Turner Collie & Braden Inc.

IN ASSOCIATION WITH
WILLIAM F. GUYTON ASSOCIATES, INC.

A REGIONAL WATER SUPPLY PLANNING STUDY

FINAL REPORT

HARRIS-GALVESTON COASTAL SUBSIDENCE DISTRICT

A STUDY PARTIALLY FUNDED THROUGH A TEXAS WATER DEVELOPMENT BOARD GRANT

March 1991

ENGINEERS • PLANNERS
TEXAS AUSTIN / DALLAS / FORT WORTH / HOUSTON COLORADO DENVER

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EXECUTIVE SUMMARY

The Harris-Galveston Coastal Subsidence District (HGCSD) is responsible for reducing or eliminating land subsidence in Harris and Galveston Counties in Texas through the control of groundwater production. To perform this task, HGCSD completed a two-phase water management study in 1982 and developed computer models to predict subsidence given water demand projections. In 1985, HGCSD developed a Regulatory Action Plan (RAP) specifying a timetable for conversion of water supply systems from groundwater to surface water sources. Since the completion of the RAP, population growth, land use, and groundwater production have changed significantly within the computer model area. These changes justify a review of the future water demand projections and historic groundwater pumpage to determine whether or not modifications to the RAP are appropriate.

The primary objective of this Regional Water Supply Planning Study is, therefore, to evaluate the changes in population growth, land development patterns, and water usage within the study area to predict future water demands and present the results in a format conforming to the HGCSD computer model grid cell input requirement.

During the course of this investigation, the Fort Bend Subsidence District (FBSD) was created to regulate groundwater pumpage and control subsidence in Fort Bend County. An interlocal agreement was executed between FBSD and HGCSD that provides for administrative assistance to FBSD to aid in the development of its own RAP. As a result, the HGCSD model area was extended to include all of Fort Bend County and the collection of aquifer characteristics and historical groundwater pumpage data for the additional model area was added to the study scope of services.

The projection of water demand was achieved using a land-use and water-use driven model based on the assumption that population growth is directly related to residential, commercial, and industrial land uses. The projection model utilized the spatial analysis capability of the ARC/INFO Geographic Information System (GIS) software to project and distribute land use, population, and water demand information and to correlate numerous data sets into the defined grid cell format.

Population projections were performed based on the 1980 census population and were utilized within the GIS to translate an existing (1986) land-use map into a year 2030 development pattern. Development was assumed to center around existing or proposed development centers and to follow major transportation corridors. Land-use-based water demand factors were then derived for gross urbanized acreage and heavy-industrial areas and applied to the 1986 land-use map. The resulting demands were compared to recorded groundwater and surface water consumption to verify the results. The demand factors were then applied to the 2030 land-use patterns and known surface water supplies and future expansions were allocated within the GIS to calculate future water demands for each of the model grid cells. Interim year water demands were then developed by interpolation from the 1986 and 2030 demand patterns.

The analysis indicated that population within the expanded model area will increase by 136 percent, from 3,145,000 in 1980 to 7,415,000 in 2030, while water demand will increase 95 percent, from 393,458 million gallons per year (mgy) in 1986 to 765,560 mgy in 2030, as land is converted from pastureland and irrigated farmland to residential and commercial development. Future development is projected to occur mainly in northeast Fort Bend County and in west and northwest Harris County. Surface water comprised approximately 45 percent of the total water supplied to the study area in 1986. However, only proposed surface water expansion projects were included in the water demand projections to allow HGCSD latitude to incorporate future surface water sources as they occur.

The study recommends that HGCSD utilize the historical groundwater pumpage estimates and aquifer data collected in conjunction with the water demand projections as input to its computer models to review the RAP and to evaluate the effect of the changes in the areal distribution of water demand and groundwater pumpage on the existing regulations. The data developed relevant to the FBSD jurisdictional area should be incorporated into the HGCSD computer models and used to develop a District Plan for Subsidence and RAP for the Fort Bend Subsidence District.

SECTION I - INTRODUCTION

The City of Houston, Texas and the surrounding metropolitan area utilizes approximately 390 billion gallons of water per year, of which 55 percent is supplied from groundwater. By the year 2030, annual water consumption is expected to exceed 765 billion gallons per year. The City of Houston's Water Master Plan Study (HWMP) indicates that, through the further development of surface water and groundwater resources, a sufficient supply of water exists, assuming the appropriate water conservation actions are exercised. The high quality and abundance of groundwater in southeast Texas makes it a relatively inexpensive supply alternative when compared to surface water transmission and treatment. Consequently, water economics drives a continuing increase in groundwater demand. However, the existing demand for groundwater has caused a significant lowering of the potentiometric head in the Chicot and Evangeline aquifer system underlying the Houston area. As a result, significant land subsidence, the lowering of the land's surface due to groundwater withdrawal, has occurred in most of Harris and Galveston counties. Areas around the Houston Ship Channel have subsided as much as ten feet between 1906 and 1978 and significant damage has resulted from increased flooding, inundation, and tidal/storm surge effects created by the loss of elevation. The Harris-Galveston Coastal Subsidence District (HGCSD) was created by the 64th State Legislature in April 1975 to control subsidence through regulation of ground-water withdrawal in Harris and Galveston counties. The District has undertaken various studies to evaluate the results of its regulatory actions and to develop or plan regulatory steps to minimize and control subsidence in its jurisdictional areas.

Project Background

In 1982, HGCSD completed a two-phase comprehensive water management study to evaluate the effects on subsidence of pumpage patterns that vary over time. The product of that study was a tandem of computer models that project aquifer response and subsequent subsidence, given an areal distribution of water demand. A groundwater flow model was developed to determine potentiometric head fluctuations within the aquifer layers due to varying pumpage patterns. The Prediction Relating Effective Stress and Subsidence (PRESS) computer model was also created to calculate the resulting subsidence, given the hydraulic characteristics of the clay layers and the potentiometric head changes as determined by the groundwater flow model. The model area, shown in Figure I-1, encompassed all of Harris and Galveston counties and portions of 11 surrounding counties.

In addition to existing and projected water demands, input data required by the models includes hydraulic characteristics in each of the five aquifer layers, potentiometric head data, and historic groundwater pumpage. Data is required across a grid, shown on Figure I-2, represented by 2.5 minutes latitude x 2.5 minutes longitude geographic cells (or one-ninth of a United States Geological Survey quadrangle map), covering an 8,400-square-mile area. Although the volume of water demand and groundwater pumpage are related through the amount of surface water supplied, the areal distribution of water demand varies widely from the distribution of groundwater pumpage. Water demand within the 2.5-minute geographic cells used in the computer models may be smaller or greater than the amount of groundwater pumped in that cell, as water is imported or exported among adjacent demand centers. Demand, then, is a function of land use and population growth, whereas groundwater pumpage is mainly a function of aquifer capability and transmission system configuration.

The District Plan

Using data provided by the computer modeling system and information resulting from the 1982 study, HGCSD formulated and adopted a District Plan for Subsidence in November 1985. The purpose and intent of this Plan was to establish policies in the areas of technical research and studies, water conservation, public information, regulation, permits and enforcement, and equity and discretion.

As part of the District Plan, a Regulatory Action Plan (RAP) was adopted to translate the legislative mandate of the District and the policy of the Plan into specific objectives and requirements. The RAP divides the District into the eight regulatory areas, estimates future water requirements, and outlines regulations to limit groundwater pumpage and restrict future subsidence to an acceptable level.

The goal of the RAP was to end subsidence in coastal areas and to minimize subsidence as soon as realistically feasible in the remaining two-county area. As a result,

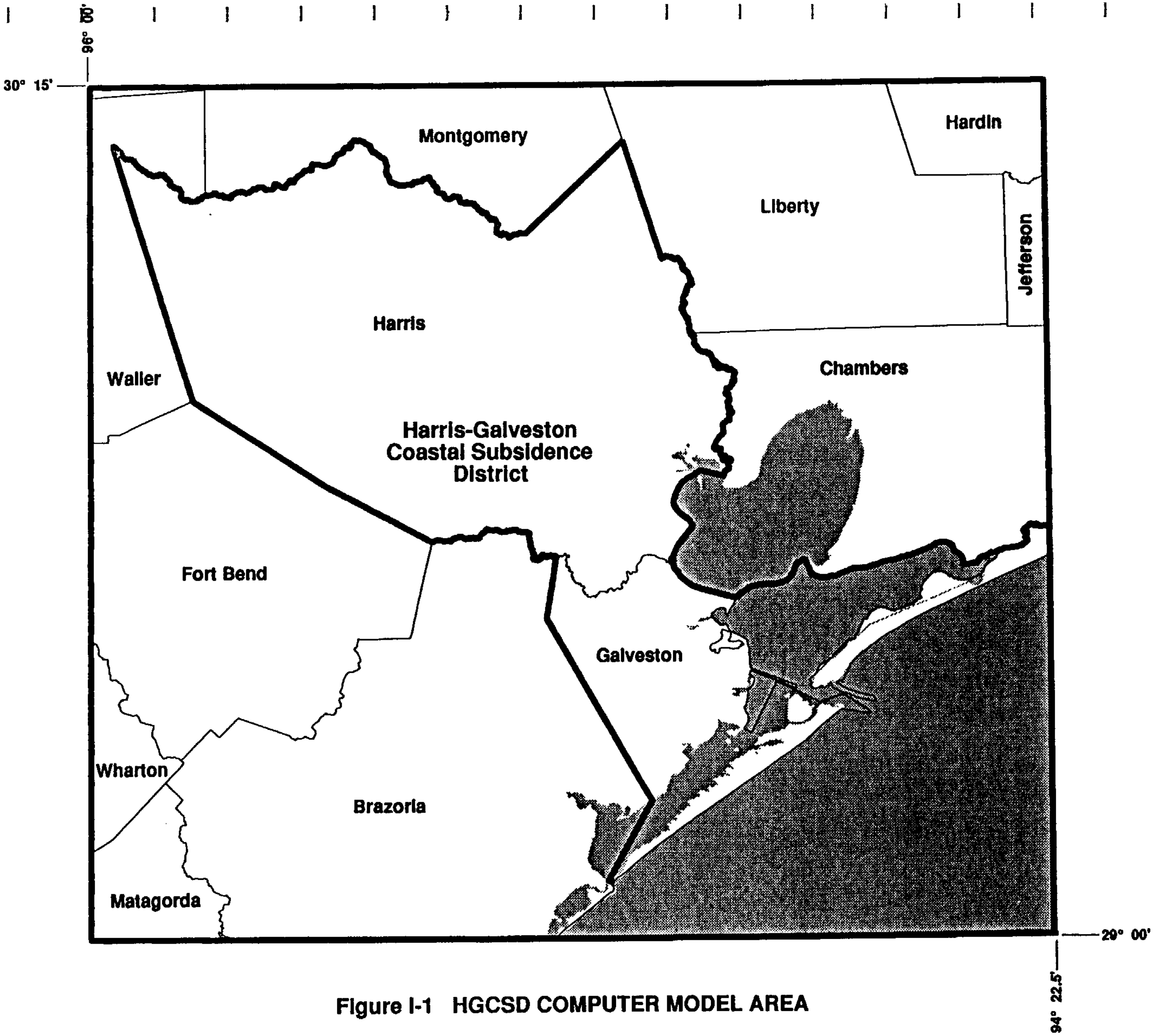

Figure I-1 HGCSD COMPUTER MODEL AREA

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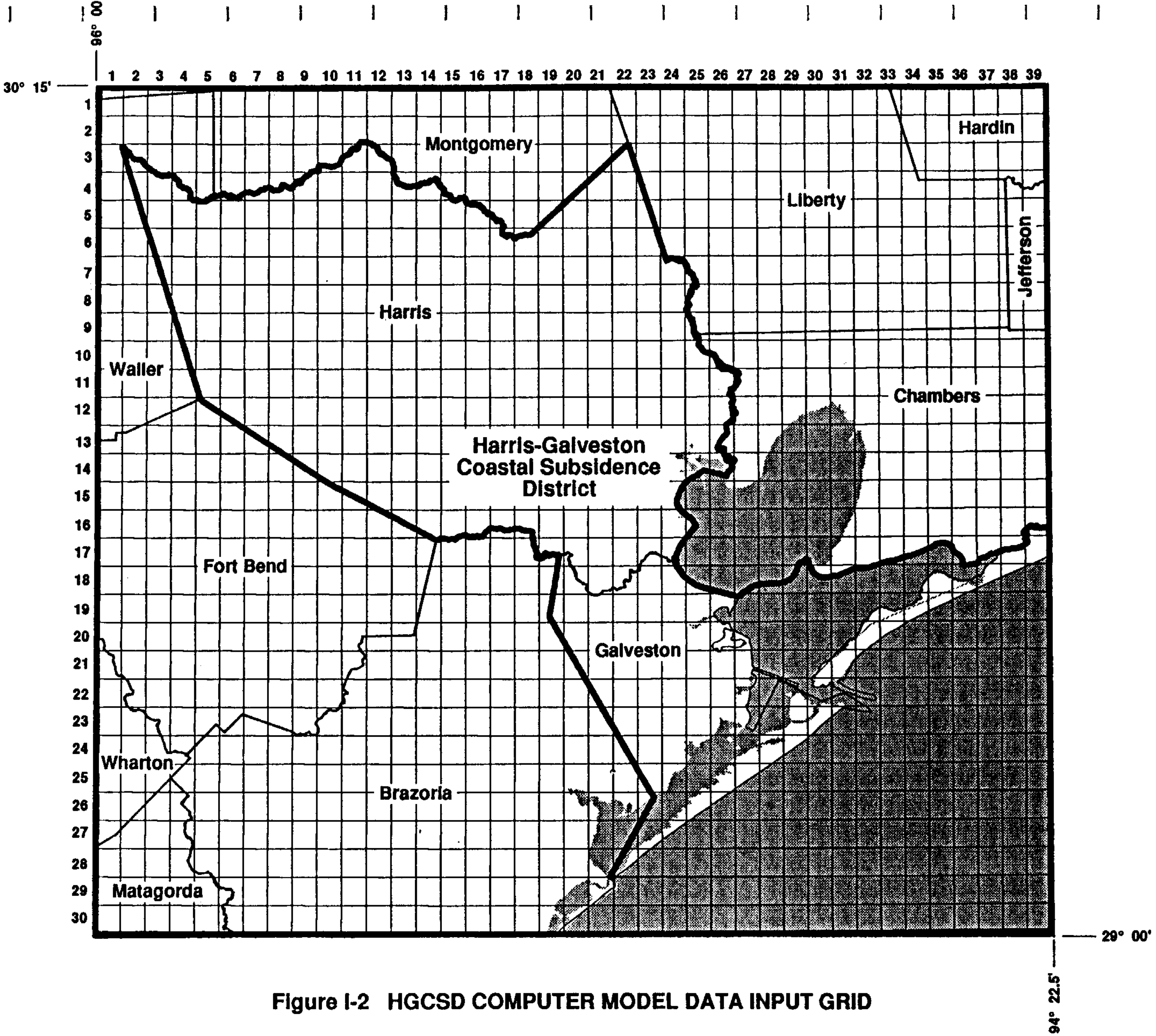


Figure I-2 HGCSD COMPUTER MODEL DATA INPUT GRID the District generally established regulatory requirements for each individual area, stipulating the amounts of groundwater that can be withdrawn from the area. The District generally will allow an increase of groundwater production, in areas other than the coastal areas, between the years in which additional surface water facilities can realistically be constructed. Overall, the total amount of groundwater withdrawals has been limited to approximately 400 million gallons per day (mgd). Surface water would then supply the difference between the groundwater and the total water demand.

Study Objective

Since the completion of the 1982 study, there have been significant changes in the population, land uses, industrial water uses, water conservation practices, and areal distribution of water demands within the model area. The purpose of this Regional Water Supply Planning Study is to determine the impact of these changes on water demands and derive a set of water demand projections consistent with the computer model input format up to the year 2030. The historical groundwater pumpage will also be updated on a grid cell basis for the areas outside the HGCSD jurisdiction (referred to as the Outside District Area).

The Fort Bend Subsidence District (FBSD) was recently created to achieve the same objective as HGCSD, the control of subsidence through the regulation of groundwater pumpage, in Fort Bend County. FBSD has entered into an interlocal agreement with HGCSD to receive administrative assistance to aid in establishing well permitting procedures and regulatory policies. As a result, the original scope of this Regional Water Supply Planning Study was expanded to include the collection of data relative to the FBSD jurisdictional area.

In addition, to aid in the development of FBSD regulatory policies, the model area will be extended three columns (7.5 minutes of longitude) to the west to include all of Fort Bend County. The resulting study area, shown in Figure I-3, will cover approximately 9,050 square miles and include all or portions of 15 counties. Historical groundwater pumpage (1960 to 1987) will be compiled for this area (termed the Western Extension Area) along with estimates of aquifer tranmissivity, storage coefficient, leakance, and initial (1900) and

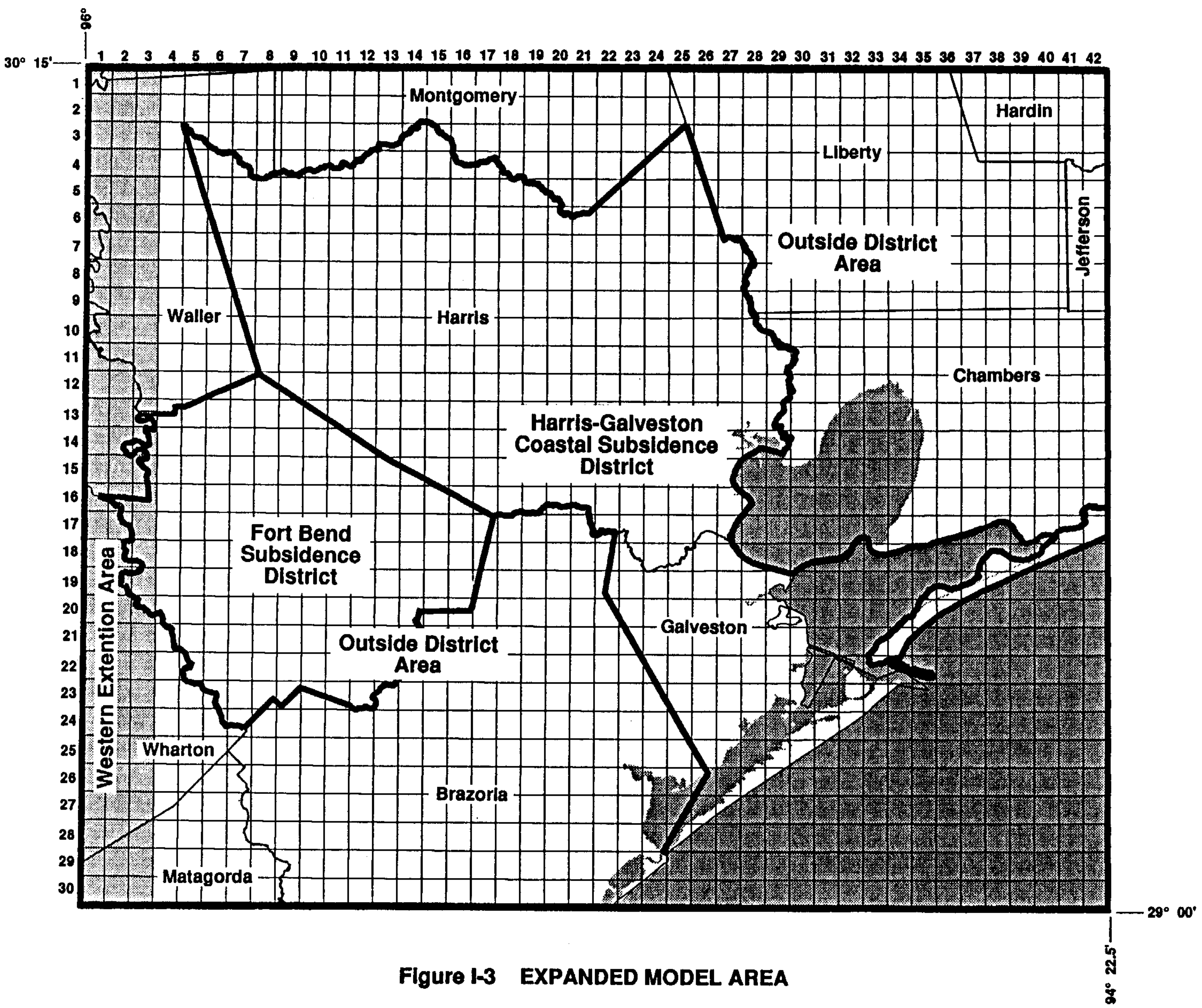


Figure I-3 EXPANDED MODEL AREA

1960 head values for each of the new grid cells. Four additional compaction analysis sites within Fort Bend County will be developed to supplement the existing 21 PRESS sites in Harris and Galveston counties.

The water demand projections will include total water demand, surface water consumption, and unfulfilled demand (demand not fulfilled by known surface water sources) for each grid cell, as well as the proportion of groundwater pumped from both the Chicot and Evangeline aquifers. Consistent with the existing model input, the proportioning of groundwater pumpage between the two aquifers will be represented by an aquifer ratio (Chicot pumpage to total groundwater pumpage) for each cell.

Since the regulatory requirements for each of the HGCSD areas are partially determined by the distribution of projected water demands through the year 2020, changes in water demand projections may necessitate changes in the RAP. HGCSD and FBSD can utilize the results of this study to develop new policies and evaluate the continued applicability of the existing District Plan and RAP to determine if modification of specific policies or area regulations is appropriate.

Report Organization

Background information outlining the creation of the HGCSD and the FBSD, the necessity and objective of the study, and the report organization is presented in this section. Section II details the general project approach and the methodology used for the projection of population and land use. The data collected, regarding existing and historic groundwater and surface water use, water conservation, and climatic variations, as well as the derivation of existing water demand factors and aquifer ratios, are presented in Section III. Section IV describes the projection methodology and the resulting future water demands and aquifer ratios. The study conclusions and recommendations are given in Section V. Documentation of the development and calibration of the four additional compaction analysis sites in Fort Bend County is included as Appendix A of the report.

General Approach

As shown in Figures II-1 and II-2, the study approach is driven by land use and water use on the assumption that population growth can be related to future industrial, commercial, and residential land uses and that the land-use classifications can be associated with a water demand factor. Using this approach, future land-use data derived from projected population growth can be translated into a projected water demand for each of the grid cells within the study area.

To establish this land use and water use driven water demand forecast model, it is necessary to obtain data on existing land use, population, groundwater and surface water production, and water demand. Available information on these topological data sets is associated with differing geographic boundaries. Population, for example, is associated with a census tract, whereas land use and water production are associated with a political boundary, such as a city or municipal utility district. Since population projections will effect the distribution of both future development and water demand, both projections are needed on the same geographical basis. In addition, all information must ultimately be deciphered into the individual grid cells as required by the computer model input format.

The spatial analysis capability of a computer-based geographic information system (GIS) makes it uniquely suited for this task. The GIS software package ARC/INFO, a product of Environmental Systems Research Institute (ESRI), Redlands, California, was utilized in the study to disseminate and reaggregate the numerous layers of information and facilitate the computation of existing and projected water demands.

Base years for analysis were 1980 and 1986. These years were selected for two reasons. First, groundwater pumpage information for portions of the study area outside the HGCSD boundary is available through the year 1986. Second, extensive information on population, land use, and water demands for these two years has been collected through previous efforts such as the 1980 census count, 1980 land-use map prepared by the City's Planning and Development Department, 1986 population estimates by Houston-Galveston Area Council (HGAC), and the population and water demand estimates from the HWMP. The population and demand distributions and growth trends, derived from these base years, were used to project future demands through the year 2030.

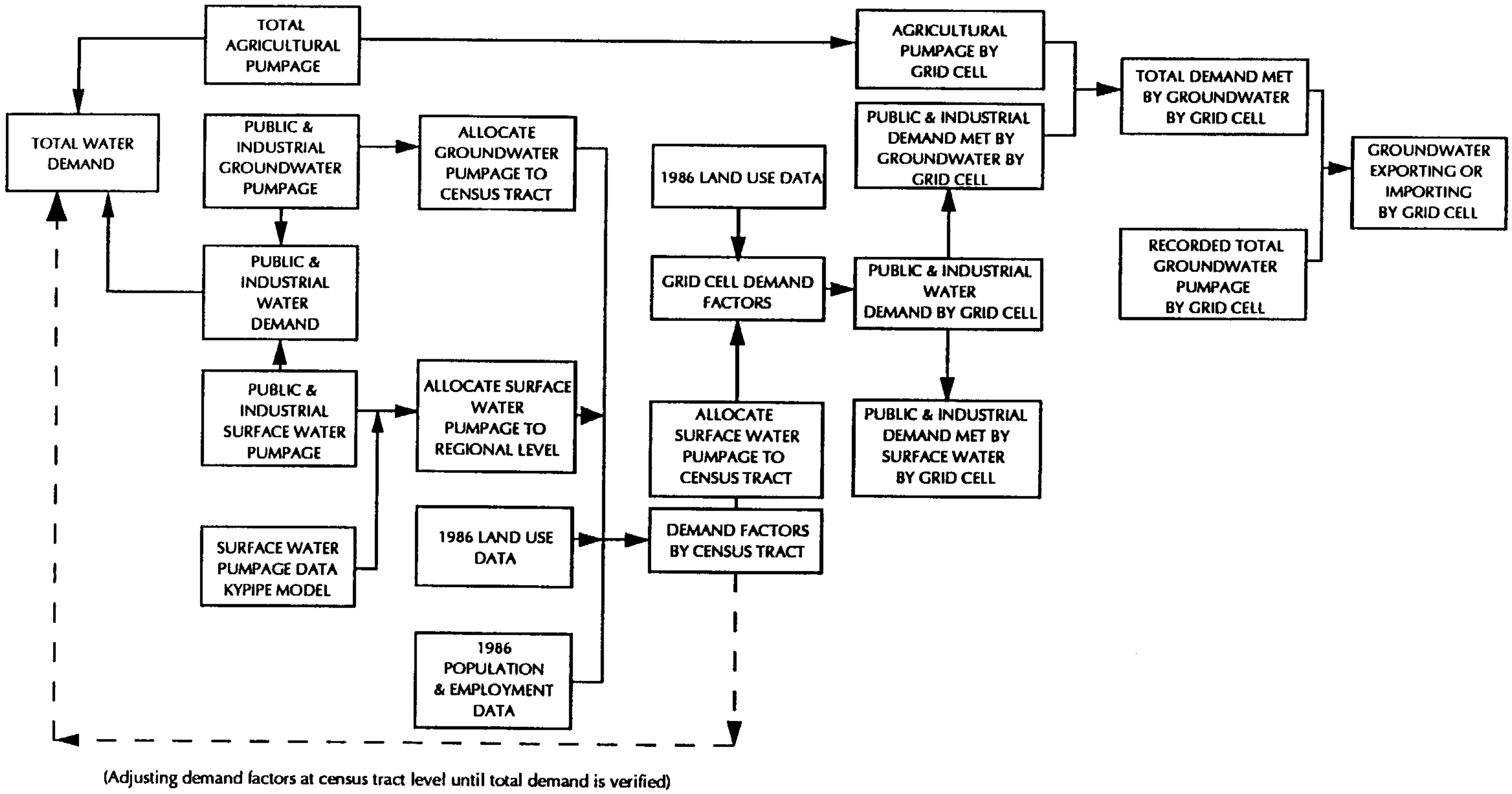
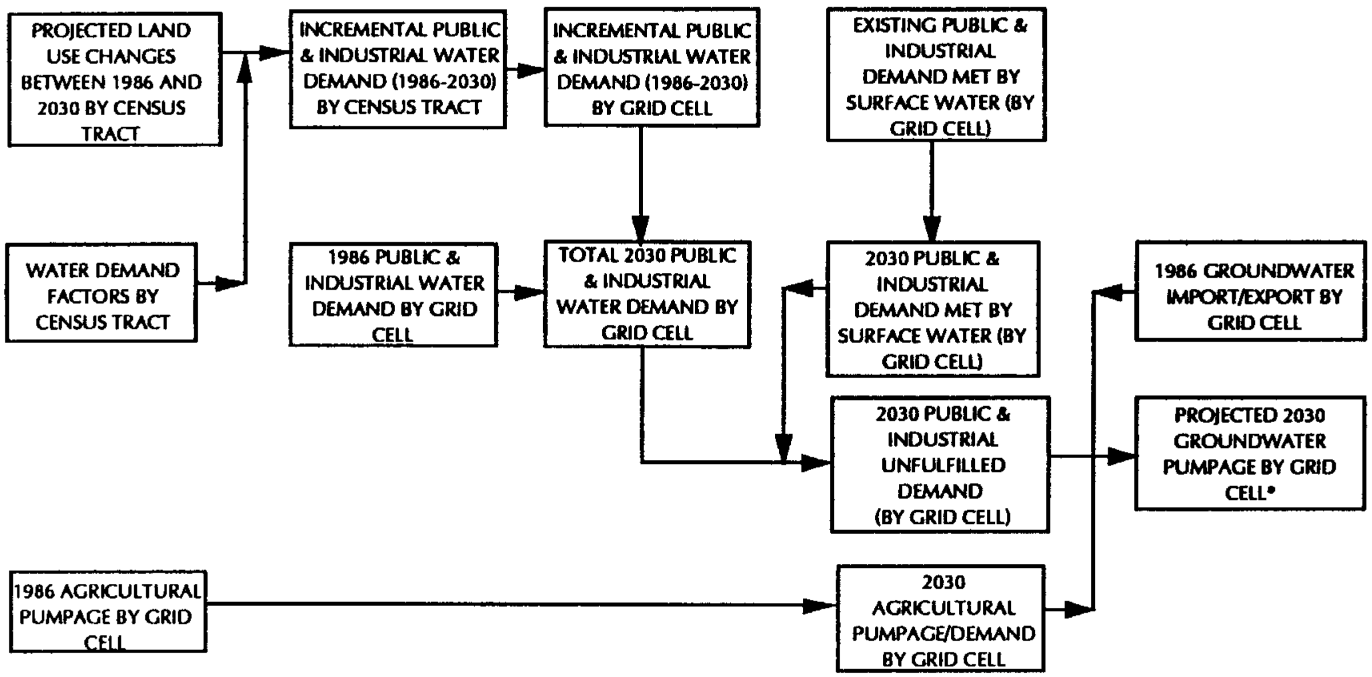


Figure II-1 ALLOCATION OF 1986 WATER DEMAND AND PUMPAGE TO GRID CELLS IN HARRIS & GALVESTON COUNTIES



*Initially, the subsidence model assumes that all unfulfilled demand will be provided by groundwater pumpage to establish a worst-case subsidence scenario. The groundwater pumpage then will be adjusted until reasonable subsidence levels can be achieved. Any unfulfilled demand which is not provided by groundwater pumpage has to be met by future surface water development.

Figure II-2 YEAR 2030 WATER DEMAND AND GROUNDWATER PUMPAGE PROJECTIONS

Existing Population

The 1980 census year was selected as the basis for the population projections, since it represented the most current official estimate of population distribution. The 1980 census population was acquired for each census tract in the study area along with estimates of the 1986 population done by HGAC. In 1980, the study area supported a population of approximately 3,145,000 persons, accounting for about 22 percent of the total population of the State of Texas. Harris County contained 2,409,547 persons, or 77 percent of the study area population in 1980. Galveston County contained 195,940 persons, or 6 percent of the study area population in 1980, while Fort Bend County maintained 130,846 persons, or 4 percent of the study area population. Population estimates developed by the HGAC, HWMP, and the Texas Water Development Board (TWDB) for 1985 and 1986 were also used in the population analysis to verify the projections.

Existing Land Use

The existing land-use map was derived from the United States Geological Survey (USGS) Land Use/Land Cover digital files available for the study area, supplemented by the City of Houston 1980 land-use map and aerial photography from 1980 and 1986. The 1:250,000 Houston and Seguin map series, which cover the southern two-thirds of the study area, were accurate to 1970 and 1973, respectively. The remaining portions of the study area, covered by the Beaumont and Austin map series, were accurate to 1980 and 1981, respectively. However, the Beaumont map series was not available in digital format. USGS provided a hard copy of the land-use map, which was subsequently digitized into the GIS.

The USGS files depict 24 land-use classifications. For the purposes of this study, the USGS land-use categories were regrouped into the 12 broader classifications listed below.

Single Family
Multifamily/High-Density
Commercial
Industrial
Parks and Green Spaces
Undevelopable (oil field,
  transporation, etc.)
Rangeland
Barren
Forest
Agricultural
Water
Wetlands

The land-use files were merged and updated to reflect both the 1980 and 1986 development patterns. The 1986 aerial photographs and information gathered from field reconnaissance surveys of various municipalities and known development areas were used to complete the land-use maps. In addition, the land-use coverage was examined with respect to Municipal Utility District (MUD) boundaries, city-limit delineations, and other pertinent political boundaries, such as census tracts boundaries and the HGCSD regulatory zones, which were also input into the graphic model. The resulting 1986 land-use map is shown in Figure II-3.

The GIS was then utilized to intersect the 1980 and 1986 land-use layers with the census tract boundaries and grid cell pattern and produce a tabulation of the acres of developed land, classified by land-use code, for each census tract and grid cell.

Population Projection

Initially, population projections done by the HGAC, the HWMP, the TWDB, and Texas A&M University were examined on a regional (study area) level. As shown in Figure II-4, the 2010 total population for the eight major counties within the study area were very similar, with the exception of the Texas A&M high series projection. The average of the TWDB high and low series forecasts approximated the mean of the four projections and was chosen to serve as a target value for the census tract projections. Considering the relative similarity in the four projections, county total projections, falling generally within the TWDB high and low series range, were also deemed as acceptable target values.

However, the TWDB forecast for Fort Bend County was not used as an upper limit for the population projections due to an unusually high amount of growth which has recently taken place in that county. The reduction of TWDB's annual growth rate from 3.9 percent to 1.7 percent in Fort Bend County after the year 2010 did not appear reasonable, considering the proposed development plans of major real estate developments in the county. Consequently, the Fort Bend County population was allowed to grow at a rate determined from historical trends and census tract population projections verified by investigation of development plans of the major communities, including First Colony, Weston Lakes, Greatwood, and Cinco Ranch. The projected 2030 population in Fort Bend

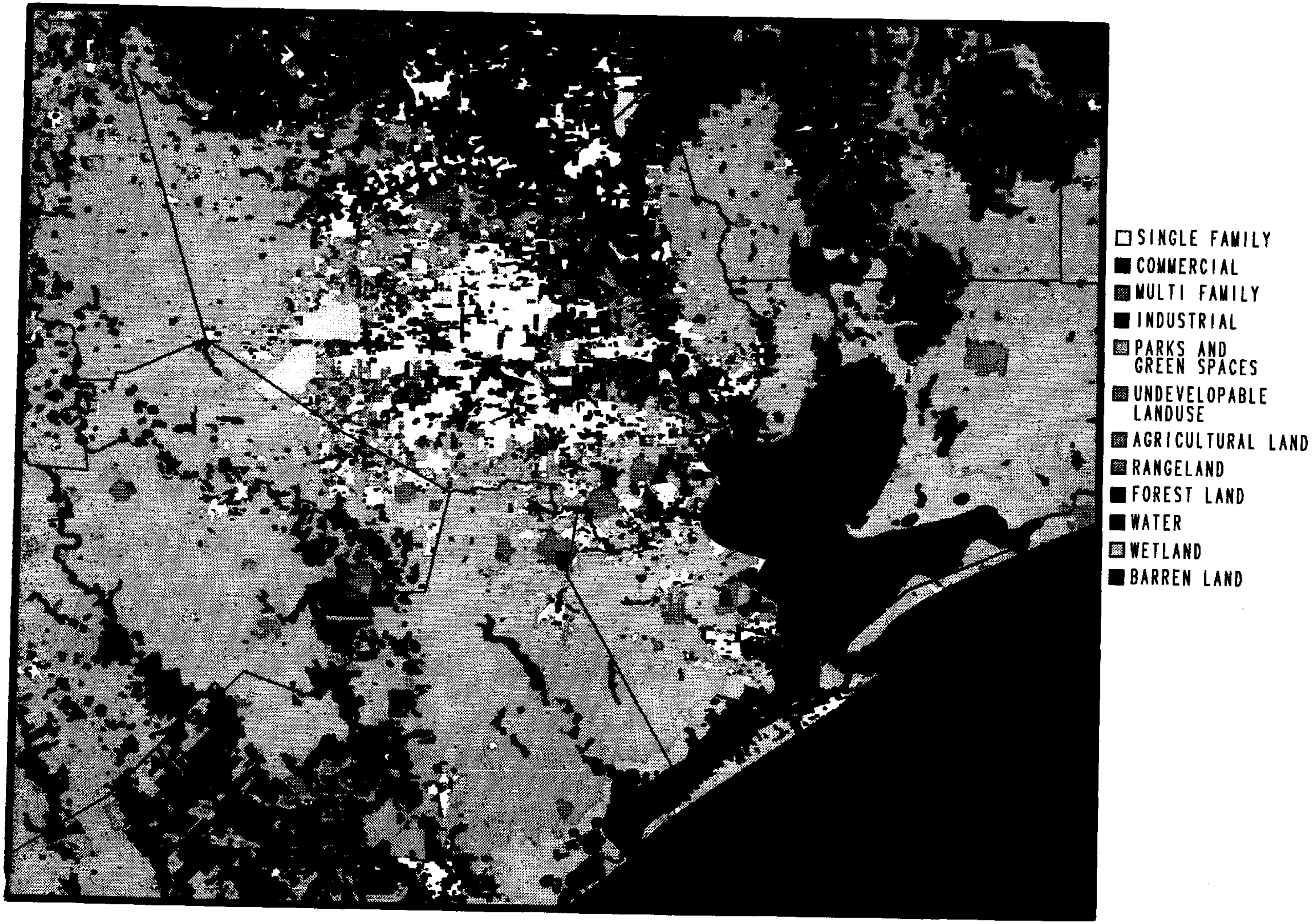
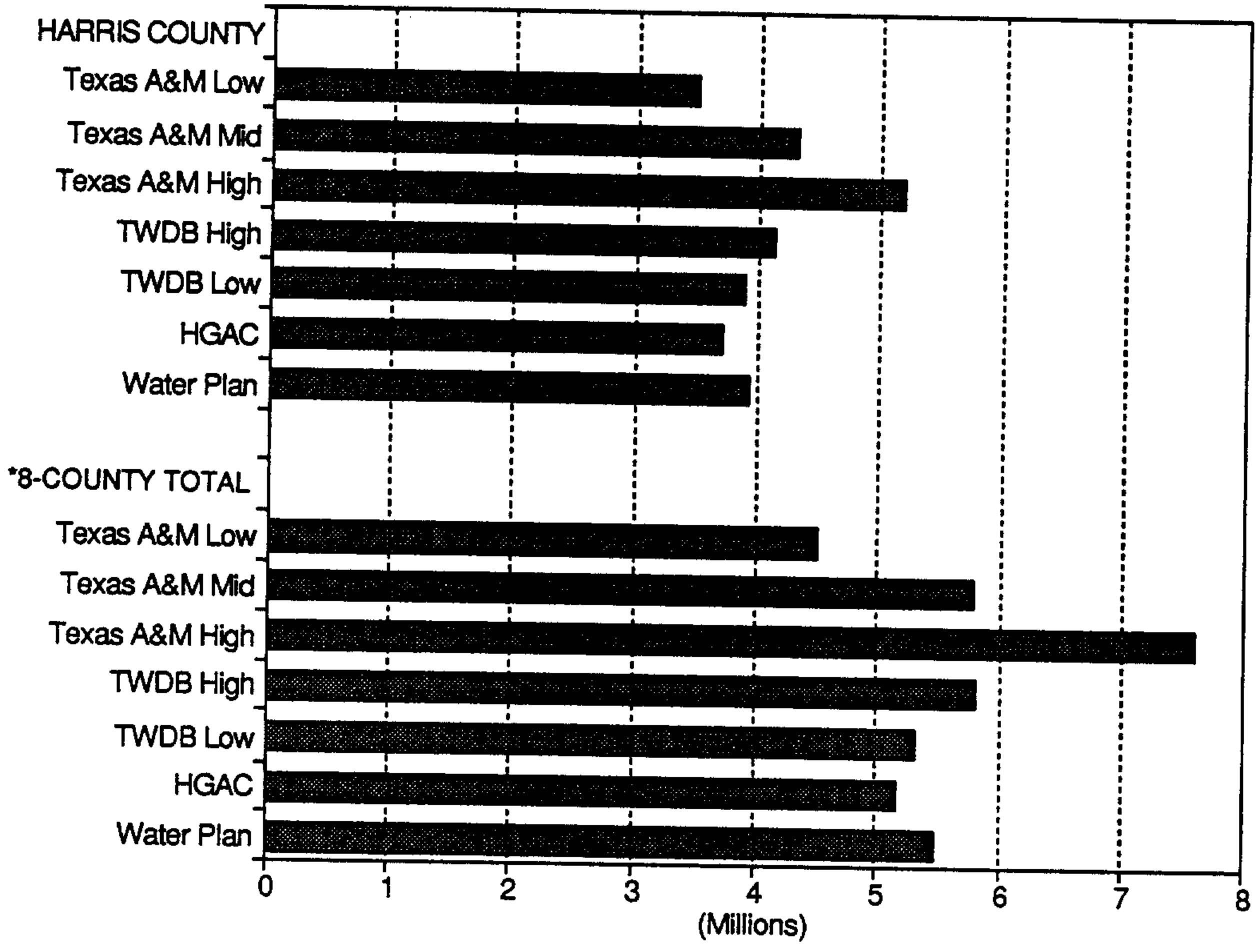


Figure II-3 1986 LAND USE MAP

FIGURE II-4 2010 POPULATION COMPARISON



***8- COUNTY TOTAL Includes Harris, Galveston, Fort Bend, Brazoria, Waller, Montgomery, Liberty, and Chambers Counties**

County exceeded the TWDB high series projection by 19 percent. Similarly, the 2030 population projections in Galveston and Brazoria counties were allowed to exceed the TWDB high series projection by 5 percent to 10 percent, based on future development information and historical development.

The population projections were based on historical annual growth rates calculated using the 1970 and 1980 census populations, the growth rates for municipalities within the study area used by TWDB for their projections, and the growth rates calculated from the 1980 census population and the 1986 population estimates made by HGAC. Each tract was examined individually and the annual growth rates in areas of recent development, or areas of planned development, were increased based on the historical growth trends displayed by developments of similar character in a similar setting. Growth rates in regions with high potential for development, such as areas along proposed transportation corridors or large single-owner landholdings, were adjusted to reflect expected growth.

A maximum population was determined for each census tract using the land available for development in the tract, as determined from the 1980 land-use tabulation and the 1980 census population density (persons per developed acre). The census tracts were permitted to grow at their selected growth rate until 75 percent of the available land for development was utilized. At that point, the growth rate was reduced by half and the tracts were permitted to continue growing until complete development (maximum population) was reached.

The population projections did not attempt to disregard work done previously by other entities. Rather, the projections were done independently and then compared closely to those done by HGAC and HWMP. The HGAC and HWMP projections were both derived using econometric models, however, the HGAC projections were conducted only up to 2010 and the HWMP projections to 2035. While similar on a regional level, the HGAC and HWMP projections showed significant variation in specific census tracts. Upon comparison, large differences between the HGAC, HWMP, and this study's projections for 2010 and 2030 populations were examined and adjustments were made to the growth rates where warranted. Some differences were deemed reasonable due to the presence of development centers which have emerged since the HGAC and HWMP projections were completed or based on current knowledge of potential developments, which was not previously considered. Fairfield Village, located in northwest Harris County, for example, did not exist at the time the previous population projections were done. In those instances, the population projections were based on known development plans, population densities typical of the planned development character, and available land for development.

The 2030 projected population for the study area is 7,415,000 which equates to an annual growth rate of 1.7 percent from 1980. Harris County population is projected to increase 1.4 percent annually to 4,883,513 in 2030, while Galveston County will increase 1.6 percent annually to 423,792 persons. A breakdown of the projected study area population is presented by county in Table II-1. Notice that the substantial population growth is predicted to occur primarily in Harris and Fort Bend counties.

Land Use Projections

Since only limited zoning restrictions exist within the study area, the projected land-use pattern was initially based on the proposed alignment of major transportation corridors to be built during the study period (1986 to 2030). A map detailing the proposed alignment and construction phasing of the major transportation improvements planned was obtained from the State Department of Highways and Public Transportation (SDHPT) and digitized into the graphic model. The ARC/INFO buffer utility was employed to define a one-mile, land-use buffer around proposed thoroughfares and a one-quarter mile buffer around major arterials. Future bands of development were also defined around municipalities within the study area using the 1980 population density and the projected increase in population from the TWDB projections.

The land-use pattern derived was then intersected with the graphic and nongraphic census tract population data and a report tabulating future land-use acres in each census tract was created. The 1980 population density was used to calculate an estimated 2030 census tract population, based on the assumption that development within a census tract would remain of like character. The calculated census tract populations were then compared to the population projections from the nongraphic growth trend analysis. The distribution of the future land use was refined and adjusted until the graphically derived

TABLE II-1 POPULATION SUMMARY

COUNTY	1980 POPULATION	2030 POPULATION	ANNUAL GROWTH RATE	TWDB* AVERAGE 2030 POPULATION	
HARRIS	2,409,547	4,883,513	1.4%	5,182,749	
GALVESTON	195,940	423,792	1.6%	374,450	
FORT BEND	130,846	763,788	3.6%	573,496	
BRAZORIA	169,587	381,693	1.6%	336,118	***
WALLER	19,798	64,051	2.4%	63,913	***
MONTGOMERY	128,487	661,947	3.3%	676,385	***
LIBERTY	47,088	143,477	2.3%	152,137	***
CHAMBERS	18,538	45,952	1.8%	46,318	***
MATAGORDA	4,012	7,559	1.3%	**	
WHARTON	17,859	29,767	1.0%	**	
GRIMES	0	0	0.0%	**	
JEFFERSON	1,448	1,522	0.1%	**	
HARDIN	1,807	3,633	1.4%	**	
AUSTIN	1,888	4,645	1.8%	**	
TOTAL	3,146,845	7,415,339	1.7%	7,405,566	

* Note: Texas Water Development Board, September 1988 series projections.

** Note: The counties indicated lie only partially within the study area. The 1980 and 2030 populations listed reflect only census tracts which influence the study area. However, the selected census tracts may not lie totally within the study area.

*** Note: The counties indicated do not lie totally within the study area. However, a substantial portion of the developed land lies in the study area and the populations listed approximate the county totals.

census tract populations matched the independent census tract population projections from the growth trend analysis.

The 2030 projected urbanized land is shown in Figure II-5. The projected land use mirrors the results of the population projections as the most significant growth appears around existing development centers in western Harris County and northeast Fort Bend County. Due to the lack of zoning in the study area, no effort was made to project the exact type of land use or any change in existing land use due to redevelopment.

The 2030 urbanized land and the nongraphic population projections (growth trend analysis) were reviewed jointly by an outside expert familiar with proposed and potential development in the study area. The population projections were compared on a tract-by-tract basis to the projections made by HGAC and HWMP. Input from the review was used to refine growth rates and adjust the land-use projections in specific census tracts, based on the perceived character of existing developments and the location of geographical features, such as landfills or oil fields, which will hinder future development.

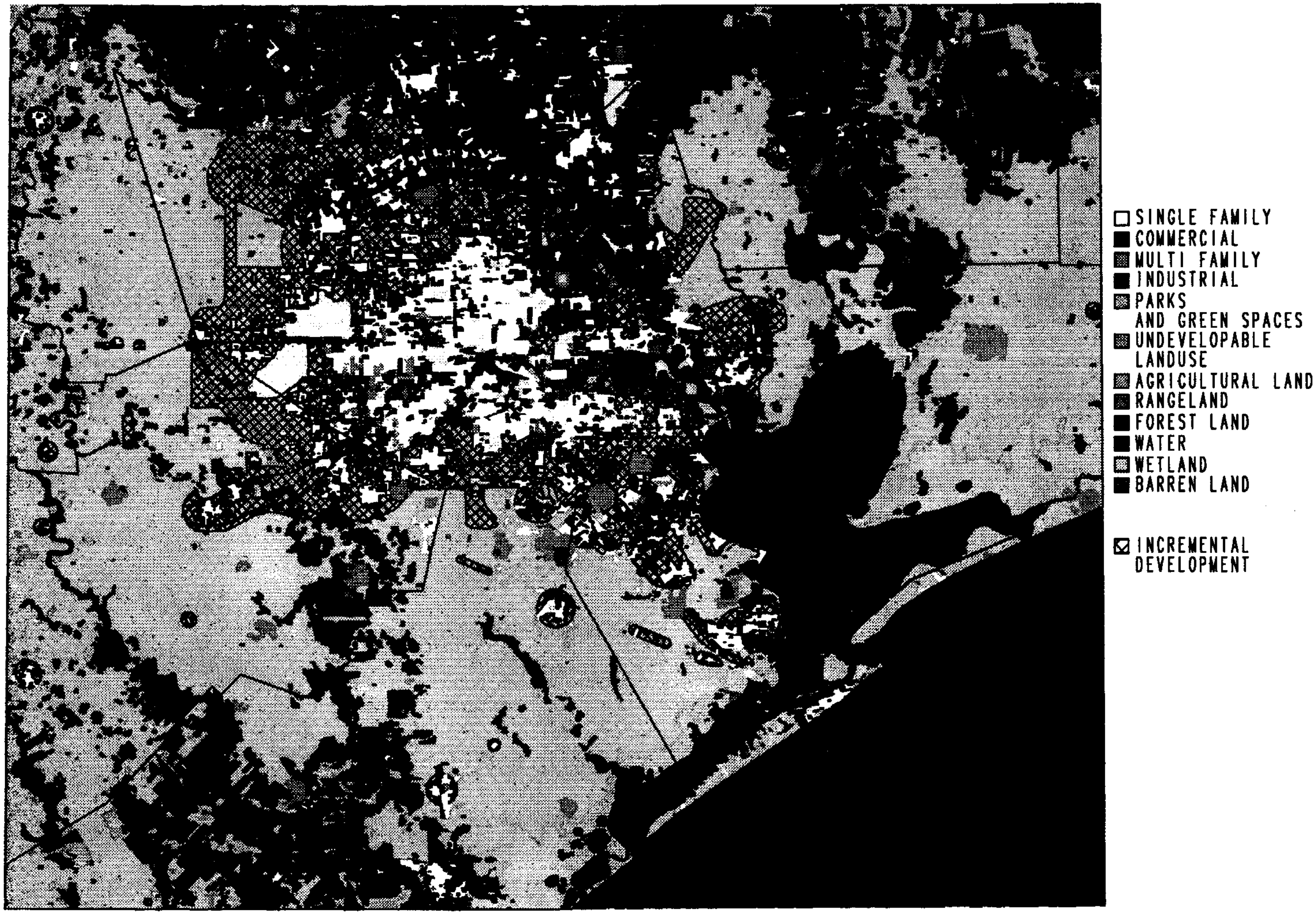


Figure II-5 2030 LAND USE MAP

Groundwater Pumpage

The HGCSD groundwater flow model requires an estimate of the groundwater pumpage from the Chicot and Evangeline aquifers for each model grid cell to calculate potentiometric head declines or water level declines that occur in response to the varying pumpage patterns. The potentiometric head declines in the layers of the model are subsequently used as inputs to the PRESS model to predict subsidence.

The Chicot and Evangeline aquifers provide essentially all of the groundwater within the study area with a very small amount of pumpage from the deeper Jasper aquifer occurring in the south-central part of Montgomery County and in the very north part of Harris County. Pumpage from the Jasper aquifer is limited and it is not considered as an input to the groundwater model and is subsequently not addressed in this report or illustrated in any tables or figures.

Previous studies conducted by HGCSD determined estimates of groundwater pumpage for the grid cells within its jurisdictional boundary for the period 1960 to 1975. Since 1975, HGCSD has maintained a database of groundwater pumpage from each of its permitted wells. However, estimates of the historic groundwater pumpage outside of the HGCSD boundary that were compiled in 1982 as part of study efforts for the RAP for the years 1960 to 1979 have not been updated since that time. The objective of the groundwater data analysis was to update the historic groundwater pumpage estimates for the grid cells within the original groundwater model area, but outside of the HGCSD boundary (called herein the Outside District Area) and the previously unmodelled 7.5-minute Western Extension Area (Figure I-3). Pumpage was estimated in the Outside District Area for the period 1980 through 1986 and in the Western Extension Area for the period 1960 through 1987. The pumpage estimates ended in 1986 and 1987, coinciding with the most recent data for public supply and industrial groundwater pumpage available from the TWDB.

The estimate of groundwater pumpage for areas outside the HGCSD jurisdictional boundary involved utilizing a variety of pumpage and hydrogeologic information sources. The pumpage was categorized as public/municipal, industrial, irrigation, and domestic use. Domestic use is defined as water for private individual consumption that is not supplied or monitored by a central water system operator or regulatory agency. The data compiled included a collection of reports and data from the USGS, the U. S. Agriculture Stabilization and Conservation Service (ASCS), the TWDB, the Texas Water Commission (TWC), the HGCSD, the City of Houston and William F. Guyton Associates, Inc., water districts, water supply corporations, and other private sources.

Pumpage for each grid cell in the Outside District Area was estimated for the two milestone years, 1980 and 1986, using the various data sources. The pumpage was then interpolated for the intervening years. Pumpage in the Western Extension Area was estimated for the years 1960, 1969, 1974, 1980, 1986, and 1987. Pumpage for the intervening years was again interpolated from these milestone years.

Water well and pumpage records for public/municipal supply, industrial, and irrigation users in the study area were collected and reviewed to obtain well locations, pumpage amounts, screen intervals, and/or total well depths. The locations of the wells were determined from published county reports by the USGS and TWDB, reports by William F. Guyton Associates, Inc., unpublished USGS and TWDB county well records, county maps of water districts and water supply corporations furnished by the TWC, and county highway maps. The wells were then assigned to their corresponding 2.5-minute x 2.5-minute model grid cells. The well's screened interval and/or total depth information was used to determine whether the well screened the Chicot and/or Evangeline aquifers.

Yearly groundwater pumpage by public/municipal supply and industrial users in Texas is reported to the TWDB on a voluntary basis. This groundwater-use inventory represents the only centralized record for the Outside District Area and Western Extension Area. The TWDB furnished tabulations of the municipal and industrial groundwater pumpage reports for the counties which include the portion of the study area outside HGCSD. In addition, pumpage data were obtained for some public supply and industrial groundwater users not listed in the TWDB pumpage inventory. The public supply and industrial groundwater users listed in the TWDB water-use data files were correlated with the associated water well records listed in the relevant reports and data files compiled. When matched with individual well records obtained from the various sources listed above, nearly all of the public supply and more than 90 percent of the industrial groundwater pumpage listed in the TWDB data files was located and assigned to the proper model cells.

In a substantial part of the model area outside HGCSD, most of the water pumped is for irrigation purposes, primarily rice irrigation. Whereas the municipal and industrial groundwater pumpage is recorded by the TWDB by user, irrigated acreage is inventoried by general tracts of land in a county and a pumpage duty applied on a county-wide basis. The sources of information used to determine irrigation pumpage were published and unpublished county irrigation surveys by the TWDB, 1984 county irrigation inventory maps furnished by the TWDB, information provided by county ASCS offices, reports and files listing records and locations for irrigation wells, and a field survey to check the locations of present areas of irrigation.

County agents and ASCS personnel indicated that the areal distribution of irrigated acreage in the Outside District Area was relatively consistent from 1980 through 1986. However, the total acreage irrigated and groundwater utilized for irrigation within each county fluctuated within this time period due to variable economic, government program, and climatic factors. Field checks conducted in the Outside District Area indicated that, in general, the present locations of irrigated acreage are similar to those outlined on the 1984 county irrigation inventory maps, although the irrigated tracts of land differ in size in some areas. In the Western Extension Area it was assumed that the general areas of irrigation did not change appreciably during the 1960 to 1987 time period. This assumption was based on a review of well records that show many of the irrigation wells were drilled prior to 1960 and that other irrigation wells drilled since then have been in the same general areas. The land that has been irrigated should be in proximity to corresponding irrigation wells which are at permanent locations. Thus, the methodology used to estimate the irrigation pumpage assumed a fixed number of well locations with variable yearly groundwater withdrawals. The yearly estimate of groundwater withdrawn from the irrigation wells was increased or decreased based upon yearly reported county-wide changes in irrigated acreage and irrigation duty (acre-feet of water applied per acre per year).

The determination of probable wells supplying groundwater for irrigation purposes was accomplished by comparing the plotted location of groundwater irrigated acreage, as outlined on 1984 county irrigation inventory maps, with reports and maps indicating the locations of irrigation wells. Tracts of plotted 1984 irrigated acreage were assigned to one or more of the following: an irrigation well or wells located within the acreage; a nearby well or group of wells; or, if no irrigation wells were located in proximity to the acreage, then merely to the grid cell coinciding with the acreage. The apportioning of tracts of irrigated acreage and related pumpage to two or more wells depended on available information, such as a well's proximity to the irrigated plot, casing diameter, screened interval, total depth, age, etc. Some of the wells assigned to the irrigated tracts of land may not be continually used to supply groundwater for irrigation. However, the irrigation wells selected are thought to be representative of wells supplying groundwater to their associated irrigated tracts of land in the grid cells.

The actual groundwater pumpage values allocated to the individual wells and the associated tracts of irrigated land are products of the estimated number of irrigated acres per well and the county-wide irrigation duties. The irrigation duties normally differed both by year and by county, reflecting, in part, the differences in yearly and areal precipitation. The duties ranged from about 1.5 to 3.8 acre-feet per acre per year and averaged about 2.3 acre-feet per acre per year. Irrigation duties were generally higher in years of lower precipitation and also for those counties, such as Wharton and Matagorda, where the average yearly precipitation is generally lower than in counties to the north and east.

Distribution of Groundwater Pumpage

The sum of the estimated public/municipal and irrigation groundwater pumpage was initially assumed to represent the total water demand in census tracts not importing or exporting water that was supplied solely by groundwater. Demand factors (gallons per developed acre) were examined in several tracts outside the City of Houston in an effort to verify this assumption. The selected tracts represented fairly rural settings with a mix of domestic, agriculture, and limited commercial development, but no heavy industrial complexes.

The demand factors calculated in the rural areas were skewed unrealistically low by groundwater pumped from wells not permitted by HGCSD. This unrecorded pumpage accounted for a substantial amount of the water supplied to these census tracts and indicated that the recorded pumpage could not be assumed to equal demand. Criteria were established based on the magnitude of the projected water demand relative to the recorded pumpage to estimate the unrecorded groundwater pumpage in each of the census tracts.

In addition, a threshold unrecorded rural demand was calculated for all census tracts from an average 1986 rural population density of 0.11 persons per acre (0.22 persons per acre in 2030) multiplied by the tract gross acreage (excluding water, wetlands, and undevelopable land) and a demand factor of 100 gallons per capita per day. This threshold demand represents the rural single-house developments which were not recorded on the land-use map, but used water from domestic wells. The rural population densities were calculated by dividing the population in rural census tracts by the gross acreage less nondevelopable property and comparing this value to residential population densities in suburban areas. All census tracts with little or no developed land (totally rural setting) were required to have a total water demand equal to or greater than the rural threshold demand.

Domestic pumpage constitutes a small percentage of the total pumpage outside HGCSD. It was estimated that domestic pumpage comprised about 4 percent of the total pumpage outside HGCSD in 1980 and 1986. This domestic pumpage is reflected in the tables showing water demand in this report. However, it is not reflected in the figures presented in this report or in the final data submitted to HGCSD for model input.

Total pumpage estimates for the model grid cells were comprised of the summation of the public/municipal supply, industrial, and irrigation groundwater estimates. An illustration of the 1986 total pumpage estimates by grid cell outside and inside HGCSD is shown in Figures III-1 and III-2. The illustration shows the pumpage by grid cell and also the relative amounts of the pumpage that occur from the Chicot and Evangeline aquifers. The areas of higher pumpage outside the HGCSD are located in the rapidly urbanizing area of northeast and east Fort Bend County, in the rice irrigation area of south Waller County, along the IH 45 corridor in the south part of Montgomery County, and in west Liberty County in a rice irrigation and industrial area. Grid cell 12/5 (row/column) in south Waller County had an average estimated pumpage of about 3.8 mgd in 1986 for irrigation and public supply, the most pumpage of any grid cell outside HGCSD.

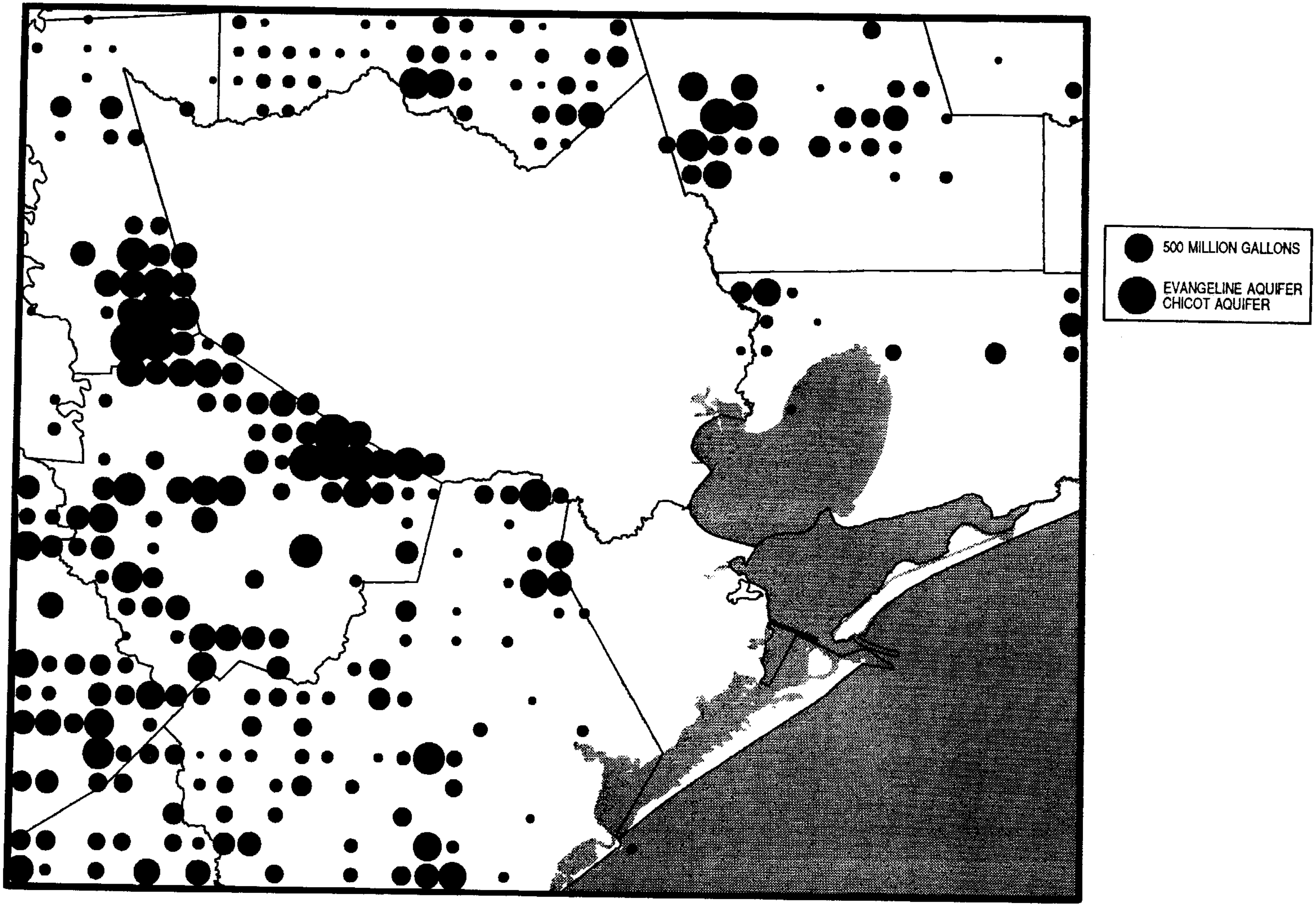


FIGURE III-1 1986 GROUNDWATER PUMPAGE BY AQUIFER OUTSIDE HGCSD

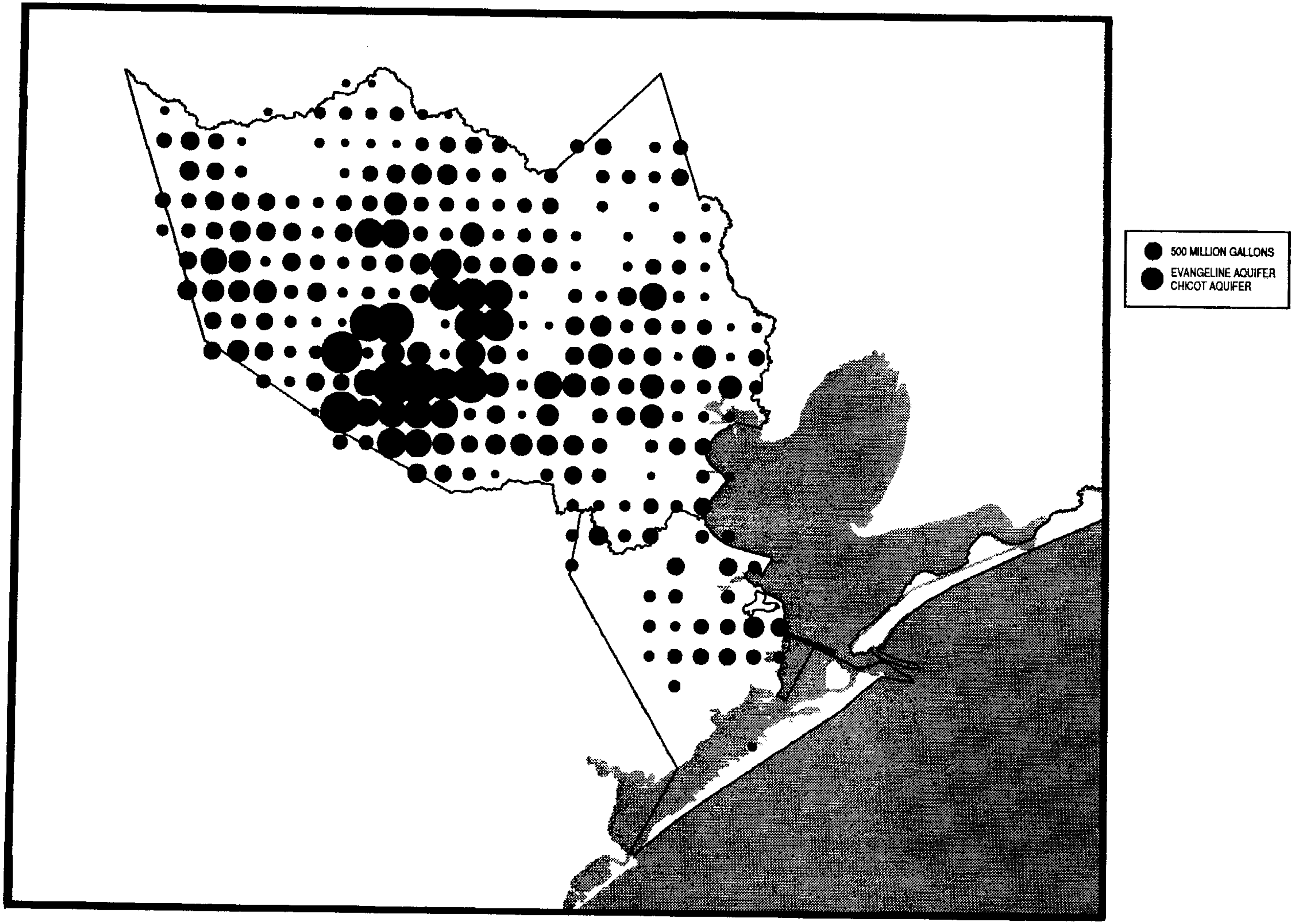


FIGURE III-2 1986 GROUNDWATER PUMPAGE BY AQUIFER INSIDE HGCSD

Sources of Groundwater Supply

Pumpage for the area outside HGCSD is principally from the Evangeline aquifer, for the northwest part of the study area. Pumpage is principally from the Chicot aquifer in Chambers, Brazoria, Wharton, and Matagorda counties. In Fort Bend County, pumpage for public supply is principally from the Evangeline aquifer while pumpage for irrigation in the central and west parts of the county is principally from the Chicot aquifer. In Waller, Montgomery, and Liberty counties pumpage is mostly from the Evangeline aquifer, with lesser amounts from the Chicot.

The wells that provide the water for domestic use outside of HGCSD normally are less than 300 feet deep and the water from most of these wells comes from the Chicot aquifer. More detailed information on the aquifers used for groundwater supply and the methodology used in estimating the aquifer ratios in the study area is presented later in this section.

Table III-1 shows the estimated public supply, industrial, and irrigation pumpage for 1980 and 1986 by county for the total study area outside HGCSD. Data in the table show pumpage for public supply increased from about 15,920 to 21,718 million gallons a year (mgy) from 1980 to 1986. The counties with the largest increases in pumpage for public supply were Brazoria, Fort Bend, and Montgomery. Pumpage for industrial use increased slightly from about 5,361 to 5,482 mgy from 1980 to 1986. Most of the increase was the result of industrial pumpage growth in Fort Bend and Liberty counties. Irrigation pumpage in the area decreased between 1980 and 1986 from about 42,700 mgy to 33,521 mgy. Rainfall comparisons between the two years indicate similar total annual amounts and similar amounts in the summer months. The reduction in pumpage for irrigation is principally due to a reduction in the number of irrigated acres from 1980 to 1986. On average, the irrigation duty changed only a very small amount from 1980 to 1986. The largest reductions in pumpage for irrigation between the years 1980 and 1986 occurred in Brazoria and Fort Bend counties.

TABLE III-1 ESTIMATED 1980 AND 1986 PUMPAGE OUTSIDE HGCSD

	1980 Groundwater Pumpage* (mgy)				1986 Groundwater Pumpage* (mgy)			
COUNTY	PUBLIC SUPPLY	INDUSTRIAL	IRRIGATION	COUNTY TOTALS	PUBLIC SUPPLY	INDUSTRIAL	IRRIGATION	COUNTY TOTALS
AUSTIN	55	0	0	55	47	0	0	47
BRAZORIA	4,894	1,098	5,713	11,705	5,800	1,126	1,602	8,528
CHAMBERS	764	599	0	1,363	755	573	221	1,549
FORT BEND	5,862	1,663	14,607	22,132	9,126	2,308	9,974	21,408
GRIMES	0	0	5	5	0	0	4	4
HARDIN	77	<0.5	0	77	97	<0.5	0	97
JEFFERSON	0	0	0	0	0	0	0	0
LIBERTY	973	116	4,759	5,848	897	533	5,335	6,765
MATAGORDA	14	114	3,568	3,696	49	25	2,989	3,063
MONTGOMERY	1,959	86	0	2,045	3,370	49	0	3,419
WALLER	723	303	8,462	9,488	897	431	7,686	9,014
WHARTON	599	1,382	5,586	7,567	680	437	5,710	6,827
YEARLY TOTAL	15,920	5,361	42,700	63,981	21,718	5,482	33,521	60,721
PERCENT OF YEARLY TOTAL	25%	8%	67%		36%	9%	55%	

* Estimated groundwater pumpage in part of the county within the study area.
mgy = Million Gallons per Year

Surface Water Pumpage and Distribution

Past and existing (1980 to 1986) surface water use records were collected from each of the entities supplying surface water to the study area. Since surface water used for agriculture/ irrigation purposes is unlikely to vary significantly during the study period, it will not have an affect on groundwater pumpage or subsidence. For this reason, it was not inventoried and is not addressed or included in this report. A major portion of the historic surface water usage was obtained from the database of information established by HWMP. Billing records were obtained from the Coastal Water Authority (CWA), detailing the surface water supplied to the industries along the ship channel. The following surface water suppliers outside the City were also surveyed for pumpage amounts and customer lists to complete the database:

Dow Chemical
Brazos River Authority (BRA)
Baytown Area Water Authority (BAWA)
San Jacinto River Authority (SJRA)
Brazosport Water Authority (BWA)
Houston Lighting and Power (HL&P)
Chocolate Bayou Water Supply Company (CBWSC)
Galveston County Water Authority (GCWA)

Known future surface water expansion projects were also inventoried. A list of the proposed contract amounts of water to be supplied from the Southeast Water Purification Plant (SEWPP) and the proposed contract modifications at the East Water Purification Plant (EWPP) were obtained. Information was also gathered concerning other proposed improvements such as the expansion of the Texas City plant operated by GCWA.

The total amount of surface water pumped in 1986 was 177,479 million gallons. As shown in Figure III-3, surface water comprised approximately 45 percent of the total water used in the study area. The major contribution was from the CWA which supplied approximately 52,000 million gallons per year (mgy) of mostly raw surface water directly to the industries along the Houston Ship Channel. EWPP supplied 51,456 mgy while GCWA provided 4,380 mgy of potable water and 19,710 mgy of chlorinated raw water to the public and industries through its Texas City plant.

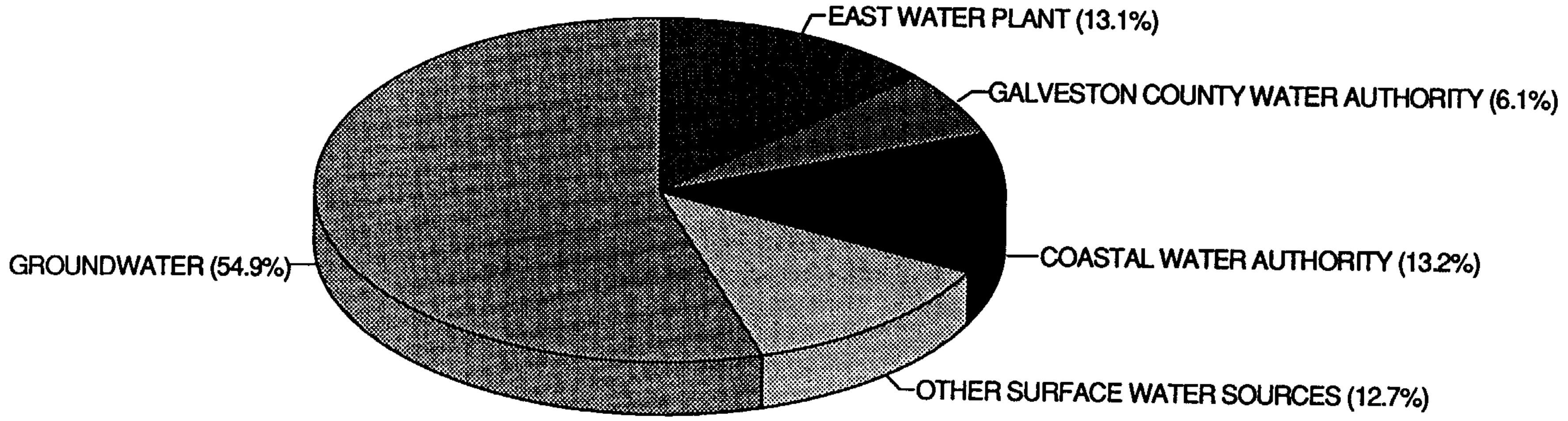


FIGURE III-3 1986 WATER SUPPLY BREAKDOWN

The surface water pumpage was initially assigned to regional locations and specific census tracts or land-use polygons based on the location of the users. However, the City of Houston's water distribution system emanating from EWPP added a degree of complexity to the distribution of the surface water within the City. A hydraulic analysis of the City's transmission lines greater than 24 inches in diameter was performed using the University of Kentucky pipe network analysis program (KYPIPE). The node representing EWPP was assumed to maintain a fixed hydraulic grade equal to the normal operating pressure of the plant. The total amount of surface water discharged from EWPP was distributed as demands to the water plants operating throughout the City until a distribution of surface water was achieved which matched the normal operating pressures at the plants. The resulting distribution of surface water served as an estimate of the existing surface water zone of influence within the City's system.

The actual extent of surface water influence was estimated based on the hydraulic analysis results by cumulating the calculated demand not fulfilled by groundwater in census tracts within the estimated zone of influence until all of the surface water supply was allocated. The resulting amount of surface water in each census tract was then converted to surface water consumption factors.

Water Conservation

The major water conservation efforts within the study area began around 1983 when the City of Houston undertook several actions designed to reduce water consumption. The City implemented a revised water rate structure which raised water rates and provided incentives for reduction in demand. The City also instituted various supply management actions, such as an aggressive leak detection and repair programs, to reduce the distribution system's unaccounted for water. Appendix C of the HWMP indicates that the City's unaccounted for water fell from 31.3 percent in 1980 to 18.3 percent in 1984 as a result of these actions.

In addition to the City of Houston's water conservation measures, several municipalities and utility districts within the study area have developed and implemented water conservation plans. The following entities currently have water conservation and drought contingency plans in place which were prepared in accordance with guidelines published by TWDB and subsequently approved by TWDB.

Harris County

City of Bellaire
Clear Lake City WA
Crosby MUD
City of Houston
La Porte Area WA
City of La Porte
City of Morgan's Point
City of Nassau Bay
City of Pasadena
City of Shoreacres
City of South Houston
Tidwell Timbers MUD
City of Webster
San Leon MUD

Montgomery County

SJRA, The Woodlands

Fort Bend County

First Colony MUD
  Nos. 1, 2, 3, 5, 6, 8
Fort Bend County MUD
  Nos. 4, 12, 13, 16

Galveston County

Galveston County WA
City of Galveston
City of Hitchcock
City of Jamaica Beach
City of League City

Brazoria County

City of Alvin
City of Angleton
City of Brazoria
Brazosport WA
City of Clute
City of Lake Jackson
City of Oyster Creek
City of Richwood

Waller County

Brookshire MWD

Liberty County

City of Dayton

WA: Water Authority
MUD: Municipal Utility District
MWD: Municipal Water District

Although not formally approved by TWDB, many other municipalities and utility districts within the study area have made strong efforts, including educational programs, literature distribution, and wastewater reuse irrigation systems, to reduce water use.

Table III-2 presents recorded water consumption within the study area. The effect of the 1983 rate increases can be seen in the reduction of the total water demand from 845 mgd to 748 mgd between 1982 and 1983. However, the net reduction of 97 mgd was not entirely due to the rate increases. The implementation of two federal programs

FIGURE III-2 CLIMATIC EFFECT ON WATER PUMPAGE WITHIN HGCSD

YEAR	POPULATION (persons)	IAH SUMMER DEPARTURE	IAH CUMULATIVE DEPARTURE	TOTAL WATER DEMAND	GROUNDWATER PUMPAGE	IRRIGATION PUMPAGE	SURFACE WATER PUMPAGE
1976		-2.9		740	458	52	282
1977		-0.4		766	426	45	342
1978		4.3		847	425	49	422
1979		3.5		813	394	37	419
1980	2,606,474	-7.2		863	432	51	431
1981		10.0		836	406	40	430
1982		-3.7		845	429	48	416
1983		9.0		748	356	21	392
1984		-2.1		822	384	31	437
1985		0.3	4.0	824	385	25	439
1986	2,923,582	-0.8	0.0	779	366	20	413
1987		4.5	-4.0	791	354	21	437
1988		-2.3	-22.0	854	380	34	474

Data from Harris-Galveston Coastal Subsidence District yearly groundwater reports.
IAH = Houston Intercontinental Airport
Departure = Departure from long-term average rainfall.
Departure in inches and pumpage/demand in millon gallons per day.

(Payment in Kind and Acreage Reduction Program) to reduce agricultural production caused a 27-mgd decrease in groundwater pumped for irrigation purposes. In addition, climatic variations accounted for some of the pumpage reduction.

To quantify the effect of the water conservation efforts, 1982 and 1988 were selected due to the similarity in their climatological conditions. An increase in total water demand was estimated based on a population increase calculated using a 2 percent annual growth rate. If the increase in demand due to population growth is excluded, a 10 percent decrease in demand attributed to water conservation was observed during these six years (1.5 percent annually). Using the same approach, the 1984 and 1988 demands were compared. The reduction in demand from water conservation dropped to 4.4 percent or approximately 1 percent annually. This suggests initial returns from the 1983 water conservation efforts were higher than 1.5 percent annually, more likely in the 2 to 3 percent range. However, subsequent water conservation measures have resulted in a reduction in demand of approximately 1 percent per year.

HGCSD has been involved in several water conservation programs in the past. All well permits issued by HGCSD are renewed annually at a public hearing. Permit holders must have operating water meters in place and are required to furnish HGCSD with information about each well. A water audit, including per capita usage and calculation of percentage of water loss, is reviewed at the hearings. Suggestions regarding water rate structures, consumer and operational water wastage, and conservation techniques are given to permitties with high water loss. Provisions are sometimes added to permits, requiring the holder to inform HGCSD about water accountability during the following year. HGCSD has also required permit holders to undertake special projects to correct large water losses.

HGCSD has recently formed a subcommittee from its governing board to support their water conservation activities. HGCSD has been very active in public education, including a traveling water conservation exhibit booth which concentrates on water uses in the home. The exhibit is typically displayed at water utility association meetings and water conservation conferences, as well as several home shows. HGCSD also publishes a quarterly newsletter which includes articles concerning water conservation. At least one issue a year has been totally devoted to water conservation. HGCSD has also sponsored water reduction technical seminars in the past and gives programs to civic, community, student, professional, and technical groups. The technical seminars focus on conducting comprehensive water audits and the implementation of cost-effective water conservation measures. Special programs have been presented to students through the public school system in association with the Texas Society of Professional Engineers (TSPE). HGCSD also maintains a library containing information concerning water use and subsidence that includes water conservation literature which is available to the public.

Climatic Conditions

Although the annual average rainfall in the study area is approximately 48 inches, variations in precipitation from year to year have a significant impact on water use. Rainfall during the summer months, which is the peak time for agricultural, lawn, and greenspace irrigation pumpage, particularly influences the amount of water used in a year. As shown in Table III-2, dry years such as 1984 and 1988 reflect increases in groundwater demand from 5 percent to 10 percent when the appropriate adjustments are made for population growth and water conservation. Wet years such as 1981 and 1987 show a similar amount of variation. The demand projections made were based on 1986 pumpage levels which appear to represent a normal precipitation year. Consequently, the projections will also represent normal precipitation conditions and be subject to 5 percent to 10 percent variation due to climatic conditions.

Calculation of Water Demand Factors

The calculation of water demand was conducted on a census tract basis and later reconciled to individual grid cells using land-use-based water demand factors (derived from 1986 groundwater and surface water usage levels) and the analysis capability of the GIS. The demands were broken into two categories: public demand and heavy-industrial demand. Public demand represented a mix of single-family residential, high-density residential, commercial, and light-industrial development typical of most of the Houston area. The heavy-industrial demand category reflected industrial complexes typical of the Houston

Ship Channel and Texas City areas. It was considered separately because of the enormous amount of water used by some industries and the high degree of variability in water use from one type of industrial process to another.

The heavy-industrial demand factors were derived from employment-based demand factors (gallons per employee), percentages of heavy-industrial employees in the workforce, and municipal demand areas established by HWMP. The heavy-industrial demand factors were initially derived by translating the HWMP factors into land-use-based factors using the GIS and the HWMP employment data. The demand factors were then refined and adjusted through an iterative process to reflect variations in demand on a census tract basis. When significant discrepancies in pumpage and demand were identified in a specific tract, the well owners, well location, and use of the water was examined and the heavy-industrial demand factors were adjusted accordingly. The resulting heavy-industrial demand factors ranged from 3,500 to 24,000 gallons per acre per day (gpad).

The public demand factor was first examined in census tracts outside of the City of Houston to eliminate the effects of surface water. Several sets of demand factors were calculated in different areas of Harris County. An average value of 756 gpad was selected from census tracts in south and west Harris County because of their typical mix of development. The acreage used in calculation includes developed land only.

The 756-gpad public demand factor was then applied along with the heavy-industrial demand factors to the 1980 and 1986 land-use tabulations for all census tracts. The calculated Harris and Galveston county water consumption totals were compared to the known existing county water consumption totals and the public demand factors were adjusted accordingly. The demands were again examined on a tract-by-tract basis to identify discrepancies. Special areas such as downtown Houston, Greenway Plaza, the Medical Center, and the high-density apartment concentrations in southwest Houston were given higher demand factors. These special demand factors ranged from 1,500 to 9,500 gpad and were derived by examining the land-use classifications in the tracts and making an estimate of the demand factor based on population data, employment data, and typical design demand factors. The calculated demands in these special tracts were also compared to the estimates made by the HWMP. The demand factor adjustments yielded an average public demand factor of 810 gpad derived in Harris and Galveston counties and subsequently applied to all other parts of the study area.

Major housing developments, consisting of strictly singlefamily residential lots with small amounts of commercial or industrial development such as Copperfield, Kingwood, First Colony, and Champions, were also given higher demand factors. A demand factor of 1,300 gpad was selected based on calculations in several developments with well-defined distribution systems which are served solely by groundwater. Similarly, smaller municipal developments and unincorporated communities such as San Felipe were given a lower demand factor (typically 150 to 500 gpad) to account for the rural nature of some of the development classified as single-family land use. The regional average public demand factor was reduced from 810 gpad to 727 gpad after these adjustments to maintain the known county water demand totals.

Existing Water Demand

The public and heavy-industrial demand factors and the surface water consumption factors for each census tract were then applied on a grid cell basis using the spatial analysis capability of the GIS. The total water demand in a grid cell was calculated by summing the public, heavy-industrial, and rural demands, all calculated from the census tract demand factors, with the recorded agricultural/irrigation pumpage (demand).

The existing total water demand (1986) by county, excluding agricultural surface water, is presented in Table III-3 and Figure III-4. Of the 259,044 mgy water demand in Harris County, 49 percent was met by groundwater and 51 percent by surface water. The Galveston County demand of 31,128 mgy was supplied by 9 percent groundwater and 91 percent surface water. In Fort Bend County, the 29,174 mgy total water demand was fulfilled by 88 percent groundwater and 12 percent surface water. The study area's total 1986 water demand was 393,458 mgy with 215,979 mgy of groundwater and 177,479 mgy of surface water.

TABLE III-3 1986 DEMAND SUMMARY

COUNTY	PUBLIC DEMAND	AGRICULTURAL DEMAND	RURAL DOMESTIC DEMAND	TOTAL WATER DEMAND	SURFACE WATER DEMAND	TOTAL GROUNDWATER DEMAND
HARRIS	252,222	6,606	216	259,044	132,967	126,077
GALVESTON	30,964	19	145	31,128	28,302	2,826
FORT BEND	18,191	9,735	1,248	29,174	3,643	25,531
BRAZORIA	18,786	1,390	1,751	21,927	7,980	13,947
WALLER	2,000	7,653	845	10,498	0	10,498
MONTGOMERY	11,353	0	100	11,453	0	11,453
LIBERTY	4,056	5,229	1,410	10,695	212	10,483
CHAMBERS	5,759	221	813	6,793	4,375	2,418
MATAGORDA	269	2,788	460	3,517	0	3,517
WHARTON	1,249	5,718	773	7,740	0	7,740
GRIMES	1	4	70	75	0	75
JEFFERSON	146	0	184	330	0	330
HARDIN	450	0	274	724	0	724
AUSTIN	74	11	275	360	0	360
TOTAL	345,520	39,374	8,564	393,458	177,479	215,979

All values in million gallons per year.

Note: Extreme variations of data between Table III-2 and III-3 area due to differences in how pumpage in grid cells was assigned in those cells located on the political boundary between two counties.

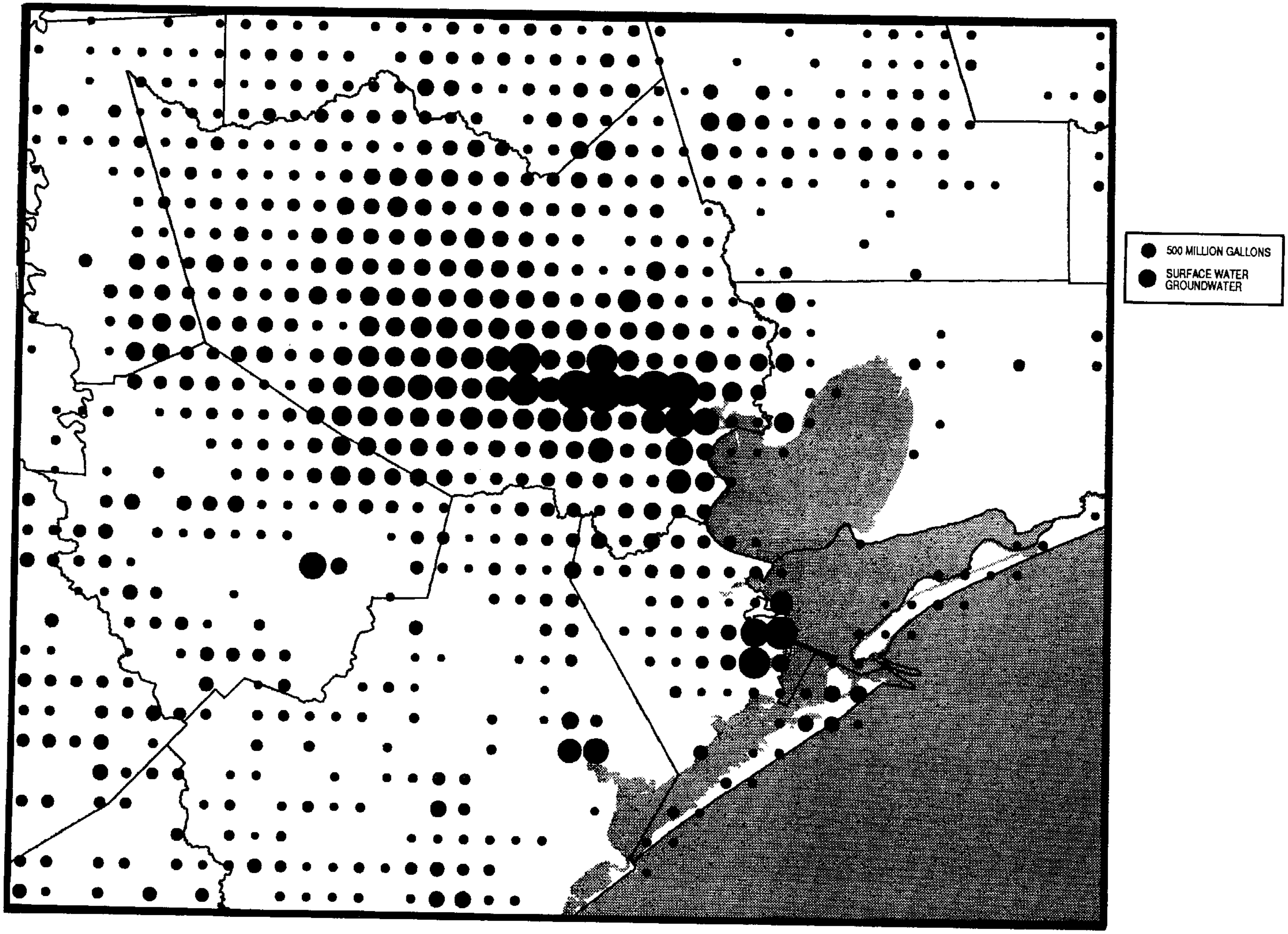


FIGURE III-4 1986 TOTAL WATER DEMAND

Importing and Exporting

Since groundwater pumpage is normally a function of aquifer capability and water demand is driven by land-use development, water may not necessarily be used in the same geographical area as it is pumped. Municipal water distribution systems and utility district systems may cause the transfer of water between several grid cells. The City of Houston, for example, operates several major well fields that export water for use in other areas within the City's water distribution system. The exact calculation of the quantity of groundwater imported or exported between cells is a nearly impossible task. However, estimates were made to generally describe importing and exporting characteristics and to identify major importing and exporting areas. The difference between the total water demand and the total groundwater pumpage (recorded and unrecorded) in a cell was used as an estimate of the amount of water imported to or exported from the cell. The values were reviewed graphically with respect to political boundaries and known transmission systems using the GIS. Adjustments were made to the demands in cells displaying unreasonable values to ensure that a balance was achieved between importing and exporting cells.

Aquifer Ratios

The HGCSD groundwater flow computer model requires input of pumpage from both the Chicot and Evangeline aquifers. This is achieved by inputing the estimated groundwater pumpage in each grid cell and an aquifer ratio (Chicot pumpage divided by total pumpage). The aquifer ratio is a decimal number from 0.0 to 1.0, that indicates the relative proportion of groundwater supplied within each grid cell by the Chicot and Evangeline aquifers. An aquifer ratio of 1.0 indicates that 95 percent or more of the groundwater pumped in the particular grid cell is from wells screening the Chicot aquifer and 5 percent or less is pumped from the underlying Evangeline aquifer. The aquifer ratio would be 0.2 for a grid cell in which approximately 20 percent of the groundwater is supplied by the Chicot aquifer and approximately 80 percent is furnished by the Evangeline aquifer.

Past aquifer ratios were estimated for the period 1980 through 1986 for the Outside District Area, for the period 1960 through 1986 for the Western Extension Area, and for 1986 for the area within HGCSD. Projected aquifer ratios were estimated for the entire model for the period 1986 through 2030 and will be discussed in a later section of this report.

The aquifer ratio for a particular cell was generally calculated by dividing the amount of estimated pumpage from the Chicot by the total amount of pumpage from the Chicot and Evangeline. To determine which aquifer(s) were potentially supplying water to a well required obtaining and reviewing data, including information on the screened intervals and/or total depths of the wells, estimated pumpage from the wells, USGS maps of the estimated depths of the base of the Chicot aquifer, and work maps prepared during the study that showed the locations of salt domes, estimated fresh-water thicknesses in the Chicot and Evangeline aquifers, and areas of poor quality water within the model boundaries.

The screened interval for a well and the depth to the base of the Chicot aquifer at the well were mainly used to estimate the amount of water that was pumped from each aquifer by the well. As an example, if a well screened the depth interval from 400 to 800 feet and the estimated base of the Chicot was about 600 feet, it was estimated that 50 percent of the water pumped from the well was supplied by the Chicot and 50 percent by the Evangeline. Occasionally, the well records reviewed did not include the screened intervals and, in such a case, other data, including total well depths, estimated aquifer depths at the well location, aquifers utilized by other comparable nearby wells, casing diameters, and use of the water, were studied to help assess the aquifer(s) supplying water to the well and the relative amounts.

The extensive inventory of wells and pumpage by HGCSD for Harris and Galveston counties provides considerable information from which to estimate the aquifer ratios within the HGCSD boundary, as opposed to the area outside the HGCSD boundary where the well records and pumpage data are not as complete. Sufficient well and pumpage records were available outside HGCSD for estimating aquifer ratios in almost all grid cells. Border cells which fell along the HGCSD boundary were analyzed by reviewing well and pumpage data compiled by HGCSD in conjunction with similar data gathered for the portions of the cells outside HGCSD. In the limited number of grid cells where sufficient well data were not available, aquifer ratios were based upon factors such as the aquifer ratios in surrounding cells, estimated aquifer depths, water use, total well depth, and casing diameter.

Estimates of the aquifer ratios for the grid cells were calculated for the selected bounding years, listed below, and then a straight-line interpolation was performed to estimate the aquifer ratios for the intervening years. In the Outside District Area, aquifer ratios were estimated for 1980 and 1986 while ratios were estimated for 1960, 1969, 1974, 1980, and 1986 in the Western Extension Area. Estimates of the 1986 aquifer ratios were also calculated for the grid cells within HGCSD. An illustration with the estimated 1986 aquifer ratios is shown on Figure III-5. The 1986 aquifer ratios should be viewed as estimates of relative groundwater withdrawals in 1986 from the aquifers, not as indicators of relative groundwater availability from the aquifers.

The regional dip of the formations composing the aquifers in the study area is to the southeast toward the Gulf of Mexico. The Chicot aquifer outcrops in the central and northwest parts of the model area, but thickens to the southeast. The Chicot aquifer contains water with acceptable amounts of dissolved minerals (total dissolved solids) to a greater distance east and south in the model area than the underlying Evangeline. The Evangeline aquifer outcrops just northwest of the study area. The Evangeline is the predominant aquifer utilized for water supplies in the central, north, and northwest part of the model area. These areas on Figure III-5 have lower aquifer ratios that indicate more of the pumpage is from the Evangeline aquifer than from the Chicot aquifer. In much of the south and southeast part of the model area, the Chicot is the only aquifer capable of providing fresh water to wells. The higher ratios in the south and east part of the model area indicate that the Chicot is the primary aquifer providing water to wells in these areas. There are no ratios given for the southeast part of the model area because much of this area is encompassed by Galveston Bay, Trinity Bay, and the Gulf of Mexico and there is no recorded pumpage in the area.

The general land-use patterns are also reflected in the aquifer ratios. Within HGCSD, public water supply and industrial pumpage predominates, deeper wells are

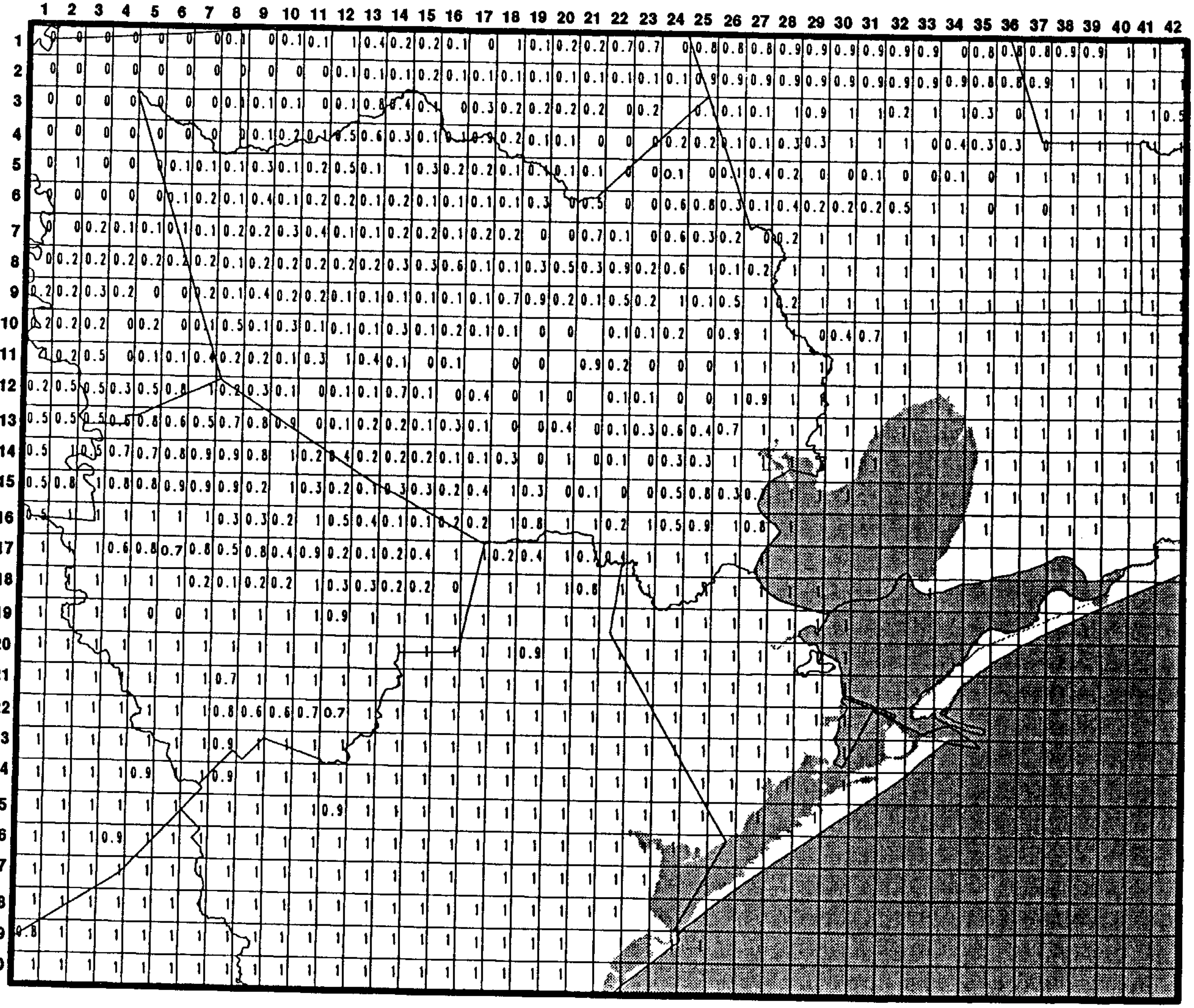


Figure III-5 ESTIMATED 1986 AQUIFER RATIOS BY GRID CELL normally used and most of the groundwater is withdrawn from the Evangeline aquifer. In the area outside HGCSD, irrigation pumpage comprises a significant part of the total pumpage. Irrigation is prevalent in the west, southwest, and northeast parts of the model area. In these areas most of the irrigation pumpage is from the Chicot aquifer.

Aquifer Properties and Heads for Western Extension Area

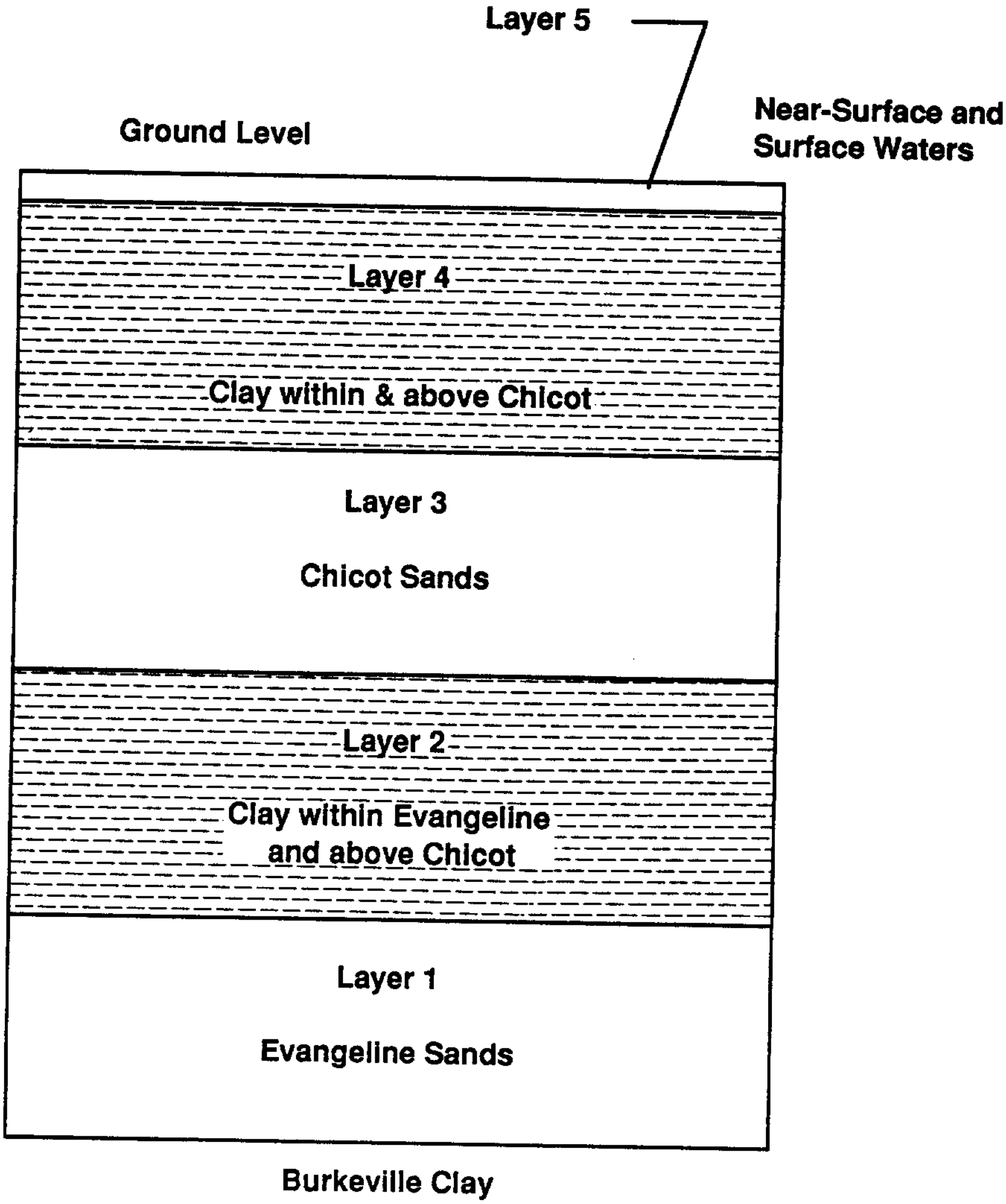
The existing groundwater flow model used by HGCSD was patterned after a USGS finite-difference digital model (Meyer and Carr, 1979), with modifications to some of the aquifer parameters and other input data as were deemed necessary to improve the calibration of HGCSD's model. The required input data for the HGCSD model include estimates of transmissivity, storage coefficient, leakance values for four of the five layers of the model, and initial (1900) and 1960 head values for five layers of the model. The required input data were estimated for the 90 grid cells in the Western Extension Area. The model is constructed with five layers, numbered from bottom to top, with the assumed stratigraphy as follows:

5. Near-surface and surface waters
4. Clay layers within and above Chicot aquifer
3. Chicot aquifer
2. Clay layers within Evangeline aquifer and between Chicot and Evangeline aquifers
1. Evangeline aquifer

The Burkeville clay formation below the Evangeline is considered to be an impermeable bottom to the model. The layers of the model are depicted on Figure III-6.

The methodology used to estimate the transmissivity, storage coefficient, leakance, and groundwater head values involved a study and evaluation of the corresponding input data from the USGS and HGCSD models and additional hydrogeologic information. The west boundary of the original HGCSD model is at the east edge of the Western Extension Area (Figure I-3). The USGS model extends to the north, south, east, and west of the Western Extension Area. Whereas both these models require similar input parameters, the

Figure III-6 CONCEPTUAL ILLUSTRATION OF MODEL LAYERS



data do not necessarily correspond to the same location, primarily because the geographic and grid cell boundaries and grid cell sizes do not match. Thus, the development of the input data for the Western Extension Area required an assessment of the differences in data and detail between the two models, an evaluation of available pumping test and water-level data within and in close proximity to the extension area, and selection of final input data that represented a synthesis of the available additional information and previous HGCSD model input data immediately to the east of the Western Extension Area.

The individual input data for the aquifer properties and head values in the Western Extension Area were developed as follows:

- Transmissivity Estimates - Transmissivity is a measure of the amount of flow that will occur in an one-foot-wide strip of an aquifer with a given potentiometric gradient across it. It is a product of the horizontal permeability of the aquifer multiplied by its thickness. The information analyzed to estimate the transmissivities of model layers one through four (shown in Figure III-6) included data from the USGS and HGCSD models and from previous pumping tests conducted in the area. The estimated transmissivity values in the Western Extension Area are shown in Figure III-7. The transmissivity values selected for layers two and four, the alternating clay layers, were essentially the same as those used in the USGS model. The model boundaries were modelled as no flow cells, as was done in the existing model. The transmissivity values for the Chicot and Evangeline aquifers were developed by slightly modifying the USGS model data after review of the transmissivity values in the HGCSD model for the cells just to the east of the Western Extension Area. Review of available pumping test data for the extension area showed that the calculated transmissivity values were consistent with the transmissivity values that were used in the USGS model for the area.

- Storage Coefficient Estimates - Storage coefficient is a term used to define theamount of water that is released from or taken into storage per square foot of an aquifer per foot of change in head normal to the aquifer. The information analyzed, with respect to the storage coefficients of the Chicot and Evangeline aquifers and the alternating clay layers, included data from the USGS and HGCSD models and from pumping tests conducted within and near the Western Extension Area. After analysis and study of the data, the storage coefficient values from the USGS model were selected for use for the grid cells in the extension area. The storage coefficient estimates for the Western Extension Area are shown on Figure III-8. The storage coefficient values selected are representative of water table conditions within the outcrop of the Chicot aquifer in the northern part of the Western Extension Area and of semi-artesian to artesian conditions in the

Figure III- 7 ESTIMATED TRANSMISSIVITY VALUES BY GRID CELLS IN THE WESTERN EXTENSION AREA

EVANGELINE AQUIFER
LAYER 1
Value = Number x 100

ROW OF MODEL (N-S) \ COLUMN OF MODEL (W-E)	1	2	3	4
1	19	19	20	20
2	31	34	36	39
3	36	39	43	46
4	36	41	46	51
5	39	46	53	59
6	39	49	58	68
7	43	57	71	85
8	44	62	80	98
9	68	86	104	124
10	69	85	103	120
11	60	84	102	120
12	62	80	97	120
13	70	85	100	115
14	62	76	91	105
15	62	71	81	90
16	71	74	76	80
17	71	74	74	76
18	71	74	74	76
19	73	80	81	80
20	74	80	79	81
21	88	90	90	90
22	88	89	89	94
23	89	90	92	97
24	89	90	95	100
25	89	91	96	102
26	89	89	94	99
27	88	88	92	97
28	88	87	91	96
29	84	88	93	95
30	46	48	50	51

CLAYS
LAYER 2
Value = Number x 1

ROW OF MODEL (N-S) \ COLUMN OF MODEL (W-E)	1	2	3	4
1	0	0	0	0
2	0	11	13	14
3	0	18	20	21
4	0	18	21	23
5	0	24	26	28
6	0	24	26	28
7	0	30	32	33
8	0	30	33	35
9	0	35	38	40
10	0	36	39	42
11	0	46	48	49
12	0	48	49	50
13	0	47	49	50
14	0	48	50	51
15	0	48	51	53
16	0	51	54	58
17	0	50	55	59
18	0	51	56	61
19	0	45	50	54
20	0	44	49	53
21	0	42	47	51
22	0	42	47	51
23	0	42	46	51
24	0	41	44	47
25	0	40	43	45
26	0	40	43	45
27	0	45	45	46
28	0	50	50	51
29	0	59	59	60
30	0	0	0	0

CHICOT AQUIFER
LAYER 3
Value = Number x 100

ROW OF MODEL (N-S) \ COLUMN OF MODEL (W-E)	1	2	3	4
1	0	1	1	1
2	1	1	1	1
3	2	3	5	7
4	3	3	7	12
5	10	13	16	20
6	10	13	16	20
7	10	13	15	18
8	10	13	15	18
9	12	17	21	26
10	20	24	27	31
11	30	33	36	39
12	44	46	49	51
13	58	59	60	61
14	86	84	82	79
15	94	92	89	87
16	105	103	102	101
17	115	113	111	109
18	126	124	121	118
19	128	125	121	118
20	131	126	121	117
21	137	133	130	127
22	140	135	131	126
23	144	137	131	125
24	159	157	154	152
25	174	173	171	169
26	173	171	169	167
27	173	172	170	168
28	172	169	167	164
29	170	166	163	159
30	67	67	73	76

CLAYS
LAYER 4
Value = Number x 0.01

ROW OF MODEL (N-S) \ COLUMN OF MODEL (W-E)	1	2	3	4
1	0	0	0	0
2	0	1	1	1
3	0	3	3	3
4	0	4	5	5
5	0	8	10	12
6	0	8	10	12
7	0	12	15	17
8	0	13	16	18
9	0	15	20	24
10	0	18	24	31
11	0	47	49	51
12	0	61	61	61
13	0	63	64	64
14	0	76	78	81
15	0	79	82	85
16	0	93	96	99
17	0	105	106	108
18	0	109	112	114
19	0	118	121	125
20	0	120	124	128
21	0	135	138	141
22	0	140	144	148
23	0	154	159	164
24	0	155	157	159
25	0	151	153	154
26	0	149	150	150
27	0	98	111	124
28	0	101	114	127
29	0	105	119	133
30	0	0	0	0

Transmissivity values in (ft)(ft)/day.
Refer to Figure I-5 for location of row and column.

Figure III-8 ESTIMATED STORAGE COEFFICIENT VALUES BY GRID CELLS IN THE WESTERN EXTENSION AREA

EVANGELINE AQUIFER
LAYER 1
Value = Number x 0.0001

ROW OF MODEL (N-S)	1	2	3	4
1	-1	-1	-1	-1
2	-1	616	433	250
3	-1	80	60	40
4	-1	80	60	40
5	-1	38	25	13
6	-1	38	25	13
7	-1	6	5	4
8	-1	6	5	4
9	-1	4	4	4
10	-1	4	4	4
11	-1	4	4	4
12	-1	4	4	4
13	-1	4	4	4
14	-1	4	4	4
15	-1	4	4	4
16	-1	4	4	4
17	-1	4	5	5
18	-1	4	5	5
19	-1	5	5	5
20	-1	5	5	5
21	-1	5	5	5
22	-1	5	5	5
23	-1	5	5	5
24	-1	5	5	5
25	-1	5	5	5
26	-1	5	5	5
27	-1	5	5	5
28	-1	5	5	5
29	-1	5	5	5
30	-1	-1	-1	-1

COLUMN OF MODEL (W-E)

CLAYS
LAYER 2
Value = Number x 0.0001

ROW OF MODEL (N-S)	1	2	3
1	4	5	5
2	4	5	5
3	6	7	9
4	6	8	9
5	9	10	12
6	9	10	12
7	11	12	14
8	11	13	14
9	13	15	16
10	13	15	17
11	17	19	20
12	18	19	21
13	18	19	21
14	18	20	21
15	18	20	22
16	18	21	23
17	18	21	24
18	18	21	25
19	15	18	22
20	15	18	21
21	15	18	20
22	15	18	20
23	14	17	20
24	14	17	20
25	14	17	20
26	14	17	20
27	20	20	19
28	20	21	21
29	23	24	25
30	23	24	25

COLUMN OF MODEL (W-E)

CHICOT AQUIFER
LAYER 3
Value = Number x 0.0001

ROW OF MODEL (N-S)	1	2	3	4
1	-1	-1	-1	-1
2	-1	300	300	300
3	-1	600	700	800
4	-1	600	700	800
5	-1	1400	1300	1200
6	-1	1400	1300	1200
7	-1	1333	1167	1000
8	-1	1333	1167	1000
9	-1	1000	1000	1000
10	-1	1000	1000	1000
11	-1	1133	1067	1000
12	-1	1067	1033	1000
13	-1	1067	1033	1000
14	-1	1000	1000	1000
15	-1	1000	1000	1000
16	-1	1000	1000	1000
17	-1	1000	1000	1000
18	-1	1000	1000	1000
19	-1	667	583	500
20	-1	667	583	500
21	-1	425	350	275
22	-1	425	350	275
23	-1	350	200	50
24	-1	467	433	400
25	-1	467	433	400
26	-1	467	433	400
27	-1	283	167	50
28	-1	283	167	50
29	-1	62	43	25
30	-1	-1	-1	-1

COLUMN OF MODEL (W-E)

CLAYS
LAYER 4
Value = Number x 0.0001

ROW OF MODEL (N-S)	1	2	3
1	0	0	0
2	0	0	0
3	1	1	1
4	2	2	2
5	2	3	4
6	2	3	4
7	3	4	6
8	4	5	6
9	6	7	9
10	9	10	12
11	13	15	17
12	21	21	21
13	23	23	23
14	27	28	28
15	28	29	30
16	29	31	34
17	27	31	34
18	24	30	35
19	28	34	39
20	30	35	41
21	38	42	47
22	41	45	50
23	45	50	54
24	49	51	54
25	52	53	53
26	50	51	52
27	49	48	47
28	53	51	49
29	58	55	52
30	58	55	52

COLUMN OF MODEL (W-E)

Storage Coefficient values are dimensionless.
Refer to Figure I-5 for location of row and column.

southern part of the extension area. The storage coefficients for the Evangeline aquifer are representative of artesian conditions in the central and southern parts of the extension area and of semi-artesian conditions in the very northern part of the extension area.

- Leakance Estimates - Leakance is a parameter in a layered system that controls the amount of interlayer flow and can be calculated as the vertical permeability of the intervening aquitard divided by its thickness. From this definition, thinner aquitards or ones composed of clays with higher permeabilities would have higher leakance values. The information analyzed to estimate the leakance values of the Chicot and Evangeline aquifers and the alternating clay layers included data from the USGS and HGCSD models. The leakance values in the USGS model were used, with slight modification in the northern part of the extension area. The USGS leakance values were raised slightly in the northern part of the extension area to be compatible with the values and trend in values in the grid cells just to the east in the HGCSD model. The leakance values are shown on Figure III-9. The leakance values are generally higher in the northern part of the extension area in the outcrop of the Chicot and near the outcrop area of the Evangeline. The leakance values are lower to the south where the strata thicken.

- Groundwater Head Estimates - The information analyzed to estimate the initial (1900) head values of the near surface water table, the Chicot and Evangeline aquifers, and the alternating clay layers included data from the HGCSD model and land surface elevations derived from topographic maps. Land surface elevation data were important because, in general, especially in the northern part of the extension area, the heads in the near surface water table should approximate the land surface elevations and change with the changes in the elevations. The USGS model set the initial 1890 through 1900 head in every layer at the same value and thus, did not estimate different head values for the individual layers relative to sea level as was done in the HGCSD model. The head data in the USGS model, therefore, were not helpful in estimating the heads in the model layers in the Western Extension Area. The information analyzed to estimate the 1960 head values of the near surface water table, the Chicot and Evangeline aquifers, and the alternating clay layers included data from the HGCSD model and historical water-level data from the USGS and TWDB for the aquifers within and near the Western Extension Area.

  Estimated initial (1900) heads for the model layers in the extension area are shown in Figure III-10. The values were estimated by extrapolating the values in the HGCSD model into the extension area and adjusting them to be compatible with changes in land surface elevations. The heads generally decrease going from north to south in the extension area as the land surface slopes down toward the coastline. The heads also decrease from east to west in the northern part of the extension area, where the land slopes westward toward the Brazos River bottom.

Figure III-9 ESTIMATED LEAKANCE VALUES BY GRID CELLS IN THE WESTERN EXTENSION AREA

LOWER CLAYS/EVANGELINE

Value = Number x 1 x E-11

ROW OF MODEL (N-S)	1	2	3	4
1	0	0	0	0
2	0	89	83	76
3	0	57	53	49
4	0	52	49	46
5	0	42	40	38
6	0	40	39	38
7	0	36	35	34
8	0	34	34	33
9	0	29	28	28
10	0	27	27	27
11	0	22	23	23
12	0	25	25	24
13	0	24	23	23
14	0	22	21	21
15	0	21	20	20
16	0	20	19	18
17	0	20	18	17
18	0	21	19	18
19	0	23	21	20
20	0	23	21	20
21	0	24	22	21
22	0	24	22	20
23	0	25	23	21
24	0	25	24	22
25	0	24	23	22
26	0	24	23	22
27	0	23	23	22
28	0	21	21	20
29	0	18	18	17
30	0	0	0	0

COLUMN OF MODEL (W-E)

CHICOT/LOWER CLAYS

Value = Number x 1 x E-11

ROW OF MODEL (N-S)	1	2	3	4
1	0	0	0	0
2	0	170	126	126
3	0	103	87	86
4	0	103	86	86
5	0	94	88	88
6	0	94	88	88
7	0	99	90	90
8	0	99	90	90
9	0	99	90	90
10	0	87	90	90
11	0	72	71	71
12	0	53	55	56
13	0	48	50	52
14	0	42	43	45
15	0	37	37	38
16	0	32	31	31
17	0	32	31	29
18	0	32	30	28
19	0	37	34	32
20	0	38	35	33
21	0	39	36	33
22	0	40	37	33
23	0	40	36	33
24	0	40	38	35
25	0	38	37	35
26	0	38	37	36
27	0	38	37	37
28	0	34	33	33
29	0	29	28	28
30	0	0	0	0

COLUMN OF MODEL (W-E)

UPPER CLAYS/CHICOT

Value = Number x 1 x E-11

ROW OF MODEL (N-S)	1	2	3	4
1	0	0	0	0
2	0	1000	1000	1000
3	0	494	476	457
4	0	411	387	363
5	0	217	178	138
6	0	200	165	131
7	0	139	118	97
8	0	134	112	91
9	0	126	100	74
10	0	81	68	55
11	0	36	33	31
12	0	26	26	25
13	0	24	24	24
14	0	22	21	21
15	0	21	20	20
16	0	21	20	18
17	0	20	18	17
18	0	19	18	17
19	0	17	16	15
20	0	15	15	14
21	0	13	13	13
22	0	12	12	12
23	0	11	11	11
24	0	11	11	11
25	0	12	12	12
26	0	12	12	12
27	0	13	13	13
28	0	11	14	14
29	0	11	13	13
30	0	0	0	0

COLUMN OF MODEL (W-E)

WATER TABLE/UPPERCLAYS

Value = Number x 1 x E-11

ROW OF MODEL (N-S)	1	2	3	4
1	0	0	0	0
2	0	1000	1000	1000
3	0	425	400	375
4	0	303	282	260
5	0	180	94	80
6	0	140	81	69
7	0	68	54	45
8	0	68	36	31
9	0	48	23	20
10	0	22	19	17
11	0	12	11	11
12	0	12	11	11
13	0	14	13	13
14	0	16	16	16
15	0	18	18	17
16	0	10	11	12
17	0	7	8	8
18	0	7	6	6
19	0	4	3	3
20	0	3	3	3
21	0	3	2	2
22	0	2	2	2
23	0	4	4	4
24	0	5	5	5
25	0	6	6	6
26	0	5	5	5
27	0	2	2	2
28	0	2	2	2
29	0	2	2	2
30	0	0	0	0

COLUMN OF MODEL (W-E)

Leakance values in 1/seconds.
Refer to Figure I-5 for location of row and column.

Figure III-10 ESTIMATED STARTING HEADS (1900) BY GRID CELLS IN THE WESTERN EXTENSION AREA

EVANGELINE AQUIFER LAYER 1

Value = Number x 1

ROW OF MODEL (N-S)	1	2	3
1	195	245	290
2	245	265	285
3	244	253	275
4	240	248	269
5	215	235	260
6	200	220	240
7	178	198	218
8	170	190	204
9	155	162	184
10	146	152	167
11	147	143	152
12	147	142	147
13	145	140	138
14	140	136	137
15	140	137	135
16	135	134	133
17	134	133	132
18	132	130	128
19	129	126	123
20	125	118	118
21	121	118	113
22	117	112	107
23	96	99	102
24	92	95	100
25	87	92	98
26	88	87	92
27	86	85	84
28	84	83	82
29	82	80	79
30	79	77	75
	1	2	3

COLUMN OF MODEL (W-E)

EVANGELINE/CHICOT CLAYS LAYER 2

Value = Number x 1

ROW OF MODEL (N-S)	1	2	3
1	197	247	293
2	248	267	288
3	246	254	277
4	242	249	271
5	221	240	261
6	205	224	240
7	179	199	219
8	165	185	202
9	152	161	182
10	143	151	166
11	146	144	151
12	146	141	146
13	143	138	137
14	139	135	136
15	138	135	134
16	134	133	132
17	133	132	131
18	131	129	127
19	128	125	122
20	124	119	117
21	120	117	112
22	116	111	106
23	95	98	101
24	91	94	99
25	86	91	97
26	87	86	91
27	84	83	82
28	82	80	79
29	80	78	77
30	78	76	73
	1	2	3

COLUMN OF MODEL (W-E)

CHICOT AQUIFER LAYER 3

Value = Number x 1

ROW OF MODEL (N-S)	1	2	3
1	200	250	295
2	250	270	290
3	250	255	280
4	245	250	273
5	228	245	262
6	210	228	240
7	180	200	220
8	160	180	200
9	150	160	180
10	140	150	165
11	145	145	150
12	145	140	145
13	142	135	135
14	138	134	134
15	135	133	132
16	133	132	131
17	132	131	130
18	130	128	126
19	127	124	121
20	123	120	116
21	119	116	111
22	115	110	105
23	94	97	100
24	90	93	98
25	85	90	96
26	86	85	90
27	83	80	80
28	80	77	77
29	78	76	75
30	76	74	70
	1	2	3

COLUMN OF MODEL (W-E)

CHICOT/WATER TABLE CLAYS LAYER 4

Value = Number x 1

ROW OF MODEL (N-S)	1	2	3
1	192	242	288
2	244	264	284
3	241	250	274
4	238	242	264
5	214	232	252
6	196	216	232
7	170	190	200
8	154	174	192
9	141	154	174
10	136	144	160
11	144	140	152
12	144	138	140
13	142	134	130
14	134	127	127
15	134	128	128
16	132	130	129
17	130	129	128
18	128	124	123
19	124	119	117
20	118	116	113
21	115	113	107
22	110	106	100
23	91	94	96
24	88	90	94
25	84	88	93
26	85	82	88
27	82	78	78
28	78	76	74
29	76	73	72
30	73	71	66
	1	2	3

COLUMN OF MODEL (W-E)

WATER TABLE LAYER 5

Value = Number x 1

ROW OF MODEL (N-S)	1	2	3
1	170	240	270
2	230	250	270
3	230	240	260
4	220	220	246
5	170	190	220
6	150	180	210
7	140	160	180
8	140	160	170
9	130	140	160
10	120	130	150
11	130	120	120
12	140	130	120
13	130	130	110
14	120	100	100
15	130	110	110
16	130	120	120
17	120	115	120
18	115	110	110
19	110	100	100
20	100	100	100
21	100	100	90
22	100	90	85
23	100	95	90
24	90	90	90
25	80	80	80
26	80	70	80
27	80	70	70
28	70	70	60
29	70	60	60
30	60	60	50
	1	2	3

COLUMN OF MODEL (W-E)

Starting head values in feet above mean sea level.
Refer to Figure I-5 for location of row and column.

Water-level data for wells in the northern part of the extension area were valuable in estimating the heads in the area. The data showed that the measured 1960 heads in the Evangeline aquifer were moderately lower than had been estimated for the Evangeline aquifer for the cells just to the east of the extension area. The 1960 water-level measurements from wells that screen the Chicot aquifer in the central and southern part of the extension area were generally compatible with the 1960 Chicot heads used in the HGCSD model for the cells just to the east. The 1960 heads in the extension area were estimated by extrapolating the head values in the HGCSD model to the west and adjusting them based on historical water levels measured in wells. The estimated 1960 heads in the Western Extension Area are shown on Figure III-11.

Figure III- 11 ESTIMATED 1960 HEADS BY GRID CELLS IN THE WESTERN EXTENSION AREA

EVANGELINE AQUIFER
LAYER 1
Value = Number x 1

ROW OF MODEL (N-S)	1	2	3
1	150	180	200
2	160	170	195
3	155	167	185
4	150	155	175
5	140	150	165
6	135	145	157
7	120	131	142
8	110	118	127
9	107	109	111
10	104	106	107
11	104	101	100
12	106	101	98
13	106	101	96
14	105	100	94
15	105	101	93
16	104	100	92
17	105	98	91
18	97	91	86
19	90	84	78
20	82	75	69
21	75	68	62
22	68	62	56
23	60	56	52
24	57	53	49
25	54	50	46
26	51	47	42
27	49	44	40
28	46	42	37
29	43	39	34
30	40	36	33

COLUMN OF MODEL (W-E)

EVANGELINE/CHICOT CLAYS
LAYER 2
Value = Number x 1

ROW OF MODEL (N-S)	1	2	3
1	152	197	215
2	166	197	210
3	178	187	205
4	175	178	195
5	145	158	186
6	136	148	162
7	120	131	146
8	112	121	130
9	107	110	113
10	104	106	109
11	105	100	102
12	107	99	100
13	106	99	96
14	103	98	93
15	102	97	92
16	101	96	91
17	100	95	91
18	93	89	85
19	87	82	77
20	81	74	68
21	72	66	60
22	64	59	54
23	59	54	50
24	55	50	46
25	50	46	42
26	46	42	38
27	42	39	36
28	38	36	32
29	34	32	29
30	30	28	26

COLUMN OF MODEL (W-E)

CHICOT AQUIFER
LAYER 3
Value = Number x 1

ROW OF MODEL (N-S)	1	2	3
1	155	215	230
2	176	220	232
3	197	210	222
4	192	198	211
5	150	167	200
6	137	152	168
7	121	130	151
8	114	124	133
9	106	112	116
10	105	107	111
11	107	99	105
12	108	96	102
13	105	98	97
14	101	93	85
15	100	93	85
16	98	91	84
17	95	90	86
18	90	87	83
19	85	81	76
20	80	74	68
21	70	65	59
22	60	56	52
23	58	53	49
24	53	48	43
25	47	42	38
26	42	38	34
27	36	34	31
28	31	29	28
29	25	24	24
30	21	21	20

COLUMN OF MODEL (W-E)

CHICOT/WATER TABLE CLAYS
LAYER 4
Value = Number x 1

ROW OF MODEL (N-S)	1	2	3
1	157	223	235
2	180	229	241
3	208	217	229
4	203	205	217
5	155	179	203
6	138	156	174
7	122	130	155
8	116	127	136
9	106	114	119
10	105	108	113
11	108	98	108
12	109	94	104
13	105	95	98
14	98	91	83
15	102	92	82
16	96	95	82
17	95	90	88
18	100	83	81
19	95	75	78
20	85	78	79
21	80	75	67
22	74	70	63
23	72	69	62
24	63	57	55
25	54	51	48
26	48	46	44
27	39	38	37
28	38	37	36
29	33	32	30
30	28	28	27

COLUMN OF MODEL (W-E)

WATER TABLE
LAYER 5
Value = Number * 1

ROW OF MODEL (N-S)	1	2	3
1	160	231	240
2	185	240	250
3	220	228	238
4	215	215	225
5	160	184	210
6	140	160	180
7	123	130	160
8	118	130	140
9	106	116	122
10	105	109	115
11	110	97	111
12	110	91	106
13	105	91	99
14	95	89	78
15	105	91	80
16	94	99	80
17	95	90	90
18	111	80	80
19	105	70	80
20	90	83	90
21	90	85	75
22	88	85	75
23	87	85	76
24	74	67	67
25	62	66	66
26	53	61	72
27	40	60	65
28	54	49	43
29	52	45	43
30	29	42	40

COLUMN OF MODEL (W-E)

Head values in feet above mean sea level.
Refer to Figure I-5 for location of row and column.

Projection Methodology

The projection of water demands was accomplished by translating the projected 2030 urbanized land into an incremental increase in water demand for each grid cell. The incremental demands were then combined with the 1986 demand scenario to develop the 2030 demand projection. Interim year demands were then interpolated on ten-year horizons.

To develop the 2030 demands, an average demand factor of 810 gpad, which was derived from the 1986 data, was applied to the projected land use in each grid cell to determine the increase in public water demand. Allowances were made for heavy-industrial growth by projecting industrial acreage with a heavy-industrial growth rate similar to that derived by HWMP. The projected acreage was subsequently excluded from the public demand calculations.

Based on the water demand factor analysis discussed in Section III, three sets of existing demand factors were identified within the study area. For areas with concentrated high-density residential and commercial developments, such as downtown and the Texas Medical Center, demand factors are ranging from 1,500 gpd to 9,500 gpd. For major single-family housing developments, such as Copperfield, Kingwood, First Colony, etc., a demand factor of 1,300 gpad was estimated. For other general areas, a demand factor of 727 gpad was used. Since the study area generally has no zoning requirements, it is not feasible to pinpoint where various types of land developments will occur. For this reason, a single demand factor is used to estimate future demand in the projected growth area. Based on the result of the existing demand analysis and considering the impact of water conservation, the 810-gpad factor was judged to best represent the character of the projected development and was used with projected incremental land-use data to calculate future public demands.

The growth in heavy-industrial demand was based on projections developed by HWMP. The demand projections were first converted from a population base to a land-use base. Refinements were then made to more accurately reflect the character of the heavy-industrial demand on a census tract level. The 2030 heavy-industrial demand projections were determined by utilizing the GIS to apply the census tract demand factors to the projected land use in each grid cell.

The 1986 agricultural pumpage (demand) was reduced relative to the amount of land in a grid cell converted from agricultural to developed land. The rural population density used in the calculation of the rural domestic demand was increased from 0.11 to 0.20 persons per acre based on the projected population growth in several rural census tracts in the study area. The 2030 total water demand in a grid cell was then determined by combining the 1986 demands with the increase (or decrease) in public, heavy-industrial, and agricultural demand.

Over the last five years, water consumption in the study area was affected by several factors. Water demands were affected by population growth of approximately 2 percent per year within HGCSD and water conservation measures which reduced demand by 1 to 1.5 percent. In addition, climatic conditions cause an inherent year to year variability in demand. However, the growth in water demand followed a generally increasing trend. Consequently, the 1990 total water demands within the HGCSD jurisdictional boundary were derived by performing a linear regression analysis on the last five years (1985-1989) of recorded groundwater pumpage and combining the result with the existing surface water consumption.

A 2010 demand scenario was interpolated from the 1986 and 2030 demands, assuming that development would continue to be concentrated in areas which have shown substantial growth in the last 20 years. The grid cells containing Kingwood, First Colony, Cinco Ranch, Copperfield, Champions, The Woodlands, and Clear Lake City were increased to 90 percent of their projected 2030 demand. The remaining grid cells in the study area were required to grow at a reduced rate to maintain the average 2010 demand (demand determined by straight-line interpolation) in the study area as a whole. The 2000 and 2020 interim year total water demands were then interpolated from the 1990, 2010, and 2030 demand projections.

Total Projected Demands

The total 2030 projected water demand, less agricultural surface water, for the study area are shown by county in Figure IV-1 and Table IV-1. The total water demand in the study area increased from 393,458 mgy in 1986 to 765,560 mgy which represents an increase of 95 percent. The total water demand growth trend for the entire study area is shown in Figure IV-2. Harris County consumed 259,044 mgy of water in 1986 and will require 449,846 mgy of water by 2030. Likewise, the total water demand in Galveston County will increase from 31,128 mgy to 128,036 mgy and from 29,174 mgy to 65,536 mgy in Fort Bend County during the next 44 years.

Demands Met By Surface Water

The expansion of surface water from 1990 to 2030 was assumed to consist of the full utilization of the City of Houston's EWPP and the SEWPP with its 96-inch supply line. The increased surface water supply was allocated to census tracts at 1990 demand levels using the same methodology as was employed in 1986. The census tracts receiving the increase in surface water were defined by the known contracts for water from EWPP and SEWPP and the configuration of the City of Houston's distribution system.

The total capacity of both EWPP and SEWPP was assumed to be available. All water not currently under contract was allocated to the City of Houston's distribution system. Groundwater wells in Galveston County and areas around the Houston Ship Channel were assumed to reduce pumping when the service area which they supplied was significantly impacted by surface water. In addition, municipalities such as Bellaire, West University, Soutside Place, Bunker Hill Village, Piney Point Village, Hedwig Village, Hunters Creek Village, Spring Valley, and Hilshire were assumed to convert from groundwater to surface water based on existing HGCSD regulations.

The full increase in surface water was assumed to occur after the year 1990, but before 2000. Beyond the year 2000, no further surface water supplies were assumed allowing latitude for HGCSD to incorporate surface water expansions as they occur and better evaluate the RAP. It should be noted that the surface water scenario presented

TABLE IV-1 2030 DEMAND SUMMARY

COUNTY	PUBLIC DEMAND	AGRICULTURAL DEMAND	RURAL DOMESTIC DEMAND	TOTAL WATER DEMAND	SURFACE WATER DEMAND	UNFULFILLED DEMAND
HARRIS	444,417	4,958	471	449,846	182,149	267,697
GALVESTON	127,727	19	290	128,036	30,517	97,519
FORT BEND	54,463	8,742	2,331	65,536	3,944	61,592
BRAZORIA	27,075	1,382	3,741	32,198	8,620	23,578
WALLER	2,905	7,494	1,845	12,244	0	12,244
MONTGOMERY	28,989	0	183	29,172	0	29,172
LIBERTY	7,123	5,197	3,035	15,355	212	15,143
CHAMBERS	15,725	221	1,596	17,542	4,777	12,765
MATAGORDA	338	2,770	992	4,100	0	4,100
WHARTON	1,655	5,708	1,583	8,946	0	8,946
GRIMES	0	4	142	146	0	146
JEFFERSON	146	0	368	514	0	514
HARDIN	602	0	583	1,185	0	1,185
AUSTIN	179	11	550	740	0	740
TOTAL	711,344	36,506	17,710	765,560	230,219	535,341

All values in million gallons per year.

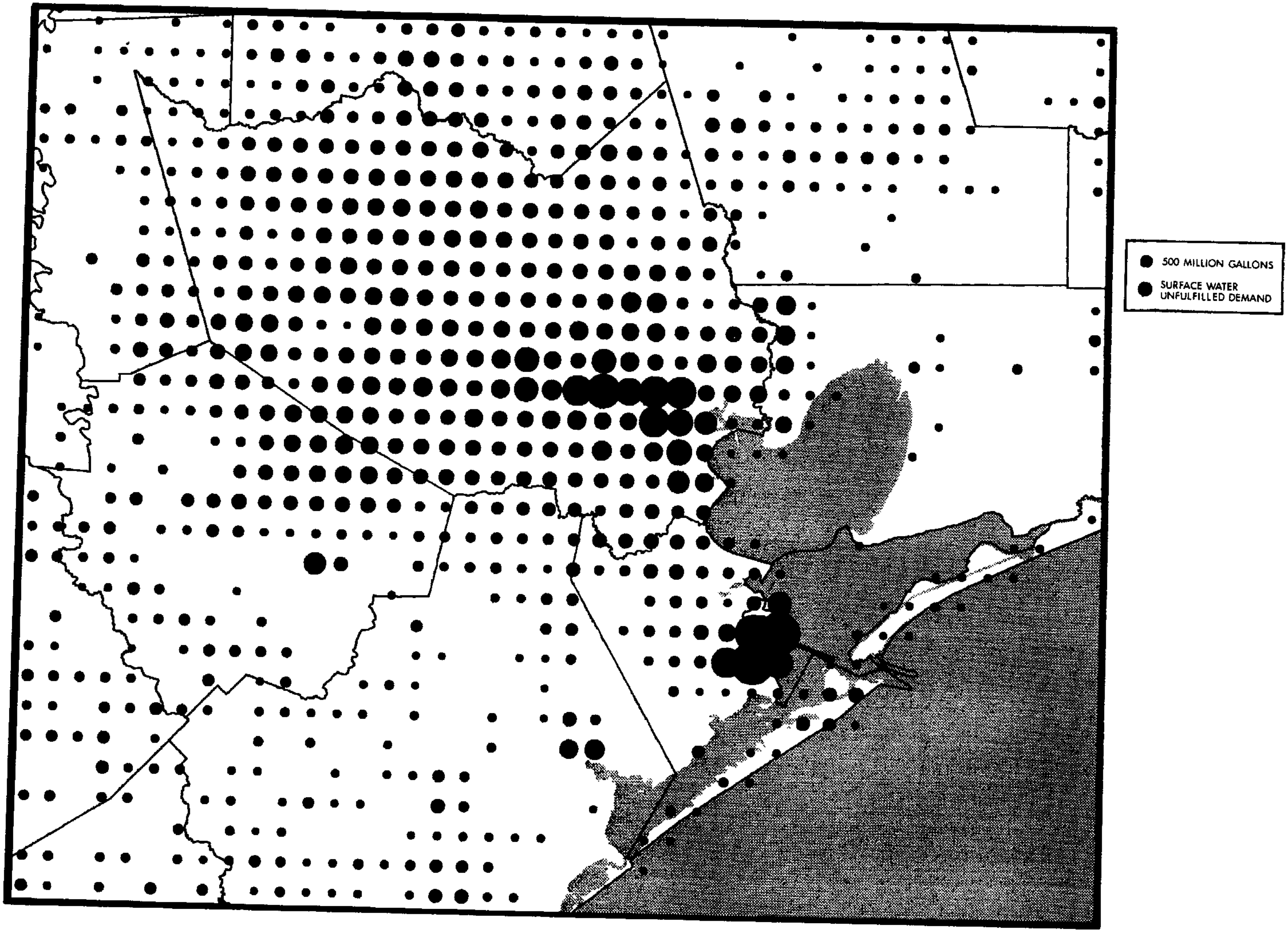
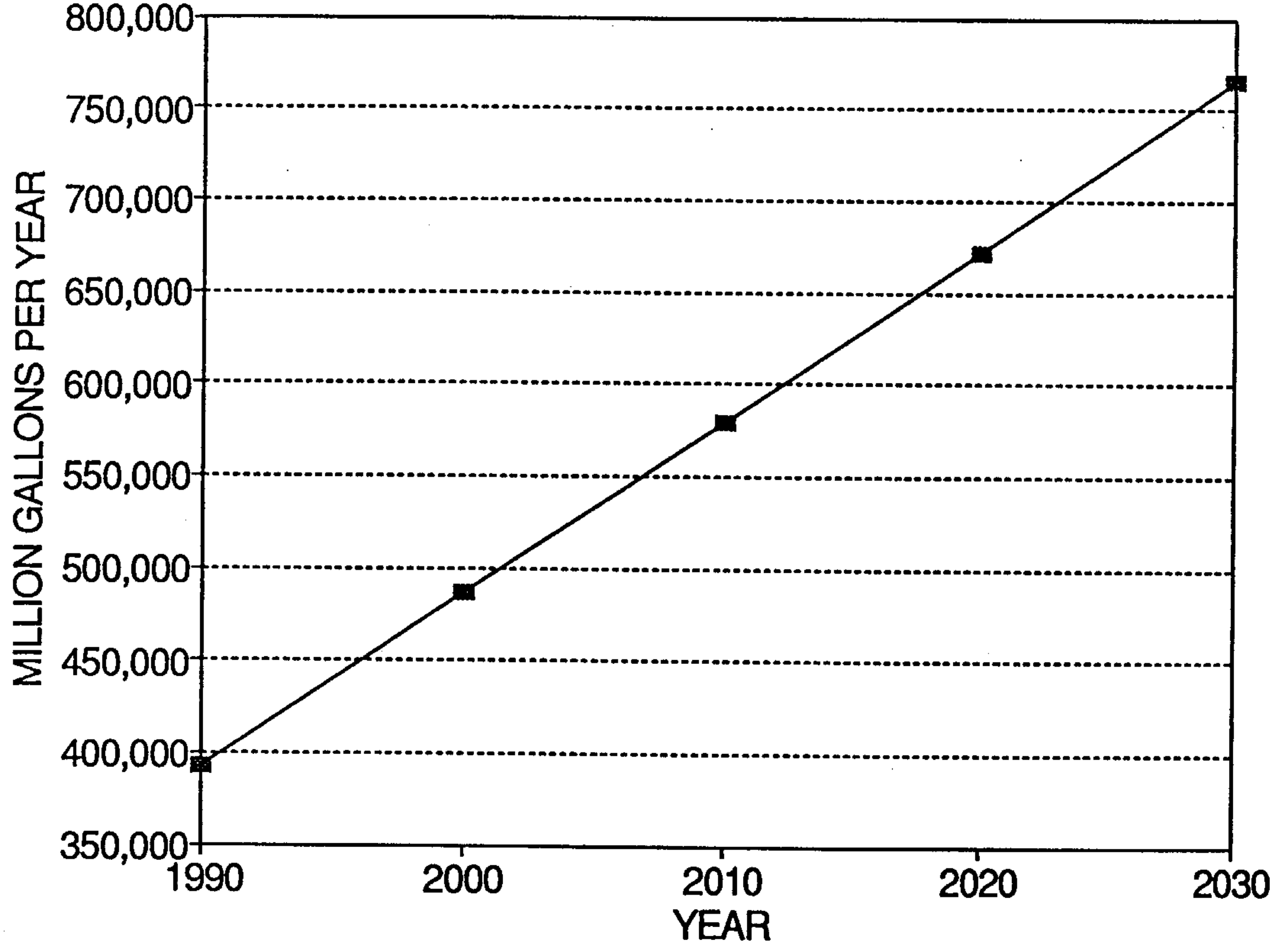


FIGURE IV-1 2030 TOTAL WATER DEMAND

Figure IV-2 TOTAL WATER DEMAND PROJECTION FOR STUDY AREA



above is most likely to be modified as HGCSD continues to evaluate the impact of subsidence from future water demands and the need to refine its 1985 District Plan.

Unfulfilled Demands

The unfulfilled water demand in a grid cell was defined as the total water demand less the agricultural/irrigation groundwater pumpage and the surface water supply. It represents the portion of the total water demand potentially supplied by groundwater.

The unfulfilled demands were determined by assuming that 1986 importing and exporting values would remain constant in grid cells not affected by surface water. Surface water was allowed to supply demand and reduce the amount of groundwater imported to a grid cell. Exporting grid cells were reduced based on the amount of surface water allocated relative to the total water demand. Several City of Houston well fields were assumed to stop or reduce exporting groundwater to adjacent cells when surface water becomes available.

Adjustments were made to future year demands to account for salt domes or water quality problems which limit the amount of groundwater which can be pumped from some cells. Affected cells were assumed to maintain 1986 groundwater pumpage levels and acquire groundwater from adjacent cells with the capability to export the required amount of water.

The year 2000 unfulfilled demand scenario was developed by interpolating between a hypothetical 1990 demand scenario, which included full surface water development and 1990 total water demands, and the 2010 demand scenario. The 2020 unfulfilled demands were calculated by straight-line interpolation between the 2010 and 2030 demands. The unfulfilled demand projections are summarized in Table IV-2.

Projected Aquifer Ratios

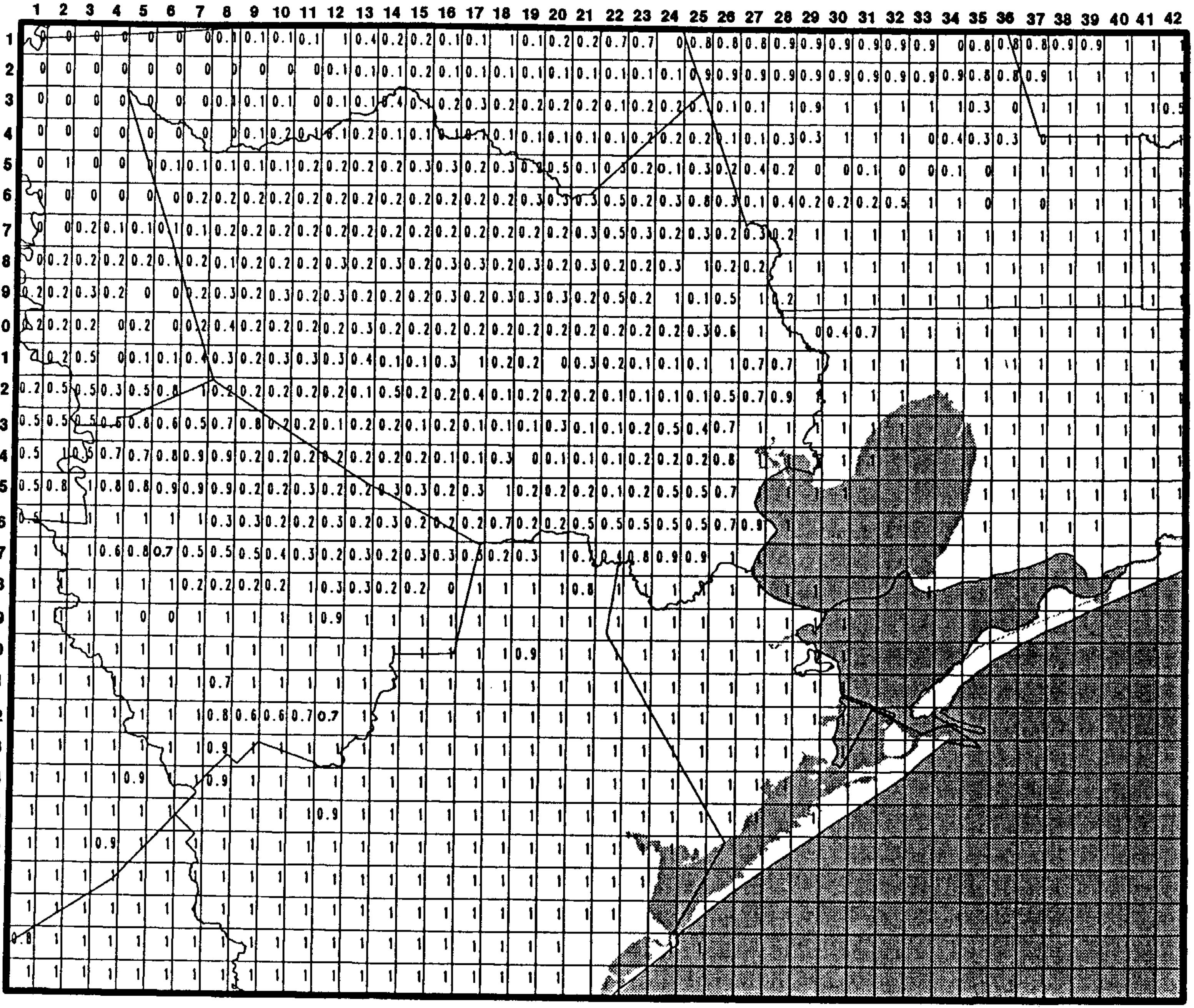
Aquifer ratios were estimated for the entire model area for 1986 and 2030. Aquifer ratios were then interpolated for the intervening years of 1990, 2000, 2010, and 2020 using values estimated for 1986 and 2030. The projected aquifer ratios for 2030 were estimated utilizing the 1986 ratios, past pumpage in each cell and estimates of future unfulfilled demand in the cell, aquifer transmissivity, aquifer thicknesses containing fresh water, aquifer potentiometric head data for the model area, and work maps outlining areas of poor quality water. Pumpage data for 1980 and 1986 and the projected demand for water in 2030 in each cell were examined to assess whether and how the use and demand for water was changing. Values of transmissivity for the cells in the USGS and HGCSD models were reviewed to estimate the individual and relative magnitudes of the transmissivities of the two aquifers. Information on the fresh water thickness in the Chicot and Evangeline aquifers was examined to help determine the relative quantity of fresh water in a cell. General potentiometric head and individual well water-level data for the Chicot and Evangeline aquifers were reviewed to help evaluate the available drawdown in each of the aquifers. Work maps outlining areas of poor quality water, such as areas near salt domes, were reviewed in order to identify grid cells in which future pumpage should probably be limited. Professional judgement was then used in combination with the available data to estimate the future aquifer ratios.

As examples, if the pumpage in a cell was estimated to remain relatively stable from 1986 through 2030 and if the division of the 1986 pumpage between the Chicot and Evangeline aquifers was reasonable, based on the values of transmissivity and fresh water thickness for the two aquifers, then the aquifer ratio in that cell normally was estimated to remain relatively constant. If the demand for water in a cell was estimated to increase significantly and the potential of the Chicot or Evangeline aquifer to supply water was previously under-utilized, then the aquifer ratio in that cell was adjusted accordingly.

Numerous salt domes exist in the model area. The domes are structures composed predominantly of halite (common salt) that have moved upward through geologic time from the subsurface toward land surface. The domes can and have, in many instances, influenced the depths to the base of fresh water and the availability of groundwater in their proximity. The estimated effects of the domes upon the aquifers were taken into consideration when estimating the future aquifer ratios that would be applicable for the cells located near the domes.

The estimated aquifer ratios for 2030 are shown on Figure IV-3. The projected aquifer ratios for 2030 are generally slightly higher for the central and north parts of Harris County than the ratios estimated for 1986. The 2030 ratios were increased in these areas because of the significant increases in estimated unfulfilled demand for the area and the possibility that some additional water would be obtained from the Chicot aquifer. The estimated ratios for 2030 in the east part of Fort Bend County also increased slightly over the 1986 values as the result of estimates of increased unfulfilled demand for the area. The 2030 aquifer ratios for much of the south and southeast part of the model area remained equal to one, as there is no formation other than the Chicot in these parts of the model area that is capable of providing fresh groundwater.

The estimated increases in unfulfilled water demand from 1986 until 2030 are so significant in some parts of the model area that it would not be practical to attempt to obtain all of the demands from the groundwater system. Groundwater pumpage will have to be less than the estimated high unfulfilled demands given in this report for part of the model area. The groundwater model should be run using the unfulfilled water demands given in this report, or a percentage of the demands, and then review how the simulated aquifer responds regarding estimated water-level declines and land subsidence. The pumpage can then be adjusted in various areas by using judgement to arrive at reasonable drawdowns for the aquifers. This iterative process will probably need to be repeated several times to arrive at a reasonable areal distribution of the maximum practical pumpage that does not induce excessive drawdown in the aquifers or unacceptable subsidence. Several different combinations of amounts of pumpage and areal distribution of pumpage should be tried along with slight modification of the aquifer ratios. Also, as future pumpage and pumpage patterns within the model area change from the present estimates, it will be advisable to re-evaluate the aquifer ratios for the model cells and adjust them to represent the actual future conditions.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
1	0	0	0	0	0	0	0	0.1	0.1	0.1	0.1	1	0.4	0.2	0.2	0.1	0.1	1	0.1	0.2	0.2	0.7	0.7	0	0.8	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0	0.8	0.8	0.8	0.9	0.9	1	1	1
2	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.8	0.9	1	1	1	1	1
3	0	0	0	0	0	0	0	0.1	0.1	0.1	0	0.1	0.1	0.4	0.1	0.2	0.3	0.2	0.2	0.2	0.2	0.1	0.2	0.2	[illegible]	0.1	0.1	1	0.9	1	1	1	1	1	0.3	0	1	1	1	1	1	0.5
4	0	0	0	0	0	0	0	0	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.3	0.3	1	1	1	0	0.4	0.3	0.3	0	1	1	1	1	1
5	0	1	0	0	0	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.2	0.3	[illegible]	0.5	0.1	0.3	0.2	0.1	0.3	0.2	0.4	0.2	0	0	0.1	0	0	0.1	0	1	1	1	1	1	1	1
6	0	0	0	0	0	0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.5	0.2	0.3	0.8	0.3	0.1	0.4	0.2	0.2	0.2	0.5	1	1	0	1	0	1	1	1	1	1
7	0	0	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.5	0.3	0.2	0.3	0.2	0.3	0.2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8	0	0.2	0.2	0.2	0.2	[illegible]	0.2	0.1	0.2	0.2	0.2	0.3	0.2	0.3	0.2	0.3	0.3	0.2	0.3	0.2	0.3	0.2	0.2	0.3	1	0.2	0.2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
9	0.2	0.2	0.3	0.2	0	0	0.2	0.3	0.2	0.3	0.2	0.3	0.2	0.2	0.2	0.3	0.2	0.3	0.3	0.3	0.2	0.5	0.2	1	0.1	0.5	1	0.2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	0.2	0.2	0.2	0	0.2	0	0.2	0.4	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.6	1	1	0	0.4	0.7	1	1	1	1	1	1	1	1	1	1	1
11		0.2	0.5	0	0.1	0.1	0.4	0.3	0.2	0.3	0.3	0.3	0.4	0.1	0.1	0.3	1	0.2	0.2	0	0.3	0.2	0.1	0.1	0.1	1	0.7	0.7	1	1	1	1		1	1	1	1	1	1	1	1	1
12	0.2	0.5	0.5	0.3	0.5	0.8	1	0.2	0.2	0.2	0.2	0.2	0.1	0.5	0.2	0.2	0.4	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.5	0.7	0.9	1	1	1	1			1	1	1	1	1	1	1	1
13	0.5	0.5	0.5	0.6	0.8	0.6	0.5	0.7	0.8	0.2	0.2	0.1	0.2	0.2	0.1	0.2	0.1	0.1	0.1	0.3	0.1	0.1	0.2	0.5	0.4	0.7	1	1	1	1	1	1			1	1	1	1	1	1	1	1
14	0.5	1	0.5	0.7	0.7	0.8	0.9	0.9	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.3	0	0.1	0.1	0.1	0.2	0.2	0.2	0.8	1	1	1	1	1				1	1	1	1	1	1	1	1
15	0.5	0.8	1	0.8	0.8	0.9	0.9	0.9	0.2	0.2	0.3	0.2	0.2	0.3	0.3	0.2	0.3	1	0.2	0.2	0.2	0.1	0.2	0.5	0.5	0.7		1	1	1					1	1	1	1	1	1	1	1
16	0.5	1	1	1	1	1	1	0.3	0.3	0.2	0.2	0.3	0.2	0.3	0.2	0.2	0.2	0.7	0.2	0.2	0.5	0.5	0.5	0.5	0.5	0.7	0.9	1							1		1	1	1			
17	1	1	1	0.6	0.8	0.7	0.5	0.5	0.5	0.4	0.3	0.2	0.3	0.2	0.3	0.3	[illegible]	0.2	0.3	1	[illegible]	0.4	0.8	0.9	0.9	1	1															
18	1	1	1	1	1	1	0.2	0.2	0.2	0.2	1	0.3	0.3	0.2	0.2	0	1	1	1	1	0.8	1	1	1	1	1	1	1	1				1									
19	1	1	1	1	0	0	1	1	1	1	1	0.9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1												
20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.9	1	1	1	1	1	1	1	1	1		1												
21	1	1	1	1	1	1	1	0.7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1													
22	1	1	1	1	1	1	1	0.8	0.6	0.6	0.7	0.7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1													
23	1	1	1	1	1	1	1	0.9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1														
24	1	1	1	1	0.9	1	1	0.9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1														
25	1	1	1	1	1	1	1	1	1	1	1	0.9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1													
26	1	1	1	0.9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1																				
27	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1																			
28	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1																				
29	0.8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1																						
30	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1																						

Figure IV-3 ESTIMATED 2030 AQUIFER RATIOS BY GRID CELL

Conclusions

- Study area population is projected to increase by 136 percent, from 3,145,000 in 1980 to 7,415,000 in 2030 at an annual compounded growth rate of 1.7 percent.
- Northern Fort Bend County and western Harris County are forecasted to be the areas of the most substantial population growth.
- The 1986 water demand in the study area was estimated to be 393,458 mgy. Approximately 45 percent of the demand was supplied by surface water and remaining 55 percent of the demand by groundwater.
- The study area water demand is forecasted to increase to 765,341 mgy in the year 2030.
- Water conservation measures have resulted in reductions in demand of approximately 1 percent per year during the last decade.
- Climatic conditions were found to cause variations of 5 percent to 10 percent in pumpage amounts.
- Land-use-based water demand factors derived for the study area were as follows:
    - 727 gpad for typical mix of residential, multifamily, commercial, and industrial development.
    - 1,500 to 9,500 gpad for areas of unusually high concentration of multifamily or commercial development.
    - 1,300 gpad for major single-family housing developments.
    - 3,500 to 24,000 gpad for heavy-industrial usage.
    - 150 to 500 gpad for rural communities.
    - 100 gpad for rural domestic development (single house).
    - 810 gpad for future developed land use.

APPENDIX A - DEVELOPMENT OF PRESS MODELS FOR FORT BEND COUNTY

As a result of the interlocal agreement executed between HGCSD and FBSD, the original scope of services of the Regional Water Supply Planning Study described in this report was amended to include the collection of data for the Western Extension Area. In addition, the development and calibration of four compaction analysis sites, to be used as input to the HGCSD PRESS model, was included in the study. The following pages document the development of the PRESS model compaction analysis sites and present the results of the calibration procedures.

GEO ASSOCIATES

Geotechnical Engineering & Groundwater Consulting

REPORT OF THE

FORT BEND COUNTY SUBSIDENCE MODELING STUDY

prepared for

Turner Collie & Braden, Inc.
Houston, Texas

October 1990

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Scope of Study

The scope of the study for modeling subsidence for four sites (hereinafter called "subsectors") within Ft. Bend County, Texas, included the following major items:

1. Collecting available data with respect to: a) groundwater potentiometric surface elevation history; b) stratigraphy from ground surface through the pumped aquifer(s); and c) historic benchmark releveling data.
2. Establishing computer models of stratigraphy and compressibility characteristics using the PRESS model basis as developed previously for the HGCSD. The subsector locations were discussed with and approved by the HGCSD staff.
3. Calibrating the PRESS models to available subsidence history records, such as benchmark releveling data, using historic aquifer potentiometric surface elevation history as the driving mechanism.
4. Consulting with the staff of the HGCSD and preparing the necessary "transition" model into each of the PRESS models noted above.
5. Incorporating findings of the study into a written report; preparing the data on magnetic media and in a format compatible with the modeling system of the HGCSD.

Subsectors Modeled

The subsectors modeled consisted of geographically identifiable areas using USGS 7-1/2 minute topographic maps as the base. Each topographic map is divisible into ninths, each ninth measuring 2-1/2 minutes latitude by 2-1/2 minutes longitude. These divisions are used by the Texas Water Development Board for well numbering purposes in Texas. The state well numbering system has been used to identify the ninths included in each subsector on Table 1.

Table 1

Ninth's of Quads Included in Subsector Models

NAME	NINTH'S OF QUADS INCLUDED	REFERENCE USGS TOPOGRAPHIC MAPS
Arcola	65-29-5 65-29-7 65-29-8	Almeda
Needville	65-34-7 65-42-1 65-42-2	Needville Guy
Richmond-Rosenberg	65-26-5 65-26-6	Richmond
Smithers Lake	65-35-3 * 65-36-1	Smithers Lake Thompsons

* *Releveling data from 65-35-2 is included to obtain 1943 releveling data points*

The subsector locations modeled for this study are shown on Exhibit 1 and identified by name and state well numbers. Not shown on this exhibit are two subsector models previously developed for Katy (65-10-5, 65-10-8, 65-10-9) and Bellaire West (65-20-4) in the HGCSD Phase II Water Management Study. These two subsectors partially overlap Ft. Bend County and provide subsidence modeling along the Ft. Bend - Harris county line.

Data Collection

The development and calibration of the subsector models requires consideration of certain site-specific data. First, the stratigraphy must be summarized through the depth affected by groundwater pumpage. Second, the records of potentiometric surface elevation changes over time must be compiled. Third, the calibration of the individual models against measured subsidence requires the review of benchmark releveling data.

Data sources primarily included the USGS Water Resources Division in Houston and the Harris-Galveston Coastal Subsidence District. Instrument logs of wells drilled over a period of years, water level observations compiled as hydrograph data files, and 1943-1978 benchmark releveling data were collected from the USGS. Mr. Glenn Locke of the USGS also provided information from his own library of Ft. Bend County data. The HGCSD provided records of benchmark data which included the measured subsidence from 1973 through 1987, detailed descriptions of benchmarks, and existing computer data files and programs pertinent to the project.

Subsector Model Preparation

Each subsector model is a one-dimensional representation of the surface conditions that govern the magnitude and rate of subsidence at that location. The subsector size was defined by the number of ninths needed to acquire sufficient data on historical water levels, stratigraphy, and historical subsidence for a reasonable calibration. Once the ninths for each subsector were established, then the available data for that geographic area was summarized.

Water levels in observation wells were plotted as a function of time for each subsector. The plots were reviewed to determine whether the Chicot aquifer hydrographs only, or both the Chicot and Evangeline aquifer hydrographs would be used to drive the individual PRESS subsector models. Then the hydrograph(s) selected were generalized for input to the PRESS model. Observation wells used for each subsector are included in Table 2.

Logs of wells within the subsector boundaries were interpreted by geologists to assess the depths and thicknesses of clay layers from the ground surface to the base of the Evangeline aquifer. The multiple logs were of various types for water, oil, and gas wells. Electric-, micro-, ISF- and other logs, as available, were interpreted. The various interpretations within each subsector were then summarized to provide a single generalized stratigraphy

Table 2

OBSERVATION WELLS USED FOR GENERALIZED HYDROGRAPHS

SUBSECTOR			
ARCOLA	NEEDVILLE	SMITHERS LAKE	RICHMOND ROSENBERG
65-29-501	65-34-701	65-35-301	65-26-501
65-29-505	65-34-702	65-35-302	65-26-502
65-29-506	65-34-703	65-35-303	65-26-503
65-29-507	65-34-704	65-35-304	65-26-504
65-29-508	65-34-706	65-36-101	65-26-506
65-29-510	65-34-707	65-36-102	65-26-507
65-29-512	65-34-709	65-36-103	65-26-508
65-29-515	65-34-710	65-36-104	65-26-509
65-29-516	65-34-711		65-26-510
65-29-517	65-34-712		65-26-512
65-29-518	65-34-715		65-26-514
65-29-701	65-34-716		65-26-515
65-29-702	65-34-717		65-26-516
65-29-703	65-42-102		65-26-517
65-29-704	65-42-103		65-26-518
65-29-705	65-42-105		65-26-601
65-29-706	65-42-202		65-26-602
65-29-709	65-42-203		65-26-603
65-29-807	65-42-204		65-26-604
65-29-808	65-42-205		65-26-605
65-29-809	65-42-206		65-26-606
65-29-810	65-42-207		65-26-607
65-29-811	65-42-208		65-26-608
65-29-812	65-42-209		65-26-609
65-29-813			65-26-610
65-29-814			65-26-612
			65-26-613
			65-26-614

Table 3

LOGS USED FOR STRATIGRAPHIC INTERPRETATION

SUBSECTOR	REFERENCE NUMBER *
Arcola	G-17 G-18 G-19 G-50 G-51 G-52 G-67
Needville	I12 I13 I14 I23 I24 I25
Richmond-Rosenberg	E2 E8 E9 E10 E11 E13 E14 E15 E20
Smithers Lake	J5 J6 J7 J51 J54 J55 K2

** Reference Number corresponds to the instrument well log identification system used by the USGS Water Resources Division, Houston, Texas Subdistrict, for Ft. Bend County.*

for that subsector. The logs used for stratigraphic interpretation in each subsector are included in Table 3, using the well log identification system of the USGS Water Resources Division in Houston, Texas.

The geotechnical parameters representing permeability, virgin compressibility, and elastic compressibility are required for clay layers within the individual subsector models. These data have been characterized as functions of depth based on work initially reported in the HGCSD Phase I Water Resource Management Program. The depth functions used in previous PRESS models for the HGCSD were carried through for Ft. Bend County. Sands are assumed to be incompressible.

The modeling process used for Ft. Bend County subsector models was similar to that used in HGCSD's Phase I and Phase II studies. Pumpage in the modeled areas of Ft. Bend County is typically from the Chicot and upper Evangeline aquifers. The PRESS models of subsectors reflect this pattern, with three of the four subsector models using only the Chicot as the pressure-controlling aquifer.

Calibration of Subsector Models

Once each individual subsector model was compiled, the PRESS program was run and subsidence calculated for the calibration period of 1906-1990. Water level data in observation wells were typically available from about 1930 through 1980, with benchmark releveling data available for 1943, 1973 and 1987.

The calculated subsidence was compared to actual subsidence as approximated by the releveling history of the subsector. The benchmark releveling histories used in calibration are identified on Table 4. The calibration process is an attempt to match calculated and observed subsidence over the calibration period by adjusting variables within the subsector model.

Calibration was an iterative process. After changing a variable value in a subsector model, the PRESS program was re-run and new values of subsidence calculated. These were again compared to measured subsidence and if a good fit to the data was not obtained, the process was begun again.

Several factors considered in calibration included: a) the selection of which sets of benchmark releveling data were appropriate for calibration; b) the selection of well hydrographs to weight most heavily in approximating the input pressure changes, (c) the variability of stratigraphy across a subsector, and d) the selection of appropriate preconsolidation stresses in the clays.

Table 4

BENCHMARK RELEVELING HISTORIES USED FOR MODEL CALIBRATION

SUBSECTOR	REFERENCE BENCHMARKS
Arcola	H306 S1214 L668 R1214 Q1214
Needville	A1219 D1219 A810
Richmond-Rosenberg	E1212 B1212 C1212 T804 TT21L
Smithers Lake	T1214 Z811 GEORGERM3 W811 PTS33M(USGS)

The initial data set for a given subsector model consisted primarily of the first interpretation of stratigraphy from well logs and the generalized hydrograph prepared from observation well data. The PREMAX (preconsolidation stress) was estimated, and the other clay parameters were calculated.

Adjustments of input variables were made in the following sequence to calibrate a subsector model:

1. Adjust PREMAX;
2. Adjust clay layer thicknesses based on well log reinterpretations;
3. Revise input pressure changes by re-interpreting the generalized hydrograph(s).

PREMAX adjustment was the primary means of calibration. If horizontal variation in thicknesses of clay layers within a subsector were minimal, then this approach is preferred. Certain subsectors had such variability in stratigraphy from one point to another that one of several stratigraphic models could be equally well justified. Adjustment of either total clay thickness, or the thickness of individual layers within compacting intervals was used, where justified by instrument logs and stratigraphy, to better fit the actual data.

In some instances, the input pressure changes were modified to achieve better calibration. The pressure changes are a function of the generalized hydrograph used in calibration runs of the PRESS program. This generalized hydrograph was prepared from plots of several individual well hydrographs. The individual wells could be located in various parts of the subsector and could be screened differently or could be influenced by nearby pumped wells. If the first generalized hydrograph produced a poor fit, another generalized interpretation of the data was used, often more heavily weighting hydrographs closer to the typical benchmark releveling data sources for the subsector.

The subsector PRESS models, as finally calibrated, have been run and calculated subsidence plotted against time on exhibits also showing the benchmark releveling data curves (Exhibits 2 through 5). The general fit of the curves to the actual subsidence data is considered good. In some locations there was a significant variation in subsidence across a subsector, especially in Richmond-Rosenberg, where the rate of subsidence varied from 0.005 to 0.025 feet per year, a five-fold change.

Description of Final Models

Arcola

The Arcola subsector contains three ninths in the far eastern corner of the county. Pumpage is within the Chicot aquifer where fresher water is found. The pumped zone is modeled between 125- and 580-foot depth.

Stratigraphy was interpreted from well logs identified in Table 3. Water level data records began in 1925 for this area. The geotechnical parameters used in the final calibrated model are shown in Table 5.

The subsidence calculated for Arcola is shown on Exhibit 2 along with the historical benchmark releveling data curves. The recent rate of subsidence (1973-1987) for the Arcola subsector is about 0.05 to 0.09 feet per year, the highest of the four subsectors modeled in this study. Rates up to 0.1 feet per year were recorded for the period 1978-1987.

Needville

The Needville subsector includes three ninths in the southwestern part of the county. Subsidence is modeled as being dependent on the pressure changes in the Chicot aquifer only. The controlling aquifer is modeled between 80- and 410-foot depth.

Table 5

GEOTECHNICAL STRATIGRAPHY AND PARAMETERS for ARCOLA SUBSECTOR SUBSIDENCE MODEL

COMPACTING INTERVAL NO.	DEPTH INTERVAL ft.	TOTAL CLAY THICKNESS ft.	EQUIVALENT CLAY LAYER THICKNESS ft.	HYDRAULIC CONDUCTIVITY ft/yr^{-1}	VIRGIN COMPRESSIBILITY yr^{-1}	ELASTIC COMPRESSIBILITY yr^{-1}
1	125 - 475	200	50	1.7×10^{-3}	1.5×10^{-4}	1.5×10^{-5}
2	475 - 655	120	40	8.4×10^{-4}	1.2×10^{-4}	1.2×10^{-5}
3	655 - 700	35	35	6.3×10^{-4}	1.1×10^{-4}	1.1×10^{-5}
4	700 - 775	10	10	5.5×10^{-4}	1.0×10^{-4}	1.0×10^{-5}
5	775 - 805	30	30	4.9×10^{-4}	9.8×10^{-5}	9.8×10^{-6}
6	805 - 945	20	10	3.9×10^{-4}	9.1×10^{-5}	9.1×10^{-6}
7	945 - 1025	60	30	3.0×10^{-4}	8.2×10^{-5}	8.2×10^{-6}
8	1025 - 1280	40	10	2.0×10^{-4}	7.1×10^{-5}	7.1×10^{-6}
9	1280 - 1430	75	15	1.2×10^{-4}	5.9×10^{-5}	5.9×10^{-6}
10	1430 - 1575	130	130	8.2×10^{-5}	5.2×10^{-5}	5.2×10^{-6}
11	1575 - 1705	35	35	5.8×10^{-5}	4.6×10^{-5}	4.6×10^{-6}
12	1705 - 1830	94	47	4.2×10^{-5}	4.1×10^{-5}	4.1×10^{-6}
13	1830 - 2190	140	20	2.3×10^{-5}	3.3×10^{-5}	3.3×10^{-6}
14	2190 - 2480	90	30	1.0×10^{-5}	2.4×10^{-5}	2.4×10^{-6}
15	2480 - 2555	75	75	6.5×10^{-6}	2.1×10^{-5}	2.1×10^{-6}
16	2555 - 2795	140	35	4.4×10^{-6}	1.8×10^{-5}	1.8×10^{-6}

Table 6

GEOTECHNICAL STRATIGRAPHY AND PARAMETERS for NEEDVILLE SUBSECTOR SUBSIDENCE MODEL

COMPACTING INTERVAL NO.	DEPTH INTERVAL ft.	TOTAL CLAY THICKNESS ft.	EQUIVALENT CLAY LAYER THICKNESS ft.	HYDRAULIC CONDUCTIVITY ft/yr^{-1}	VIRGIN COMPRESSIBILITY yr^{-1}	ELASTIC COMPRESSIBILITY yr^{-1}
1	100 - 530	100	20	1.8×10^{-3}	1.7×10^{-4}	1.7×10^{-5}
2	960 - 1530	245	35	1.6×10^{-4}	6.5×10^{-5}	6.5×10^{-6}
3	1530 - 1580	50	50	7.2×10^{-5}	4.9×10^{-5}	4.9×10^{-6}
4	1700 - 1800	100	100	4.4×10^{-5}	4.1×10^{-5}	4.1×10^{-6}
5	1900 - 2030	130	130	2.6×10^{-5}	3.4×10^{-5}	3.4×10^{-6}
6	2030 - 2720	510	51	9.2×10^{-6}	2.4×10^{-5}	2.4×10^{-6}

Stratigraphy was interpreted from well logs identified in Table 3. Water level records began in 1936 for the area. The geotechnical parameters and stratigraphy used in the final calibrated model are included in Table 6.

The comparison of calculated and actual subsidence is shown on Exhibit 3. The recent rate of subsidence (1973-1987) for the Needville subsector is about 0.014 to 0.015 feet per year.

Richmond-Rosenberg

The Richmond-Rosenberg subsector, comprised of two ninths, contained adequate data for calibration as a dual controlling aquifer. The older wells in this subsector are screened within the Chicot, but newer wells for municipal water supply have screened the Evangeline aquifer. The upper aquifer was assumed to exist between depths of 70 and 475 feet, while the lower aquifer was modeled between depths of 650 and 1590 feet.

Stratigraphy was interpreted from several well logs identified in Table 3. The earliest water level data was recorded in 1905. The geotechnical parameters and stratigraphy used in the final calibration are included in Table 7.

Table 7

GEOTECHNICAL STRATIGRAPHY AND PARAMETERS for RICHMOND/ROSENBERG SUBSECTOR SUBSIDENCE MODEL

COMPACTING INTERVAL NO.	DEPTH INTERVAL ft.	TOTAL CLAY THICKNESS ft.	EQUIVALENT CLAY LAYER THICKNESS ft.	HYDRAULIC CONDUCTIVITY ft/yr^{-1}	VIRGIN COMPRESSIBILITY yr^{-1}	ELASTIC COMPRESSIBILITY yr^{-1}
1	0 - 250	90	30	2.6×10^{-3}	3.3×10^{-4}	3.3×10^{-5}
2	400 - 680	45	15	9.1×10^{-4}	1.2×10^{-4}	1.2×10^{-5}
3	830 - 930	90	45	3.9×10^{-4}	9.1×10^{-5}	9.1×10^{-6}
4	930 - 1120	40	40	2.7×10^{-4}	8.0×10^{-5}	8.0×10^{-6}
5	1120 - 1270	150	150	1.8×10^{-4}	6.8×10^{-5}	6.8×10^{-6}
6	1270 - 1570	75	15	1.0×10^{-4}	5.6×10^{-5}	5.6×10^{-6}
7	1570 - 1625	40	40	6.4×10^{-5}	4.7×10^{-5}	4.7×10^{-6}
8	1675 - 1735	60	60	4.9×10^{-5}	4.3×10^{-5}	4.3×10^{-6}
9	1735 - 1775	15	15	4.4×10^{-5}	4.1×10^{-5}	4.1×10^{-6}
10	1775 - 1835	60	60	3.8×10^{-5}	3.9×10^{-5}	3.9×10^{-6}
11	1895 - 1965	15	15	3.3×10^{-5}	3.7×10^{-5}	3.7×10^{-6}
12	1965 - 2015	70	70	2.8×10^{-5}	3.5×10^{-5}	3.5×10^{-6}
13	2015 - 2085	70	70	2.1×10^{-5}	3.2×10^{-5}	3.2×10^{-6}
14	2085 - 2345	90	30	1.4×10^{-5}	2.7×10^{-5}	2.7×10^{-6}

The subsidence calculated for Richmond-Rosenberg was calibrated to some of the greater subsidence rates measured in this subsector, which contained highly variable rates of subsidence throughout its history. Subsidence rates between 1973 and 1987 have ranged from 0.005 to 0.025 feet per year as shown on Exhibit 4.

Smithers Lake

Smithers Lake subsector contains two ninths in the central part of the county. Pumpage is dominated by wells in the Chicot and upper Evangeline aquifers. The pumped zone is modeled as a single controlling aquifer between 420- and 730-foot depth.

Stratigraphy was interpreted from well logs identified in Table 3. The geotechnical parameters used in the final calibrated model are shown in Table 8. Water level data records began in 1936, but no observation wells cover the entire period. The variation among observation well records could justify several interpretations of the historical "typical" hydrograph for the Smithers Lake subsectors.

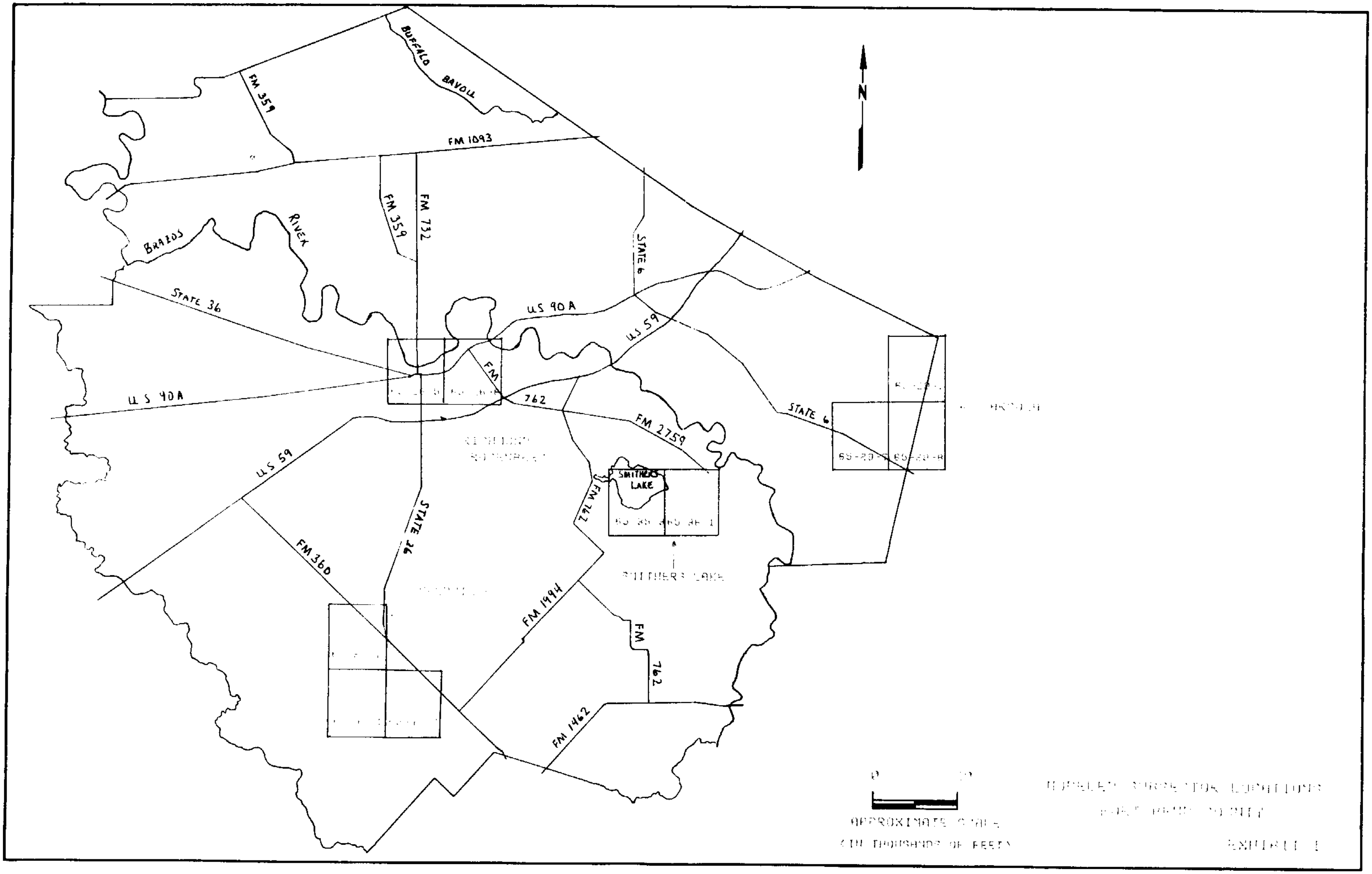
The subsidence calculated for Smithers Lake is shown on Exhibit 5 along with historical benchmark releveling curves. Substantial variation in releveling data exists in the vicinity of this subsector. Part of this is attributed to significant stratigraphic variation across the subsector, and part to other causes such as

Table 8

GEOTECHNICAL STRATIGRAPHY AND PARAMETERS for SMITHERS LAKE SUBSECTOR SUBSIDENCE MODEL

COMPACTING INTERVAL NO.	DEPTH INTERVAL ft.	TOTAL CLAY THICKNESS ft.	EQUIVALENT CLAY LAYER THICKNESS ft.	HYDRAULIC CONDUCTIVITY ft/yr^{-1}	VIRGIN COMPRESSIBILITY yr^{-1}	ELASTIC COMPRESSIBILITY yr^{-1}
1	0 - 350	135	45	2.3×10^{-3}	2.6×10^{-4}	2.6×10^{-5}
2	350 - 410	55	55	1.4 X 10-3	1.4×10^{-4}	1.4×10^{-5}
3	410 - 860	100	20	7.2×10^{-4}	1.1×10^{-4}	1.1×10^{-5}
4	860 - 920	40	20	3.8×10^{-4}	9.0×10^{-5}	9.0×10^{-6}
5	920 - 1055	20	10	3.0×10^{-4}	8.2×10^{-5}	8.2×10^{-6}
6	1055 - 1230	30	30	2.0×10^{-4}	7.1×10^{-5}	7.1×10^{-6}

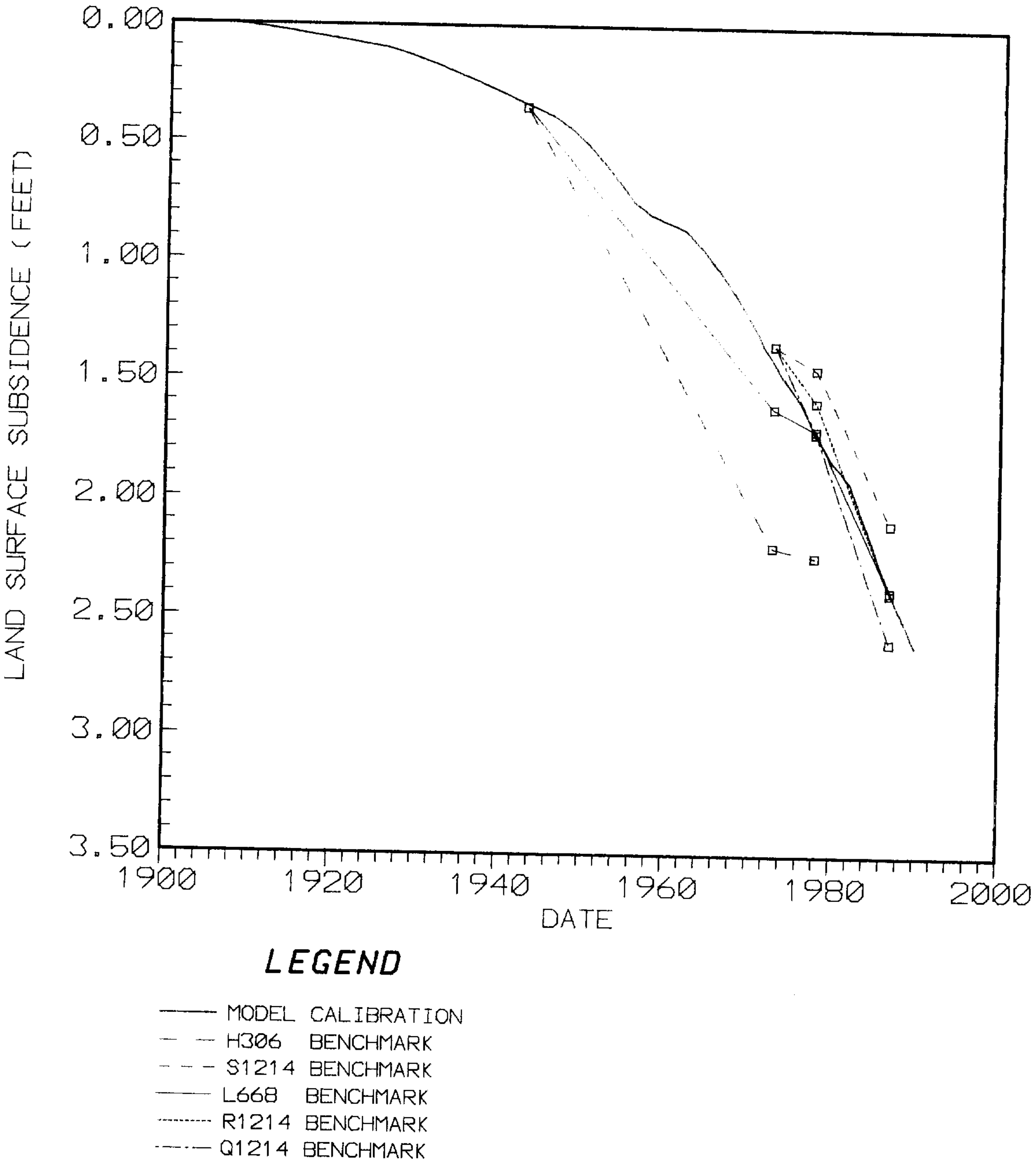
changing pumpage patterns in and around the subsector. One interesting condition southwest of Smithers Lake is an old sulfur mine that pumped substantial quantities of groundwater for years beginning in 1969 and probably influenced regional subsidence near Smithers Lake prior to ceasing operation in 1984. Recent average rates of subsidence in the Smithers Lake subsector (1973-1987) range from 0.025 to 0.036 feet per year.



[illegible] [illegible] LOCATIONS

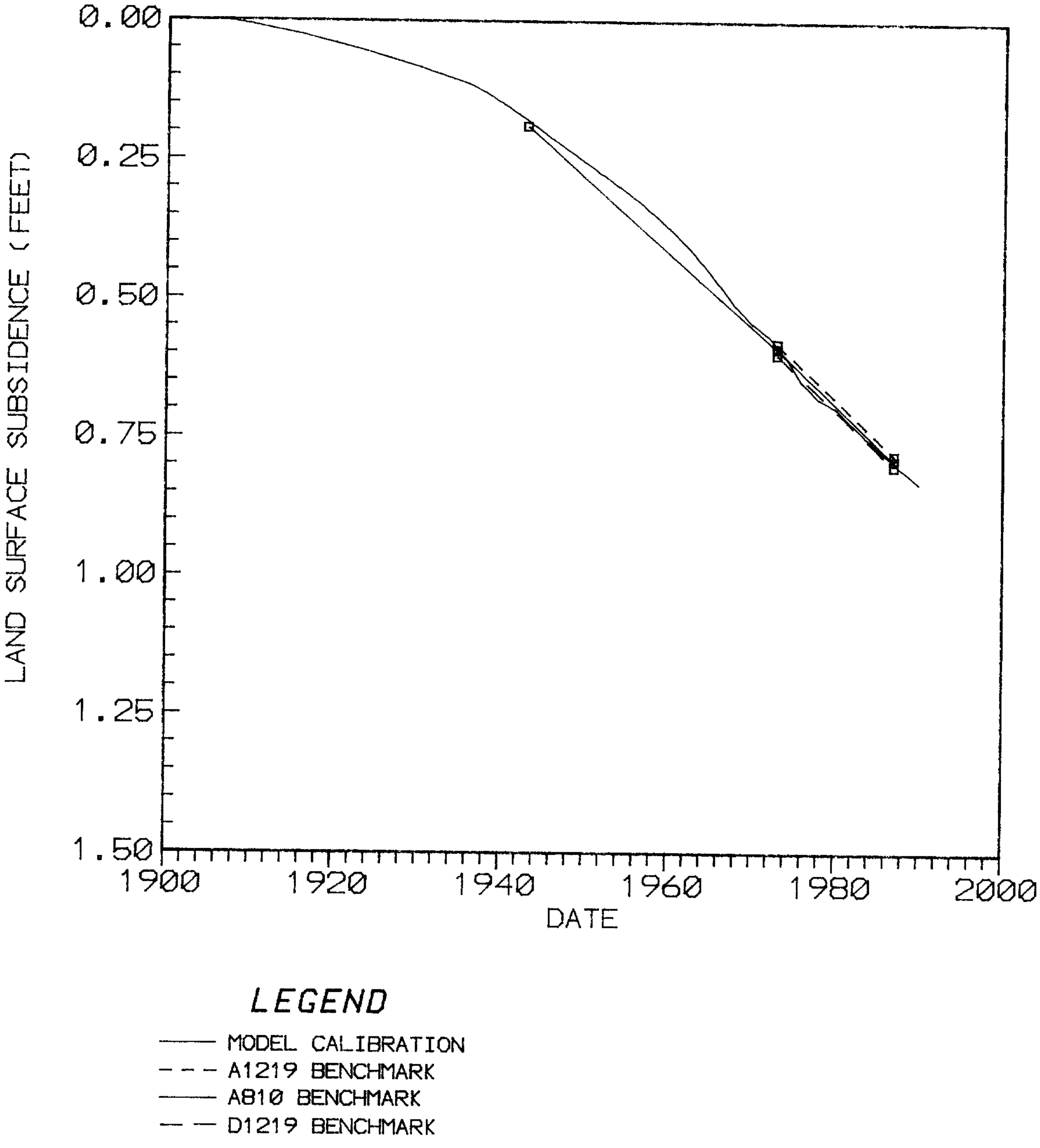
FORT BEND COUNTY

EXHIBIT 1



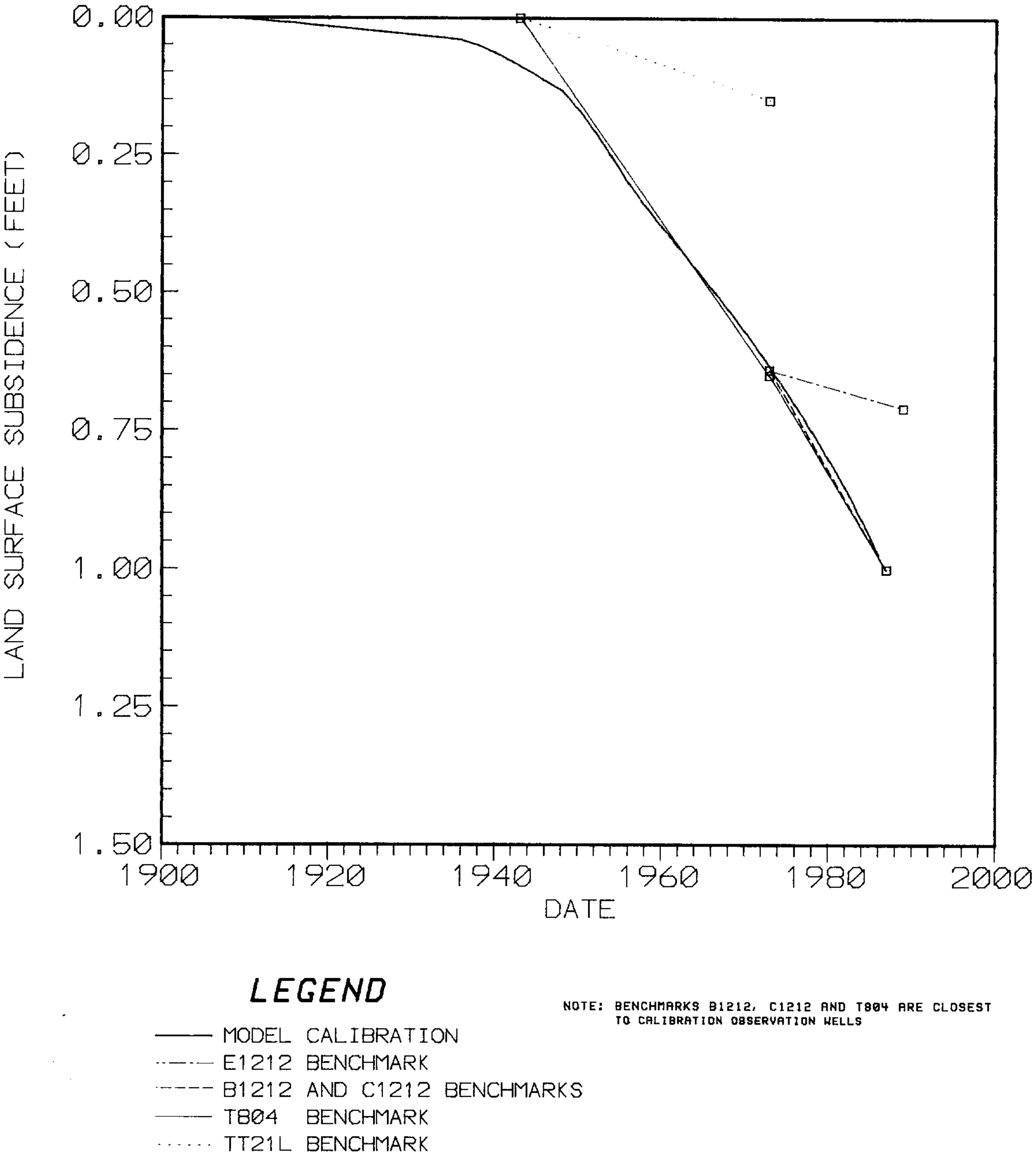
ARCOLA SUBSECTOR
HISTORICAL SUBSIDENCE CALIBRATION

EXHIBIT 2



NEEDVILLE SUBSECTOR
HISTORICAL SUBSIDENCE CALIBRATION

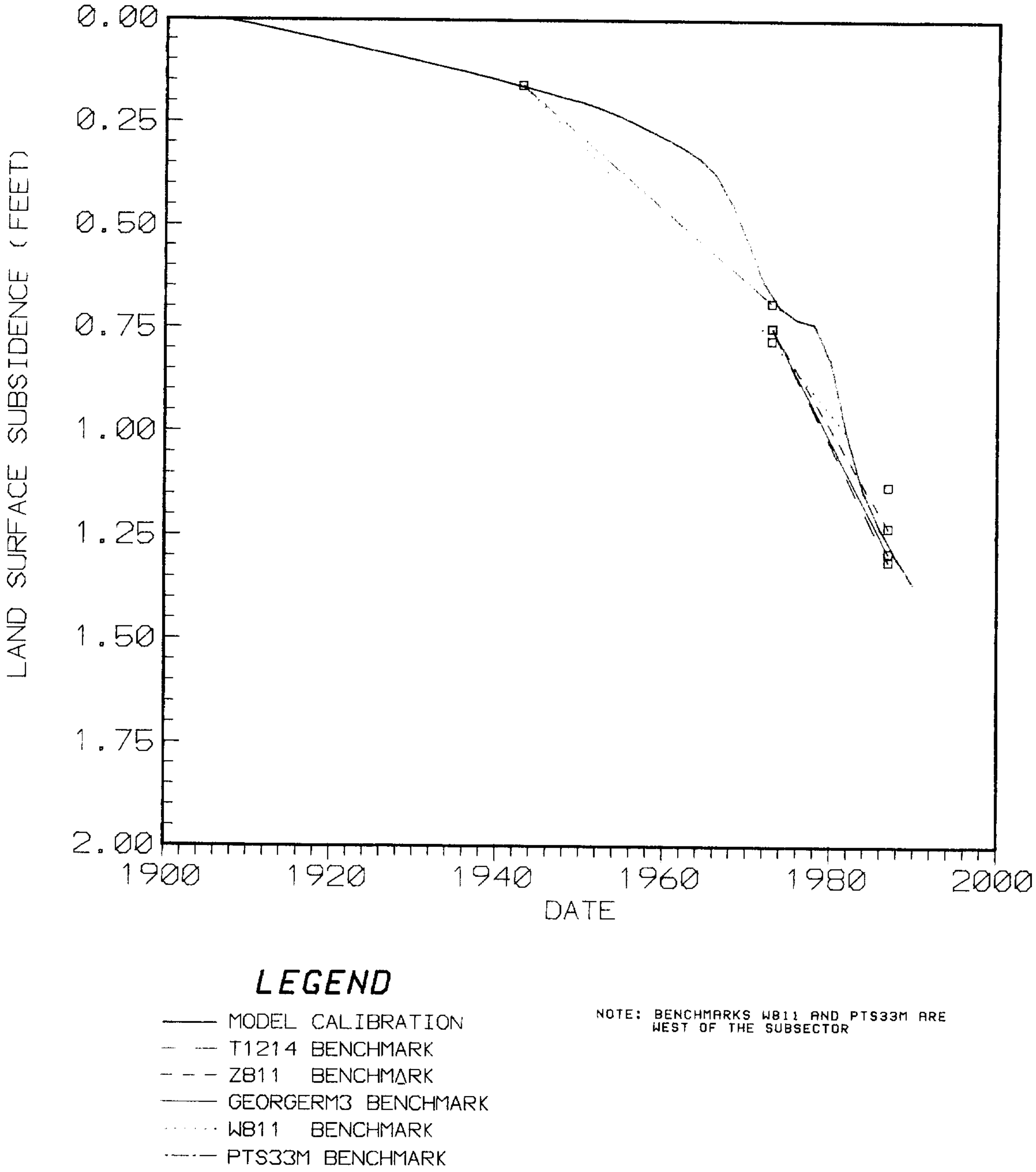
EXHIBIT 3



NOTE: BENCHMARKS B1212, C1212 AND T804 ARE CLOSEST TO CALIBRATION OBSERVATION WELLS

RICHMOND-ROSENBERG SUBSECTOR
HISTORICAL SUBSIDENCE CALIBRATION

EXHIBIT 4



SMITHERS LAKE SUBSECTOR
HISTORICAL SUBSIDENCE CALIBRATION

EXHIBIT 5

WS 9-483-709

March 1991 - Regional Water Supply Planning Study

Final Report

Complete File is Kept because Of Colored Map Copies.

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