improvements along West Fork to address flooding in Arcola area by raising channel capacity to 2-year flood level; local inline or offline mitigation will be necessary. Approximately 230 ft of ROW would be required.	$8.4 Million Total Cost - equivalent to $4.2 million per mile	2.21 Based Upon Total Cost and Benefit of CV-28
	CV-28-Phase 3	Various locations along East Fork not done in prior phases	Localized conveyance improvements along West Fork to address flooding raising channel capacity to 2-year flood level; local inline or offline mitigation will be necessary	Varies	Typically 2.2
Projects DP-18/DP-13 Diversion Ponds Along Ditch C-12		Along Ditch C-12 south of State Highway 6 near Manvel	Series of diversion ponds along Ditch C-12 to temporarily retain flood waters, with initial construction of ponds to address 2-year flooding and subsequent pond expansion to address 5-year flooding events.	$4.6 million overall for two phases	4.51 Overall for two phases
	DP-18-Phase 1	Ditch C-12	Capture floods of 5-yr or larger; store floods upto 10-yr event; reduce flooding for larger events along Ditch C12 downstream of State Higway 6; total of 48 acres of land acquistion needed.	Cost of $1.8	1.82 Based Upon Total Cost and Benefit
	DP-13-Phase 2	Ditch C-12	Capture floods of 2-yr or larger; store floods up to 5-yr event; reduce flooding for larger events along Ditch C12 downstream of State Higway 6; total of 76 acres of land acquistion needed. 48 acres acquired as part of Phase 1	Cost of $1.1 If constructed after Project DP-18	13.53 if this Project Constructed After Project DP-18
CV-16 Chocolate Bayou and East Fork Improvements		Chocolate Bayou	Eliminate flooding for 2-yr flood and reduce flooding for larger storms from upper end of East Fork of Chocoloate Bayou to Saltwater Barrier along mainstem of Chocolate Bayou. Channel would be widening to have average of 230 ft of ROW and estimated 234 acres of land acquisition	$83.3 Million Total Cost - equivalent to $3.3 million per mile	2.65 Based Upon Total Cost and Benefit
	CV-16-Mod	East Fork of Chocolate Bayou above confluence with South Hayes Creek	Eliminate flooding for 2-yr flood and reduce flooding for larger storms from East Fork of Chocoloate Bayou. Channel would be widening to have average of 230 ft of ROW and estimated 54 acres of land acquistion	$26.5 Million Total Cost - equivalent to $3.3 million per mile	2.65 Based Upon Total Cost and Benefit
	CV-16-Mod-Phase 1	East Fork of Chocolate Bayou at confluence with West Fork	Eliminate flooding for 2-yr flood and reduce flooding for larger storms on East Fork for fist 2 miles upstream of confluence with West Fork. Channel would be widen to average 230 ft of ROW.	$6.6 Million Total Cost - equivalent to $ 3.3 million per mile	2.65 Based Upon Total Cost and Benefit
	CV-16-Mod-Phase 2	Various locations along East Fork not done in prior phases	Eliminate flooding for 2-yr flood and reduce flooding for larger storms on East Fork.	$6.6 Million Total Cost - equivalent to $ 3.3 million per mile	2.65 Based Upon Total Cost and Benefit

Table ES-1 Recommended Projects

Overall Project	Project Phase	Location	Description	Total Cost and Marginal Cost if Constructed After Indicated Project	B/C for Project and Phase
Brunner Ditch BR-3B		Brunner Ditch west of Chocolate Bayou	Eliminate 100-yr flooding along Brunner Ditch, West Fork, and North and South Hayes Creeks and reduce flooding along Chocolate Bayou in Alvin Vicinity. Total land acquistion approximately 237 acres	$93.7 Million Total Cost at $10.6 million per mile	1.86 based upon total cost and benefit
	BR-3B-Phase 1	Existing Brunner Ditch connection to Chocolate Bayou	Increase to 100-year flood level capacity of existing northeast to southwest leg of Brunner Ditch as first step in Project BR-3B. ROW to be increased to average of 380 ft	$29 Million Total Cost	1.86 based upon total cost and benefit
	BR-2B-Phase 2	Existing Brunner Ditch connection to Chocolate Bayou	Increase to 100-year flood level capacity of existing southeast to northwest leg of Brunner Ditch. ROW increased to average 380ft. Combine construction with Grand Parkway development if possible. Combined length Phase 1 and Phase 2 approximately 5.4 miles	$29 Million Total Cost	1.86 Based Upon Total Cost and Benefit
	BR-2B-Phase 3	Brunner Ditch extension and tributary to near FM 1462	Extend Brunner Ditch northward toward Chocolate Bayou and connected to widened, reversed-grade tributary to Chocolate Bayou to handle 100-yr flood in excess of Chocolate Bayou capacity near FM 1462 to reduce flooding along Chocolate Bayou from FM 1462 southward to approximately Saltwater Barrier. Phase lenght of 3.4 miles	$36.2 million	1.86 Based Upon Total Cost and Benefit

Table ES-1 Recommended Projects

Overall Project	Project Phase	Location	Description	Total Cost and Marginal Cost if Constructed After Indicated Project	B/C for Project and Phase
Brunner Ditch BR-2B		Brunner Ditch Extension nortward from vicinity of FM 1462 to West Fork near confluence with East Fork	Eliminate 100-yr flooding along West Fork and North and South Hayes Creeks and reduce flooding along Chocolate Bayou downstream of East Fork by Brunner Extension and widening of West Fork and North and South Hayes Creeks.	$178 Million Total Cost at $6.6 million per mile	1.68 based upon total cost and benefit
	BR-2B-Phase 1	Extension of Brunner Ditch northward from Brunner Ditch near FM 162 to West Fork	Provide conveyanc of 100-year discharge from upstream tributaries by extending and widening Brunner Ditch above widening Brunner Ditch Project BR-3B-Phase 2. ROW approximately 420 ft; land acquistion 592 acres	$42 million	1.68 based upon total cost and benefit
	BR-2B-Phase 2	West Fork from upper end of West Fork to confluence with extended Brunner Ditch	Increase conveyance of West Fork to 100-year flood level by widening and deepening of channel (already partially improved as part of Project CV-28). ROW 250 ft over lenght of 8.7 miles	$58 million	1.68 based upon total cost and benefit
	BR-2B-Phase 3	North and South Hayess Creeks from upstream end to confluence with extended Brunner Ditch	Increase conveyance of North and South Hayes Creeks to 100-year flood level by widening and deepening of channel. Delay this phase until needed because of future growth in these watersheds. ROW 230 ft with total of 210 acreas of land acquisition	$78 million	1.68 based upon total cost and benefit
Siphon projects SI-1, SI-2, SI-3, SI-4 and SI-5		Siphons and areas upstream of siphons along GCWA canal in Manvel area	Increase capacity of siphons and channels upstream of siphons to 100-year capacity; add mitgation ponds downstream of State Highway 6	--	--
	Phase 1 Siphon Improvement Project SI-4	East Fork Trib B	Eliminate 100-year flooding upstream of Highway 6 by increasing siphon capacity, widening channel upstream of siphon, and constructing mitigation pond. 51 acres of land acquistion required; channel widening will require average 130 feet of ROW	$8.3 Million Total Cost - equivalent to $5.1 million per mile	1.06 Based Upon Total Cost and Benefit
	Phase 2 Siphon Improvement Project SI-2	West Fork Trib B	Eliminate 100-year flooding upstream of Highway 6 by increasing siphon capacity, widening channel upstream of siphon, and constructing mitigation pond. 159 acres of land acquistion required; channel widening will require average 250 feet of ROW	$21 Million Total Cost - equivalent to $29.9 million per mile	1.19 Based Upon Total Cost and Benefit
	Siphon Improvement Project Phase 3 SI-1	West Fork Trib A	Eliminate 100-year flooding upstream of Highway 6 by increasing siphon capacity, widening channel upstream of siphon, and constructing mitigation pond. 288 acres of land acquistion required; channel widening will require average 210 feet of ROW	$37.6 Million Total Cost - equivalent to $16.6 million per mile	1.64 Based Upon Total Cost and Benefit
	Phase 4 Siphon Improvement Project SI-3	East Fork Trib A	Eliminate 100-year flooding upstream of Highway 6 by increasing siphon capacity, widening channel upstream of siphon, and constructing mitigation pond. 178 acres of land acquistion required; channel widening will require average 220 feet of ROW	$24.7 Million Total Cost - equivalent to $13.6 million per mile	0.56 Based Upon Total Cost and Benefit
	Siphon Improvement Project Phase 5 SI-5	Ditch C12	Eliminate 100-year flooding along ditch downstream of SH 6 by increasing siphon capacity, widening channel upstream of siphon, and constructing mitigation pond. 406 acres of land acquistion required; channel widening will require average 150 feet of ROW	$52.8 Million Total Cost - equivalent to $48.1 million per mile	0.88 Based Upon Total Cost and Benefit
	Modified SI-5: Project SI-5/DP-13	Ditch C-12	Combination of Phase 5 Siphon Improvement Project SI-5 with mitigation requirements provided by ponds used for Projects DP-18/DP-13	Varies with channel where siphon located; see individual siphons projects above	1.06 Based Upon Total Cost of and Benefit of combined Projects SI-5 and DP-13