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SANDY CREEK/LAKE TRAVIS NPS WATER QUALITY STUDY

FINAL REPORT

by

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Principal Investigator

LOWER COLORADO RIVER AUTHORITY

July, 1996

TEXAS WATER DEVELOPMENT BOARD GRANT #92-483-335

SANDY CREEK/LAKE TRAVIS NPS WATER QUALITY STUDY

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EXECUTIVE SUMMARY

Lake Travis has been classified as an oligotrophic reservoir, meaning the lake generally has high clarity, low nutrient concentrations and low productivity. The LCRA adopted the Lake Travis Non-Point Source Ordinance in 1989 out of concern for the effects of development in the watershed upon the water quality of the reservoir. The ordinance requires a review of its effectiveness in protecting the water quality of Lake Travis. This study provides technical information for the review.

The Sandy Creek NPS Water Quality Study, funded by the LCRA and the Texas Water Development Board (TWDB), is being performed to determine the types and amounts of non-point source pollution in a representative watershed of Lake Travis, and to determine the effects of non-point source pollution on lake water quality. Sandy Creek Arm is an embayment on the north side of Lake Travis.

The watershed of Lake Travis and the subwatershed of Sandy Creek are both mostly rangeland, consisting of 50% pasture, 39% woodland, 8% urban, 2% industry and 1% other land uses. The area receives about 33 inches of precipitation per year, and yields about 3 inches of runoff per year. The remainder is lost to evaporation, infiltration and transpiration by plants. Most of the runoff occurs from storm events.

Among the 21 storm events monitored during the course of this study, two were significant; the 50-year flood event of December 1991, and a well-documented storm event in June 1993. Substantial amounts of pollutants were sampled and analyzed from these storm events for this study.

Over 1,800 tons of sediment washed into Sandy Creek Arm from the December 1991 flood event. Partial data indicate that weighted average soil loss from the December 1991 flood exceeded 36 tons per square mile. The Soil Conservation Service estimates that 395 tons per square mile entered Lake Travis from the Pedernales River watershed. Similar proportions of nutrients entered the lake, causing severe algal blooms in April of 1992. Lake Travis was brought down to normal operating levels by July 1992 and the effects on water quality gradually dissipated.

The effects on lake water quality from the June 1993 storm event were increased nutrient concentrations, followed by higher primary productivity. Eutrophic concentrations of total phosphorus were measured at all lake sampling sites two days after the storm. (Clarity was lessened, but TSS concentrations near the surface remained low.) Nitrogen was consumed at a faster rate than phosphorus, which was

still at near-eutrophic levels when all available nitrogen was used up a month after the storm. These data may have implications for determination of the limiting nutrient in Lake Travis.

The Lake Travis non-point source ordinance contains performance standards for total suspended solids, total phosphorus and oil & grease. Required removal rates for these parameters are structured according to land slope and proximity to the lake. These parameters were chosen to address three adverse impacts to lakes and reservoirs: sedimentation, eutrophication, and toxins.

The Lake Travis Ordinance would be more effective if their were a "sunset clause" for exemptions of pre-existing platted but as yet undeveloped land. The ordinance would also be more effective if requirements for Best Management Practices included that they be designed to completely contain and treat the first flush of runoff.

Data from this study has been used to calibrate a computer simulation of Sandy Creek Arm, for the purpose of analyzing various scenarios of future development in the watershed. The CE-QUAL-W2 model was used to simulate three scenarios: existing conditions (calibration), full development of the watershed without the ordinance in place, and the effects of full development of the watershed with the ordinance.

The results of the modeling were that phosphorus is the limiting nutrient in Lake Travis, and phosphorus removal required by the ordinance has the effect of increasing dissolved oxygen levels by about 1 mg/L in the summer months. These results indicate that the Lake Travis Non-Point Source Pollution Control Ordinance is effective in protecting water quality.

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1.0 Introduction

In 1989, the LCRA Board of Directors implemented its Water Quality Leadership Policy by adopting one of the first non-point source (NPS) pollution ordinances in the United States. The Lake Travis NPS Pollution Control Ordinance is applicable to the part of the Lake Travis watershed within Travis County. In 1992, LCRA adopted a similar ordinance for the watershed of the Highland Lakes in Burnet and Llano counties.

The Lake Travis NPS Pollution Control Ordinance is based on current pollutant removal technology, as opposed to performance-based ordinances which require that all discharges meet certain water quality criteria. A technology-based approach focusses on what is achievable, using pollutant removal efficiency as a standard instead of effluent concentration. As technology improves, water quality treatment should also improve, and this is provided for in the ordinance. LCRA has received awards for the Lake Travis Ordinance from the EPA and other environmental organizations.

The Lake Travis Ordinance requires that a review be performed by February 1994, to evaluate the effectiveness of the ordinance in protecting the water quality of Lake Travis. This study is designed provide technical information for the review.

The Sandy Creek NPS Water Quality Study, funded by the LCRA and the Texas Water Development Board (TWDB), is being performed to determine the types and amounts of non-point source pollution in a representative watershed of Lake Travis, and to determine the effects of NPS pollution on lake water quality. Sandy Creek Arm is an embayment on the north side of Lake Travis. The location of the study area is shown in Figure 1.

The Austin area receives about 33 inches of precipitation per year, as shown in Figure 2. The average amount of annual runoff in Austin is about 3 inches per year, as shown in Figure 3. The difference between rainfall and runoff is attributable to evaporation, infiltration and transpiration by plants. Dependent on antecedent moisture conditions, at least one-half to one inches of rain must fall before runoff occurs.

Most of the runoff in the Austin area results from short-term, high intensity storm events. Development of the watershed has a directly effect on rates and amounts of runoff, especially creation of impervious cover such as roads and buildings. Higher rates of runoff generally correspond to higher rates of erosion and pollutant loading of streams and reservoirs. The Lake Travis Non-Point Source Pollution Control ordinance is intended to address these concerns. The area subject to the ordinance is shown in Figure 4.

Figure 1

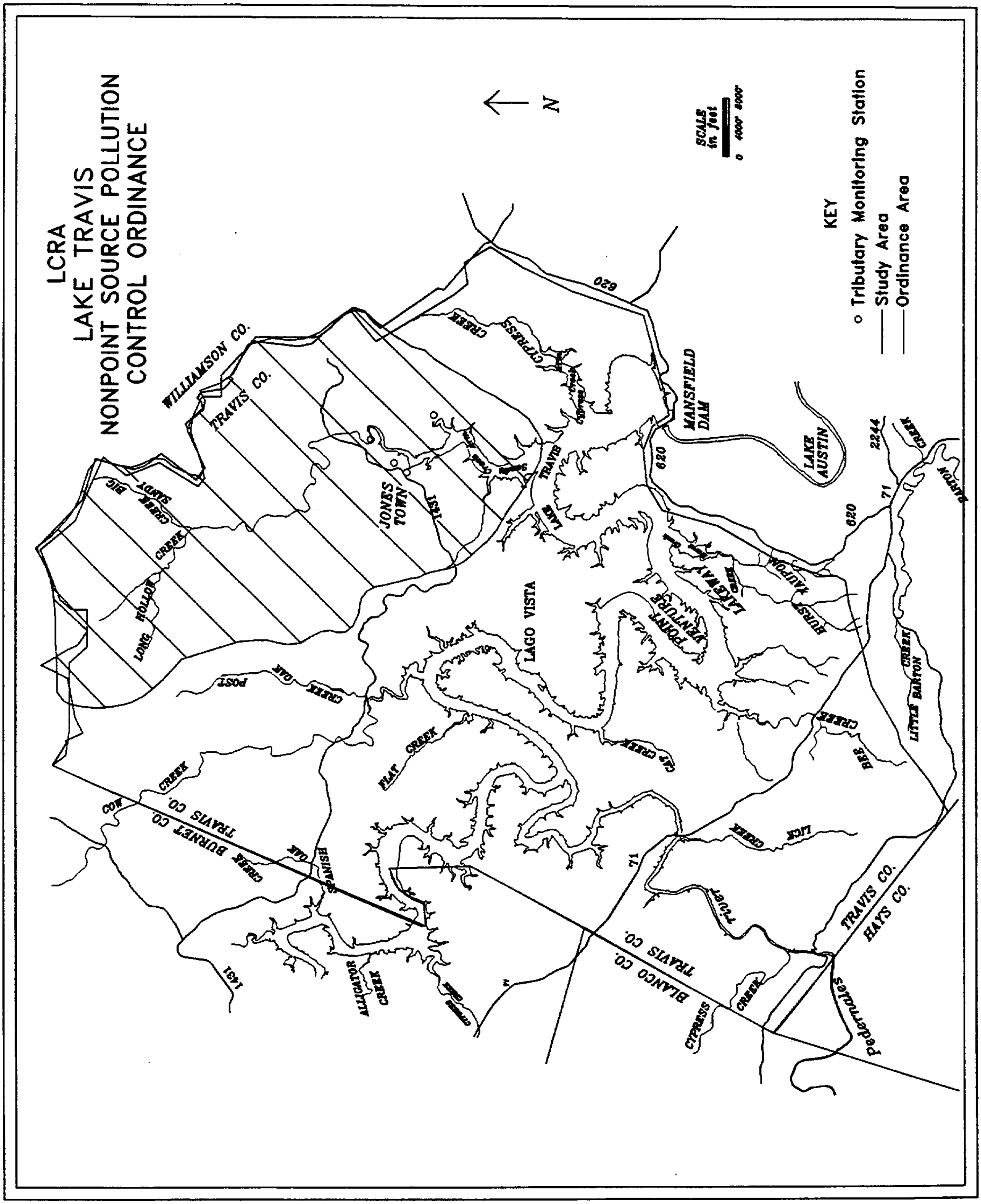
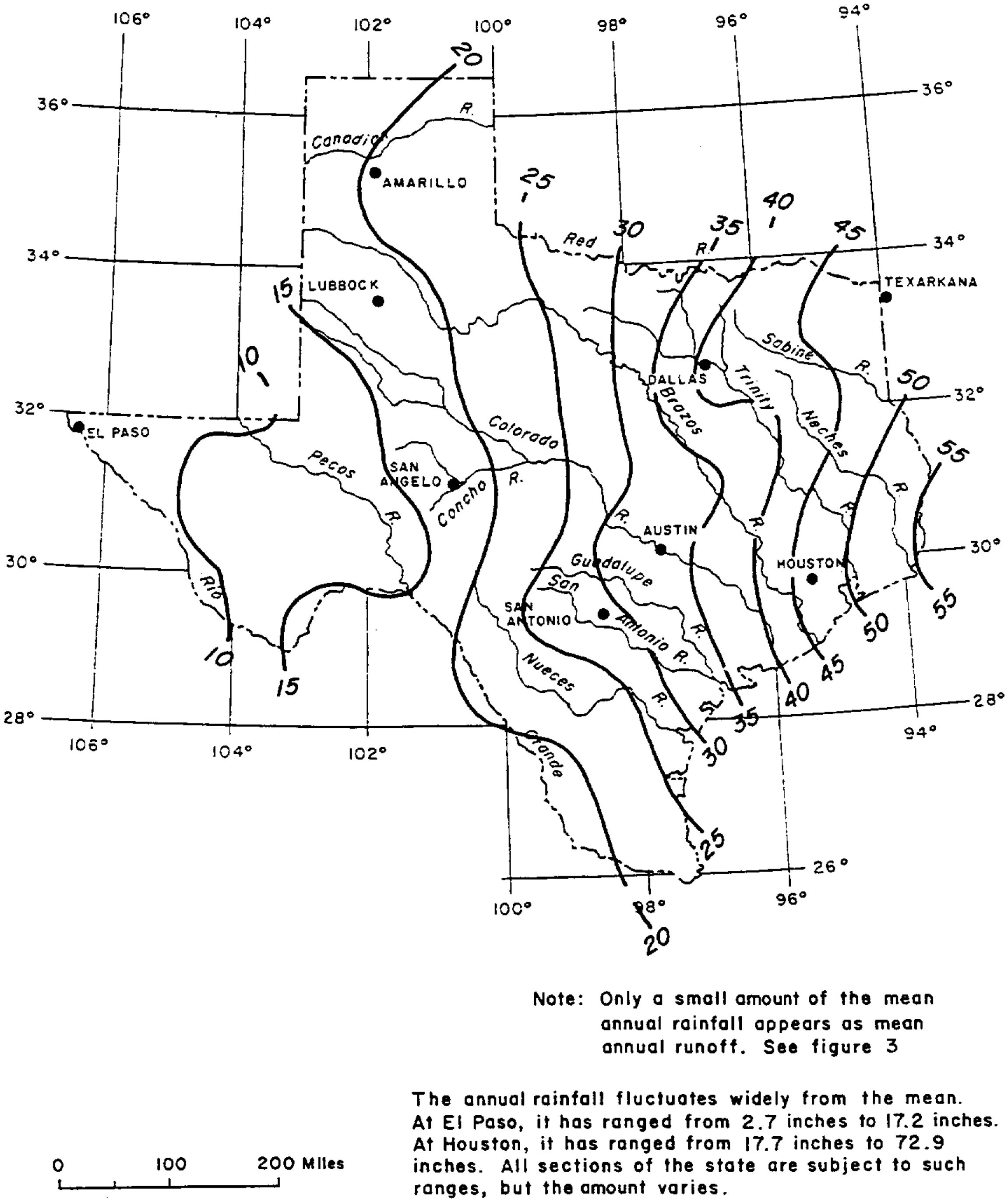

LCRA
LAKE TRAVIS
NONPOINT SOURCE POLLUTION
CONTROL ORDINANCE
N
SCALE
in feet
0 4000' 8000'
KEY
Tributary Monitoring Station
Study Area
Ordinance Area
WILLIAMSON CO.
TRAVIS CO.
BIG SANDY CREEK
LONG HOLLOW CREEK
JONESTOWN
1431
620
CYPRESS CREEK
MANSFIELD DAM
LAKE AUSTIN
LAKE TRAVIS
LAGO VISTA
POINT VENTURE
LAKEWAY
HURST
2244
71
BARTON CREEK
LITTLE BARTON CREEK
BEE CREEK
POST OAK CREEK
FLAT CREEK
CAP CREEK
COW CREEK
BURNET CO.
TRAVIS CO.
SPANISH OAK CREEK
LICK CREEK
ALLIGATOR CREEK
BLANCO CO.
CYPRESS CREEK
HAYS CO.
Pedernales

Figure 2



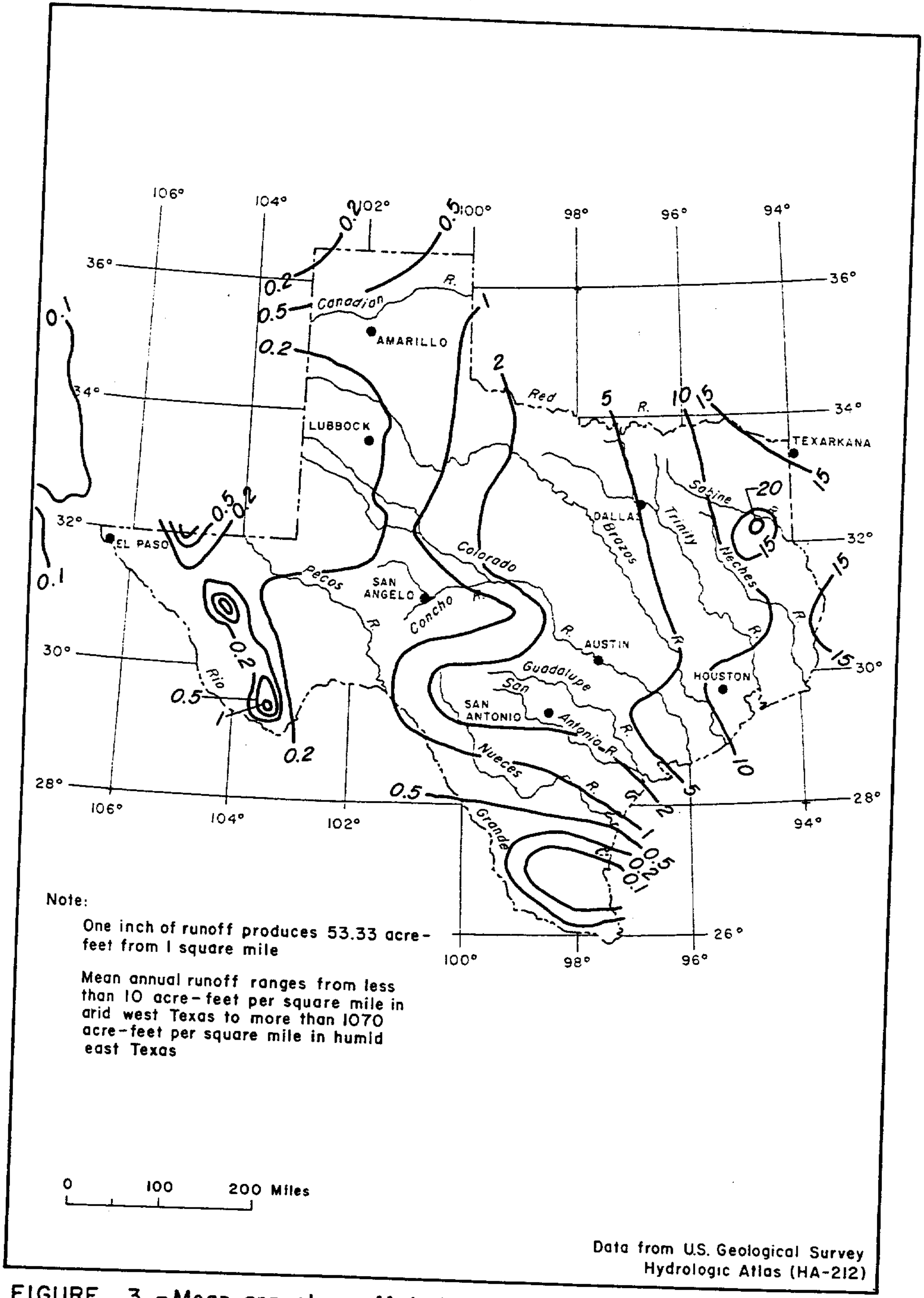
Note: Only a small amount of the mean annual rainfall appears as mean annual runoff. See figure 3

The annual rainfall fluctuates widely from the mean. At El Paso, it has ranged from 2.7 inches to 17.2 inches. At Houston, it has ranged from 17.7 inches to 72.9 inches. All sections of the state are subject to such ranges, but the amount varies.

Data from TWDB Report 64

FIGURE 2.-Mean annual rainfall, in inches, 1940-65

Figure 3



Note:

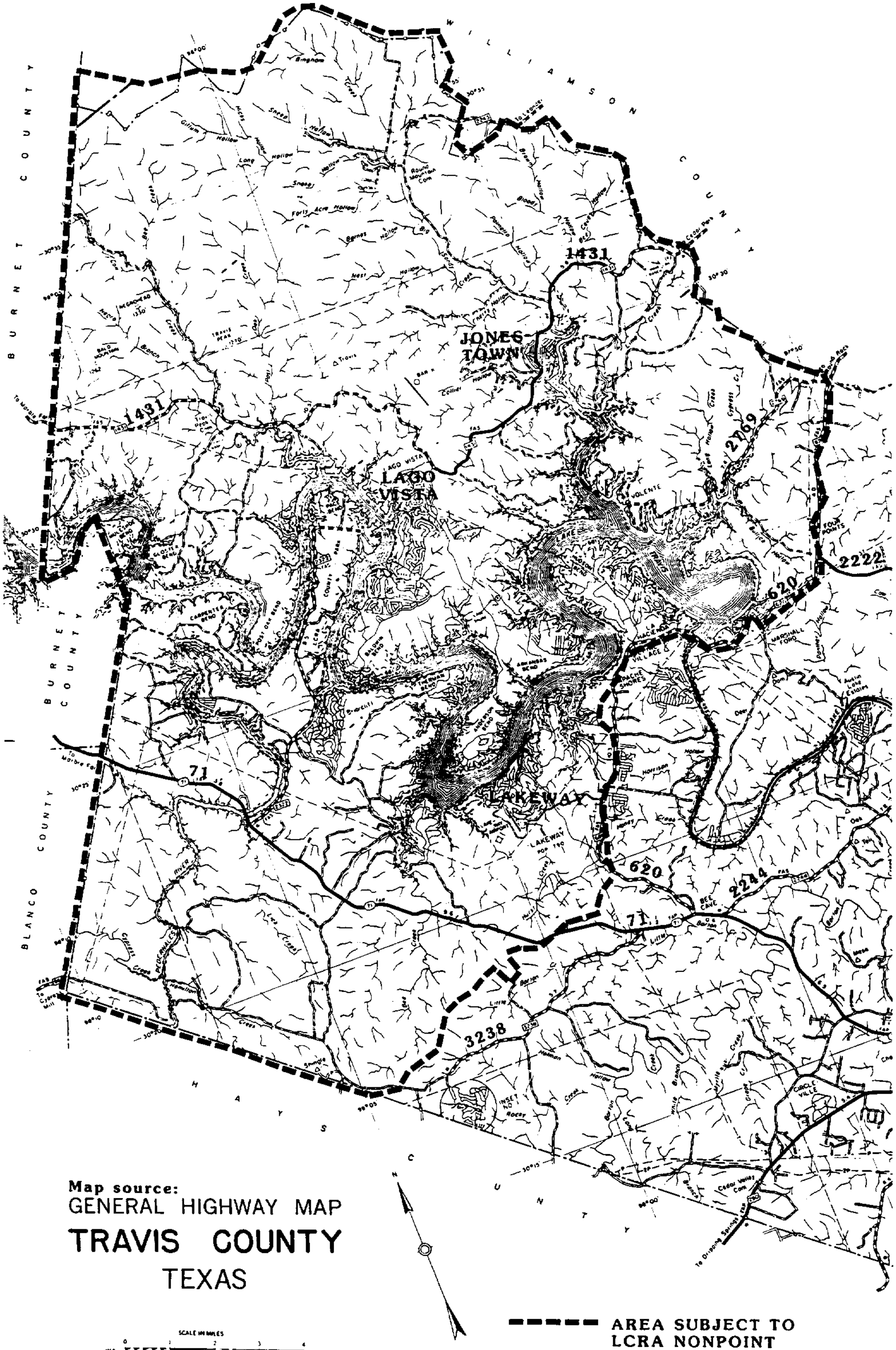
One inch of runoff produces 53.33 acre-feet from 1 square mile

Mean annual runoff ranges from less than 10 acre-feet per square mile in arid west Texas to more than 1070 acre-feet per square mile in humid east Texas

Data from U.S. Geological Survey Hydrologic Atlas (HA-212)

FIGURE 3.-Mean annual runoff, in inches

Figure 4



Map source:
GENERAL HIGHWAY MAP
TRAVIS COUNTY
TEXAS

▬ ▬ ▬ ▬ AREA SUBJECT TO LCRA NONPOINT SOURCE POLLUTION CONTROL ORDINANCE

1.1 Purpose

The purpose of this study is to evaluate the effectiveness of the LCRA Lake Travis Non-Point Source Pollution Control Ordinance in protecting water quality. An empirical approach has been taken by studying a representative subwatershed and portion of the lake, documenting existing ambient conditions, and predicting water quality resulting from development in the watershed with/without the ordinance in place. Secondary purposes include confirmation of assumptions and standards in the LCRA Non-Point Source Technical Manual, and comparison of trophic conditions in the main body of the lake to that of backwater coves.

1.2 Methodology

The design of the Sandy Creek/Lake Travis NPS Water Quality Study is predicated on the concept of a scale model. Lake Travis is an impounded canyon formed by the Colorado River in the Texas Hill County. The reservoir is 64 miles long, its maximum width is 11,500 feet, and it impounds 1,170,052 acre-feet of water in the conservation pool. It is not economically feasible to collect sufficient data in the main water body and all of the embayments (backwater arms and coves) of the lake. For the purpose of this study it was necessary to find a representative embayment and tributary sub-watershed to serve as a scale model of the reservoir.

The watershed of Lake Travis within Travis County is fairly uniform in terms of geology, soils and vegetation, making it amenable to the scale model approach. Several potential study areas were considered, including Cypress Creek Arm, Sandy Creek Arm, Hurst Creek Arm and backwater areas of the Pedernales River. Sandy Creek Arm was selected because of its similarity to Lake Travis as a whole, in terms of morphology of the embayment, ratio of embayment volume to watershed area, percentage land use in the watershed, and occurrence of lakeshore development for direct measurement of non-point source pollution. Sandy Creek Arm has well-defined tributaries for measurement and sampling of runoff entering the lake. Furthermore, LCRA has gathered over ten years of lake monitoring data at one site (Sandy Creek Arm at Lime Creek), for historical reference.

2.0 Study Design

As previously mentioned, the Sandy Creek Study is designed to be a scale model of Lake Travis. Sandy Creek Arm is a microcosm of the main body of the lake. The embayment and tributary watershed are similar to that of Lake Travis as a whole. Therefore, results of the Sandy Creek Study should be applicable to the area covered by the Lake Travis Non-Point Source Pollution Control Ordinance.

2.1 Data Requirements

2.1.1 Runoff Data Requirements

Non-point source pollution enters Lake Travis in stormwater runoff. It was necessary to measure rainfall amount, duration and intensity using several tipping-bucket raingages in the watershed. Runoff was estimated by applying the well-established principle of stage-discharge relationships in streams with known stream channel geometry and flow characteristics. Stage was measured using pressure transducers calibrated with permanent staff gauges. Sampling of runoff was conducted using ISCO-brand automatic samplers capable of collecting and refrigerating flow-proportioned samples. Chemical analyses were performed by the LCRA Environmental Laboratory using EPA methods.

2.1.2 Lake Data Requirements

Profiles of temperature, pH, specific conductance and dissolved oxygen were measured using Hydrolab-brand portable probes and data loggers. Lake samples were collected at specific depths using a Kemmerer sampler. Samples were properly preserved in the field. Chemical analyses were performed by the LCRA Environmental Laboratory using EPA methods.

2.2 Field Installations

Runoff monitoring stations were established at locations where access was allowed near the shoreline of the lake, and where runoff could be reasonably estimated from accurate stage measurements. Lake sampling sites were located "downstream" of the confluence of tributaries with Sandy Creek Arm.

2.2.1 Runoff Monitoring Stations

Four runoff monitoring stations were established on major tributaries to Sandy Creek Arm, on Big Sandy Creek, Lime Creek, Collier Hollow, and the main drainage of the village of Jonestown. The Sandy Creek site was located in the small development of Pecan Terrace, near a low-water crossing which provided a stable channel cross-section. The Lime Creek site was located on available private property on a straight stretch of the stream where the channel is eroded into limestone bedrock. The Collier Hollow site was located at the overpass of FM 1431, where the passes through a double box culvert which provided a structural control for flow measurement. The

Jonestown site was located just upstream of low-water crossing which provided a stable channel cross-section. Enclosed shelters were erected at these sites for enclosure of the monitoring equipment. Electrical and telephone service was provided at the runoff monitoring stations for telemetry of stormwater data.

2.2.2 Lake Sampling Sites

Lake sampling sites were established at five sites in Sandy Creek Arm. The Sandy Creek lake site was located approximately 5,000 feet downstream of the confluence with Big Sandy Creek. The Jonestown lake site was located approximately 1,000 feet downstream of the confluence with the Jonestown drainage. The Collier Hollow lake site was located approximately 1,500 feet downstream of the confluence with Collier Hollow. The Lime Creek lake site was located approximately 4,000 feet downstream of the confluence of Lime Creek. A lake monitoring site was also located 5,000 downstream of Long Hollow, in the main body of Lake Travis. The lake sampling sites were located using a global positioning system (GPS) instrument.

2.3 Sampling Protocol

2.3.1 Flow-Proportioned Sampling

The runoff samples were collected using automatic, refrigerated samplers controlled by a totalizing flow meter. When the stage in the stream reached a trigger level, the sampler was initiated. This sample would represent the initial first flush of runoff from the watershed. After the first sample, the flow meter was programmed to collect samples when a certain quantity of flow had passed the gauge. The sample interval was set using a procedure to calculate the quantity of runoff from a design storm event.

The chosen design storm was the average annual storm event in Austin, Texas, which is 2 inches of rain falling in 24 hours (NOAA). The SCS curve number technique was used to calculate the amount of runoff (SCS, TP-40) from the average annual storm event. Watershed conditions including drainage area, slope, soils, vegetative cover and development were accounted for. This procedure determines peak discharge and total runoff from the watershed. Using these rainfall-runoff characteristics, the interval for stormwater sampling was calculated by dividing the total amount of runoff in cubic feet by the number of bottles in the sampler. The interval for flow-proportioned sampling was programmed into the flow meter, which sends a pulse to the automatic sampler when a sample is to be collected.

2.3.2 Sample Transfer & Handling

Runoff samples were stored in refrigerated samplers at 4 degrees centigrade until the samplers could be serviced. As soon as possible after the storm event, samples were transferred to new sample bottles, labeled and placed on ice for delivery to the LCRA Environmental Laboratory. Preservation of the samples was performed at the lab.

2.3.3 Chain of Custody

Standard LCRA Environmental Laboratory chain of custody forms were used to submit samples to the laboratory according to EPA protocols. These records are available in the project files.

3.0 Data Collection

3.1 Stormwater Runoff

Storm event data was collected during the period from December 1991 to June 1993. Rainfall and streamflow were measured continuously, although only the records of qualifying storm events were kept in separate data files. The monitoring stations were polled or visited on a biweekly basis, to assure that equipment was operational and calibrated. For example, height of water measured with transducers was checked against water stage observed on staff gauges installed in the streambed. This check was important in that streamflow was calculated from stage measurements.

3.1.1 Rainfall

Precipitation was measured using tipping-bucket raingauges. The raingauges were cleaned when needed and checked by opening the housing and "clicking" a certain number of times. This was checked against the corresponding rainfall amount on the data logger, in hundredths in inches. Malfunctioning gauge equipment was replaced.

3.1.2 Runoff Flow Data

Rating tables of stage vs. discharge were developed for each runoff monitoring station using standard open-channel flow equations. Stream channel geometry was measured by conducting surveys of cross-sections and profiles. Stream channel characteristics such as sedimentation, vegetative cover, channel armoring were accounted for. The rating tables were calibrated to the "point of zero flow" on permanent staff gauges set in the stream, and input directly into data loggers at each site. Pressure transducers were used to measure stage to the nearest 0.01 feet. The flow meters automatically convert stage to discharge in cubic feet per second, and log these values every ten minutes during a storm event. Rainfall data from tipping-bucket raingauges located at the runoff monitoring sites, as well as control data on when the automatic samplers were activated, were also fed into the flow meters. The flow meters were downloaded by telemetry after each storm event.

3.1.3 Runoff Water Quality Data

Rainfall intensity, water stage, streamflow and water quality were monitored at each runoff station. A total of 21 storm events were monitored between December 1991 and June 1993. Due to the vagaries of weather and watershed conditions, not all storm events were sampled at all stations. As of January 1994, records were available for a total of between 7 and 16 storm events at each runoff station. Table 1 shows the history of stormwater monitoring for the Sandy Creek Study.

3.2 Lake Water Quality

3.2.1 Ambient Data

Five lake monitoring sites were established in the cove of Sandy Creek Arm. Four of the lake monitoring sites were located downstream from the confluence of tributaries: Sandy Creek, Jonestown urban drainage, Collier Hollow, and Lime Creek. A fifth site was located in open water below Long Hollow to represent ambient conditions in the reservoir. The effects of NPS pollutant loading on the cove were measured at the five lake monitoring sites on a monthly basis.

3.2.1 Post-Storm Data

Two significant storm events occurred during the course of the Sandy Creek Study which had demonstrative effects on Sandy Creek Arm. The first was the flood of December 1991. Unfortunately, a safety-related boating ban on Lake Travis did not allow lake water quality samples to be collected in Sandy Creek Arm after the flood.

The second notable storm event occurred in June 1993. LCRA was able to sample Sandy Creek Arm three days after the storm. Post-storm lake water quality data from this event is discussed later in this report.

Table 1

MEASURED STORM EVENTS

STORM DATE	JONESTOWN	COLLIER H.	SANDY CR.	LIME CR.
12/08/91	X	X		
12/20/91		X	X	X
02/04/92				
05/16/92	X			
05/19/92	X			
05/21/92				
06/02/92		X	X	
07/18/92		X		
08/11/92	X	X		
09/21/92	X			
11/19/92	X			
12/15/92				
01/19/93				
02/09/93				
03/19/93				
04/07/93	X			
04/29/93	X			X
05/05/93	X			
05/23/93	X			
06/21/93		X	X	
TOTAL	10	6	3	2

4.0 Data Analysis

4.1 Watershed Characteristics

The Sandy Creek watershed was selected for this study because of its similarity to the larger Lake Travis watershed. Sandy Creek Arm, like Lake Travis, is a flooded steep-walled canyon within the Edwards Plateau. Both have major tributaries (Pedernales River contributes to Lake Travis; Sandy Creek contributes to Sandy Creek Arm). Both have slopes of 5 to 15 percent or greater near stream channels, geology is massive limestone and dolomite of the Glen Rose and Edwards Formations, soils are poorly developed thin clay loam, and vegetation consists of Juniper, oak and sumac assemblage (Garner & Young, 1976). Both have isolated lakeshore developments (Lakeway/Lago Vista to Lake Travis, Jonestown to Sandy Creek Arm). The topography of the study area is shown in Figure 5.

4.1.1 Watershed Area

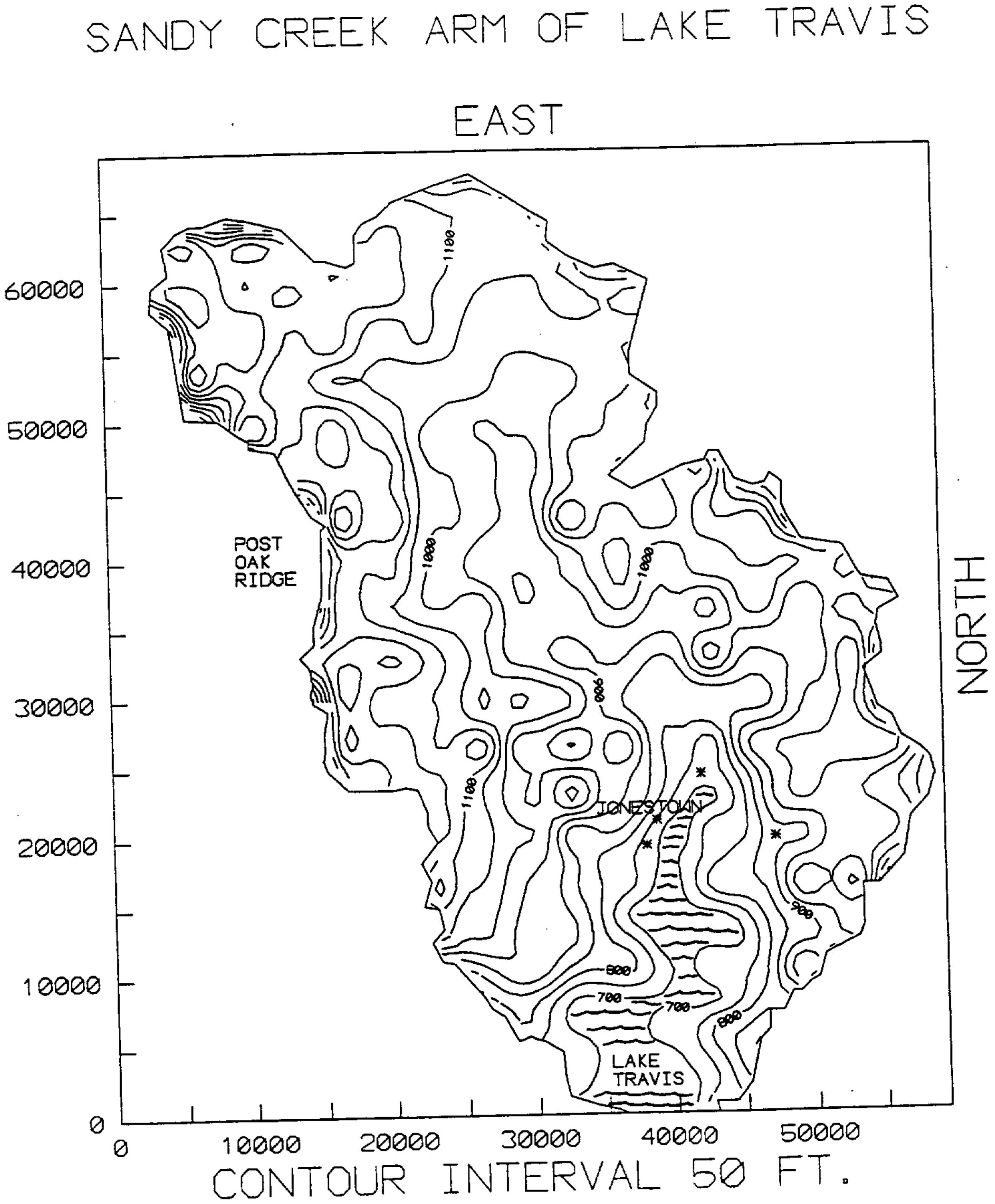
The area of the study area is about 37,000 acres, and the volume of Sandy Creek Arm is 37,400 acre-feet. Sandy Creek Arm has the same tributary area to volume ratio (1:1) as Lake Travis overall. Sandy Creek Arm is large enough to be a scale model of Lake Travis, and small enough for the effects of non-point source pollution to be measurable.

4.1.2 Geomorphology

The study area is part of the Edwards Plateau, in an area of steep ravines and mesas capped by hard limestone. The land surface has moderate relief, and soils are thin and clayey, resulting in relatively high rainfall-runoff relationships. However, good vegetative cover and non-intensive land use (mostly woodlands and pasture) have the effect of retarding runoff. Generally, when antecedent moisture conditions are dry, runoff does not occur from at least the first one-half inch of rainfall. When the soil becomes saturated, runoff rates can be high. Flash floods are a concern in the area.

Erosive rates of runoff and relatively high stream gradients have created a landscape characterized by steep hills and valleys. The topography of the study area is terraced, caused by layering of hard and soft beds of the Glen Rose limestone formation. Stream patterns in the study area are mostly controlled by the resistance of underlying limestone formations to erosion. Sharp bends in creeks occur where streams have encountered resistant bedrock. Almost no alluvial or floodplain deposits exist in the steep ravines. The ravines drain into canyons, the most prominent of which is the canyon of the Colorado River which has been inundated by Lake Travis.

Figure 5


SANDY CREEK ARM OF LAKE TRAVIS
EAST
NORTH
60000
50000
40000
30000
20000
10000
0
0
10000
20000
30000
40000
50000
POST
OAK
RIDGE
1100
1000
1000
900
1100
JONESTOWN
900
800
700
700
800
LAKE
TRAVIS
CONTOUR INTERVAL 50 FT.

4.1.3 Soils and Vegetation

Soils in the watershed of Sandy Creek Arm, like the watershed of Lake Travis as a whole, is controlled by the underlying geology. The Glen Rose formation, which underlies most of the area, is typically thinly bedded limestone (Garner & Young, 1976). The softer beds alternate with the harder beds, resulting in terraced topography with ledges and slopes, typical of the Texas hill country. Soils which have developed on the Glen Rose formation (Brackett and Tarrant series) are clay and clay loam soils, thinly bedded and poorly developed (SCS, Soil Survey of Travis County, 1975).

A revealing study is available on the development and erosion of soils in the region ("Microtopography, Runoff processes, Sediment Transport, and Their Implications for Land Use Planning in the Central Texas Hill Country", Marsh and Marsh, 1994). In that study, the authors challenge the common characterization of hill country soils as uniformly thin soils on steep slopes. Terraced topography has a stabilizing effect on soil erosion. The terraces have relatively little slope (>5 percent) and relatively good vegetative cover which hold the soils in place. The terraces have soil depths of several feet alternating with the ledges upon which little or no soil is developed. The authors argue that previous estimates of soil erodibility in the hill country may be too high. Lower values of soil loss are presented, accounting for terraced topography.

4.1.4 Land Use

Land use patterns in the Sandy Creek watershed were mapped from aerial photographs, as shown in Figure 6. Stormwater runoff contains pollutants derived from the land, and the type of land use determines the type and amount of pollutants. In terms of percentage land use, the watersheds of Sandy Creek Arm and Lake Travis have similar proportions, as shown in Figure 7. Therefore, the water quality of runoff from the Sandy Creek watershed should be similar to that of the Lake Travis watershed as a whole.

4.2 Lake Characteristics

4.2.1 Water Volume

Lake Travis contains 1,170,752 acre-feet of water at the conservation pool level of 681.1 feet MSL. Similar the main body of Lake Travis, Sandy Creek Arm is long, narrow and deep. At the Long Hollow site on Sandy Creek Arm, the lake is as much as

Figure 6

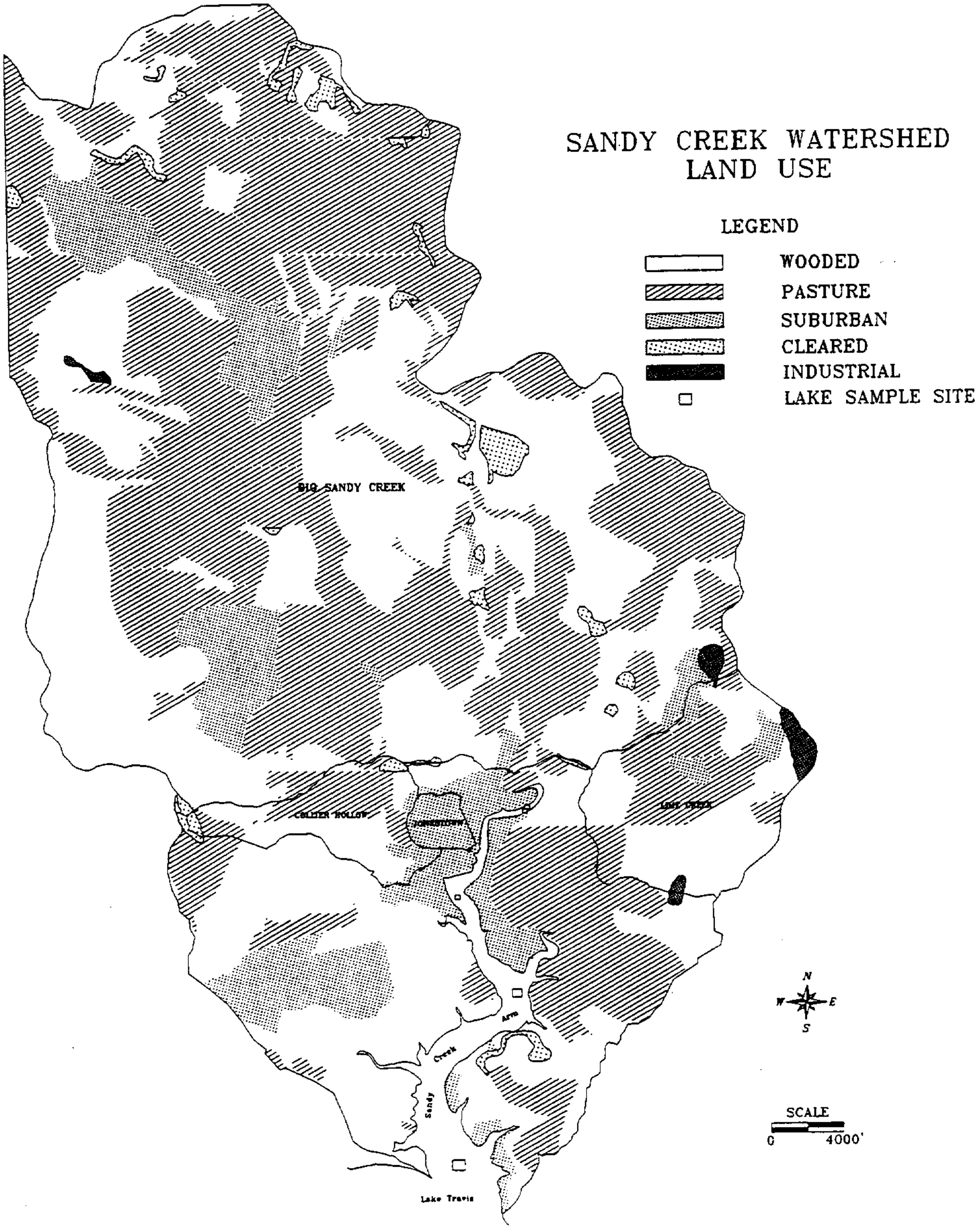
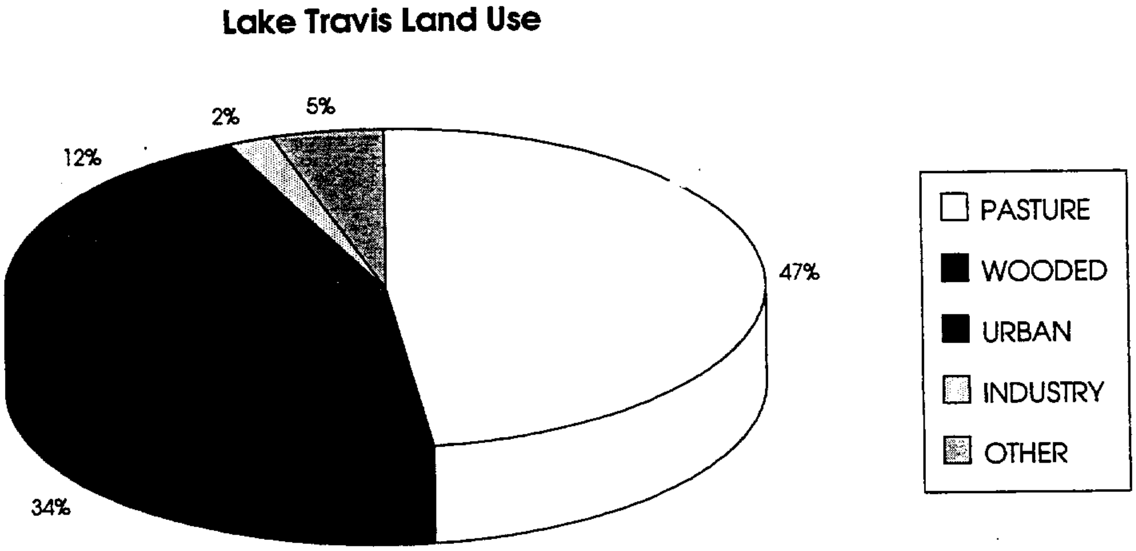
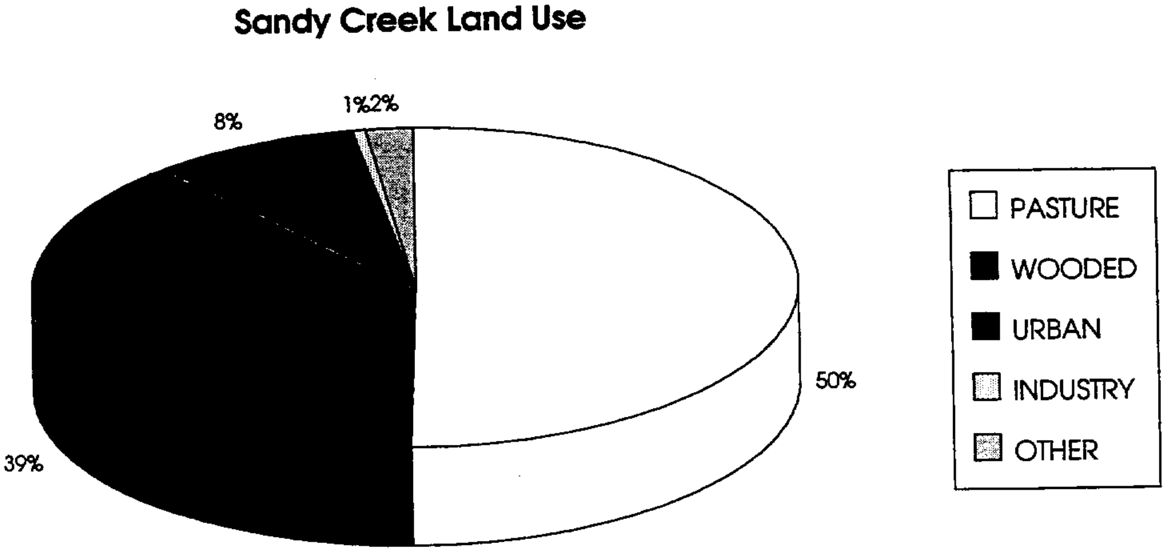

SANDY CREEK WATERSHED
LAND USE
LEGEND
WOODED
PASTURE
SUBURBAN
CLEARED
INDUSTRIAL
LAKE SAMPLE SITE
BIG SANDY CREEK
COLLIER HOLLOW
JONESTOWN
LIME CREEK
Sandy Creek Arm
Lake Travis
N
W
E
S
SCALE
0
4000'

Figure 7



Lake Travis Land Use
2%
5%
12%
47%
34%
PASTURE
WOODED
URBAN
INDUSTRY
OTHER



Sandy Creek Land Use
8%
1%2%
50%
39%
PASTURE
WOODED
URBAN
INDUSTRY
OTHER

120 feet deep. From bathymetric surveys of lake Travis conducted by LCRA, the flooded canyon of Sandy Creek Arm contains 37, 400 acre-feet of water at conservation pool level.

4.2.2 Geomorphology

Lake Travis is essentially an impounded series of canyons and feeder valleys carved into the Glen Rose limestone formation. The canyons of the Colorado River may be characterized as entrenched meanders. Side slopes in the canyons commonly exceed 30 percent. Impoundment of the canyons created a lake which is long, narrow and sinuous with many hundreds of miles of shoreline.

The LCRA recently completed a bathimetric survey of Lake Travis (LCRA, 1993). This survey was compared to the land survey performed before the closure of Mansfield Dam in 1941. Volumetric calculations based on contours of the lake bottom from soundings indicate that the storage capacity of Lake Travis has not changed appreciably in its 50 years of existence. The volume of Lake Travis has not been significantly reduced by sedimentation, despite heavy sediment inflows during the floods of the late 1950s and early 1990s, probably due to sediment capture in upstream reservoirs.

4.2.3 Limnology

The water in Sandy Creek Arm, like the downstream reaches of Lake Travis, is clear and warm. Light penetration and temperature are key factors in the limnology of the reservoir. The water color is consistently described as various shades of green due to moderate and seasonal amounts of phytoplankton. The lake develops strong thermal stratification in the warm summer months each year, and dramatic oxygen depletion occurs below the thermocline at a depth of 30-40 feet. Dissolved oxygen concentrations in the epilimnion are nearly always above the stream standard of 6.0 mg/L set by the Texas Natural Resource Conservation Commission (TNRCC). However, temperature and D.O. levels drop precipitously in the thermocline resulting in anoxic conditions in the hypolimnetic zone. The discharge penstocks in Mansfield Dam are set at depths well below the thermocline, and anoxic releases from Lake Travis into Lake Austin have occasionally been a concern.

4.2.4 Trophic Conditions

Several studies have shown that the trophic status of Lake Travis is oligotrophic (Cleveland & Armstrong, 1987; Miertschin, 1989; Rast & Slade, 1991). This means the lake generally has high clarity, low nutrient concentrations and low productivity. In other words, Lake Travis is still a young, healthy reservoir.

The previous studies of the trophic status of Lake Travis included limited data from Sandy Creek Arm. LCRA has monitored a site on Sandy Creek Arm below Lime Creek since 1982. In over 100 samples collected over a period of 14 years (excluding the 1991 Christmas flood), TSS did not exceed 10 mg/L and Chlorophyll-A did not exceed 0.01 mg/L. In many cases, TSS and Chl-A were at or below detection levels. These results are similar to those gathered at other sampling sites in the main water body of Lake Travis. The historical data show that Sandy Creek Arm responds to pollutant inputs, in terms of suspended solids and nutrients, in the same fashion as Lake Travis as a whole.

One reason why non-point source pollution has had minimal impact to date is that Lake Travis has a relatively small tributary area (1.12 million acres) compared to the volume of the reservoir (1.17 million acre-feet). The tributary-area/volume ratio for Lake Travis is one acre of land per acre-ft of capacity (1:1). By comparison, the ratio for Town Lake is 15:1, and the ratio for Lake LBJ is 23:1. The larger the ratio of tributary area to volume, the greater the potential for sedimentation and eutrophication (conclusion based on data from "Water Quality in the Lower Colorado River Basin", internal LCRA report, 1993; also Limnology, Wetzel, 1975). Town Lake has been described as a water body with a trophic status between mesotrophic and eutrophic (City of Austin, 1992). Studies are underway to assess the effects of eutrophication (sedimentation and excess algal growth) of Lake LBJ. LCRA showed its concern for Lake LBJ with passage of the Highland Lakes NPS Pollution Control Ordinance in 1992.

Another reason why Lake Travis is still oligotrophic is the low level of development within the tributary watershed. Studies have shown that the amount of non-point source pollution entering a water body is related to the amount of impervious cover in the watershed (Metropolitan Washington Council of Governments, 1987). The Texas Hill Country is a rural area, except for isolated lakeshore developments such as Lakeway and Lago Vista. With these exceptions, most of the watershed of Lake Travis is undeveloped rangeland. The Lake Travis NPS Ordinance was created in anticipation of planned development in the watershed.

4.3 Rainfall-Runoff Relationships

It was found that, starting with dry conditions in the study area, rainfall events of less than one inch failed to produce runoff in the undeveloped watersheds of Lime Creek, Sandy Creek and Collier Hollow. Generally, the first one-half to one inch of rainfall was lost to infiltration and evapotranspiration, depending on the antecedent moisture condition of the soil. Conversely, the Jonestown urban drainage exhibited immediate response of runoff to almost any rain event, due to small size of the subwatershed (208 acres) and higher amount of impervious cover (15-20%) from urban development.

4.3.1 Stormwater Hydrographs

In each watershed, the runoff response was highly variable from one storm event to another, but some patterns were evident. A representative stormwater hydrograph is shown in Figure 8. Rainfall from the summer thundershower of June 21, 1993 occurred over a period of less than two hours. Lag time between peak rainfall intensity and peak runoff was less than one-half hour. The rising limb of the hydrograph was steep, the peak rate of flow was short-lived, and the falling limb of the hydrograph was gradual. Most of the samples from this event were collected during the "first flush" of runoff (first 30 minutes) and during the period of peak flow. Sampling frequency relaxed as runoff from the storm event declined.

Groundwater was found to affect streamflow at two of the four runoff monitoring stations. The watershed of Sandy Creek contains over a dozen springs, according to USGS quadrangle maps. Throughout 1991 and 1992, low flow of 10-12 cubic feet per second was perennial in Sandy Creek during dry periods, with diurnal variations in flow which indicated evaporative loss during daylight hours and higher, consistent streamflow during nighttime hours. (Flow ceased in Sandy Creek during the drought in summer, fall and winter of 1993.) There are indications of sinkholes in the streambed of Lime Creek, which may contribute streamflow during dry periods and cause erratic response to rainfall events. This factors were taken into account in the analysis of pollutant loading data.

4.3.2 Pollutant Loading Calculations

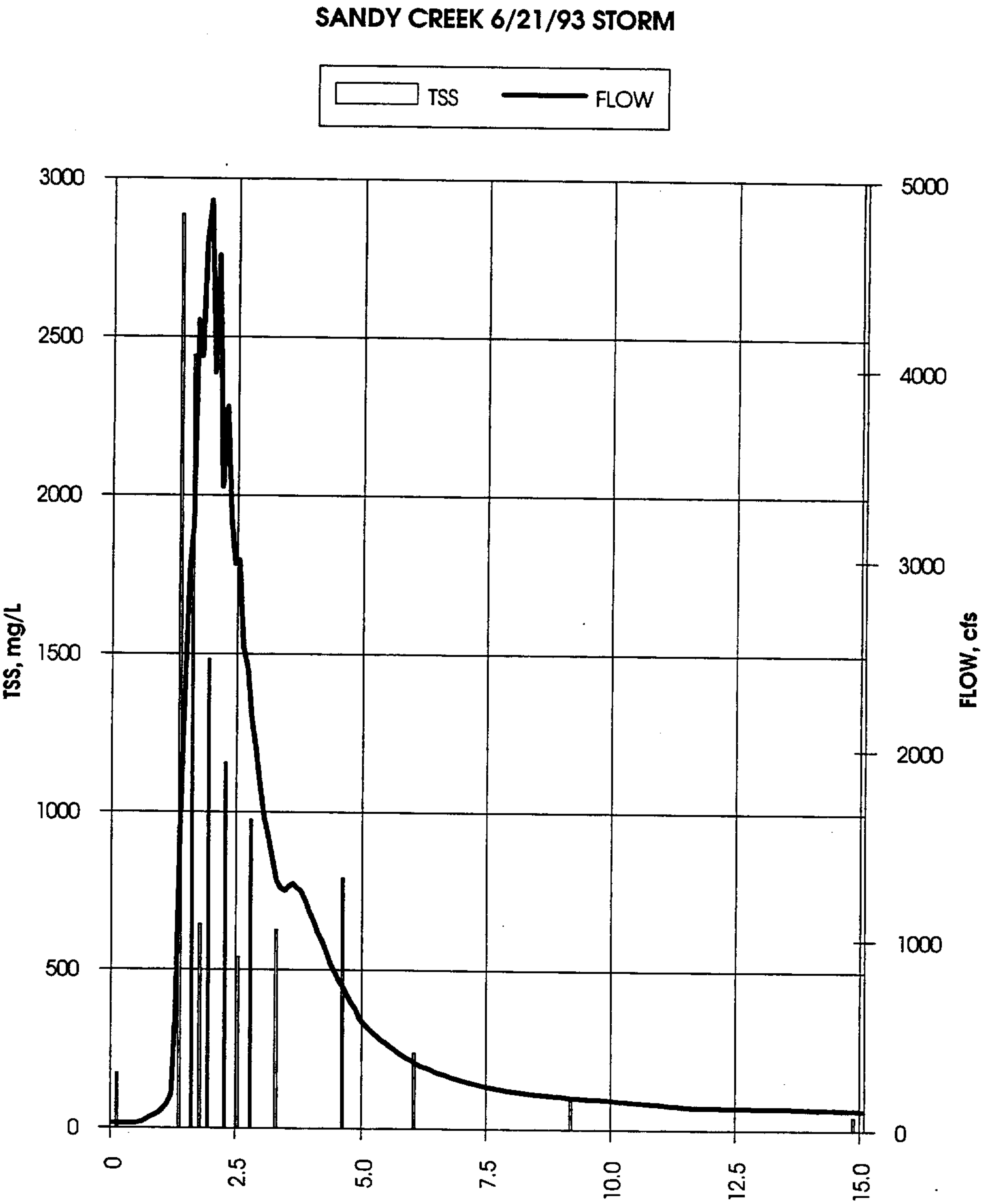
With the exceptions mentioned above, streamflow in the study area is intermittent; that is, the water table is always beneath the streambed and runoff occurs only in response to rainfall. This condition of zero baseflow allows the calculation of pollutant loading from individual storm events, using the following equation:

Mass = Flow Rate X Duration X Concentration

gram = liter/sec X seconds X milligram/liter X 1/1000 g/mg

The calculation shown above was performed for the interval of time represented by each sample collected during a storm event. The total loading of pollutants is simply the sum of sampled intervals. Pollutant loading from storm events at each runoff

Figure 8


SANDY CREEK 6/21/93 STORM
TSS
FLOW
TSS, mg/L
FLOW, cfs
3000
2500
2000
1500
1000
500
0
5000
4000
3000
2000
1000
0
0
2.5
5.0
7.5
10.0
12.5
15.0

monitoring site were calculated using spreadsheets. Loading calculations were performed for the following parameters:

total phosphorus
nitrate-N + nitrite-N
total organic carbon
total suspended solids

Two monitored rainfall events warrant individual discussion. The first is the Christmas flood of 1991. One of the most apparent effects of the flooding which resulted from heavy rains in December of 1991 was erosion and sedimentation in the Colorado River watershed; especially sediment loading of reservoirs such as Lake Travis. Other example was a well-documented storm event in June 1993. These events are described in the following sections.

4.3.2.1 Example #1: Christmas Flood of 1991

One of the most apparent effects of the flooding which resulted from heavy rains on December 20, 1991 was erosion and sedimentation in the Colorado River watershed; especially sediment loading of reservoirs such as Lake Travis. Records from runoff monitoring stations in the study area showed that the rainfall on December 20th reached an intensity of 2.4 inches of rain per hour. Peak flow in Big Sandy Creek near Jonestown was 1,500 cubic feet per second. The erosive force of this rate of runoff, in the steep ravines and valleys of the Texas Hill Country, was enough to detach and carry heavy sediment loads into Sandy Creek Arm.

Despite placement on elevated platforms, two of the runoff stations (Jonestown and Sandy Creek) were inundated by the record flood of Christmas 1991. Data from the flood event, however, was obtained from three of the four runoff monitoring stations, and all the stations were repaired after the flood.

From over 75 samples taken during the initial runoff event on December 20 and 21, the amount of sediment discharged into Sandy Creek Arm was as follows:

December 20-21, 1991:

Tributary	Watershed Area (sq.mi.)	Total Rainfall (inches)	Sediment Runoff (ac-ft)	Yield (tons/sq mile)
Big Sandy Creek	43.8	3.13	1,241	37.9
Lime Creek	3.8	3.10	58	25.5
Collier Hollow	1.7	3.14	21	13.0

The differences in sediment yield shown above between the watersheds tributary to Lake Travis was due to differences in land use, vegetative cover, slope, soils and other factors specific to each watershed. These partial data indicate that weighted average soil loss from the December 1991 flood exceeded 36 tons per square mile. This is a minimal estimate, because only the runoff resulting from the first 3 inches of rainfall was sampled. Total rainfall amounts in the Lake Travis watershed exceeded 10 inches.

The Soil Conservation Service estimated that the sediment yield from the North Grape Creek tributary to the Pedernales River was 31.9 acre-feet per acre, or approximately 395 tons/sq mile during the flood ("Erosion and Sedimentation Study of Selected Subwatersheds Above Lake LBJ and Lake Travis", SCS, 1992). These values may be compared to the average annual sediment yield in the Lake Travis watershed of 358 tons/sq mile ("A Comprehensive Study of Texas Watersheds and Their Impacts on Water Quality and Water Quantity", Texas State Soil and Water Conservation Board, 1991). Therefore, a substantial amount of sediment entered Lake Travis from the 50-year flood of December 1991. The tremendous influx of sediment from the Pedernales and upper Colorado River basins can only be estimated, because no runoff sampling was conducted during the flood except in the watershed of Sandy Creek Arm. However, sediment loading from the December 1991 flood did not have a measurable effect on the water storage capacity of Lake Travis, according to bathymetric surveys and volumetric calculations conducted by LCRA in 1993.

The flooding which washed tons of sediment into Lake Travis also brought in a significant amount of coliform bacteria and nutrients (nitrogen and phosphorus). The bacteriological contamination dissipated with time, but nutrients remained in the water until consumed by phytoplankton or settled to the bottom. In a method similar to that used for sediment loading, the amount of total phosphorus flushed into Sandy Creek Arm of Lake Travis was estimated as follows:

December 20-21, 1991:

Tributary	Watershed Area (sq.mi.)	Phosphorus Loading (pounds)	Maximum Conc. (mg/L)	Phosphorus Loading (lb/sq mile)
Lime Creek	3.8	65.8	0.97	17.3
Collier Hollow	1.7	11.9	1.10	7.0

These calculations indicate phosphorus loading of at least 7 pounds per square mile of watershed. The Sandy Creek Arm watershed is approximately 57.8 square miles, therefore total loading was about 405 pounds of phosphorus. This equates to a minimum of 153,000 grams of phosphorus into Sandy Creek Arm, which has a surface area of 1,888,000 square meters (0.08 grams per sq. meter). Phosphorus loading rates of 0.1 to 1.0 grams per square meter of surface area are potentially eutrophic

(Vollenweider, 1968). Therefore, the flood of December 1991 created temporary eutrophic conditions in Lake Travis. This condition lead to excessive growth of aquatic plants and algae. Severe algal blooms were reported in several coves of Lake Travis in April 1992, four months after the flood.

4.3.2.2 Example #2: June 1993 Storm Event

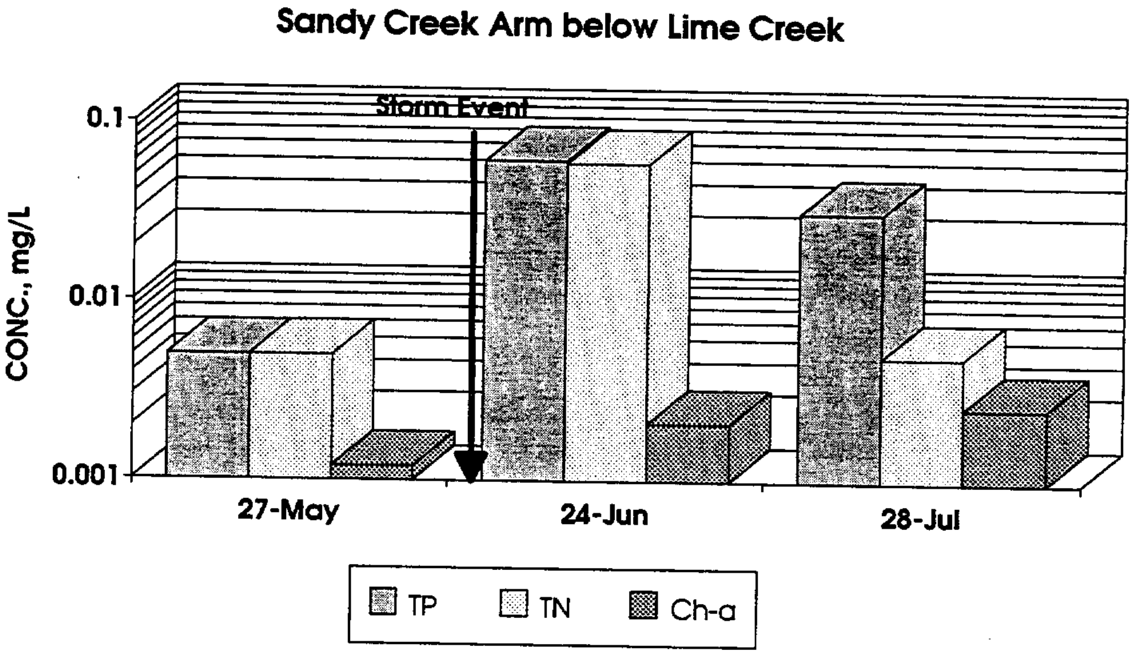
A well-defined, significant storm event occurred on June 21, 1993. There had been no significant rainfall for several weeks prior the storm, and no rain afterward for three months. Ambient water quality conditions had been measured at five sites in Sandy Creek Arm on May 27. Approximately 3.2 to 4.9 inches of rain fell in the evening of June 21, and runoff from the storm continued through the next day (June 22). Runoff samples were collected at all four tributary monitoring stations. Post-storm samples were collected in Sandy Creek Arm on June 24, and again on July 28. This was the most representative and well-documented storm event in the database for this study.

The storm event on June 21, 1993 resulted in loading of 350 pounds of nitrate-nitrogen, 1,367 pounds of phosphorus, 18.5 tons of total organic carbon, and 1,296.3 tons of suspended solids to Sandy Creek Arm from the four tributaries. Most of the sediment settled quickly and had little effect on TSS concentrations at a depth of one foot. However, clarity of the lake (as indicated by Secchi disk measurements) two days after the storm was less than that before the storm.

The most dramatic effect on water quality of the lake from the June 21 storm came from nutrient loading. At the five lake sampling sites between May 27 and June 24, available nitrogen (ammonia-N plus nitrate-N) went from non-detectable levels (<0.010) to an average of 0.045 mg/L. Phosphorus went up by a factor of 2 or more to 0.062 mg/L. After the storm, total P at all five sites was greater than the EPA criteria for eutrophic conditions of 0.025 mg/L (EPA, 1986), and was equal to or greater than 0.040 mg/L at three out of five sites.

By July 28 however, available nitrogen was back to non-detectable levels, and phosphorus went from a high concentration of 0.062 to a low of 0.031 mg/L in Sandy Creek Arm. From June 24 to July 28 (period of no rain after the storm), Chlorophyll-a levels went from an average of 0.0017 to as high as 0.0080 mg/L. Ch-a showed a consistent trend higher at sites progressively upstream. The data indicate that nutrient loading from the storm event caused increased productivity. Moreover, nitrogen was consumed at a faster rate than phosphorus, which was still at near-eutrophic levels when all available nitrogen was used up. These trends are shown in Fiqure 9.

Figure 9


Sandy Creek Arm below Lime Creek
Storm Event
CONC., mg/L
0.1
0.01
0.001
27-May
24-Jun
28-Jul
TP
TN
Ch-a

5.0 Computer Modeling

5.1 CE-QUAL-W2 Model

Data from the Sandy Creek NPS Water Quality Study has been used to calibrate a computer simulation of Sandy Creek Arm, for the purpose of analyzing various scenarios of future development in the watershed. In addition, the model can be used to simulate beneficial effects of pollutant removal as required under the Lake Travis Ordinance. The U.S. Geological Survey was under contract to utilize the Corps of Engineers CE-QUAL-W2 model for this exercise.

The CE-QUAL-W2 model is calibrated using runoff and lake water-quality data. The simulations have been performed to provide quantitative estimates of the effectiveness of the Lake Travis Non-Point Source Pollution Control Ordinance in protecting water quality. Three scenarios were modeled:

Scenario 1: Existing conditions
Scenario 2: Expected build-out conditions without the ordinance in place
Scenario 3: Expected build-out with the ordinance in place

The model chosen for use is CE-QUAL-W2, version 2, a two-dimensional, laterally averaged, hydrodynamic and water quality model. The model, under continuous development since 1975, is available from the Environmental Laboratory, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi. The source code and users manual is available from the Corps by mail or over the Internet.

CE-QUAL-W2 assumes lateral homogeneity and is best suited for relatively long and narrow water-bodies that exhibit water-quality gradients in both the longitudinal and vertical directions. The Sandy Creek embayment satisfactorily matches these model requirements. The model can be applied to rivers, lakes, reservoirs and estuaries.

5.1.1 Model Capabilities

CE-QUAL-W2 simulates lake hydrodynamics and transport as well as lake water quality. The following kinds of data are needed for application of the model:

a. Geometric data
b. Initial conditions
c. Boundary conditions
d. Hydraulic parameters
e. Kinetic parameters
f. Calibration and verification data

No attempt is made here to describe the theoretical and numerical basis of CE-QUAL-W2. This information is found in considerable detail in the Users Manual mentioned above and in numerous journal papers. CE-QUAL-W2 uses the laterally-averaged equations of fluid motion for six physical lake processes – horizontal momentum, constituent transport, free water surface elevation, hydrostatic pressure, continuity of mass, and an equation of state (density function dependent upon temperature, total dissolved solids or salinity and suspended solids). Lateral-averaging reduces the equations to two-dimensions (longitudinal and vertical dimensions) or the so-called x-z plane and greatly reduces computational time and storage that would be required with a three-dimensional calculation. Solution of the six equations is by numerical finite difference methods.

5.2 Model Application

5.2.1 Geometric Data

The most fundamental input task is assembling the geometric data. These data will be used to define the finite difference representation of Sandy Creek embayment. Figure 10 shows a bathimetric map of the embayment. From this contour map were obtained the bathymetric cross-sections used in the model input. The embayment was divided into 29 longitudinal segments each 1,000 feet in length. Segment 1 (most upstream) and 29 (most downstream) are external boundary segments.

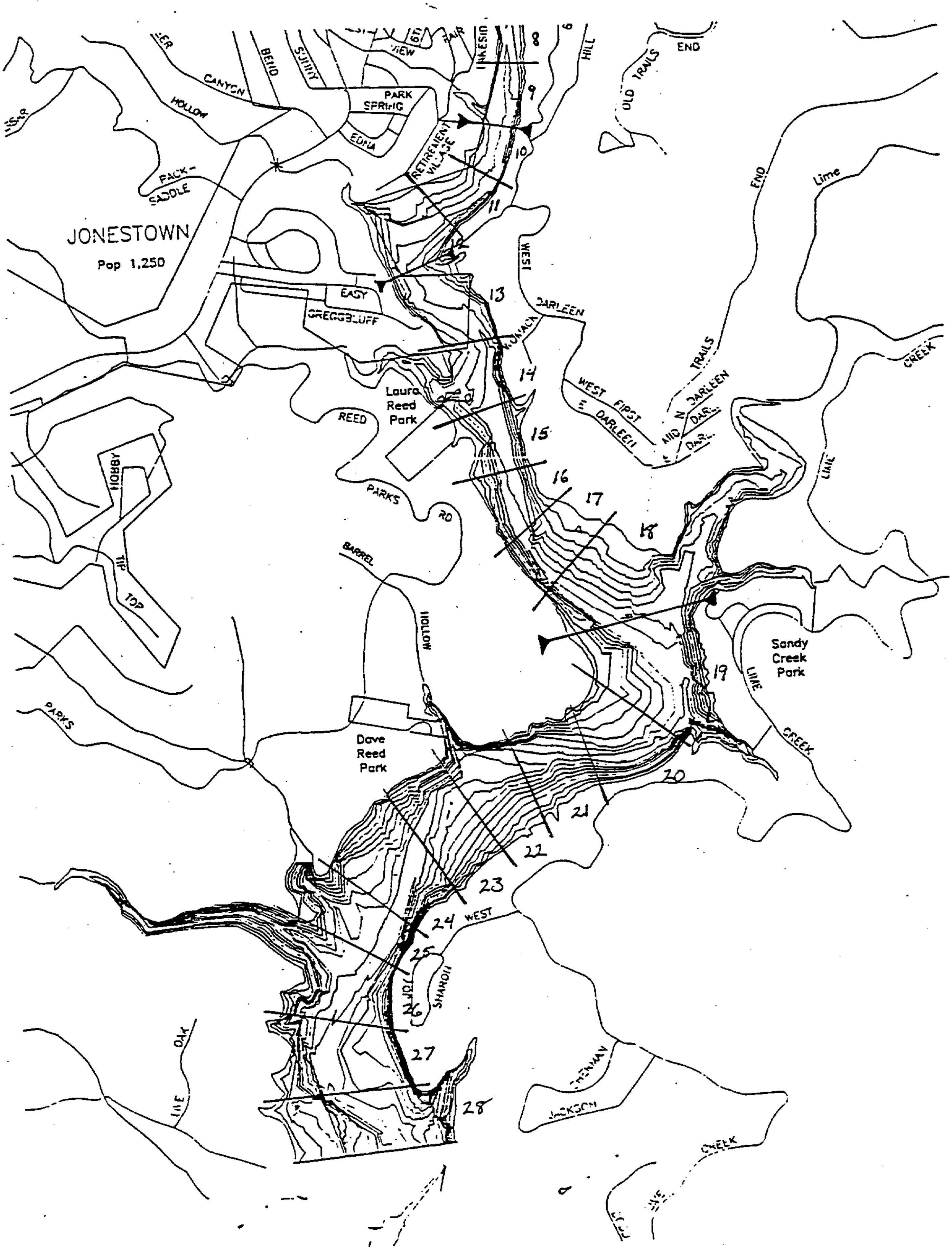
The geometric layout of the CE-QUAL-W2 model for Sandy Creek Arm is shown in Figure 11. The shaded portions of the plot represent a profile of Sandy Creek Arm from the headwaters at Sandy Creek to the main body of the lake near Starnes Island.

The embayment was divided vertically into as many as 17 layers, each 10 feet thick with layer 1 and layer 17 as boundary layers. The number of model layers decreased in the upstream direction in the embayment. The minimum elevation of the embayment is 170.68 meters above National Geodetic Vertical Datum. Tributary inflows and water-quality loads were placed at longitudinal segments 2, 9, 12, and 18 in the geometric framework of the model.

5.2.2 Initial Conditions

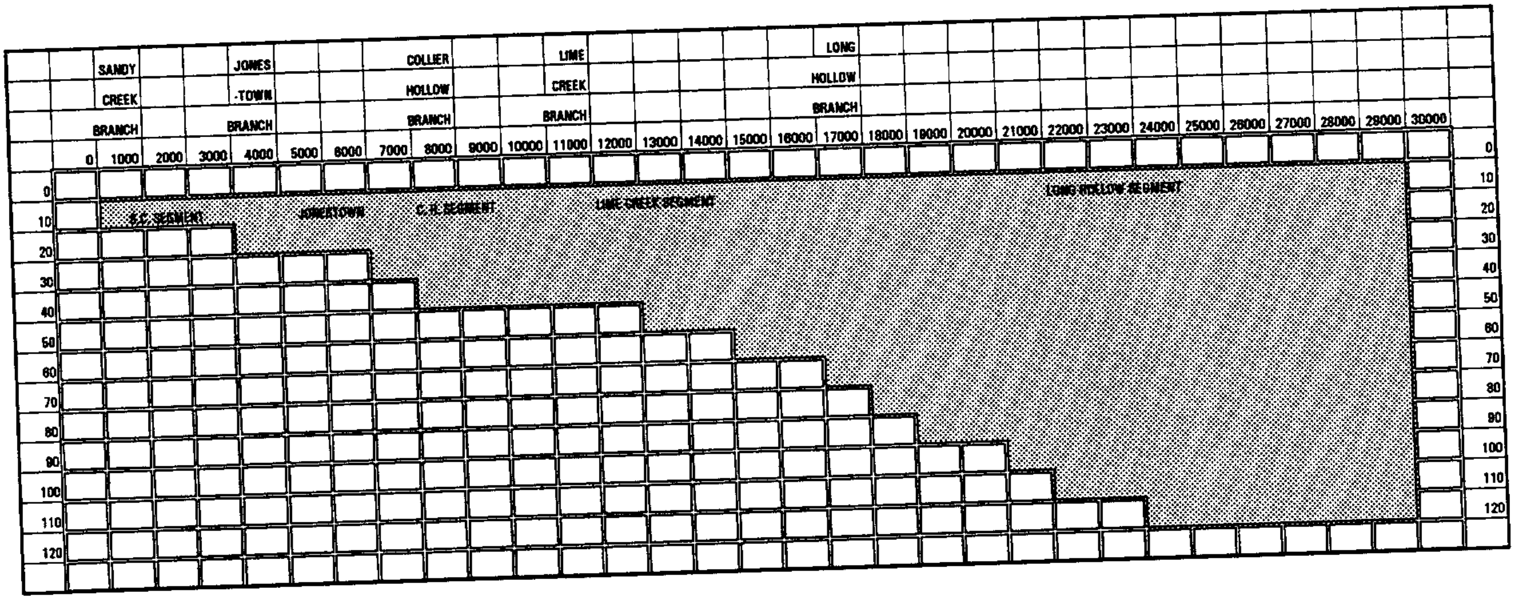
The initial conditions include starting and ending times of the simulation, starting water surface elevation, initial temperature and water quality constituent concentrations. Complete, field-measured vertical profiles were available for temperature, conductivity, dissolved oxygen and pH. Conductivity was used to estimate a total dissolved solids, (TDS) concentration by establishing a relation between TDS and conductivity using top and bottom layer measurements of TDS and conductivity measured in 1991. pH was not

Figure 10



JONESTOWN
Pop 1,250
CANYON
HOLLOW
PACK-SADDLE
BEND
SUNNY
VIEW
PARK
SPRING
EDNA
RETIREMENT VILLAGE
LAKESIDE
HILL
OLD TRAILS
END
EASY
GREGG BLUFF
WEST
DARLEEN
MONACK
WEST FIRST
E DARLEEN
N DARLEEN
TRAILS
END
Lime
CREEK
LIME
Laura Reed Park
REED
PARKS
RD
ABROII
TIP TOP
BARREL
HOLLOW
Sandy Creek Park
LIME CREEK
Dave Reed Park
PARKS
WEST
SHARON
JOHN
OAK
LIME
JACKSON
CREEK
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28

Figure 11


SANDY CREEK BRANCH
JONES-TOWN BRANCH
COLLIER HOLLOW BRANCH
LIME CREEK BRANCH
LONG HOLLOW BRANCH
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
18000
19000
20000
21000
22000
23000
24000
25000
26000
27000
28000
29000
30000
0
10
20
30
40
50
60
70
80
90
100
110
120
S.C. SEGMENT
JONESTOWN
C.H. SEGMENT
LIME CREEK SEGMENT
LONG HOLLOW SEGMENT

simulated. In addition, concentrations at top and bottom depths only were available at five vertical lake sampling points for chlorophyll A, TOC, TKN, NH_3, NO_3, NO_2, NO_2/NO_3, total Phosphorus, Ortho-phosphorus, TSS, and TDS. The measured top and bottom values for these constituents were averaged and the average value used for the entire profile. The choice of only top and bottom measurements for these constituents substantially reduced laboratory analysis costs.

Other constituents forming initial conditions were estimated as follows:

1. CE-QUAL-W2 includes one algal compartment and this algal value was obtained by multiplying chlorophyll A values by a conversion factor of 67.

2. Organic materials used in the model were assigned by ratios of the total organic carbon (TOC) concentration e.g. detritus = 0.2 TOC concentration.

3. Relations between TKN, NH3, NO2, NO2/NO3 were developed to fill-in missing data for NO2/NO3 and NH3 at tributary inflow sites using available data at nearest lake sampling vertical.

4. As CE-QUAL-W2 simulates biologically available phosphorous, ortho-phosphorus values were used as input.

5. TSS was measured in verticals at top and bottom and for watershed inflow loads.

5.2.3 Boundary Conditions

CE-QUAL-W2 requires external inflows, head, and water-surface boundary conditions. Inflows, (including nonpoint source loads from watersheds draining to Sandy Creek embayment), as boundary conditions were available for 18 storm runoff events. As seen, only one storm event produced runoff at all four watershed monitoring sites e.g. event of June 21, 1993. Flow data was available for each event but not all events had water quality data. Note, as described above, that watershed inflows and nonpoint source loads entered the model representing Sandy Creek embayment at longitudinal segments 2, 9,12, and 18. The actual hydrographs of storm flow were represented by a triangular hydrograph equivalent to the actual hydrograph by using the time-to-peak, total duration, and volume of storm runoff for each measured event.

The external head boundary condition at the downstream boundary was set at segment 29, some distance downstream from vertical sampling site 5. This choice means that Sandy Creek embayment is modeled in CE-QUAL-W2 much like an estuary. A file of time-varying elevations, vertical temperature profiles, and time-varying vertical profiles for all modeled water-quality constituents was provided at this boundary location. Internal head boundary conditions were calculated by the model at branch connections.

A concern of specifying an external downstream head boundary condition (required as measured boundary outflows were not possible) is that the specified boundary value may pre-determine internal model values. Thus, the calibrated model could be relatively insensitive to watershed inputs. As it turned out, this does not appear to be the case. Watershed flow and nonpoint source loads into Sandy Creek embayment are quite small compared to the assimilative capacity of the embayment. However, sensitivity analyses described below, with large simulated inputs, do evoke a water-quality response in the CE-QUAL-W2 calibrated model representing Sandy Creek embayment thereby indicating a reliable model formulation.

Surface boundary processes included surface heat exchange and wind speed and direction. Meteorological data was taken by NOAA Climate Data for Austin, Texas supplemented by data from the Applied Research Laboratory station near Lake Travis dam.

5.2.4 Hydraulic Parameters

Hydraulic parameters including horizontal and vertical dispersion coefficients, vertical eddy diffusivity and Chezy coefficient for model calculation of boundary friction were specified using typical values or were computed by the model internally.

5.2.5 Kinetic Parameters

Up to 60 coefficients can be specified for water quality constituent kinetics. Literature values, based on reasonable assumptions, were used.

Additional related water quality parameters for watershed input sites included estimates of dissolved oxygen (DO) and TDS in watershed flows. DO for inflows was assumed at saturation value calculated using air temperature and pressure readings from NOAA Climate Data for Austin area. TDS for watershed inflows were estimated using a regression relation (R2=0.52) between measured TDS and stream flow at a nearby USGS streamgaging station (Bull Creek at Loop 360). For other water quality constituents, a measured event mean concentration value was used with the triangular hydrograph representation of the watershed runoff events at each of the four watershed sites.

5.3 Model Calibration and Verification

For the Sandy Creek embayment application, it was decided to use a summer period for calibration and a winter period for verification, each of about four months duration. The summer period, during 1992 had the most number of sampled watershed runoff events. Both calibration and verification periods began and ended with observed vertical profile lake water quality data at up to five locations. By the study design, these vertical sampling sites (measured about monthly during the course of the investigation) were just downstream from the segments where the four watershed flow and nonpoint source loads enter Sandy Creek embayment. Water quality data at the fifth site, above the outlet of the embayment into Lake Travis, was specified as the external downstream head and water quality boundary condition. At this site, time-varying heads and interpolated values for all calculated water quality constituents were provided for all model computation time steps (internally determined in the model) by interpolation between daily Lake Travis water surface elevations and monthly sampled vertical water-quality.

According to the Users Manual, the usual sequence for calibration is to check the water budget first, then calibrate the hydrodynamics and temperature, and finally calibrate the water quality compartments. Because it was not possible to measure Sandy Creek embayment outflows due to deep water (over 100 feet) and low velocities, a water budget check was not possible. As mentioned, the "estuary case" was selected and the time-varying downstream Lake Travis water-surface elevation was specified. However, to avoid errors, the bathymetry, measured storm runoff volumes (generally small in comparison to embayment volume), and the possibility of evaporation computations (as part of surface exchange calculation) and seepage gains and losses, were carefully checked.

Next, coefficients affecting hydrodynamics and temperature were re-checked and simulated temperature profiles at the five lake vertical sampling sites were compared with observed, monthly temperature profiles. Finally, TDS and DO computed and observed profiles were compared at the five vertical sampling sites. For other water quality constituents i.e. those measured only at top and bottom of the profile, two-dimensional x-z contours of simulated values by CE-QUAL-W2 were generated for comparison with the few observed values and for overall reasonableness of model simulation.

Calibration of CE-QUAL-W2 is an iterative process whereby key model coefficients applicable to Sandy Creek embayment are adjusted until an adequate fit of observed versus predicted data is obtained. As stated in the Users Manual, "....there are no hard and fast guidelines for determining when an adequate fit is obtained. The model user must continually ask himself is the model giving reasonable results based on the model assumptions and data being supplied for use?"

Finally, verification of the CE-QUAL-W2 model for Sandy Creek embayment was performed by simulating a winter period – without model coefficient adjustment – and comparison with measured data for the same winter period.

5.4 Modeling Steps

5.4.1 Calibration

Using the above described procedures, a calibration procedure was performed for CE-QUAL-W2 for the "estuary case" using Sandy Creek embayment watershed flow and nonpoint source loads for a 1992 summer period. Storm loads for NH_3, TOC, NO_2/NO_3, PO_4, and TSS were computed on a storm-event basis as described above and these data were used in combination with monthly water-quality analyses at lake sampling verticals.

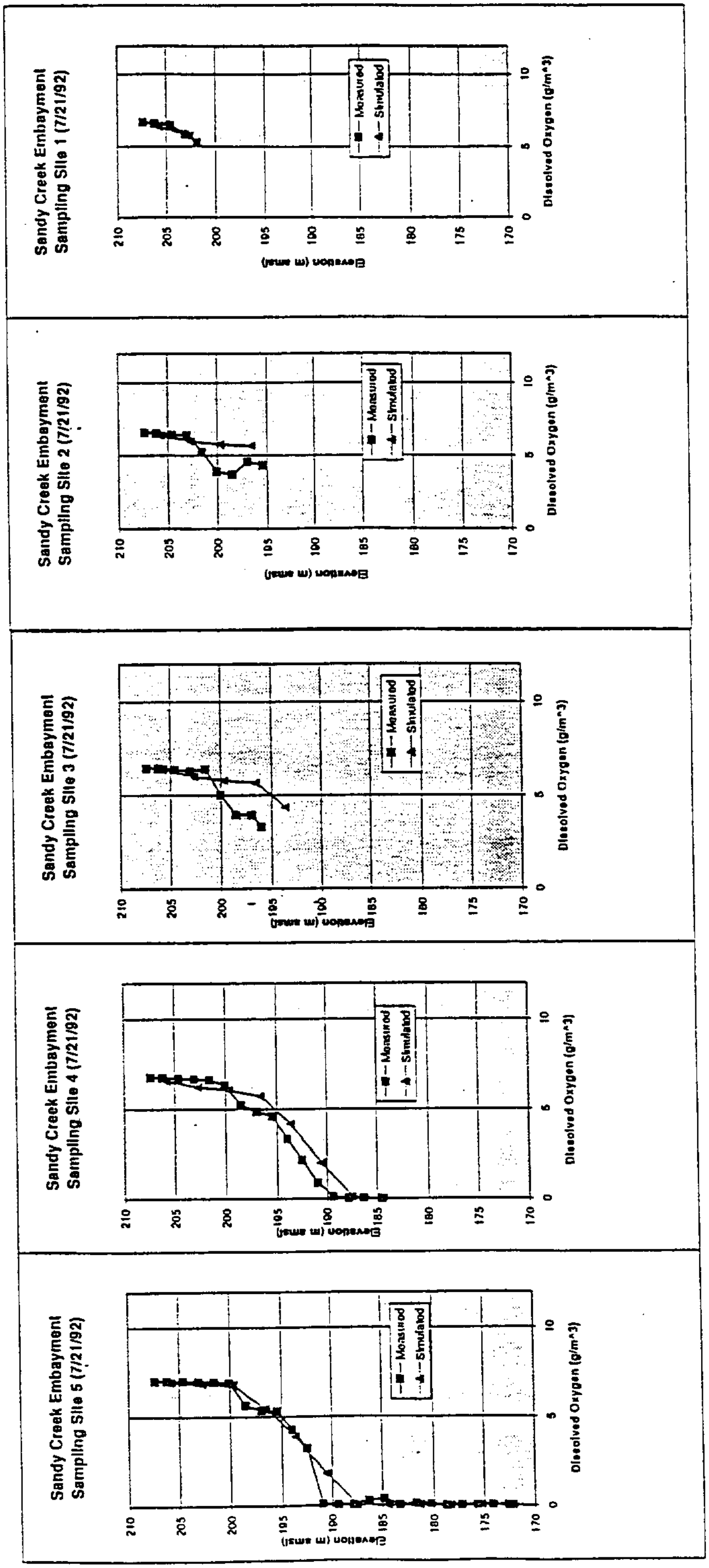
Figure 12 shows a series of vertical profile plots of measured versus simulated values for dissolved oxygen at the five sampling locations in Sandy Creek embayment for July 21, 1992. The DO profile shows close agreement between simulated and observed values on this date with the presence of a thermocline clearly indicated. By this time in the computation, the model simulation has been continuously computing for more than two months of simulation time. The dissolved oxygen profile, using an expanded set of interacting model parameters similarly shows adequate agreement between simulated and observed values, generally within about one g/m^3 (mg/l) of DO. These DO simulations appear to follow the processes observed and lead to anoxic conditions below depths of about 20 feet in Sandy Creek embayment. Similarly, the TDS profiles show close agreement. For each of the computed constituent profiles, results are somewhat poorer in shallow water.

Figure 13 shows x-z plane contour plots with computed results for phosphorus only, for July 6 and 21, 1992. Recall that measured vertical profile data are available only at five stations and only for temperature, TDS, and dissolved oxygen for the full profile. Hence, full comparison with measured data is not possible. However, in general, the x-z plane contour plots and the vertical (simulated versus observed) plots for the two summer days appear to provide reasonable results based on the model assumptions and the data supplied for use. The results shown are only representative of typical CE-QUAL-W2 simulations for a summer time period (stratified condition).

5.4.2 Verification

CE-QUAL-W2 for Sandy Creek embayment was verified for a winter period during February-March, 1993. No model parameters were changed from those values established during calibration. During winter, Sandy Creek embayment is well-mixed in the vertical, showing little variation with depth in temperature or dissolved oxygen. The comparison between computed and observed results are quite good and essentially verify the calibrated CE-QUAL-W2 model of Sandy Creek embayment for general use in both summer and winter conditions. The model appears to give reasonable results based on the model assumptions and data base used.

Figure 12


Sandy Creek Embayment Sampling Site 1 (7/21/92)

Sandy Creek Embayment Sampling Site 2 (7/21/92)

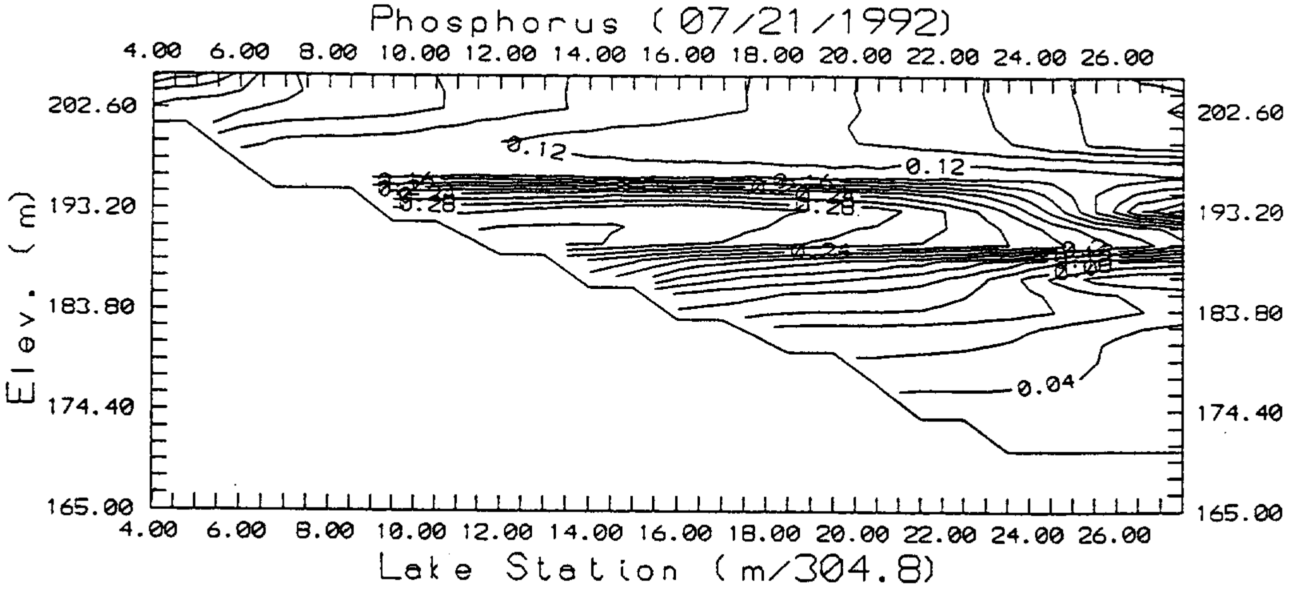
Sandy Creek Embayment Sampling Site 3 (7/21/92)

Sandy Creek Embayment Sampling Site 4 (7/21/92)

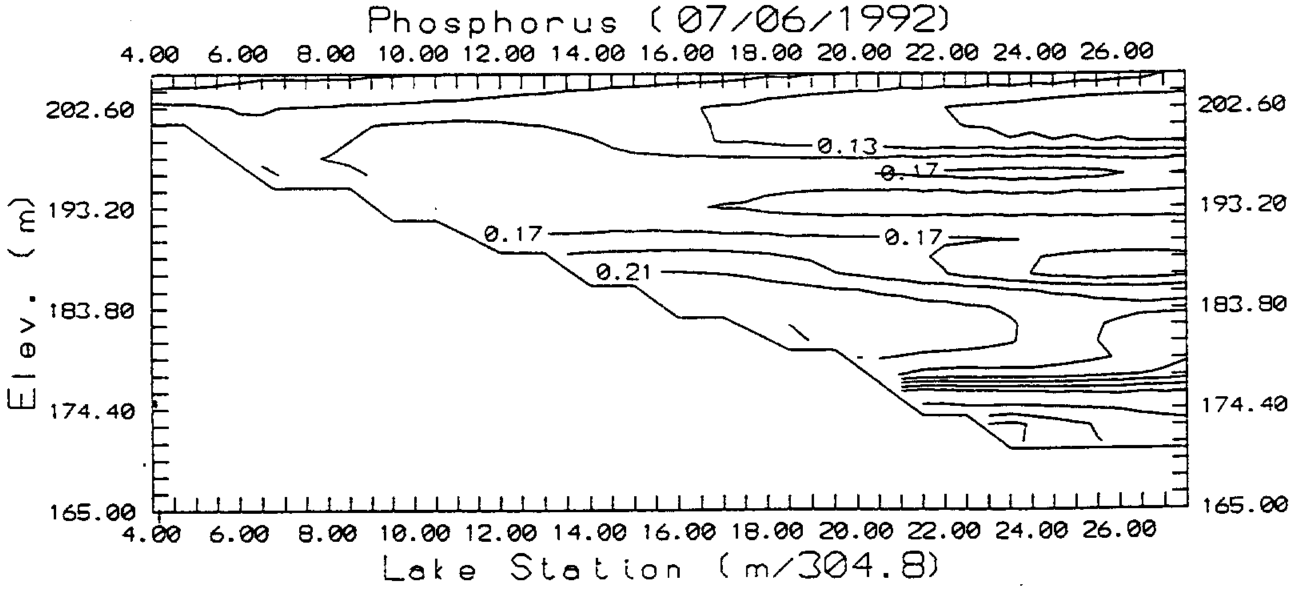
Sandy Creek Embayment Sampling Site 5 (7/21/92)

Figure 13

Scenario 2



Scenario 3



5.4.3 Simulation

Before proceeding with simulations for unobserved conditions, a series of sensitivity runs were made to further test the calibrated model.

a. Test 1 – Summer conditions. Increase orthophosphorous concentrations 100 percent at the downstream boundary. Hold all other conditions the same. The model responded in a reasonable way. The dissolved oxygen profile was shifted down by up to 1 g/m3 in response to the implied oxygen demand exerted by this nutrient increase. In more shallow locations, dissolved oxygen appeared to be slightly increased, perhaps due to increased algal concentrations.

b. Test 2 – Summer conditions. Ten-fold increase in phosphorous loads for all watershed storm water inputs. Hold other conditions the same. The model responded in a reasonable way showing algal concentration increases, especially in shallow water. It should be pointed out that even for a ten-fold increase in storm water loads for phosphorous, such loads are still relatively small.

5.5 Modeling Simulations

Following calibration, verification and model sensitivity analyses, the CE-QUAL-W2 calibrated model for Sandy Creek embayment was deemed satisfactory for simulation analyses, according to the study design plan. Before describing simulation analyses, several caveats should be mentioned relative to final model use and interpretation of results.

1. The model for Sandy Creek embayment appears to meet, reasonably well, all of the hydrodynamic and temperature assumptions. The "laterally averaged" assumption appears to offer no constraint on use. However, the use of the "estuary case" assumption with use of interpolated head and water quality values at the downstream boundary is a point of concern. This assumption, from the few checks made, does not appear to interfere with model use for simulation analyses. However, if expanded use of the CE-QUAL-W2 model for Sandy Creek embayment is intended, further study of this assumption is warranted. As alternative of the "estuary case" assumption is a full simulation of Lake Travis and computation of the downstream boundary condition within a larger scope of total Lake Travis lake modeling.

2. The model application also appears to meet reasonably well the water quality compartment assumptions although only a few water quality components were used. Several assumptions and approximations were necessary to overcome missing data. The watershed flow and nonpoint source data was well planned but

simulations were the same as used in summer and winter calibration analyses. The simulation was begun with no watershed runoff for 20 days, then two 1-year, 3-hour design events from all watersheds were input to the Sandy Creek embayment CE-QUAL-W2 model, spaced 30 days apart. Four sets of simulation calculations for scenarios 2 and 3 for both summer and winter periods were simulated.

5.5.2 Simulation Results

Seasonal scenarios of were modeled using data from August 17, 1992 for summer conditions and March 25, 1993 for winter conditions. The results are shown in Table 2 and Figures 14 and 15. The table displays dissolved oxygen values at the Lime Creek lake sampling site, as measured values compared to Scenarios 2 (fully developed w/o ordinance and Scenario 3 (fully developed w/ ordinance in place). The figures shows these data plotted for summer and winter conditions.

Figure 14 shows the effect of the ordinance on dissolved oxygen in summer. The stream standard for Lake Travis of 6.0 mg/L is shown as a vertical line. Increased nutrient loading and resultant algal growth and decay in Scenario 2 and 3 has the effect of reducing the concentration of dissolved oxygen. However, reductions in pollutant loading required by the ordinance has a consistently beneficial effect on DO. At a depth of 40 feet, DO is approximately 1 mg/L higher with the ordinance in place. In the epiliminetic zone above 40 feet, the TNRCC stream standard is maintained.

Figure 15 shows the same scenarios in winter. The lake is generally higher in dissolved oxygen concentrations in winter, and is not stratified. Nutrient loading due to development has the effect of reducing DO concentrations. According to the model, the 70 percent pollutant removal requirement does not have a measurable effect in the winter months. However, DO concentrations remain above the TNRCC stream standard.

Table 2

			CE-QUAL-W2 OUTPUT RESULTS					
			Dissolved Oxygen, mg/L or g/m3					
SUMMER CONDITIONS (meas. 8/17/92)				*Stream*	WINTER CONDITIONS (meas. 3/25/93)			
Depth	Meas.	Scen. 2	Scen. 3	*Standard*	Depth	Meas.	Scen. 2	Scen. 3
1	7.04	6.98	6.92	6	1	10.27	9.04	9.04
5	7.06	6.87	6.91	6	5	10.27	9.08	9.08
10	6.94	6.75	6.89	6	10	10.34	9.11	9.11
15	6.84	6.48	6.66	6	15	10.37	9.01	9.01
20	6.76	6.20	6.42	6	20	10.40	8.90	8.90
25	6.51	6.00	6.33	6	25	10.35	8.78	8.79
30	6.16	5.80	6.24	6	30	10.21	8.66	8.67
35	5.78	4.95	5.69	6	35	10.14	8.40	8.42
40	5.69	4.10	5.14	6	40	9.30	8.13	8.16
45	5.29	2.40	3.34	6	45	9.12	7.89	7.92
50	2.59	0.70	1.54	6	50	8.95	7.65	7.68
55	0.18	0.35	0.82	6	55	8.89	7.53	7.56
60	0.05	0.00	0.10	6	60	8.86	7.41	7.44
65	0.05	0.00	0.05	6	65	8.85	7.36	7.39
70	0.04	0.00	0.00	6	70	8.78	7.31	7.33
75	0.04	0.00	0.00	6	75		7.30	7.32
80		0.00	0.00	6	80		7.29	7.30

Figure 14

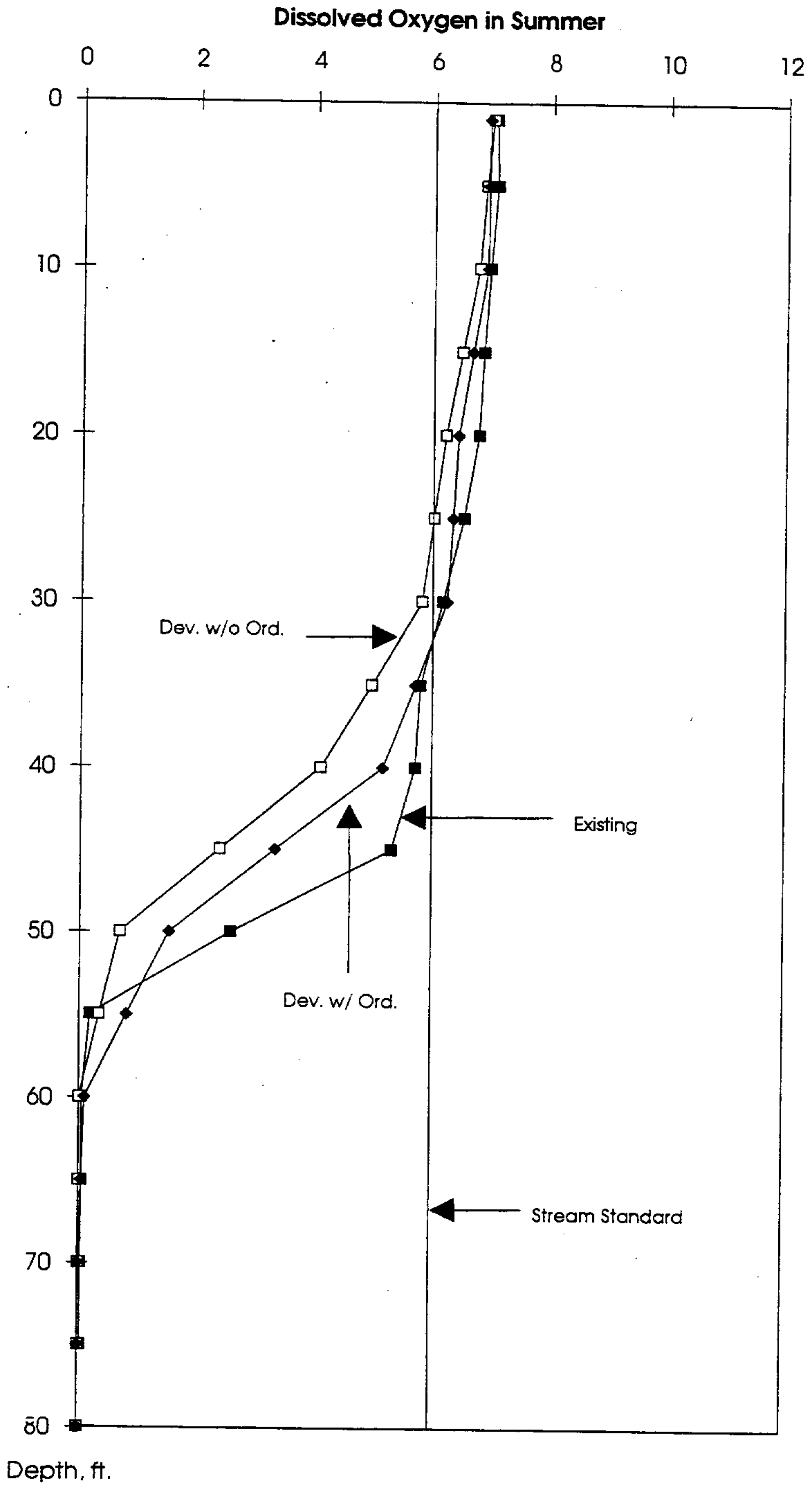
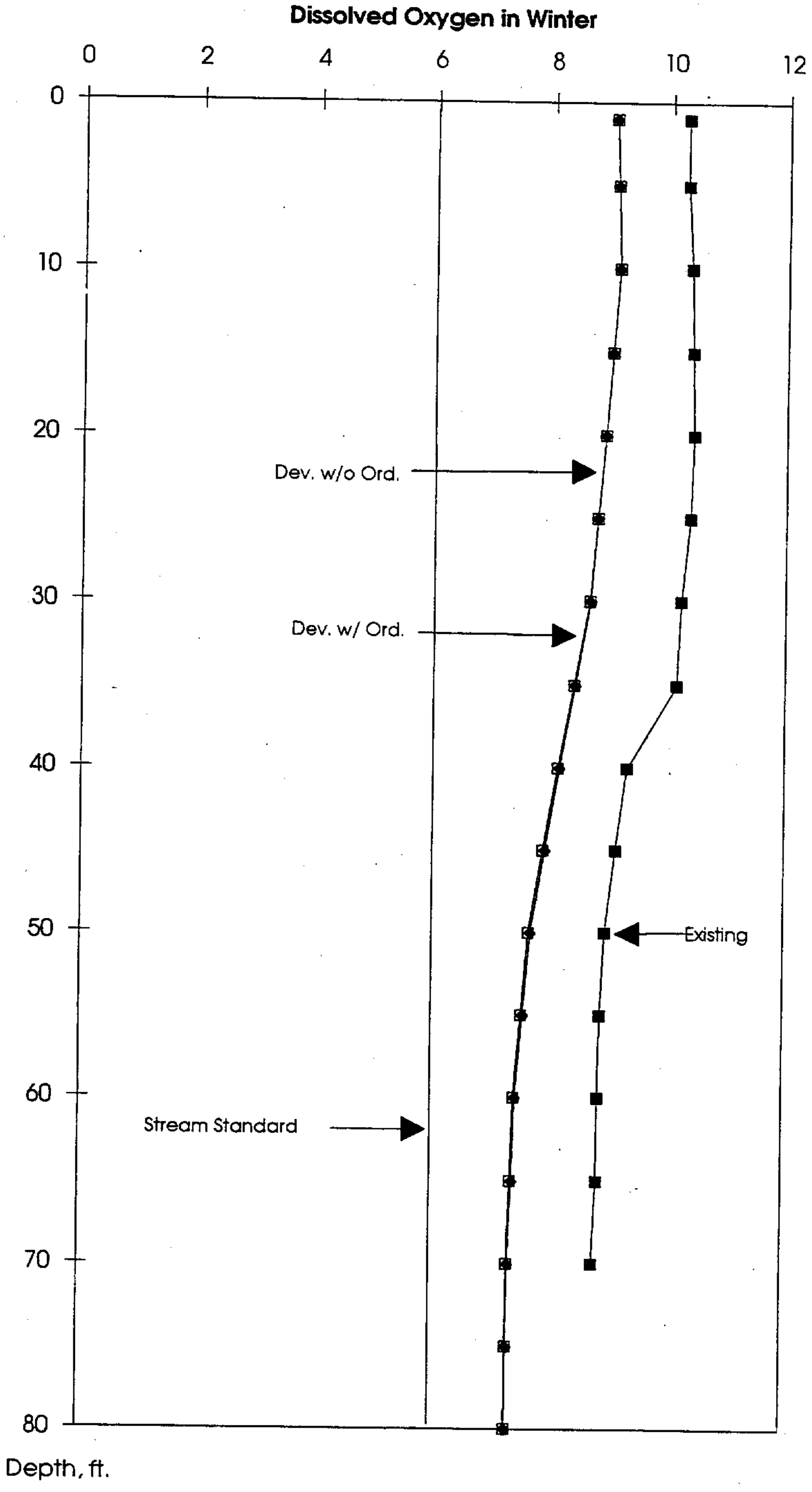

Dissolved Oxygen in Summer
0
2
4
6
8
10
12
0
10
20
30
40
50
60
70
80
Dev. w/o Ord.
Existing
Dev. w/ Ord.
Stream Standard
Depth, ft.

Figure 15


Dissolved Oxygen in Winter
0
2
4
6
8
10
12
0
10
20
30
40
50
60
70
80
Depth, ft.
Dev. w/o Ord.
Dev. w/ Ord.
Existing
Stream Standard

5.6 Modeling Results

Table 3 summaries the results of the CE-QUAL-W2 simulations of Sandy Creek Arm. It should be noted that there was wide variation in some parameters, but the following numbers are representative.

Table 3

SANDY CREEK STUDY - MODELING PARAMETERS & RESULTS			
	EXISTING CONDITIONS	FULLY DEVELOPED w/o ORDINANCE	FULLY DEVELOPED w/ ORDINANCE
PARAMETERS:			
Impervious Cover	5%	29%	29%
Annual Loading, TSS	540 tons	4725 tons	1795 tons
Annual Loading, TP	1795 pounds	18897 pounds	6926 pounds
RESULTS:			
Estimated TSS	4 mg/L	20 mg/L	10 mg/L
Estimated TP	0.05 mg/L	0.17 mg/L	0.12 mg/L
Estimated Chl-A	0.001 mg/L	0.008 mg/L	0.001 mg/L
Estimated D.O.	5.8 mg/L	4.9 mg/L	5.7 mg/L

Phosphorous is an important nutrient for consideration in water quality planning for Sandy Creek embayment and in Lake Travis. Phosphorous is a common fertilizer for lawns and is also a nutrient seen in waste-water. Phosphorous is also a regulated nutrient in the Lake Travis ordinance. Based on selected model simulated algal concentrations (chlorophyll-a), increased algal concentrations occur especially in shallow areas of Sandy Creek embayment where full light penetration and high water temperatures are common in summer months.

Phosphorous is an important nutrient for water-quality planning in Sandy Creek embayment. CE-QUAL-W2 analyses indicate that phosphorous is the limiting nutrient for at least the top 20 to 30 feet of the embayment. This result is consistent with model calculations which indicate that increased phosphorous loading due to land use impacts produces modest impacts on Sandy Creek embayment water quality.

Dissolved oxygen (D.O.) is a primary indicator parameter for eutrophication. The calibrated CE-QUAL-W2 model for Sandy Creek Arm indicates that during the summer months, when oxygen demands are highest, nutrient loading from uncontrolled development could have a negative effect on D.O.. However, the effect is only felt in the upper 20 to 30 feet of the embayment, and no significant effect is demonstrated in the winter scenario. Pollutant removal of 70 percent, as required by the Lake Travis Ordinance, lessens the impact in terms of D.O. In all cases, D.O. concentrations in the epilimnion (upper most, well-mixed layer) of the reservoir remain above the stream water quality standard for D.O. in Lake Travis (6.0 mg/L).

6.0 Conclusions

Measured and simulated water quality were compared to the 10-year LCRA water quality database for Sandy Creek Arm. The ambient conditions represented in the Reservoir and Stream Sampling (RSS) database compare well with the initial baseline condition simulated with the CE-QUAL-W2 model. Total suspended solids (TSS) concentrations in the database are generally very low (usually about 5 mg/L). Total phosphorous values are generally less than 0.1 mg/L; more recent data using better analytical techniques indicate typical concentrations around 0.05 mg/L. Chlorophyll-A concentrations are very low and seasonally distributed.

Empirical data and computer simulations indicate that Lake Travis is an oligotrophic reservoir with relatively high levels of dissolved oxygen. Computer simulations of the summer months when thermal stratification occurs, and winter months when the lake is not stratified, yielded different results. Non-point source pollution, in the form of nutrient loading, has the most impact on water quality in the summer months when oxygen demand is highest. Differences in dissolved oxygen concentrations resulting from pollutant removal, as required by the Lake Travis ordinance, are significant when compared to stream water quality standards. In the simulations of summer conditions without the ordinance in place, dissolved oxygen concentrations in the upper layer of the lake are at or below the stream standard of 6.0 mg/L for Lake Travis. Having the ordinance in place results in decreased phosphorus and chlorophyll concentrations, and an increase in dissolved oxygen of about 1 mg/L in the summer months. The calibrated CE-QUAL-W2 model for Sandy Creek Arm indicates that phosphorus is the limiting nutrient. Therefore, the Lake Travis ordinance is targeting the proper performance standard for nutrients.

Sedimentation of Lake Travis has not been a problem to date; however, protection of water clarity is appropriate for a lake used extensively for drinking water and contact recreation.

Regulation of TSS is necessary to protect these uses. Therefore, the ordinance is regulating the pollutants of concern, especially nutrients, in Lake Travis.

6.1 Relevance to Lake Travis NPS Ordinance

The Lake Travis non-point source ordinance contains performance standards for total suspended solids, total phosphorus and oil & grease. Required removal rates for these parameters are structured according to land slope and proximity to the lake. According to the technical manual for the ordinance (LCRA, 1991), these parameters were chosen to address three adverse impacts to lakes and reservoirs: sedimentation, eutrophication, and toxins.

Table 4

RESERVOIR ENVIRONMENTAL CONCERNS		
IMPACT	PARAMETER	REASON
Sedimentation	Suspended Solids	Addresses siltation, excessive plant growth, attached pollutants.
Eutrophication	Total Phosphorus	Addresses excessive plant growth, algal blooms, oxygen depletion.
Toxins	Oil & Grease	Addresses petroleum hydrocarbons, toxic organic compounds.

The Sandy Creek NPS Water Quality Study has developed site-specific data on the effect of non-point source pollution on the water quality of Lake Travis.

6.1.1 Ordinance Assumptions

The Sandy Creek NPS Ordinance, by design, is not a non-degradation ordinance. It allows a reasonable amount of increased pollution to Lake Travis. The ordinance requires a minimum removal of 70% of the increase in pollution due to development. The amount of pollution released from areas with high percentage of impervious cover is several times that of native land. The pollutant loading of Lake Travis could be increased by 30% of that amount, plus the level of "baseline" pollution.

One of the tacit assumptions in the ordinance is that allowable increases in pollution will not result in impediments to water usage related to water quality. Use attainability studies for Lake Travis (Segment 1404) have not resulted in stream standards for TSS, Phosphorus nor Oil & Grease (TNRCC, 1992). There are no "go-by's" for the parameters in the ordinance; only professional judgement of officials of the LCRA.

At this time, it is known that non-point source pollution from stormwater inflow does create temporary eutrophic conditions in some parts of Lake Travis. High TSS and nutrient concentrations from storms in December 1991 and June 1993 have lead to algal blooms and relatively high concentrations of Chlorophyll-a, indicating higher short-term primary productivity. However, the attenuation capability of a 1.17 million acre-foot reservoir like Lake Travis is considerable. It must be said that non-point source pollution has had no measurable long-term effect on Lake Travis to date. The question is, how much development would it take to cause measurable impact, and how much protection would be required?

6.1.2 Ordinance Exemptions

Land platted as of Feb. 1, 1990 (the effective date of the ordinance) is exempted from the performance standards. The actual baseline level of pollution under the current ordinance is that which could result if all exempted properties were to be developed. Agricultural activities, including livestock pasturing and use of the land for planting, growing, cultivating and harvesting crops are also exempted. The Lake Travis Ordinance would be more effective if their were a "sunset clause" for exemptions of pre-existing platted but undeveloped land.

6.1.3 Ordinance Parameters

The three parameters used as performance standards in the Lake Travis ordinance represent the kinds of pollution LCRA wishes to control. By comparison, the City of Austin Save-Our-Springs (SOS) Ordinance contains thirteen parameters, some of which are whole classes of pollutants by themselves (volatile organic compounds, pesticides, herbicides). LCRA has taken a less strenuous but still conservative approach which does not unnecessarily impede development of the Lake Travis watershed.

Total Suspended Solids (TSS) consists of colloidal and settleable particulate matter. In areas of high pH and alkalinity (such as the Highland Lakes), toxic metals tend to precipitate and become suspended solids. These elements may attach to sediment particles or flocculate and settle to the bottom. In addition, some relatively insoluble organic compounds, such as chlordane and PCBs, tend to be adsorbed onto sediment particles. Thus treatment for TSS can result in removal of other pollutants.

TSS is used as an effluent limitation parameter in the EPA National Pollutant Discharge Elimination System, and in other federal and state environmental programs. From an engineering standpoint, Settleable Solids is a parameter which can be used to design treatment facilities without need for extended detention; however, TSS includes colloidal sediment which impacts water clarity and should also be removed from runoff.

Total Phosphorus is a substance for which water can be effectively treated, and to some extent be eliminated from the environment through phosphate detergent bans, etc. However, data from this study and others indicate that phosphorus is not the limiting nutrient in Lake Travis (Cleveland & Armstrong, 1987; Miertschin, 1989; Rast & Slade, 1991). Reduction of phosphorus alone would probably not prevent algal blooms and excessive aquatic plant growth. However, as stated in the introduction to the Technical Manual, best management practices for the removal of phosphorus from runoff have the effect of removing some amounts of certain forms of nitrogen as well. For example, removal of nutrients by plant uptake covers forms of phosphorus and nitrogen, and extended detention can result in volatilization of ammonia-nitrogen.

Oil and Grease is a "basket category" of toxic organic compounds including petroleum hydrocarbons, but non-toxic compounds such as vegetable oils, animal fats and waxes. It is the former group which contain known carcinogens such as benzene and many other toxic chemicals. Volatile, semi-volatile and non-volatile organics are included in the category of Total Petroleum Hydrocarbons (TPH). Chlorinated compounds including pesticides, herbicides and other hazardous chemicals are persistent in the environment and should be removed. Treatment of water for Oil & Grease by separation, air stripping or carbon absorption may result in removal of chemicals classified as hazardous. If analyzed at an acceptable detection limit, the absence of Oil & Grease indicates that the total concentration of organic compounds is minimal, although the concentration of one or more hazardous chemicals may be toxic.

6.2 Study Conclusions

Measured and simulated water quality were compared to the 10-year LCRA water quality database for Sandy Creek Arm. The ambient conditions represented in the Reservoir and Stream Sampling (RSS) database compare well with the initial baseline condition simulated with the CE-QUAL-W2 model. Total suspended solids (TSS) concentrations in the database are generally very low (usually about 5 mg/L). Total phosphorous values are generally less than 0.1 mg/L; more recent data using better analytical techniques indicate typical concentrations around 0.05 mg/L. Chlorophyll-A concentrations are very low and seasonally distributed.

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