TRANS–TEXAS WATER PROGRAM

SOUTHEAST AREA

Technical Memorandum

Galveston Bay Freshwater Inflows Study

April 22, 1998

Sabine River Authority of Texas
Lower Neches Valley Authority
San Jacinto River Authority
City of Houston
Brazos River Authority
Texas Water Development Board

This document is a product of the Trans–Texas Water Program: Southeast Area. The program's mission is to propose the best economically and environmentally beneficial methods to meet water needs in Texas for the long term. The program's three planning areas are the Southeast Area, which includes the Houston-Galveston metropolitan area, the South-Central Area (including Corpus Christi), North-Central Area (including Austin) and the West-Central Area (including San Antonio).

The Southeast Area of the Trans–Texas Water Program draws perspectives from many organizations and citizens. The Policy Management Committee and its Southeast Area subcommittee guide the program; the Southeast Area Technical Advisory Committee serves as program advisor. Local sponsors are the Sabine River Authority of Texas, the Lower Neches Valley Authority, the San Jacinto River Authority, the City of Houston and the Brazos River Authority.

The Texas Water Development Board is the lead Texas agency for the Trans–Texas Water Program. The Board, along with the Texas Natural Resource Conservation Commission, the Texas Parks & Wildlife Department and the Texas General Land Office, set goals and policies for the program pertaining to water resources management and are members of the Policy Management Committee.

This is the final version of this document.

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1. Introduction

As a part of the Trans-Texas Water Program (TTWP) for the Southeast Area, a number of important environmental issues were identified which are associated with future water resources management in the region. The Policy Management Committee for the Southeast Area TTWP subsequently created several focus groups to deal with some of these specific water issues. One of the groups was the Galveston Bay Freshwater Inflow Group (GBFIG), an ad hoc committee concerned with the health and productivity of Galveston Bay. As a result of the GBFIG's work, an analysis of projected freshwater inflows into Galveston Bay was conducted as a part of the TTWP and this technical memorandum summarizes the result of those studies.

1.1 Background

The State of Texas has studied the health and productivity of Galveston Bay for several years. This work has recently lead to a determination of recommended freshwater inflows for maximum productivity of Galveston Bay. In anticipation of these recommendations, the GBFIG was concerned over a number of issues related to current and future freshwater inflows into Galveston Bay:

- Based on existing authorized water rights permits, what are the impacts from current and future diversions on freshwater inflows to the bay?
- Does the geographic distribution of freshwater inflows significantly change over time due to existing authorized diversions?
- How do current and future projected freshwater inflows compare to the recommended freshwater inflows necessary to maximize fisheries productivity?

1.2 Scope

GBFIG determined that a number of additional water availability hydrologic investigations were necessary to address the above questions. This technical memorandum describes the water availability studies that have been conducted to date. The objective of this study is to develop preliminary estimates of freshwater inflows into the bay under three different inflow scenarios;

- naturalized conditions,
- intermediate development conditions
- full development conditions.

Naturalized conditions are those streamflows which represent basin runoff that would have occurred in the absence of water resources development, water use or other human activities in the watershed. Intermediate Development conditions are simulated by estimating inflows based upon less than total use of full water rights and return flows. Full Development conditions represent full use of existing water rights and the respective return flows. These three scenarios were selected to compare water rights conditions to the State of Texas Bay and Estuary analysis. This study analyzes the statistical frequency of certain hydrologic flow conditions occurring within Galveston Bay.

1.3 Study Area

The Galveston Bay watershed contains 33,000 square miles and consists of the following two river basins and three coastal basins:

- Trinity River
- San Jacinto River
- Neches-Trinity Coastal
- Trinity-San Jacinto Coastal
- San Jacinto-Brazos Coastal

The commonly referenced Galveston Bay actually consists of four separate embayments, including:

- Galveston Bay
- Trinity Bay
- East Bay
- West Bay

Data prepared for the Texas Bay & Estuary Program suggests that the Trinity and San Jacinto Rivers typically contribute in excess of 80 percent of annual freshwater inflows into Trinity Bay and Galveston Bay while the coastal river basins primarily contribute freshwater inflows into East and West Bays.

2. State of Texas Bay & Estuary Study

The Texas Water Development Board (TWDB) and the Texas Parks & Wildlife Department (TPWD), under the Texas Bay & Estuary (B&E) Program, have recently completed a report on the effects of freshwater inflows on Galveston Bay. The report examines two main topics:

- Establishing the effects of freshwater inflows on living organisms, and
- Presentation of the methodology used in determining the freshwater inflow needs of the bay which would maintain an ecologically sound environment and a productive estuary.

The Galveston Bay B&E report builds upon the framework of an earlier study "Trinity -San Jacinto Estuary: A study of the influence of Freshwater Inflows" March 1981, (LP-113.)

The Galveston B&E study computed freshwater inflows into Galveston Bay for the historical period of 1941-1990. Freshwater inflows were determined by:

- compiling historical gauged inflow from the Trinity and San Jacinto basins,
- computing rainfall-runoff relationships for ungaged watersheds, and accounting for any diversions and return flows within those ungaged watersheds.

The results of this study over the period of record from 1941 to 1990 show that an average of 10.1 million acre-feet per year of freshwater flows into Galveston Bay from the contributing watersheds in the following geographic distribution:

- Trinity basin-54%
- San Jacinto basin-28%
- San Jacinto-Brazos basin-10%
- Neches-Trinity basin-6%
- Trinity-San Jacinto basin-2%

Table 1 shows the statistical distribution of freshwater inflows into Galveston Bay from 1941 to 1990 from the B&E study. The TWDB and TPWD used these inflows in a number of biological, chemical and biochemical models. Parameters essential to fisheries productivity included:

- sediments
- nutrients
- salinity
- flow circulation
- other

Galveston Bay simulation models were developed for each of these parameters. Each of these parameters were then used as inputs into the TxEMP model, which is an optimization model used to search for feasible solutions to maintain the ecological health of the bay. The Galveston Bay B&E TxEMP

Table 1: Galveston Bay Annual Freshwater Inflows [1.]

	Hist-Min	***10th %***	***25th %***	***Median***	***Average***	***75th %***	***90th %***	***Hist-Max***
January	41,630	150,485	311,617	699,490	900,903	1,446,186	2,090,450	2,858,000
February	70,990	155,190	415,427	946,475	929,369	1,345,840	1,865,649	2,577,000
March	73,530	164,399	327,000	652,800	927,065	1,504,404	1,982,064	2,729,000
April	136,200	193,935	384,400	632,500	1,038,525	1,590,000	2,388,805	5,290,000
May	139,400	260,000	461,500	1,273,700	1,522,301	2,127,080	3,616,000	4,571,000
June	56,540	190,324	351,900	839,700	1,218,681	1,826,800	3,222,000	4,011,820
July	44,350	107,705	219,765	340,376	632,396	936,127	1,559,200	2,439,189
August	20,590	77,980	136,747	225,265	379,458	550,350	754,760	2,110,600
September	15,740	93,325	193,340	330,246	533,187	625,930	1,466,565	2,484,919
October	21,100	49,885	117,258	251,895	538,943	556,100	1,476,164	3,590,900
November	31,300	89,480	190,740	351,500	651,704	744,110	1,740,750	4,565,000
December	55,290	93,865	194,560	626,802	768,678	1,075,700	1,812,163	2,582,000
Total Flow	706,660	1,626,573	3,304,254	7,170,749	10,041,210	14,328,627	23,974,570	39,809,428

1. ***Prepared by Texas Water Development Board Period of Record – 1941 to 1990***
   Historical Annual Minimum Inflow – 1,871,280 acre-feet (1956)
   Historical Annual Maximum Inflow – 21,454,740 acre-feet (1973)

analysis has determined that the peak performance of the annual fisheries harvest is 11.6 million pounds and the required freshwater inflow necessary to generate that harvest is approximately 5,220,000 acre-feet per year. Important to this maximum fisheries harvest, the B&E analysis optimized the monthly distribution of inflows into the bay using the TxEMP model. Table 2 illustrates the optimized monthly inflow distribution used to compute maximum fisheries harvest. Table 2 shows that the largest quantity of inflows are needed in the month of May (almost 1.3 million acre-feet or 24 % of annual inflows) and the lowest month of inflows occurs in October (over 75,000 acre-feet or 2.5 % of annual inflows). The B&E analysis establishes each monthly inflow as an independent quantity of need. Evaluation of future required inflows will focus on the ability to achieve each separate monthly flow target shown in Table 2.

Table 2: Maximum Harvest Monthly Inflow Distribution

Month	Inflow (acre-feet)	Percentage (%)
January	150,600	3
February	160,600	3
March	652,500	13
April	632,400	12
May	1,279,900	24
June	833,200	16
July	210,800	4
August	150,600	3
September	100,400	2
October	75,300	2
November	351,300	6
December	622,400	12
Total	**5,220,000**	**100**

3. Water Availability Analysis

A water availability model was developed to determine the relationship of current and future water right diversions on freshwater inflows into Galveston Bay. The model was created to analyze the impact of water right diversions and reservoir operations on future inflows into Galveston Bay and requires as input data the following basic parameters:

- Reservoir Facilities
- Hydrologic Data
- Water Rights Diversions
- Return Flows

Each of these data types is input into a river basin model that is essentially a water balance accounting program. Basically, the model adds and subtracts water inputs from upstream to downstream points.

3.1 Model Selection and Configuration

This water availability study used the Texas A & M Water Rights Analysis Package (WRAP3) software. WRAP3 is a generalized computer model which has the capability to simulate a stream/reservoir system, allows for flexible river-tributary configurations and water use under a priority-based water allocation system. The model also provides the flexibility to simulate interbasin transfers and/or other developed water sources, such as groundwater imports.

Control points are model parameters that describe the relative configuration of a river basin system and indicate the location of streamflow data, reservoirs and water right diversion points. Figure 1 represents a schematic of the Galveston Bay WRAP3 model, showing the various reservoirs, stream segments and associated control points. The model includes the two river basins and three coastal basins, with interbasin transfers that occur throughout the watershed.

This Galveston Bay watershed simulation model is very complex in its construction. The model is a multi-basin, multi-reservoir system. Figure 1 shows that three rivers (the San Jacinto, Brazos, and Trinity Rivers) and eleven bayous and creeks provide input of fresh water into Galveston Bay either directly or through interbasin transfers.

Water is accounted for in the Galveston Bay model in monthly timesteps. Therefore, all of the input data is structured in monthly increments. The control points illustrate the theoretical quantity of water in existence at any specific location. In this model, control point number 9,000 is used to account for the summation of all inflows into Galveston Bay. The model additionally is configured to illustrate contributing inflows from all of the individual creeks, bayous, and rivers and specific watershed basins using the appropriate control points.

It should be noted that the modeled San Jacinto basin is based on a model developed for this specific basin as a part of a previous San Jacinto River Basin Water Availability Study (Wurbs, TAMU). For this current analysis, return flows were incorporated into the originally prepared model.

3.2 Scenarios

Three water availability analysis inflow scenarios were developed: naturalized, intermediate development, and full development conditions. These conditions were selected for analytical and comparative purposes. Two types of comparisons can potentially be performed using these conditions. First, the impact on freshwater inflows from water rights diversions can be tracked over time. This can be seen by comparing water use data input in the three scenarios as seen below:

Naturalized Conditions: No water rights diversions.

Intermediate Development Conditions: Year 1997 water usage diversions in the San Jacinto and Coastal basins and downstream of Lake Livingston in the Trinity basin. Full development conditions upstream of Lake Livingston in the Trinity basin.

Full Development Conditions: Maximum use of current water right permit diversions for the entire study area.

The expectation is that total inflows into Galveston Bay will decrease from the naturalized to the full development condition. At issue is how much change will occur.

Secondly, these inflow conditions can be compared to the Galveston Bay B&E analysis results. The B&E study computes recommended freshwater inflow targets. GBFIG study results can then be compared to the B&E targets to determine the relationship of the targets to inflows resulting from intermediate and full development water rights diversions.

One factor related to water availability models should be noted. Water availability models are by their nature theoretical and do not reflect actual flow conditions. Generally, various water rights diversion assumptions are superimposed on historical hydrologic conditions. For instance, year 1998 water diversions are applied to year 1954 rainfall and runoff conditions. This procedure is valid for analyzing water availability, but may create confusion when compared to actual historical river streamflow conditions.

The following chapters describe each of the scenarios under study. The final chapters present a discussion of the results including a comparison of this Galveston Bay water availability analysis results to the B&E study.

4. Reservoir Facilities

The primary surface water supply reservoirs analyzed in this study were Lake Houston, Lake Conroe and Sheldon Reservoir within the San Jacinto basin, and Lake Livingston and Lake Anahuac within the Trinity River basin. Although, the current plan for the Wallisville Salt Water Barrier calls for a pool elevation of two feet, the plan will not create a permanent impoundment. The Wallisville Salt Water Barrier project is therefore not considered in this analysis. Additional reservoirs exist in the upper Trinity basin upstream of Lake Livingston; however, those reservoirs were not modeled in detail. Instead, the analysis of water availability incorporates these reservoirs through the inflow data used for the Trinity basin as further discussed in the next section of this report.

4.1 Ownership and Capacity

Lake Houston was built in 1954. The City of Houston owns and operates Lake Houston. Lake Livingston was completed in 1969. Lake Livingston was developed by the City of Houston in cooperation with the Trinity River Authority, which operates that facility. Lake Conroe was completed in 1973. The San Jacinto River Authority operates Lake Conroe. The Wallisville barrier is expected to begin operation in 1998. The Wallisville structure will be operated by the U.S. Army Corps of Engineers. Lake Anahuac is owned and operated by the Chambers and Liberty Counties Navigation District and is located on Turtle Bayou in Chambers County. The original project began operation in 1914 with modifications to the dam and spillway occurring in 1952 and 1990. Table 3 summarizes key data for each reservoir.

The area and capacity information in Table 3 for Lake Houston and Lake Conroe reflects the reservoir characteristics expected to exist as of the year 2000. These areas and volumes were projected based on volumetric surveys made by the Texas Water Development Board in 1994[(1)] and 1996[(2)] , respectively. The information shown for Lake Livingston is also for the year 2000 and is based on a study made in 1991 by the Bureau of Reclamation[(3)] . The capacity and area values shown for the Wallisville project are based on the Corps' design studies[(4)]. More detailed area and capacity tables are in Appendix A.

4.2 Water Rights

The combined sum of the water rights associated with these reservoir projects is 1,667,002 acre-feet per year. Approximately 71 percent of the total rights belong to the City of Houston, which has the right to divert 1,175,467 acre-feet per year. The Trinity River Authority owns rights amounting to 403,200 acre-feet per year, or 24.0 percent of the total. The San Jacinto River Authority (SJRA) owns rights amounting to 33,333 acre-feet per year or 2 percent of the total, and the Chambers Liberty Counties Navigation District owns rights amounting to 51,600 acre-feet per year or 5 percent of the total. Table 4 summarizes water rights associated with each reservoir.

Table 3: Key Data for the Dams and Reservoirs

	Lake Houston	Lake Livingston	Lake Conroe	Wallisville Salt Barrier	Lake Anahuac
Owner/operator	Houston	TRA	SJRA	USACOE	CLCND
Year Started operation	1954	1969	1973	1998 (Est.)	1914
Capacity (Acre-Feet)	131,540	1,718,778	413,941	-	29,500
Surface area (Acres)	11,817	82,950	20,074	3,800	5,200
Drainage area (Sq. Mi.)	2,828	16,583	445	17,845	199
Elev. At top of conservation storage	44.5	131.0	201.0	-	4.0

Note: The Wallisville salt water barrier will normally be operated at or slightly above normal water levels. It will not have any conservation storage as such.

Table 4: Reservoir Capacities and Associated Water Rights

	Water Rights					
	Houston	**SJRA**	**TRA**	**CLCND**	**Other**	**Total**
Lake Livingston	902,800	0	351,600	0	0	1,254,400
Lake Houston	168,000	0	0	0	0	168,000
Lake Conroe	66,667	33,333	0	0	0	100,000
Lake Anahuac	-	-	-	54,127	-	54,127
Wallisville SWB	38,000	0	51,600	0	0	89,600
Sheldon Reservoir	0	0	0	0	875	875
Total	1,175,467	33,333	403,200	54,127	875	1,667,002

5. Hydrologic Data

Hydrologic data used in the simulation model includes:

- Naturalized streamflows
- Evaporation

Naturalized streamflows represent the basin runoff that would have occurred in the absence of water resources development, water use or other human activities in the watershed. Naturalized streamflows are generated from actual streamflow runoff. Adjustments must be made to actual runoff data to compute naturalized flows. Naturalized streamflows, for the period of record of 1946 -1980, for all basins contributing to Galveston Bay have been compiled from the sources, shown in Table 5. A brief description of each source of streamflow data is provided below.

5.1 San Jacinto River Basin

The San Jacinto River Basin Water Availability study (Wurbs, TAMU) utilized the naturalized streamflows developed for the 1983 Texas Department of Water Resources model. These flows were based on adjustments of historical gauged flows and extension of recorded flows using regression analyses. This Galveston Bay study uses the same naturalized flows for the San Jacinto River Basin.

5.2 Coastal Basins

The State of Texas LP-113 study and the subsequent Bay and Estuary study of freshwater inflows to Galveston Bay generated basin runoff volumes for the ungaged watersheds in the coastal basins. These flows were computed by applying weighted daily precipitation depths, Soil Conservation Service Curve Numbers, and soil depletion index values into calibrated water yield models. Although both studies employ similar methods for computing watershed run off, they use slightly different watershed delineations. In order to develop continuous records of naturalized flows for the coastal basin watersheds, two or more watersheds of the above studies are combined into "control point" basins. The purpose of this combination is to create basins that have similar boundaries to the Bay and Estuary and the LP-113 studies.

5.3 Trinity River Basin

The naturalized streamflows downstream from Livingston Dam are obtained from the TNRCC database as two sets of flows; baseflows and storm runoff. The summation of baseflow and storm runoff are used as the naturalized streamflows for the watersheds downstream of Lake Livingston.

Model inflows into Lake Livingston are not naturalized flows. For the period from 1946 to 1970, adjustments were made to the inflows developed for the 1997 Trans-Texas Water Program *Report on System Operation of Surface Water Supply Sources in the Houston Area*. The inflows used in the System Operation study approximate the future full development of existing water rights condition but do not include return flows originating in the Dallas-Fort Worth Metroplex. The current (year 1997) level of return flows were developed and added to the Systems Operation Study inflows for this Galveston Bay study. The period of record was extended from

1971 through 1980 by relating historical flows at gauging stations above Lake Livingston and making appropriate adjustments to approximate current conditions.

As described above, inflow data upstream and into Lake Livingston and inflow data downstream of Lake Livingston and in all the other Galveston Bay subwatersheds are created differently. Inflow data upstream of Lake Livingston represent streamflow that are *projected* to occur in the future upon full development utilization of all existing water rights permits in the upper Trinity basin. Additionally, these same set of flows are used in both the intermediate development condition and full development condition model scenario simulations. All of the inflow data within the remaining Galveston Bay water availability model subwatersheds are naturalized flows. Computed flows in these subwatersheds will change from the intermediate to the full development condition scenario based on the quantity of diversions and return flows within each subwatershed. The intermediate development condition therefore is actually a hybrid analysis using full development conditions upstream of Lake Livingston but actual year 1997 conditions in all other subwatersheds.

5.4 Evaporation Data

Evaporation data was taken from a 1978 City of Houston water availability study.[5] Monthly depths of net reservoir loss from lake surfaces from the City of Houston study were originally obtained from data published by the TWDB. [6]

Table 5: Streamflow Data Sources

Watershed	Period of Record	Source of Data
San Jacinto River Basin	1940 - 1980	San Jacinto River Basin Water Availability Model, prepared for the TNRCC by Dr. Ralph A. Wurbs of Texas A&M University, October 1996.
Trinity River Basin Below Lake Livingston	1941 - 1980	Trinity River Basin Water Availability Model (24-20 to 24-46)
Coastal Basins	1941 - 1976	Trinity-San Jacinto Estuary: A study of the influence of Freshwater Inflows, Texas Department of Water Resources, LP-113, 1981.
(ungaged areas)	1977 - 1990	Freshwater Inflows to Galveston Bay, TWDB
(gaged areas)	1977 - 1990	Sub-basin runoff generated assuming equal runoff rates per square mile of contributing drainage area (GBFIG study).

6. Water Rights Diversions

Different sets of water rights diversion data were used in this Galveston Bay study depending upon which scenario was considered. The naturalized flow condition model does not include any water rights diversions. The full development condition model contains the full permitted diversions from the TNRCC water rights master file database listed in Appendix B. The intermediate development condition model downstream of Lake Livingston and all other watershed basins contain current (year 1997) surface water usage amounts based on records of major water rights holders, TWDB data, and the assumption of full usage for minor water rights. The intermediate and full development condition water rights usage amounts are summarized in Table 6.

6.1 Trinity Basin Fixed Rights

There are several large water rights on the Trinity River downstream from Lake Livingston that are senior to the Lake Livingston rights. When the Livingston project was being developed, contractual agreements were signed by the City of Houston, the TRA and three of the owners of such prior rights, defining obligations to release water from Lake Livingston in recognition of the downstream priorities. These were referred to as the "fixed right" obligations associated with Lake Livingston. Basically, they set the annual downstream withdrawal amounts for each of the senior rights that are to be supported by releases from Lake Livingston.

Under the terms of the agreements, the users of Lake Livingston consented to release water as required to make reliable:

- 88,820 acre-feet per year of diversions by the Chambers-Liberty Counties Navigation District
- 33,000 acre-feet per year by the Dayton Canal Company
- 86,000 acre-feet per year by the Devers Canal Company.

All of these uses were for irrigation.

The Chambers-Liberty Counties navigation District's diversion point is just upstream from the Wallisville Salt Water Barrier site, and the other two fixed rights diversion points are near the Coastal Water Authority diversion station.

Since these settlements were in recognition of senior certified filings and permits, for the most part, they do not constitute part of the Lake Livingston yield and must be satisfied in preference to that yield. The one exception is the Devers right, of which 27,500 acre-feet per year is earmarked as being part of the project yield, to be charged against the Lake Livingston permit.

In addition to the three "fixed right" agreements, a fourth senior right of 45,000 acre-feet, belonging to the Southern Canal Company, was purchased outright by the City Houston, is still owned by the City, and its effect on Lake Livingston will be similar to that of the three fixed right agreements.

The downstream water rights situation has been affected by a recent purchase by the San Jacinto River Authority of

Table 6: Water Right Diversions

	Full Development Condition (ac-ft/yr)	Intermediate Development Condition (ac-ft/yr)
Brazos Water Rights diverted to San Jacinto - Brazos Basin		
Gulf Coast Water Authority	224,931	130,911
Choc Bayou Water Co.	155,000	100,000
Total	379,931	230,911
San Jacinto - Brazos Water Rights		
Choc Bayou Water Co.	57,500	230,911
Gulf Coast Water Authority	12,000	2,394
Other Water Rights	9,363	9,363
Total	78,863	30,757
San Jacinto Water Rights		
San Jacinto River Authority	88,333	80,142
City of Houston	234,667	58,759
Water Rights	23,043	23,043
Total	346,043	161,944
San Jacinto - Trinity Water Rights		
Houston Lighting & Power	30,000	30,000
Other Water Rights	15,539	15,539
Total	45,539	45,539
Lower Trinity Water Rights		
Chambers Liberty CND (1)	88,820	22,000
Trinity River Authority	403,200	89,015
City of Houston	985,800	477,305
Dayton Canal (2)	33,000	-
Devers Canal (3)	2,500	2,500
San Jacinto River Authority	56,000	-
Other Water Rights(4)	65,184	45,607
Total	1,634,504	636,427
Neches - Trinity Water Rights		
U.S. Anahuac NWR	26,932	9,900
Other Water Rights	28,118	28,118
Total	55,050	38,018
Grand Total	2,560,553	1,143,596

(1) 88,820 ac-ft/yr maximum diversion from Trinity River, an additional 54,127 ac-ft/yr is permitted from Turtle Bayou, Lake Anahuac, and Trinity Bay and is included in the "Other Water Rights" value.

(2) 33,000 ac-ft/yr maximum diversion from Trinity River, an additional 5,000 ac-ft/yr is permitted from Big Ditch, a tributary of the Trinity River and is included in the "Other Water Rights" value.

(3) An additional 27,500 ac-ft/yr is supplied under a "fixed rights" contractual agreement with the Trinity River Authority.

(4) In 1997 CLCND did not use 20,000 Ac-Ft of their Turtle Bayou Rights.

56,000 acre-feet per year that was formerly part of the Devers rights.

For purposes of this study, it was assumed that the downstream water right obligations at Lake Livingston are not altered by that purchase.

In all, there are 252,820 acre-feet per year of prior rights downstream from Lake Livingston that involve obligations for pass-through or releases from the lake. Of that amount, only 27,500 acre-feet per year would count as new yield developed by Lake Livingston.

6.2 Interbasin Transfers

There are a total of two "surface water" interbasin transfers which are simulated in this Galveston Bay water availability model. The first transfer is from the Brazos Basin to the Brazos-San Jacinto River Basin, via the Chocolate Bayou Water Company and the Gulf Coast Water Authority's canal systems. The second transfer is from the Trinity River to the San Jacinto River Basin, via the Coastal Water Authority's main canal. Additionally, for the future case, the San Jacinto River Authority's Trinity River rights will be conveyed through the CWA main canal. Groundwater use within the San Jacinto basin is a significant source of "importation", the impact of which is explained later in Section 7, Return Flows.

6.3 Unappropriated Streamflow

The WRAP3 software used in this water availability study has the capability to compute available unappropriated streamflows at each of the control points. For this analysis, water rights diversions are simulated to occur at the reservoir associated with a particular water right. Modeled water rights generally occur at reservoirs upstream of their actual point of diversion. Streamflows downstream of reservoirs therefore represent theoretical worst-case flow conditions.

7. Return Flows

Return flows represent water discharged back into streams after it has been previously diverted and used. Examples of return flows include:

- effluent from wastewater treatment plants
- runoff from irrigation
- return of water used in industrial processes.

Return flow factors are used in the WRAP3 software and represent the ratio of return flow to the diversion amount. Return flow factors vary by water use type.

Return flow factors used in this study are listed in Table 7. Return flows into Lake Livingston have been assumed to remain the same for both the existing and full development cases.

Table 7: Return Flow Factors

Use Type	Return Flow Factor
Municipal COH (1 Existing	1.04
Municipal COH (1 Future	0.85
Municipal (Non-COH)	0.60
Industrial	0.61
Irrigation	0.55
Mining	0.00

7.1 Municipal

Two municipal return flow factors were used in this water availability study, one for the City of Houston (COH) and the other for all other municipal water rights. The basis for segregating the COH's municipal use over all others is due to the City's significant amount of groundwater use. Currently, the COH relies on a conjunctive use of approximately 65% surface water and 35% groundwater. Relating total municipal demand to total municipal wastewater discharges (excluding inflow/infiltration), results in a municipal return flow factor of 0.68. In order to account for that portion of return flows resulting from groundwater, a ratio of the total return flow factor (0.68) to the current surface water usage (0.65) was computed resulting in an existing "adjusted" return flow factor of 1.04. For the future case, the COH will convert to 80 percent surface water use in conformance with the Harris-Galveston Coastal Subsidence District groundwater conversion schedule, which results in an "adjusted" return flow factor of 0.85.

As discussed, the computed return flows associated with groundwater within the City of Houston was determined. These groundwater based return flows will generally exist within the Buffalo Bayou subwatershed of the San Jacinto river basin. An additional source of groundwater return flows exists within the San Jacinto river basin upstream of Lake Houston. The source of these groundwater flows are the large number (over 400) of municipal utility districts. This water availability study includes these existing flows based on wastewater discharge information compiled by the Texas Natural Resources Conservation Commission. Groundwater return flows upstream of Lake Houston are approximately 52,000 acre-feet per year. This level of groundwater return flows are used in both the intermediate and full development condition simulations.

7.2 Other Uses

The industrial return flow factor was determined by relating the City of Houston Surface Water Contract customer demands located along the ship channel to the TNRCC reported return flows.

The irrigation return flow factor was obtained from extensive irrigation studies in the Texas Rice Belt[7]. This five-year study was a joint effort between the Soil Conservation Service, the Texas Agricultural Experiment Station and the Texas Rice Research Foundation.

7.3 Location

Along with the return flow quantities, return flow locations are specified for each water right in the model. The control point at which the return flows were applied was determined for major water right holders. The return flow location is determined based on review of specific data provided by these major users and area maps. The WRAP3 software assumes that return flows re-enter the system in the same month as the diversion.

8. Summary of Findings

Prior to reviewing the Galveston Bay water availability model results, it is important to note two major distinctions between the Bay & Estuary study and this current analysis:

- The period of record of the B&E study is 49 years (1941 - 1990), while the Galveston Bay water availability study period of record is 35 years (1946 -1980)
- The Bay & Estuary study analyzed historical freshwater inflows, while this current study determined inflows by superimposing current and future diversions upon naturalized streamflows.

To illustrate the impact of the different period of record, analysis of average annual inflows into Galveston Bay reveals that the periods from 1942-1945 and from 1981 through 1989 were historically very wet periods. When these thirteen years are deleted from the historical record; average annual inflows decrease from 10.1 to 9.04 million acre-feet. This thirteen year period affects the total average annual inflows by approximately ten (10) percent.

The second significant distinction primarily results from the current study being a water rights analysis program versus the B&E study which computed freshwater inflow targets based on historical streamflows. Another difference between both studies relates to inflows into Lake Livingston from the upper Trinity River watershed. This Galveston Bay water availability study assumed full development and diversions within the upper Trinity River watershed. Full development means that all of the currently permitted surface water rights are assumed to be diverted from the system and used by each water right holder primarily in the Fort Worth and Dallas regions. This water use situation does not currently exist in reality, and will not exist until some relatively distant future time period.

This water availability study assumes imposition of the upper Trinity basin full development case for both the intermediate and full development condition hydrologic simulation models. The resultant intermediate development condition hydrologic model does not represent actual existing inflow conditions, but more of a theoretical analysis of ultimate surface water use upstream of Lake Livingston imposed on actual existing year 1997 surface water use downstream of Lake Livingston and in all other Galveston Bay watershed basins.

For this study, differences due to the period of record were reconciled by truncating the period of record used in the Bay & Estuary study to 35 years (1946 - 1980). This data truncation will allow for more appropriate comparisons between the two studies. However, the inherent differences between the modeling approaches of both studies needs to be considered when comparing the two sets of inflows (B&E vs. water availability)to each other.

As a result of decreasing the B&E study period of record, the average inflow into the bay is 9.04 million acre-feet as opposed to 10.1 million acre-feet. Table 8 shows the statistical distribution of flows into the bay for the B&E study reduced period of record. As discussed in Chapter 2, the B&E study concluded that the maximum fisheries productivity of Galveston Bay occurs with monthly inflows that sum up to 5,220,000 acre-feet per year. For this current study, this maximum fisheries productivity target was established to assess monthly inflows for comparison to the naturalized, intermediate, and full development condition simulations.

Table 9 shows the statistical distribution of inflows into the bay for the “naturalized conditions”. On average, under natural conditions freshwater inflows into Galveston Bay are about 8.9 million acre-feet.

Table 10 shows the statistical distribution of inflows into the bay for the “intermediate development conditions”. On average, the intermediate development condition scenario results show that approximately 7.5 million acre-feet of water is theoretically available.

Table 11 shows the statistical distribution of inflows into the bay for the “full development conditions”. On average, under full use of existing water rights permits, inflows into the bay are about 7.1 million acre-feet.

Table 12 presents a comparison of the monthly inflows ranking for each scenario to the desired B&E monthly inflow target.

Figure 2 shows the average monthly inflows distribution for the water availability scenarios and the “maximum harvest” monthly inflow. Figure 2 also contains the B&E study MinQ monthly inflows distribution. MinQ inflows represent the minimally acceptable inflows required to maintain the bay and estuary fisheries harvest. Inflows below the MinQ monthly target for sustained periods could potentially harm the bay fisheries ecosystem.

Determination of Galveston Bay freshwater inflow trends can be seen by comparing the results from the above referenced tables. Key findings include:

- The B&E study (Table 8) and the naturalized condition (Table 9) total annual inflows within each percentile ranking show less than 10 percent difference between the two studies. This situation suggests that historical diversions and reservoir development throughout the Trinity basin has had little effect on annual inflows into Galveston Bay. Therefore, comparisons between the intermediate and full development conditions versus the naturalized condition can be viewed as similar to comparisons between the intermediate and full development conditions versus the B&E study inflows.
- Figure 2 shows that average monthly inflows for the naturalized, intermediate, and full development conditions exceed the maximum harvest target inflow in the months of January, February, April, July, August, September, October and November. This fact suggests that there will be minimal problems meeting or exceeding required inflow targets for these eight months.

- In three months (May, June, and December), the MaxH target inflow is greater than the average intermediate and full development condition inflow, and in March, the MaxH target is only slightly higher (58,915 acre-feet) than the full development condition inflow. For the months of May, June and December, the total combined shortfall from the full development condition to the MaxH target inflow is approximately 297,800 acre-feet or approximately 12 percent of total inflows for these three months.
- Inflows for the full development condition significantly exceed all MinQ monthly targets except in the month of December (80,400 acre-feet). In December, the MinQ and MaxH inflows are equivalent. Interestingly, the December naturalized condition inflow is only slightly higher (45,600 acre-feet) than the MinQ target inflow.
- Table 12 shows that for six months (January, February, July, August, September, October) the full development condition inflows exist in a range between the 10th percentile and the median which is similar to the MaxH target inflows. In the remaining six months full development condition inflows exist between the median and average inflows ranking. During these six months, the naturalized condition inflows also exist between the median and average inflows ranking.
- Review of the historical minimum (Hist-Min) percentile ranking for the three scenarios indicates that minimum annual inflows would significantly increase over time as a result of increases in diversions. This situation implies that the worst case annual inflow condition should improve over time by as much as 651,600 acre-feet per year.

Table 8: B&E Study Annual Inflows for Reduced Period of Record

	Water Theoretically Available (Acre-Feet)							
Month	***Hist-Min***	***10th %***	***25th %***	***Median***	***Average***	***75th %***	***90th %***	***Hist-Max***
January	41,630	115,170	272,045	615,200	883,903	1,475,253	1,853,368	2,858,000
February	70,990	154,348	392,010	982,116	939,375	1,345,180	1,926,922	2,577,000
March	73,530	146,220	290,960	574,200	779,555	1,146,200	1,857,800	2,250,030
April	136,200	189,300	353,650	619,800	976,482	1,557,880	2,201,000	3,132,680
May	139,400	196,850	386,500	1,235,500	1,381,790	1,817,413	3,211,200	4,571,000
June	56,540	159,260	322,031	517,200	1,011,118	1,582,090	2,716,680	4,011,820
July	44,350	106,892	190,316	287,700	458,110	530,860	934,414	2,374,048
August	20,590	61,638	118,378	198,855	299,346	433,290	710,352	878,280
September	15,740	76,012	165,230	300,800	507,748	576,707	1,352,350	2,484,825
October	21,100	44,824	90,654	227,150	499,404	407,759	1,011,730	3,590,900
November	31,300	89,244	158,425	305,000	600,394	547,902	1,098,918	4,565,000
December	55,290	90,918	171,645	612,200	704,386	1,019,400	1,607,972	2,582,000
Total Q	706,660	1,430,676	2,911,844	6,475,721	9,041,612	12,439,932	20,482,706	35,875,583

Table 9: Naturalized Conditions

	Water Theoretically Available (Acre-Feet)							
Month	***Hist-Min***	***10th %***	***25th %***	***Median***	***Average***	***75th %***	***90th %***	***Hist-Max***
January	33,358	103,694	268,001	525,016	854,894	1,421,759	1,838,401	2,859,665
February	106,198	165,626	401,575	899,958	920,752	1,263,949	1,881,874	2,459,079
March	47,552	148,719	295,545	583,461	814,636	1,262,599	1,864,710	2,228,501
April	154,595	204,462	454,995	642,070	1,067,286	1,514,503	2,635,333	3,274,374
May	171,559	288,420	497,248	1,087,628	1,507,560	2,412,847	3,256,737	4,835,160
June	79,489	185,994	255,799	480,448	898,343	1,294,658	2,426,712	3,978,661
July	18,956	90,297	130,044	196,060	374,206	527,675	791,283	2,267,940
August	22,891	44,652	78,016	141,399	226,105	378,185	538,835	643,340
September	17,096	69,503	129,666	298,614	478,180	550,328	1,181,435	2,362,366
October	15,582	34,080	89,328	219,872	488,306	455,257	1,064,364	3,024,584
November	17,358	67,099	129,710	297,823	584,148	508,463	1,162,346	4,217,206
December	49,439	65,765	155,288	534,502	667,979	927,062	1,485,357	2,389,294
Total Q	734,073	1,468,312	2,885,212	5,906,851	8,882,394	12,517,282	20,127,387	34,540,170

Table 10: Intermediate Development Conditions

	Water Theoretically Available (Acre-Feet)							
Month	***Hist-Min***	***10th %***	***25th %***	***Median***	***Average***	***75th %***	***90th %***	***Hist-Max***
January	47,708	105,955	217,916	504,378	775,485	1,260,396	1,658,089	2,751,772
February	76,274	106,135	286,608	772,752	790,456	1,153,430	1,628,202	2,206,862
March	67,984	128,986	249,246	439,053	653,207	851,585	1,369,791	1,951,635
April	119,262	206,188	313,272	549,212	854,003	1,177,001	1,949,122	2,672,934
May	90,478	148,013	270,275	1,040,550	1,214,792	1,884,553	2,879,303	3,760,395
June	77,722	93,299	185,188	357,107	789,729	1,230,355	2,169,372	3,628,845
July	64,915	89,213	108,240	172,709	346,478	506,300	724,760	2,120,820
August	64,930	71,872	89,897	125,997	219,085	355,428	461,382	845,227
September	55,012	83,633	111,064	226,889	389,052	423,985	1,035,879	2,043,430
October	52,366	57,747	75,340	186,665	398,347	416,378	759,097	2,678,973
November	49,500	60,402	103,815	237,151	498,177	463,846	1,151,606	3,668,744
December	47,368	89,296	144,443	337,483	583,952	780,380	1,426,240	2,058,823
Total Q	813,517	1,240,740	2,155,304	4,949,945	7,512,764	10,503,635	17,212,843	30,388,460

Table 11: Full Development Conditions

	Water Theoretically Available (Acre-Feet)							
Month	***Hist-Min***	***10th %***	***25th %***	***Median***	***Average***	***75th %***	***90th %***	***Hist-Max***
January	92,922	116,260	170,926	459,318	711,995	1,209,398	1,630,678	2,726,326
February	94,953	121,039	268,497	552,599	713,753	1,020,140	1,582,836	2,182,662
March	103,073	120,962	201,910	416,151	591,085	848,500	1,275,206	1,866,497
April	137,082	160,634	257,955	485,991	786,323	1,127,789	1,910,660	2,636,822
May	128,723	149,822	216,087	994,010	1,121,687	1,770,307	2,673,458	3,709,206
June	144,361	157,811	184,035	326,385	762,473	1,108,249	2,109,110	3,520,184
July	134,403	148,145	173,986	213,797	362,621	460,431	679,226	2,066,364
August	132,235	137,970	149,168	175,338	258,265	317,315	470,027	800,584
September	114,073	130,879	156,290	245,233	397,583	425,692	888,863	1,999,581
October	108,832	112,715	125,432	153,831	386,480	308,176	648,426	2,630,031
November	100,153	105,371	125,524	208,061	477,654	392,370	1,073,146	3,437,842
December	94,920	107,582	161,865	264,869	543,040	654,577	1,392,403	1,969,655
Total Q	1,385,729	1,569,191	2,191,677	4,495,583	7,112,961	9,642,942	16,334,039	29,545,754

Findings associated with geographic distribution of inflows are shown in Table 13 and include the following:

- With time the Trinity River basin contribution significantly decreases in approximately the same proportion as inflow increases in the San Jacinto and the San-Jacinto-Brazos river basins. This situation occurs as a result of future increases in interbasin transfers from the Trinity river to the San Jacinto and San Jacinto-Brazos basins.
- Inflow contributions from the two river basins will decrease in relationship to the coastal basins. Combined inflows from the Trinity and San Jacinto river basins will decrease from approximately 84% to 76%. This situation implies that lower inflow quantities are projected to occur within the upper portions of Galveston and Trinity bays.
- The percentage of inflow contributions from the coastal basins is projected to increase over time from approximately 16% to 24%.

Table 12: Monthly Inflows Distribution Ranking

	B&E MaxH Distribution	***B&E Max Harvest Ranking***	***Naturalized Flow Condition***	***Intermediate Development Condition***	***Full Development Condition***
January	150,600	10%	18%	17%	14%
Febuary	160,600	10%	9%	17%	18%
March	652,500	50%	56%	57%	58%
April	632,400	50%	50%	52%	58%
May	1,279,900	50%	52%	63%	67%
June	833,200	50%	70%	72%	72%
July	210,800	25%	51%	56%	49%
August	150,600	30%	51%	59%	26%
September	100,400	10%	16%	21%	**
October	75,300	15%	22%	25%	**
November	351,300	50%	55%	67%	70%
December	622,400	50%	55%	66%	70%

** Below 10^{th} Percentile

Table 13: Inflows Distribution by Basin

Basin	***Inflows Distribution (acre-feet)*** Naturalized Condition	***Intermediate Development Condition***	***Full Development Condition***
Trinity	5,684,700 (64%)	3,906,600 (52%)	3,058,600 (43%)
San Jacinto	1,776,500 (20%)	2,103,600 (28%)	2,347,300 (33%)
San Jacinto-Brazos	799,400 (9%)	901,500 (12%)	924,700 (13%)
Trinity-San Jacinto	88,800 (1%)	150,300 (2%)	213,400 (3%)
Neches-Trinity	532,900 (6%)	525,900 (7%)	569,000 (8%)

9. Conclusions and Recommendations

Conclusions

The key findings of the Galveston Bay Freshwater Inflows study consist of the following:

- Increases in water rights diversions will continue to decrease the availability of freshwater inflows that enter Galveston Bay. Future projected diversions may decrease inflows by as much as 30 percent lower than inflows that would have historically occurred during naturalized flow conditions.
- Based on the model construction, it is difficult to determine whether diversions upstream of Lake Livingston or downstream of the lake and in any of the local watersheds has the greatest impact on freshwater inflows. Future studies should investigate this issue.
- River basin geographic distribution of inflows are projected to occur with lower flows than historically occurring in upper Trinity Bay and greater than historical flows occurring in upper Galveston, East and West bays.
- With maximum use of existing permitted water rights, there does not appear to be a problem in meeting Galveston Bay monthly inflow targets in eight months (January, February, April, July, August, September, October, November) of the year.
- In the months of May, June and December, there may be a potential for insufficient freshwater inflows into Galveston Bay. The total projected shortfall for these months (297,800 acre-feet) represent approximately 12% of total inflows for these months.
- While the models discussed in this study illustrate projected inflows, this study did not analyze the relationship of inflows to fisheries harvest. The simulation scenarios in this study illustrate that total inflow quantity, monthly distribution, and geographic distribution will change. There was no analysis conducted to determine which of these parameters may have the greatest impact on fisheries productivity.
- Projected worst case inflow conditions should significantly improve. This improvement suggests that future low flow conditions may not be as harsh as has historically occurred. As development within the Galveston Bay watershed continues, return flows should increase, therefore increasing total projected monthly inflow.

Recommendations

Based on this study, a number of recommendations for further analysis can be made.

- Additional hydrologic analysis should be conducted to extend the period of record from 35 to approximately 55 years. A longer period of analysis will provide a more accurate assessment of inflows for the months of March, May, June and December.
- The TWDB should run the hydrodynamic model (TxBlend) for the three

water availability scenarios and then TPWD/TWDB should evaluate the resulting monthly salinity gradients output for geographic/spatial effects on the ecosystem, especially fixed communities like oyster reefs and wetlands.

- The State B&E program should evaluate the effects of reduced inflows (eg. less than MinQ) on biological production, such as the period when inflows are reduced over several years in a row (eg. as in a drought of 3-4 years). Special emphasis could be placed on examining monthly effects from reduced inflows in spring (May-June).
- An explicit determination of fisheries harvest should be generated for the monthly inflows shown in this study to assess the temporal and spatial relationship of inflows quantity to fisheries harvest.

10. References

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Appendix A
Reservoir Data

Appendix B
Water Rights Data