5.0 HYDROLOGIC AND WATER QUALITY METHODOLOGY

5.1 Introduction

To calculate non-point source loads to Galveston Bay, a variety of environmental data were collected from a number of sources and synthesized together within a computerized Geographic Information System (GIS). The project data requirements included detailed rainfall and runoff information from area hydrologic monitoring networks, available local non-point source monitoring data from the past 15 years, and a detailed land use database of the study area. For this project, an original land use map was developed from interpreted satellite imagery to provide a high resolution (approximate mapping resolution: 30 by 30 meter) snapshot of the watershed land use as it existed in 1990. All of this information was incorporated into the Rice University ARC/INFO GIS system (Section 6.0) for the purpose of illustrating the spatial trends in non-point source loads to the bay.

This project was designed to be a "washoff" study; that is, a study of non-point source loads originating from different land uses. Land use has been recognized as one of the major factors affecting non-point sources of pollution, and has been the focus of most of the non-point source studies performed in the U.S. to date. Because of the emphasis on surface runoff from different land uses, however, several other secondary factors were not incorporated directly in this calculation, such as septic tanks, sanitary sewer by-passes and overflows, sanitary sewage leakage into storm sewers, and atmospheric deposition (see Section 5.4.3). A more detailed assessment of total non-point source loads to the bay may need to consider these secondary NPS factors.

A total of eight different water quality constituents or constituent classes were evaluated for the study: sediment, nutrients (total phosphorous and total nitrogen), biochemical oxygen demand, oil and grease, fecal coliforms, heavy metals, and synthetic organic constituents. For each land use class, typical concentrations of each constituent were estimated from available NPS data, in particular, data collected from Houston-area NPS studies. Total NPS loads were then calculated by multiplying runoff volumes (Sections 5.2 and 5.3) estimated by an SCS hydrologic model (SCS, 1986) with the appropriate NPS concentration for each land use (Section 5.4). The magnitude of upper watershed loads (Lake Houston and Lake Livingston) to Galveston Bay is discussed in Section 5.5.

In summary, the non-point source calculation for Galveston Bay focused on the effects of land use in the watershed immediately adjacent to Galveston Bay. As described in Section 6.0, a detailed land use map based on selected land use categories was developed, incorporated into the GIS system, and used as the basis for the load calculation. Exhibit 5.1 presents a summary of the entire non-point source load calculation.

5.2 Description of Three Cases Used for NPS Calculations

To evaluate the effect of non-point sources to the bay under varying conditions, three different cases were evaluated:

- **Case 1: Annual NPS Loads During an Average Year**
- **Case 2: Annual NPS Loads During a Wet Year**
- **Case 3: NPS Loads During an Individual Storm Event**

The first two cases were analyzed to evaluate annual non-point source loads to the bay, first under average rainfall conditions and second under wet conditions, when higher NPS loads would be expected. For example, the two annual cases may be useful for devising management strategies for conservative (non-degrading) water quality constituents that may accumulate in the bay over time, such as heavy metals and sediment.

The third case was analyzed to estimate water quality conditions during an actual storm event. To understand the effect of non-conservative NPS constituents on bay water quality, loads generated by individual storm events are a more accurate indicator of potential NPS problems than annual loads. For example, knowledge of fecal coliform loads during a single storm is important, as NPS fecal coliforms are not persistent in the bay and affect the resources of the bay only during and immediately after rainfall events. The individual storm reflects a generic storm with an approximately uniform rainfall pattern, and does not account for any particular season or antecedent conditions.

Management of water quality in Galveston Bay needs to account for both long-term and short-term NPS problems. The three cases described above provide NPS data that can be used to analyze different types of water quality problems and eventually develop appropriate management strategies.

5.3 Hydrology

Although land use is the primary variable in this project, the NPS process is driven by a hydrologic process, the rainfall/runoff response. This section describes the methods used to calculate runoff volumes for each of the three cases. Also included is a summary of the input data and assumptions used in the runoff calculation.

5.3.1 Rainfall Analysis

To provide the statistical basis for the rainfall input, precipitation from ten raingages maintained by National Oceanic and Atmospheric Administration (NOAA) were analyzed in detail. The ten gages were selected to ensure that 1) at least 20 years of data could be used in the statistical evaluation, 2) the raingages provided a representative coverage of the entire watershed, and 3) a higher density of raingages would be provided in the Houston metropolitan area. Figure 5.1 shows the location and Table 5.1 provides a brief description of each raingage.

Each gage was analyzed using 21 years of annual rainfall data (see Table 5.2). First, high or low recorded rainfall outliers at each gage were identified and removed from the data, using the method set forth by the Water Resources Council in 1967 (Chow, 1988). The complete outlier analysis is included in Appendix I. The method determines outliers by defining a maximum permissible range (V) for the log-transformed data set. The acceptable range of annual rainfalls were then defined using

$$V = \mu \pm \sigma^* K_n$$

where μ is the mean of the transformed data, σ is the standard deviation, and K_n is a coefficient dependent on the sample size (see Appendix I for values of K_n). Based on this analysis, one high-rainfall outlier (1979 data from the Alvin gage), and four low-rainfall outliers (1988 data from the Barker, Houston WSMCO, Cleveland, and San Jacinto Dam gages) were removed from the statistical analysis. The high outlier was affected by intense tropical storm-related precipitation, while the low outliers reflected severe drought conditions that were experienced in the watershed during 1980.

Case 1: Average Year

For Case I, a Log Pearson Type III (Bedient and Huber, 1988) analysis of twenty-one years of data (excluding the outliers) was performed to estimate the mean annual rainfall for each gage (see Appendix I for calculation summaries for each gage). The resulting annual rainfalls ranged from 41.57 inches per year at Galveston to 57.43 inches per year at Liberty, farther to the east (Table 5.3). The calculated average rainfall for the Houston WSMCO (Intercontinental Airport) was 47.74 inches per year. Although the rainfall pattern was not a smooth spatial distribution across the watershed, the expected pattern of higher rainfalls in the eastern portion of the study area was observed in the data.

Case 2: Wet Year

For Case 2, the wet year, a ten-year annual rainfall was derived from a Log Pearson Type III analysis of the raingage data. This case corresponds to a rainfall which is equaled or exceeded on the average once every ten years, or ten times every 100 years. In general, Case 2 rainfalls were approximately 30% higher than the Case 1 rainfalls (Table 5.3). The Liberty gage had the highest annual rainfall calculated for this case: 74.49 inches per year.

Case 3: Individual Storm

The rainfall calculation for Case 3, the individual storm, required a different approach than the annual rainfall analyses used for the other two cases. The annual maximum daily rainfall was determined from the daily rainfall data collected at the Houston WSMCO gage (Intercontinental Airport) during the period 1970 through 1990. For example, the maximum daily rainfall in 1970 was 4.64 inches, and represents the highest rainfall recorded for any single day during the entire year. The mean of the annual maximum daily rainfalls from the 21 year period of record was used as the basis for the Case 3 rainfall (Table 5.4). The resulting rainfall value, 4.89 inches, was adjusted to represent an average rainfall from an individual storm over the entire 4,200+ square mile basin. The adjustment factor, based on a relationship presented in Chow et. al. (1988) reduced the point rainfall value of 4.89 inches to an areally-adjusted rainfall value of 4.5 inches, an 8% reduction. This value was used at all 10 raingages for the Case 3 hydrologic modeling tasks.

Thiessen Weighting Procedure

To perform the hydrologic modeling, rainfall for each raingage was distributed over the watershed using the Thiessen polygon method (Bedient and Huber, 1988), an areal weighting procedure (Figure 5.1). In the Thiessen method, the rainfall at any location is assumed to be equal to the rainfall at the nearest gage, as defined by a series of polygons constructed from perpendicular bisectors of lines connecting a raingage with its closest neighbors. By weighting each gage according to the area of its Thiessen polygon, an average rainfall for the entire study area was calculated. The Thiessen weights are presented in Table 5.5, and the actual weighted rainfalls for each gage and the average watershed rainfall are shown in Table 5.6.

Rainfall/Runoff Calibration

By using the average watershed rainfalls in Table 5.5, actual rainfall records that were similar to Case 1 and Case 2 were selected for the purpose of calibrating the rainfall runoff model. For Case 1, a year closest to the average year, 1987, was selected as a representative average year for calibration purposes. For Case 2, 1983 was selected. In addition, actual storm events were selected for the purpose of calibrating the rainfall/runoff model.

5.3.2 Runoff Methodology

To convert the calculated rainfalls to runoff volumes, the Soil Conservation Service (SCS) curve number method (1986) was selected. The advantages of the SCS approach included simplicity, ability to account for different land uses and soil types, and the widespread application of this model for a variety of hydrologic problems. The main disadvantage of this method is that it does not provide an estimate of annual runoff volumes directly; only runoff from individual storms can be calculated.

Description of SCS Method

The SCS curve number method was originally developed as a means to estimate runoff over 24-hour periods from ungaged agricultural basins. A series of "curve numbers" were developed empirically from daily rainfall/runoff data collected from research plots. The curve numbers reflect land use, land cover, and soil type, and their effects on the amount of runoff expected from a given 24-hour rainfall.

In 1975 the original curve number method was expanded to include urban watersheds (SCS, 1975; See Appendix IV). This method allowed consideration of a variety of urban land uses, as shown in Table 5.7. Runoff volume, Q in inches, is calculated as a function of curve number (CN), initial abstraction I_a in inches, (the amount of rainfall that either infiltrates or accumulates on the ground surface before runoff begins) and 24-hour rainfall P in inches:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}$$

S, the potential maximum retention after runoff begins, is related to the soil and cover conditions of the watershed through the CN. The CN has a range of 0 to 100, and S is related to CN by:

$$S = \frac{1000}{CN} - 10$$

Higher curve numbers, for example, represent land uses with less infiltration potential, and therefore higher, runoff potential.

Calculation of Annual Runoff

To adapt the SCS methodology for the estimation of runoff due to annual rainfall, a statistical evaluation of hourly rainfall data from an existing NPS study (Winslow and Associates, 1986) was used. Application of a rainfall statistics program, SYNOP, indicated that during an average year approximately 84 separate storms with more than 0.01 inches of rainfall occur in the area. The mean rainfall of the 84 events was 0.308 inches (assuming a log-normal distribution), and the coefficient of variation was 1.154 (in log space). Using this information, a statistical analysis was performed to distribute a year's worth of rainfall into different sizes of storms. For example, the Case 1 annual rainfall was divided into five different size storms for each gage, such as the distribution shown below. As can be seen above, the rainfall totals were selected to provide an equal number of storms per year:

Storm Type	Rainfall (inches)	Number of Storms per Year
Very small storms	0.049	17
Small storms	0.16	17
Average storms	0.30	17
Large storms	0.566	17
Very large storms	1.873	17
Annual Rainfall	**50.13**	**85**

The theoretical distribution of rainfall was used for two reasons: 1) it could be derived quickly and efficiently compared to an empirical distribution, which would have required use of the SYNOP program; and 2) the theoretical distribution was easier to apply in the ARC/INFO program. The extensive rainfall database could be represented statistically in the runoff calculation using the data listed above rather than a detailed empirical distribution consisting of hundreds or thousands of rainfall values.

A summary of the rainfall distributions used for Cases 1 and 2 are shown in Tables 5.8 and 5.9, respectively. Calculation methods for the rainfall analyses are shown in Appendix II. For Case 3, a uniform 4.5 inch Type-II rainfall over a 24-hour period was assumed for each raingage.

The actual runoff calculation and calibration was performed using the ARC/INFO GIS. This methodology is described in more detail in Section 6.0.

5.4 Event Mean Concentrations (EMCs)

Rainfall data and the SCS runoff methodology were employed to calculate the volume of runoff from different land uses, subwatersheds, and watersheds in the study area. To calculate NPS loads from these areas, typical concentrations of each water quality constituent in runoff were required. These water quality data, defined as event mean concentrations or EMCs, were developed for each land use type defined for the Galveston Bay project.

An EMC is the average concentration of water quality constituents over the course of an entire storm event. If several water quality samples are collected at different times during the storms, an event mean concentration can be calculated by flow-weighting the water quality data. The result is that samples collected during high-flow periods near the peak of the storm are weighted more heavily than samples collected during periods with lower flow rates.

Eight water quality constituents were evaluated for the purpose of developing EMCs:

- Total Suspended Solids (TSS), reported in mg/l
- Total phosphorous (TP), reported in mg/l
- Total Nitrogen (TN), reported in mg/l
- Five-Day Biochemical Oxygen Demand (BOD), reported in mg/l
- Oil and Grease (O&G), reported in mg/l
- Fecal Coliform (FC), reported in colony forming units per 100 ml, abbreviated as cfu/100 ml or colonies per 100 ml
- Dissolved Copper (Cu), reported in mg/l
- Chlorinated Hydrocarbon and Organophosphorous Pesticides, reported in mg/l, abbreviated as pesticide

In addition, an annual NPS load assessment was developed using EMCs for the following dissolved metals: Lead, Zinc, Arsenic, Cadmium, Chromium, Mercury, and Silver.

These parameters are an expanded version of an original list developed by GBNEP. Biochemical oxygen demand was added to the original list because of the importance of oxygen demanding substances on water quality. Dissolved copper was selected for the detailed mapping analysis because the NURP program indicated copper as a metal of concern; for example 50% of the priority pollutant samples collected during the NURP program exceeded the freshwater ambient 24-hour instantaneous maximum criterion established by EPA ("acute" criterion; Cole et al, 1984). Dissolved copper was selected instead of total copper because little local total copper data were available for the Houston area. One major implication of using dissolved rather than total copper is that the reported loadings are more accurate for doing dilution calculations and comparing against water quality standards (which are based on dissolved metals) than for estimating the total amount of copper in the water column and on sediments.

Most of the EMCs used in the Galveston Bay NPS calculation were derived from an extensive compilation and analysis of local non-point source water quality data. When local data were not available, EMCs from the technical literature or studies such as the EPA's NURP were used.

5.4.1 Houston Area EMC Database

The Houston area EMC database was derived from three main sources as described in Section 4.3:

- Rice University NPS Studies
- USGS Houston Urban Runoff Program Data
- Texas Water Commission/Winslow Associates Houston Ship Channel NPS Study

EMCs were compiled from over 30 different stations and approximately 250 station-storms (a separate storm event at a sampling station). For the Rice University studies, EMCs were taken directly from journal articles and technical reports summarizing studies performed in the 1974 - 1978 time frame. Data from the HURP, which was active from approximately 1968 - 1984, were obtained after meeting with Dr. Fred Liscum of the Houston USGS office and obtaining a file from the USGS water quality database. The data, consisting of discrete water quality sampling and flow information, were weighted to obtain EMC values for each station-storm. The TWC Ship Channel study, performed in 1986, had both flow-composited sampling data (samples composited automatically in the field) and discrete sampling data performed at specific times during a storm. Unfortunately, flow data were not reported and could not be located for individual samples, preventing the flow weighting of some of the concentration data. A simple average was performed to estimate the EMCs from the TWC study.

The resulting 250 EMCs represent a comprehensive collection of Houston area NPS data in one database. To incorporate this information into the Galveston Bay study, the EMC data were divided into land use/watershed area categories as shown in the following table.

Designation	Area	Land Use	Example Watershed
A1	< 10 sq. mi.	> 50% Residential	Lazybrook Storm Sewer
A2	< 10 sq. mi.	> 50% Comm. + Indust.	Bettina St. Ditch
A3	< 10 sq. mi.	Forest	Basin P-10, Woodlands
A5	< 10 sq. mi.	Mixed	Sherwood Storm Sewer

B1	10 - 100 sq. mi.	< 10 % Developed	Basin P-30, Woodlands
B2	10 - 100 sq. mi.	10 - 50 % Developed	Keegan's Bayou @ Roark Rd.
B3	10 - 100 sq. mi.	> 50% Developed	Brays Bayou @ Main Street
C1	> 100 sq. mi.	< 10% Developed	Cypress Creek @ I-45
C2	> 100 sq. mi.	10 - 50 % Developed	Buffalo Bayou @ Shepherd

Summary statistics for each of the EMC categories are provided in Table 5.10, and the actual EMC database is provided in Appendix III. The A1, A2, and A3 categories provided the principal sources of EMC data for the Galveston Bay project (see Section 5.4.3).

5.4.2 Other Sources of EMC Data

Despite the relatively large size of the Houston Area EMC database, several data gaps remained to be filled before an EMC could be assigned to each land use and water quality parameter combination. For example, very little oil and grease data were collected in Houston during the studies described above. Sources of additional NPS data collected outside of the Houston area are summarized below:

- Final Report of the Nationwide Urban Runoff Program (USEPA, 1983)
- Priority Pollutant Survey from the NURP Program (Cole et al, 1984)
- Oil and grease studies performed by Stenstrom et al (1984)
- USGS Austin NPS study (Veehnius & Slade, 1990)
- Various agricultural NPS studies (see Appendix III)

Results from these studies were used to fill in the data gap when the final EMC/land use table for the Galveston Bay project was prepared as described below.

5.4.3 Selection of Project EMCs

Project EMCs are presented in Table 5.11. For example, total suspended solids EMCs range from 201 mg/l for agricultural areas to 39 mg/l for forested areas. Oil and grease EMCs ranged from 4 to 13 mg/l in urban areas, and were assumed to be present at very low concentrations elsewhere. EMCs for the water land use category (lakes and streams) were assumed to be zero for all parameters.

A detailed description of the data sources and explanations used to select these EMCs is presented in Table 5.12, and a subjective assessment of the relative accuracy of each EMC value is then provided in Table 5.13. The major factors used to select EMCs are the following:

- The Houston area EMC database was used in determining TSS, TN, and TP values for the urban, residential, and forest land uses. For open and barren land uses, NURP data were used for all of these parameters except TSS.

- Most EMCs were based on data from small watersheds (<10 sq. miles), with one predominate land use. This was done to ensure the best correlation between the final EMCs and actual land use. One consequence of this approach was that the contribution from some sources, such as by-passes, overflows, and sanitary sewage leakage into large storm sewers, is probably not represented in the EMCs.

- The 1987 USGS study of the watersheds upstream of Barker/Addicks reservoirs (USGS, 1987) was used for most of the agricultural EMCs.

- Data collected by Stenstrom (1984) were used for the oil and grease EMCs for urban areas.

- Because of the lack of wetlands data, an assumption was made that wetlands had low EMCs, similar to forested areas. The process of pollutant reduction and attenuation in wetlands was not addressed, also because of a lack of reliable data. Because wetlands loads are generally low compared to most other land uses (except for the possible exception of the total nitrogen parameter), it was assumed that wetlands had low EMCs that were similar to the low EMCs exhibited by forest lands.

- Heavy metals EMCs for the two urban land use categories were calculated using the entire Houston Area EMC database (see category E1 in Table 5.10 and Table E1 in Appendix III). Values reported as "not detected" were assumed to be equal to half the detection limit. Rural heavy metal EMCs were based on the Barker/Addicks reservoir study (USGS, 1987). The Barker/Addicks watersheds, which are predominantly agricultural and open/pasture, exhibited concentrations of heavy metals that were very similar to concentrations from the urban watersheds (see Appendix III). The limitation in the metals database prevented a more detailed analysis of appropriate EMCs, or the possible reason why urban EMCs appear to be similar to non-urban EMCs (although the urban and non-urban EMCs may be similar, urban loads will still be significantly higher because of higher urban runoff volumes). All metals data reported in the project are based on dissolved metals analysis performed by the USGS; little total metals data were available.

- Pesticides were evaluated using two USGS studies: a combined urban/rural study conducted in Austin, Texas (Veehnius and Slade, 1990), and the Barker/Addicks reservoir study (USGS, 1987). The Austin data was selected because an extensive urban pesticide database for the Houston area was not available. The urban EMC data were derived from urban catchments in the Austin project, while rural data were developed from the Barker/Addicks study. There were no local pesticide loading data from different rural land uses, and therefore all rural land uses were assumed to have the same EMCs as measured from the Barker/Addicks reservoir study. Because most of the pesticide data had numerous "below detection limit" values, a simple methodology based on percentage of reported values was developed to provide representative EMCs (see Appendix III). The pesticides include the following compounds: Aldrin, Chlordane, DDD, DDE, DDT, Diazinon, Dieldrin, Endosulfan, Endrin, Heptochlor, Heptochlorepoxide, Lindane, Malathion, Methoxychlor, Mirex, Parathion, and Trihion. Diazinon, an organophosphorous compound, was the most common pesticide in both studies, found in 31 of 36 urban samples from Austin and 94 of 179 samples in the Barker/Addicks study (a rural watershed). Chlorinated pesticides were more common in the urban areas than rural areas.

Other organic compounds, such as phenol, pentachlorophenol, chloroform, 2-methoxy-2-methyl propane and bis(2-ethylhexyl)phthalate were not included in the load calculation either because of lack of local NPS data or a large number of "not detected" values in the database. Pesticides were the only synthetic organic constituents with field data at high enough concentrations to perform an NPS load assessment with any confidence. Cole et al (1984) provides the most detailed review of priority pollutants found in NURP urban runoff samples; widely varying analytical detection limits greatly complicate the analysis of this data, however.

Considerable care was devoted to ensuring representative EMCs for this project because the final project NPS loads were very sensitive to the EMC data. A subjective assessment of EMC accuracy was performed, based on the amount and quality of local NPS data (see Table 5.13). Largely because of the extensive local NPS database, the conventional water quality parameters, such as TSS, BOD, and nutrients, have a higher degree of accuracy associated with them than do metals or synthetic organic constituents. Also, EMCs associated with urban land uses have a higher degree of confidence than do rural EMCs because more of the Houston area data were collected in urban areas. Overall, the accuracy of most of the EMCs is considered to be relatively good due to the extensive local database on NPS pollutants collected over a number of years by several different groups.

5.4.4 Comparison With Other EMC Data

The EMC data used for this project are similar to NPS data reported in other studies (Table 5.14). Fecal coliform concentrations matched other data sources very closely. Although the rural EMC data were not as extensive as those in the urban database, they indicated that agricultural NPS concentrations lie at the low end of the reported range for sediment and nutrient loads from other agricultural watersheds. One possible explanation is the extensive rice cultivation in the watershed: flooded rice fields are relatively low generators of sediments and nutrients compared to typical row crops (McCauley, 1991).

5.5 Assessment of Upper Watershed Non-Point Source Loads

As described in Section 2.0, Objectives, the Galveston Bay NPS project defined by GBNEP focused on the immediate drainage areas around the bay, a 4,238 square mile area. The larger "upper watersheds," consisting of the 2,828 square mile Lake Houston and the 16,600 Lake Livingston drainage, were not included directly in the non-point source assessment performed with the GIS System. The reasons for the secondary emphasis on the upper watersheds were three-fold:

1. The upper watersheds are some distance from the bay, and, therefore, do not have the same effect on water quality as the watersheds immediately adjacent to the bay.

2. The two large reservoirs, Lake Houston and Lake Livingston, act as natural treatment systems for pollutants and serve to reduce or attenuate some loads before they reach the bay (Baca, 1982; Hydroscience, 1976).

3. The design of the Galveston Bay study emphasized assessing the impacts of land use, particularly urban land uses, on NPS loads. Both upper watersheds can be considered to be generally rural in nature, with the exception of the Dallas metroplex on the Upper Trinity River. Therefore, most of the urban areas of interest were located in watersheds immediately adjacent to the bay.

Lake Houston, completed in 1954, lies to the north of the study area and is used as a water supply and recreational area for the City of Houston and surrounding communities. Approximately 150,000 to 200,000 acre-ft of water are diverted each year for municipal and industrial purposes. Approximately 73% of the drainage is forested, 14% open land, and less than 5% is represented by urban development (Baca, 1982; Newell, 1981). Average inflow into the 146,000 acre reservoir is approximately 2000 cfs, yielding a typical hydraulic residence time of 1-2 months. Newell (1981) provides more information on NPS loads to the Lake and Baca (1982) provides data regarding the ability of Lake Houston to attentuate and reduce pollutant loadings to the bay.

In the northernmost portion of the project study area lies Lake Livingston, a 2,000,000 acre-ft reservoir that drains a 16,600 square mile watershed encompassing much of north-central Texas. The dam was completed in 1968 and shortly afterward impoundment began for the purpose of municipal and industrial water supply for the Houston metropolitan region. Average discharge from the reservoir is approximately 7,000 cfs, corresponding to a hydraulic residence time of 4-5 months.

To assess the impacts of the upper watersheds, a statistical analysis of historical runoff and water quality data was conducted to: (1) calculate the total volume of runoff that would be expected from the two lakes for the three cases, and (2) calculate the average concentrations for pollutants discharged from the lakes. Lake loads were then calculated by multiplying runoff volume and average concentration (comprised of point source loads, low flow loads, and NPS loads).

5.5.1 Runoff Analysis

In order to estimate the total runoff volume for Cases 1 and 2, the annual discharge data for the two upper watersheds were compared to the annual Galveston Bay project rainfall using a linear regression as shown in Exhibits 5.2 and 5.3. A relatively strong correlation (r^2=0.76) was observed with the Lake Houston data; this is to be expected because of the proximity of the Lake Houston drainage area to a large portion of the study area. The Lake Livingston correlation was not as strong (r^2=0.53) but still indicated that annual rainfall in the Houston area and runoff from the lakes are not independent parameters. Therefore, the regression relationships were used to estimate the annual runoff volume from the upper watersheds for the two annual cases: Case 1 (average year) and case 2 (wet year).

Using the regression equations (based on actual discharge data) and GBNEP basin-wide rainfalls, the following annual runoff volumes were estimated for the upper watersheds:

	Lake Houston	Lake Livingston
Case 1 (average year)	1.4 million acre-ft	4.7 million acre-ft
Case 2 (wet year)	2.2 million acre-ft	6.8 million acre-ft

For Case 3, the individual storm, the selection of representative runoff volumes was much more difficult. An assessment of 20 actual storm events indicated a weak relationship at best between a large rainfall event over the

Houston metropolitan area and discharge from the two dams. Therefore, median daily discharge values were computed from runoff data provided by the Texas Water Development Board (Brock, 1991) and the flowrate (in cubic feet per second) was converted to runoff volume for a 24-hour period for the NPS assessment:

	Lake Houston	Lake Livingston
Case 3 (individual storm)	3,482 acre-ft	5,368 acre-ft

The 24-hour flow duration was selected to correspond to the duration of the Case 3 rainfall event: 24 hours. The runoff estimates shown above may under-represent the effect of the lakes during actual storm events, however, as large runoff events in the Houston area typically occur over periods longer than 24 hours.

5.5.2 Water Quality Data Analysis

A water quality data analysis was performed to determine average concentrations of water quality parameters in the discharge from each lake. The two databases were utilized: the Texas Water Commission (TWC) and the USGS Water Resources publications (USGS, 1970-1989). The parameters of interest included total nitrogen, total phosphorous, fecal coliform, biochemical oxygen demand, total suspended solids, oil and grease, arsenic, cadmium, chromium, copper, nickel, lead, and zinc. To ensure that the data reflected pollutant removal/transformation processes occurring in the lakes, only stations representative of dam discharge (i.e., located either immediately downstream of the lakes or directly upstream of the dam near the discharge point) were used for the calculation. Note that the lake discharge data represents a mixture of point source loads, low-flow loads, and NPS loads that have been exposed to any in-lake attenuation processes.

The historical data were obtained from the TWC and the USGS databases and averaged by parameter, year, and source of data. Table 5.15 lists the calculated concentrations from the analysis for each parameter. The average annual concentration for each parameter was extracted from the two databases to calculate an overall average for the parameter for the whole period of record from both data sources. For parameters with little data, or data with a large percentage of "below detection" values, concentrations representative of non-urban runoff EMCs were used. Oil and grease, heavy metals, and synthetic organic constituent concentrations for the lakes were estimated using the non-urban EMCs in Table 5.11.

5.5.3 Upper Watershed Load Estimates

Annual load estimates for the three cases were performed by multiplying the average concentration for each parameter by the total runoff for each rainfall event. The load estimates for Lake Houston and Livingston are listed in Table 5.16. Overall, Lake Livingston contributes more loads to Galveston Bay than Lake Houston for all the parameters except for fecal coliform. Both lakes contribute substantial amounts of pollutants into the bay. For example, in an average year, BOD from Lake Houston is about 5.8 million kilograms, and that from Lake Livingston is approximately 14.0 million kilograms. The impacts of these loads on Galveston Bay are discussed in Section 7.0.

5.5.4 Comparison with Other Studies

In order to evaluate the accuracy of results from this analysis, the calculated total suspended solids, total phosphorous, and total nitrogen loads were compared to results from the 1988 Texas Water Development Board's (TWDB) "Suspended-Sediment Load of Texas Streams" study, a journal article on loads to Lake Houston by Baca, Bedient, and Olsen (1982), and a draft report by Stanley (1989).

For Lake Houston, the calculated GBNEP TSS loads were within 20% of those calculated by Baca et al. (1982): 43 million kg/yr for the GBNEP total versus 36 million kg/yr for the 1981 study (Table 5.17). The nutrient loads for Lake Livingston from Stanley et al. (1989), were also very close to the nutrient loads calculated for this project. The TWDB load rates published in 1988 for the Lake Livingston discharge (Trinity River at Romayor) were 10 times higher than the GBNEP loads (57 million kg/yr versus 650 million kg/yr). The reasons for this difference are unknown.

Table 5.1 - Location and Period of Record for Raingages

Non-Point Source Characterization Project
Galveston Bay National Estuary Program

STATION	LATITUDE	LONGITUDE	PERIOD OF RECORD
Alvin (Houston Area WSO)	29°25'	95°13'	1918 to 1990
Anahuac TBCD	29°47'	94°40'	1918 to present
Cleveland	30°22'	95°05'	1955 to present
Galveston WSO	29°18'	94°48'	1918 to present
Houston WSMCO (Intercontinental)	29°58'	95°21'	1969 to present
Houston FAA Airport (Hobby)	29°39'	95°17'	1932 to present
Houston - Barker	29°49'	95°44'	1949 to present
Houston - Independent Heights	29°52'	95°25'	1949 to present
Houston - San Jacinto Dam	29°55'	95°09'	1960 to present
Houston WSO	29°28'	95°05'	1990 to present
Liberty	30°03'	94°48'	1918 to present

NOTES:
1. Gage locations and periods of record in NOAA, 1918 - 1990.
2. See Figure 5.1 for locations of raingages.
3. On November 1, 1990, the Alvin (Houston Area WSO) gage located in eastern Brazoria county, became inactive. The rainfall amounts from the Houston WSO gage, located in Galveston county were used for November and December of 1990.

Table 5.2 - Annual Rainfall Summary

Non-Point Source Characterization Project
Galveston Bay National Estuary Program

Year	ANNUAL RAINFALL (inches)									
	Alvin	Anahuac	Cleveland	Galveston WSO	Houston WSMCO (Intercontinental Airport)	Houston FAA Airport (Hobby Airport)	Houston - Barker	Houston - Independent Heights	Houston - San Jacinto Dam	Liberty
1970	48.82	58.91	42.15	48.47	48.19	56.31	48.04	53.79	53.26	52.02
1971	38.27	43.90	39.96	35.97	37.83	36.91	41.44	41.37	44.48	39.27
1972	53.34	47.47	53.15	39.95	50.80	55.22	39.04	59.79	56.72	59.26
1973	71.93	75.98	89.38	60.47	70.16	80.65	59.54	74.46	70.88	83.26
1974	51.85	54.13	66.56	43.26	49.29	57.97	56.25	55.89	54.54	63.54
1975	43.73	63.47	56.02	48.54	50.97	49.07	46.35	49.51	46.29	59.65
1976	54.5[illegible] [3]	47.05	53.30	42.06	54.62	69.66	44.74	60.49	57.85	53.50
1977	34.53	45.15	39.43	42.07	34.94	41.79	36.81	41.62	42.95	61.11
1978	41.43	37.84	45.80	29.28	44.93	44.47	41.05	42.79	45.01	42.35
1979	102.58	70.65	75.87	59.35	58.97	83.02	53.15	64.43	77.00	70.11
1980	41.15	53.96	38.37	34.58	38.99	39.70	34.46	41.39	51.28	56.77
1981	52.79	64.88 [1]	58.50	46.78	55.98	82.14	51.05	47.90 [1]	75.23 [1]	65.57 [1]
1982	42.89	47.81	53.04	34.26	42.87	46.41	33.04	39.89	37.11 [1]	57.10
1983	60.48	61.48 [1]	59.76	53.90	53.21	56.47 [2]	52.34	60.77	59.78	83.62
1984	45.99	35.42	45.74	35.64	48.19	49.72	45.02	44.95	40.61	47.46
1985	59.12	59.46	53.31	41.24	49.14	47.54	48.28	47.15	50.42 [2]	61.92
1986	51.75	52.99	66.21	36.34	44.93	53.82	49.99	51.72	57.02	63.63
1987	49.59	51.65	52.51	36.84	40.60	44.10	41.47	47.47	57.96	61.48
1988	34.19	33.78	25.01	39.88	22.93	26.65	24.94	28.99	27.32 [1]	34.18
1989	44.0[illegible] [1]	58.60	65.20	40.59	52.73	53.30	36.82	59.12	57.26 [4]	62.52
1990	36.8 [5]	50.50	46.77	38.19	40.37	35.90 [1]	36.84	38.70	53.04 [4]	54.00

NOTES:

1. Record incomplete - one month of records missing.
2. Records incomplete - one or more days missing.
3. Angleton gage used due to lack of information on Alvin gage.
4. Baytown gage used due to lack of information on San Jacinto Dam gage.
5. In 1990, the Houston Area WSO gage was moved from Alvin to Galveston County. There are two months missing in this record.
6. Data from NOAA, 1970 - 1990.
7. See Figure 5.1 for locations of the raingages.

Table 5.3 - Case 1 and Case 2 Rainfall
Non-Point Source Characterization Project
Galveston Bay National Estuary Program

RAINGAGE	Case 1: Average Year Rainfall (inches)	Case 2: Wet Year Rainfall (inches)
Alvin (Houston Area WSO)	46.99	60.55
Anahuac TBCD	51.98	67.71
Cleveland	53.72	72.18
Galveston WSO	41.57	53.06
Houston WSMCO (Intercontinental)	47.74	59.35
Houston FAA Airport (Hobby)	50.89	73.27
Houston - Barker	44.19	54.79
Houston - Independent Heights	50.33	63.87
Houston - San Jacinto Dam	53.46	68.74
Liberty	57.43	74.49

NOTES:
1. Derivation of rainfall amounts shown in Appendix I.
2. See Figure 5.1 for the locations of the raingages.

Table 5.4 - Case 3 Rainfall
Non-point Source Characterization Project
Galveston Bay National Estuary Program

Annual Maximum Daily
Rainfall at Houston WSMCO
(Intercontinental) Gage

Year	(inches)
1970	4.64
1971	3.28
1972	7.47
1973	5.63
1974	2.84
1975	3.57
1976	8.16
1977	2.64
1978	3.36
1979	6.92
1980	3.36
1981	5.98
1982	3.59
1983	6.69
1984	9.25
1985	3.18
1986	3.81
1987	2.42
1988	1.94
1989	10.34
1990	3.52
Total	102.59

21-year average = 4.89 inches

Areally Adjusted Rainfall = (21-year average)*(weighting factor)
= (4.89)*(0.92)
= 4.50 inches

NOTES:
1. Rainfall values located in NOAA, 1970 - 1990.
2. See Figure 5.1 for the location of the raingage.
3. Areal Distribution Weighting Coefficient, 92% obtained for 2000+ square miles from Chow et al (1988).

Table 5.5 - Thiessen Weights for Raingages

Non-Point Source Characterization Project
Galveston Bay National Estuary Program

RAINGAGE	AREA OF THIESSEN POLYGON (square miles)	WEIGHTING COEFFICIENTS FOR RAINGAGES (percent)
Alvin (Houston Area WSO)	824	19.4
Anahuac TBCD	599	14.1
Cleveland	739	17.4
Galveston WSO	160	3.8
Houston WSMCO (Intercontinental)	87	2.1
Houston FAA Airport (Hobby)	454	10.7
Houston - Barker	354	8.3
Houston - Independent Heights	254	6.0
Houston - San Jacinto Dam	309	7.3
Liberty	466	11.0
Total	4245	100

NOTE:
1. Areas of Thiessen polygons obtained from ARC/INFO GIS System.
2. See Figure 5.1 for locations of raingages.

Table 5.6 - Thiessen Weighted Rainfall
Non-Point Source Characterization Project
Galveston Bay National Estuary Program

Year	ANNUAL WEIGHTED RAINFALLS (inches)										Annual Galveston Bay Watershed Rainfall
	Alvin	Anahuac	Cleveland	Galveston WSO	Houston WSMCO (Intercontinental Airport)	Houston FAA Airport (Hobby Airport)	Houston - Barker	Houston - Independent Heights	Houston - San Jacinto Dam	Liberty	
1970	9.48	8.31	7.34	1.82	.99	6.02	4.00	3.22	3.88	5.71	50.76
1971	7.43	6.19	6.96	1.35	.78	3.95	3.45	2.47	3.24	4.31	40.13
1972	10.35	6.70	9.25	1.50	1.04	5.91	3.25	3.58	4.13	6.50	52.21
1973	13.96	10.72	15.56	2.27	1.44	8.63	4.96	4.45	5.16	9.13	76.29
1974	10.07	7.63	11.59	1.63	1.01	6.20	4.69	3.34	3.97	6.97	57.10
1975	8.49	8.95	9.75	1.83	1.05	5.25	3.86	2.96	3.37	6.54	52.05
1976	10.58	6.64	9.28	1.58	1.12	7.45	3.73	3.62	4.21	5.87	54.08
1977	6.70	6.37	6.86	1.58	.72	4.47	3.07	2.49	3.13	6.70	42.09
1978	8.04	5.34	7.97	1.10	.92	4.76	3.42	2.56	3.28	4.65	42.04
1979	19.91	9.96	13.21	2.23	1.21	8.88	4.43	3.85	5.61	7.69	76.99
1980	7.99	7.61	6.68	1.30	.80	4.25	2.87	2.48	3.73	6.23	43.93
1981	10.25	9.15	10.18	1.76	1.15	8.79	4.25	2.86	5.48	7.19	61.07
1982	8.33	6.74	9.23	1.29	.88	4.96	2.75	2.39	2.70	6.26	45.54
1983	11.74	8.67	10.40	2.03	1.09	6.04	4.36	3.63	4.35	9.17	61.50
1984	8.93	5.00	7.96	1.34	.99	5.32	3.75	2.69	2.96	5.21	44.14
1985	11.48	8.39	9.28	1.55	1.01	5.08	4.02	2.82	3.67	6.79	54.10
1986	10.05	7.47	11.52	1.37	.92	5.76	4.16	3.09	4.15	6.98	55.48
1987	9.63	7.28	9.14	1.39	.84	4.72	3.45	2.84	4.22	6.75	50.25
1988	6.64	4.76	4.35	1.50	.47	2.85	2.08	1.73	1.99	3.75	30.13
1989	8.55	8.26	11.35	1.53	1.08	5.70	3.07	3.54	4.17	6.86	54.10
1990	7.14	7.12	8.14	1.44	.83	3.84	3.07	2.31	3.86	5.92	43.68

NOTES:
1. See Figure 5.1 for locations of raingages.
2. Weighted rainfall were calculated by multiplying the actual rainfalls in Table 5.2 by the Thiessen Weighting Coefficients located in Table 5.5.

Table 5.7 - SCS Runoff Curve Number Table
Non-Point Source Characterization Project
Galveston Bay Natioonal Estuary Program

Land Use Description	Curve Number by Hydrologic Soil Group A	B	C	D
Agriculture				
Cultivated land				
Without conservation treatment	72	81	88	91
With conservation treatment	62	71	78	81
Pasture or range land				
Poor Condition	68	79	86	89
Good Condition	39	61	74	80
Meadow				
Good Condition	30	58	71	78
Wood or Forest Land				
Thin stand, poor cover, no mulch	45	66	77	83
Good cover	25	55	70	77
Open spaces, lawns, parks, golf courses, cemeteries, etc.				
Good condition: grass cover on 75% or more of the area	39	61	74	80
Fair condition: grass cover on 50-75% of the area	49	69	79	84
Commercial and business areas (85% impervious)	89	92	94	95
Industrial districts (72% impervious)	81	88	91	93
Residential				
1/8 ac or less (65% impervious)	77	85	90	92
1/4 ac or less (38% impervious)	61	75	83	87
1/3 ac or less (30% impervious)	57	72	81	86
1/2 ac or less (25% impervious)	54	70	80	85
1 ac or less (20% impervious)	51	68	79	84
Paved parking lots, roofs, driveways, etc.	98	98	98	98
Streets and roads				
Paved with curbs and storm sewers	98	98	98	98
Gravel	76	85	89	91
Dirt	72	82	87	89

Notes:

1. Source of Curve Number Table: SCS, 1986
2. Hydrologic Soil Type
   A: generally sand, loamy sand, or sandy loam high infiltration potential
   B: generally silt loam or loam soils with moderate infiltration potential
   C: generally sandy clay loam with low infiltration potential
   D: generally clay loam, silty clay loam, sandy clay, silty clay, or clay with very low infiltration potential

Table 5.8 - Case 1: Average Year Rainfall Summary

Non-Point Source Characterization Project
Galveston Bay National Estuary Program

Rainfall by Storm Size:

Storm Size	Rainfall (inches)
Very small storm (P1)	0.049
Small storm (P2)	0.16
Average storm (P3)	0.301
Large storm (P4)	0.566
Very large storm (P5)	1.873
Size	50.13

Gage	Actual Annual Rainfall (inches)	Ratio of Annual Rainfall to 50.13 inches	Rainfall by Storm Size (inches)					Number of Storms for each Storm Size	Calculated Annual Rainfall (inches)
			P1	P2	P3	P4	P5		
Alvin (Houston Area WSO)	46.99	0.94	0.05	0.15	0.28	0.53	1.76	17	46.99
Anahuac	51.98	1.04	0.05	0.17	0.31	0.59	1.94	17	51.98
Cleveland	53.72	1.07	0.05	0.17	0.32	0.61	2.01	17	53.72
Galveston	41.57	0.83	0.04	0.13	0.25	0.47	1.55	17	41.57
WSMCO (Intercontinental)	47.74	0.95	0.05	0.15	0.29	0.54	1.78	17	47.74
FAA Airport (Hobby)	50.89	1.02	0.05	0.16	0.31	0.57	1.90	17	50.89
Barker	44.19	0.88	0.04	0.14	0.27	0.50	1.65	17	44.19
Independent Heights	50.33	1.00	0.05	0.16	0.30	0.57	1.88	17	50.33
San Jacinto Dam	53.46	1.07	0.05	0.17	0.32	0.60	2.00	17	53.46
Liberty	57.43	1.15	0.06	0.18	0.34	0.65	2.15	17	57.43

NOTES:
1. Actual Rainfalls taken from Table 5.3.
2. Calculated Annual Rainfalls = ratio * ((P1*17) + (P2*17) + (P3*17) + (P4*17) + (P5*17) + (P6*17))

Table 5.9 - Case 2: Wet Year Rainfall Summary
Non-Point Source Characterization Project
Galveston Bay National Estuary Program

Rainfall by Storm Size:

Storm Size	Rainfall (inches)
Very small storm (P1)	0.049
Small storm (P2)	0.16
Average storm (P3)	0.301
Large storm (P4)	0.566
Very large storm (P5)	1.873
Size	50.13

Gage	Actual Annual Rainfall (inches)	Ratio of Annual Rainfall to 50.13 inches	Rainfall by Storm Size (inches)					Number of Storms for each Storm Size	Calculated Annual Rainfall (inches)
			P1	P2	P3	P4	P5		
Alvin (Houston Area WSO)	60.55	1.21	0.06	0.19	0.36	0.68	2.26	17	60.55
Anahuac	67.71	1.35	0.07	0.22	0.41	0.76	2.53	17	67.71
Cleveland	72.18	1.44	0.07	0.23	0.43	0.81	2.70	17	72.18
Galveston	53.06	1.06	0.05	0.17	0.32	0.60	1.98	17	53.06
WSMCO (Intercontinental)	59.35	1.18	0.06	0.19	0.36	0.67	2.22	17	59.35
FAA Airport (Hobby)	73.27	1.46	0.07	0.23	0.44	0.83	2.74	17	73.27
Barker	54.79	1.09	0.05	0.17	0.33	0.62	2.05	17	54.79
Independent Heights	63.87	1.27	0.06	0.20	0.38	0.72	2.39	17	63.87
San Jacinto Dam	68.74	1.37	0.07	0.22	0.41	0.78	2.57	17	68.74
Liberty	74.49	1.49	0.07	0.24	0.45	0.84	2.78	17	74.49

NOTES:
1. Actual Rainfalls taken from Table 5.3.
2. Calculated Annual Rainfalls = ratio * ((P1*17) + (P2*17) + (P3*17) + (P4*17) + (P5*17) + (P6*17))

Table 5.10 - Event Mean Concentrations (EMCs) by Watershed Type
Houston EMC Database
Non-Point Source Characterization Project
Galveston Bay National Estuary Program

Watershed			Parameter (mg/l except fecal coliform in col/100ml)											Dissolved Metals (µg/l)						
Type	Area/Land Use		TSS	TN	TP	BOD	O&G	FC	NH3	TKN	NO3+NO2	NO2	NO3	Cu	Cd	Cr	Pb	Hg	Ag	Zn
A1:	< 10 sq mi > 50% Residential																			
		Median	**166**	**2.10**	**0.37**	**8.5**	9.4		1.09	1.62	0.36	0.06	0.44	4.16	1.00	10.00	2.18	0.10	1.00	35.37
		Average	236	2.63	0.62	9.3	11.7		1.19	2.15	0.51	0.07	0.43	4.88	1.30	9.00	4.59	0.09	0.90	49.09
		Std Dev	259	2.62	0.81	4.4	7.1		0.89	2.34	0.39	0.03	0.08	2.63	0.95	3.16	4.77	0.03	0.32	46.40
		No. Data Pts	52	45	53	28	14		10	53	42	8	5	10	10	10	10	10	10	10
A2:	< 10 sq mi > 50% Commercial & Industrial																			
		Median	**100**	**3.41**	**0.79**	**15.0**	8.3	**4.3**	0.52	2.88	0.57	0.03	0.38	3.97	1.00	0.00	4.16	0.10	0.00	55.20
		Average	145	3.50	0.84	17.8	7.6	4.3	0.52	2.94	0.64	0.03	0.38	4.14	1.38	4.81	7.89	0.12	0.18	75.40
		Std Dev	140	1.46	0.42	9.3	4.8	0.0	0.53	1.30	0.32	0.01	0.01	3.62	0.97	8.08	8.90	0.04	0.40	68.43
		No. Data Pts	27	26	26	13	21	3	2	26	24	2	2	6	6	6	6	6	6	6
A3:	< 10 sq mi Forest																			
		Median	**39**	**0.83**	**0.06**			**3.2**	0.07	0.75		0.00	0.04							
		Average	70		0.06			3.1	0.07	0.81		0.01	0.06							
		Std Dev	76		0.02			0.4	0.04	0.60		0.00	0.04							
		No. Data Pts	7	6	6			5	8	6		8	8							
A5:	< 10 sq mi Mixed																			
		Median	92	2.12	0.32	7.1				1.81	0.41									
		Average	232	5.55	0.36	7.9				5.11	0.44									
		Std Dev	345	6.57	0.14	3.5				6.42	0.36									
		No. Data Pts	6	6	6	6				6	6									
B1:	10 - 100 sq mi < 10% Developed																			
		Median	171	1.20	0.15			3.6	0.10	1.22		0.01	0.15							
		Average	243	1.20	0.17			3.5	0.15	1.15		0.01	0.17							
		Std Dev	247	0.74	0.12			0.5	0.11	0.59		0.01	0.12							
		No. Data Pts	11	9	9			9	12	8		12	12							

NOTES:
1. Data Source: Houston Area EMC Database. See Appendix and text for description of watershed type. Values in bold used in Table 5.11.
2. Abbreviatons:
BOD - Biochemical Oxygen Demand (5-day)
TSS - Total Suspended Solids
NH3 - Ammonia Nitrogen
TKN - Total Kjeldahl Nitrogen
NO3 - Nitrate Nitrogen
NO2 - Nitrite Nitrogen
TN - Total Nitrogen
TP - Total Phosphorus
O&G - Oil and Grease
FC - Fecal Coliforms in Log (colonies)/100 ml
3. TN does not equal the sum of the constituent parts because of differences in original data and rounding errors.

Table 5.10 - Event Mean Concentrations (EMCs) by Watershed Type
Houston EMC Database
Non-Point Source Characterization Project
Galveston Bay National Estuary Program

Watershed			Parameter (mg/l except FC in col/100 ml)											Dissolved Metals (µg/l)						
Type	Area/Land Use		TSS	TN	TP	BOD	O&G	FC	NH3	TKN	NO3+NO2	NO2	NO3	Cu	Cd	Cr	Pb	Hg	Ag	Zn
B2:	10 - 100 sq mi 10 - 50% Developed																			
		Median	316	3.54	1.03	9.0		4.6	0.27	2.18	0.76	0.30		3.00	1.00	7.23	1.00	0.10	0.32	
		Average	429	3.95	1.02	12.2		4.6	0.31	2.65	1.02	0.25		3.12	1.32	5.64	4.85	0.14	0.47	25.61
		Std Dev	350	3.24	0.51	10.6		0.4	0.15	2.69	0.78	0.10		1.86	0.82	6.00	9.74	0.13	0.49	32.48
		No. Data Pts	48	36	45	32		2	3	44	36	3		19	19	19	19	19	17	19
B3:	10 - 100 sq mi > 50% Developed																			
		Median	260	3.27	0.81	8.6		3.9	0.65	2.22	0.74	0.15		3.00	1.00	10.00	2.36	0.10	0.10	13.29
		Average	322	4.02	1.01	11.0		3.9	0.62	2.63	1.16	0.26		3.21	1.11	5.77	3.70	0.11	0.49	16.52
		Std Dev	253	2.18	0.73	9.5		1.0	0.34	1.70	1.08	0.25		2.61	0.85	5.32	3.40	0.09	0.52	13.17
		No. Data Pts	86	75	85	73		2	10	85	76	10		27	27	27	27	27	27	27
C1:	> 100 sq mi < 10% Developed																			
		Median						3.5												
		Average						3.6												
		Std Dev						0.7												
		No. Data Pts						9												
C2:	> 100 sq mi 10 - 50% Developed																			
		Median	391	2.78	1.02	6.0		4.9	0.30	2.02	0.94	0.45		2.00	0.00	0.00	0.00	0.22		20.00
		Average	507	3.80	1.29	8.5		4.9	0.30	2.58	1.22	0.48		3.35	0.33		0.66	0.27		41.34
		Std Dev	373	2.63	0.78	8.6			0.03	1.39	1.37	0.09		2.34				0.21		52.37
		No. Data Pts	21	20	21	21		2	4	20	20	3		3	3	3	3	3	2	3
	Entire Houston Area EMC Data Base for Metals																			
		Median												3.30	0.50	5.00	2.40	0.05	0.50	18.30
		Average												3.70	0.80	7.00	5.60	0.09	0.63	30.10
		Std Dev												1.90	0.50	3.20	7.60	0.08	0.26	38.90
		No. Data Pts												58	55	37	52	60	34	64

NOTES:
1. Data Source: Houston Area EMC Database. See Appendix and text for description of watershed type. Values in bold used in Table 5.11.
2. Abbreviatons:
BOD - Biochemical Oxygen Demand (5-day)
TSS - Total Suspended Solids
NH3 - Ammonia Nitrogen
TKN - Total Kjeldahl Nitrogen
NO3 - Nitrate Nitrogen
NO2 - Nitrite Nitrogen
TN - Total Nitrogen
TP - Total Phosphorus
O&G - Oil and Grease
FC - Fecal Coliforms in Log (colonies)/100 ml
3. TN does not equal the sum of the constituent parts because of differences in original data and rounding errors.

Table 5.11 Event Mean Concentrations (EMCs) Used for Non-Point Source (NPS) Calculations

Non-Point Source Characterization Project
Galveston Bay National Estuary Program

Water Quality Parameters Used for Mapping

Land Use Category	Total Suspended Solids (mg/l)	Total Nitrogen (mg/l)	Total Phosphorus (mg/l)	Biochemical Oxygen Demand (mg/l)	Oil and Grease (mg/l)	Fecal Coliforms (colonies/100 ml)	Dissolved Copper (µg/l)	Pesticides (µg/l)
High Density Urban	166	2.10	0.37	9	13	22,000	3.1	0.4
Residential	100	3.41	0.79	15	4	22,000	3.1	0.4
Agricultural	201	1.56	0.36	4	0	2,500	3.1	0.1
Open/Pasture	70	1.51	0.12	6	0	2,500	3.1	0.1
Forest	39	0.83	0.06	6	0	1,600	3.1	0.1
Wetlands	39	0.83	0.06	6	0	1,600	3.1	0.0
Water	0	0	0	0	0	0	0.0	0.0
Barren	2200	5.20	0.59	13	0	1,600	3.1	0.1

Supplemental Metals and Synthetic Organic Hydrocarbons (not mapped)
(µg/l)

Land Use Category	Dissolved Lead	Dissolved Zinc	Dissolved Arsenic	Dissolved Cadmium	Dissolved Chromium	Dissolved Mecury	Dissolved Silver	
High Density Urban	2.4	18.3	3.0	0.5	5.0	0.1	0.5	
Residential	2.4	18.3	3.0	0.5	5.0	0.1	0.5	
Agricultural	2.4	18.3	3.0	0.5	5.0	0.1	0.5	
Open/Pasture	2.4	18.3	3.0	0.5	5.0	0.1	0.5	
Forest	2.4	18.3	3.0	0.5	5.0	0.1	0.5	
Wetlands	2.4	18.3	3.0	0.5	5.0	0.1	0.5	
Water	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Barren	2.4	18.3	3.0	0.5	5.0	0.1	0.5	

Table 5.12 - Sources of Event Mean Concentrations (EMCs) Used for Non-Point Source (NPS) Calculation
Non-Point Source Characterization Project
Galveston Bay National Estuary Program

Land Use by Category	Total Suspended Solids	Total Nitrogen	Total Phosphorus	Biochemical Oxygen Demand
High density urban	Houston Area EMC Database, Table A1 Median Value	Houston Area EMC Database, Table A1 Median Value	Houston Area EMC Database, Table A1 Median Value	Houston Area EMC Database, Table A1 Median Value
Residential	Houston Area EMC Database, Table A2 Median Value	Houston Area EMC Database, Table A2 Median Value	Houston Area EMC Database, Table A2 Median Value	Houston Area EMC Database, Table A2 Median Value
Agricultural	USGS Barker - Addicks Reservoir Study, 1987 Median of Inflow Stations, Table 12	USGS Barker - Addicks Reservoir Study, 1987 Median of Inflow Stations, Table 12	USGS Barker - Addicks Reservoir Study, 1987 Median of Inflow Stations, Table 12	USGS Barker - Addicks Reservoir Study, 1987 Median of Inflow Stations, Table 12
Open/Pasture	Nationwide Urban Runoff Program, 1983 Median of "Open" Land Uses, Table 6.12	Nationwide Urban Runoff Program, 1983 Median of "Open" Land Uses, Table 6.12	Nationwide Urban Runoff Program, 1983 Median of "Open" Land Uses, Table 6.12	Nationwide Urban Runoff Program, 1983 Based on BOD/COD ratio of Residential Land Use and Median COD of Open Land Use, Table 6-12
Forest	Houston Area EMC Database, Table A3 Median Value	Houston Area EMC Database, Table A3 Median Value	Houston Area EMC Database, Table A3 Median Value	Assumed = Open/Pasture
Wetlands	Assumed = Forest	Assumed = Forest	Assumed = Forest	Assumed = Open/Pasture
Water	Assumed = 0	Assumed = 0	Assumed = 0	Assumed = 0
Barren	Bedient, et al, 1980b and Newell, 1981	Nationwide Urban Runoff Program, 1983 CA1 Watershed (Basin with highest erosion and "open" land use)	Nationwide Urban Runoff Program, 1983 CA1 Watershed (Basin with highest erosion and "open" land use)	Nationwide Urban Runoff Program, 1983 CA1 Watershed (Basin with highest erosion and "open" land use)

NOTES:
1. Tables A1, A2, and A3 for Houston Area Database are included in Appendix II and summarized in Table 5.10.
2. All tables other than A1, A2, and A3 refer to tables in the original source.

Table 5.12 - Sources of Event Mean Concentrations (EMCs) Used for Non-Point Source (NPS) Calculation
Non-Point Source Characterization Project
Galveston Bay National Estuary Program

Land Use by Category	Oil and Grease	Fecal Coliforms	Dissolved Copper	Pesticides	Other Dissolved Metals						
					Lead	Zinc	Arsenic	Cadmium	Chromium	Mecury	Silver
High density urban	Stenstrom, et al, 1984 Table 8	Houston Area EMC Database, Table A2 and C1 Nationwide Urban Runoff Program, 1983 (Warm weather conditions)	Houston Area EMC Database, Table E; (see text)	USGS Austin Study 1990 (see text)	See Dissolved Copper						
Residential	Stenstrom, et al, 1984 Table 8	Houston Area EMC Database, Table A2 and C1 Nationwide Urban Runoff Program, 1983 (Warm weather conditions)	Houston Area EMC Database, Table E; (see text)	USGS Austin Study 1990 (see text)	See Dissolved Copper						
Agricultural	Assumed = 0	USGS Barker - Addicks Reservoir Study, 1987 Median of Inflow Stations, Table 12	USGS Barker - Addicks Reservoir Study, 1987 (see text)	USGS Barker - Addicks Reservoir Study, 1987 (see text)	See Dissolved Copper						
Open/Pasture	Assumed = 0	Assumed same as agricultural	Assumed same as agricultural	Assumed same as agricultural	See Dissolved Copper						
Forest	Assumed = 0	Houston Area EMC Database, Table A3	Assumed same as agricultural	Assumed same as agricultural	See Dissolved Copper						
Wetlands	Assumed = 0	Assumed = Forest	Assumed same as agricultural	Assumed same as agricultural	See Dissolved Copper						
Water	Assumed = 0	Assumed = 0	Assumed = 0	Assumed = 0	See Dissolved Copper						
Barren	Assumed = 0	Assumed = Forest	Assumed same as agricultural	Assumed same as agricultural	See Dissolved Copper						

NOTES:
1. Tables A1, A2, and A3 for Houston Area Database are included in Appendix and summarized in Table 5.10.
2. All tables other than A1, A2, and A3 refer to tables in the original source.

Table 5.13 - Relative Accuracy of Project Event Mean Concentrations (EMCs)
Non-Point Source Characterization Project
Galveston Bay National Estuary Program

Estimated Relative Accuracy of EMCs

Land Use Category	Total Suspended Solids	Total Nitrogen	Total Phosphorus	Biochemical Oxygen Demand	Oil and Grease	Fecal Coliforms	Dissolved Copper	Pesticides
High Density Urban	Good	Good	Good	Good	Fair	Good	Fair	Poor
Residential	Good	Good	Good	Good	Fair	Good	Fair	Poor
Agricultural	Fair	Fair	Fair	Fair	Fair	Fair	Poor	Poor
Open/Pasture	Fair	Fair	Fair	Fair	Fair	Fair	Poor	Poor
Forest	Good	Good	Good	Fair	Fair	Good	Poor	Poor
Wetlands	No data	No data	No data	No data	No data	No data	No data	No data
Water	No data	No data	No data	No data	No data	No data	No data	No data
Barren	Good	Fair	Fair	Fair	Fair	Fair	Poor	Poor

Estimated Relative Accuracy of EMCs

Land Use Category	Dissolved Lead	Dissolved Zinc	Dissolved Arsenic	Dissolved Cadmium	Dissolved Chromium	Dissolved Mercury	Dissolved Silver	
High Density Urban	Fair	Fair	Fair	Fair	Fair	Fair	Fair	
Residential	Fair	Fair	Fair	Fair	Fair	Fair	Fair	
Agricultural	Poor	Poor	Poor	Poor	Poor	Poor	Poor	
Open/Pasture	Poor	Poor	Poor	Poor	Poor	Poor	Poor	
Forest	Poor	Poor	Poor	Poor	Poor	Poor	Poor	
Wetlands	Poor	Poor	Poor	Poor	Poor	Poor	Poor	
Water	Poor	Poor	Poor	Poor	Poor	Poor	Poor	
Barren	Poor	Poor	Poor	Poor	Poor	Poor	Poor	

NOTES:
1. Good rating refers to EMCs based on extensive Houston-Area NPS data.
2. Fair rating refers to EMCs based on either large national database or single local NPS study.
3. Poor rating refers to EMCs based on limited database or database with significant non-detect values that indicate large range in possible EMCs.

Table 5.14 - Comparison of GBNEP Event Mean Concentrations (EMCs) With Other Studies
Non-Point Source Characterization Project
Galveston Bay National Estuary Program

	Total Suspended Solids		Total Nitrogen	
Land Use Category	Data Souce	Reported EMCs (mg/l)	Data Souce	Reported EMCs (mg/l)
High density urban	**GBNEP**	**166**	**GBNEP**	**2.10**
	NURP, Table 6.12	69	NURP, Table 6-12	1.75
	USGS Austin, Table 3	379 - 2740	USGS Austin, Table 3	2.08 - 4.35
	NOAA, Table 5	180	NOAA, Table 5	2.76
	TWC/Winslow, Table 2.6	77 - 126	TWC/Winslow, Table II-6	1.92
Residential	**GBNEP**	**100**	**GBNEP**	**3.41**
	NURP, Table 6-12	101	NURP, Table 6-12	2.64
	USGS Austin, Table 3	379 - 2740	USGS Austin, Table 3	2.08 - 4.35
	NOAA,Table 5	180	NOAA,Table 5	2.76
	TWC/Winslow, Table II-6	67 - 95	TWC/Winslow, Table II-6	1.98 -3.28
Agricultural	**GBNEP**	**201**	**GBNEP**	**1.56**
	Literature (see Appendix D)	153 - 720	Literature (see Appendix D)	12.15 - 23.3
			Omernik, 1977	6.08
Open/Pasture	**GBNEP**	**70**	**GBNEP**	**1.51**
	TWC/Winslow, Table II-6	88	TWC/Winslow, Table II-6	2.22
	Literature (see Appendix D)	1524	Literature (see Appendix D)	4.30
			USGS Austin, Table 3 (?)	0.44 - 0.56
Forest	**GBNEP**	**39**	**GBNEP**	**0.83**
	Literature (see Appendix D)	28 - 174	Literature (see Appendix D)	0.55 - 2.69
			Omernik, 1977	0.50

NOTES:
1. NURP: U.S. EPA, 1983.
2. USGS Austin: USGS, 1990.
3. NOAA: NOAA, 1987b.
4. NOAA Urban EMCs derived from NURP data, using different calculation method
5. TWC/Winslow: Winslow and Associates, 1986.

Table 5.14 - Comparison of GBNEP Event Mean Concentrations (EMCs) With Other Studies
Non-Point Source Characterization Project
Galveston Bay National Estuary Program

	Total Phosphorus		Fecal Coliforms	
Land Use Category	Data Souce	Reported EMCs (mg/l)	Data Souce	Reported EMCs (Colonies per 100 ml.)
High density urban	**GBNEP**	**0.37**	**GBNEP**	**22,000**
	NURP, Table 6-12	0.20	NURP, Table 6-18	21,000
	USGS Austin, Table 3	0.44 - 1.70	USGS Austin, Table 3	600 - 49,000
	NOAA, Table 5	0.42	NOAA, Table 5	21,000
Residential	**GBNEP**	**0.79**	**GBNEP**	**22,000**
	NURP, Table 6-12	0.38	NURP, Table 6-12	101
	USGS Austin, Table 3	0.44 - 1.70	USGS Austin, Table 3	600 - 49,000
	NOAA, Table 5	0.42	NOAA, Table 5	21,000
Agricultural	**GBNEP**	**0.36**	**GBNEP**	**2,500**
	Literature (see Appendix D)	1.86 - 1.91	Literature (see Appendix D)	9,772
	Omernik, 1977	0.21		
Open/Pasture	**GBNEP**	**0.12**	**GBNEP**	**2,500**
	Literature (see Appendix D)	0.10	Literature (see Appendix D)	6,310 - 31,623
	Omernik, 1977	0.10	USGS Austin, Table 3 (?)	340 - 2,900
	USGS Austin 1990, Table 3 (?)	0.015 - 0.02		
Forest	**GBNEP**	**0.06**	**GBNEP**	**1,600**
	Literature (see Appendix D)	<0.1 - 0.82		
	Omernik, 1977	0.02		

NOTES:
1. NURP: U.S. EPA, 1983.
2. USGS Austin: USGS, 1990.
3. NOAA: NOAA, 1987b.
4. NOAA Urban EMCs derived from NURP data, using different calculaton method.
5. TWC/Winslow: Winslow and Associates, 1986.

Table 5.15 - **Average Concentrations for Lake Houston and Lake Livingston Non-Point Source Load Calculations**

Non-Point Source Characterization Project
Galveston Bay National Estuary Program

Parameter	Units of Concentration	Lake Houston		Lake Livingston	
		Average Conc.	Number of Samples	Average Conc.	Number of Samples
Suspended Solids [1]	(mg/l)at 105° C	25	121	10	205
Total Nitrogen [1]	(mg/l as N)	1.44	217	2.48	43
Total Phosphorus [1]	(mg/l as P)	0.38	216	0.34	257
Oil & Grease [2]	(mg/l)	0	–	0	–
Fecal Coliforms [1]	(colonies/100 ml)	330	54	19	88
BOD [1]	(mg/l)	3.4	97	2.5	154
Dissolved Copper [2]	(mg/l)	3.1	–	3.1	–
Pesticides [2]	(μg/l)	0.1	–	0.1	–
DISSOLVED METALS					
Lead [2]	(μg/l as Pb)	2.4	–	2.4	–
Zinc [2]	(μg/l as Zn)	18.3	–	18.3	–
Arsenic [2]	(μg/l as As)	3.0	–	3.0	–
Cadmium [2]	(μg/l as Cd)	0.5	–	0.5	–
Chromium [2]	(μg/l as Cr)	0.1	–	0.1	–
Silver [2]	(μg/l as Ag)	0.5	–	0.5	–

NOTES:
1. Source: Average of Texas Water Commission and United States Geological Survey (USGS) data. See Appendix IV, Table IV.5.
2. Source: Assumed equal to GBNEP Forest/Agricultural/Open/Pasture Land Uses after evaluating available USGS data (see Table 5.11).

Table 5.16 - Lake Houston and Lake Livingston Loads for Cases 1, 2, and 3

Non-Point Source Characterization Project
Galveston Bay National Estuary Program

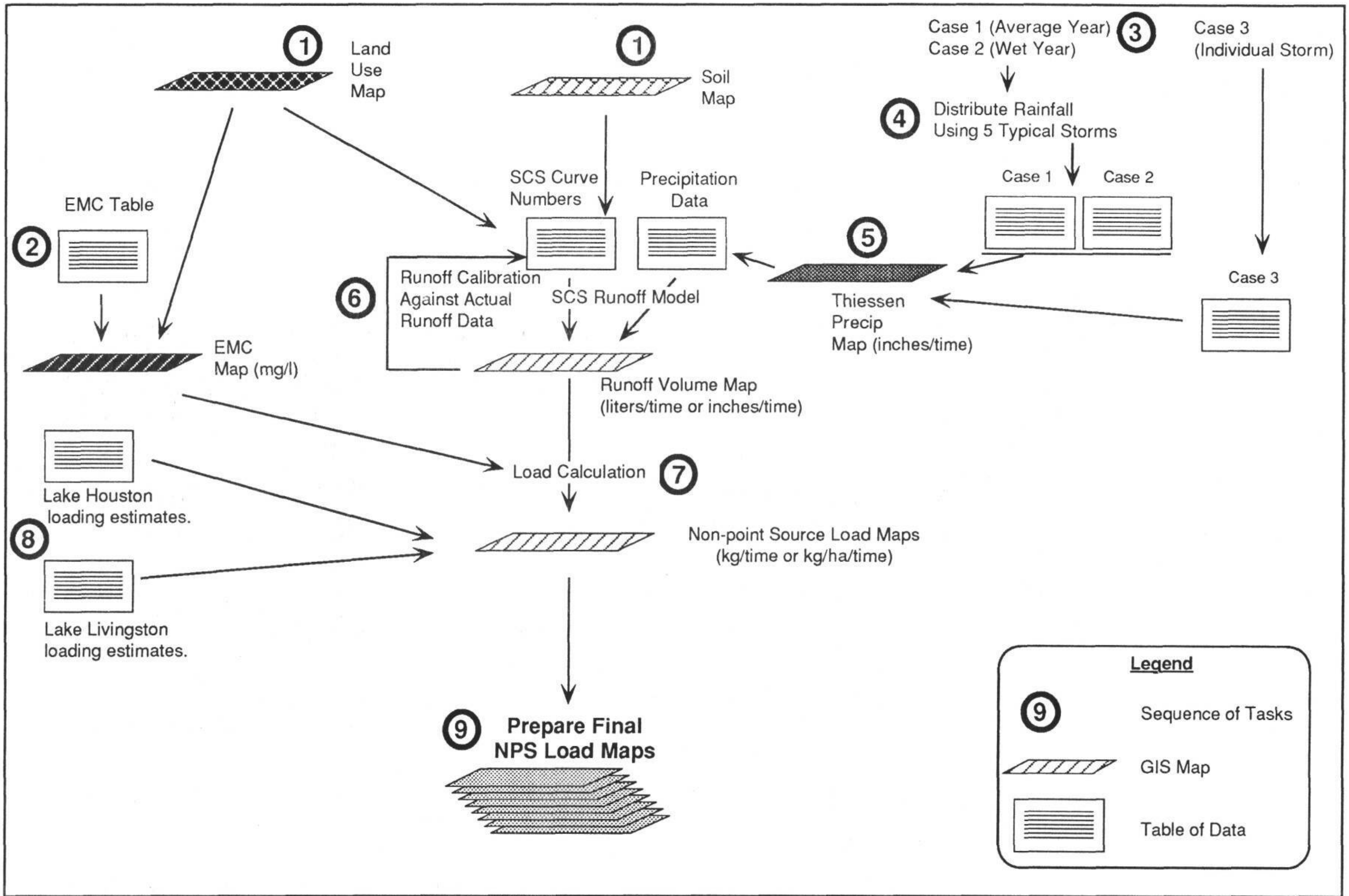
		Case 1		Case 2		Case 3	
Parameter	Units	Lake Houston	Lake Livingston	Lake Houston	Lake Livingston	Lake Houston	Lake Livingston
Runoff Volume	(thousand acre-ft)	1,380	4,660	2,200	6,800	2.1	5.4
Total Suspended Solids	(million kg)	43	57	68	84	0.1	0.1
Total Nitrogen	(thousand kg)	2,451	14,257	3,908	20,804	3.7	16.4
Total Phosphorus	(thousand kg)	647	1,955	1,031	2,852	1.0	2.3
Biochemical Oxygen Demand	(million kg)	5.8	14	9.2	21	0.01	0.02
Oil and Grease [5]	(million kg)	0	0	0	0	0	0
Fecal Coliform	(xE15 col)	5.6	1.1	9.0	1.6	0.01	0.001
Dissolved Copper	(kg)	5,277 [3]	17,821	8,413 [3]	26,005	8.0 [3]	20.5
Pesticides	(kg)	170 [4]	575 [4]	271 [4]	839 [4]	0.26 [4]	0.66 [4]

NOTES:
1. All parameter data is the result of a compilation of USGS Water Resources Data for Texas and information from the Texas Water Development Board.
2. For discharge values refer to section 5.5.1.
3. Calculated assuming GBNEP Copper concentration of 3.1 μg/l.
4. Calculated assuming GBNEP Pesticide Concentration of 0.1 μg/l.
5. Calculated assuming Oil and Grease concentration of 0.0 mg/l

Table 5.17 - Comparison of Lake Houston and Lake Livingston Calculated Loads to Other Studies
Non-Point Source Characterization Project
Galveston Bay National Estuary Program

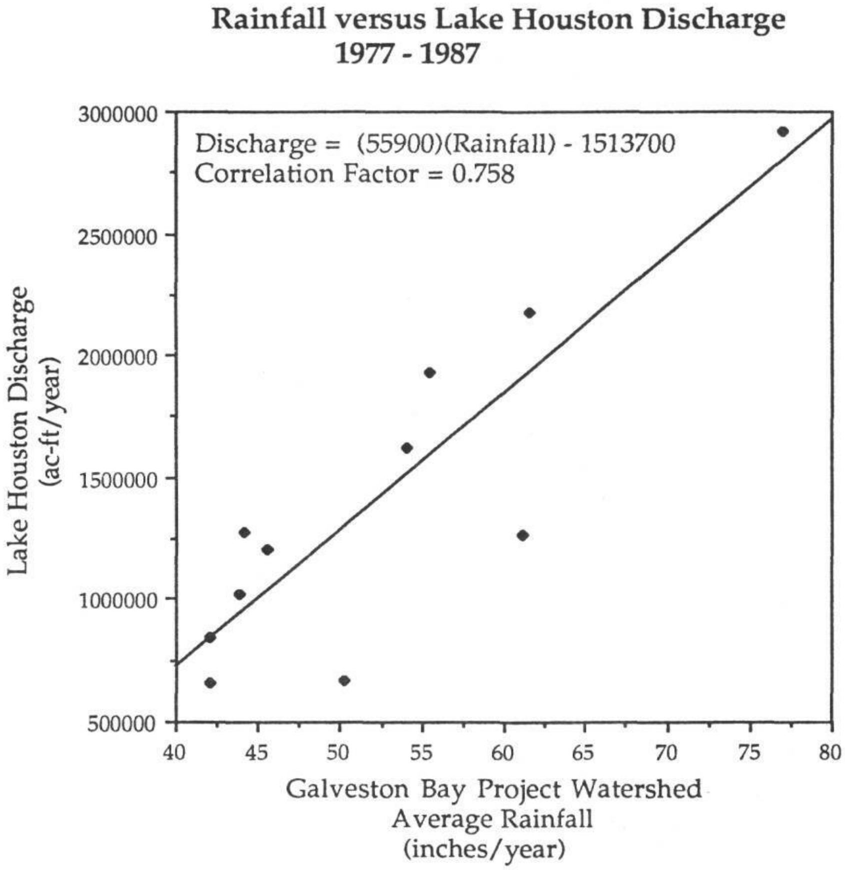
Lake Houston			Lake Livingston			
Parameter	GBNEP	Baca, et al., 1982	Discharge	GBNEP	Stanley, 1989	TWDB, 1988
Total Suspended Solids (million kg/year)	43	36	Total Suspended Solids (million kg/year)	57	-	650
Total Nitrogen (thousand kg/year)	2,451	1,783	Total Nitrogen (thousand lbs/year)	14,257	12,894	-
Total Phosphorus (thousand kg/year)	647	707	Total Phosphorus (thousand lbs/year)	1,955	2,361	-

NOTES:
1. All GBNEP Loads from Case 1, Average Year.
2. See Table 5.1 and 5.2 for methodology for calculation of GBNEP Case 1 Discharge from Lake Houston and Lake Livingston.
3. Discharge used by Baca, et al (1982) from 1975 (Average Flow Year).
4. Discharge used by Stanley from 1975 (Average Flow Year).
5. Values reported by Stanley originally from Hydroscience, 1976, Eutrophication Analysis of Lake Livingston Reservoir, Report to Texas Water Quality Board, Austin.



Groundwater Services, Inc. Houston, Texas	Rice University Dept. of Environmental Science and Engineering	GSI JOB NO. G-1220 ISSUED: 10/25/91 REVISED: **EXHIBIT: 5.1**	**FLOWCHART OF NON-POINT SOURCE LOAD CALCULATION** Non-Point Source Characterization Project Galveston Bay National Estuary Program

Exhibit 5.2 - Case 1 and Case 2 Discharges from Lake Houston
Non-Point Source Characterization Project
Galveston Bay National Estuary Program

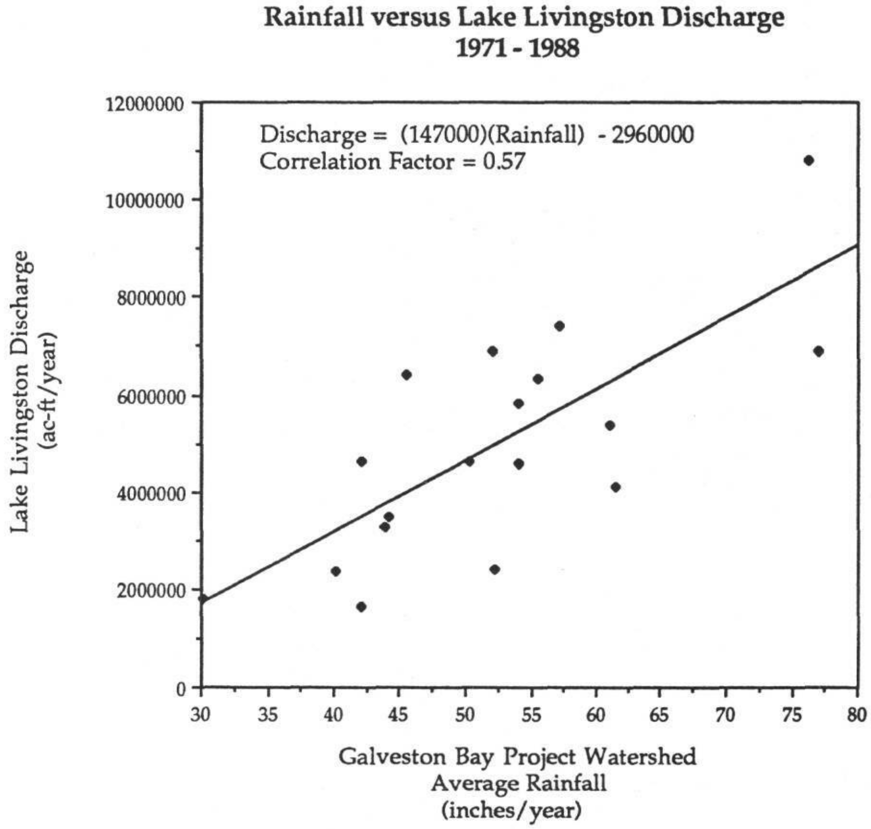


Case 1 Rainfall = 51.81 in	Case 2 Rainfall = 66.37 in
Case 1 Discharge = 1,381,495 ac-ft	Case 2 Discharge = 2,195,122 ac-ft

Note:
1. Lake Houston Discharge data obtained from the Texas Water Development Board.
2. Rainfall data obtained from Table 5.3.

Exhibit 5.3 - Case 1 and Case 2 Discharges from Lake Livingston

Non-Point Source Characterization Project
Galveston Bay National Estuary Program



Case 1 Rainfall =	51.81 in	Case 2 Rainfall =	66.37 in
Case 1 Discharge =	4,656,070 ac-ft	Case 2 Discharge =	6,796,390 ac-ft

Note:

1. Discharge data for Lake Livingston taken from flow measurements at the USGS Trinity at Goodrich gage.
2. Rainfall data obtained from Table 5.4.