NATURAL SALT POLLUTION AND WATER SUPPLY RELIABILITY IN THE BRAZOS RIVER BASIN

By

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TABLE OF CONTENTS

TABLE OF CONTENTS iii

LIST OF TABLES v

LIST OF FIGURES vii

CHAPTER 1 INTRODUCTION 1

- Statement of the Problem 1
- Scope of the Study 1
- Organization of the Report 2
- Study Organization and Sponsors 3
- Prior Studies 3

CHAPTER 2 THE BRAZOS RIVER BASIN 5

- Basin Description 5
- Reservoirs 7
- Water Use 12

CHAPTER 3 COMPILATION AND ANALYSIS OF MONTHLY SALT LOADS AND CONCENTRATIONS 17

- USGS Sampling Program 17
- Basic Data Files 18
- Overview Summary of Data 21
- Spatial Variations 22
- Temporal Variations 23
- Salt Concentration Versus Discharge Relationships 24

CHAPTER 4 ANALYSIS OF IMPACTS OF SALT CONTROL DAMS BASED ON ADJUSTMENTS TO MEASURED DATA 51

- Salt Control Impoundments 51
- Mean Discharges, Loads, and Concentrations 53
- Concentration-Duration Relationships 56
- Computational Procedures 57

CHAPTER 5 DEVELOPMENT OF A COMPLETE SET OF UNREGULATED MONTHLY SALT LOADS AND CONCENTRATIONS 67

- Monthly Data for 1964-1984 67
- Discharge Versus Salt Load Regression Equations 75
- Mean Salt Concentrations on Good Quality Tributaries 90
- Combination of Salinity Data with Naturalized Flows 90
- Previously Proposed Salt Control Impoundments 92
- Addition of a Random Component to the Salt Loads 99

TABLE OF CONTENTS (Continued)

CHAPTER 6 RESERVOIR SYSTEM SIMULATION STUDIES 109

Scope of Simulation Analyses 109
RESSALT Model 109
Brazos River Basin System 111
Hydrologic Input Data 114
Measures of System Reliability 115
Organization of the Simulation Study 117

CHAPTER 7 RESERVOIR SYSTEM SIMULATION FOR ALTERNATIVE WATER USE SCENARIOS 119

Water Use Requirements and Reservoir Operating Policies . 119
Simulation Runs 121
Overall System Water and Salt Load Balance 123
Comparison of 1900-84 and 1964-84 Simulation Periods 126
Comparison of Predevelopment, 1984, and 2010 Conditions of River Basin Development 126
System Reliability for 1984 and 2010 Water Use Scenarios With and Without Salt Constraints 128
Impacts of Proposed Salt Control Impoundments 130
Alternative Sets of Unregulated Loads 131
Negative Incremental Streamflows and Salt Loads 137

CHAPTER 8 RESERVOIR SYSTEM YIELD/RELIABILITY ANALYSES 139

Water Use Requirements and Reservoir Operating Policies . 139
Relationships Between Yield, Allowable Salt Concentrations, and Reliability 140
Comparison of Alternative Salt Constraint Operating Plans 141
Evaluation of Reservoir Storage Reallocations 155
Impacts of Proposed Salt Control Dams 158
Effects of Alternative Sets of Unregulated Loads 158

CHAPTER 9 SUMMARY AND CONCLUSIONS 165

Natural Salt Pollution in the Brazos River 165
Water Supply Reliability 166
Management Strategies 167
Generalized Modeling and Analysis Capabilities 168

REFERENCES 169

LIST OF TABLES

2.1 Reservoirs Included in Simulation Study 8
2.2 Reservoir Data 9
2.3 Conservation Storage Capacities for 1984 and 2010 Conditions of Sedimentation 11
2.4 1984 Water Use 12
2.5 1984 Water Use Comparison 14
3.1 Selected USGS Streamflow Gaging and Water Quality Sampling Stations. 19
3.2 Mean Discharges, Loads, and Concentrations for Period-of-Record ... 25
3.3 Mean Discharges, Loads, and Concentrations for Comparable Time Periods 26
3.4 Concentration-Duration Curves for Total Dissolved Solids 42
3.5 Concentration-Duration Curves for Chloride 43
3.6 Concentration-Duration Curves for Sulfate 44
4.1 Mean Discharges, Loads, and Concentrations for 1964-1986 54
4.2 Mean Discharges, Loads, and Concentrations for 1969-1977 54
4.3 1969-77 Mean Discharges and Loads for Stations 3, 4, and 6 (Plan 1) as a Percentage of Downstream Stations 55
4.4 1969-77 Mean Discharges and Loads for Stations 4 and 6 (Plan 2) as a Percentage of Downstream Stations 55
5.1 Outline of Computational Tasks Involved in Developing the Salinity Data Set 68
5.2 Completeness of Measured Data 71
5.3 Regression Equations Used to Fill in Missing Data 72
5.4 1964-1984 Mean Regulated Discharges, Loads, and Concentrations 76
5.5 1964-1984 Mean Unregulated Discharges, Loads, and Concentrations .. 76
5.6 Comparison of Measured, Regulated, and Unregulated Mean Discharges . 77
5.7 Comparison of Measured, Regulated, and Unregulated Mean TDS Loads .. 77
5.8 Comparison of Measured, Regulated, and Unregulated Mean TDS Concentrations 77
5.9 Regression Coefficients Used to Extend Unregulated Salt Loads 89
5.10 Mean Discharges, Loads, and Concentrations for Stations 19 and 20 .. 91
5.11 Statistics for 1900-84 Unregulated Discharges 94
5.12 Statistics for 1900-84 Unregulated TDS Loads 94
5.13 Statistics for 1900-84 Unregulated Chloride Loads 95
5.14 Statistics for 1900-84 Unregulated Sulfate Loads 95
5.15 Means for 1964-84 Unregulated Discharges and Salt Loads 96
5.16 Means for 1964-84 Discharges and Loads at Stations 3, 4, and 6 97
5.17 Discharge and Load Multipliers Representing the Effects of the Salt Control Impoundments 97
5.18 Mean Unregulated TDS Concentrations With and Without the Salt Control Impoundments 98
5.19 Mean Unregulated Chloride Concentrations With and Without the Salt Control Impoundments 98
5.20 Mean Unregulated Sulfate Concentrations With and Without the Salt Control Impoundments 98
5.21 Statistics for the 1964-84 Measured Loads at the Richmond Gage 101
5.22 Statistics for Random Deviation from Expected Values of 1900-84 TDS Loads 103
5.23 Statistics for Random Deviations from Expected Values of 1900-84 Chloride Loads 103
5.24 Statistics for Random Deviations from Expected Values of 1900-84 Sulfate Loads 104
5.25 Statistics for 1900-84 Unregulated TDS Loads with Random Component . 104
5.26 Statistics for 1900-84 Unregulated Chloride Loads with Random Component 105
5.27 Statistics for 1900-84 Unregulated Sulfate Loads with Random Component 105
5.28 Concentration-Duration Curves at Whitney Gage (Station 15) for Alternative Data Sets 106
5.29 Concentration-Duration Curves at Richmond Gage (Station 25) for Alternative Data Sets 106

LIST OF TABLES (Continued)

7.1 Annual Diversion Requirements for 1984 and 2010 Water Use Scenarios. 120
7.2 Simulation Runs Cited in Chapter 7 122
7.3 System Water Balances for 18 Runs 124
7.4 System TDS Load Balances for 18 Runs 124
7.5 Richmond Gage Means for 18 Runs 125
7.6 System Reliability for 18 Runs 125
7.7 Comparison of Predevelopment, 1984, and 2010 Conditions of River Basin Development 127
7.8 Volume Reliabilities by Control Point 129
7.9 Period Reliabilities by Control Point 129
7.10 TDS Concentration-Duration Curves at Richmond Gage for RESSALT Simulation Runs 1-4 132
7.11 TDS Concentration-Duration Curves at Richmond Gage for RESSALT Simulation Runs 13-16.......... 132
7.12 Chloride Concentration-Duration Curves at Richmond Gage for RESSALT Simulation Runs 1-4 133
7.13 Chloride Concentration-Duration Curves at Richmond Gage for RESSALT Simulation Runs 13-16 133
7.14 TDS and Chloride Concentration-Duration Curves at Richmond Gage for RESSALT Simulation Run 17 136
8.1 Volume Reliability, Yield, and Allowable Salt Concentration Relationships for 1984 Sediment Conditions 142
8.2 Period Reliability, Yield, and Allowable Salt Concentration Relationships for 1984 Sediment Conditions 143
8.3 Volume Reliability, Yield, and Allowable Salt Concentration Relationships for Alternative Operating Plans for 1984 Sediment Conditions 149
8.4 Period Reliability, Yield, and Allowable Salt Concentration Relationships for Alternative Operating Plans for 1984 Sediment Conditions 152
8.5 Volume Reliability, Yield, and Allowable Salt Concentration Relationships for Alternative Operating Plans for 2010 Sediment Conditions 153
8.6 Period Reliability, Yield, and Allowable Salt Concentration Relationships for Alternative Operating Plans for 2010 Sediment Conditions 154
8.7 Volume Reliability, Yield, and Allowable Salt Concentration Relationships for Permanent Storage Reallocation Plan for 1984 Sediment Conditions 156
8.8 Volume Reliability, Yield, and Allowable Salt Concentration Relationships for Seasonal Storage Reallocation Plan for 1984 Sediment Conditions 157
8.9 Volume Reliability, Yield, and Allowable Salt Concentration Relationships for Alternative Operating Plans for 1984 Sediment Conditions with Salt Control Impoundments 160
8.10 Period Reliability, Yield, and Allowable Salt Concentration Relationships for Alternative Operating Plans for 1984 Sediment Conditions with Salt Control Impoundments 161
8.11 Volume Reliability, Yield, and Allowable Salt Concentration Relationships for Alternative Operating Plans for 2010 Sediment Conditions with Salt Control Impoundments 162
8.12 Period Reliability, Yield, and Allowable Salt Concentration Relationships for Alternative Operating Plans for 2010 Sediment Conditions with Salt Control Impoundments 163
8.13 Period Reliability, Yield, and Allowable Salt Concentration for 1984 Sediment Conditions for Alternative Salt Loads.......... 164

LIST OF FIGURES

2.1 The Brazos River Basin and the Reservoirs Included in the Simulation Study 6
3.1 Streamflow Gaging and Water Quality Sampling Stations 20
3.2 Stations Included in the Following Figures 27
3.3 Discharge Hydrograph, Seymour Gage (Station 7) 28
3.4 TDS Concentration Versus Time, Seymour Gage (7) 28
3.5 Chloride Concentration Versus Time, Seymour Gage (7) 29
3.6 Sulfate Concentration Versus Time, Seymour Gage (7) 29
3.7 Discharge Hydrograph, Possum Kingdom Gage (Station 13) 30
3.8 TDS Concentration Versus Time, Possum Kingdom Gage (13) 30
3.9 Chloride Concentration Versus Time, Possum Kingdom Gage (13) 31
3.10 Sulfate Concentration Versus Time, Possum Kingdom Gage (13) 31
3.11 Discharge Hydrograph, Whitney Gage (Station 15) 32
3.12 TDS Concentration Versus Time, Whitney Gage (15) 32
3.13 Chloride Concentration Versus Time, Whitney Gage (15) 33
3.14 Sulfate Concentration Versus Time, Whitney Gage (15) 33
3.15 Discharge Hydrograph, College Station Gage (Station 21) 34
3.16 TDS Concentration Versus Time, College Station Gage (21) 34
3.17 Chloride Concentration Versus Time, College Station Gage (21) 35
3.18 Sulfate Concentration Versus Time, College Station Gage (21) 35
3.19 Discharge Hydrograph, Richmond Gage (Station 25) 36
3.20 TDS Concentration Versus Time, Richmond Gage (25) 36
3.21 Chloride Concentration Versus Time, Richmond Gage (25) 37
3.22 Sulfate Concentration Versus Time, Richmond Gage (25) 37
3.23 Annual Average Concentrations, Seymour Gage (Station 7) 38
3.24 Annual Average Concentrations, Possum Kingdom Gage (13) 38
3.25 Annual Average Concentrations, Whitney Gage (Station 15) 39
3.26 Annual Average Concentrations, College Station Gage (21) 39
3.27 Annual Average Concentrations, Richmond Gage (Station 25) 40
3.28 Concentration-Duration Curves for TDS 40
3.29 Concentration-Duration Curves for Chloride 41
3.30 Concentration-Duration Curves for Sulfate 41
3.31 Arithmetic Average of Monthly TDS Concentrations 45
3.32 Arithmetic Average of Monthly Chloride Concentrations 45
3.33 TDS Concentration Versus Discharge, Seymour Gage (7) 46
3.34 Chloride Concentration Versus Discharge, Seymour Gage (7) 46
3.35 TDS Concentration Versus Discharge, Possum Kingdom Gage (13) 47
3.36 Chloride Concentration Versus Discharge, Possum Kingdom Gage (13) 47
3.37 TDS Concentration Versus Discharge, Whitney Gage (15) 48
3.38 Chloride Concentration Versus Discharge, Whitney Gage (15) 48
3.39 TDS Concentration Versus Discharge, College Station Gage (21) 49
3.40 Chloride Concentration Versus Discharge, College Station Gage (21) 49
3.41 TDS Concentration Versus Discharge, Richmond Gage (25) 50
3.42 Chloride Concentration Versus Discharge, Richmond Gage (25) 50
4.1 Proposed Salt Control Impoundments and Stations Referenced in Chapter 4 52
4.2 TDS Concentration-Duration Curves for Seymour Gage (Station 7) 58
4.3 Chloride Concentration-Duration Curves for Seymour Gage (7) 58
4.4 Sulfate Concentration-Duration Curves for Seymour Gage (7) 59
4.5 TDS Concentration-Duration Curves for Possum Kingdom Gage (13) 59
4.6 Chloride Concentration-Duration Curves for Possum Kingdom Gage (13) 60
4.7 Sulfate Concentration-Duration Curves for Possum Kingdom Gage (13) 60
4.8 TDS Concentration-Duration Curves for Whitney Gage (Station 15) 61
4.9 Chloride Concentration-Duration Curves for Whitney Gage (15) 61
4.10 Sulfate Concentration-Duration Curves for Whitney Gage (15) 62
4.11 TDS Concentration-Duration Curves for College Station Gage (21) 62
4.12 Chloride Concentration-Duration Curves for College Station Gage (21) 63
4.13 Sulfate Concentration-Duration Curves for College Station Gage (21) 63
4.14 TDS Concentration-Duration Curves for Richmond Gage (25) 64
4.15 Chloride Concentration-Duration Curves for Richmond Gage (25) 64
4.16 Sulfate Concentration-Duration Curves for Richmond Gage (25) 65

LIST OF FIGURES (Continued)

5.1 Stations Used in Chapter 5 Tasks 1-3 69
5.2 Stations Included in the Regression Analyses to Fill In Missing Data 71
5.3 Regulated and Unregulated Discharge Hydrographs at Station 10 78
5.4 Regulated and Unregulated Discharge Hydrographs at Station 12 78
5.5 Regulated and Unregulated Discharge Hydrographs at Station 14 79
5.6 Regulated and Unregulated Discharge Hydrographs at Station 15 79
5.7 Regulated and Unregulated Discharge Hydrographs at Station 21 80
5.8 Regulated and Unregulated Discharge Hydrographs at Station 25 80
5.9 Regulated and Unregulated TDS Loads at Station 10 81
5.10 Regulated and Unregulated TDS Loads at Station 12 81
5.11 Regulated and Unregulated TDS Loads at Station 14 82
5.12 Regulated and Unregulated TDS Loads at Station 15 82
5.13 Regulated and Unregulated TDS Loads at Station 21 83
5.14 Regulated and Unregulated TDS Loads at Station 25 83
5.15 Regulated and Unregulated TDS Concentrations for Station 10 84
5.16 Regulated and Unregulated TDS Concentrations for Station 12 84
5.17 Regulated and Unregulated TDS Concentrations for Station 14 85
5.18 Regulated and Unregulated TDS Concentrations for Station 15 85
5.19 Regulated and Unregulated TDS Concentrations for Station 21 86
5.20 Regulated and Unregulated TDS Concentrations for Station 25 86
5.21 Regulated and Unregulated Chloride Loads for Station 15 87
5.22 Regulated and Unregulated Chloride Concentrations for Station 15 .. 87
5.23 Regulated and Unregulated Sulfate Loads for Station 15 88
5.24 Regulated and Unregulated Sulfate Concentrations for Station 15 ... 88
5.25 Control Points Included in RESSALT Model 93
5.26 TDS Concentration-Duration Curves at Whitney Gage (Station 15) for Alternative Data Sets 107
5.27 TDS Concentration-Duration Curves at Richmond Gage (Station 25) for Alternative Data Sets 107
5.28 Chloride Concentration-Duration Curves at Whitney Gage (Station 15) for Alternative Data Sets 108
5.29 Chloride Concentration-Duration Curves at Richmond Gage (Station 25) for Alternative Data Sets 108
6.1 System Modeled 113
6.2 System Schematic 113
7.1 TDS Concentration-Duration Curves at Richmond Gage for RESSALT Simulation Runs 1-4 134
7.2 TDS Concentration-Duration Curves at Richmond Gage for RESSALT Simulation Runs 13-14 134
7.3 Chloride Concentration-Duration Curves at Richmond Gage for RESSALT Simulation Runs 1-4 135
7.4 Chloride Concentration-Duration Curves at Richmond Gage for RESSALT Simulation Runs 13-14 135
8.1 Volume Reliability, Yield, and Allowable TDS Concentration Relationships for 1984 Sediment Conditions 144
8.2 Volume Reliability, Yield, and Allowable Chloride Concentration Relationships for 1984 Sediment Conditions 145
8.3 Volume Reliability, Yield, and Allowable Sulfate Concentration Relationships for 1984 Sediment Conditions 146
8.4 Reliability Versus Yield Relationships for 1984 Sediment Conditions for Level I Salt Constraints 150
8.5 Reliability Versus Yield Relationships for 1984 Sediment Conditions for Level II Salt Constraints 150
8.6 Reliability Versus Yield Relationships for 1984 Sediment Conditions for Level III Salt Constraints 151

CHAPTER 1
INTRODUCTION

Statement of the Problem

The Brazos River Basin is representative of several major river basins in the Southwestern United States in regard to natural salt pollution. Geologic formations underlying portions of the upper watersheds of the Brazos, Colorado, Pecos, Canadian, Red, and Arkansas Rivers, in the states of Texas, Oklahoma, New Mexico, Kansas, and Colorado, are sources of salt emissions to the rivers. Millions of years ago, this region was covered by a shallow inland sea. The salt-bearing geologic formations were formed by salts precipitated from evaporating sea water. Salt springs and seeps and salt flats in upstream areas of the basins now contribute large salt loads to the rivers. The natural salt contamination significantly impacts water resources development and management.

Water quality in the Brazos River is seriously degraded by natural contamination by salts consisting largely of sodium chloride with moderate amounts of calcium sulfate and other dissolved solids. The primary source of the salinity is groundwater emissions in an area of the upper basin consisting of the Salt Fork Brazos River watershed and portions of the adjacent Double Mountain Fork Brazos River and North Croton Creek watersheds. High salt concentrations significantly affect water management and utilization. Water in the three main stream reservoirs is unsuitable for municipal use without costly desalinization processes. The quality of the river improves significantly in the lower basin with dilution from good quality tributaries.

Population and economic growth combined with depleting groundwater reserves are resulting in ever-increasing demands on the surface water resources of Texas and the Brazos River Basin. Effective management of the highly stochastic water resources of a river basin requires an understanding of the amount of suitable quality water which can be provided under various conditions. Reservoir system reliability analyses support planning studies and management decisions regarding (1) improvements in reservoir system operating policies, water rights allocations, and water supply contracts, (2) facility expansions and construction of new water supply projects, and (3) projects and strategies for dealing with salt pollution. Consideration of water quality as well as quantity is important in evaluating reservoir system reliability in the Brazos River Basin.

Scope of the Study

The primary objectives of the investigation documented by this report are:

1. to develop a better understanding of the natural salt pollution problem and its impact on water management in the Brazos River Basin,
2. to develop expanded generalized reservoir system simulation modeling capabilities which incorporate salinity considerations,

3. to formulate and evaluate approaches for improving reservoir system yields and reliabilities while dealing with high salt concentrations, and

4. to perform a water supply reliability study for the major system of reservoirs operated by the Corps of Engineers and Brazos River Authority, which reflects constraints imposed by water quality.

The investigation involved a number of tasks including: (1) compiling and analyzing available information, including prior studies and measured data, characterizing the natural salt pollution problem in the Brazos River Basin; (2) developing a generalized reservoir system simulation model called RESSALT; (3) formulating methodologies for performing reservoir system reliability studies, using RESSALT, which incorporate salt concentration considerations, (4) developing the necessary RESSALT input data files; and (5) performing various reservoir system simulation analyses. The study focused on sensitivity analyses of the effects that alternative water management scenarios and modeling assumptions have on estimates of salinity levels and water supply reliabilities. Alternative reservoir system operating policies were formulated and evaluated. The impacts of a previously proposed salt control plan on reservoir system yields and reliabilities were also analyzed. Thus, study results provide an enhanced understanding of the impacts on water supply capabilities of both the natural salt pollution problem and alternative resource management strategies.

Although focusing on a particular reservoir system in the Brazos River Basin, the study hopefully contributes to an enhanced understanding of the interactions between natural salt pollution and reservoir system reliability in general. Study findings are, to a significant extent, pertinent to similar problems in a number of other river basins in Texas and neighboring states. The RESSALT model is generalized for application to any reservoir system regardless of location. The general analysis methodology could be readily applied to other river basins and reservoir systems.

The studies documented by this report are a component of a larger research effort. The relationship between the work reported here and past and ongoing studies is outlined later in this introductory chapter.

Organization of the Report

Chapters 2 and 3 describe the Brazos River Basin, the reservoir system, and the natural salt pollution problem. Reductions in salinity which can be achieved by controlling runoff from the primary salt source area are estimated in Chapter 4. Salt concentrations are analyzed in Chapters 3 and 4 based on published field data without reference to the RESSALT simulation model. Chapter 5 outlines the computational adjustments to the measured salt data, described in Chapter 3, which were made to develop the salt load input data file required for RESSALT. The same salt load input file is being used in the salt version of the Water Rights Analysis Program (TAMUWRAP) cited later in this chapter. The reservoir system reliability study, using the RESSALT simulation model, is reported in Chapters 6, 7, and 8. The summary and conclusions are presented in Chapter 9.

Study Organization and Sponsors

This report is one of several prepared in conjunction with a research project entitled "Reservoir System Reliability Considering Water Rights and Water Quality," which is sponsored by the Cooperative Research Program administered by the U.S. Geological Survey and Texas Water Resources Institute. The Texas Water Development Board jointly funded the project and served as the nonfederal sponsor for the federal/state research program. This research project builds upon and extends a project sponsored by the Texas Advanced Technology Program (TATP) entitled "Natural Salt Pollution and Reservoir System Yield." The TATP is administered by the Texas Higher Education Coordinating Board. This report is based largely on thesis and dissertation research partially supported by graduate research assistantships funded by the TATP project.

The primary objective of the overall project, entitled "Reservoir System Reliability Considering Water Rights and Water Quality," is to integrate salinity and water rights considerations in comprehensive river/reservoir-system reliability studies. The investigation involves developing expanded generalized simulation modeling capabilities and applying the models to the Brazos River Basin. The present report concentrates on salinity without addressing water rights. Studies integrating water rights and salinity considerations are documented in a separate report. The water rights studies involve developing and applying a salt concentration version of the Water Rights Analysis Program (TAMUWRAP).

Prior Studies

Brazos River Basin natural salt pollution control studies conducted by the U.S. Army Corps of Engineers (USACE) are documented by a survey report (USACE 1973), environmental impact statement (USACE 1976), and draft general design memorandum (USACE 1983). Various other agencies prepared reports as input to the USACE managed studies. Alternative plans for addressing the salt problem were formulated and evaluated in these studies. The survey report (USACE 1973) recommended construction of a system of salt control dams to contain the runoff from the primary salt source areas. In the restudy documented by the draft general design memorandum (USACE 1983), the previously recommended salt impoundment plan and alternative plans were found not to be economically feasible based on current evaluation methods and conditions even though natural salt pollution is definitely a serious problem.

The analyses of salt loads and concentrations presented in the USACE (1973, 1976, 1983) reports are based on a report prepared by the Environmental Protection Agency (EPA 1973), which is included as Appendix VII of the USACE (1973) survey report. The EPA developed a computer simulation model to compute monthly salt (chloride, sulfate, and total dissolved solids) concentrations for the period 1941-1962. The EPA report includes an analysis of salt concentrations with and without the proposed salt control dams. The EPA analysis utilized measured salinity data collected by the U.S. Geological Survey (USGS) and described by Rawson (1967) and Rawson, Flugrath, and Hughes (1968).

The salinity analyses included in the studies cited above are based on field measurements made prior to 1967. A majority of the water quality measurements presently available were made since that time. The USGS conducted an extensive water quality sampling program from 1964 through 1986 in support of the USACE salt pollution control studies. The contract work of Ganze and Wurbs (1989), accomplished for the USACE, consisted of compiling the USGS data into a readily usable format and performing various analyses. The primary focus was on evaluation of the impacts of the proposed salt control dams on concentrations at downstream locations. This salt concentration data base is used in the present study and is addressed in detail in Chapters 3 and 4.

The present study also builds upon a study performed from September 1986 through August 1988 as a part of the Cooperative Research Program of the U.S. Geological Survey and Texas Water Resources Institute, jointly sponsored by the Brazos River Authority (Wurbs, Bergman, Carriere, Walls 1988; Wurbs and Carriere 1988). This study addressed simulation modeling and water availability in the Brazos River Basin, but did not include consideration of salinity. Most of the basic hydrology and reservoir data outlined in Chapter 6 were developed in this study. The original version of the Water Rights Analysis Program (TAMUWRAP) was developed in conjunction with the study (Wurbs and Walls 1989). TAMUWRAP is a generalized reservoir/river simulation model designed to analyze water management under a prior appropriation water rights permit system.

Although the present report does not address water rights, the overall study includes integrating both salinity and water rights considerations in comprehensive river basin planning and analysis. Water rights aspects of the study are covered in a separate report being prepared concurrently.

CHAPTER 2
THE BRAZOS RIVER BASIN

Basin Description

As indicated by Figure 2.1, the Brazos River Basin extends from eastern New Mexico southeasterly across the state of Texas to the Gulf of Mexico. The basin has an overall length of approximately 640 miles, with a width varying from about 70 miles in the High Plains in the upper basin to a maximum of 110 miles in the vicinity of the city of Waco to about 10 miles near the city of Richmond in the lower basin. The basin drainage area is 45,600 square miles, with about 43,000 square miles in Texas and the remainder in New Mexico. The basin encompasses about 16 percent of the land area of Texas. Approximately 9,570 square miles in the northwest portion of the basin, including all the area in New Mexico and a portion of the area in Texas, are non-contributing to downstream streamflows. Mean annual precipitation varies from about 16 inches/year in the western (upstream) end of the basin to over 50 inches/year in the lower basin near the Gulf.

From its inception at the Salt Fork and Double Mountain Fork, the Brazos River flows in a meandering path some 920 miles to the city of Freeport at the Gulf of Mexico. In its upper reaches, the Brazos River is a gypsum-salty intermittent stream. Toward the coast, it is a rolling river flanked by levees, cotton fields, and hardwood bottoms. Upon its descent from the high plains and Caprock Escarpment, the Brazos River flows through a small, semiarid region of gypsum and salt encrusted hills and valleys containing numerous salt springs and seeps. This area of the upper basin is the primary source of the salt contamination.

The 1980 and 1990 population of the Brazos River Basin was 1.53 million and 1.73 million, respectively (Texas Water Development Board 1990). The population is expected to increase to between 3.1 and 3.8 million people by 2040. Lubbock is the largest city in the basin. The 1987 population of the Lubbock Metropolitan Area was 225,000. The cities of Waco, Abilene, Bryan-College Station, Killeen, and Temple, each have populations exceeding 25,000. The area economy is based on agriculture, agribusiness, manufacturing, mineral production, trades, and services.

A significant portion of the water diverted from the Brazos River is actually used in the adjoining San Jacinto-Brazos Coastal Basin. The San Jacinto-Brazos Coastal Basin has a drainage area of 1,440 square miles bordered by the Brazos River Basin, Gulf, Galveston Bay, and Houston. There are no major reservoirs with conservation storage capacity to capture runoff in the coastal basin. However, the Galveston County Water Authority operates a 12,500 acre-foot capacity off-channel reservoir which stores and regulates water diverted from the Brazos river through a canal system. Water supply sources include saline water from the Gulf, groundwater pumped within the coastal basin, and surface water diversions primarily from the Brazos Basin but also from the Trinity River and San Jacinto River Basins.

The 1980 and 1990 population of the San Jacinto-Brazos Coastal Basin was 536,800 and 647,100, respectively (TWDB 1990). The basin population is projected to increase to between

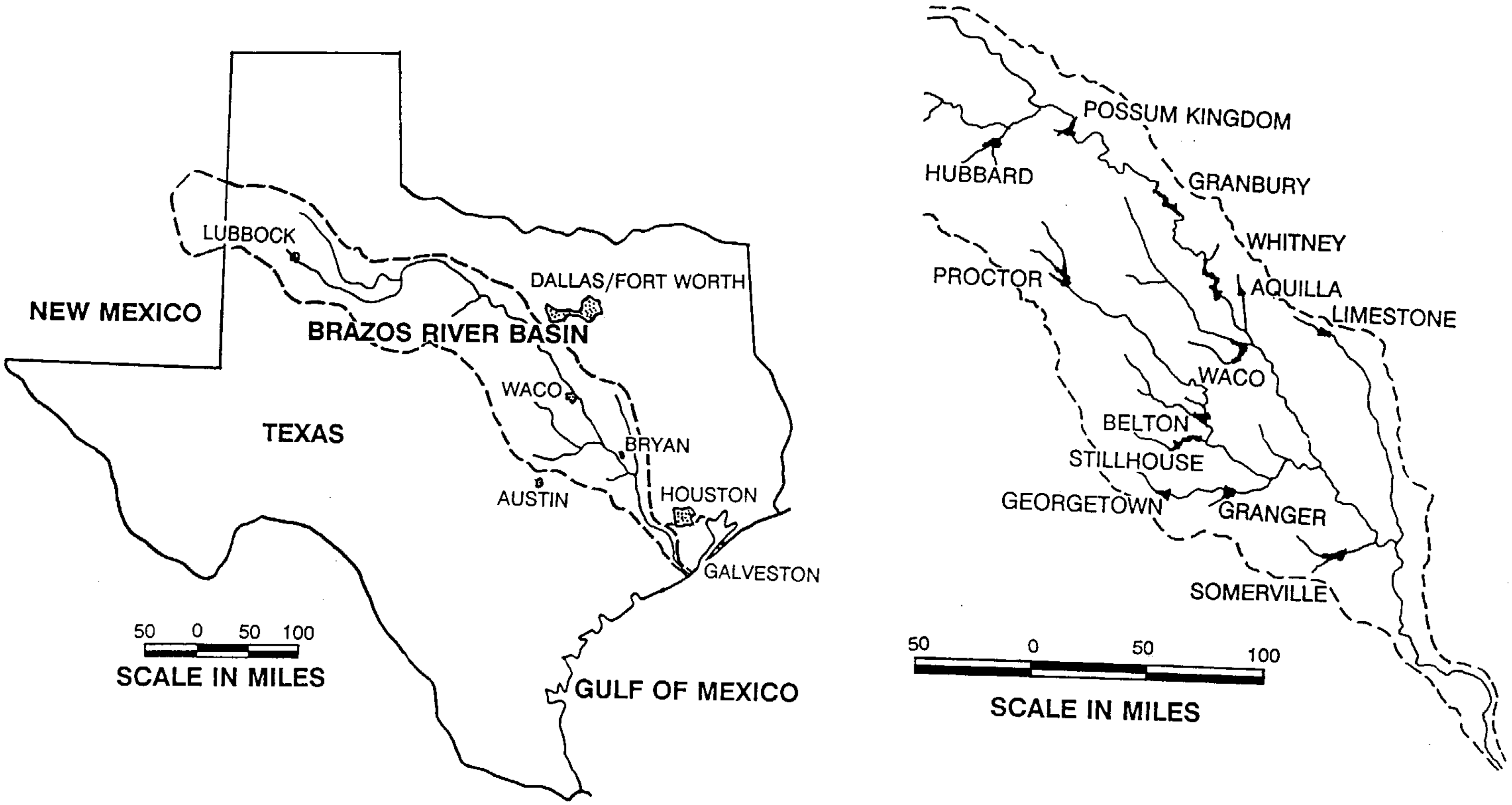

Figure 2.1 The Brazos River Basin and the Reservoirs Included in the Simulation Study

1.1 and 1.3 million by 2040. Major cities located wholly or partially within the coastal basin include Houston, Pasadena, Galveston, Texas City, Missouri City, League City, and Deer Park.

Reservoirs

A total of about 1,200 reservoirs included in the Texas Water Commission dam inventory are located in the Brazos River Basin. Forty reservoirs in the Brazos River Basin have storage capacities exceeding 5,000 acre-feet. The reservoir system simulation studies documented in Chapters 6-8 include the 13 reservoirs listed in Tables 2.1, 2.2, and 2.3. Reservoir locations are shown in Figure 2.1. The 13 reservoirs contain all of the controlled (gated) flood control storage capacity and about 78 percent of the conservation storage of the approximately 1,200 reservoirs in the basin (Wurbs, Bergman, Carriere, Walls 1988).

U.S. Army Corps of Engineers (USACE) Reservoirs

As indicated by Table 2.1, nine of the reservoirs were constructed by the USACE as components of a comprehensive basin-wide plan of development. The nine USACE projects contain about half of the conservation capacity and all of the flood control capacity of the 40 major reservoirs in the basin. Georgetown, Aquilla, Granger, Proctor, Somerville, Stillhouse Hollow, Waco, Belton and Whitney Reservoirs are each operated by the Fort Worth District for flood control, water supply, and recreation. Whitney Lake serves the additional purpose of hydroelectric power generation. Fort Worth District personnel operate and maintain the nine federal multiple purpose projects. The USACE is totally responsible for flood control operations. Conservation releases are made as directed by the local project sponsor, which for most of the conservation capacity, is the Brazos River Authority (BRA). The BRA has contracted for the water supply capacity in each of the USACE projects, except Fort Hood military base has 3.2 percent of the conservation storage in Belton Lake and the City of Waco has 12.5 percent of the conservation storage capacity in Lake Waco. The City of Waco is also the primary customer for the 87.5 percent of the Lake Waco conservation capacity controlled by the BRA. The Southwestern Power Administration is responsible for marketing hydroelectric power from Whitney Reservoir, which it sells to the Brazos Electric Power Cooperative.

Brazos River Authority (BRA) System

In addition to controlling the conservation storage in the nine USACE projects, the BRA constructed, owns, and operates Granbury, Limestone, and Possum Kingdom Reservoirs. The 12 reservoirs are operated as a system to supply downstream municipal, industrial, and agricultural water users as well as users located in the vicinities of the reservoirs.

Possum Kingdom Reservoir, completed in 1941, provides water supply and hydroelectric power. BRA sells the power to the Brazos Electric Power Cooperative. Lake Granbury, completed in 1969, provides cooling water for a gas-fired plant near the lake and to Squaw Creek Reservoir for the Comanche Peak Nuclear Power Plant. Granbury and Possum Kingdom Reservoirs provide makeup water, as needed, to maintain constant operating levels in Tradinghouse Creek and Lake Creek Reservoirs which are owned and operated by utility companies for stream-electric power plant cooling. A recently constructed desalting water

Table 2.1
RESERVOIRS INCLUDED IN SIMULATION STUDY

Fort Worth District (FWD) of U.S. Army Corps of Engineers (USACE) and Brazos River Authority (BRA)

Whitney Lake and Whitney Dam; Brazos River; flood control, water supply, hydroelectric power, and recreation.

Aquilla Lake and Aquilla Dam; Aquilla Creek; flood control, water supply, and recreation.

Waco Lake and Waco Dam; Bosque River; flood control, water supply, and recreation.

Proctor Lake and Proctor Dam; Leon River; flood control, water supply, and recreation.

Belton Lake and Belton Dam; Leon River; flood control, water supply, and recreation.

Stillhouse Hollow Lake and Stillhouse Hollow Dam; Lampasas River; flood control, water supply, and recreation.

Georgetown Lake and Georgetown Dam; formerly North Fork Lake and North Fork Dam; North Fork San Gabriel River; flood control, water supply, and recreation.

Granger Lake and Granger Dam; formerly Laneport Lake and Laneport Dam; San Gabriel River; flood control, water supply, and recreation.

Somerville Lake and Somerville Dam; Yequa Creek; flood control, water supply, and recreation.

Brazos River Authority

Possum Kingdom Lake and Morris Sheppard Dam; Brazos River; hydroelectric power, water supply, and recreation.

Lake Granbury and DeCordova Bend Dam; Brazos River; water supply and recreation.

Limestone Lake and Sterling C. Robertson Dam; Navasota River; water supply and recreation.

West Central Texas Municipal Water District

Hubbard Creek Reservoir and Hubbard Creek Dam; Hubbard Creek; water supply and recreation.

Table 2.2
RESERVOIR DATA

Reservoir	Hubbard	Possum Kingdom	Granbury	Whitney	Aquilla	Waco
Storage Capacity (ac-ft)						
Flood Control	-	-	-	1,372,400	86,700	553,300
Water Supply	297,910	551,860	104,790	50,000	33,600	104,100
Hydroelectric Power	-	-	-	198,000	-	-
Sediment Reserve (ac-ft)						
Flood Control Pool	-	-	-	8,155	6,900	20,600
Conservation Pool	19,840	118,380	48,700	51,645	18,800	48,400
Accumulative Storage (ac-ft)						
Flood Control Pool	-	-	-	1,999,500	146,000	726,400
Conservation Pool	317,750	570,240	153,490	627,100	52,400	152,500
Inactive Pool	-	221,050	52,500	379,100	-	-
Lowest Outlet Invert	3,470	0	2,500	4,250	0	580
Elevation (feet msl)						
Top of Dam	1,208	1,024	706.5	584	582.5	510
Flood Control Pool	-	-	-	571	556	500
Conservation Pool	1,183	1,000	693	533	537.5	455
Inactive Pool	-	970	675	520	-	-
Lowest Outlet Invert	1,136	875	640	449	503	400
Stream	Hubbard	Brazos	Brazos	Brazos	Aquilla	Bosque
Drainage Area (sq mi)	1,085	23,596	25,679	27,189	252	1,652
Gage Station Number	367	376	381	387	389	400
Gage Drainage Area (sq mi)	1,089	23,811	25,818	27,244	308	1,656
Drainage Area Ratio	1.0	1.0	1.0	1.0	1.0	1.0
Date of:						
Initial Impoundment	1962	1941	1969	1951	1983	1965
Accumulative Capacity Data	1962	1974	1969	1959	1983	1965

Reservoir	Proctor	Belton	Stillhouse	Georgetown	Granger	Limestone	Somerville
Storage Capacity (ac-ft)							
Flood Control	310,100	640,000	390,660	87,600	162,200	-	337,700
Water Supply	31,400	372,700	204,900	29,200	37,900	210,990	143,900
Sediment Reserve (ac-ft)							
Flood Control Pool	4,700	15,600	4,100	6,100	16,500	-	9,700
Conservation Pool	28,000	69,300	30,800	7,900	27,600	14,450	16,200
Accumulative Storage (ac-ft)							
Flood Control Pool	374,200	1,091,320	630,400	130,800	244,200	-	507,500
Conservation Pool	59,400	447,490	235,700	37,100	65,500	225,440	160,100
Lowest Outlet Invert	70	11	780	238	222	0	220
Elevation (feet msl)							
Top of Dam	1,205	662	698	861	555	380	280
Flood Control Pool	1,197	631	666	834	528	-	258
Conservation Pool	1,162	594	622	791	504	363	238
Lowest Outlet Invert	1,128	483	515	720	457	325.5	206
Stream	Leon	Leon	Lampasas	San Gabriel	San Gabriel	Navasota	Yequa
Drainage Area (sq mi)	1,259	3,531	1,313	247	709	675	1,007
Gage Station Number	412	418	424	426	431	448	443
Gage Drainage Area (sq mi)	1,261	3,542	1,321	248	738	968	1,009
Drainage Area Ratio	1.0	1.0	1.0	1.0	1.0	0.697	1.0
Date of:							
Initial Impoundment	1963	1954	1968	1980	1980	1978	1967
Accumulative Capacity Data	1963	1975	1968	1980	1980	1978	1967

treatment plant provides the capability to treat water from Lake Granbury to supplement the water supply for the City of Granbury. Lake Limestone, completed in 1978, supplies water to off-channel cooling lakes owned by the Texas Power and Light Company.

BRA uses Lake Belton to supply water under contracts with the Cities of Temple and McGregor, and through Bell County Water Control and Improvement District No. 1 and two water supply corporations, to several other cities and communities. Water from Lake Whitney is contracted for use by the Cities of Cleburne, Whitney, and Rio Vista. Lake Waco supplies the City of Waco. A reallocation of 8.6 percent of the flood control capacity of Lake Waco to conservation is planned to meet the increasing water needs of the City of Waco and its suburbs. Water from Proctor Reservoir is provided to several cities under a contract between BRA and the Upper Leon River Municipal Water District. Proctor also provides water for agricultural use to individual farmers around the lake and to a corporation of farmers along the Leon River downstream of the dam. Stillhouse Hollow Reservoir supplies water to a number of communities and rural water supply corporations. Somerville Reservoir and the recently completed Georgetown, Granger, and Aquilla Reservoirs are also committed for municipal and industrial water supply.

In addition to the uses cited above, BRA operates the upstream reservoir system to regulate flows for municipal, industrial, and irrigation uses in the lower Brazos Basin and the neighboring San Jacinto-Brazos Coastal Basin. Downstream water customers include a large chemical plant at the mouth of the Brazos River, several thermal-electric generating plants, municipalities and industries in the coastal area south of Houston, and rice farmers in the lower basin and adjoining coastal basin. Water is diverted to users through extension canal systems.

Hubbard Creek Reservoir

Although the reservoir system simulation study (Chapters 6-8) focused on the 12-reservoir USACE/BRA system, Hubbard Creek Reservoir was also included in the RESSALT model due to its significant storage capacity and location. In terms of conservation storage capacity, Hubbard Creek is the fourth largest reservoir in the basin. It is located upstream and thus affects inflows into the three main stream Brazos River reservoirs. Hubbard Creek Reservoir is a municipal water supply project owned by the West Central Texas Municipal Water District, whose member cities include Abilene, Breckenridge, Anson, and Albany.

Reservoir Storage Capacities

Pertinent basic data describing the physical characteristics of the reservoirs are cited in Table 2.2. Reservoir operations are based on the top of conservation and flood control pool elevations tabulated. Flood control operations are in effect whenever the water surface rises or is predicted to rise above the top of conservation pool elevation. The inactive pool elevation at Possum Kingdom Reservoir is contractually set to accommodate hydroelectric power operations. Likewise, the inactive pool elevation at Granbury Reservoir is contractually set to accommodate withdrawals of cooling water for a stream-electric plant near the reservoir. The inactive pool at Whitney Reservoir is also dead storage for hydroelectric power. Withdrawals from the inactive pools can physically be made at these three reservoirs. Drawdown limits are set by contractual operating policies, not outlet structures. The other 10 projects can be emptied to the invert of the lowest outlet structure.

The accumulated storage capacities cited in Table 2.2 are total capacity, including sediment reserves and inactive storage, below the indicated elevation for the topography existing at the indicated year. A portion of this capacity can be expected to have since been lost due to disposition of sediment. The streams have heavy sediment loads, and the reservoirs are efficient sediment traps. The incremental flood control and water supply storage capacities listed in Table 2.2 are exclusive of sediment reserve storage. Sediment reserves in the flood control and conservation pools are also tabulated. Thus, more capacity is actually available than indicated by the incremental data prior to depletion of the sediment reserve.

Elevation versus capacity and area relationships for Possum Kingdom, Whitney, and Belton Reservoirs have been updated based on surveys at the dates indicated in Table 2.2. The area and capacity data for the other projects have not been updated by field surveys since project design and construction. The USACE and BRA provided elevation/storage/area tables for initial or resurveyed topographic data as well as for the projected future condition of sedimentation (termed ultimate) upon which designated sediment reserves are based. Ultimate refers to the condition in which the designated (typically 50 or 100 year) sediment reserve has been depleted. In the present study, linear interpolation was applied to the initial (or resurveyed) and ultimate storage data to develop estimates for years 1984 and 2010 conditions of sedimentation. The storage capacities below the top of inactive and conservation pools, for 1984 and 2010 conditions of sedimentation, tabulated in Table 2.3, were used in the modeling study.

Table 2.3
CONSERVATION POOL STORAGE CAPACITIES
FOR 1984 AND 2010 CONDITIONS OF SEDIMENTATION

Reservoir	1984 Sedimentation			2010 Sedimentation		
	Conservation Storage Capacity (acre-feet)					
	Inactive	Active	Total	Inactive	Active	Total
Hubbard Creek	3,400	308,070	311,470	3,320	300,730	304,050
Possum Kingdom	0	544,510	544,510	0	477,600	477,600
Granbury	43,910	95,250	139,160	29,020	85,320	114,340
Whitney	363,610	238,170	601,780	347,510	227,950	575,460
Aquilla	0	52,210	52,210	0	47,340	47,340
Waco	360	133,750	134,110	58	108,880	108,940
Proctor	40	46,850	46,890	0	31,400	31,400
Belton	10	428,250	428,260	0	372,700	372,700
Stillhouse	530	225,310	225,840	125	209,700	209,830
Georgetown	230	36,540	36,770	167	34,540	34,710
Granger	210	64,190	64,400	155	57,070	57,230
Limestone	5,810	218,050	223,860	2,950	214,060	217,010
Somerville	150	154,450	154,600	31	146,140	146,170
Total	418,260	2,545,600	2,963,860	383,330	2,313,430	2,696,760

Water Use

Total inbasin annual water use in the Brazos River Basin is projected by the Texas Water Development Board (1990) to increase from 2,035,000 acre-feet in 1990 to 2,474,000 and 2,877,000 acre-feet in years 2000 and 2040, respectively. Much of the water diverted from the Brazos River is used in the adjoining San Jacinto-Brazos Coastal Basin. Total inbasin annual water use in the San Jacinto-Brazos Coastal Basin is projected by the TWDB to increase from 403,000 acre-feet in 1990 to 480,000 and 755,000 acre-feet in 2000 and 2040, respectively.

Year 1984 Water Use

Table 2.4 is a tabulation of year 1984 water use summarized by Wurbs et al. (1988) from a TWDB data base. In Table 2.4 and the following discussion, water use is viewed from the perspective of three geographical areas: the Brazos River Basin above and below Possum Kingdom Reservoir and the San Jacinto-Brazos Coastal Basin. The first and last sets of data in Table 2.4 are total inbasin water use in the Brazos River Basin and Jacinto-Brazos Coastal Basin, respectively. The middle set of data shows inbasin water use in the Brazos River Basin excluding water use in all counties located above Possum Kingdom Reservoir. This represents inbasin water use at locations adjacent to and below the 12 USACE/BRA reservoirs. All data are for water withdrawals, except stream electric use which reflects consumptive use only.

Table 2.4
1984 WATER USE

Source	Municipal	Manufacturing	Steam Electric	Mining	Irrigation	Livestock	Total
1984 Water Use in the Brazos River Basin (acre-feet/year)							
Surface	173,900	169,200	75,900	600	106,000	38,200	563,800
Ground	131,400	12,200	11,300	13,600	2,394,100	26,100	2,588,700
Total	305,300	181,400	87,200	14,200	2,500,100	64,200	3,152,500
1984 Water Use in the Brazos River Basin Excluding the Subbasin Above Possum Kingdom Reservoir (acre-feet/year)							
Surface	97,200	164,800	68,700	600	85,000	26,200	442,500
Ground	103,500	7,600	3,300	12,000	99,700	9,900	236,000
Total	200,700	172,400	72,000	12,600	184,700	36,100	678,500
1984 Water Use in the San Jacinto-Brazos Coastal Basin (acre-feet/year)							
Surface	26,580	102,970	1,940	2,440	176,420	470	310,820
Ground	72,480	3,220	530	190	11,000	700	88,120
Total	99,060	106,190	2,480	2,630	187,420	1,170	398,940

A majority of the water use in the Brazos Basin consists of irrigation in the High Plains from the Ogallala Aquifer. The groundwater irrigation in the extreme upper basin has little impact on operation of the USACE/BRA reservoir system. There are few reservoirs and relatively little surface water use in the upper basin. Surface water from the Brazos River and several of its tributaries upstream of Possum Kingdom Reservoir is too saline for most beneficial uses. The city of Lubbock and several other smaller cities in the upper basin obtain water via pipeline from Lake Meredith in the Canadian River Basin. About 9,570 square miles of drainage area located in the upper extreme of the basin are noncontributing to downstream streamflows. Consequently, the upper third of the basin accounts for a large portion of the total basin water use but does not play a significant role in the operation of the USACE/BRA reservoir system.

As indicated by Table 2.4, municipal, manufacturing, steam electric, mining, irrigation, and livestock are all significant water uses in the basin below Possum Kingdom Reservoir. Hydroelectric power and recreation are also important uses but are not included in the data because they involve no water diversions or withdrawals. Surface water use exceeds groundwater use. Groundwater is important to reservoir operations both as an alternative water supply source and as a source of return flows to the stream system. Groundwater also provides base flow directly to the streams.

Brazoria and Fort Bend Counties, at the lower end of the Basin, have the largest surface water use of any area in the basin. Most of this water use is for manufacturing, primarily by chemicals and petroleum refining industries, and irrigation. In addition to the fresh water use shown in the tables, 1,275,000 acre-feet of saline water from the Gulf was used in Brazoria County in 1984 for manufacturing purposes.

Significant quantities of water are also diverted from the Brazos River in Brazoria and Fort Bend Counties for transport to the adjoining San Jacinto-Brazos Coastal Basin. Water use in the San Jacinto-Brazos Coastal Basin is also tabulated in Table 2.4. A majority of the surface water use represents diversions from the Brazos River Basin through Brazos River Authority, Chocolate Bayou Company, and Dow Chemical Company conveyance facilities. Texas Department of Water Resources (1984) data indicate that 87 percent of the surface water used in the San Jacinto-Brazos Coastal Basin in 1980 had been transported from the Brazos River Basin.

Water Amount Comparison

Various water amounts for 1984 are tabulated in Table 2.5 for comparative purposes in developing a basin overview (Wurbs, Bergman, Carriere, Walls 1988). The 1984 annual streamflow at the Richmond gage was about five percent of the volume of the precipitation falling on the watershed above the gage. The total surface water withdrawn for beneficial uses in 1984 throughout the basin was about 23 percent of the 1984 streamflow at the Richmond gage or eleven percent of the 1940-1984 mean annual streamflow at the Richmond gage. The total 1984 within basin surface water use, excluding the upper basin above Possum Kingdom Reservoir, was 443,000 acre-feet. An additional 270,000 acre-feet was diverted from the Brazos River for use in the San Jacinto - Brazos Coastal Basin. About 60 percent of the 794,000 acre-

Table 2.5
1984 WATER USE COMPARISON

Annual Precipitation (acre-feet)

Watershed (excluding 9,566 square mile non-contributing area):	1984	1940-1984 Mean
Above Richmond Gage	50,000,000	52,080,000
Above Waco Gage	26,160,000	26,630,000
Above Cameron Gage	10,250,000	11,320,000

Annual Streamflow (acre-feet)

Gage	1984	1940-1984 Mean
Richmond	2,413,000	5,188,000
Waco	303,000	1,558,000
Cameron	309,000	1,172,000

1984 Basin Water Use (acre-feet)

Subbasin	Surface Water	Ground Water	Total
Above Possum Kingdom	121,000	2,353,000	2,474,000
Brazoria and Fort Bend Counties	207,000	33,000	240,000
Remainder of Basin	236,000	203,000	439,000
Total	564,000	2,589,000	3,153,000

1984 Interbasin Diversions (acre-feet)

From Canadian (Lake Meredith) to Brazos Basin	38,000
From Colorado (Oak Creek Reservoir) to Brazos Basin	2,000
From Brazos to San Jacinto-Brazos Coastal Basin	270,000

1984 Conservation Releases from 12-Reservoir System (acre-feet)

Whitney Hydropower Releases	186,000
Possum Kingdom Hydropower Releases	79,000
All Other Water Supply Releases	329,000

1984 Reservoir Evaporation (acre-feet)

Reservoirs	Gross	Net
12 BRA Reservoirs	557,000	382,000
1,166 Other Reservoirs	337,000	248,000
Total	894,000	630,000

feet total 1984 water use from the Brazos River and its tributaries occurred in the lowermost two counties in the basin (26%) and in the adjoining coastal basin (34%). The total annual surface water use represents a volume equivalent to about 20 percent of the 3,910,000 ac-ft conservation storage capacity of the 40 major reservoirs.

A total of 329,000 acre-feet was released from the 12 BRA reservoirs under water rights permits associated with the reservoirs, excluding water released through hydroelectric power turbines. A portion of the 186,000 acre-feet and 79,000 acre-feet of water released through the hydroelectric plants at Whitney and Possum Kingdom Reservoirs, respectively, was diverted at downstream locations for other beneficial uses. The reservoir releases shown were made under water rights permits associated with the reservoirs. The BRA Canal A and Canal B systems diverted an additional 130,000 acre-feet under separate water rights permits for use in the San Jacinto - Brazos Basin and in the Brazoria and Fort Bend Counties portion of the Brazos Basin.

Reservoir evaporation withdraws more surface water than all the beneficial uses in the basin combined. Total 1984 withdrawals of surface water for beneficial use in the basin and annual gross reservoir evaporation are equivalent to 20 and 23 percent, respectively, of the conservation storage capacity of the 40 major reservoirs. The evaporation amounts were estimated using water surface area and evaporation rate data (Wurbs, Bergman, Carriere, Walls 1988).

CHAPTER 3
COMPILATION AND ANALYSIS OF MONTHLY SALT LOADS AND CONCENTRATIONS

The primary source of the natural salt pollution is groundwater emissions concentrated largely within an area consisting of the Salt Fork of the Brazos River watershed and portions of the adjacent Double Mountain Fork of the Brazos River and North Croton Creek watersheds (USACE 1973 and 1983). This semiarid region of about 1,500 square miles consists of gypsum and salt encrusted hills and valleys studded with salt springs and seeps. Salt concentrations in the three reservoirs located on the main stream of the Brazos River are too high for most beneficial uses without special and costly treatment processes or significant dilution.

Previous Corps of Engineers studies (USACE 1973 and 1983; Ganze and Wurbs 1989) as well as the studies documented by the present report quantify salt concentrations and loads in terms of mean monthly values for total dissolved solids (TDS), chloride (Cl), and sulfate (SO_4). Ganze and Wurbs (1989) and Ganze (1990) document a compilation and analysis of available salt data conducted for the USACE. The present chapter summarizes this work.

USGS Sampling Program

Although the U.S. Geological Survey (USGS) operated a daily chemical-quality station on the Brazos River at Waco from December 1906 to November 1907, most of the chemical-quality data on surface waters of the Brazos River Basin have been collected since 1941. From 1941 through 1963, the USGS collected chemical-quality data, for varying periods, at about 35 daily sampling stations and periodic or miscellaneous chemical-quality data at hundreds of additional sites in the basin. Systematic collection of water quality data was significantly expanded by the USGS in 1964 to assist the Corps of Engineers in its comprehensive planning study of the Brazos River Basin. Early water quality data for the Brazos River and its tributaries are summarized by Irelan and Mendieta (1964), Rawson (1967), and Rawson, Flugrath, and Hughes (1968).

The USGS began publication of annual reports, containing records of chemical analyses, suspended sediment, and water temperature, in 1941. In the early years, the water quality data were recorded in annual reports entitled "Quality of Surface Waters of the United States," which were part of the overall water-supply paper series. The water quality data for Texas were also reproduced in annual reports of the Texas Board of Water Engineers and later the Texas Water Development Board. Since 1961, the USGS has published its records in annual reports on a state-boundary basis. This series of annual reports for Texas began with the 1961 water year with a report that contained only data relating to the quantities of surface water. Beginning with the 1964 water year, a similar annual report series was initiated for water quality data. Beginning with the 1975 water year, the annual report was changed to its present format, with data on quantities and quality of surface water contained in each of three volumes covering the different river basins of the state. The pertinent USGS annual reports prior to 1975 are entitled "Water Resources Data for Texas, Part 2. Water Quality Records." Since 1975, the pertinent annual reports have been entitled "Water Resources Data, Texas, Volume 2. San

Jacinto River Basin, Brazos River Basin, San Bernard River Basin, and Intervening Coastal Basins."

In early years, salt concentrations were usually determined directly by laboratory analysis of water samples. In many cases, instantaneous concentrations are recorded at several times during a year. Mean concentrations were typically recorded for time intervals of a day or several days. However, the monthly mean salt concentrations and loadings published by the USGS in recent years are computed from measured mean daily specific conductance and discharge, combined with relationships between specific conductance and salt concentrations. Laboratory analyses of water samples to determine salt concentrations are performed periodically to provide data for developing the specific conductance versus salt concentration relationships. These relationships are updated at several-year intervals to reflect current data.

The USGS maintains the National Water Data Storage and Retrieval System (WATSTORE) to provide convenient access to the data collected. Although the mean daily specific conductances and discharges can be obtained on magnetic tape from a WATSTORE computer file, the monthly salt loadings and concentrations, computed from daily specific conductances, are not stored in the computer system. The monthly salt loadings and concentrations must be obtained from the printed annual reports or recomputed using daily specific conductance and discharge data available from the computer data base combined with appropriate relationships for specific conductance versus salt concentrations. The data used in the present study were taken from the printed annual reports.

Basic Data Files

Ganze and Wurbs (1989) compiled the monthly TDS, Cl, and SO_4 loads and discharges published annually by the USGS for the period 1964-1986 at 26 sampling stations. The data files are printed in the report (Ganze and Wurbs 1989) as well as being available on diskette. Mean annual concentrations are also tabulated for earlier periods not covered by the monthly data.

A total of 39 stations in the basin have mean monthly data for at least three years during the period 1964-1986. The 26 stations were selected because of their record lengths and pertinent locations. The monthly salt data were taken from the USGS annual report series. Since the format of the USGS reports changed over the years, some computational manipulations were required to develop a data set with consistent format and measurement units. The USGS water quality measurements were at or near streamflow gages. The 26 gaging stations are listed in Table 3.1, and their locations are shown in Figure 3.1. The 13 reservoirs listed in Tables 2.1-2.3 are also included on the map.

The main stream of the Brazos River begins at the confluence of the Salt Fork and Double Mountain Fork, which is 923.2 river miles above the Brazos River mouth at the Gulf of Mexico. Stations 1 and 2, which are the most upstream gaging stations included in the study, are located on the Salt Fork and Double Mountain Fork, respectively, 34.5 and 54.3 river miles above their confluence. The Seymour, Possum Kingdom, Whitney, College Station, and Richmond streamflow gages (stations 7, 13, 15, 21, and 25) are located at river miles 847.4,

Table 3.1
SELECTED USGS STREAMFLOW GAGING AND WATER QUALITY SAMPLING STATIONS

Study Station Number	USGS Station Number	Station Name	Drainage Area (sq mile)	Period Covered by Annual Data (water year)	Period Covered by Monthly Data (water year)
1	08080500	Double Mountain Fork Brazos River Near Aspermont	8,796	1949-51,57-86	1964-86
2	08081000	Salt Fork Brazos River Near Peacock	4,619	1950-51,65-86	1965-86
3	08081200	Croton Creek Near Jayton	290	1962-86	1966-86
4	08081500	Salt Croton Creek Near Aspermont	64	1969-77	1969-77
5	08082000	Salt Fork Brazos River Near Aspermont	5,130	1949-51,57-82	1964-82
6	08082180	North Croton Creek Near Knox City	251	1966-86	1966-86
7	08082500	Brazos River at Seymour	15,538	1960-86	1964-86
8	08083240	Clear Fork Brazos River at Hawley	1,416	1968-79,82-84	1968-79,82-84
9	08085500	Clear Fork Brazos River at Fort Griffin	3,988	1950-51,68-76, 1979,82-84	1968-76,79,82-84
10	08086500	Hubbard Creek Near Breckenridge	1,089	1956-66,68-75	1968-75
11	08087300	Clear Fork Brazos River at Eliasville	5,697	1962-82	1964-82
12	08088000	Brazos River Near South Bend	22,673	1942-48,78-81	1978-81
13	08088600	Brazos River at Possum Kingdom Dam Near Graford	27,190	1942-86	1964-86
14	08090800	Brazos River Near Dennis	25,237	1971-86	1971-86
15	08092600	Brazos River at Whitney Dam Near Whitney	27,189	1949-86	1964-86
16	08093360	Aquilla Creek Above Aquilla	255	1980-82	1980-82
17	08093500	Aquilla Creek Near Aquilla	308	1968-81	1968-81
18	08098290	Brazos River Near Highbank	30,436	1968-79,81-86	1968-79,81-86
19	08104500	Little River Near Little River	5,228	1965-73,80-86	1965-73,80-86
20	08106500	Little River at Cameron	7,065	1960-86	1964-86
21	08109500	Brazos River Near College Station	39,599	1962-83	1967-83
22	08110000	Yegua Creek Near Somerville	1,009	1962-66	1964-66
23	08110325	Navasota River Above Groesbeck	239	1968-86	1968-86
24	08111000	Navasota River Near Bryan	1,454	1959-81	1964-81
25	08114000	Brazos River at Richmond	45,007	1946-86	1964-86
26	08116650	Brazos River Near Rosharon	45,339	1969-80	1969-80

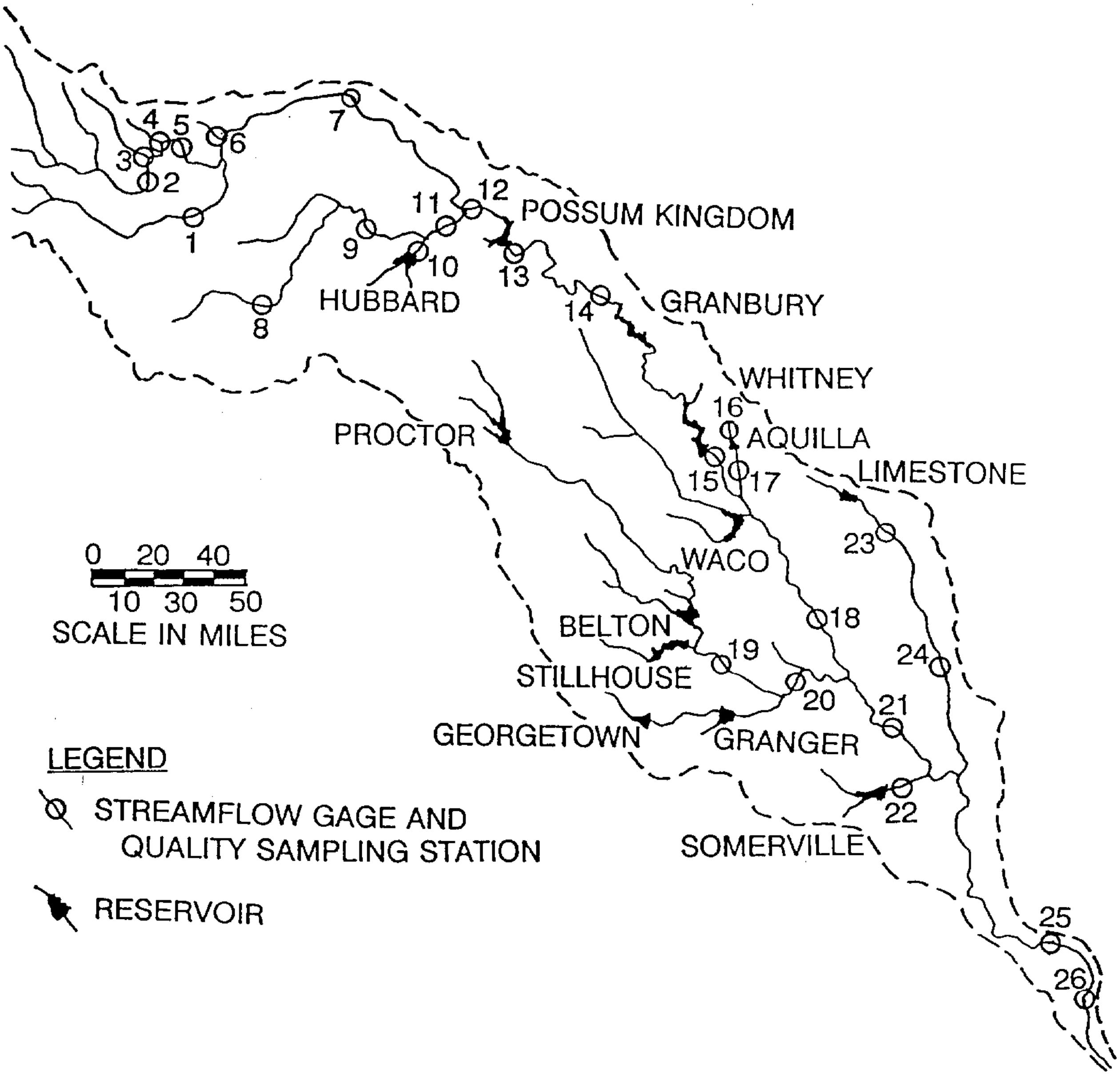

Figure 3.1 Streamflow Gaging and Water Quality Sampling Stations

687.5, 442.4, 281.1, and 92.0, respectively. The gaging station on the Brazos River at the town of Seymour (station 7) is downstream of the primary salt source area, but is upstream of Possum Kingdom, Granbury, and Whitney Reservoirs. The gaging station at Possum Kingdom (Morris Sheppard) Dam near the town of Graford (station 13) is located on the Brazos River immediately below the dam. The gaging station at Whitney Dam near the town of Whitney (station 15) is also located just below the dam.

Discharges and salt loads are cited in units of cubic feet per second (cfs) and tons/day, respectively. Salt concentrations are cited in units of milligrams of salt solute per liter of water (mg/1) or parts of salt solute per million parts of water (ppm). Assuming a liter of water has a mass of one kilogram, the units mg/1 and ppm are equivalent. Concentration, load, and discharge are related as follows:

$$\text{concentration} = \text{load/discharge}$$

Concentration, in mg/l, can be computed from load, in tons/day, and discharge, in cfs, using the following conversion factor:

$$((\text{tons/day})/(\text{ft}^3/\text{sec}))\ (370.8) = \text{mg/l}$$

Overview Summary of Data

Salinity is measured in terms of total dissolved solids (TDS), chloride (Cl), and sulfate (SO_4). Chloride and sulfate are major constituents of total dissolved solids in the Brazos River Basin. Streamflow rates and salt loads and concentrations vary greatly with location and over time.

Discharges, loads, and concentrations averaged over the period-of-record at each of the 26 stations are shown in Table 3.2. The periods covered by annual data, as tabulated in Table 3.1, are reflected in the data presented in Table 3.2. Since the periods-of-record vary between stations, the means are not strictly comparable. Adding or deleting a few years of data can significantly change the averages. Table 3.3 shows discharges, loads, and concentrations at selected stations averaged over the period 1964-1986 or as close thereto as available data allows. The values shown for stations 1, 3, 7, 13, 15, 20 and 25 are averaged over the period 1964-1986. The averages for the other stations in Table 3.3 are for somewhat shorter periods.

Monthly discharge and salt concentration hydrographs for the Seymour, Possum Kingdom, Whitney, College Station, and Richmond gages (stations 7, 13, 15, 21, and 25), shown in Figure 3.2, are plotted as Figures 3.3-3.22. Mean annual concentration hydrographs for these stations are shown in Figures 3.23-3.27. Concentration-duration curves based on the monthly data are tabulated in Tables 3.4-3.6 and plotted as Figures 3.28-3.30.

Spatial Variations

Salinity levels at stations 2, 3, 4, 5, and 6 are very high. These stations represent runoff from the primary salt pollution source area. Tributaries entering the Brazos River downstream of Whitney Reservoir have relatively low salt concentrations. Salt concentrations in the main stem significantly decrease in a downstream direction as low salt-content inflows dilute the flows from the upper watershed. For example, as indicated in Table 3.3, the 1964-1986 mean total dissolved solids concentrations are 3,591 mg/l, 1,512 mg/l, 928 mg/l, and 339 mg/l at the Seymour, Possum Kingdom, Whitney, and Richmond gages (stations 7, 13, 15 and 25), respectively. The 1964-1986 mean total dissolved solids, chloride, and sulfate concentrations at the Richmond gage are 9.4%, 5.3%, and 8.0%, respectively, of the corresponding values at the Seymour gage. Figures 3.28-3.30 graphically illustrate the decreases in salt concentrations with distance downstream.

Relatively little of the streamflow at the Richmond gage originates from the watershed above the Seymour gage. However, a large proportion of the salt load at the Richmond gage originates from the watershed above the Seymour gage. The 1964-1986 mean discharge at the Seymour gage is 3.9% of the mean discharge at the Richmond gage. The 1964-1986 loads of total dissolved solids, chloride, and sulfate at the Seymour gage are 41%, 73%, and 49%, respectively, of the loads at the Richmond gage.

The extremely saline inflows from the upper Brazos River Basin are a drastic contrast to the flows from the Little River Watershed. As indicated in Table 3.3, the mean concentrations of total dissolved solids, chloride, and sulfate at the Little River gage near Cameron (station 20) are 256 mg/1, 31 mg/1, and 30 mg/1, respectively. Thus, the TDS, C1, and SO_4 concentrations at the Cameron gage (station 20) are 76%, 39%, and 54% of the corresponding means at the Richmond gage or 7.1%, 2.1%, and 4.3% of the corresponding means at the Seymour gage. The 1964-86 mean discharge at the Cameron gage is 550% of the discharge at the Seymour gage. Yet the TDS, Cl, and SO_4 loads at the Cameron gage are only 39%, 11%, and 24% of the corresponding loads at the Seymour gage. The 1964-86 mean discharge at the Cameron gage is 22% of the discharge at the Richmond gage. The TDS, Cl, and SO4 loads at the Cameron gage are 16%, 8%, and 12% of the loads at the Richmond gage.

Variations in salt concentrations between the primary salt source areas (stations 2, 3, 4, 5, and 6) and other areas in the basin are most pronounced for chloride. At station 4, chloride and sulfate accounts of 63% and 5%, respectively, of the total salt load (total dissolved solids load). At station 5, chloride and sulfate accounts for 66% and 13%, respectively, of the total salt load. Continuing downstream to the Seymour gage (station 7), chloride and sulfate make up 41% and 19% of the total dissolved solids load. The total dissolved solids load at the Richmond gage includes 23% chloride and 16% sulfate. The total dissolved solids load at the Cameron gage on the Little River (station 20) includes 12% chloride and 12% sulfate.

Temporal variations also depend upon location. A review of Figures 3.2-3.26 shows that the variations in mean monthly salt concentrations over time are much less drastic at the Possum Kingdom and Whitney gages than at the Seymour, College Station, and Richmond gages. The Seymour gage has the greatest variations in salt concentrations over time. Regulation of streamflow by the Possum Kingdom, Granbury, and Whitney Reservoirs has a damping effect on the fluctuations in salt concentrations at the other gages.

Temporal Variations

Temporal variations are viewed from the perspectives of (1) the general overall variations over the period-of-analysis, (2) seasonal or within-year monthly variation patterns, and (3) long-term trends or changes.

Overall Variations

Figures 3.3-3.22 show a tremendous variation in salt concentrations over time. For example, during the water years 1964-1986 analysis period, at the Seymour gage, total dissolved solids concentrations ranged from a mean monthly value of 618 mg/l in August 1964 to 15,400 mg/l in May 1984, chloride concentrations ranged from 190 mg/l in June 1975 to 7,740 mg/l in May 1984, and sulfate concentrations ranged from 112 mg/l in November 1963 to 2,225 mg/l in March 1976. During the 1964-1986 analysis period, at the Richmond gage, total dissolved solids concentrations ranged from 153 mg/l in November 1984 to 978 mg/l in October 1978, chloride concentrations ranged from 28 mg/l in November 1984 to 355 mg/l in October 1978, and sulfate concentrations ranged from 24 mg/l in December 1965 to 185 mg/l in October 1963.

As indicated by Tables 3.4-3.6, at the Seymour gage, mean monthly total dissolved solids, chloride, and sulfate concentrations of 11,900 mg/l, 5,760 mg/l, and 1,800 mg/l, respectively, were equaled or exceeded during 10% of the 276 months of the 1964-1986 analysis period. At the Seymour gage, mean monthly total dissolved solids, chloride, and sulfate concentrations of 2,420 mg/l, 851 mg/l, and 539 mg/l, respectively, were equaled or exceeded 90% of the time. At the Richmond gage, TDS, Cl, and SO_4 concentrations of 635 mg/l, 192 mg/l, and 113 mg/l were equaled or exceeded 10% of the time. At the Richmond gage, mean monthly TDS, Cl, and SO_4 concentrations of at least 235 mg/l, 43 mg/l, and 37 mg/l, respectively, occurred during 90% of the 276 months of the 1964-1986 analysis period.

Seasonal Variations

A seasonal pattern of concentration variations is much more pronounced for the Seymour gage than for the other gages. This is apparently due to the effects of reservoir regulation on flows at the Possum Kingdom and Whitney gages and, to a lesser extent, at the College Station and Richmond gages. Arithmetic averages of the monthly means for each of the 12 months of the year are plotted in Figure 3.31. The averages for the 12 months of the year are relatively constant at the Possum Kingdom and Whitney gages. For example, 1964-1986 averages for total dissolved solids at the Whitney gage vary from a low of 880 mg/l for July to a high of 996 mg/l for January, which represents a relatively small seasonal or monthly variation. At the Whitney gage, averages for chlorides range from 321 mg/l for July to 374 mg/l for January, and sulfate averages range from 167 mg/l for July to 194 mg/l for December. However, the variations are much greater at the Seymour and Richmond gages. At the Seymour gage, the arithmetic averages of the mean monthly concentrations range from lows in September to highs in February. The ranges for total dissolved solids, chloride, and sulfate are 3,240-10,600 mg/l, 1,310-4,650 mg/l, and 701-1,620 mg/l, respectively. At the Richmond gage, the arithmetic averages of the mean monthly concentrations are minimum in May and maximum in August. The ranges are 335-546 mg/l, 78-158 mg/l, and 55-95 mg/l, respectively, for total dissolved solids, chloride, and sulfate.

Trends Over Time

Significant changes have occurred in the Brazos River Basin during the past several decades due to the activities of man. Municipal, industrial, and agricultural water use has greatly increased. River flows have been regulated by construction of numerous reservoir projects, and changes in land use have occurred. Oil field operations which may contribute to salt pollution have been modified as a result of fluctuating oil prices and other factors. In addition to the impacts of man's activities, natural changes in salt availability and transport could have occurred. Natural and/or man-induced changes in the basin could logically be expected to affect salt concentrations.

However, an examination of the data indicates that any trends or long-term changes in salt concentrations that may have occurred are very small relative to the tremendous random variability. Trends are not evident from the plots of mean monthly salt concentrations in Figures 3.3-3.22 and the plots of mean annual salt concentrations in Figures 3.3-3.27. Ganze and Wurbs (1989) performed several exercises for isolating trends or long-term changes in salt concentrations which included: (1) a linear regression analysis of mean annual concentrations at the five stations shown in Figure 3.2, (2) a linear regression analysis of 5-year moving averages of mean annual concentrations at the Seymour and Richmond gages, and (3) observing accumulative mass plots to detect changes in slopes. No clearly defined trends were identified by these analyses. Changes in concentrations over time, due to construction of reservoir projects and diversion of water for beneficial use, are addressed further in Chapter 7.

Salt Concentration Versus Discharge Relationships

Mean monthly TDS and chloride concentrations versus mean monthly discharge plots for the five stations shown in Figure 3.2 are presented as Figures 3.33-3.42. Ganze and Wurbs (1989) document various regression and correlation analyses performed to quantify the relationships between discharge and concentration. Discharge and concentration are not as closely correlated as might be expected. Figures 3.33-3.42 show the significant scatter in the data.

Salt loads versus discharge are much more closely correlated than concentration versus discharge but still not as closely correlated as might be expected. Load versus discharge relationships are developed and applied in developing the data sets of Chapter 5.

Table 3.2
MEAN DISCHARGES, LOADS, AND CONCENTRATIONS FOR PERIOD-OF-RECORD

Study Station Number	Abbreviated Station Name	Tributary	Years of Record	Mean Discharge (cfs)	Load (tons/day) TDS	Load (tons/day) Cl	Load (tons/day) SO4	Concentration (mg/l) TDS	Concentration (mg/l) Cl	Concentration (mg/l) SO4
1	Aspermont	Double Mountain Fork	33	147	562	136	218	1,353	324	510
2	Peacock	Salt Fork	24	43	680	334	83	5,317	2,585	657
3	Jayton	Croton Creek	24	13	237	96	58	6,321	2,487	1,617
4	Aspermont	Salt Croton Creek	9	4	673	388	27	56,923	32,856	2,273
5	Aspermont	Salt Fork	29	81	1,887	942	217	8,606	4,153	989
6	Knox City	North Croton Creek	21	17	216	82	60	4,723	1,786	1,323
7	Seymour	Main Stem	27	292	2,638	1,018	447	3,356	1,295	569
8	Hawley	Clear Fork	15	46	235	51	94	1,893	411	759
9	Fort Griffin	Clear Fork	15	151	391	105	116	961	258	286
10	Breckenridge	Hubbard Creek	19	93	73	25	4	268	91	20
11	Eliasville	Clear Fork	21	319	614	201	148	715	234	172
12	South Bend	Main Stem	11	760	2,601	996	561	1,261	486	274
13	Possum Kingdom	Main Stem	45	836	2,959	1,127	636	1,299	493	279
14	Dennis	Main Stem	19	892	3,103	1,205	622	1,291	501	259
15	Whitney	Main Stem	38	1,376	3,174	1,120	633	856	302	171
16	Aquilla	Aquilla Creek	3	55	35	2	10	236	14	69
17	Aquilla	Aquilla Creek	14	147	102	6	29	257	14	73
18	Highbank	Main Stem	18	2,530	4,154	1,287	772	609	189	113
19	Little River	Little River	16	912	768	79	61	313	32	25
20	Cameron	Little River	26	1,544	1,094	129	126	263	31	30
21	College Station	Main Stem	22	4,364	5,315	1,379	944	452	117	80
22	Somerville	Yegua Creek	5	252	114	20	33	167	30	48
23	Groesbeck	Navasota River	19	161	56	9	6	131	22	13
24	Bryan	Navasota River	23	600	232	61	38	144	38	23
25	Richmond	Main Stem	41	6,545	6,140	1,431	1,020	351	81	58
26	Rosharon	Main Stem	12	7,305	6,462	1,491	1,004	328	76	51

Table 3.3
MEAN DISCHARGES, LOADS, AND CONCENTRATIONS FOR COMPARABLE TIME PERIODS

Study Station Number	Abbreviated Station Name	Tributary	Years of Record	Mean Discharge (cfs)	Load (tons/day)			Concentration (mg/l)		
					TDS	Cl	SO4	TDS	Cl	SO4
1	Aspermont	Double Mountain Fork	1964-86	126	580	153	209	1,540	416	548
2	Peacock	Salt Fork	1965-86	40	684	339	81	5,782	2,830	698
3	Jayton	Croton Creek	1964-86	13	225	93	53	6,391	2,541	1,591
4	Aspermont	Salt Croton Creek	1969-77	4	676	425	33	56,923	32,856	2,273
5	Aspermont	Salt Fork	1964-82	60	1,660	1,094	219	12,407	6,066	1,235
6	Knox City	North Croton Creek	1966-86	17	211	80	58	4,723	1,786	1,323
7	Seymour	Main Stem	1964-86	269	2,601	1,074	504	3,591	1,482	696
13	Possum Kingdom	Main Stem	1964-86	686	2,795	111	571	1,512	601	309
15	Whitney	Main Stem	1964-86	1,230	3,075	1,134	591	928	342	178
20	Cameron	Little River	1964-86	1,481	1,024	123	119	256	31	30
21	College Station	Main Stem	1964-83	4,529	5,348	1,368	938	438	112	77
25	Richmond	Main Stem	1964-86	6,868	6,267	1,466	1,030	339	79	56

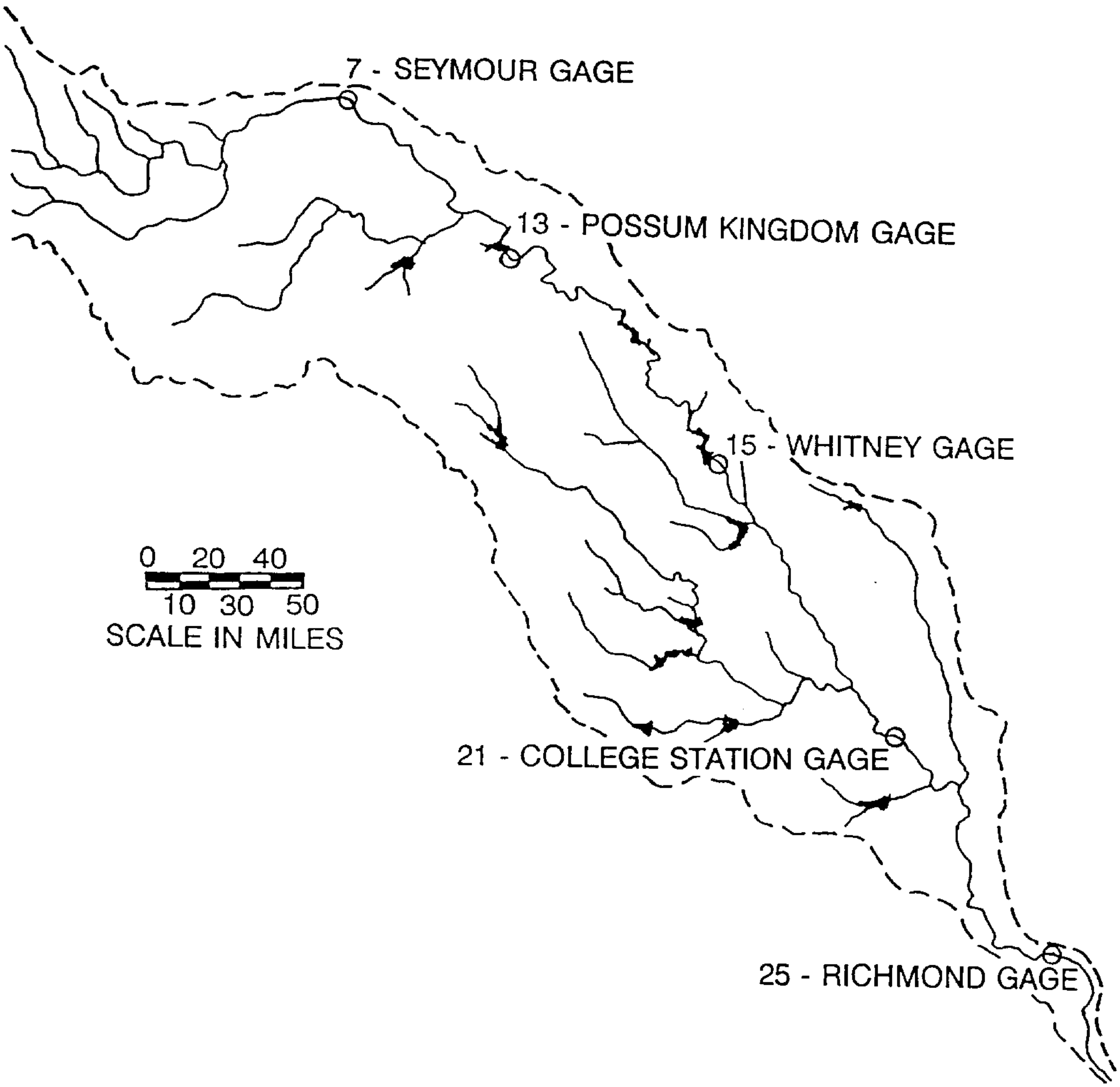

Figure 3.2 Stations Included in the Following Figures

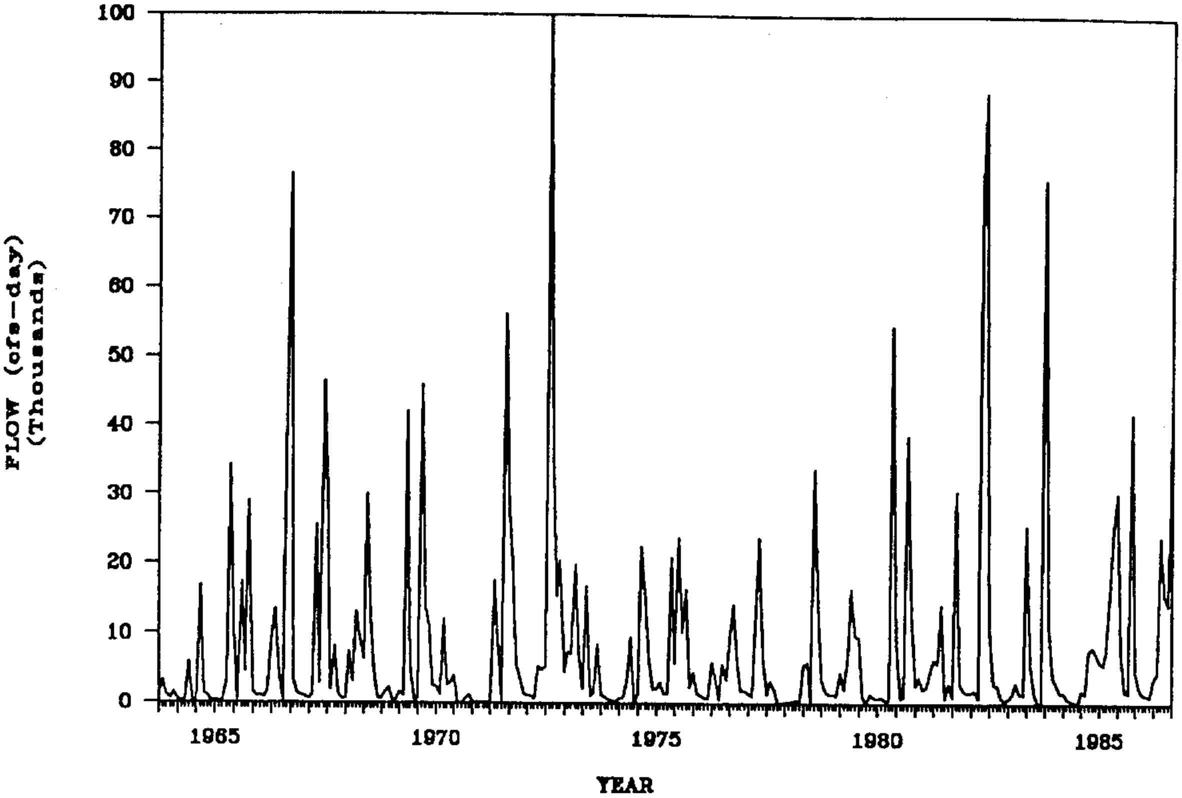

Figure 3.3 Discharge Hydrograph, Seymour Gage (Station 7)

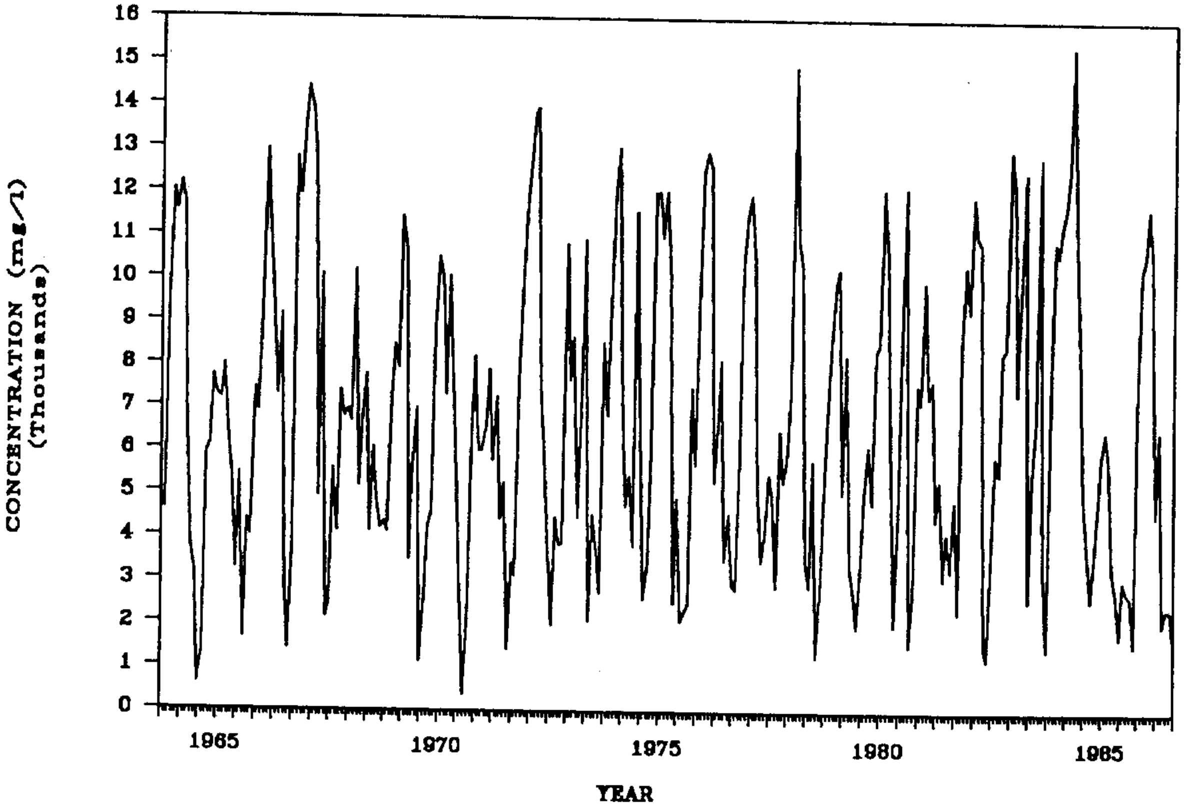

Figure 3.4 TDS Concentration Versus Time, Seymour Gage (Station 7)

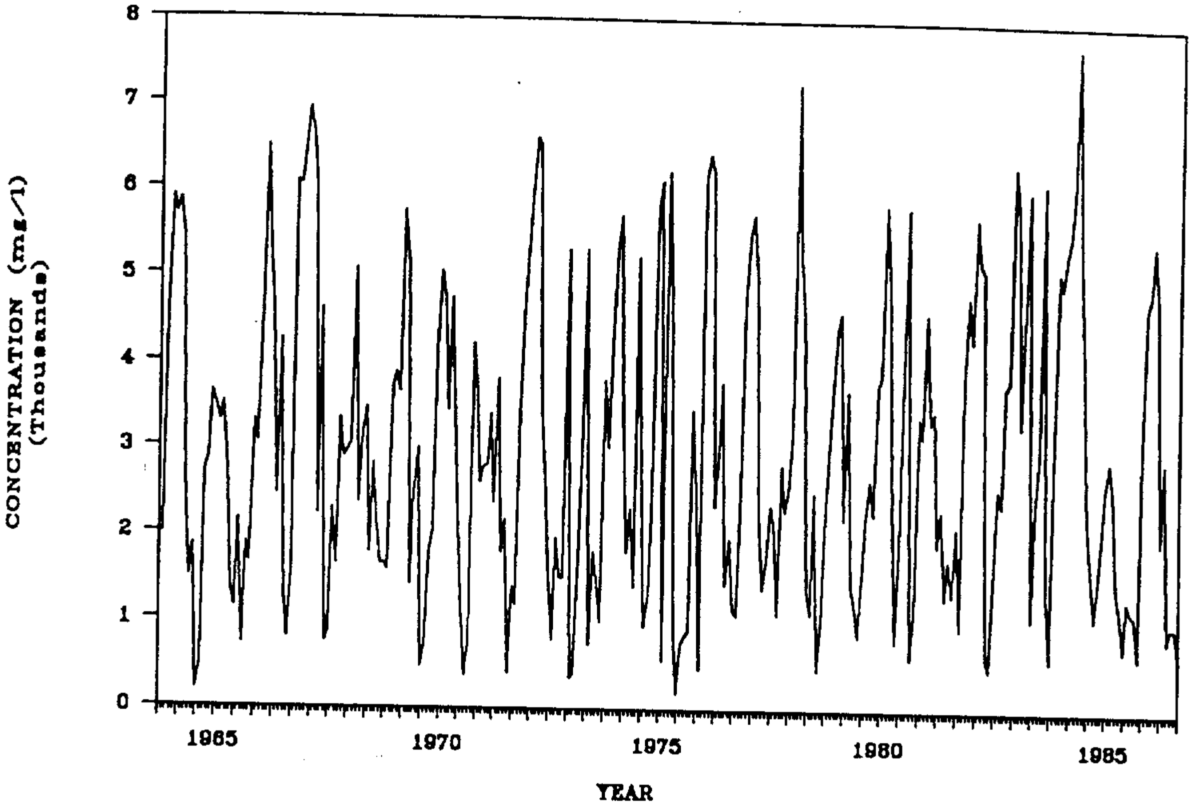

Figure 3.5 Chloride Concentration Versus Time, Seymour Gage (Station 7)

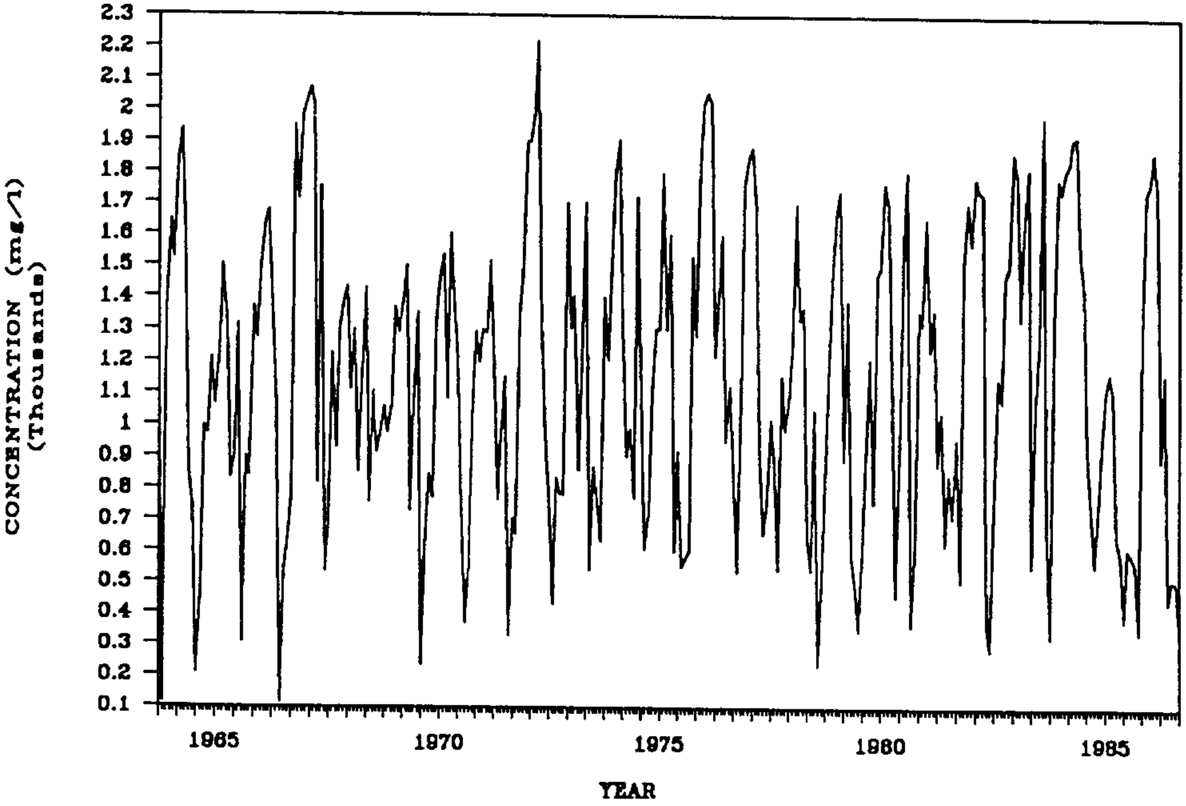

Figure 3.6 Sulfate Concentration Versus Time, Seymour Gage (Station 7)

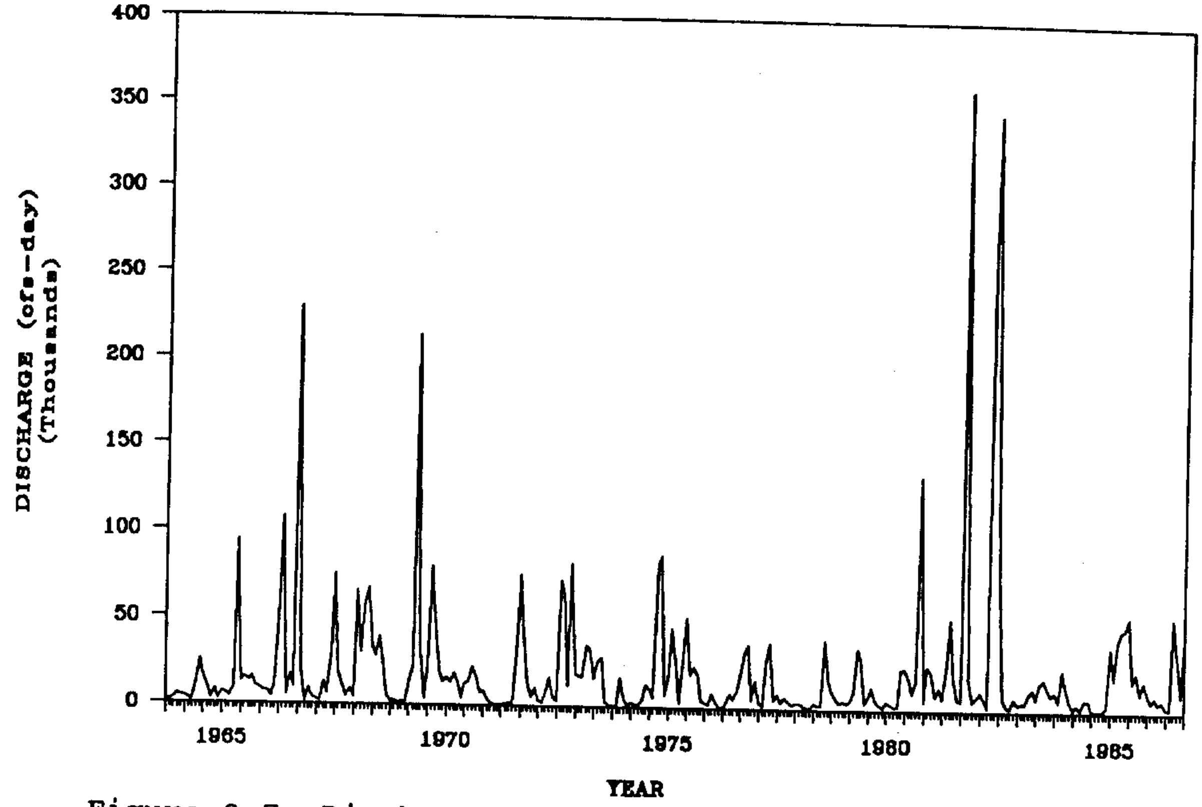

Figure 3.7 Discharge Hydrograph, Possum Kingdom Gage (Station 13)

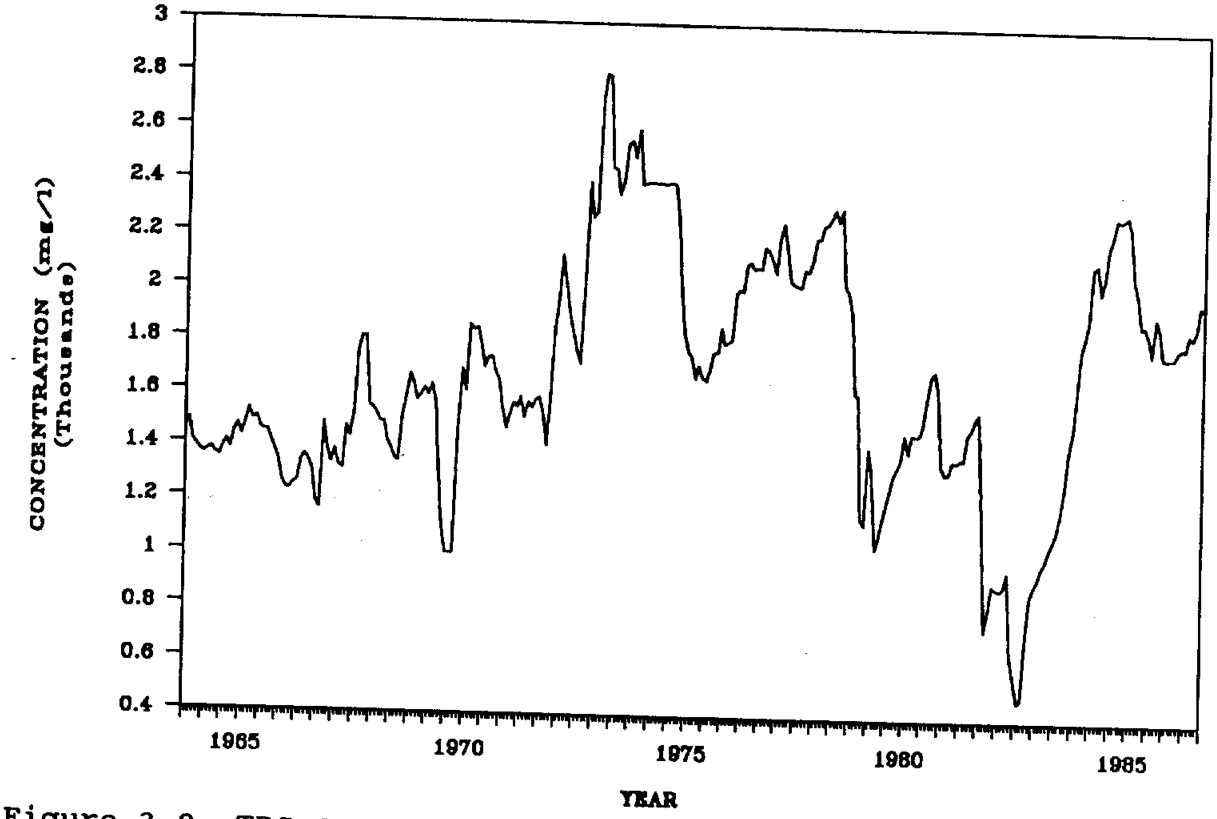

Figure 3.8 TDS Concentration Versus Time, Possum Kingdom Gage (Station 13)

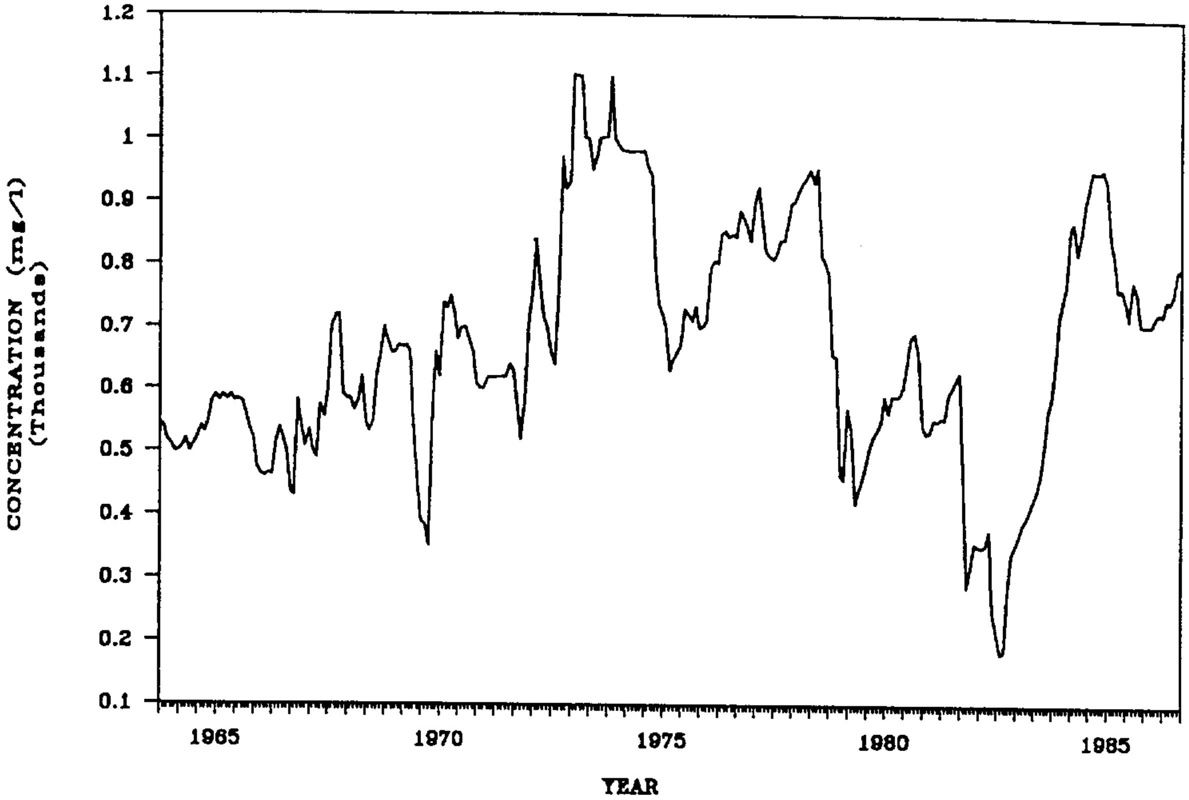

Figure 3.9 Chloride Concentration Versus Time, Possum Kingdom Gage (Station 13)

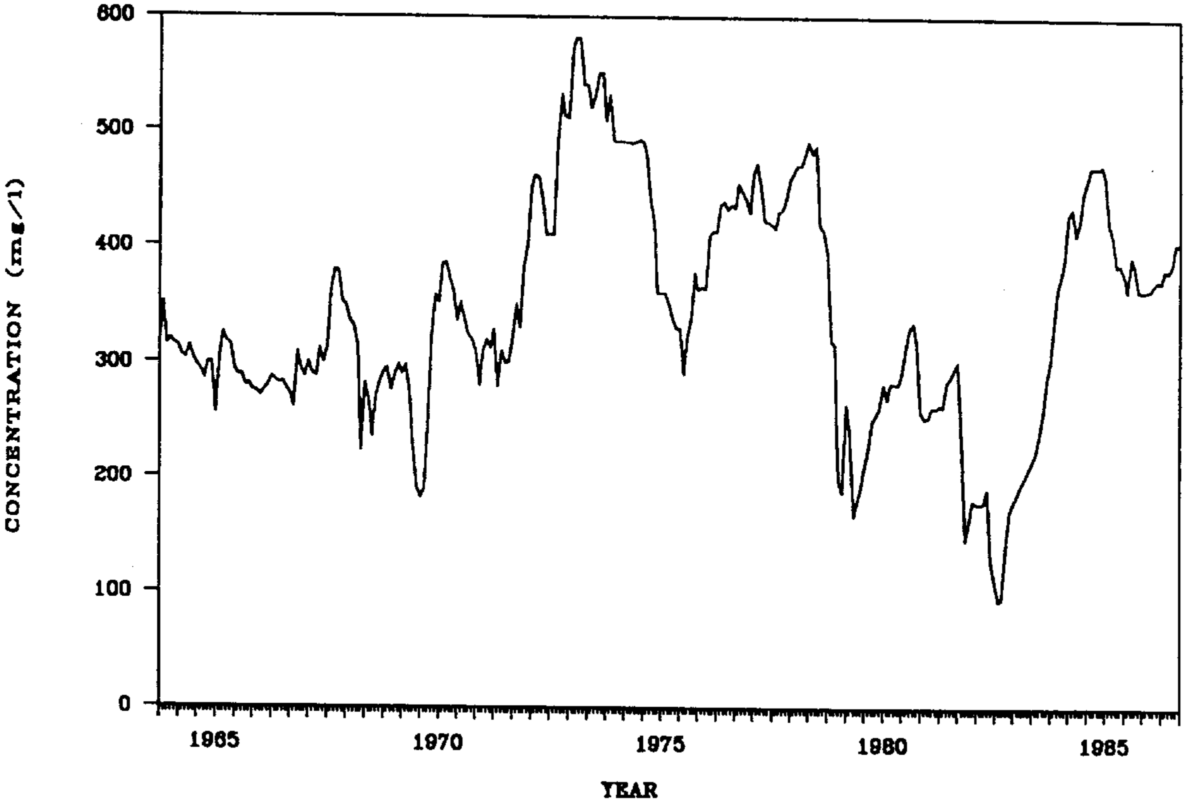

Figure 3.10 Sulfate Concentration Versus Time, Possum Kingdom Gage (Station 13)

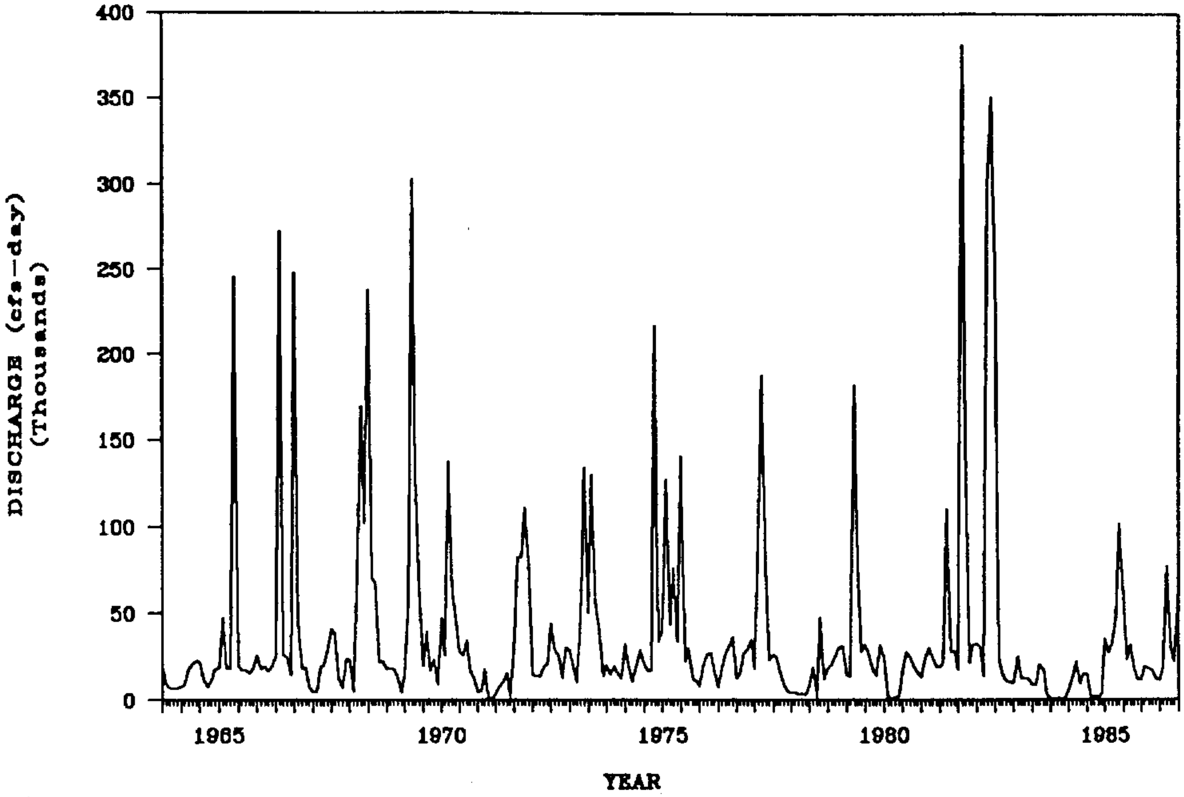

Figure 3.11 Discharge Hydrograph, Whitney Gage (Station 15)

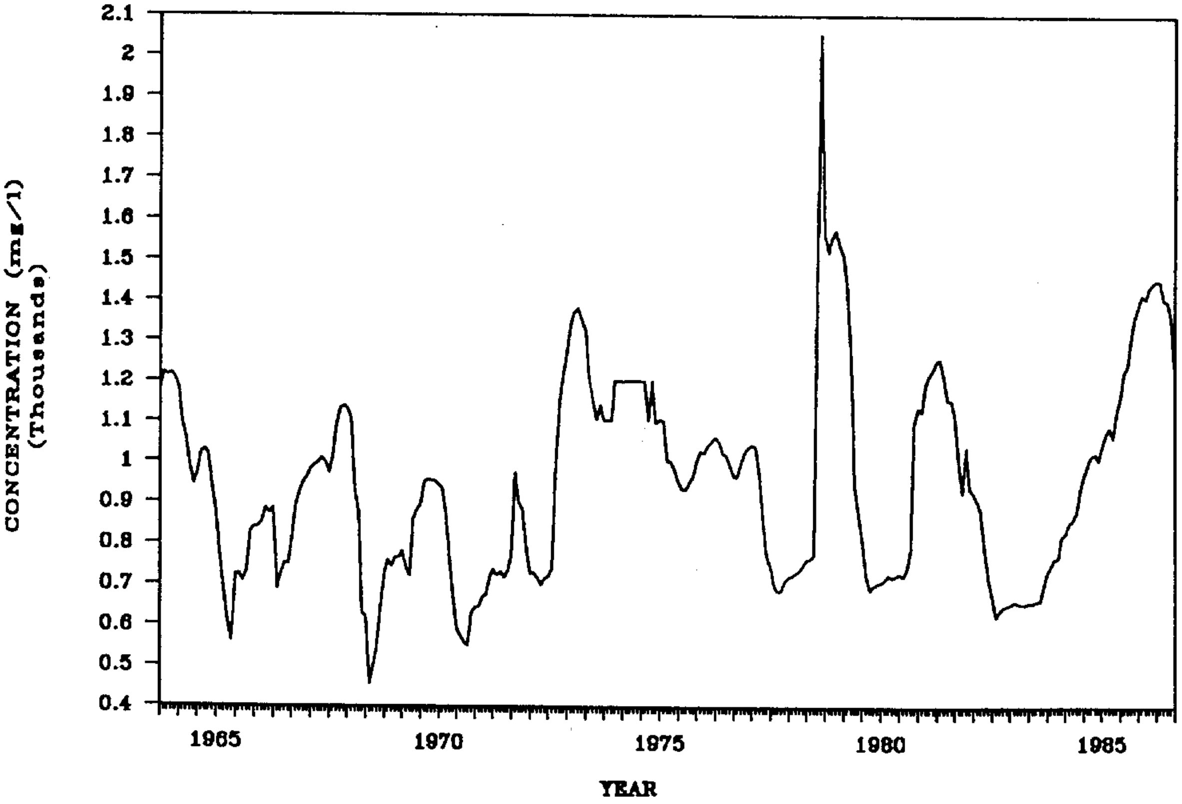

Figure 3.12 TDS Concentration Versus Time, Whitney Gage (Station 15)

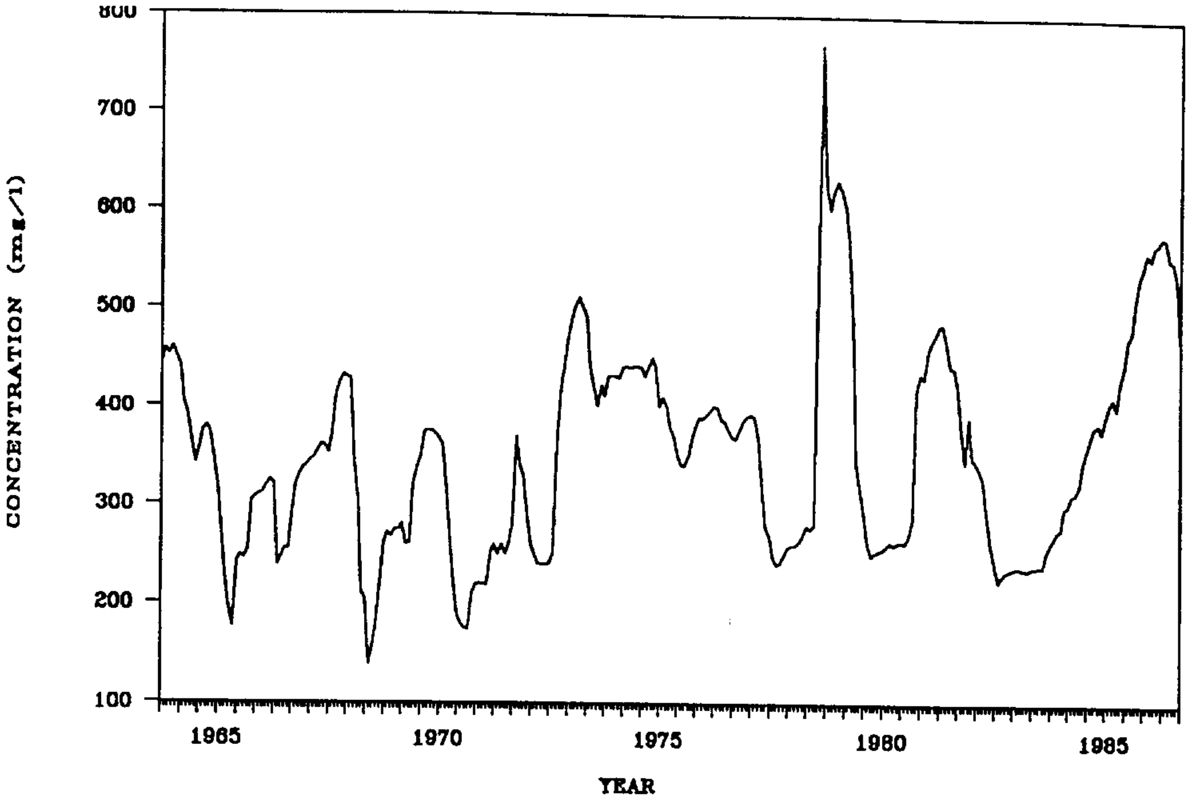

Figure 3.13 Chloride Concentration Versus Time, Whitney Gage (Station 15)

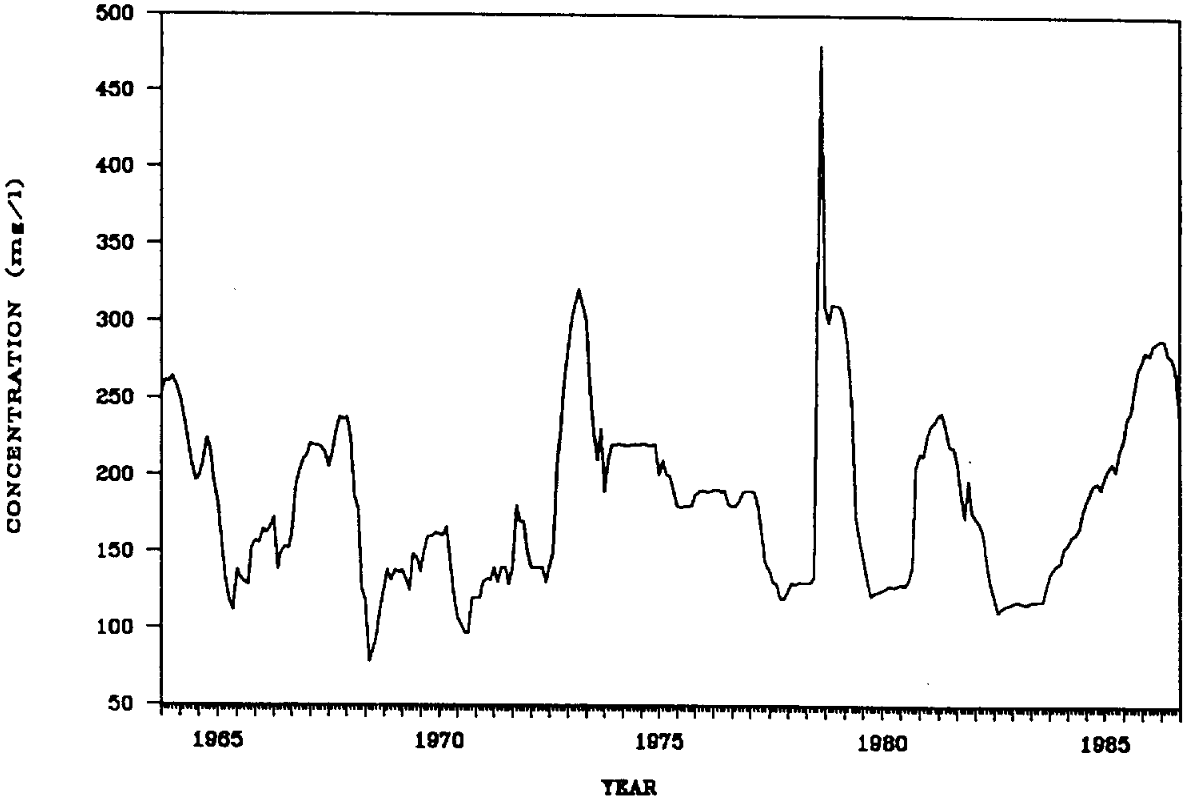

Figure 3.14 Sulfate Concentration Versus Time, Whitney Gage (Station 15)

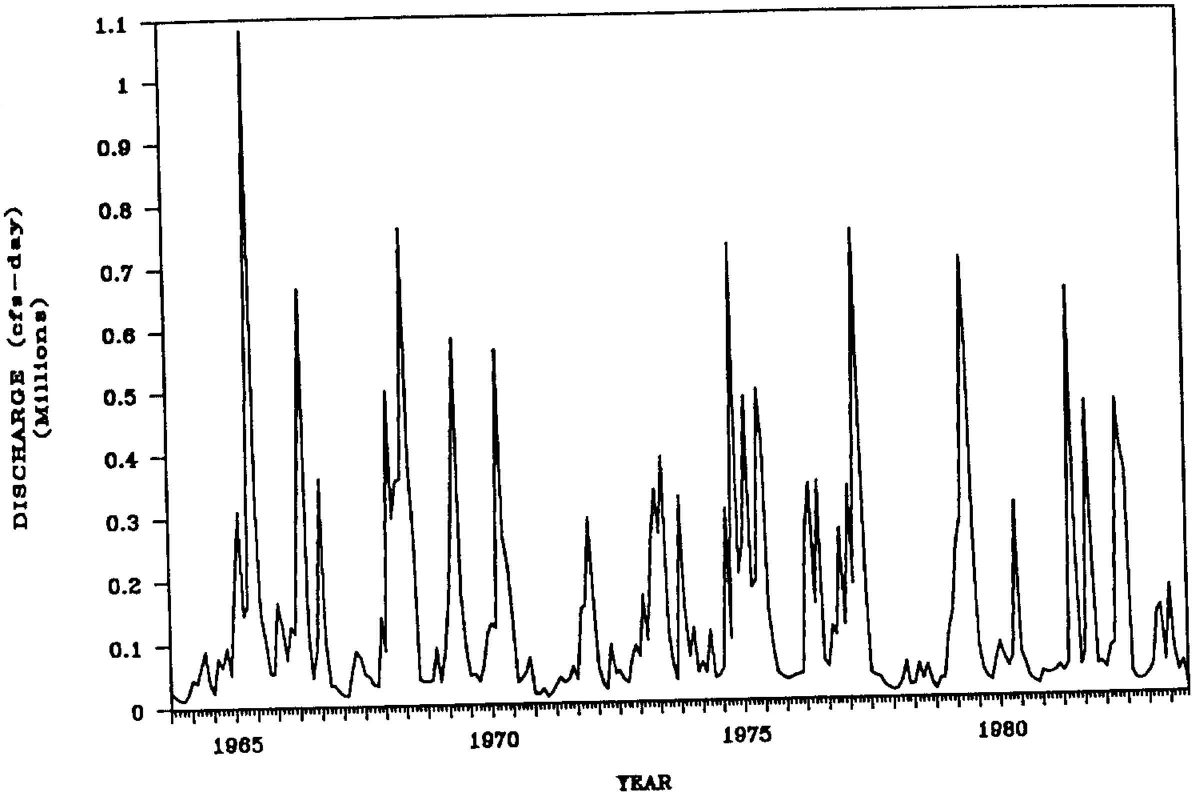

Figure 3.15 Discharge Hydrograph, College Station Gage (Station 21)

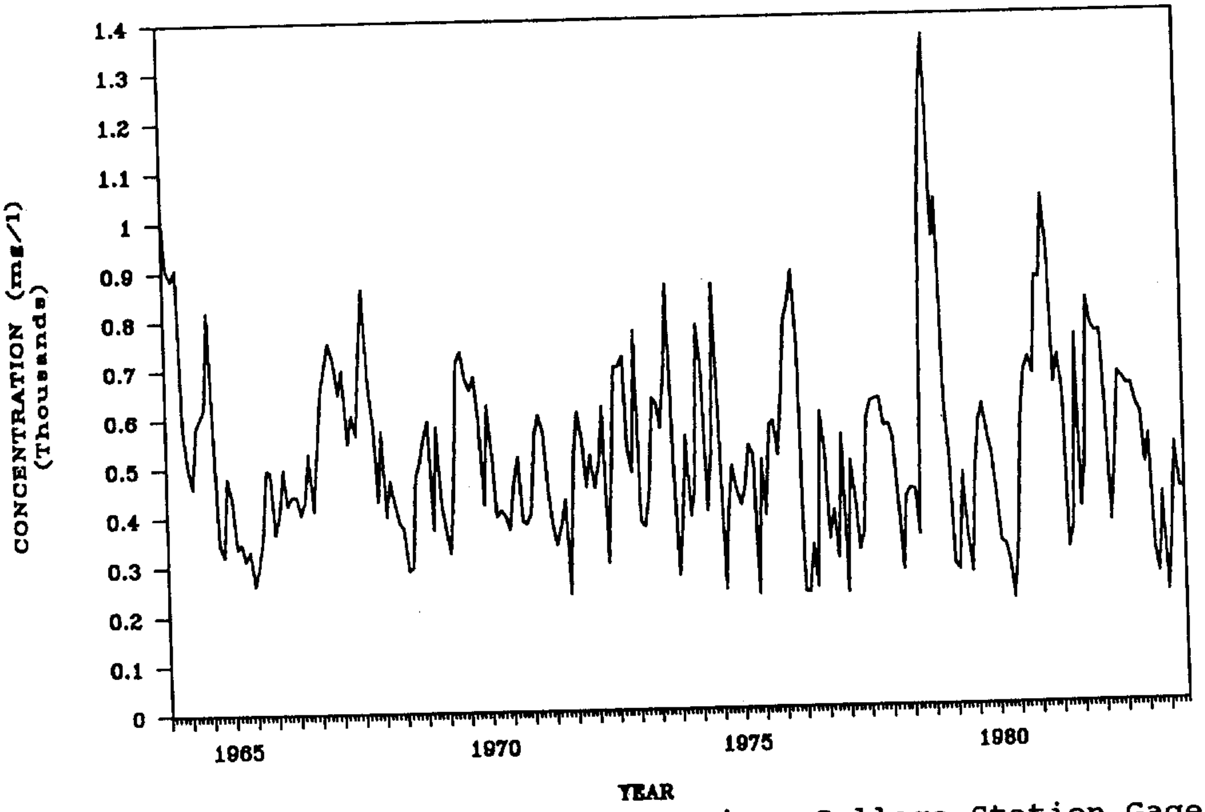

Figure 3.16 TDS Concentration Versus Time, College Station Gage (Station 21)

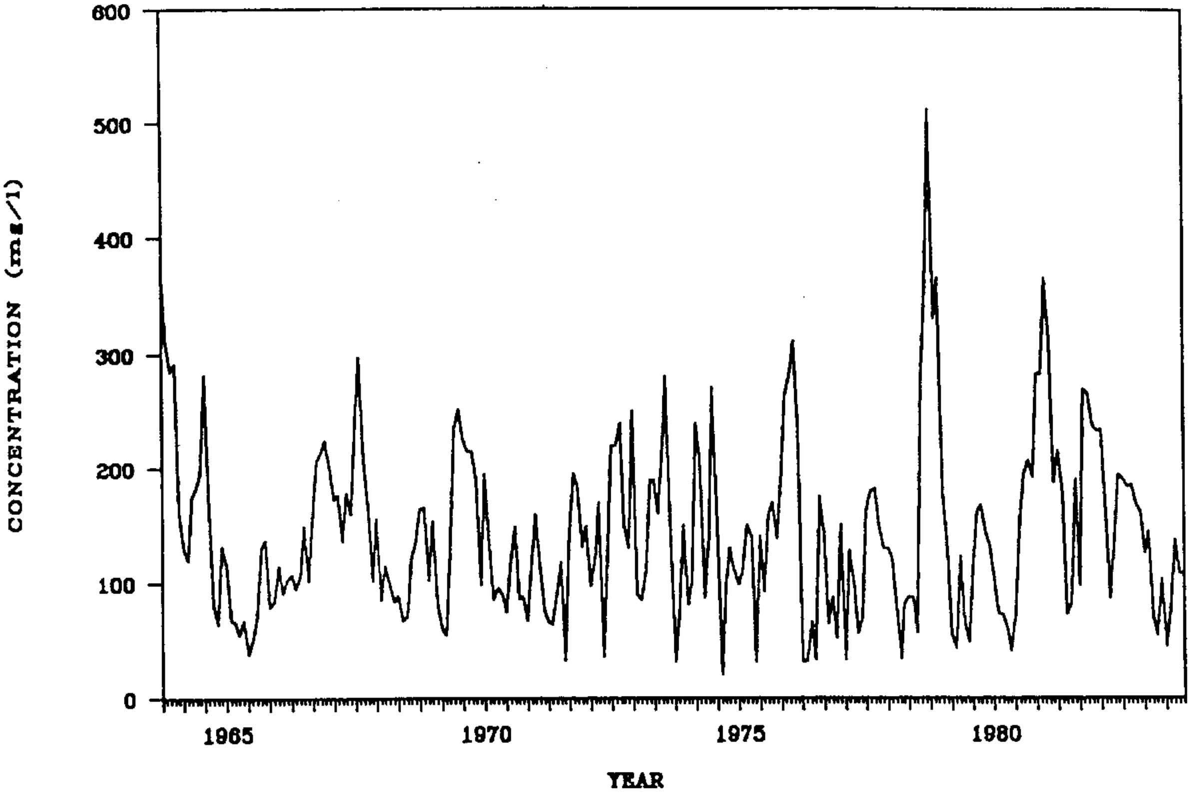

Figure 3.17 Chloride Concentration Versus Time, College Station Gage (Station 21)

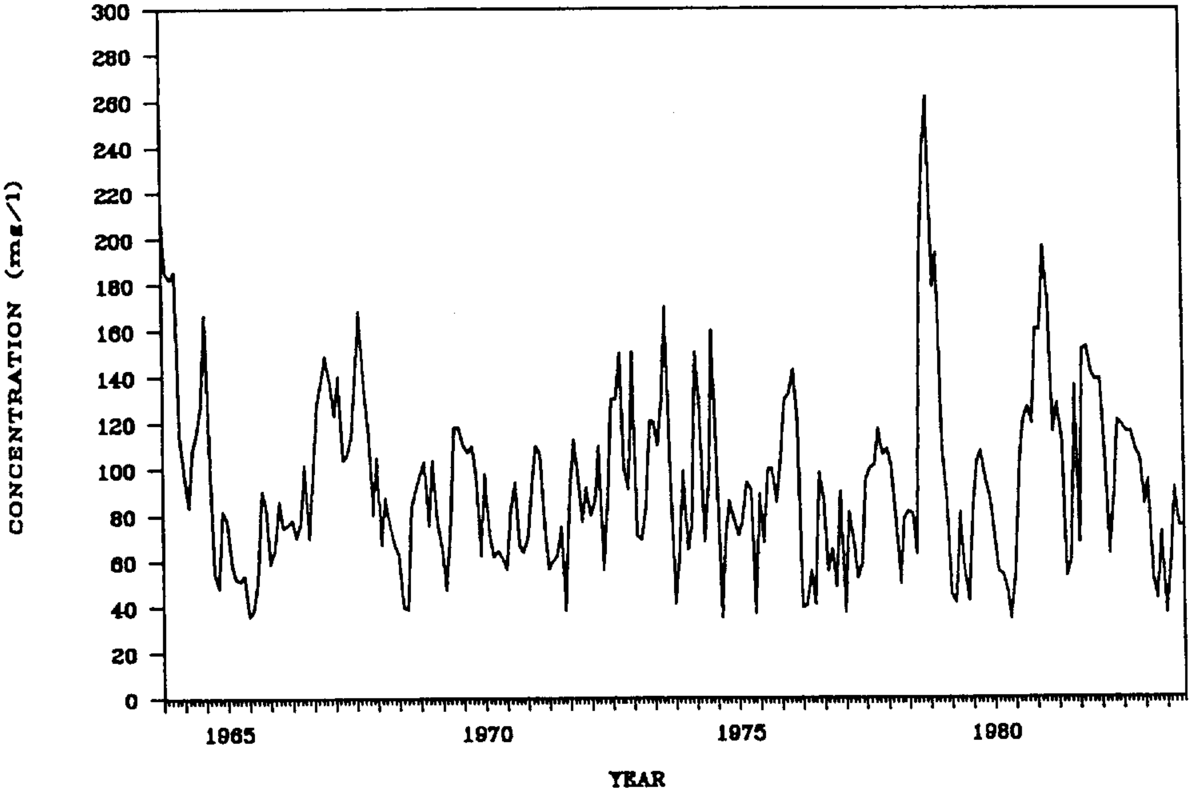

Figure 3.18 Sulfate Concentration Versus Time, College Station Gage (Station 21)

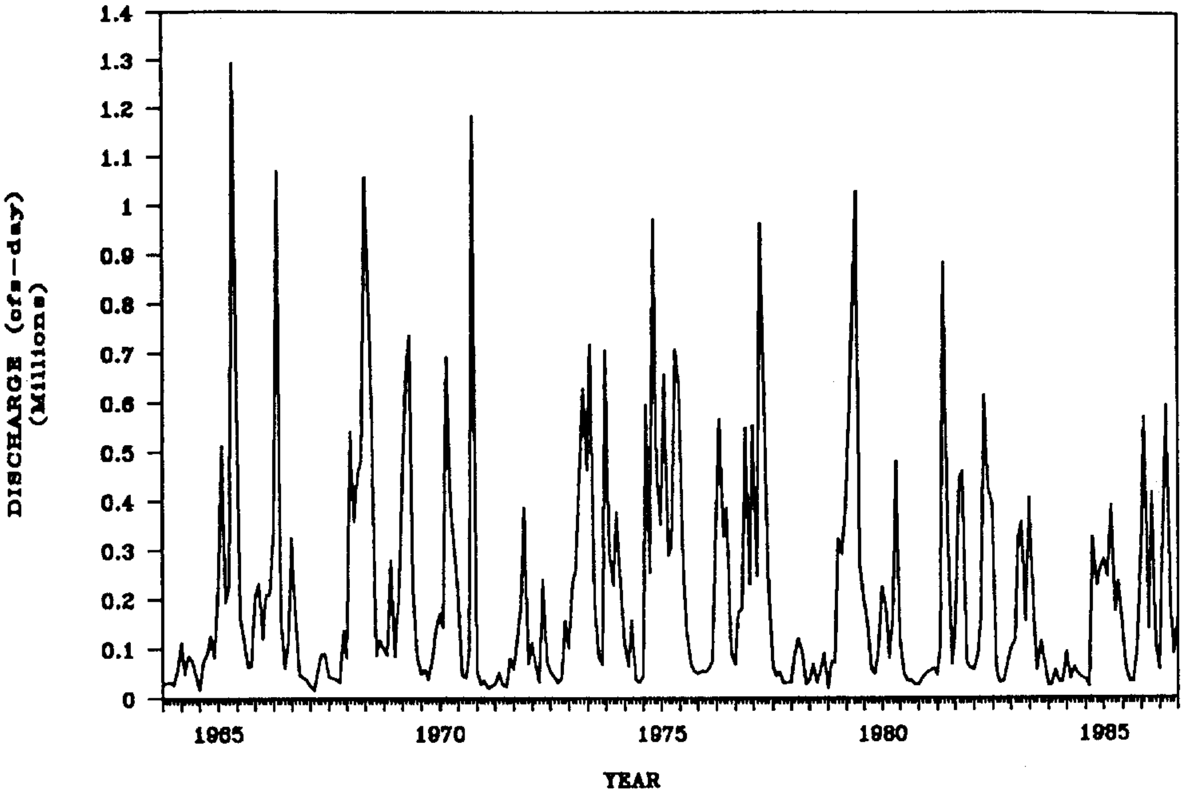

Figure 3.19 Discharge Hydrograph, Richmond Gage (Station 25)

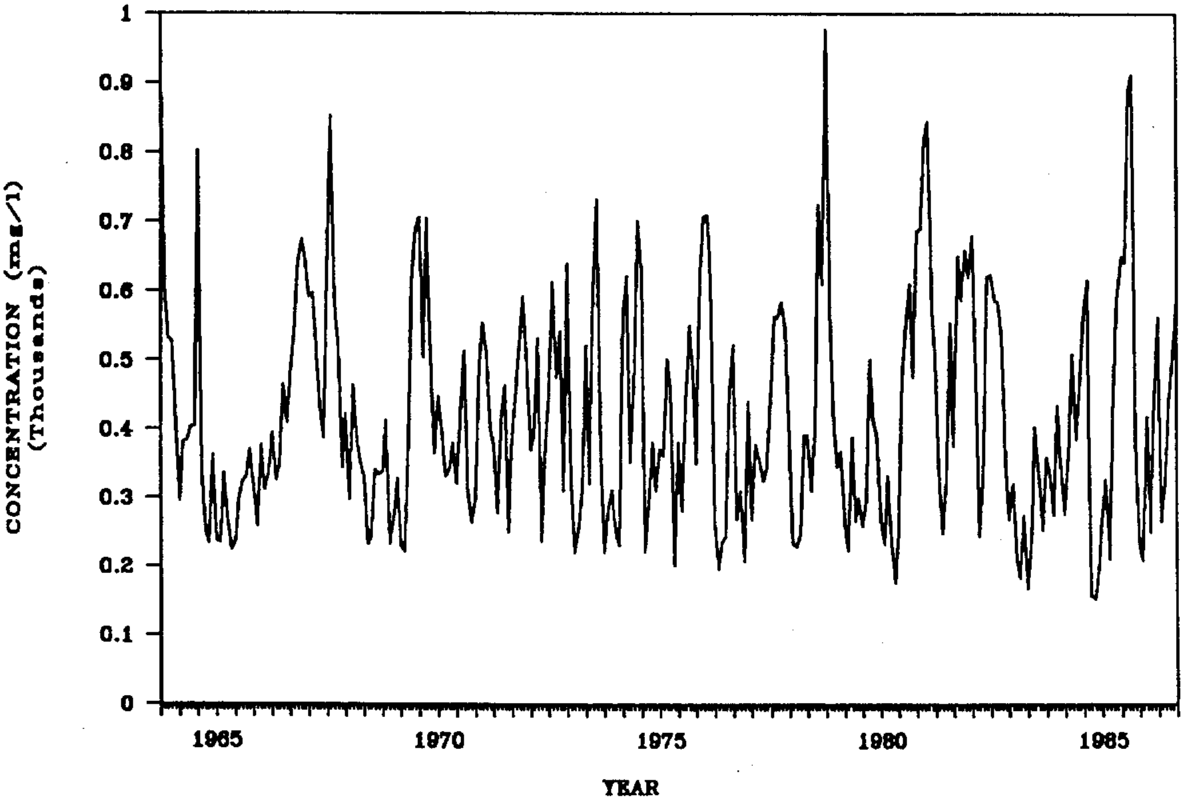

Figure 3.20 TDS Concentration Versus Time, Richmond Gage (Station 25)

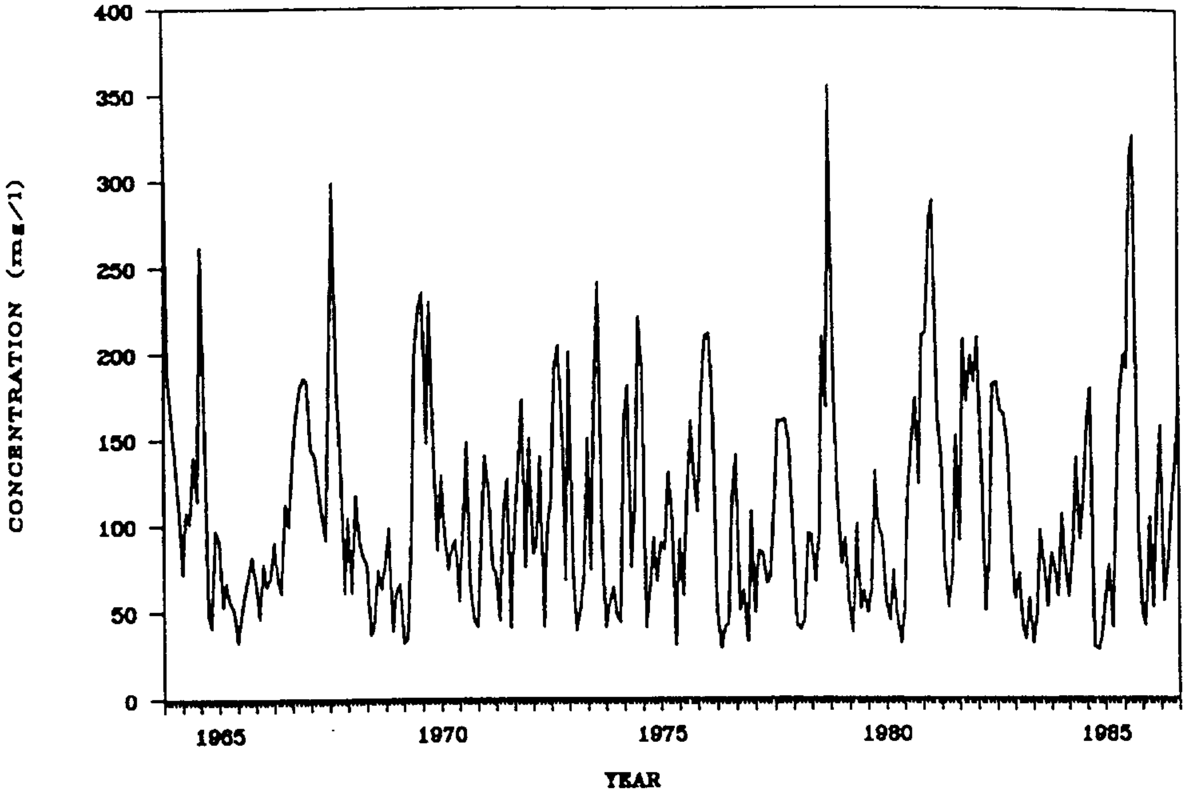

Figure 3.21 Chloride Concentration Versus Time, Richmond Gage (Station 25)

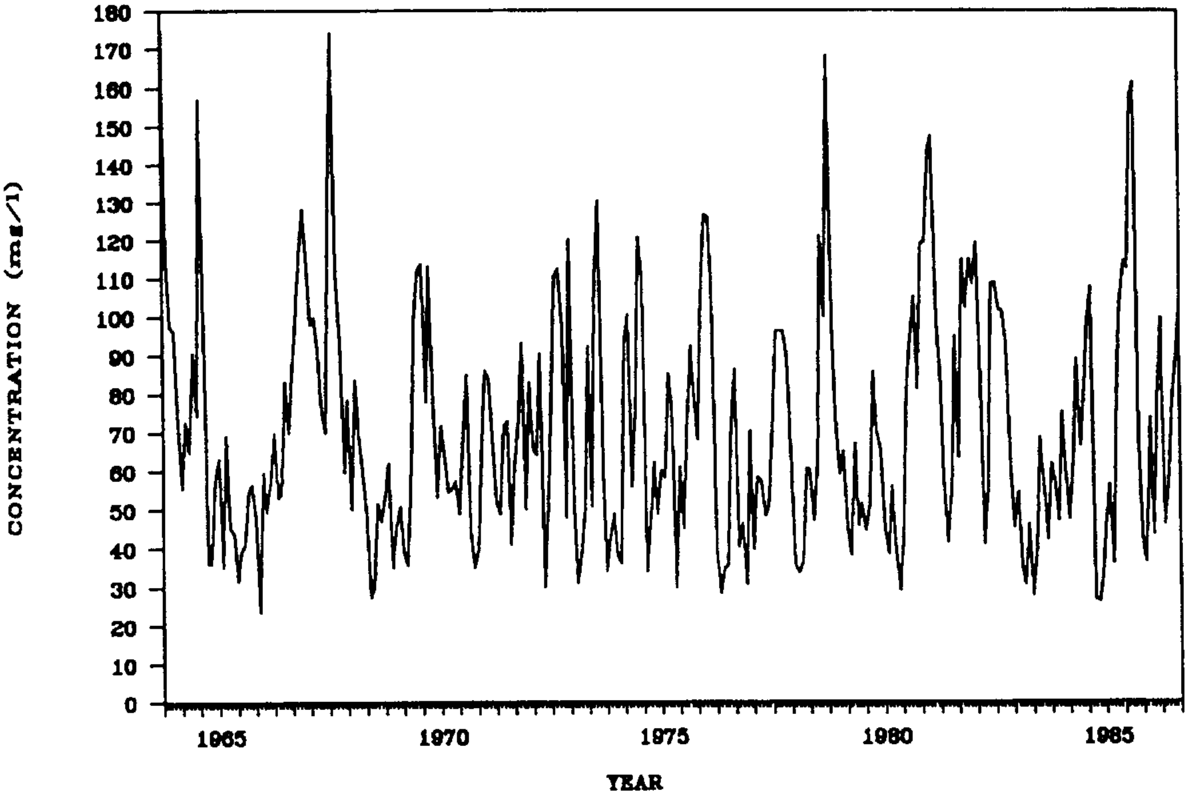

Figure 3.22 Sulfate Concentration Versus Time, Richmond Gage (Station 25)

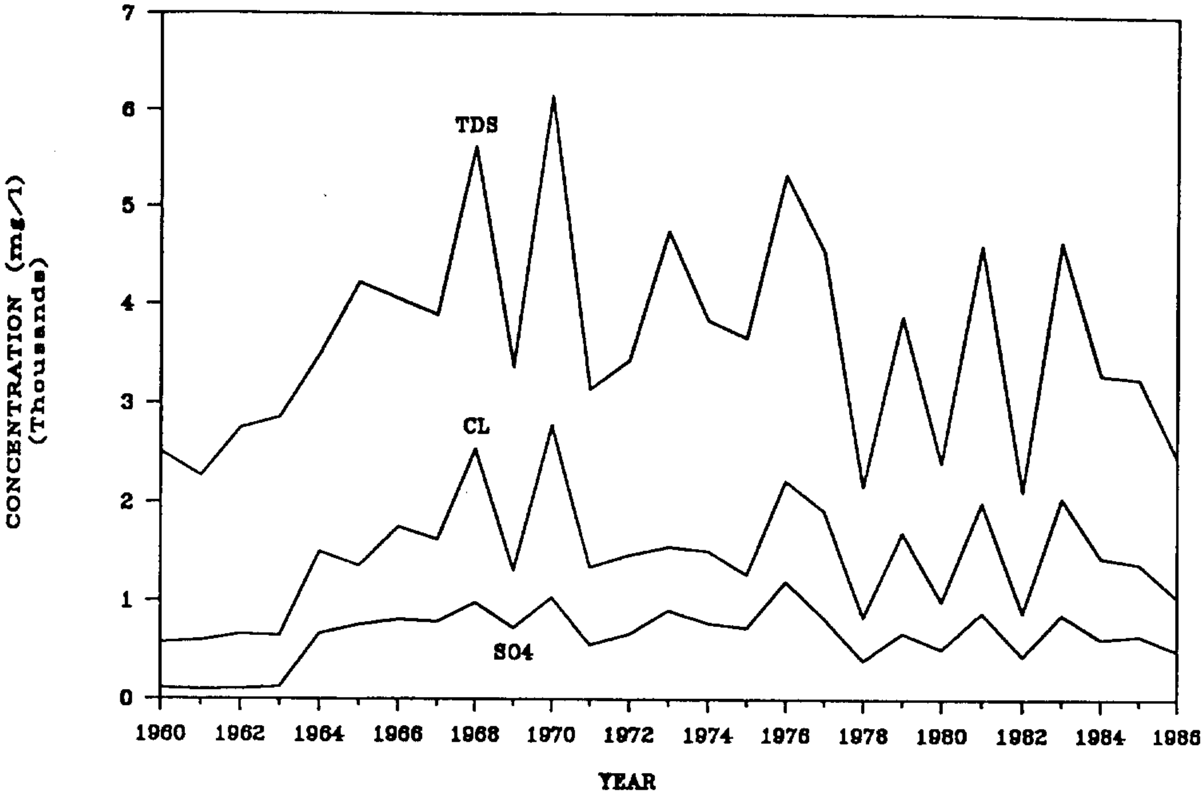

Figure 3.23 Annual Average Concentrations, Seymour Gage (Station 7)

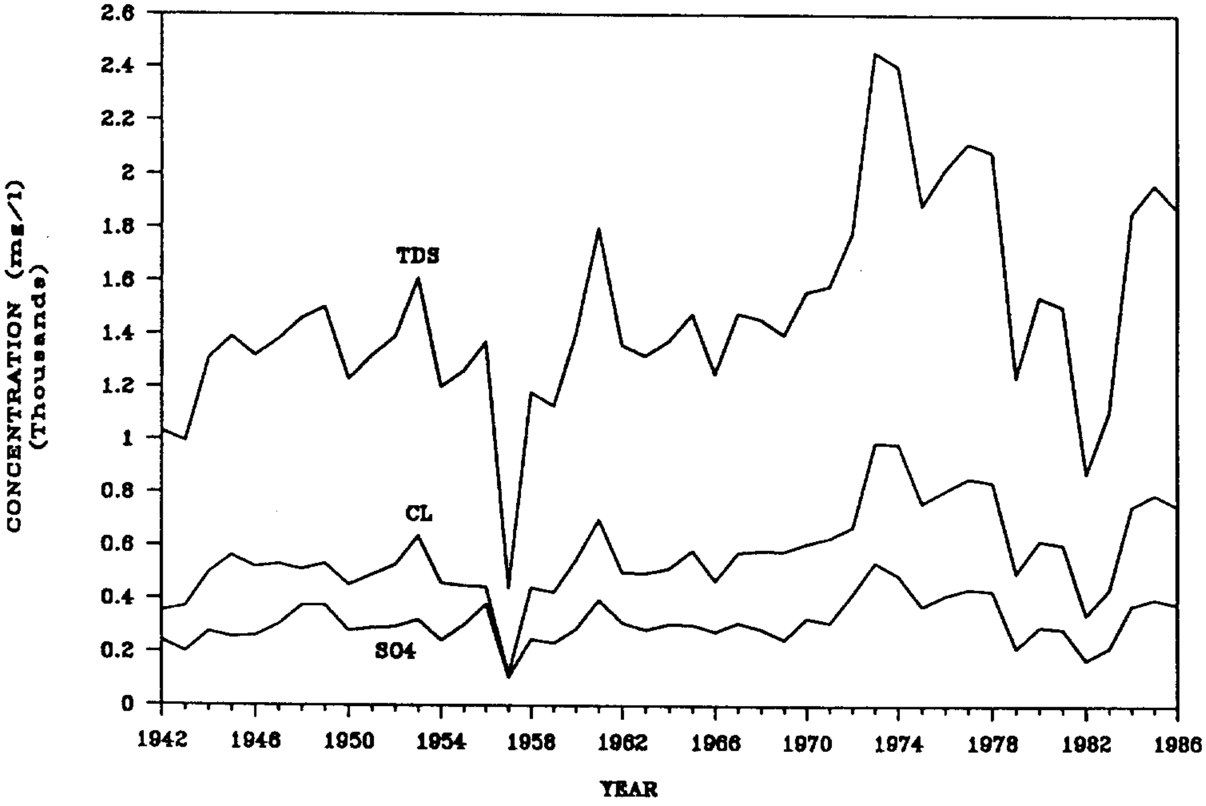

Figure 3.24 Annual Average Concentrations, Possum Kingdom Gage (Station 13)

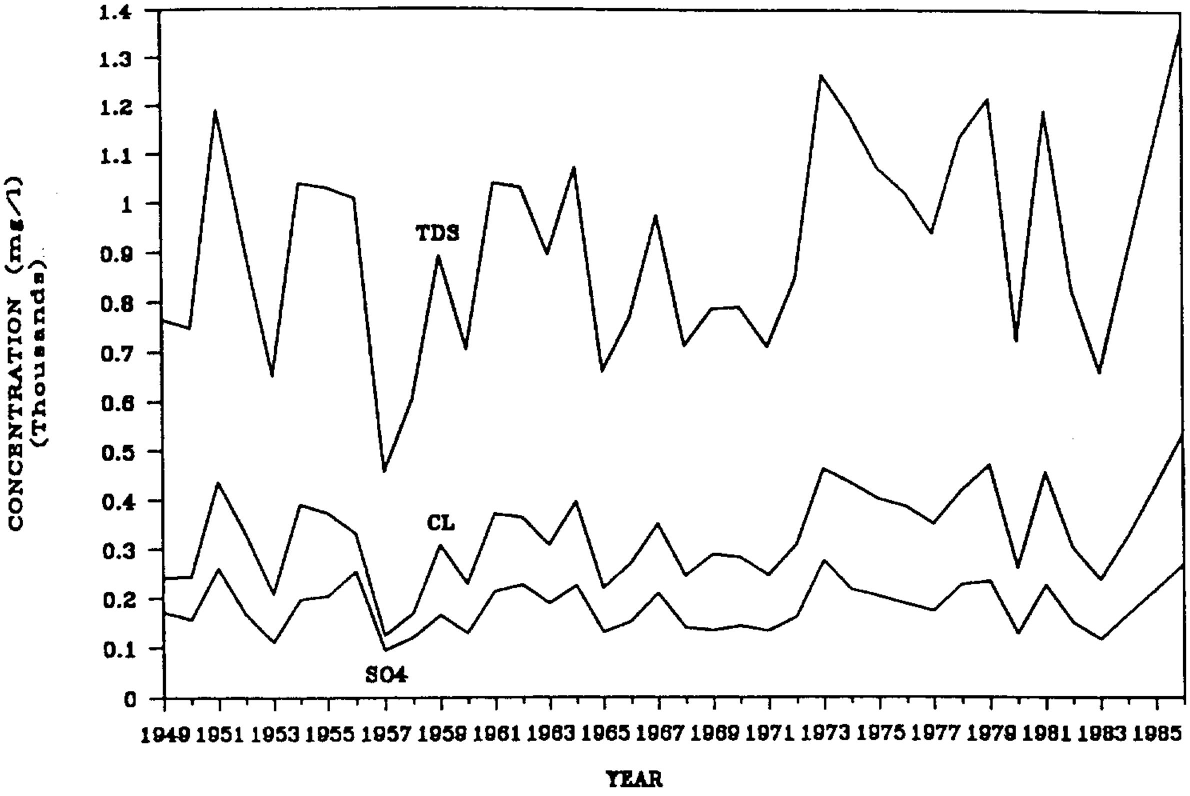

Figure 3.25 Annual Average Concentrations, Whitney Gage (Station 15)

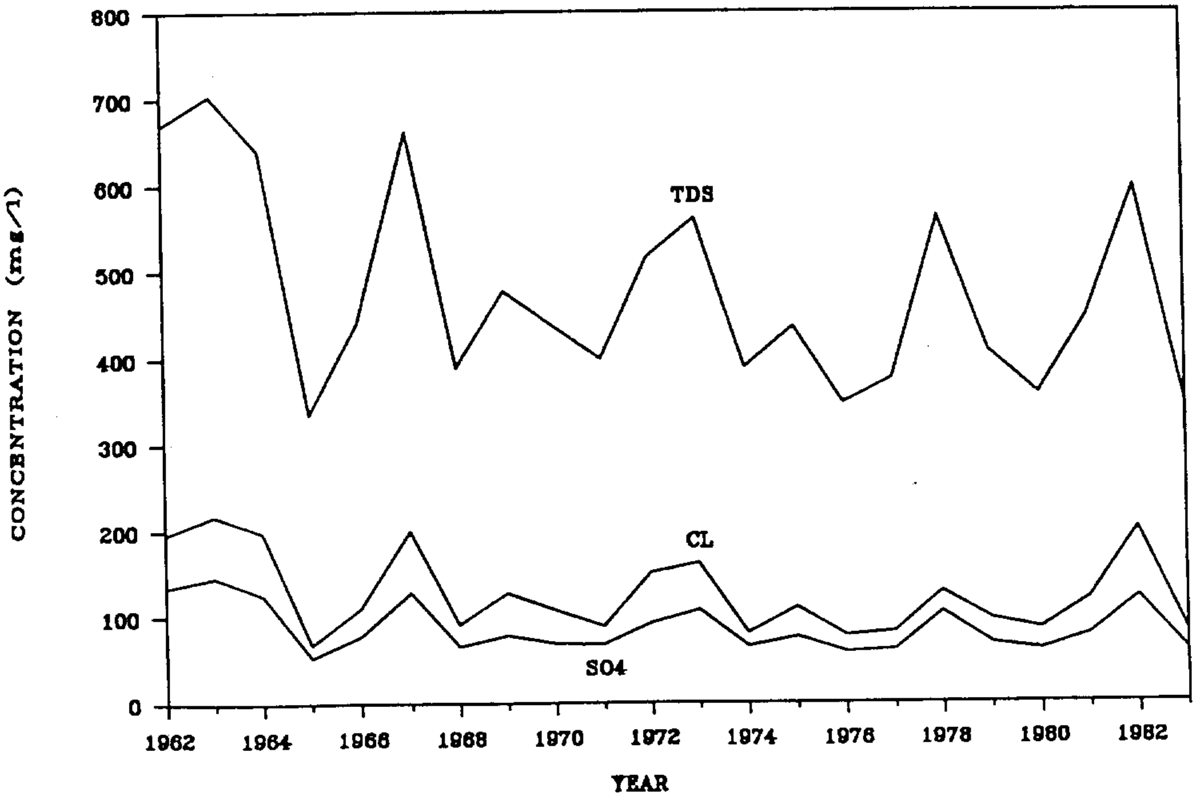

Figure 3.26 Annual Average Concentrations, College Station Gage (Station 21)

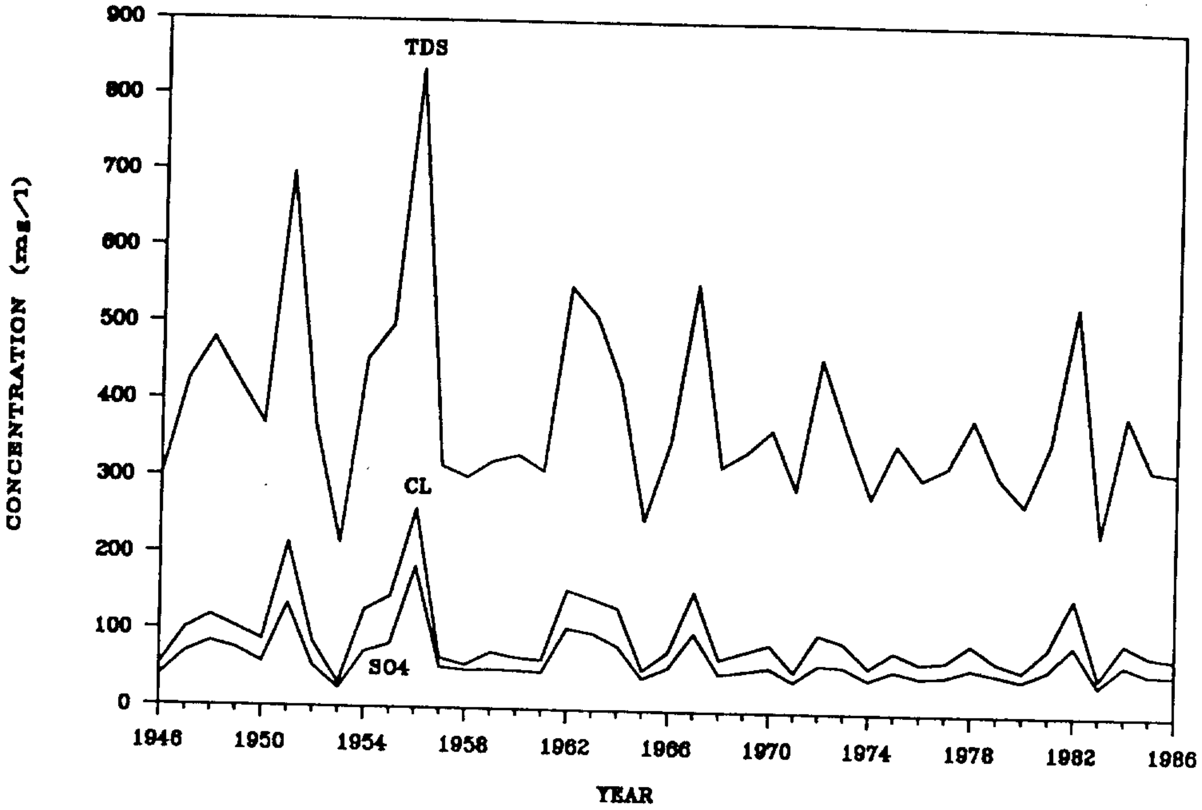

Figure 3.27 Annual Average Concentrations, Richmond Gage (Station 25)

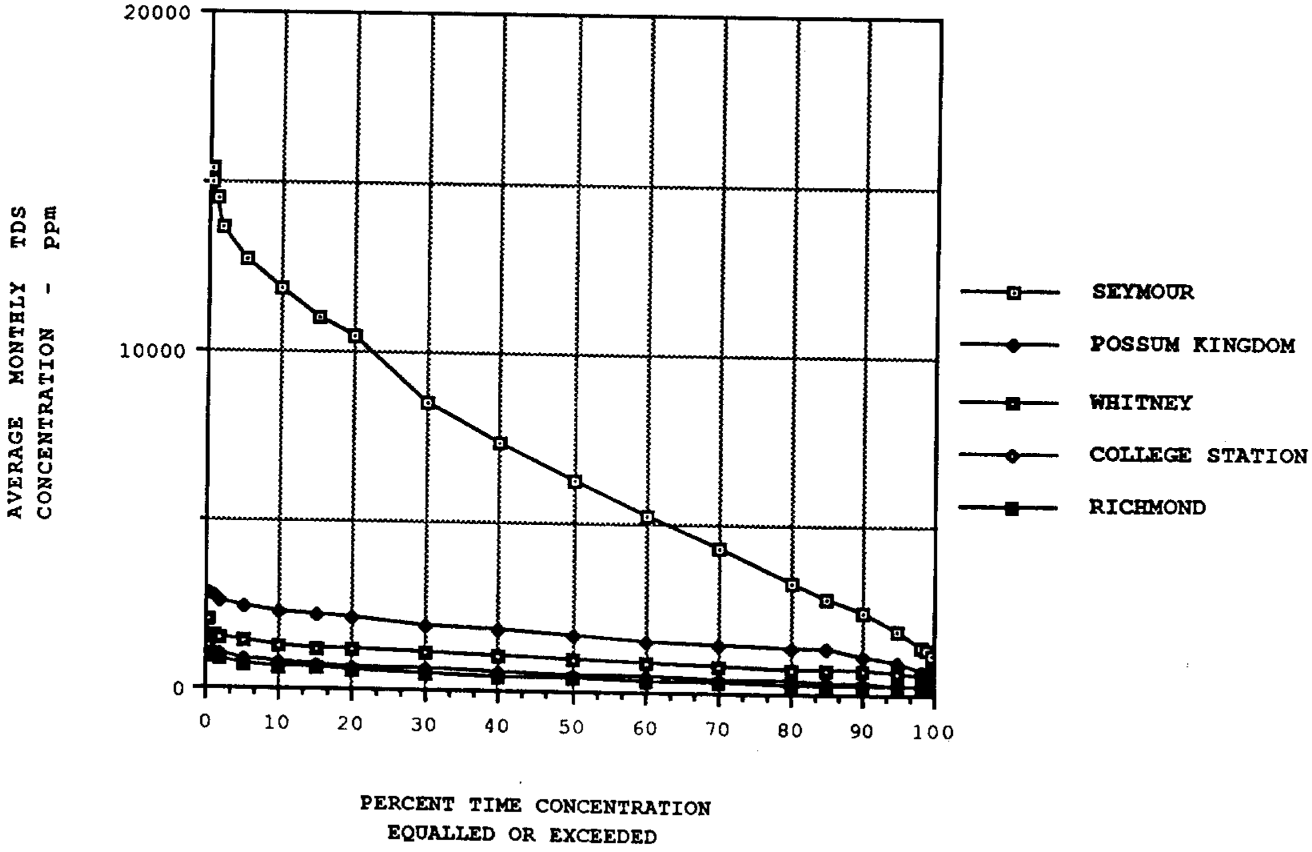

Figure 3.28 Concentration-Duration Curves for TDS

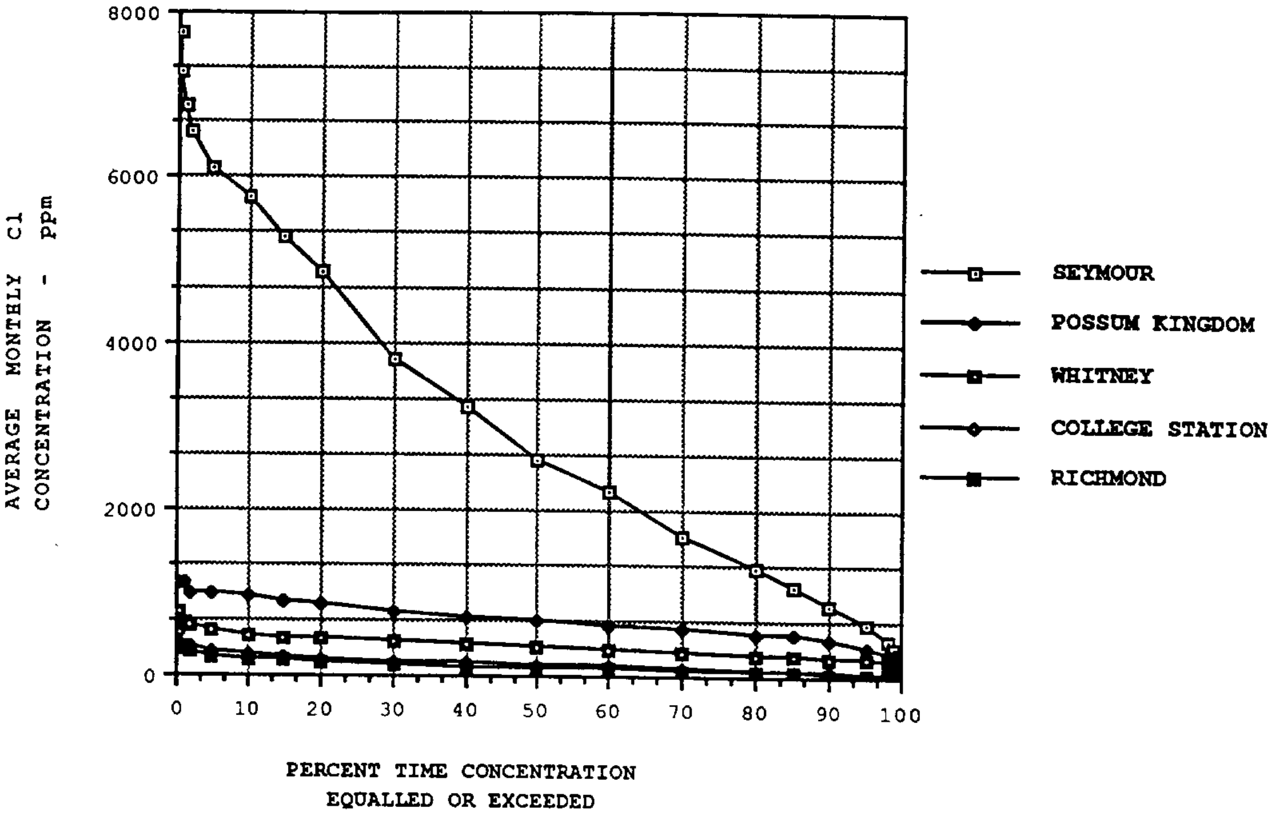

Figure 3.29 Concentration-Duration Curves for Chloride

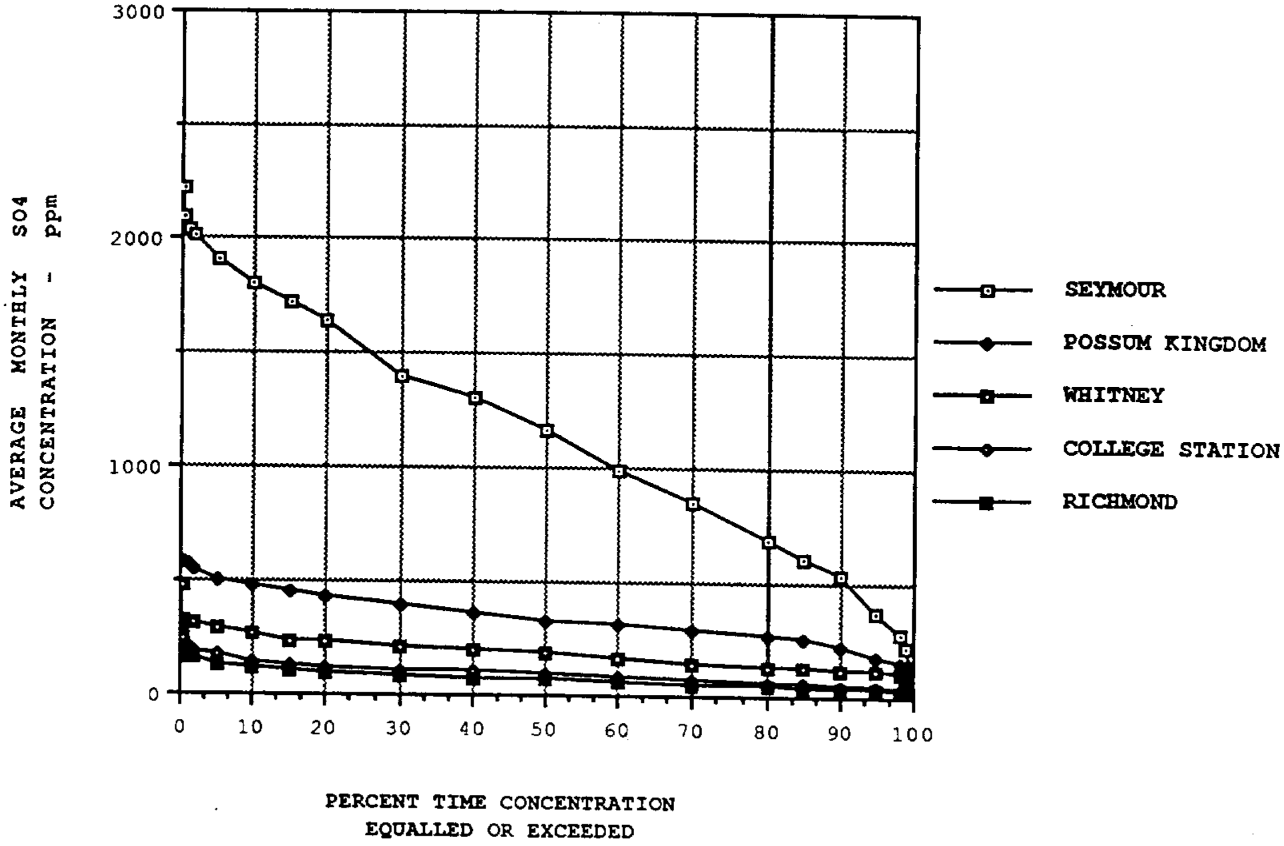

Figure 3.30 Concentration-Duration Curves for Sulfate

Table 3.4
CONCENTRATION-DURATION CURVES FOR TOTAL DISSOLVED SOLIDS

Percent Equalled or Exceeded	Seymour Gage (mg/l)	Possum Kingdom Gage (mg/l)	Whitney Gage (mg/l)	College Station Gage (mg/l)	Richmond Gage (mg/l)
0.01	15,400	2,810	2,050	1,360	978
0.05	15,400	2,810	2,050	1,360	978
0.1	15,400	2,810	2,050	1,360	978
0.2	15,400	2,810	2,050	1,360	978
0.5	15,000	2,800	1,580	1,260	910
1	14,500	2,710	1,560	1,040	902
2	13,700	2,540	1,520	1,010	845
5	12,700	2,420	1,400	870	701
10	11,900	2,290	1,250	763	635
15	11,000	2,190	1,210	704	601
20	10,500	2,090	1,170	659	566
30	8,530	1,890	1,070	596	498
40	7,320	1,780	1,000	557	426
50	6,220	1,620	945	505	382
60	5,270	1,510	864	448	346
70	4,320	1,420	750	412	317
80	3,320	1,350	723	370	264
85	2,800	1,300	699	339	250
90	2,420	1,130	666	313	235
95	1,870	948	639	270	218
98	1,400	739	567	238	198
99	1,290	583	552	231	169
99.5	1,190	508	487	228	164
99.8	817	500	476	225	161
99.9	774	495	472	223	160
99.95	742	492	469	221	159
99.99	692	486	464	218	157
100	618	475	456	212	153

Table 3.5
CONCENTRATION-DURATION CURVES FOR CHLORIDE

Percent Equalled or Exceeded	Seymour Gage (mg/l)	Possum Kingdom Gage (mg/l)	Whitney Gage (mg/l)	College Station Gage (mg/l)	Richmond Gage (mg/l)
0.01	7,740	1,100	771	512	355
0.05	7,740	1,100	771	512	355
0.1	7,740	1,100	771	512	355
0.2	7,740	1,100	771	512	355
0.5	7,270	1,100	637	370	340
1	6,850	1,100	625	364	328
2	6,530	1,000	612	353	290
5	6,110	989	551	288	213
10	5,760	949	484	250	192
15	5,270	892	451	220	176
20	4,850	844	437	198	162
30	3,810	756	400	173	135
40	3,240	706	376	154	108
50	2,610	652	350	134	93
60	2,210	594	316	113	80
70	1,690	562	270	91	67
80	1,290	522	256	79	55
85	1,080	503	247	69	49
90	851	447	236	60	43
95	647	362	218	41	36
98	455	282	176	35	34
99	339	223	169	32	33
99.5	297	195	156	30	32
99.8	271	192	148	28	31
99.9	256	190	146	27	31
99.95	244	189	145	26	30
99.99	224	187	143	24	30
100	190	183	139	20	28

Table 3.6
CONCENTRATION-DURATION CURVES FOR SULFATE

Percent Equalled or Exceeded	Seymour Gage (mg/l)	Possum Kingdom Gage (mg/l)	Whitney Gage (mg/l)	College Station Gage (mg/l)	Richmond Gage (mg/l)
0.01	2,220	582	481	262	185
0.05	2,220	582	481	262	185
0.1	2,220	582	481	262	185
0.2	2,220	582	481	262	185
0.5	2,090	582	325	239	172
1	2,040	574	317	213	166
2	2,010	547	313	191	157
5	1,910	501	291	170	124
10	1,800	481	267	143	113
15	1,720	459	237	133	105
20	1,640	436	228	121	98
30	1,400	396	214	109	86
40	1,300	364	195	100	73
50	1,160	328	181	90	64
60	986	309	160	80	58
70	854	289	141	72	51
80	686	273	132	62	45
85	604	258	127	57	40
90	539	219	122	51	37
95	367	180	116	41	33
98	281	147	103	39	29
99	224	118	93	38	27
99.5	145	99	83	38	25
99.8	137	98	80	37	25
99.9	132	97	79	37	25
99.95	128	97	79	37	25
99.99	122	96	79	36	24
100	112	94	78	35	24

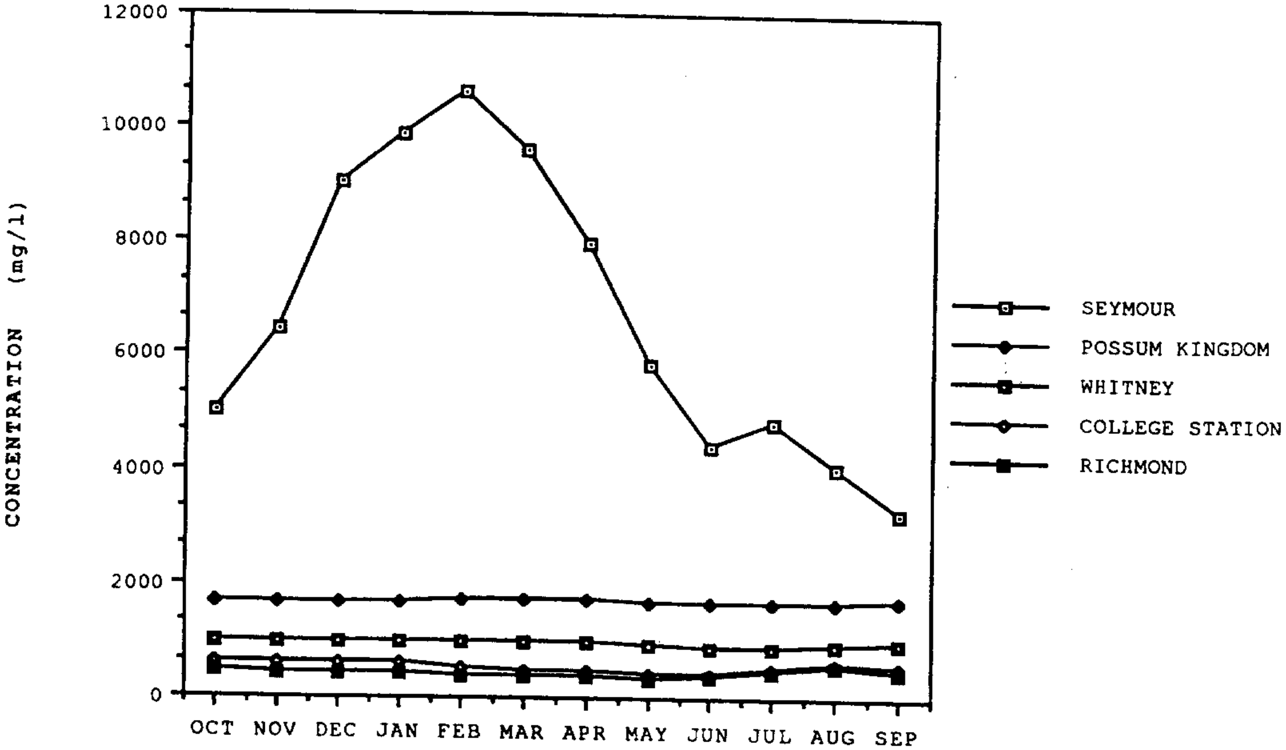

Figure 3.31 Arithmetic Average of Monthly TDS Concentrations

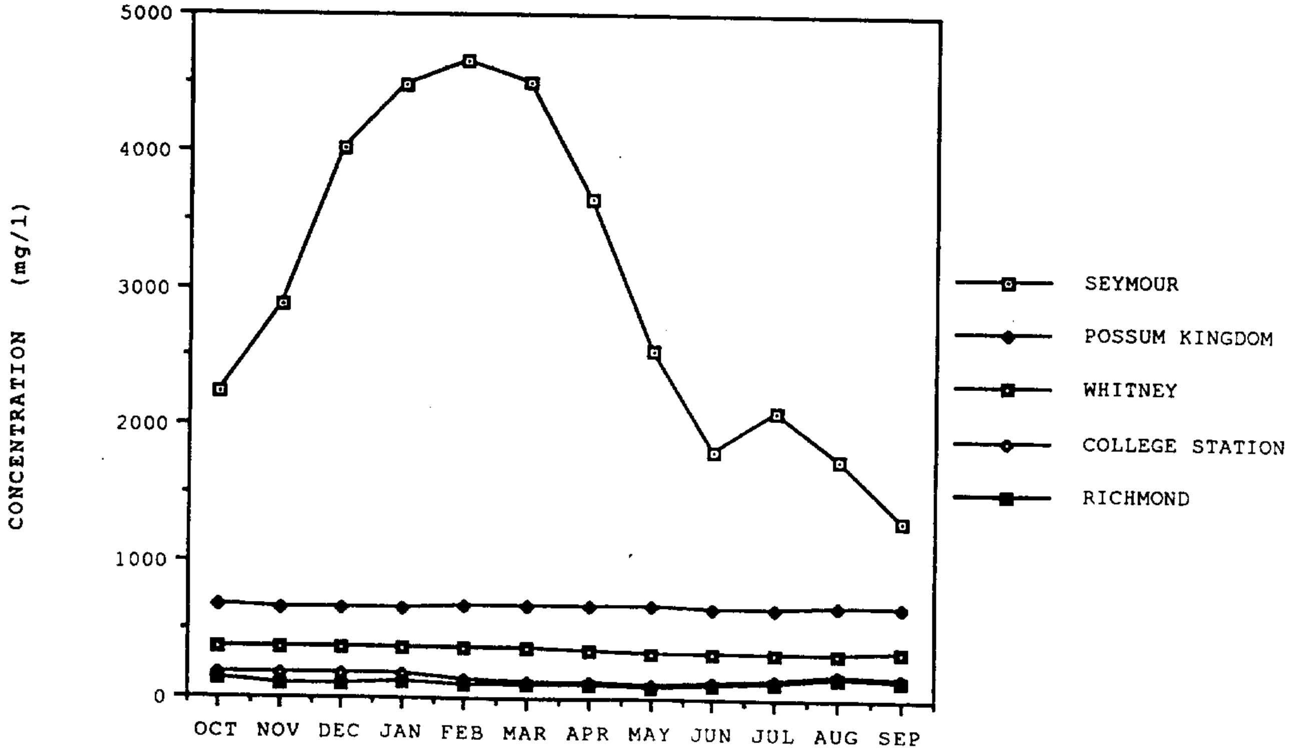

Figure 3.32 Arithmetic Average of Monthly Chloride Concentrations

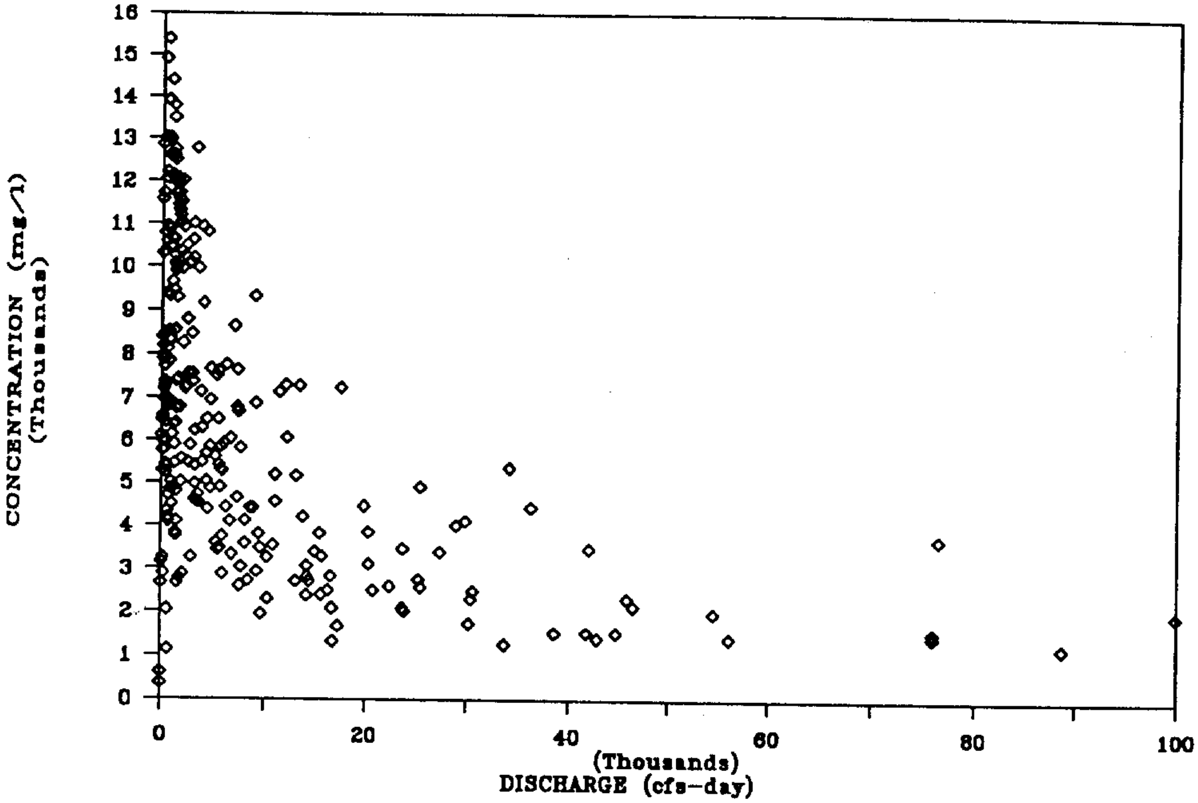

Figure 3.33 TDS Concentration Versus Discharge, Seymour Gage (Station 7)

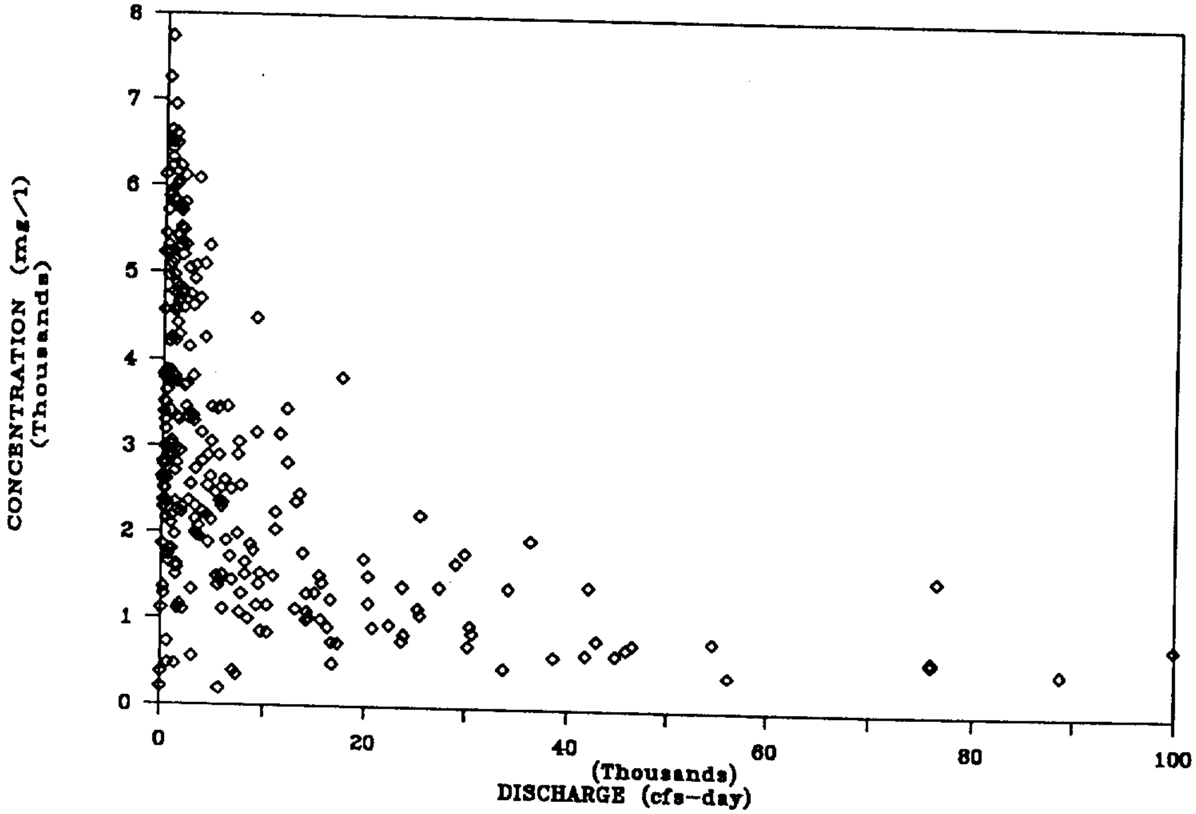

Figure 3.34 Chloride Concentration Versus Discharge, Seymour Gage (Station 7)

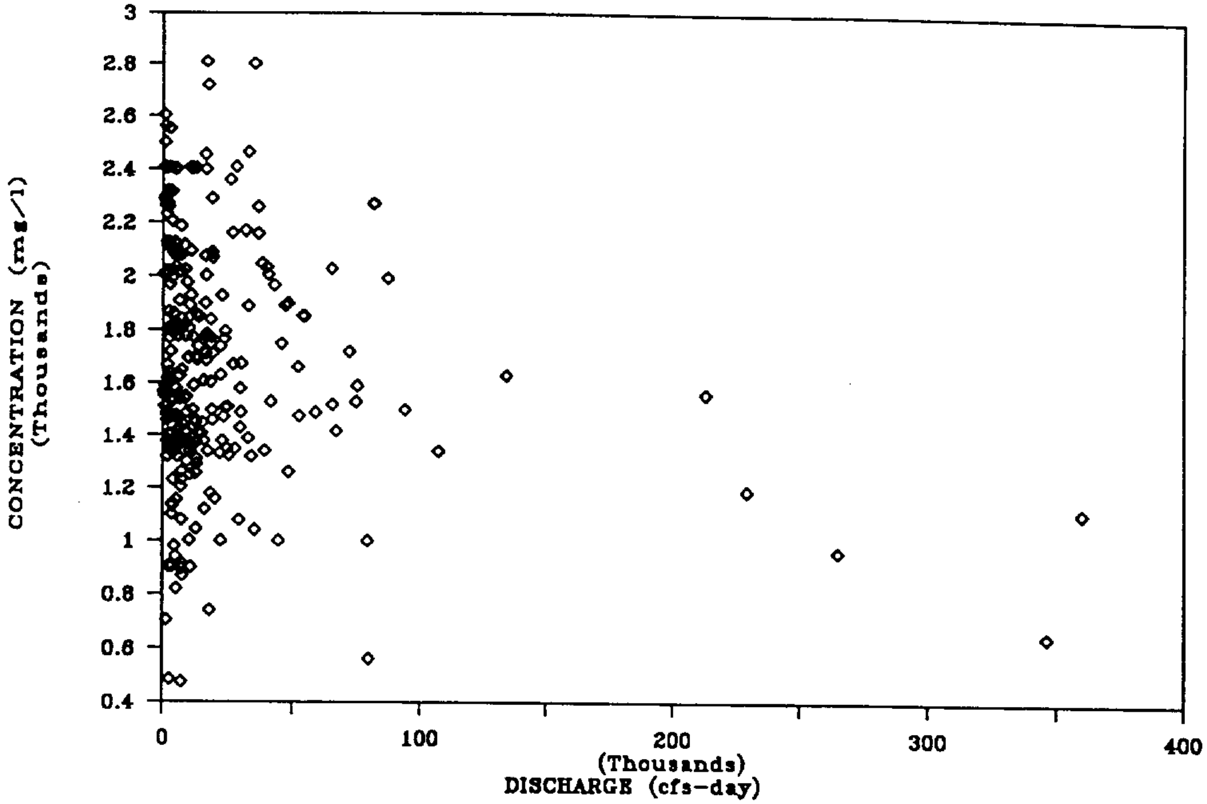

Figure 3.35 TDS Concentration Versus Discharge, Possum Kingdom Gage (Station 13)

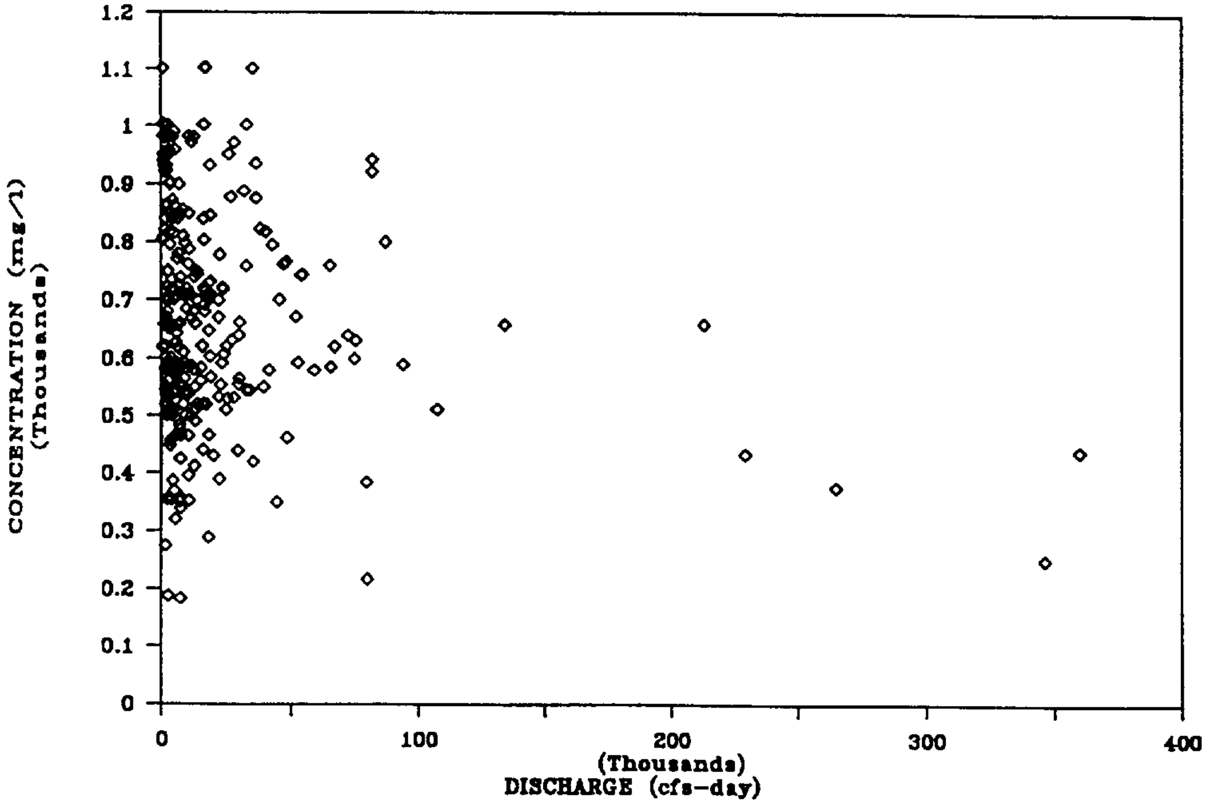

Figure 3.36 Chloride Concentration Versus Discharge, Possum Kingdom Gage (Station 13)

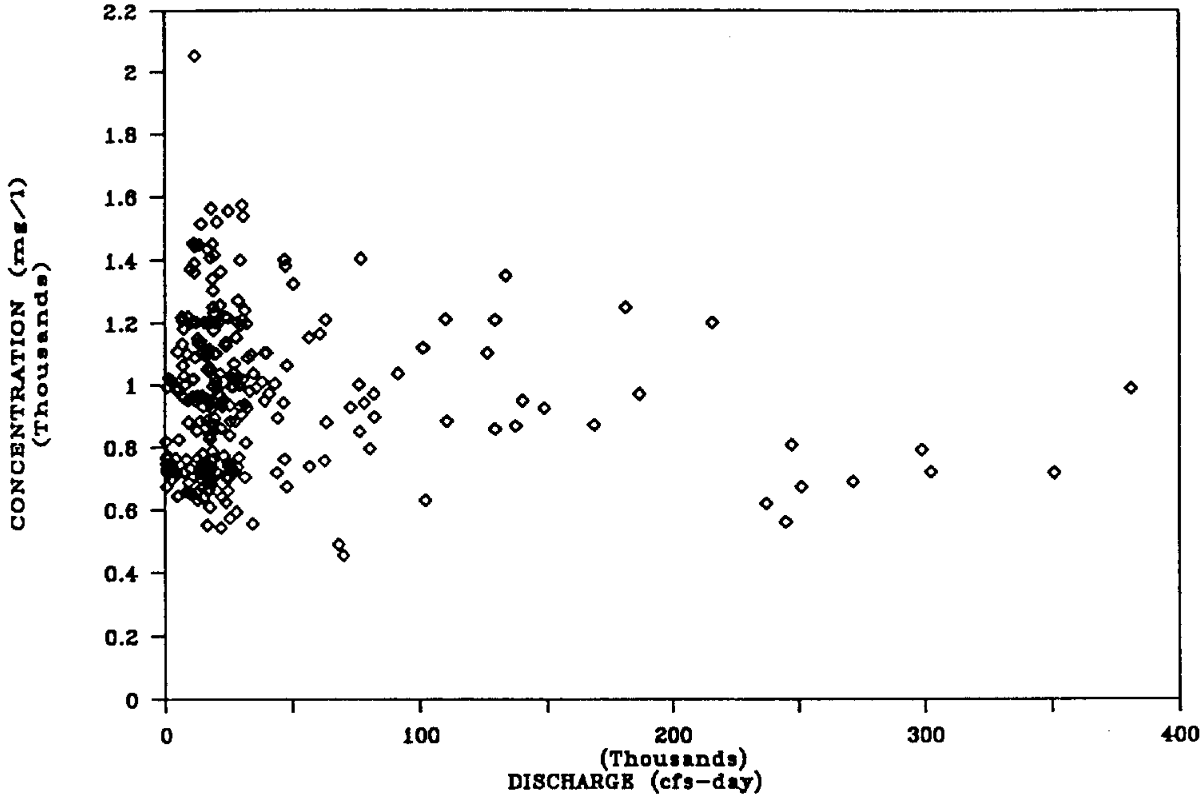

Figure 3.37 TDS Concentration Versus Discharge, Whitney Gage (Station 15)

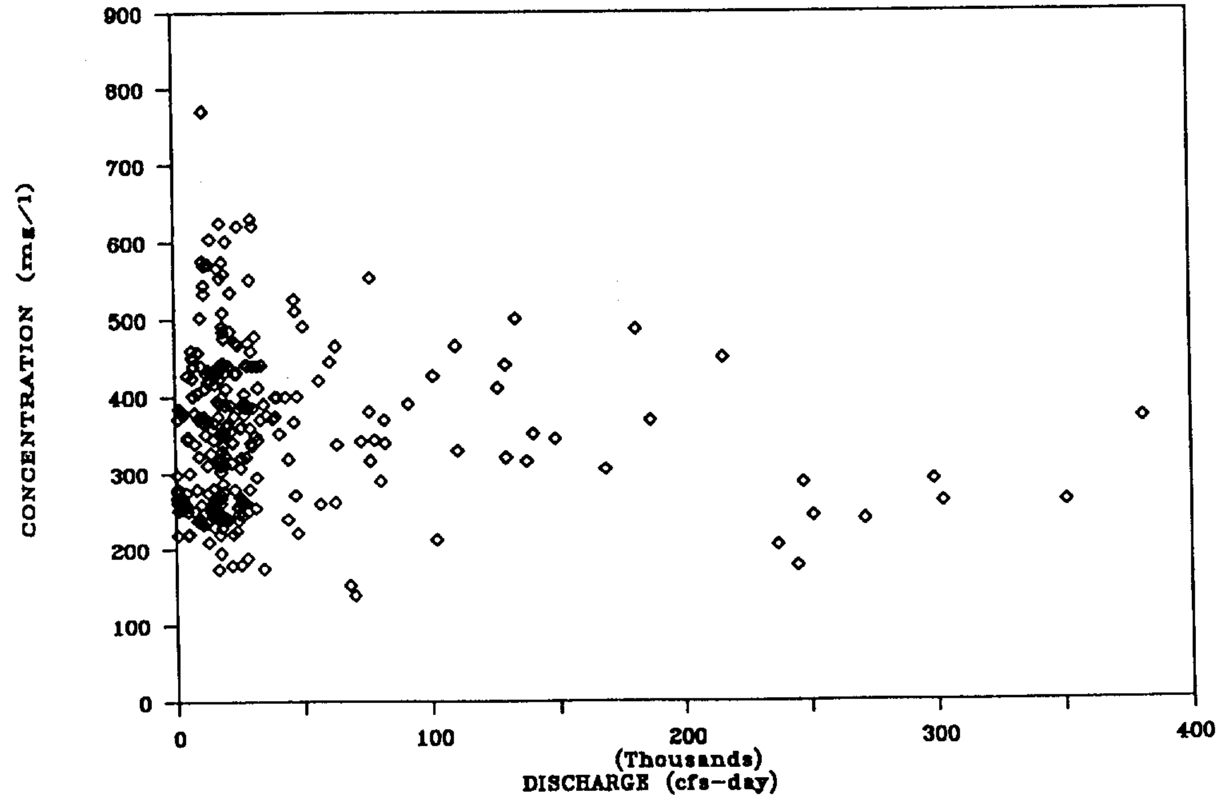

Figure 3.38 Chloride Concentration Versus Discharge, Whitney Gage (Station 15)

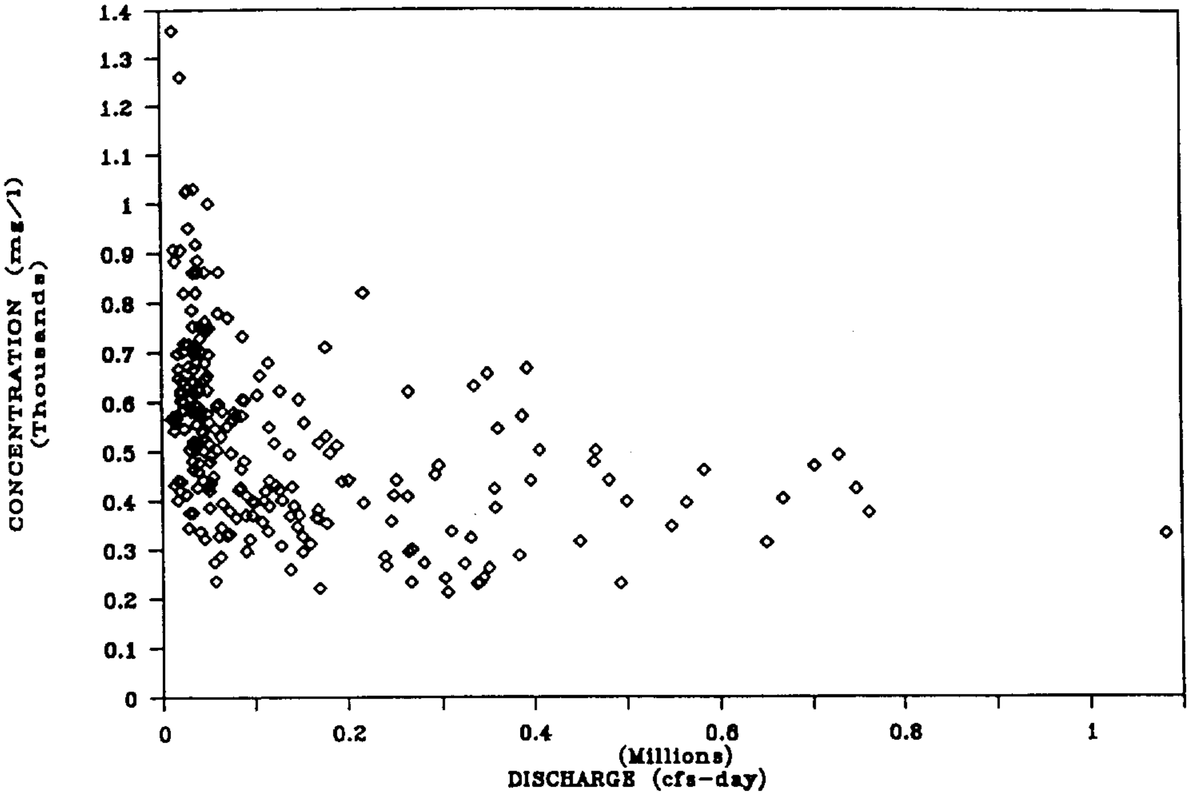

Figure 3.39 TDS Concentration Versus Discharge, College Station Gage (Station 21)

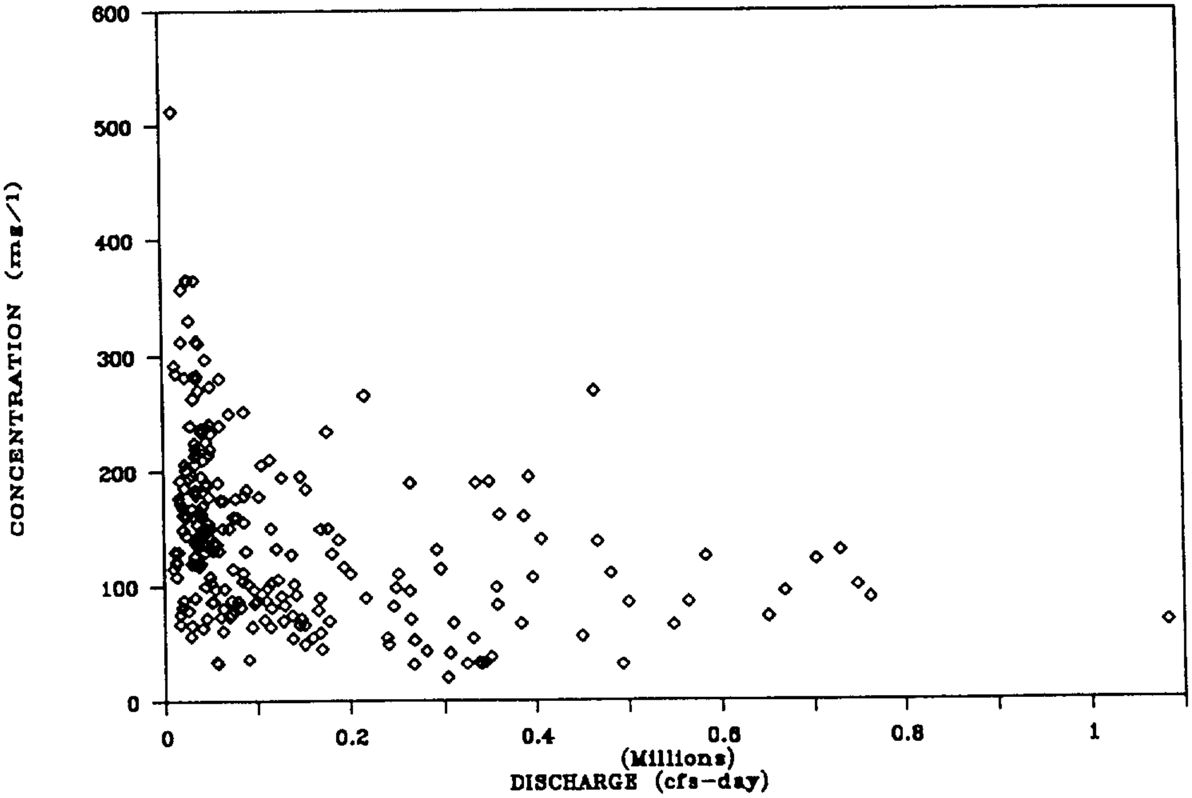

Figure 3.40 Chloride Concentration Versus Discharge, College Station Gage (Station 21)

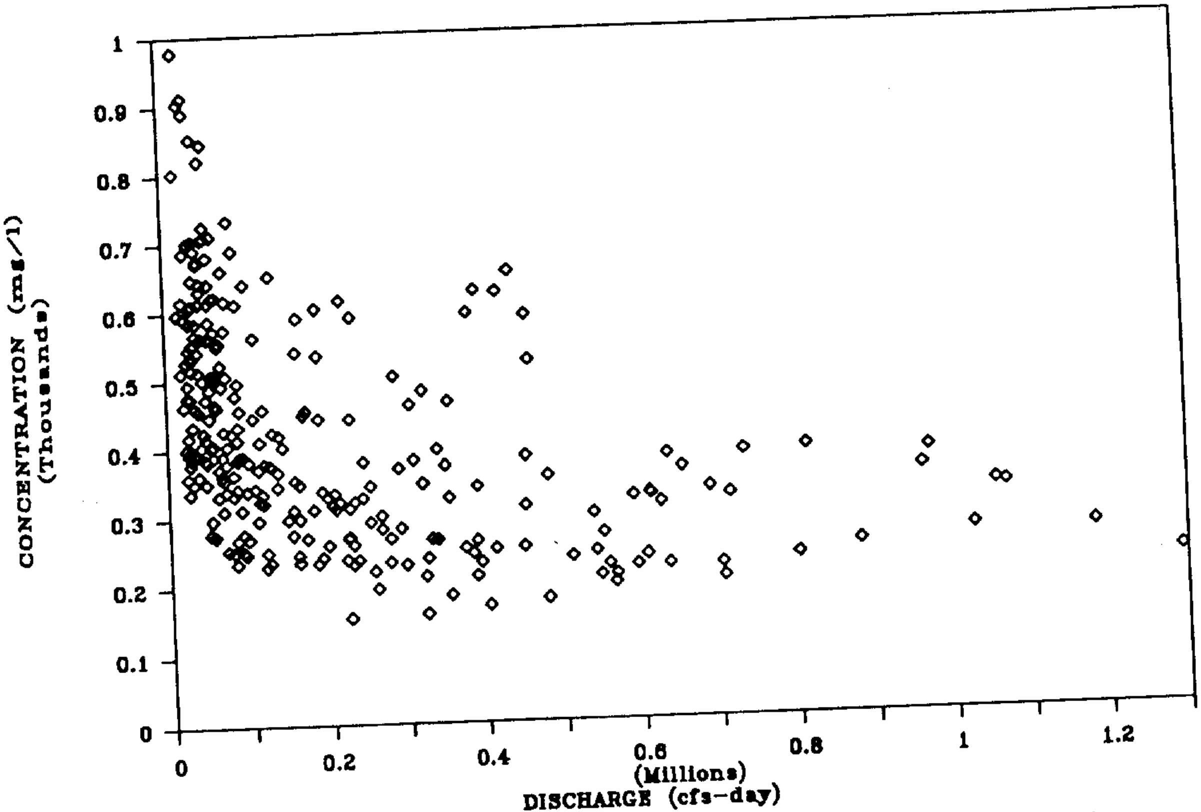

Figure 3.41 TDS Concentration Versus Discharge, Richmond Gage (Station 25)

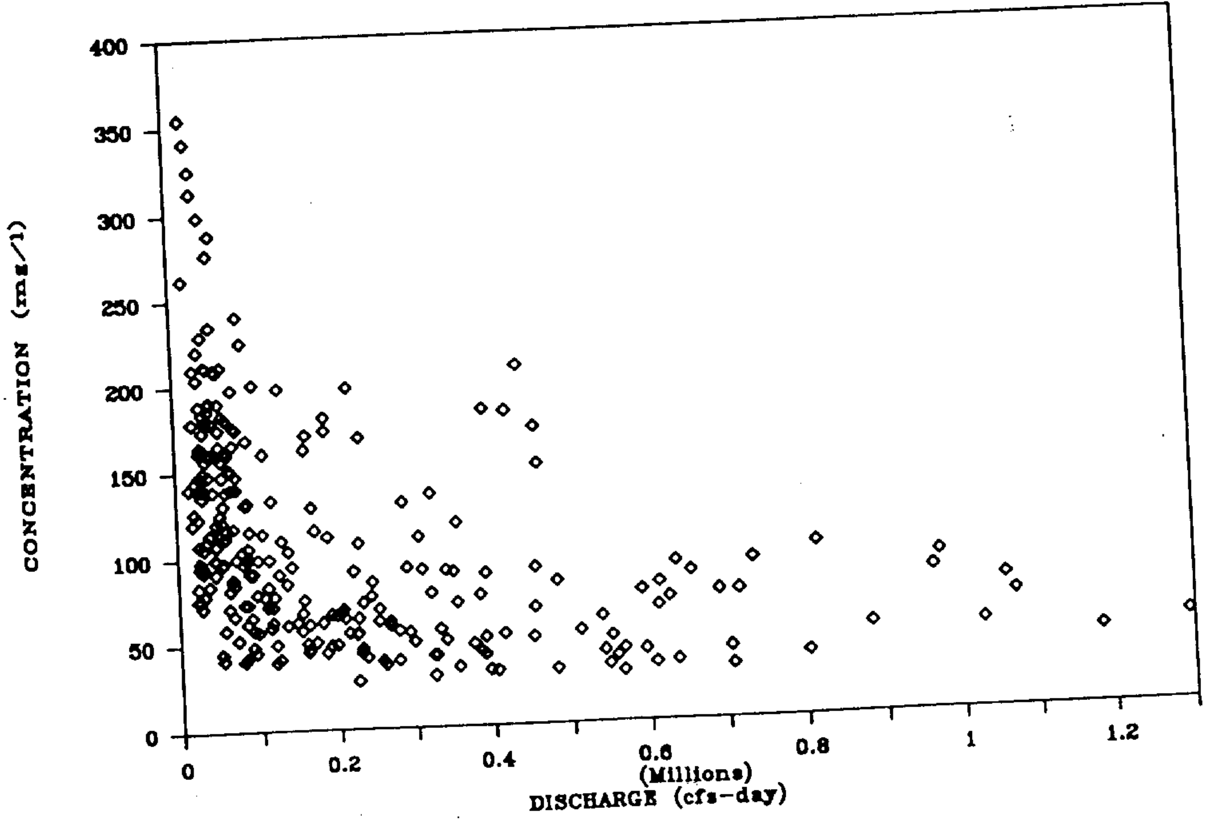

Figure 3.42 Chloride Concentration Versus Discharge, Richmond Gage (Station 25)

CHAPTER 4
ANALYSIS OF IMPACTS OF SALT CONTROL DAMS BASED ON ADJUSTMENTS TO MEASURED DATA

Chapter 4, like Chapter 3, summarizes work previously performed for the USACE (Ganze and Wurbs 1989). Proposed salt control dams are evaluated based on the premise that all salt loads and discharges at the dam sites are totally contained. The corresponding concentrations at downstream locations are determined by adjusting loads and discharges based on simple mass balances. Thus, the measured data of Chapter 3 are adjusted to represent the effects of removing or containing all loads and discharges at selected upstream locations. The mean monthly discharges and salt loads and concentrations for each month during the 1964-1986 analysis period at the Seymour, Possum Kingdom, Whitney, and Richmond gages (stations 7, 13, 15, and 25) and during the 1964-1983 analysis period at the College Station gage (station 21) were adjusted to reflect removal of all loads and discharges at stations 3, 4, and 6, which are near the sites of the proposed salt control dams. Concentration versus exceedence frequency plots are presented for each of the five downstream locations. The analyses also include comparison of long-term average salt loads and concentrations at stations 3, 4, and 6 with the corresponding means at the selected five downstream stations.

Although motivated by the proposed salt control impoundments, the analysis is equally pertinent to other plans for containing or disposing of the salt loads at stations 3, 4, and 6. Chapter 4 simply presents approximate adjustments to the historical salt concentrations at selected downstream stations to represent the effects of removing all flows and salt loads just downstream of selected primary salt source watersheds.

Salt Control Impoundments

The Brazos River Basin Natural Salt Pollution Control Study (USACE 1973 and 1983) involved formulation and evaluation of a comprehensive array of strategies for dealing with the salt pollution problem. A number of the alternative plans consist of systems of salt control dams located in the primary salt source areas of the upper basin. The recommended plan consists of three impoundments: Croton Lake on Croton Creek, Dove Lake on Salt Croton Creek, and Kiowa Peak Lake on North Croton Creek. The locations of the three dam sites are shown in Figure 4.1 along with nearby stream gaging stations. Croton Creek and Salt Croton Creek are tributaries of the Salt Fork of the Brazos River. Dove Creek is a tributary of Salt Croton Creek. North Croton Creek enters the main stem of the Brazos River just below the Salt Fork confluence. The Croton Lake, Dove Lake, and Kiowa Peak Lake dam sites are referred to as sites 10, 14, and 19, respectively, in the Corps of Engineers reports.

The proposed salt control dams would impound the runoff from their upstream watersheds. A connecting pipeline would be provided for transferring excess water from Croton and Dove Lakes to Kiowa Peak Lake. The impounded water will be partially lost over time due to evaporation, with the remaining brine being permanently stored in Kiowa Peak Lake. Each of the three dams would consist of an earth-fill embankment and outlet structures for emergency releases only. No releases are planned during the project life.

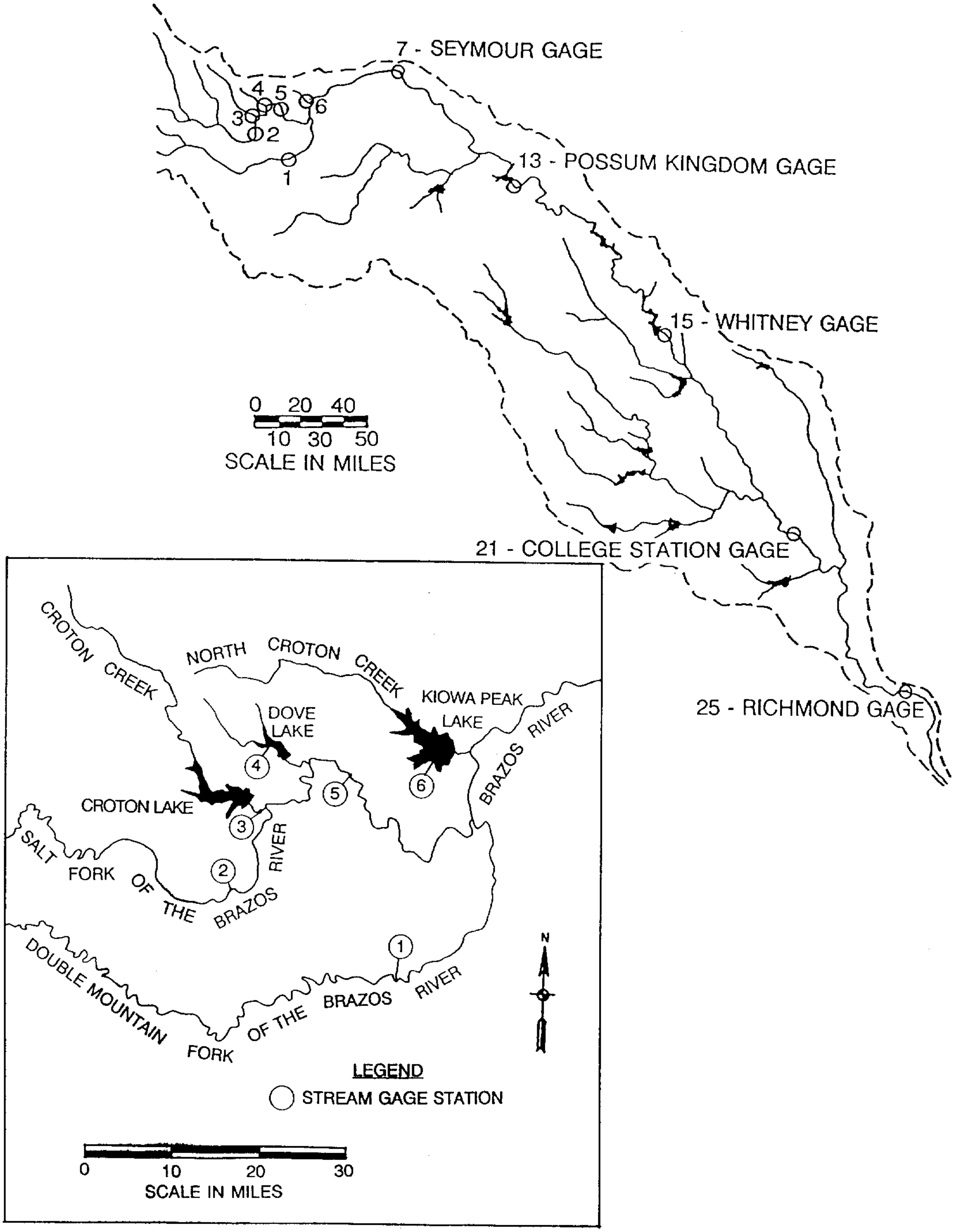

Figure 4.1 Proposed Salt Control Impoundments and Stations Referenced in Chapter 4

The present study considered two alternative salt control impoundment plans. Plan 1 consists of dam sites 10, 14, and 19 as described above. Plan 1 in the present study is labeled plan 4B in the previous Corps of Engineers reports (USACE 1973 and 1983). Plan 2 consists of dam sites 14 and 19. Thus, plan 1 is the Corps of Engineers recommended plan which includes the three lakes: Croton, Dove, and Kiowa Peak. Croton Lake (dam site 10) is omitted in plan 2.

As indicated in Figure 4.1, the three salt control dam sites are located near the streamflow gages on Croton Creek near Jayton (station 3), Salt Croton Creek near Aspermont (station 4), and North Croton Creek near Knox City (station 6). The analysis is based on the premise that the salt control dams permanently store or remove all of the discharge and salt loads at the corresponding stations. Thus, for purposes of the present analysis, salt control dam plan 1 is defined as permanent storage or removal of all discharges and salt loads at stations 3, 4, and 6. Plan 2 consists of permanent storage or removal of all discharges and salt loads at stations 4 and 6.

Mean Discharges, Loads, and Concentrations

Mean discharges, loads, and concentrations over the periods 1964-1986 and 1969-1977, respectively, are tabulated in Tables 4.1 and 4.2. The gage on Salt Croton Creek near Aspermont (station 4) has a period-of-record of 1969-1977. All of the other stations in Tables 4.1 and 4.2 have longer periods-of-record which include 1969-1977. All the stations except stations 2, 4, 5, 6, and 21 have periods-of-record covering 1964-1986. As discussed later, missing data were filled in for stations 4, 5, and 6. The synthesized data for stations 4, 5, and 6 are included in the means in Table 4.1. Thus, the means in Table 4.1 include the 1964-1986 period for all stations except stations 2 and 21, which have periods-of-record of 1965-1986 and 1964-1983, respectively.

Tables 4.1 and 4.2 also include the sum of the means at stations 3, 4, and 6 and at stations 4 and 6. These values represent the means of the discharges and loads removed by the salt control dam plans 1 and 2.

The mean discharges and loads at stations 3, 4, and 6 are expressed as a percentage of the sum of the corresponding means at the five downstream locations in Table 4.3. This provides a representation of the percentage of the discharges and loads of the five downstream locations which would be removed by construction of salt control dam plan 1. Likewise, the mean discharges and loads at stations 4 and 6 are expressed as a percentage of the sum of the corresponding means at the five downstream locations in Table 4.4 representing the impacts of salt control dam plan 2. The 1969-1977 means from Table 4.2 were used in developing Tables 4.3 and 4.4 because only measured data are reflected, unlike the 1984-1986 means in Table 4.1 which include synthesized or computationally filled-in data.

As indicated by Table 4.2 the sum of the 1969-1977 mean loads for stations 3, 4, and 6 (plan 1) are 1,035 tons/day, 523 tons/day, and 129 tons/day for TDS, Cl, and SO_4, respectively. At the Richmond gage (station 25), the 1969-1977 mean loads for TDS, Cl, and SO_4 are 7,181 tons/day, 1,632 tons/day, and 1,130 tons/day, respectively. Thus, as indicated

Table 4.1
MEAN DISCHARGES, LOADS, AND CONCENTRATIONS FOR 1964-1986

Station	Discharge (cfs)	Load (tons/day)			Concentration (mg/l)		
		TDS	Cl	SO_4	TDS	Cl	SO_4
2	40	684	339	81	5,782	2,830	698
3	13	225	93	53	6,536	2,690	1,558
4	5	676	425	53	54,560	34,356	2,634
5	62	1,660	1,094	219	9,999	6,589	1,321
6	17	211	80	58	4,719	1,801	1,301
7	269	2,601	1,074	504	3,591	1,482	696
13	686	2,795	1,111	571	1,512	601	309
15	1,230	3,075	1,134	591	928	342	178
21	4,529	5,348	1,365	938	438	112	77
25	6,868	6,267	1,466	1,030	339	79	56
3,4,6	34	1,112	599	144	12,145	6,539	1,573
4,6	21	887	506	91	15,534	8,865	1,590

Table 4.2
MEAN DISCHARGES, LOADS, AND CONCENTRATIONS FOR 1969-1977

Station	Discharge (cfs)	Load (tons/day)			Concentration (mg/l)		
		TDS	Cl	SO_4	TDS	Cl	SO_4
2	41	594	289	80	5,378	2,614	722
3	12	200	72	59	6,034	2,185	1,783
4	4	673	388	27	56,923	32,856	2,273
5	63	1,548	775	179	9,088	4,547	1,051
6	11	163	62	43	5,397	2,070	1,427
7	251	2,693	1,073	520	3,982	1,586	769
13	608	3,029	1,214	625	1,849	741	381
15	1,285	3,339	1,234	637	964	356	184
21	4,760	5,631	1,413	967	439	110	75
25	7,828	7,181	1,632	1,130	340	77	54
3,4,6	28	1,035	523	129	13,793	6,969	1,717
4,6	16	835	451	70	19,906	10,739	1,665

Table 4.3
1969-77 MEAN DISCHARGES AND LOADS FOR STATIONS 3, 4, AND 6 (PLAN 1) AS A PERCENTAGE OF DOWNSTREAM STATIONS

Downstream Station	Sta 3, 4 & 6 Discharge	Stations 3,4 & 6 Loads		
		TDS	Cl	SO_4
7	11.16%	38.43%	48.74%	24.81%
13	4.61%	34.17%	43.08%	20.64%
15	2.18%	31.00%	42.38%	20.25%
21	0.59%	18.38%	37.01%	13.34%
25	0.36%	14.41%	32.05%	11.42%

Table 4.4
1969-77 MEAN DISCHARGES AND LOADS FOR STATIONS 4 AND 6 (PLAN 2) AS A PERCENTAGE OF DOWNSTREAM STATIONS

Downstream Station	Sta 4 & 6 Discharge	Stations 4 & 6 Loads		
		TDS	Cl	SO_4
7	6.37%	31.01%	42.03%	13.46%
13	2.63%	27.57%	37.15%	11.20%
15	1.25%	25.01%	36.55%	10.99%
21	0.34%	14.83%	31.92%	7.24%
25	0.20%	11.63%	27.63%	6.19%

by Table 4.3 the sum of the mean loads of TDS, C1, and SO_4 at the salt control dam sites (stations 3, 4, and 6) are 14.4%, 32.0%, and 11.4%, respectively, of the mean loads at the Richmond gage (station 25). The sum of the 1969-1977 mean discharges at stations 3, 4, and 6 is 28 cfs or 0.36% of the mean discharge of 7,828 cfs at the Richmond gage. The sum of the mean discharges for stations 3, 4, and 6 is 11.2% of the mean discharge at the Seymour gage. The sum of the mean TDS, C1, and SO4 loads at stations 3, 4, and 6 is 38.4%, 48.7%, and 24.8% of the corresponding mean loads at the Seymour gage.

Of the three salt control dam sites (stations 3, 4, and 6), station 4 has the smallest drainage area and mean discharge. However, station 4 has the highest total dissolved solids and chloride loads of the three stations. Mean 1969-1977 total dissolved solids loads for stations 3, 4, and 6 are 200 tons/day, 673 tons/day, and 163 tons/day, respectively. Mean chloride loads are 72 tons/day, 388 tons/day, and 62 tons/day at stations 3, 4, and 6, respectively. Station 3 has the highest sulfate load. Mean sulfate loads are 59 tons/day, 27 tons/day, and 43 tons/day at stations 3, 4, and 6, respectively. Thus, station 4 accounts for 65%, 74%, and 21%, respectively, of the total dissolved solids, chloride, and sulfate loads of the three stations. The mean discharge at station 4 is only 4% of the sum of the mean discharges at stations 3, 4, and 6.

Salt control dam plans 1 and 2 are compared in the analysis. The difference between the two plans is the salt control dam at station 3. The 1969-1977 mean discharge at station 3 is 43% of the sum of the discharges at stations 3, 4, and 6. The total dissolved solids, chloride, and sulfate loads at station 3 are 19%, 14%, and 46%, respectively, of the sum of the corresponding loads at stations 3, 4, and 6. As indicated by Tables 4.3 and 4.4, salt control dam plans 1 and 2 account for 14.4% and 11.6%, respectively, of the total dissolved solids load at the Richmond gage, 32.0% and 27.6%, respectively, of the chloride load at the Richmond gage, and 11.4% and 6.2%, respectively, of the sulfate load at the Richmond gage.

Concentration-Duration Relationships

Monthly discharges and salt loads for the Brazos River near Seymour, Possum Kingdom, Whitney, College Station, and Richmond gages (stations 7, 13, 15, 21, and 25) were adjusted to reflect the salt dams using spreadsheet computations. The adjustments reflect the removal of the discharges and salt loads at stations 3, 4, and 6. An adjustment procedure was adopted for the Seymour gage, a different procedure was adopted for the Possum Kingdom and Whitney gages, and another procedure was adopted for the College Station and Richmond gages. In all cases, the adjustments consisted of reducing discharges and salt loads for each month of the 1964-1986 analysis period. Concentrations were then computed by dividing adjusted salt loads by adjusted discharges. Exceedence frequency versus salt concentration relationships were developed using the STATS (Statistical Analysis of Time Series) computer program developed by the USACE Hydrologic Engineering Center. The computations were repeated for alternative salt control dam plans 1 and 2. The computational procedures are outlined in detail in a later section of this chapter. The results are discussed below.

As previously discussed, mean monthly salt concentrations at the five selected locations, without the upstream salt control dams, are plotted in Figures 3.4-3.6, 3.8-3.10, 3.12-3.14, 3.16-3.18, and 3.20-3.22. Concentration-duration curves for these data are presented as Tables 3.4-3.6 and Figures 3.28-3.30. As discussed below, this information has been repeated for salt control dam plans 1 and 2 and presented in Figures 4.2-4.16. Ganze and Wurbs (1989) provide these data in tabular as well as graphical format.

As an example of interpreting the concentration-duration curves, at the Whitney gage (Table 3.5 and Figure 4.9), a mean monthly chloride concentration of 437 mg/l was equalled or exceeded during 20% of the 276 months in the 1964-1986 analysis period. With computational adjustments reflecting the impacts of the proposed alternative salt control dam plans 1 and 2, respectively, the computed mean monthly chloride concentrations equalled or exceeded 258 mg/l and 281 mg/l during 20% of the months in the 1964-1986 analysis period. Thus, without salt control dams, a chloride concentration of 437 mg/l is predicted to be equalled or exceeded 20% of the time at the Whitney gage. With construction of salt control dam plan 1, a chloride concentration of 258 mg/l is predicted to be equalled or exceeded 20% of the time. With proposed salt control dam plan 2, a chloride concentration of 281 mg/l is predicted to be equalled or exceeded 20% of the time.

Computational Procedures

The procedures adopted for computing monthly discharges and salt loads and concentrations, as reflected in Figures 4.2-4.16, at the Seymour, Possum Kingdom, Whitney, College Station, and Richmond gages for salt control dam plans 1 and 2 are outlined below.

Basic Premises

The salts are assumed to be conservative with no chemical reactions with their environment. Chloride is truly conservative. Sulfate and total dissolved solids can realistically be assumed to be conservative as an approximation which greatly simplifies the analysis. Thus, the computations involve simple mass balances without consideration of chemical reactions.

As previously discussed, salt control dam plan 1 consists of permanent storage or removal of all discharge and salt loads occurring at stations 3, 4, and 6. Plan 2 consists of permanent storage or removal of all discharge and salt loads occurring at stations 4 and 6. The discharges and salt loads at five downstream stations (stations 7, 13, 15, 21, and 25) were adjusted to reflect the impacts of the upstream salt control dams. The mean monthly concentrations were then computed by dividing adjusted salt load by adjusted discharge.

The salt control dams are viewed as resulting in a reduction in both water volume and salt load at all downstream locations. The same total water volume and salt load removed at stations 3, 4, and 6 are also removed at all downstream locations. It is assumed that a cubic foot of water or ton of salt removed at stations 3, 4, or 6 would have otherwise eventually reached the Richmond gage. However, the water and salt may not have reached the Richmond gage until many months or years later. The timing of the effects at downstream locations of the salt control dams located in the upper basin is actually affected by complex transport and storage mechanisms in the stream/reservoir system. However, in the computations, the reduction in discharge and salt load, due to the salt control dams, in a given month is assumed to be reflected

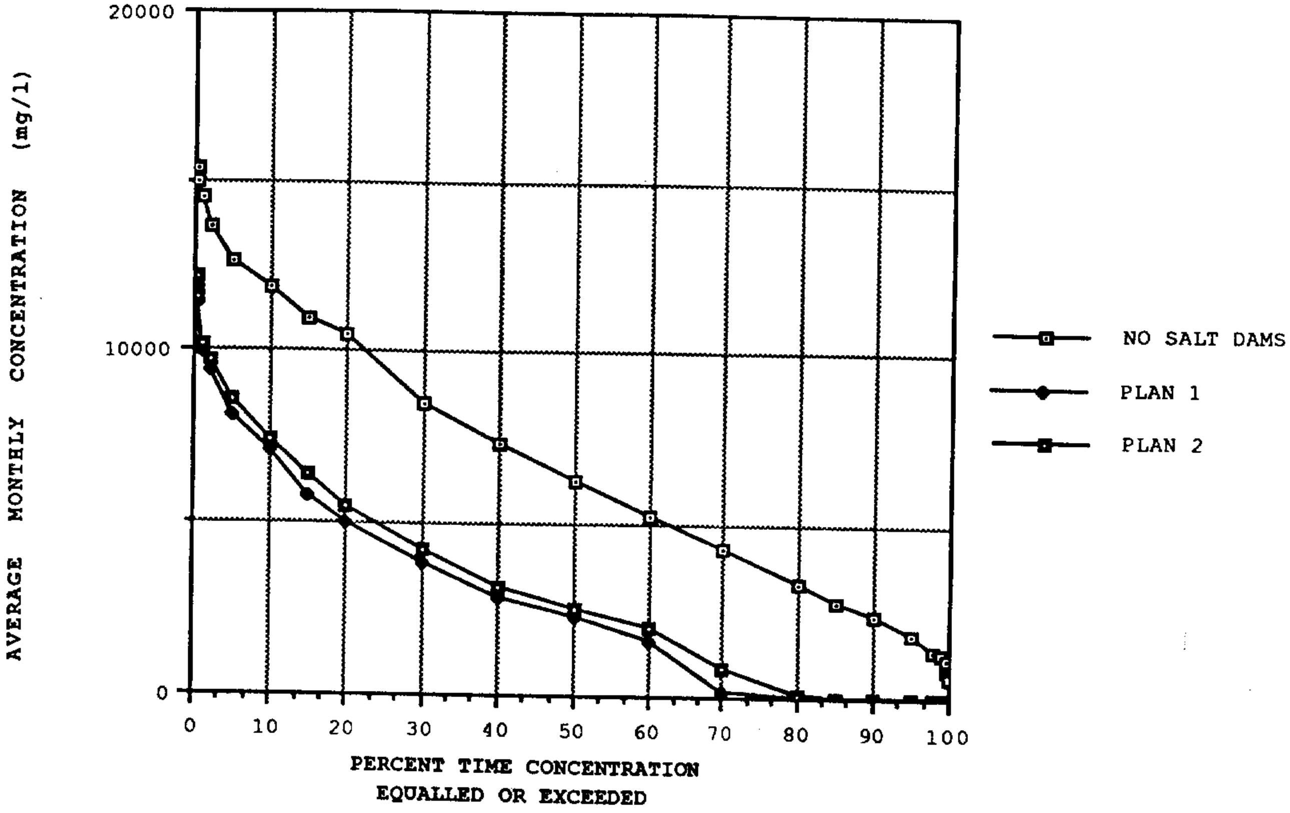

Figure 4.2 TDS Concentration-Duration Curves for Seymour Gage (Station 7)

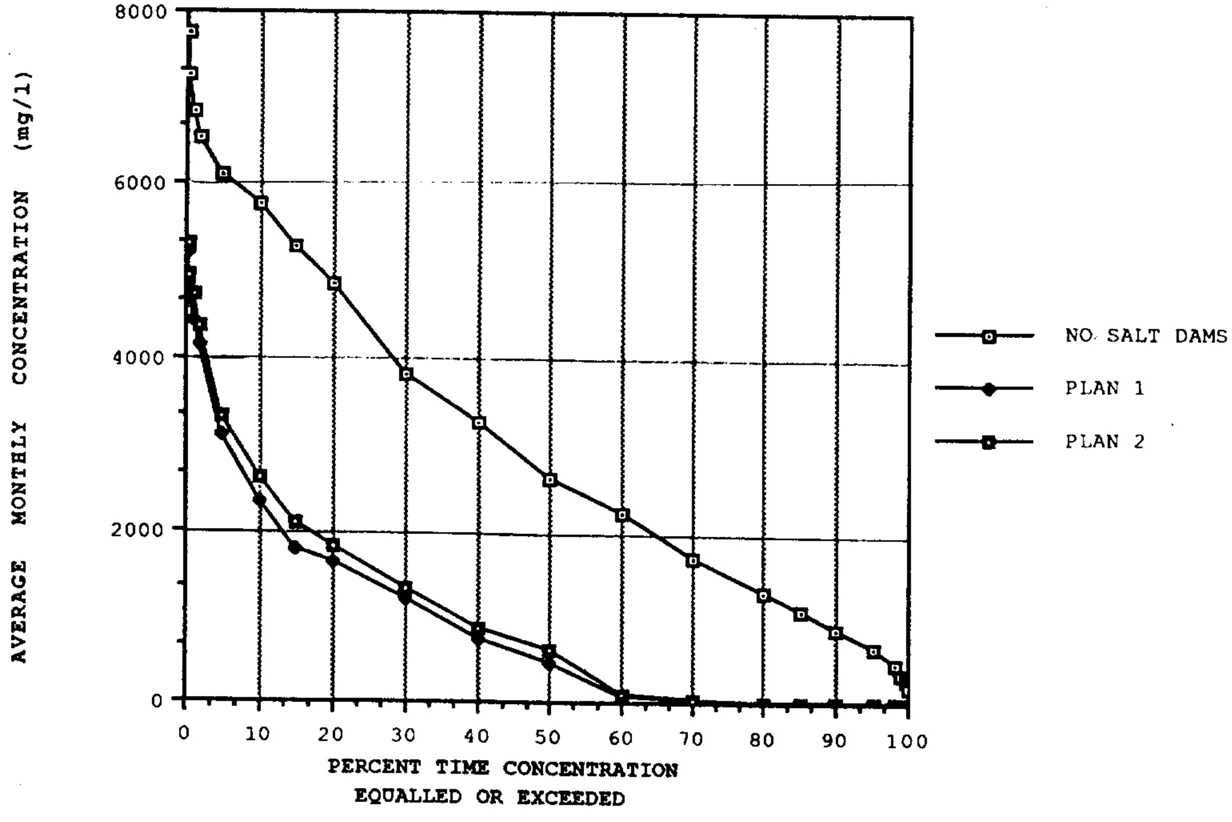

Figure 4.3 Chloride Concentration-Duration Curves for Seymour Gage (Station 7)

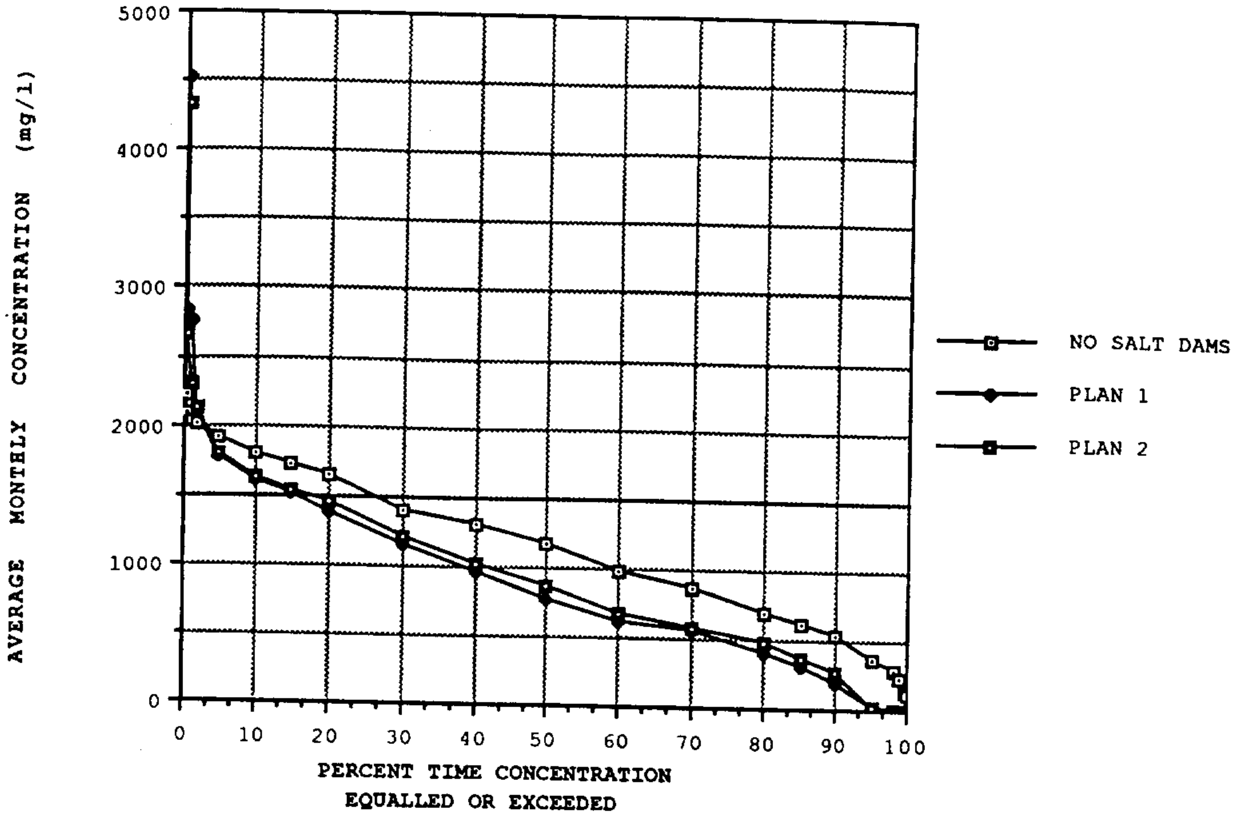

Figure 4.4 Sulfate Concentration-Duration Curves for Seymour Gage (Station 7)

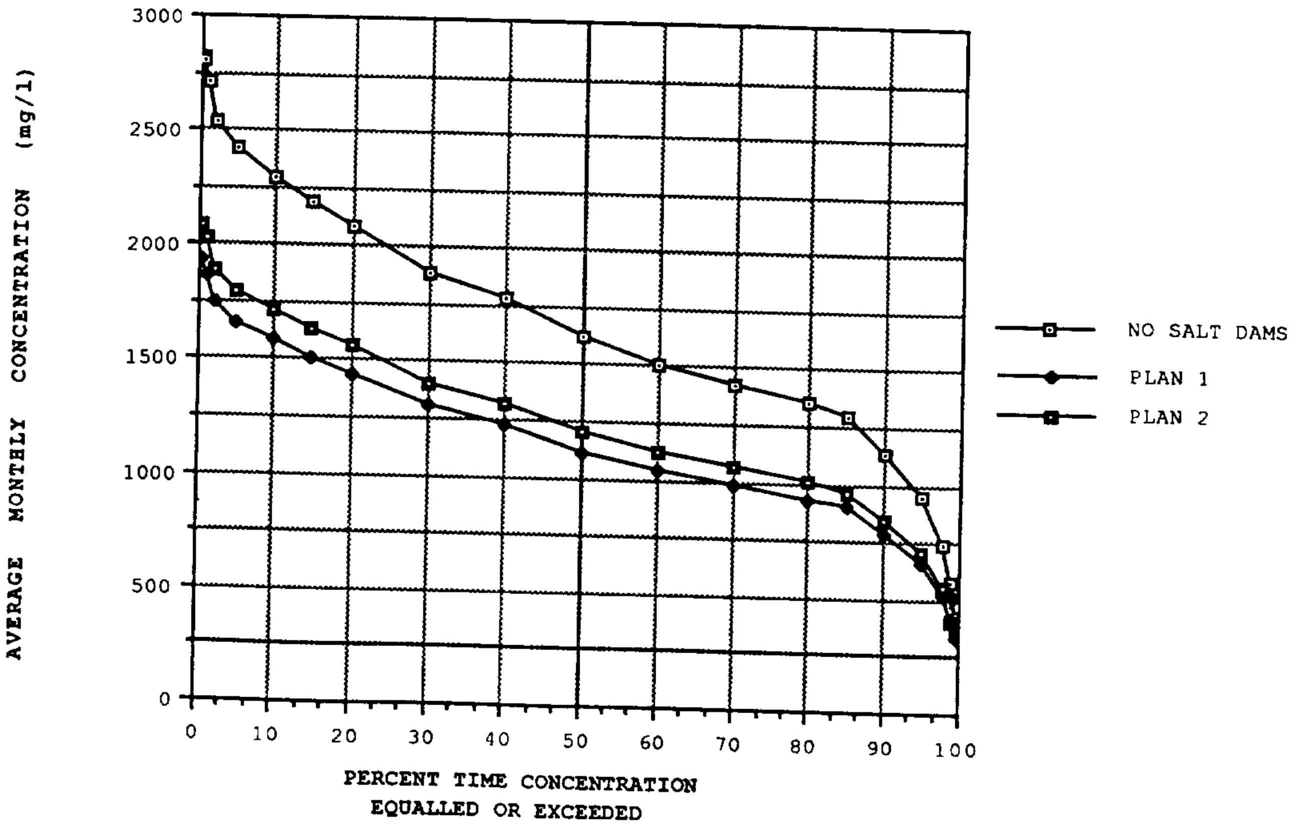

Figure 4.5 TDS Concentration-Duration Curves for Possum Kingdom Gage (Station 13)

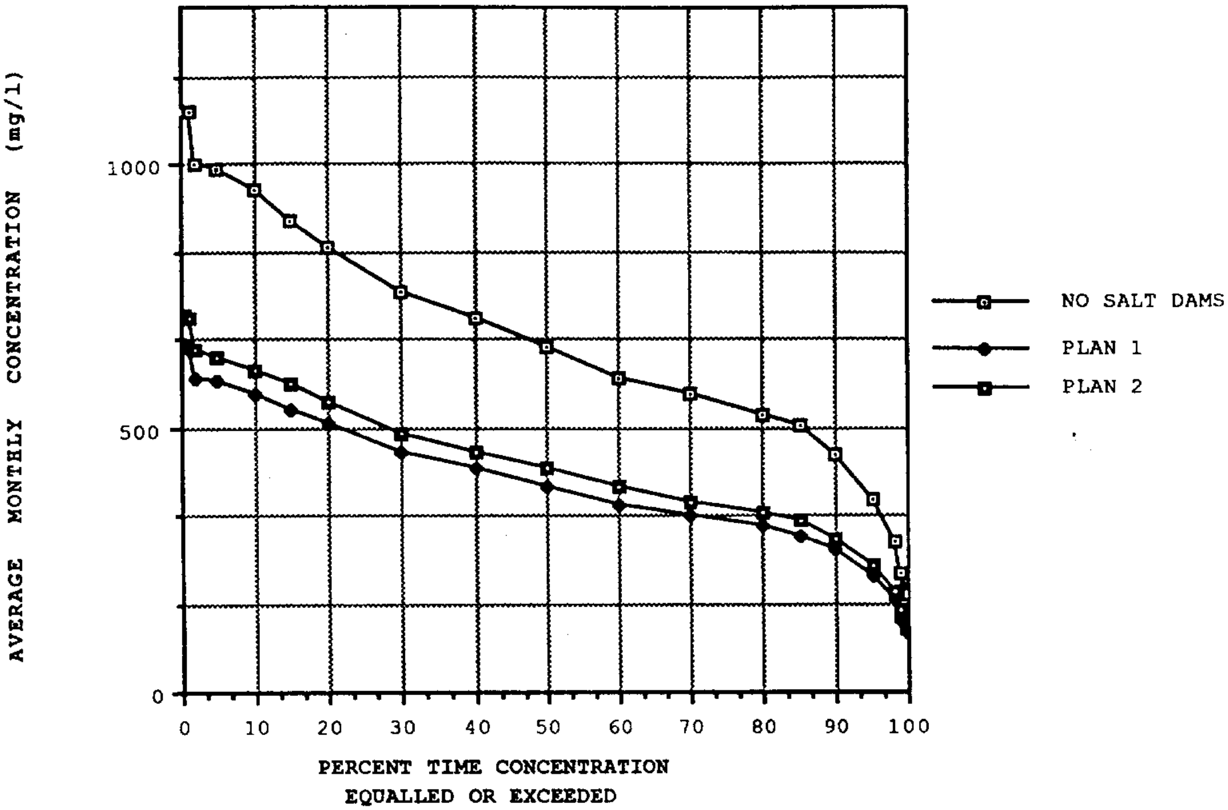

Figure 4.6 Chloride Concentration-Duration Curves for Possum Kingdom Gage (Station 13)

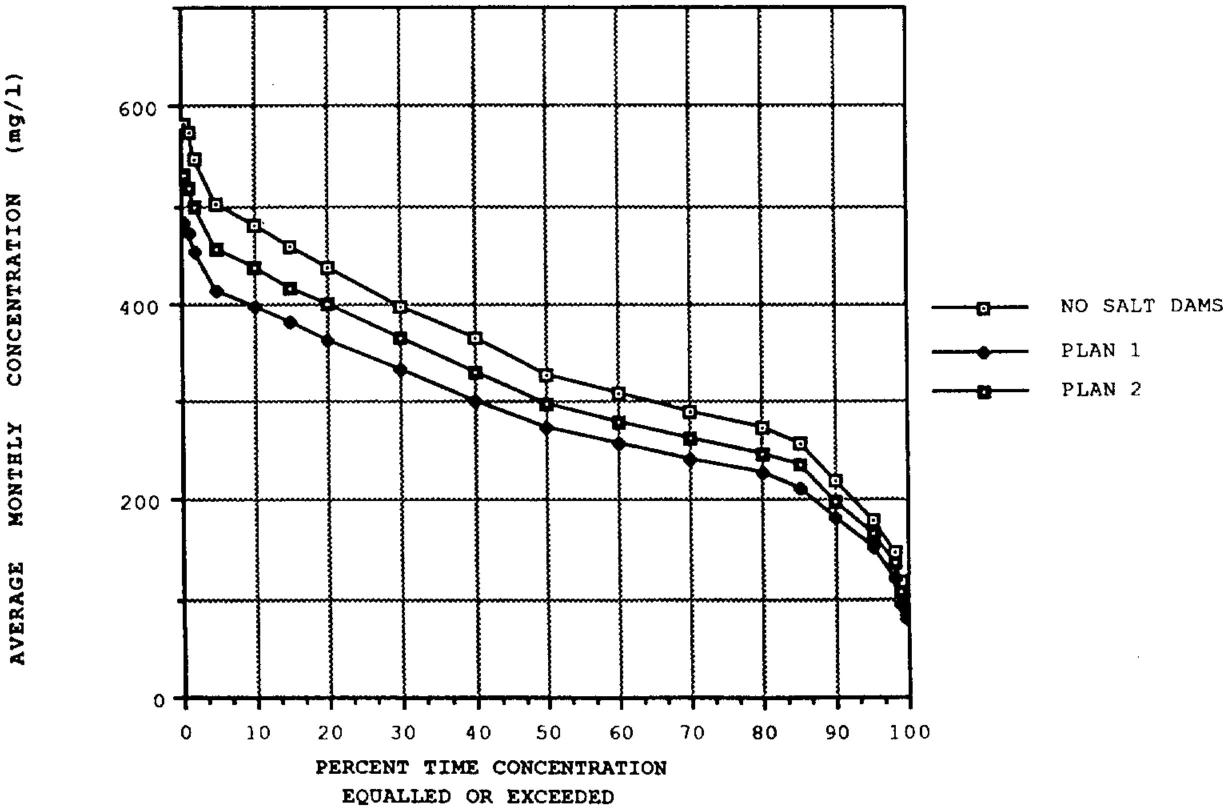

Figure 4.7 Sulfate Concentration-Duration Curves for Possum Kingdom Gage (Station 13)

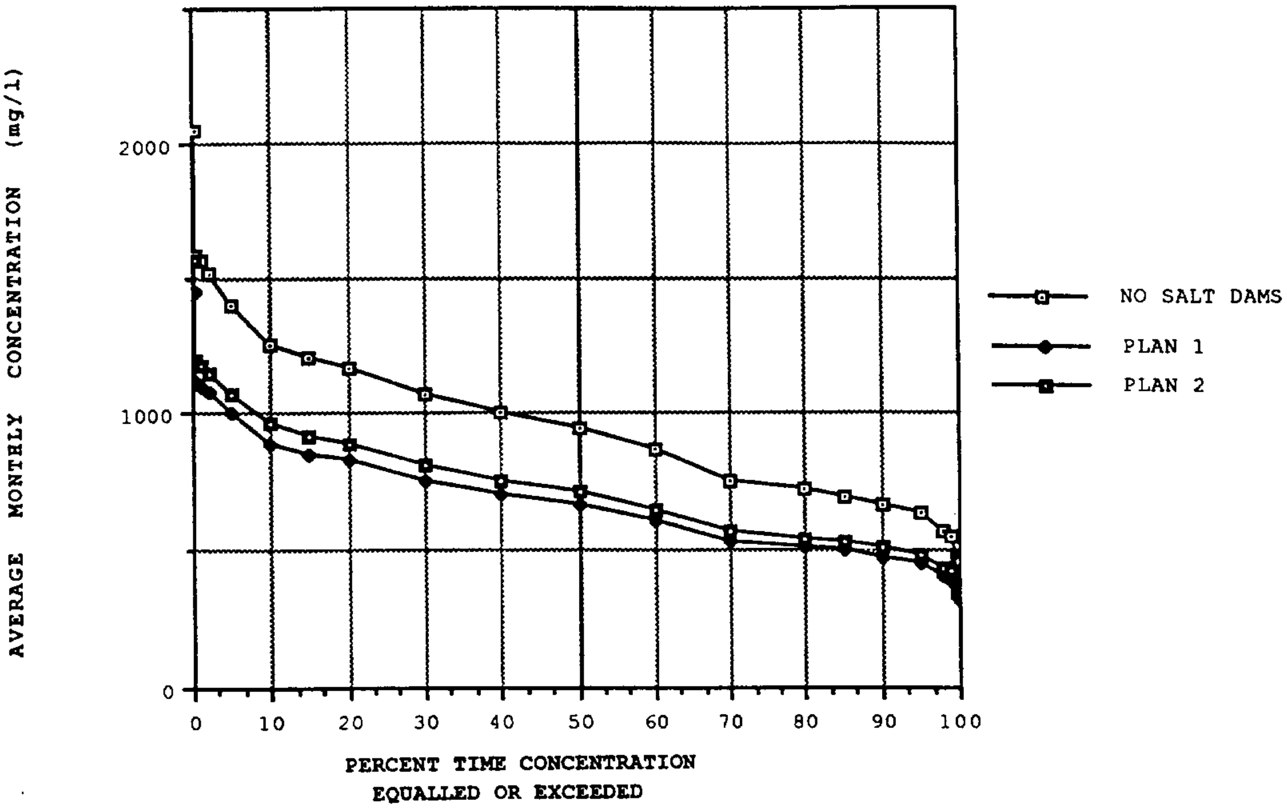

Figure 4.8 TDS Concentration-Duration Curves for Whitney Gage (Station 15)

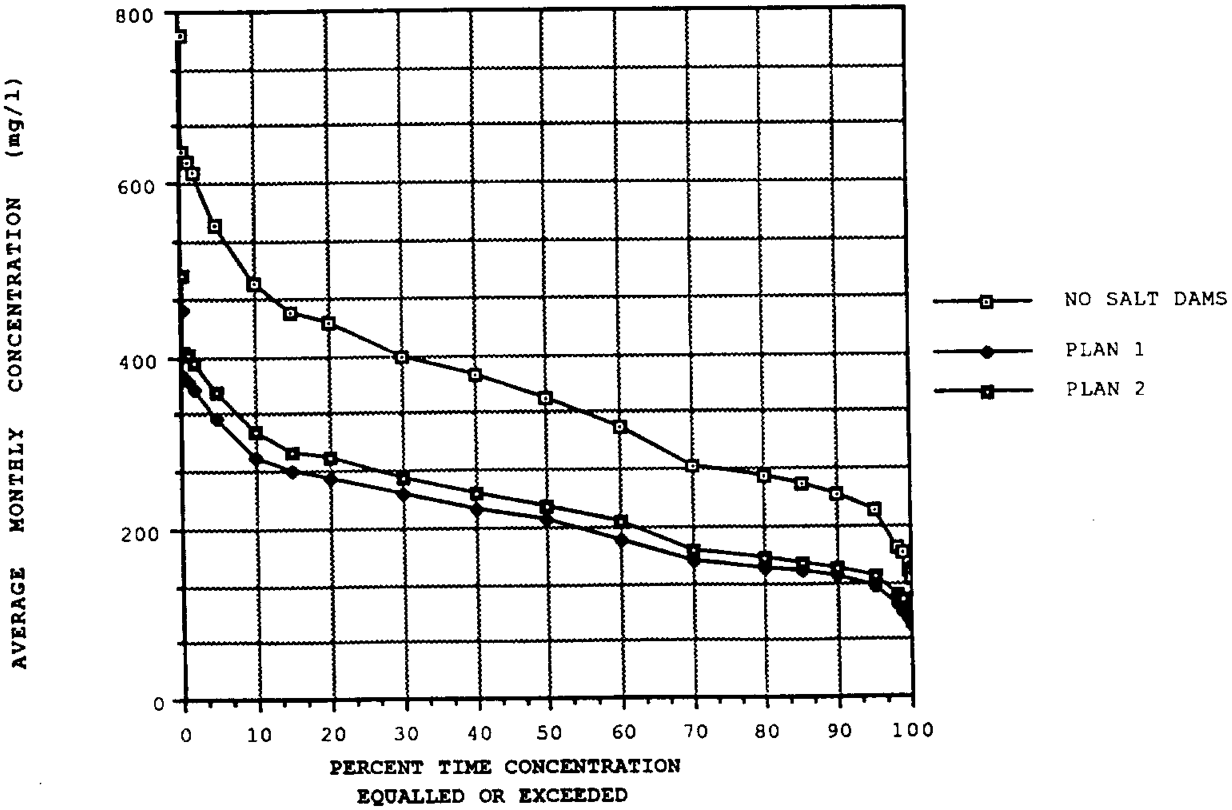

Figure 4.9 Chloride Concentration-Duration Curves for Whitney Gage (Station 15)

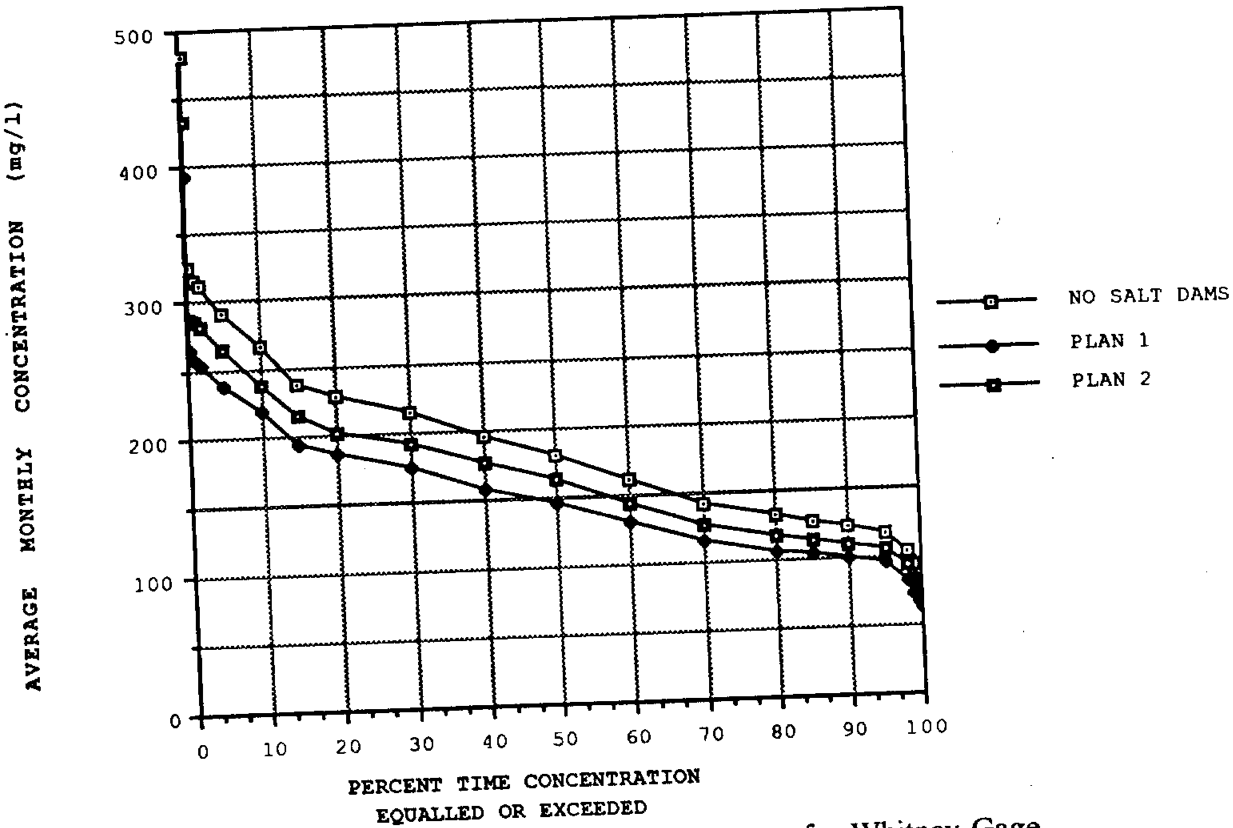

Figure 4.10 Sulfate Concentration-Duration Curves for Whitney Gage (Station 15)

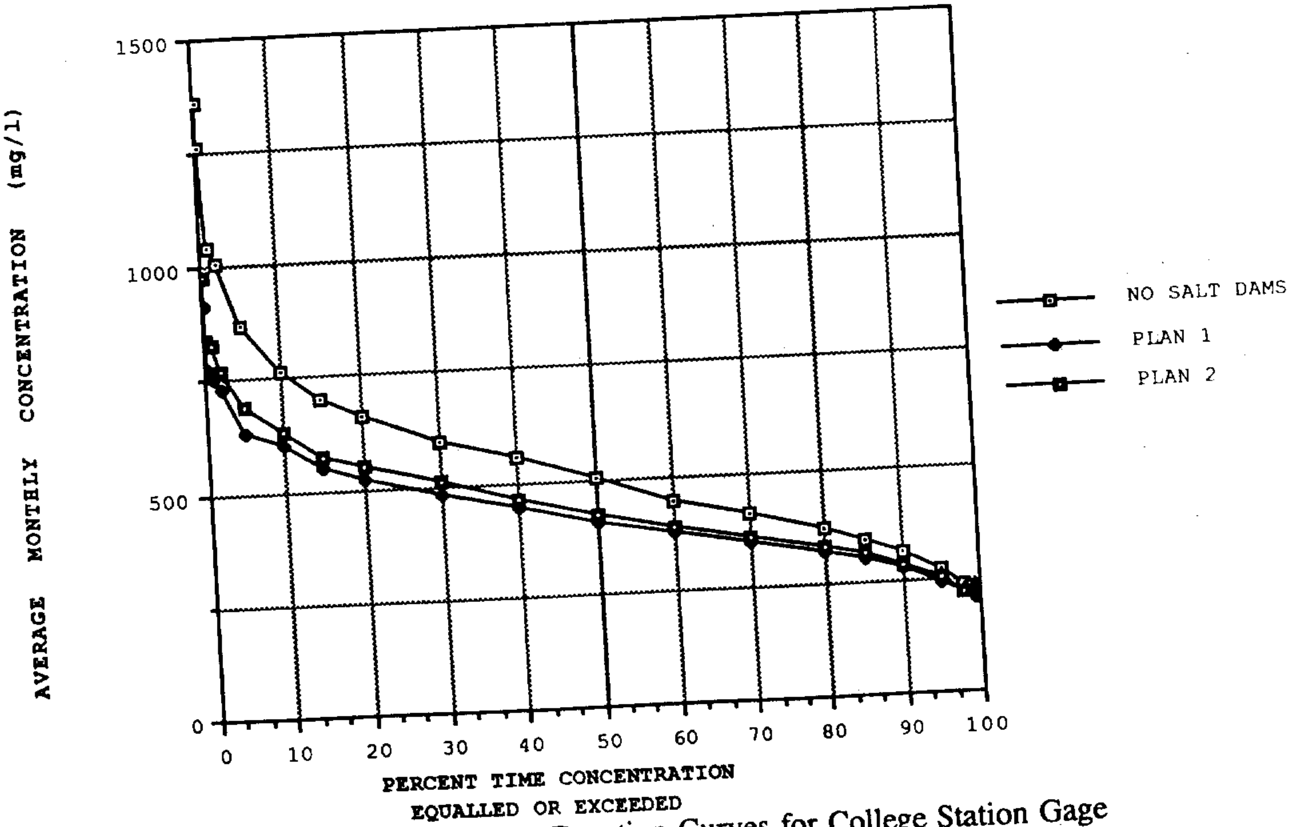

Figure 4.11 TDS Concentration-Duration Curves for College Station Gage (Station 21)

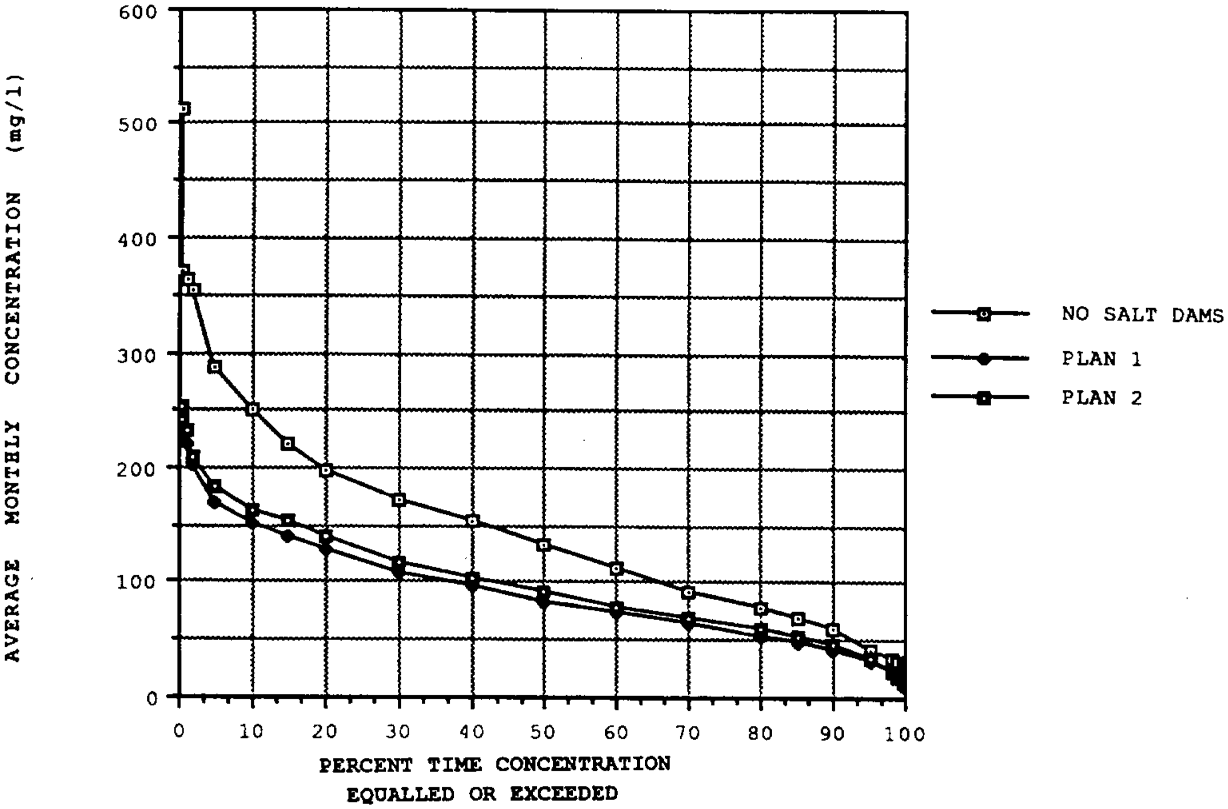

Figure 4.12 Chloride Concentration-Duration Curves for College Station Gage (Station 21)

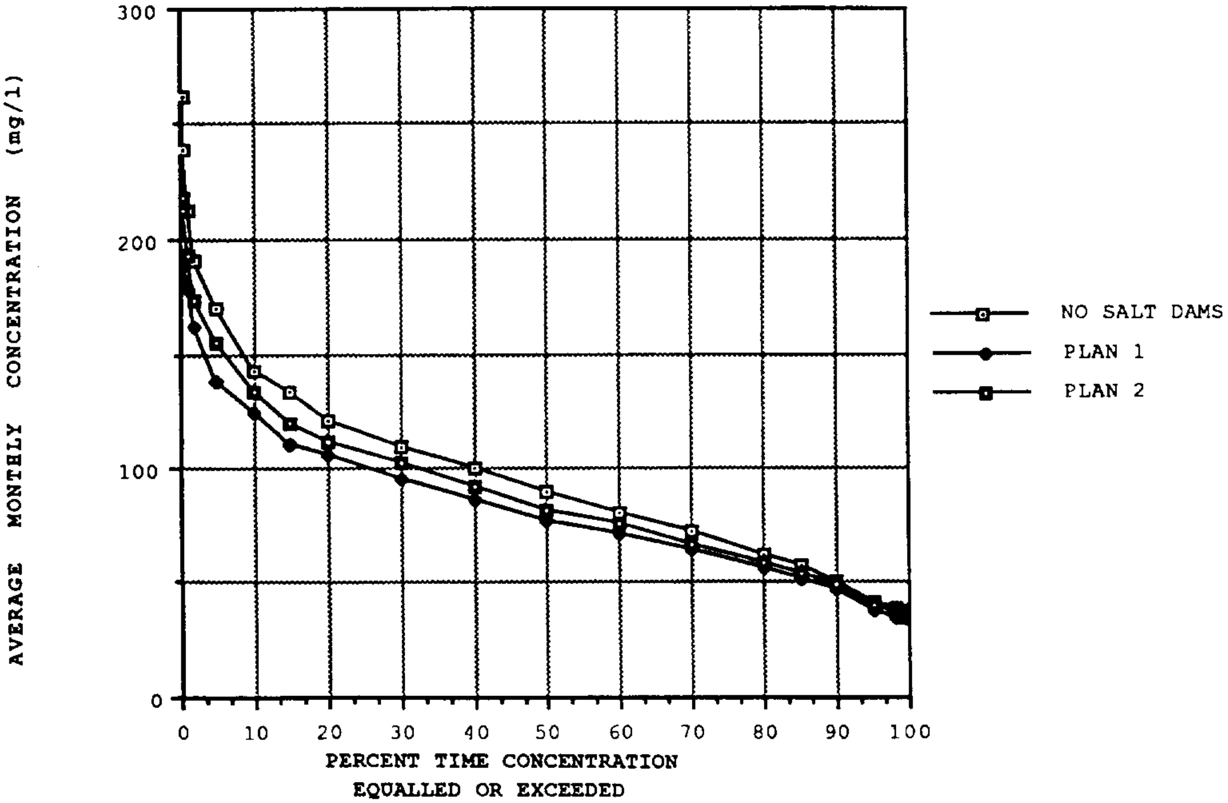

Figure 4.13 Sulfate Concentration-Duration Curves for College Station Gage (Station 21)

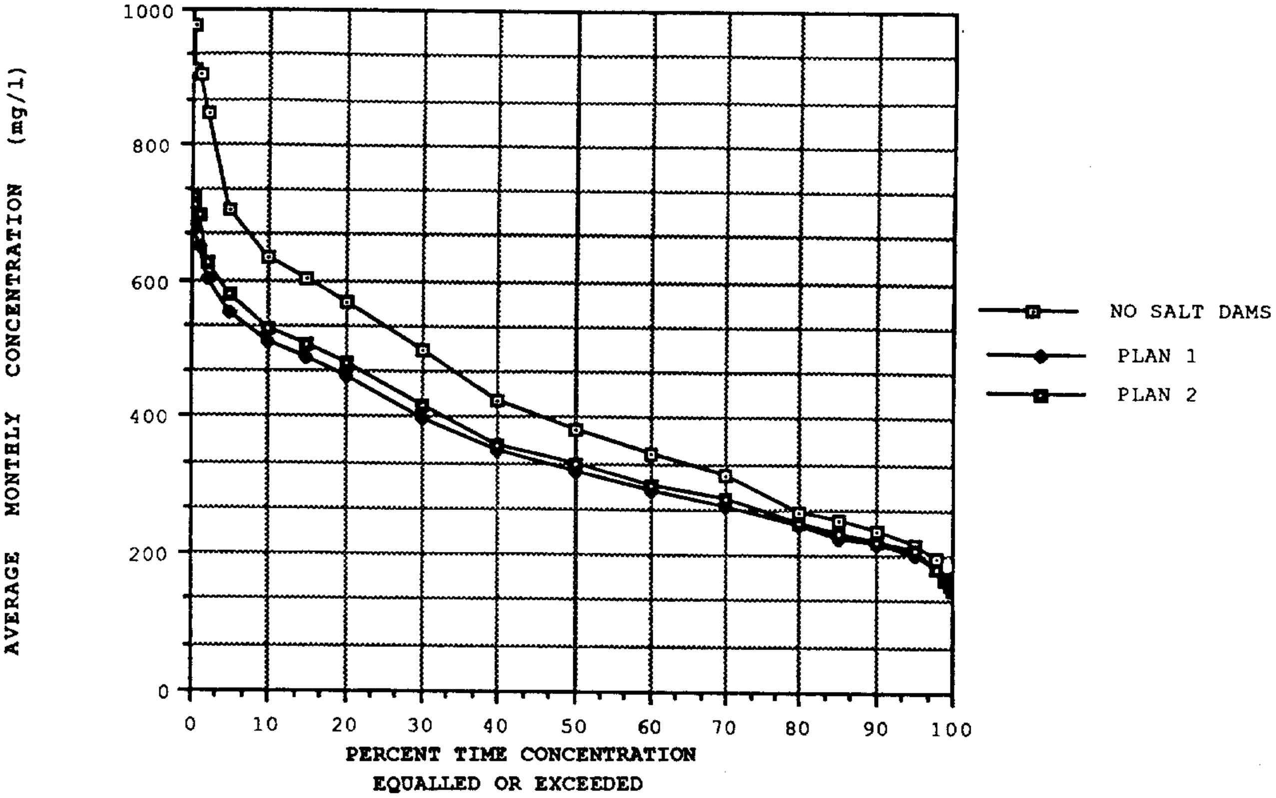

Figure 4.14 TDS Concentration-Duration Curves for Richmond Gage (Station 25)

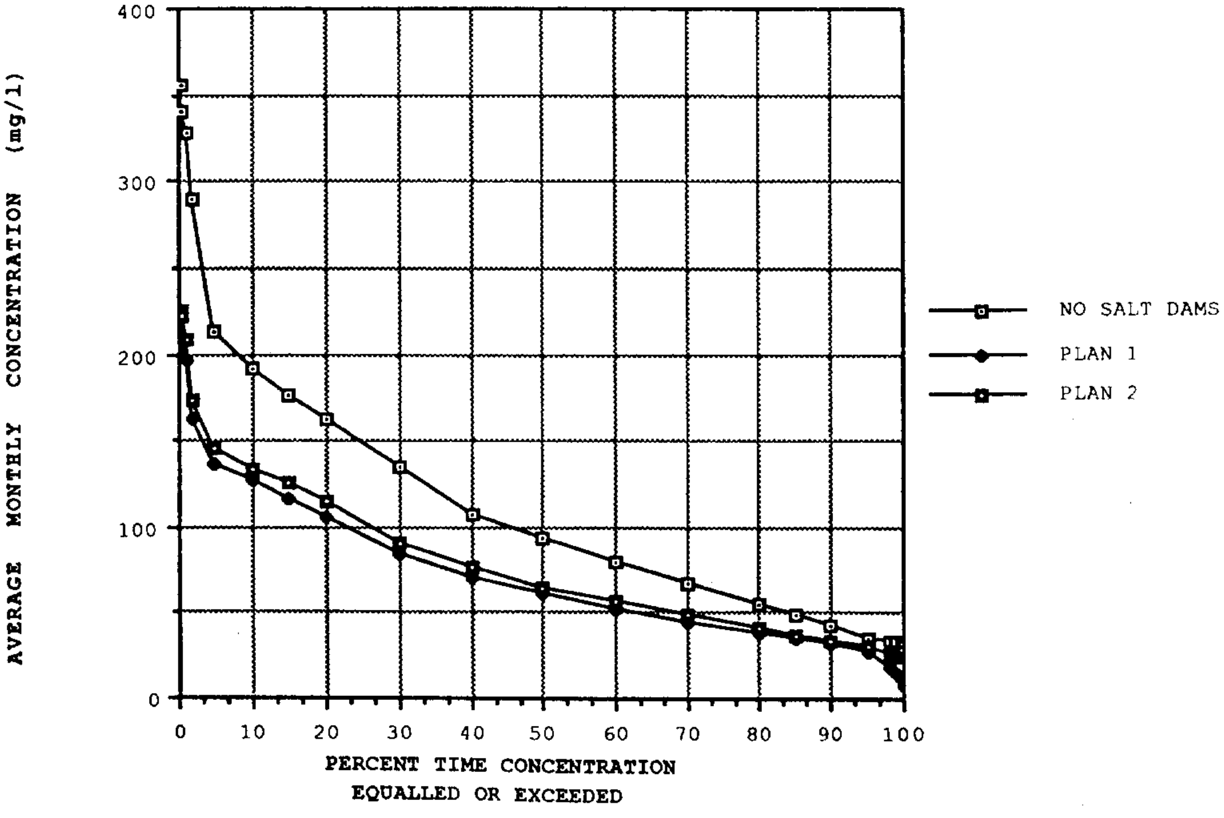

Figure 4.15 Chloride Concentration-Duration Curves for Richmond Gage (Station 25)

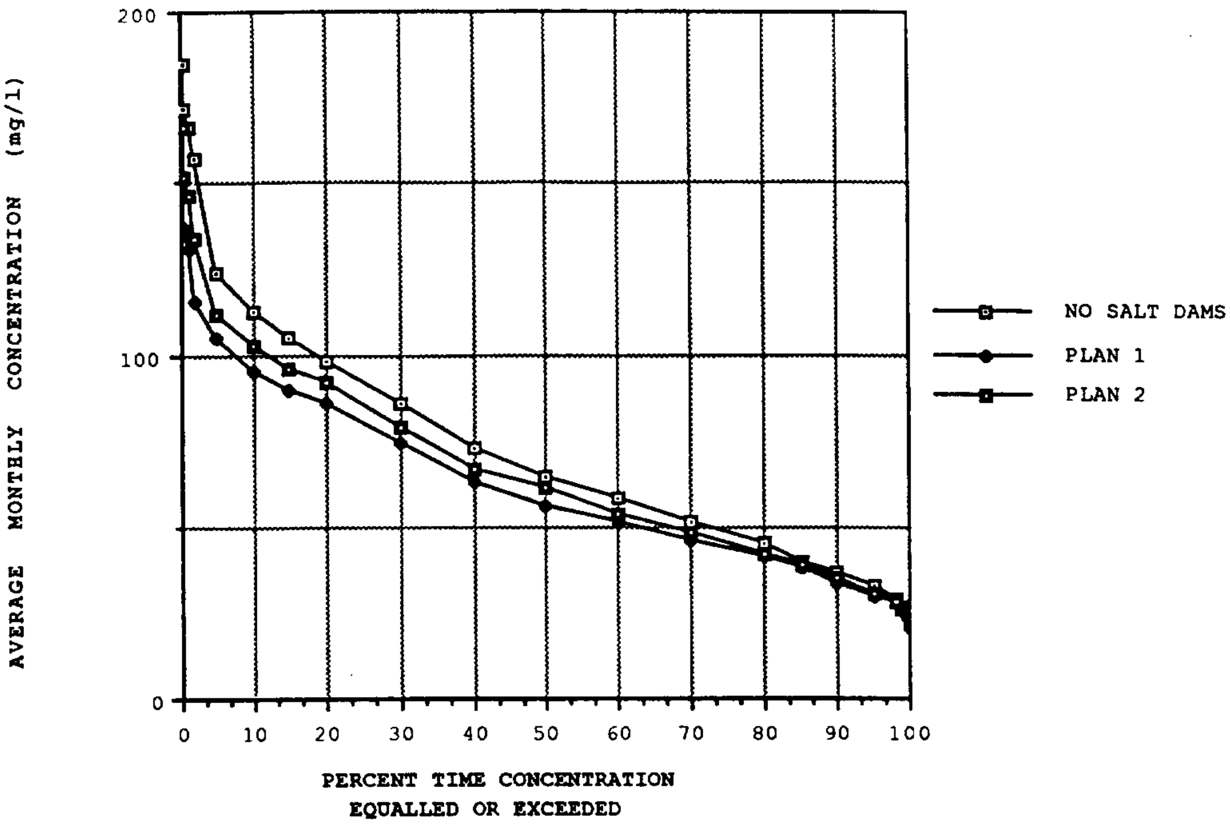

Figure 4.16 Sulfate Concentration-Duration Curves for Richmond Gage (Station 25)

at all downstream locations in the same month and in the same amount, with the important exceptions of storage delays caused by Possum Kingdom, Granbury, and Whitney Reservoirs and some other timing adjustments necessary for the Seymour gage. The computational procedures are described below.

Data Synthesis for Gages at Salt Control Dam Sites

Salt concentration versus duration relationships were developed based on mean monthly concentrations for each month of the period 1964-1986. However, the period-of-record for stations 4 and 6 are 1969-1977 and 1966-1986, respectively. The records were extended by regression with other stations. At station 4, mean monthly discharges and salt loads were synthesized for the periods 1964-1968 and 1978-1986. The data synthesis at station 6 covered 1964-1965. Data were also filled in for station 5, which has a period-of-record of 1964-1982, to cover the period 1983-1986.

The synthesized data were used to develop concentration versus duration relationships at the Seymour gage which reflect the salt control dams. However, the synthesized data were not used in the computations at the Possum Kingdom, Whitney, College Station, and Richmond gages. Of the five stations, the Seymour gage is the only station for which synthesized monthly discharges and salt loads were used to compute adjustments for the upstream salt control dams.

The data synthesis involved regressing discharges and salt loads at stations 2, 3, 4, 5, 6, and 7. The same computational procedures were repeated for monthly discharges, total dissolved solids, chloride loads, and sulfate loads. The missing data for 1964-1965 at station 6 were filled in by regressing station 6 versus station 7 minus station 5 data covering 1966-1982. The missing data for 1983-1986 at station 5 were synthesized by relating station 5 to station 7 minus station 6. The missing salt load data for 1964-1968 and 1978-1986 at station 4 were filled in by regressing station 4 versus station 5 minus stations 2 and 3 for 1969-1977. The missing discharges for 1978-1986 at station 4 were filled in the same way. Measured discharges at station 4 are available for 1964-1968 even though salt loads were not measured. Linear regression was used in all cases.

Salt Concentrations at the Seymour Gage (Station 7)

For salt control dam plan 1, the sum of the pertinent discharge and load values at stations 3, 4, and 6 were subtracted from the corresponding values at station 7 (Seymour gage) for each month of the 1964-1986 analysis period. For salt control dam plan 2, the sum of pertinent values at stations 4 and 6, rather than 3, 4, and 6, were subtracted from the values at station 7. In a number of months the discharge and/or salt load differences were negative, meaning the measured discharge or salt loads at the salt control dam sites were greater than at the Seymour gage. In this case, the quantities at the Seymour gage for that month were adjusted to zero and the remaining discharge or salt load difference was subtracted from the next month's quantity. The discharge or salt load removal continued through as many future months as necessary. Thus, the total discharge and salt load at the salt control dam sites were removed at the Seymour gage in the same month when possible, but in future months if necessary due to quantities at the Seymour gage going to zero.

CHAPTER 5
DEVELOPMENT OF A COMPLETE SET OF UNREGULATED MONTHLY SALT LOADS AND CONCENTRATIONS

The RESSALT salt load input data file consists of unregulated TDS, Cl, and SO_4 loads for each month of the January 1900 through December 1984 simulation period at each pertinent location. "Unregulated" streamflows, loads, and concentrations represent natural conditions without the reservoirs. A previously developed set of naturalized (unregulated) streamflows, documented by Wurbs et al. (1988), were used in the RESSALT model. Salinity data described in the present chapter were combined with the previously developed unregulated flows to obtain the salt loads used in the simulation study.

Available measured salinity data are discussed in Chapter 3. Chapters 6, 7, and 8 document the reservoir system simulation studies. Chapter 5 describes the adjustments to the measured data (Chapter 3) made to develop the salt load input required for the RESSALT reservoir system simulation model presented in Chapter 6. The work summarized by Chapter 5 is further addressed by Saleh (1993).

The computational tasks involved in developing the salt concentration data set are summarized in Table 5.1 and discussed in the following paragraphs. Pertinent stations are shown in Figure 5.1. The USGS water quality sampling program was significantly expanded in 1964, and most of the available data were collected since that time. Therefore, the procedures for adjusting and synthesizing salt data vary for the period before 1964 and the period 1964 and after. The computational procedures also vary between three groups of streamflow gaging and water quality sampling stations located on the: (1) Clear Fork and Hubbard Creek below Hubbard Creek Reservoir; (2) main stream of the Brazos River; and (3) better quality tributaries confluencing with the Brazos River below Whitney Dam.

Discharge, load, and concentration units of acre-feet/month, tons/month, and milligrams/liter (or parts per million) are used in Chapters 5-8. The units are related as follows.

concentration = load / discharge

mg/l = ((tons/month) / (ac-ft/month)) * 735.5

Monthly Data for 1964-1984 (Task 1 in Table 5.1)

Measured data were adjusted to develop streamflows, salt concentrations, and loads for each month during the period 1964-1984 for stations 12, 13, 14, 15, 18, 21, and 25 on the Brazos River and station 10 on Hubbard Creek. Stations 9 and 11 on the Clear Fork and station 7 on the Brazos River were used in the regression analyses to synthesize data missing at the other stations. Computations included filling in missing data and removing the effects of the four reservoirs.

Table 5.1
OUTLINE OF COMPUTATIONAL TASKS INVOLVED IN DEVELOPING THE SALINITY DATA SET

Task 1.- Development of a complete set of unregulated monthly discharges, loads, and concentrations for the period January 1964 - December 1984 for stations on Hubbard Creek (station 10) and the Brazos River (stations 12, 13, 14, 15, 18, 21 & 25).

a. Regression analyses to fill in data missing from the measured records at stations 9, 10, 11, 12, 14, 18 & 21.

b. Data adjustments to remove the effects of storage and evaporation in Hubbard, Possum Kingdom, Granbury, and Whitney Reservoirs.

    1. Volume balance computations of discharge inflows for Hubbard, Possum Kingdom, and Whitney Reservoirs, given gaged outflows, and computation of outflows for Granbury Reservoir, given gaged inflows.

    2. Computation of salt load inflows for Hubbard, Possum Kingdom, and Whitney Reservoirs and outflows for Granbury Reservoir based on mean concentrations, adjusted for evaporation, combined with discharges.

    3. Computation of incremental discharges and salt loads and then accumulating the incrementals to develop cumulative "unregulated" discharges and salt loads. Concentrations are computed as loads divided by discharges.

Task 2.- Development of discharge versus salt load regression equations to be used in synthesizing monthly salt loads and concentrations for the period January 1900 through December 1963 for the stations on Hubbard Creek and the Brazos River (stations 10, 12, 13, 14, 15, 18, 21, and 25).

Task 3.- Computation of long-term mean salt concentrations, adjusted to remove the effects of evaporation at selected major reservoirs, for stations 19 and 20 on the Little River.

Task 4.- Combination of the salinity data developed in Tasks 1-3 above with previously developed naturalized streamflows to develop unregulated salt loads for input to the RESSALT simulation model.

Task 5.- Development of an alternative data set for stations 12, 13, 14, 15, 18, 21, and 25 on the main stream Brazos River which reflects the impacts of the three proposed salt control impoundments.

a. Regression analyses, presented in Chapter 4, to fill in missing data during the 1964-86 period at the sites of the proposed salt control dams (stations 3, 4, and 6).

b. For the period 1964-84, the summation of discharges are subtracted from the corresponding values at the downstream stations 12, 13, 14, 15, 18, and 21.

c. For the period 1900-63, discharges and loads are adjusted based on 1964-84 means.

Task 6.- Development of an alternative set of salt loads with a random component which reflects those variations in loads and concentrations which are independent of discharge.

a. Development of normally distributed random deviations from the expected values of the monthly loads at the Richmond gage (station 25) by combining random numbers with the standard error statistic.

b. Development of the corresponding random deviations from the expected values of the salt loads at the other stations based on the ratios of the means.

c. Computation of loads by adding the random deviations of Tasks 6a&b to the loads developed in Tasks 1-4.

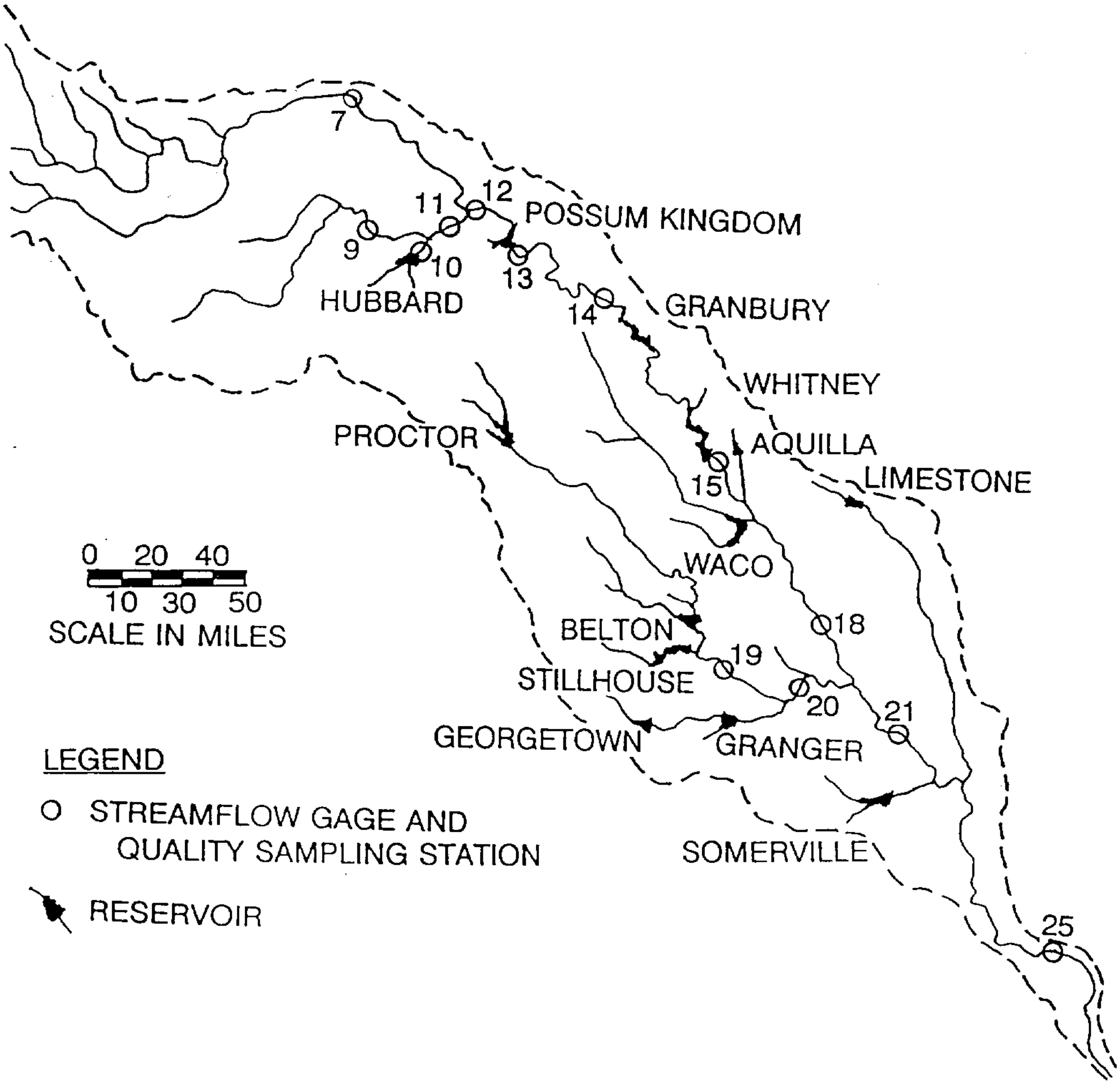

Figure 5.1 Stations Used in Chapter 5 Tasks 1-3

Missing Data

The pertinent stations are shown in Figure 5.2 and tabulated with periods of missing data in Table 5.2. Records are complete during 1964-1984 for stations 7, 13, and 25. There are several months during 1964-1984 with missing data at each of the other stations. Available data at each station were used to develop regression equations for use in synthesizing discharges and loads for the months with missing data. The regression equations are shown in Table 5.3.

The discharge records at station 10 are complete for 1964-1984, but salt loads are missing for October 1975 and subsequent months. Salt loads at station 10 are regressed with the discharges at station 10 to fill in the missing loads. Likewise, missing loads at station 9 are synthesized by regressing with discharges. Both flows and loads are missing from the measured data for October 1982 through December 1984 at station 11, and are synthesized by regressing with the sum of the values at stations 9 and 10 which are located immediately upstream. Loads at station 12 are regressed with the sum of the loads at upstream stations 7 and 11.

Missing flows and loads at station 14 are filled in by regressing with the upstream station 13. Measured data are complete during 1964-1984 at stations 15 and 25, but there are gaps at stations 18 and 21. Missing flows and loads at stations 18 and 21 are filled in using a multiple linear regression with stations 15 and 25.

Unregulated Flows and Salt Loads

The RESSALT reservoir system simulation model presented in Chapter 6 computes regulated flows, loads, and concentrations for user-specified system operating policies. The streamflow and salt concentration input data for RESSALT should represent the unregulated conditions which would have occurred without the reservoirs. The sequences of measured and synthesized (filled-in) data described above were next adjusted to remove the effects of storage and evaporation in Hubbard, Possum Kingdom, Granbury, and Whitney Reservoirs. The following paragraphs describe the adjustment computations which include: (1) developing streamflow discharges into and out of the reservoirs, based on volume balances; (2) developing salt loads into and out of the reservoirs, based on long-term mean concentrations; and (3) computation of incremental discharges and salt loads and then accumulating the incrementals to develop unregulated discharges and salt loads. The unregulated concentrations are the unregulated salt loads divided by the corresponding unregulated discharges.

Stations 10, 13, and 15 are located just downstream of the dams at Hubbard, Possum Kingdom, and Whitney Reservoirs. The measured data represent outflows from the reservoirs. The discharges flowing into these three reservoirs were computed based on volume balances. Likewise, station 14 located upstream of Granbury Reservoir was treated as representing reservoir inflows, and volume balance computations were performed to estimate outflows. The volume balance computations are based on the equation:

$$S_2 = S_1 + I - O - \text{Evap}$$

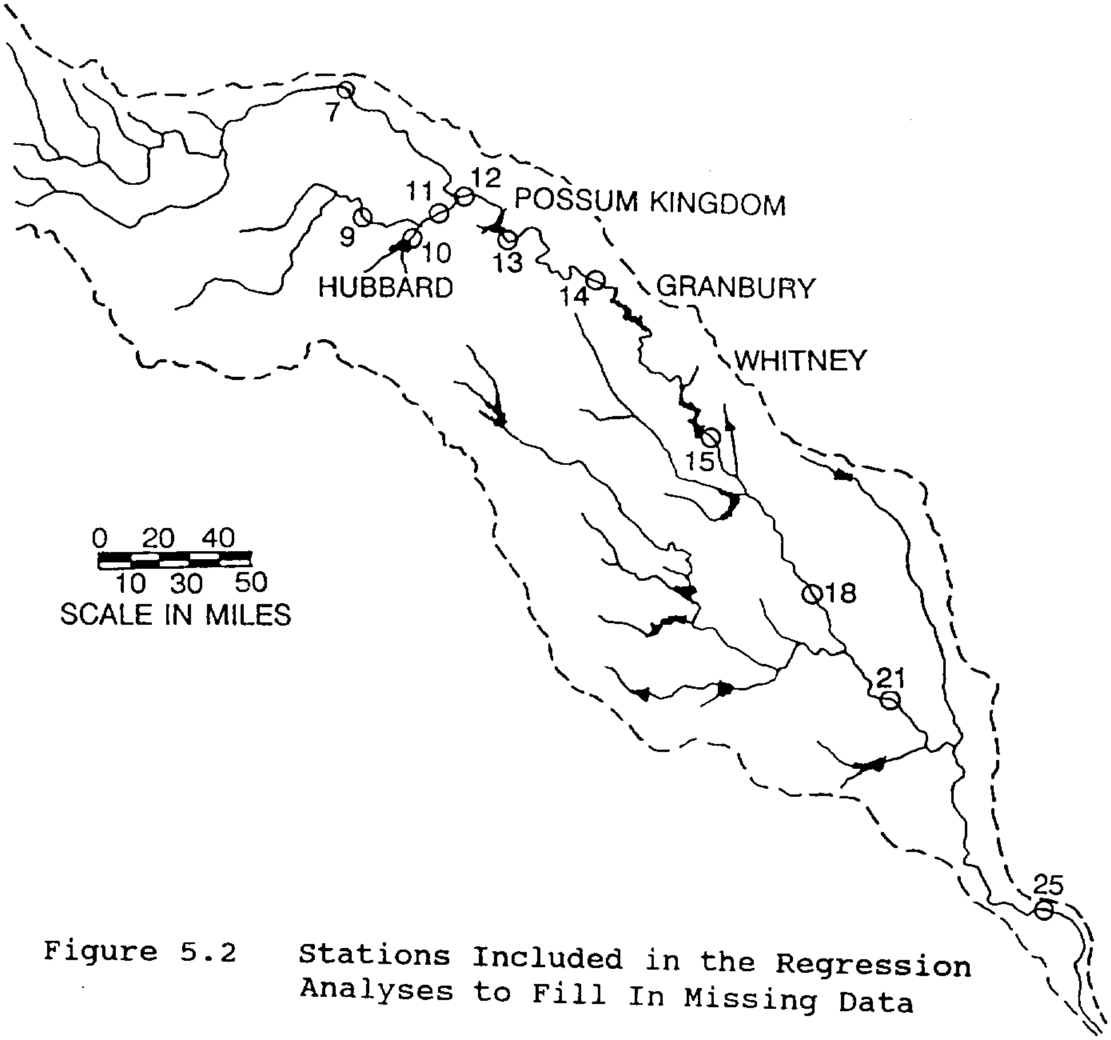

Figure 5.2 Stations Included in the Regression Analyses to Fill In Missing Data

Table 5.2
COMPLETENESS OF MEASURED DATA

Station	Months with Missing Data During 1964-1984	
	Discharge	Salt Concentration
7	complete	complete
9	complete	Jan 64 - Sep 67 & Oct 84 - Dec 84
10	complete	Oct 75 - Dec 84
11	Oct 82 - Dec 84	Oct 82 - Dec 84
12	complete	Jan 64 - Oct 77 & Oct 81 - Dec 84
13	complete	complete
14	Jan 64 - Dec 68	Jan 64 - Sep 70
15	complete	complete
18	Jan 64 - Oct 67	Jan 64 - Oct 67
21	Oct 83 - Dec 84	Oct 83 - Dec 84
25	complete	complete

Table 5.3
REGRESSION EQUATIONS USED TO FILL IN MISSING DATA

Loads at Station 10 for Oct 75 - Dec 84:

TDS(10) = 0.5913*Q(10) $R^2=0.982$
Chloride(10) = 0.2262*Q(10) $R^2=0.978$
Sulfate(10) = 0.0779*Q(10) $R^2=0.922$

Loads at Station 9 for Jan 64 - Sept 67 and Oct 84 - Dec 84:

TDS(9) = 0.0151*Q(9) $R^2=0.876$
Chloride(9) = 0.3476*Q(9) $R^2=0.847$
Sulfate(9) = 0.1028*Q(9) $R^2=0.823$

Loads and Discharges (Q) at Station 11 for Oct 82 - Dec 84:

TDS(11) = 6,662 + 0.7309*TDS(9+10) $R^2=0.593$
Chloride(11) = 2,664 + 0.7481*Chloride(9+10) $R^2=0.498$
Sulfate(11) = 1,391 + 0.6369*Sulfate(9+10) $R^2=0.508$
Q(11) = 3,263 + 1.108*Q(9+10) $R^2=0.921$

Loads at Station 12 for Jan 64 - Oct 77 and Oct 81 - Dec 84:

TDS(12) = 3,610 + 0.998*TDS(7+11) $R^2=0.859$
Chloride(12) = 2,217 + 1.022*Chloride(7+11) $R^2=0.787$
Sulfate(12) = 601 + 1.039*Sulfate(7+11) $R^2=0.767$

Loads at Station 14 for Jan 64 - Sept 70:

TDS(14) = 7,846 + 1.040*TDS(13) $R^2=0.746$
Chloride(14) = 2,165 + 1.019*Chloride(13) $R^2=0.724$
Sulfate(14) = 1,280 + 1.019*Sulfate(13) $R^2=0.792$

Discharges (Q) at Station 14 for Jan 64 - Dec 68:

Q(14) = 2,375 + 1.291*Q(13) $R^2=0.906$

Loads and Discharges at Station 18 for Jan 64 - Oct 67:

TDS(18) = -12,620 + 0.897*TDS(15) + 0.222*TDS(25) $R^2=0.964$
Chloride(18) = -3,659 + 0.595*Chloride(15) + 0.393*Chloride(25) $R^2=0.890$
Sulfate(18) = -2,145 + 0.886*Sulfate(15) + 0.249*Sulfate(25) $R^2=0.965$
Q(18) = -24,223 + 1.000*Q(15) + 0.195*Q(25) $R^2=0.894$

Loads and Discharges at Station 21 for Oct 83 - Dec 84:

TDS(21) = 4,754 + 0.455*TDS(15) + 0.576*TDS(25) $R^2=0.907$
Chloride(21) = 967 + 0.522*Chloride(15) + 0.479*Chloride(25) $R^2=0.954$
Sulfate(21) = 400 + 0.554*Sulfate(15) + 0.552*Sulfate(25) $R^2=0.948$
Q(21) = -4,830 + 0.798*Q(15) + 0.504*Q(25) $R^2=0.884$

Notes:

1. Loads and discharges are in units of tons/month and acre-feet/month.
2. R^2 denotes the coefficient of determination. R is the correlation coefficient.

where S_1 and S_2 denote gaged reservoir storage at the beginning and end of the monthly computational time interval, respectively, and I and O denote inflow and outflow volumes during the month. Outflows (O) are known at stations 10, 13, and 15 and inflows (I) are computed. At station 14, outflows are computed for given inflows. The monthly evaporation volume (Evap) is computed as:

$$\text{Evap} = ((A_1 + A_2) / 2) * \text{evaporation rate}$$

where A_1 and A_2 denote the reservoir water surface area at the beginning and end of the month and are determined from a storage versus area curve for the reservoir. The reservoir evaporation rates were obtained from a data base maintained by the TWDB which is discussed in Chapter 6. Gross, rather than net, evaporation rates were used.

The volume balance equation above neglects lakeside diversions for beneficial use. At Possum Kingdom, Granbury, and Whitney Reservoirs, most releases are to the river downstream and thus are reflected in the outflow term (O). However, Hubbard Creek had significant lakeside diversions not reflected in the measured outflows. The volume balance computations resulted in negative inflows in some months. The negative values were assumed to represent diversions, and the inflows were set equal to zero. Thus, the unregulated flows at station 10 were at least somewhat adjusted for lakeside diversions.

The unregulated salt loads corresponding to the unregulated streamflow discharges described above were computed by combining the discharges with long-term mean concentrations. The computations are based on the assumptions that, for the period 1964-1984, for each reservoir: (1) the mean or total streamflow outflow equals inflow minus evaporation, and (2) the mean or total salt load inflow equals outflow. The mean outflow concentration is higher than the mean inflow concentration because reservoir evaporation removes water but not salt load. The computed mean inflow or outflow concentration was assumed to be constant for the entire 1964-1984 period. For Hubbard, Possum Kingdom, and Whitney Reservoirs, the 1964-1984 mean outflow concentration was based on measured data. The 1964-1984 mean inflow concentration was computed by adjusting the 1964-1984 inflow volume for computed evaporation. This concentration was then combined with the discharges previously computed for each month to obtain the corresponding salt loads. At Granbury Reservoir, the 1964-1984 mean inflow concentration was based on measured data, and the 1964-1984 mean outflow was computed in a similar manner. Outflow loads for each month were computed by combining the constant concentration with the previously computed discharges.

The next step was to compute the incremental discharges and salt loads for each month for each reach of river. Incrementals represent local flows and loads entering the river reaches between the stations. Incremental discharges and TDS, Cl, and SO_4 loads for each month from 1964 through 1984 were computed by subtracting corresponding values at adjacent stations as follows.

station 10 incrementals = Hubbard Reservoir computed inflows

station 12 incrementals = station 12 minus station 10 values station 13 incrementals = Possum Kingdom Reservoir computed inflows minus station 12 values

station 14 incrementals = station 14 minus station 13 values

station 15 incrementals = Granbury Reservoir computed outflows minus Whitney Reservoir computed inflows

station 18 incrementals = station 18 minus station 15 values

station 21 incrementals = station 21 minus station 18 values

station 25 incrementals = station 25 minus station 21 values

Unregulated flows and salt loads at each station were then computed by accumulating values starting at station 10 and working downstream. This procedure resulted in negative loads and/or discharges being computed for some months. The computed loads and discharges were adjusted as follows to remove negative values. Negative values were set equal to zero for that month, and an equivalent amount was removed from the corresponding value for the next month.

Concentrations were computed by dividing loads by discharges. As outlined above, unregulated discharges were computed and used to develop sequences of unregulated monthly salt concentrations for the period 1964-84 for each of the selected stations. However, as discussed in Task 4 below, another set of previously developed unregulated discharges, based on more detailed "naturalization" adjustments, were actually used in the RESSALT model. The unregulated concentrations of Chapter 5 were combined with the previously developed unregulated discharges to compute unregulated salt loads inputted to RESSALT.

Alternative Perspective on Unregulated Salt Loads

The unregulated salt load computations can be viewed from an equivalent alternative perspective as follows. This alternative computational approach reflects the same premises and yields identical results as the salt load adjustment procedure outlined above. Loads at a station are adjusted to remove the impacts of upstream reservoirs by subtracting a monthly load adjustment factor (L_{adj}) for each reservoir, which is computed from the 1964-84 mean (M) reservoir inflow (MQ_{in}), outflow (MQ_{out}), evaporation (MEvap), and salt load outflow (ML_{out}) from the reservoir. For each month of the period-of-analysis, the salt loads at a station are adjusted by subtracting the load adjustment factors (L_{adj}) for that month, which are computed for each upstream reservoir as follows:

$$L_{adj} = L_{in} - L_{out}$$

$$L_{adj} = Q_{in}\ (MC_{in}) - L_{out}$$

where 1964-84 mean inflow concentration $MC_{in} = ML_{in}/MQ_{in} = ML_{out} / (MQ_{out} + MEvap)$

Summary of Results

The means of the unregulated and regulated flows, loads, and concentrations for the period 1964-1984 are tabulated in Tables 5.4 and 5.5. The unregulated conditions of Table 5.4 reflect measured data supplemented by synthesized data filling in any gaps (missing data) during the 1964-1984 period. Table 5.5 reflects the unregulated data developed as outlined above. Tables 5.6-5.8 provide a comparison of selected regulated and unregulated data from Tables 5.4 and 5.5 and the measured data for the indicated period-of-record. Regulated and unregulated monthly discharge hydrographs for selected stations are plotted in Figures 5.3-5.8. The corresponding monthly TDS loads and concentrations are plotted in Figures 5.9-5.20. Chloride and sulfate loads and concentrations for station 15 are plotted in Figures 5.21-5.24.

Since stations 13, 15, and 25 have measured data covering the entire 1964-1984 period, the measured and regulated means in Tables 5.6-5.8 are the same. The other stations include filled-in as well as measured data in the regulated means. As indicated in Table 5.7, the means of the 1964-1984 salt loads are the same for regulated and unregulated conditions since the computations were based on preserving the salt mass. For regulated conditions, evaporation from the four reservoirs reduces the discharge means with corresponding increases in salt concentrations, as compared to unregulated conditions. As indicated by Table 5.6, the 1964-84 mean unregulated streamflow is 294% of the regulated flow below Hubbard Dam (station 10) and 105% of the regulated flow at the Richmond gage (station 25). The unregulated flows were approximately adjusted only for the effects of four reservoirs, even though the flows are actually affected by other reservoirs in the basin as well. For example, regulated flows at the Richmond gage are reduced by evaporation from all 13 reservoirs included in the RESSALT model (Chapters 6-8) as well as the numerous other reservoirs in the basin. Thus, from this perspective, the computed unregulated salt concentrations are conservatively high.

Discharge Versus Salt Load Regression Equations
(Task 2 in Table 5.1)

The 1964-1984 unregulated monthly discharges and salt loads described above were used to develop regression equations for the stations on the Brazos River, Clear Fork, and Hubbard Creek. The previously developed naturalized streamflow sequences described in Chapter 6 were then inputted to the regression equations to develop monthly salt loads for the period 1900-1963. Concentrations for this period were computed as salt loads divided by the corresponding discharges.

The following relationship between unregulated streamflows (Q), in acre-feet/month, and salt loads (L), in tons/month, was adopted:

$$L = a * Q^b$$

where a and b are regression coefficients. For linear regression, $b=1$, $L=a*Q$, and "a" is a constant concentration in tons/acre-feet. The regression coefficients and corresponding correlation coefficients are tabulated in Table 5.9.

Table 5.4
1964-1984 MEAN REGULATED DISCHARGES, LOADS, AND CONCENTRATIONS

Station	Discharge (ac-ft/month)	Load (tons/month)			Concentration (mg/l)		
		TDS	Cl	S04	TDS	Cl	S04
10	2,640	1,590	604	211	442	168	59
11	17,700	18,300	6,030	4,260	759	250	177
12	38,500	100,500	41,500	20,900	1,921	793	399
13	41,400	82,900	34,300	16,900	1,472	610	301
14	56,600	94,400	38,000	18,800	1,226	493	245
15	75,500	92,900	34,000	17,800	904	332	173
18	137,000	113,000	33,900	21,500	606	182	115
21	265,000	157,000	40,000	27,500	436	111	76
25	417,000	191,000	44,400	31,200	337	78	55

Table 5.5
1964-1984 MEAN UNREGULATED DISCHARGES, LOADS AND CONCENTRATIONS

Station	Discharge (ac-ft/month)	Load (tons/month)			Concentration (mg/l)		
		TDS	Cl	S04	TDS	Cl	S04
10	7,770	1,590	604	211	151	57	20
11	22,900	18,300	6,030	4,260	589	194	137
12	43,600	100,500	41,500	20,900	1,695	700	352
13	52,900	82,800	34,300	16,900	1,151	477	235
14	68,200	94,400	38,000	18,900	1,018	410	203
15	94,900	92,900	34,000	17,900	720	264	138
18	156,000	116,000	34,700	22,100	531	159	101
21	285,000	157,000	40,000	27,500	406	104	71
25	436,000	191,000	44,400	31,200	322	75	53

Stations

10 Hubbard Creek below Hubbard Creek Dam
11 Clear Fork near Eliasville
12 Brazos River near Southbend
13 Brazos River below Possum Kingdom Dam
14 Brazos River near Dennis
15 Brazos River below Whitney Dam
18 Brazos River near Highbank
21 Brazos River near College Station
25 Brazos River near Richmond

Table 5.6
COMPARISON OF MEASURED, REGULATED, AND UNREGULATED MEAN DISCHARGES

Station	Period of Record	Mean Discharge (ac-ft/month)			Unregulated /Regulated (percent)
		Measured Flow	1964-84 Regulated	1964-84 Unregulated	
10	1967-75	1,900	2,640	7,770	294
11	1964-82	19,100	17,700	22,900	129
12	1978-81	38,500	38,500	43,600	113
13	1964-84	41,400	41,400	53,000	128
14	1971-84	54,000	56,600	68,200	120
15	1964-84	75,500	75,500	94,900	126
18	1968-84	143,000	137,000	156,000	114
21	1964-84	276,000	265,000	285,000	107
25	1964-84	417,000	417,000	436,000	105

Table 5.7
COMPARISON OF MEASURED, REGULATED, AND UNREGULATED MEAN TDS LOADS

Station	Period of Record	Mean TDS Load (tons/month)			Unregulated /Regulated (percent)
		Measured Load	1964-84 Regulated	1964-84 Unregulated	
10	1967-75	1,180	1,590	1,590	100
11	1964-82	19,100	18,300	18,300	100
12	1978-81	72,000	100,000	100,000	100
13	1964-84	82,800	82,800	82,800	100
14	1971-84	91,800	94,400	94,400	100
15	1964-84	92,800	92,800	92,900	100
18	1968-84	119,000	113,000	113,000	100
21	1964-83	164,000	157,000	157,000	100
25	1964-84	191,000	191,000	191,000	100

Table 5.8
COMPARISON OF MEASURED, REGULATED, AND UNREGULATED TDS CONCENTRATIONS

Station	Period of Record	Mean TDS Concentration (mg/l)			Unregulated /Regulated (percent)
		Measured Concentration	1964-84 Regulated	1964-84 Unregulated	
10	1967-75	459	442	151	34
11	1964-82	736	759	589	78
12	1978-81	1,410	1,921	1,700	88
13	1964-84	1,470	1,470	1,150	78
14	1971-84	1,250	1,230	1,020	83
15	1964-84	904	904	720	80
18	1968-84	611	606	531	88
21	1964-83	437	436	406	93
25	1964-84	337	337	322	96

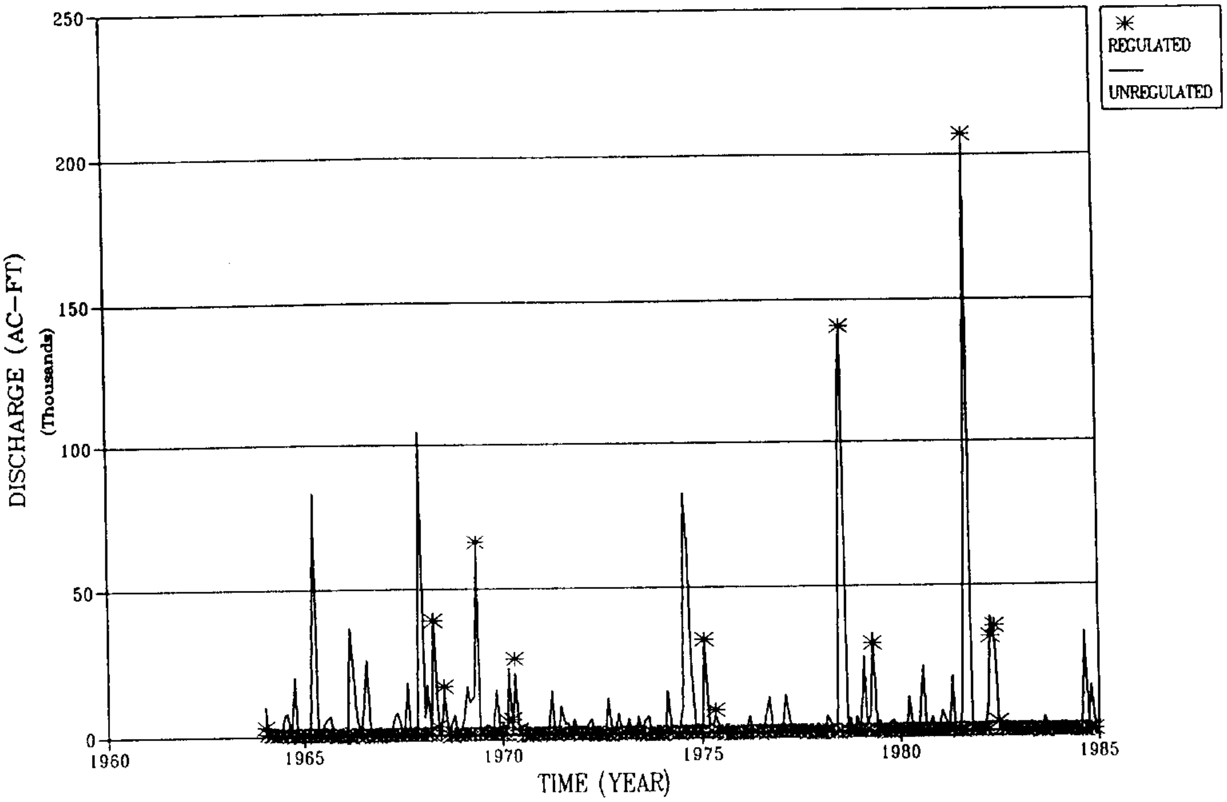

Figure 5.3 Regulated and Unregulated Discharge Hydrographs at Station 10 (Hubbard Gage)

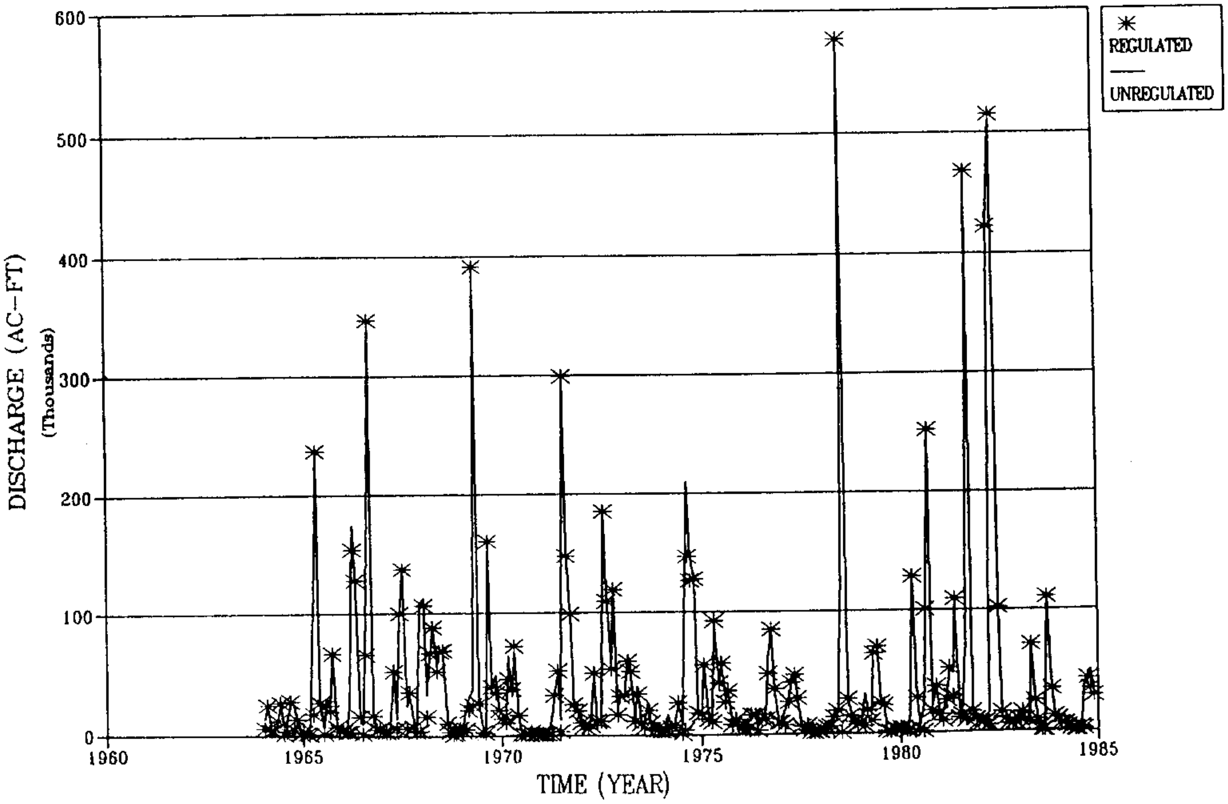

Figure 5.4 Regulated and Unregulated Discharge Hydrographs at Station 12 (Southbend Gage)

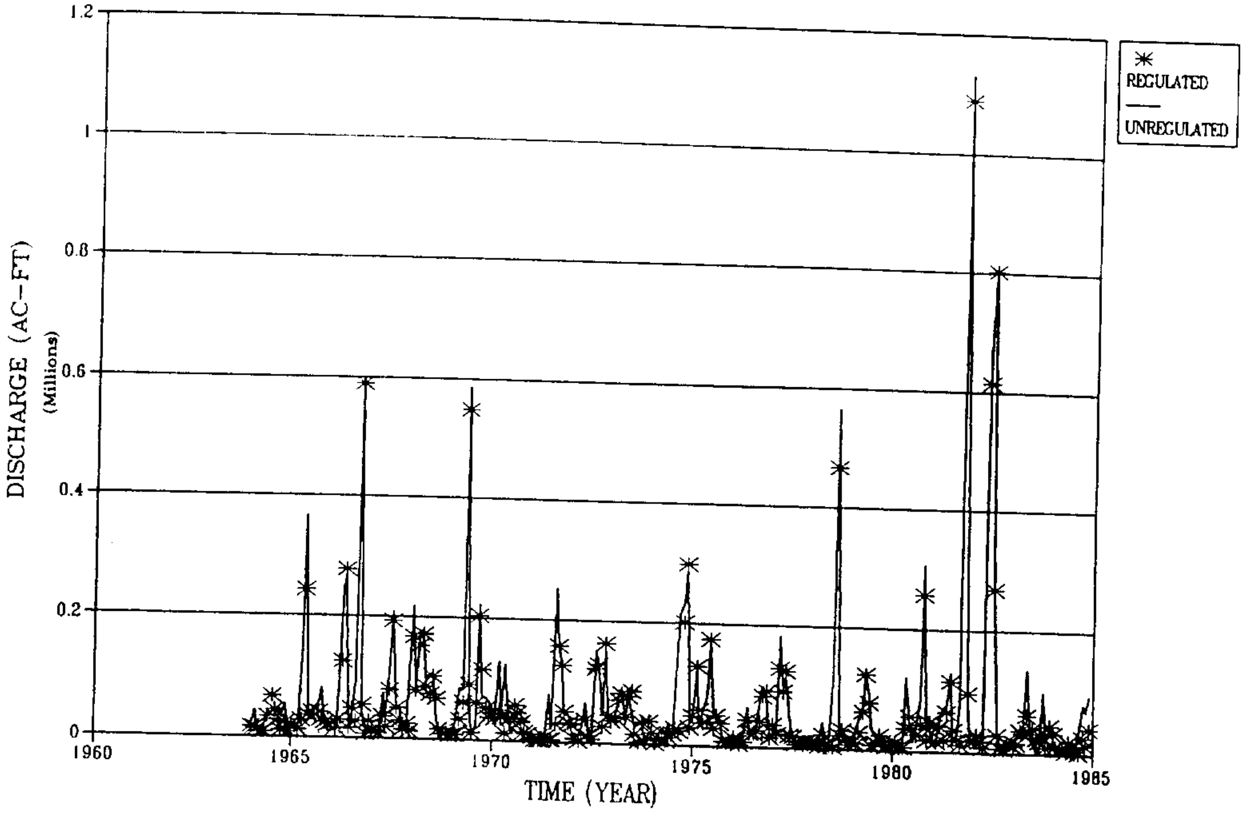

Figure 5.5 Regulated and Unregulated Discharge Hydrographs at Station 14 (Dennis Gage)

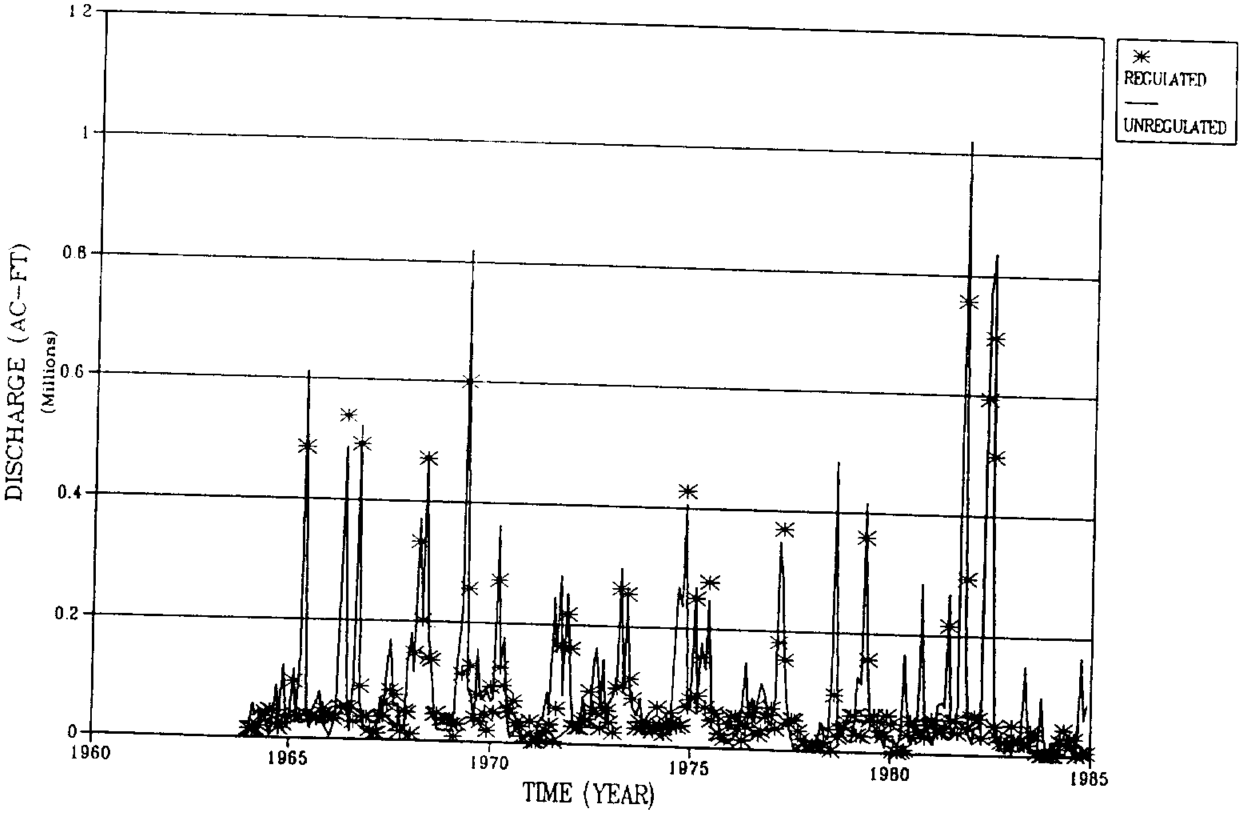

Figure 5.6 Regulated and Unregulated Discharge Hydrographs at Station 15 (Whitney Gage)

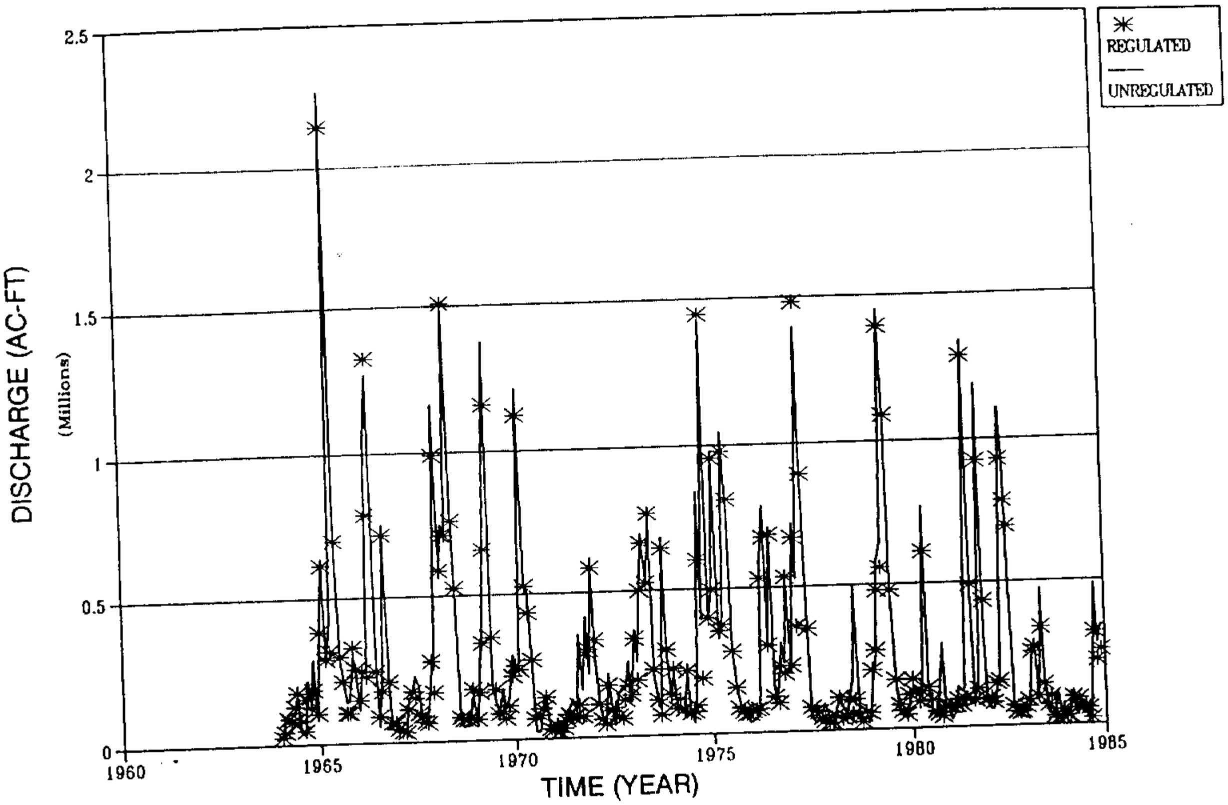

Figure 5.7 Regulated and Unregulated Discharge Hydrographs at Station 21 (College Station Gage)

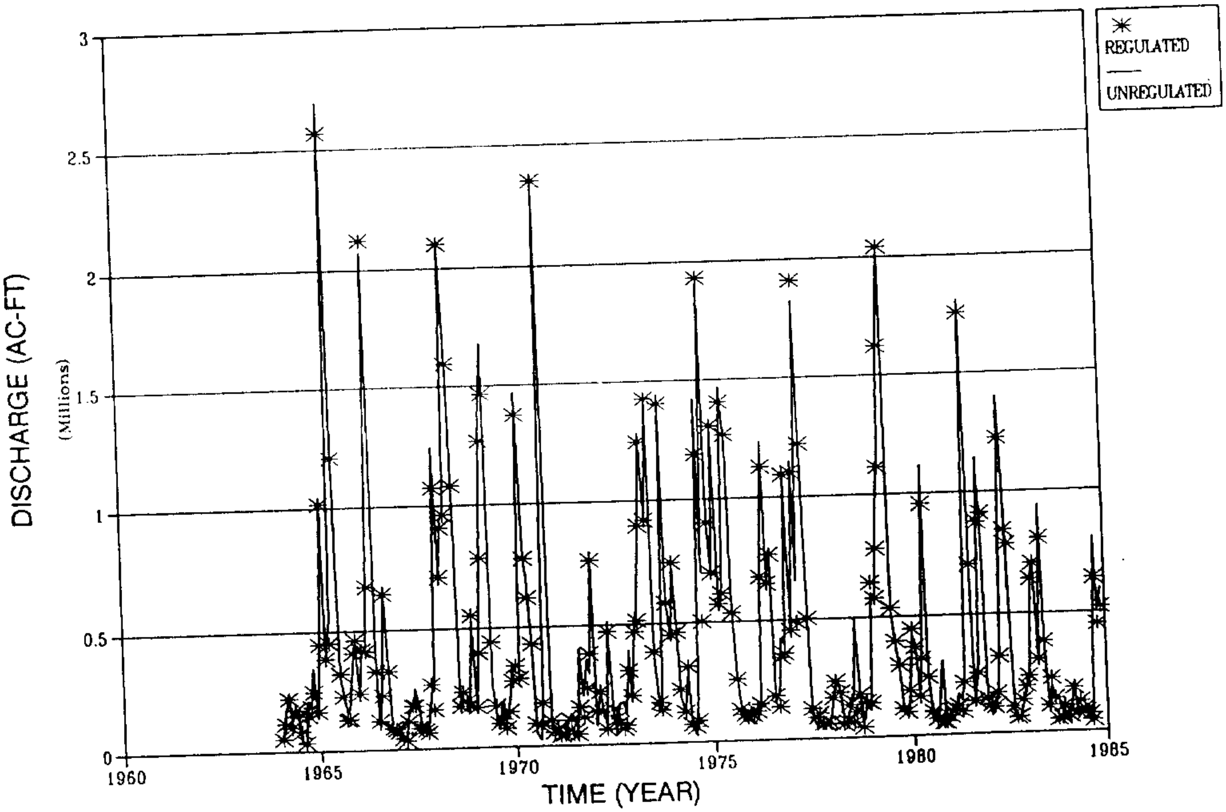

Figure 5.8 Regulated and Unregulated Discharge Hydrographs at Station 25 (Richmond Gage)

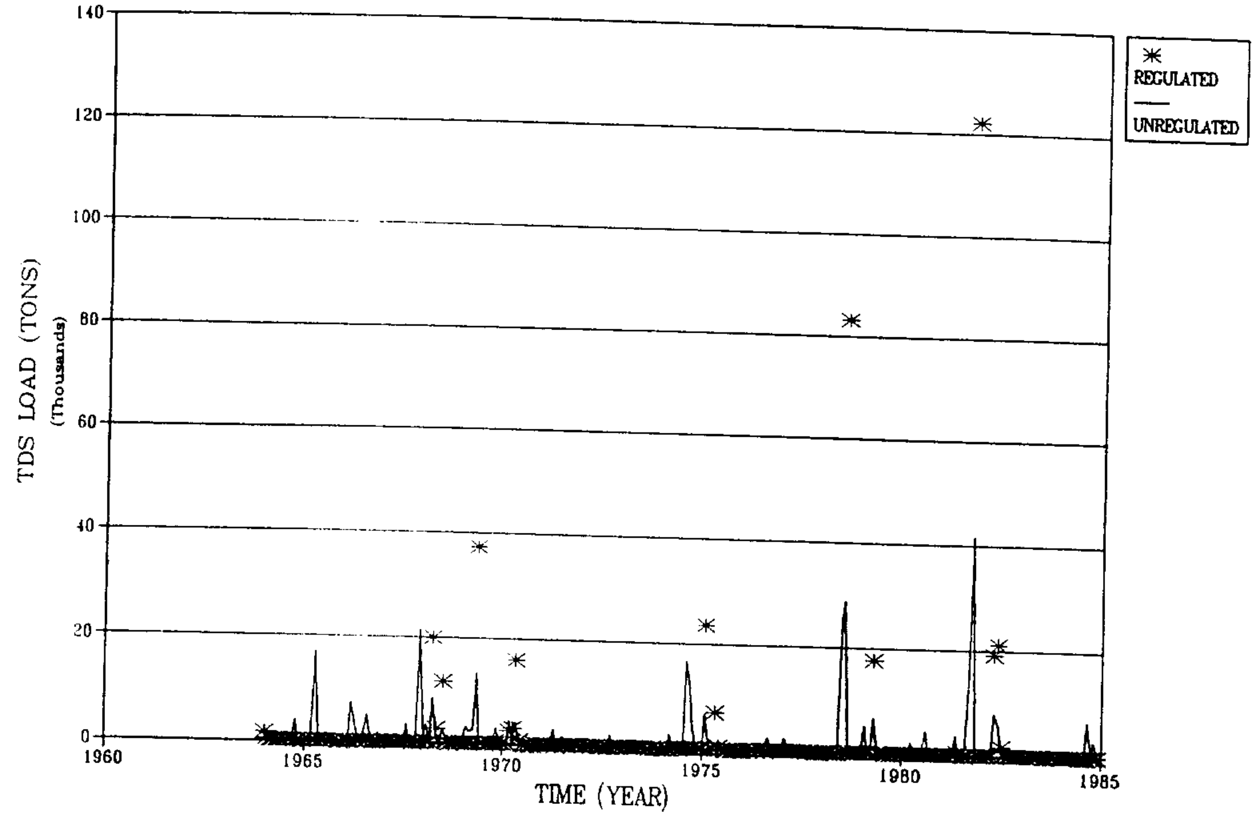

Figure 5.9 Regulated and Unregulated TDS Loads at Station 10 (Hubbard Gage)

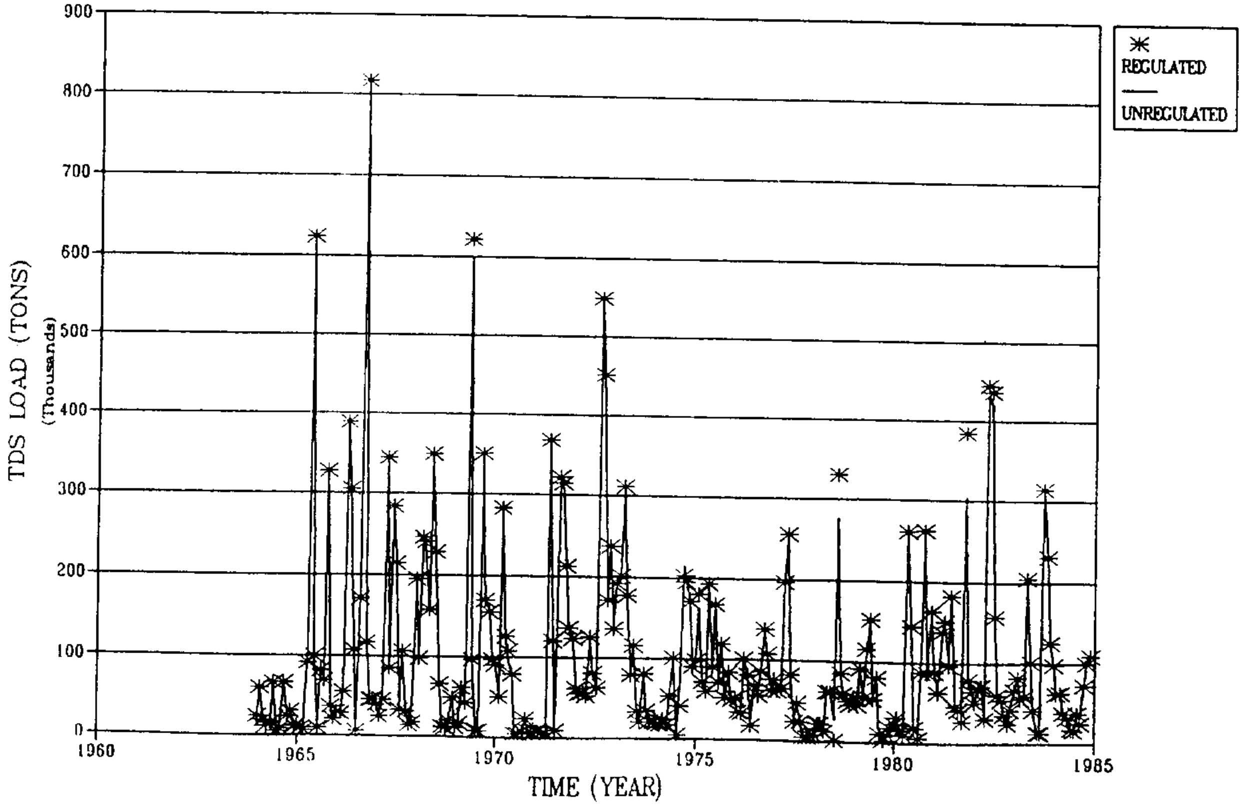

Figure 5.10 Regulated and Unregulated TDS Loads at Station 12 (Southbend Gage)

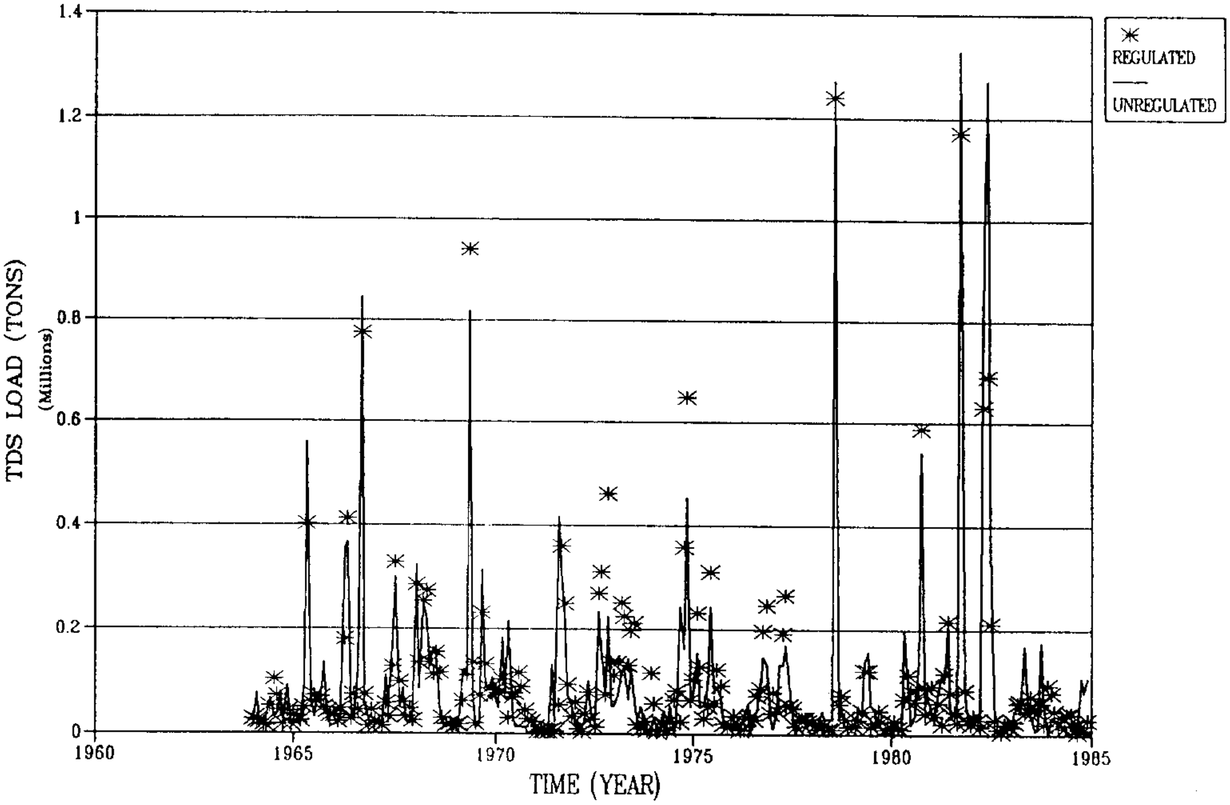

Figure 5.11 Regulated and Unregulated TDS Loads at Station 14 (Dennis Gage)

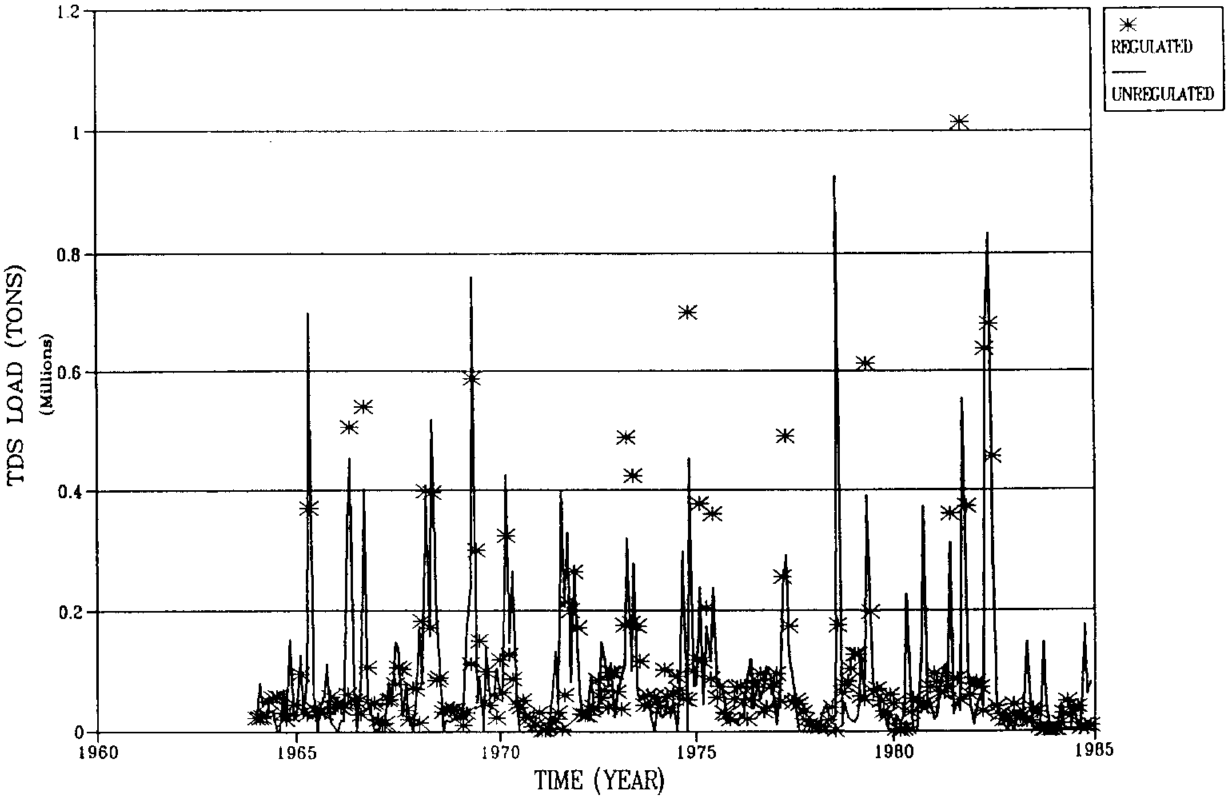

Figure 5.12 Regulated and Unregulated TDS Loads at Station 15 (Whitney Gage)

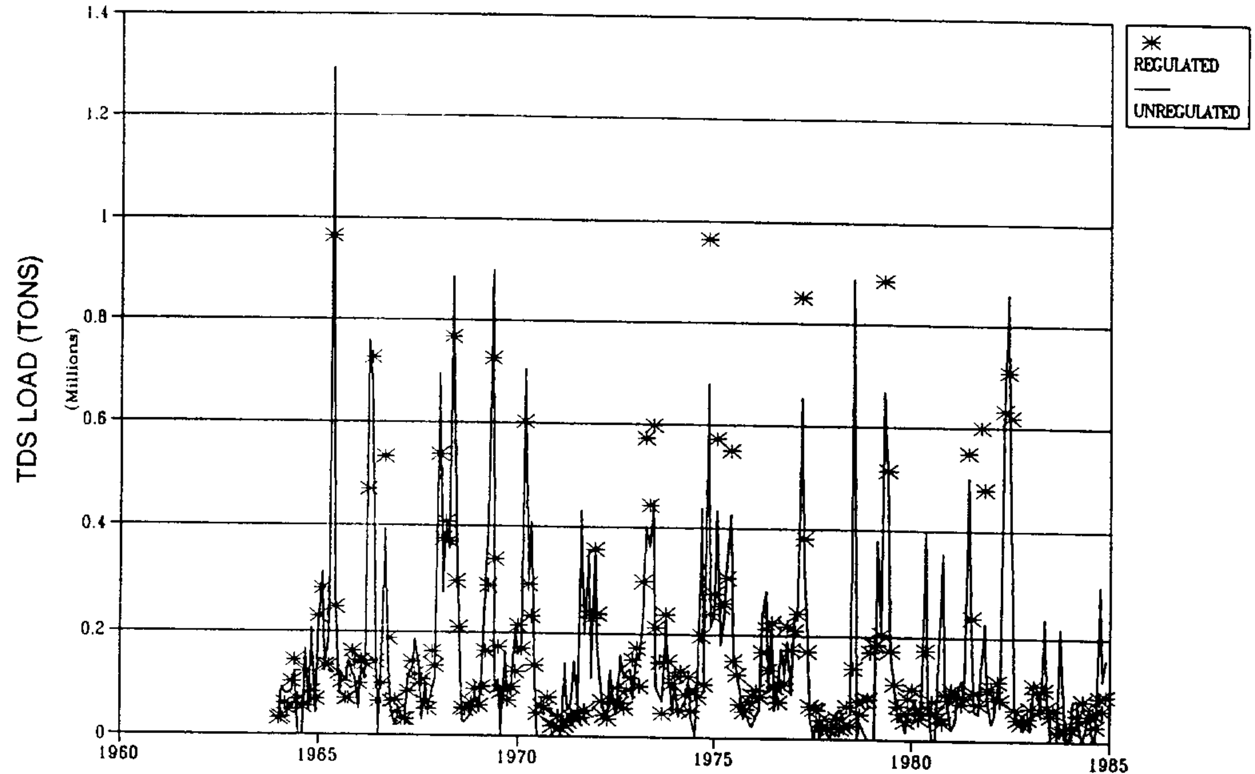

Figure 5.13 Regulated and Unregulated TDS Loads at Station 21 (College Station Gage)

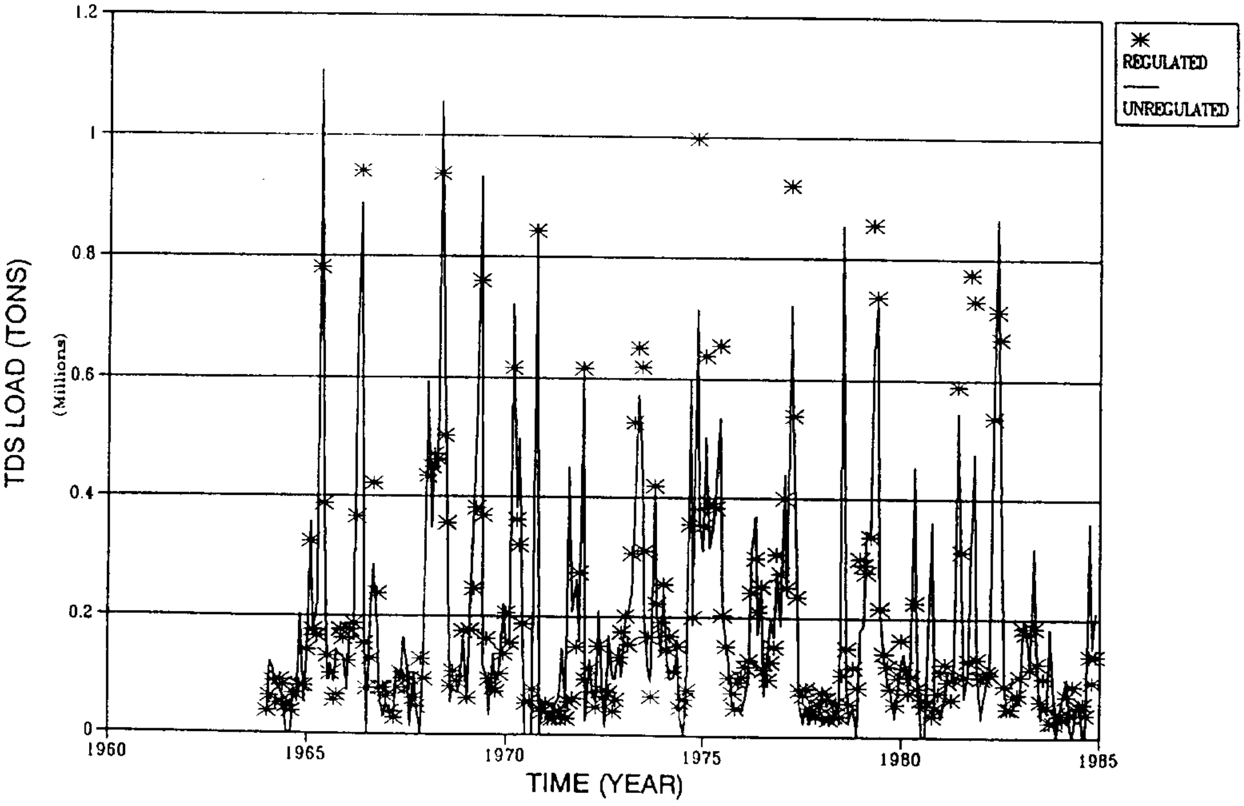

Figure 5.14 Regulated and Unregulated TDS Loads at Station 25 (Richmond Gage)

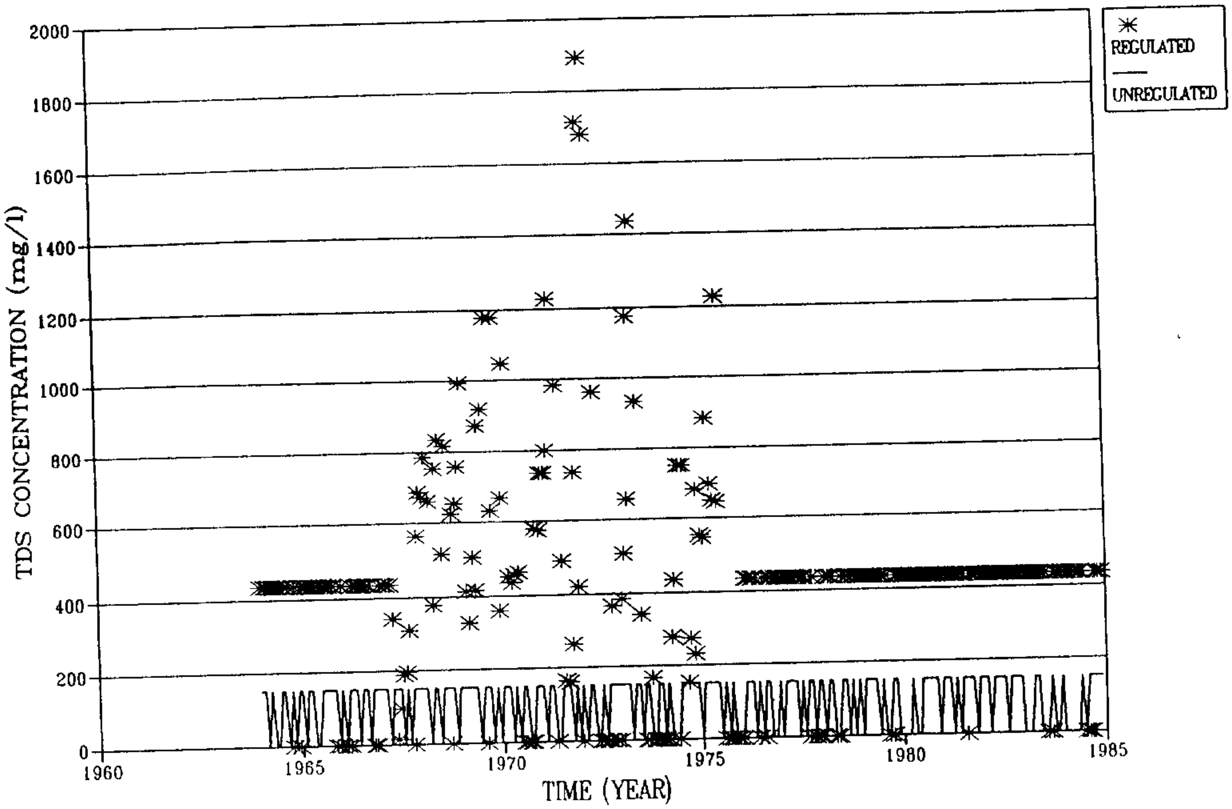

Figure 5.15 Regulated and Unregulated TDS Concentrations at Station 10 (Hubbard Gage)

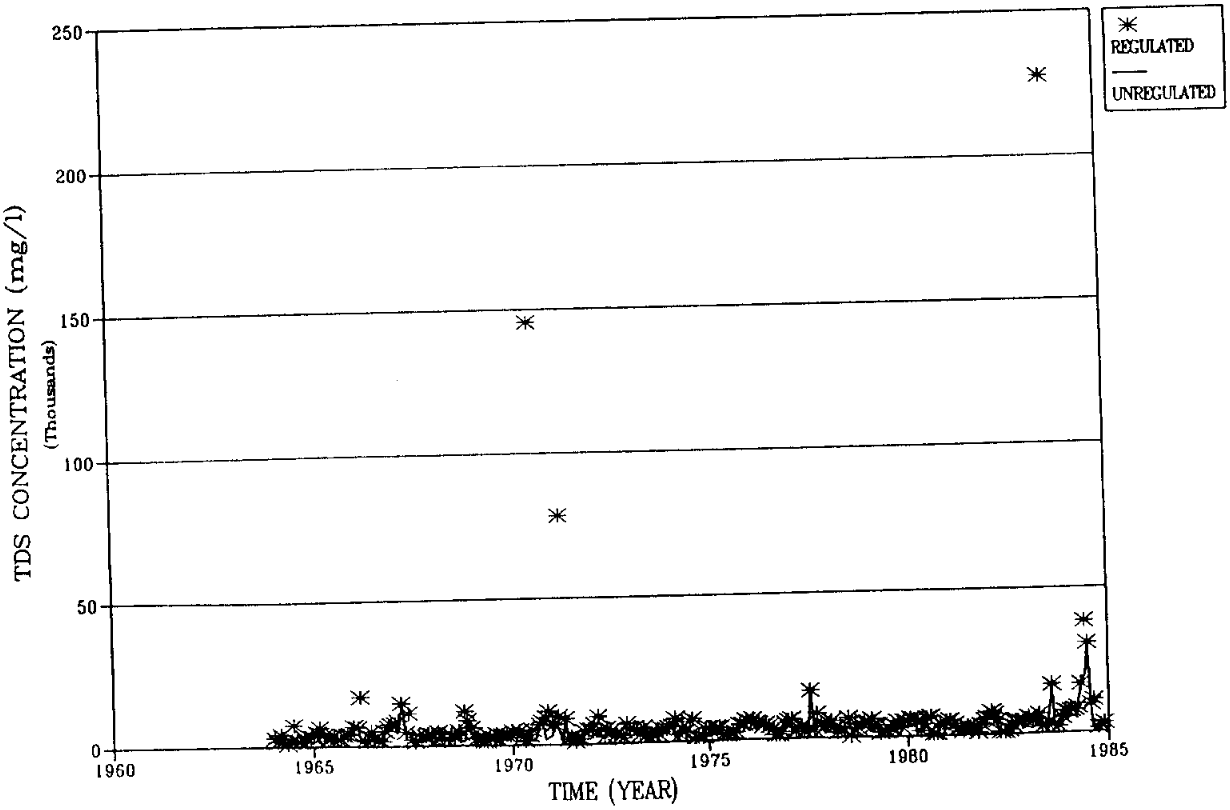

Figure 5.16 Regulated and Unregulated TDS Concentrations at Station 12 (Southbend Gage)

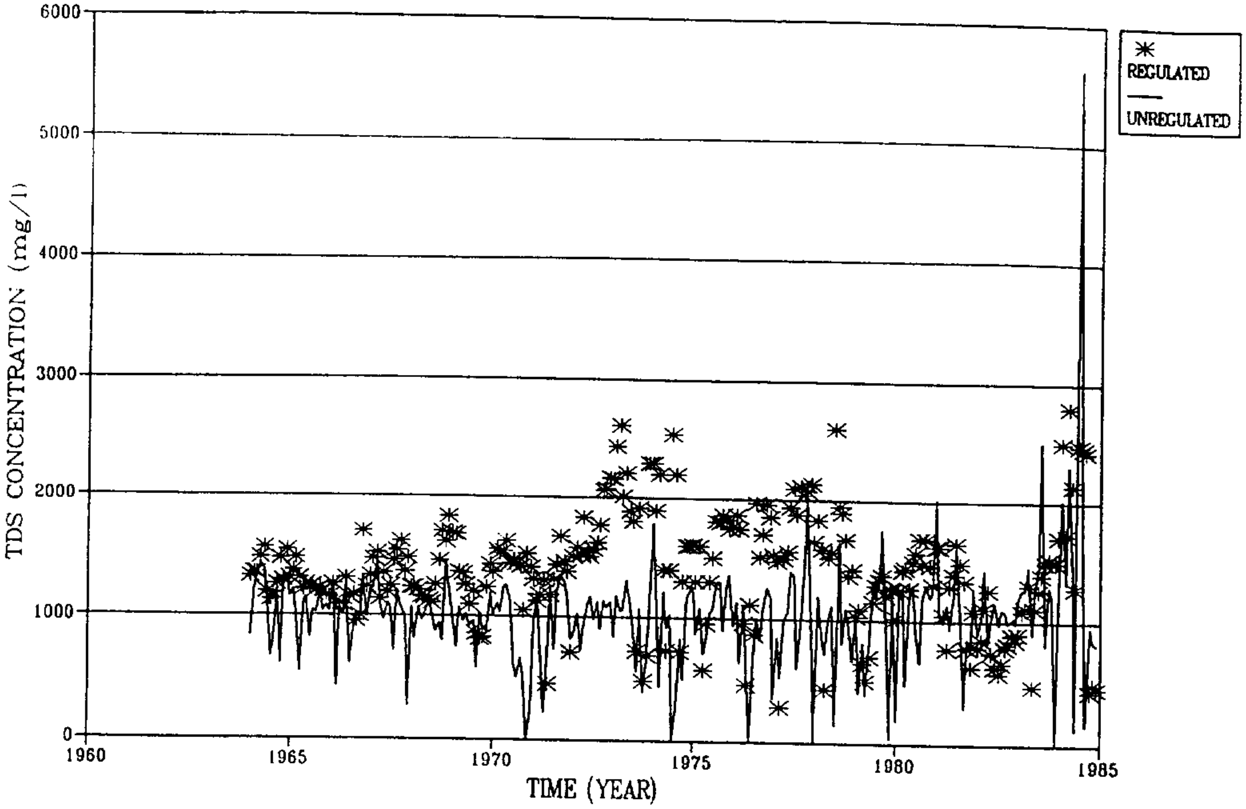

Figure 5.17 Regulated and Unregulated TDS Concentrations at Station 14 (Dennis Gage)

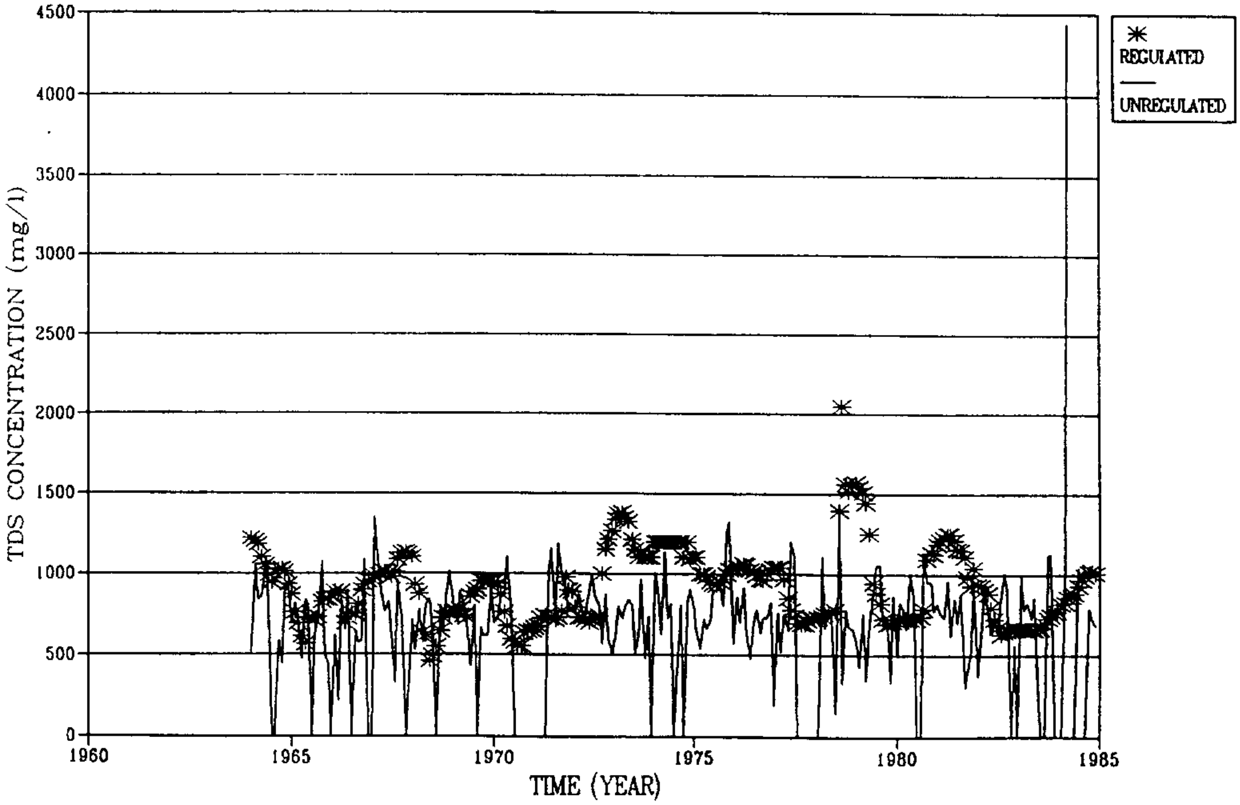

Figure 5.18 Regulated and Unregulated TDS Concentrations at Station 15 (Whitney Gage)

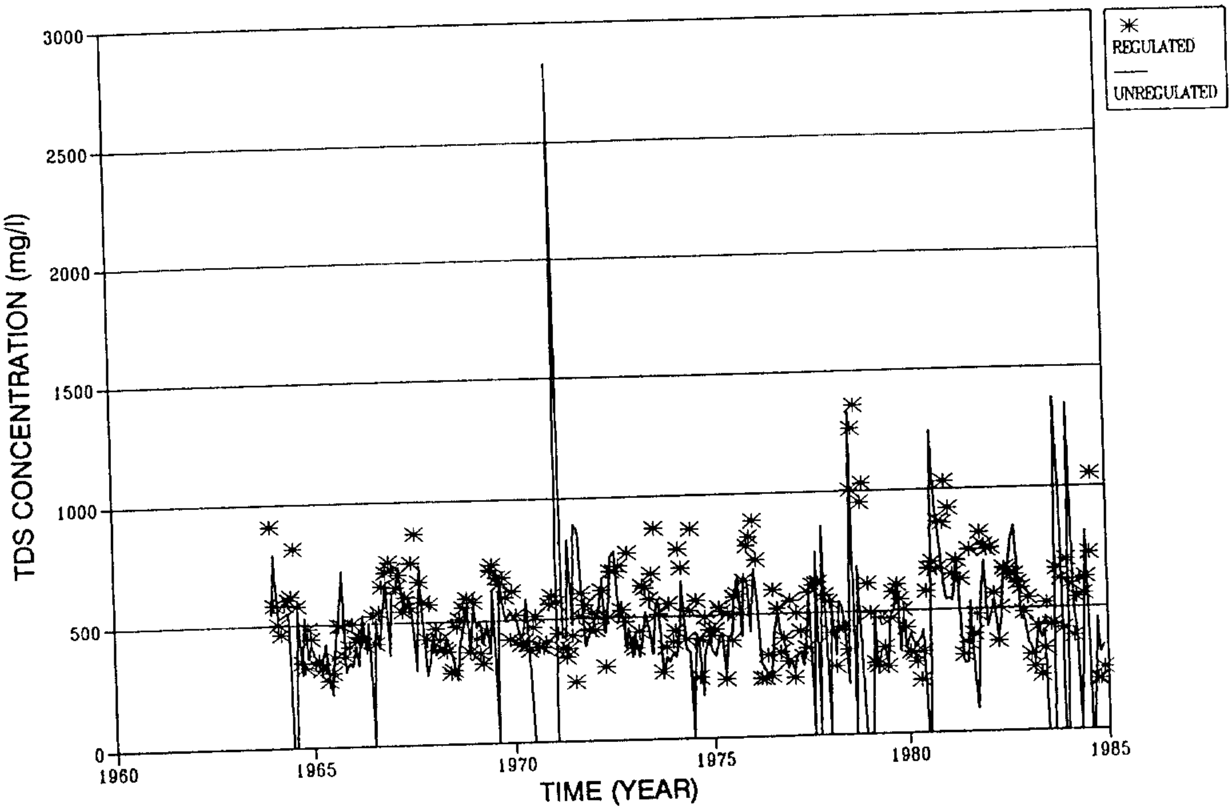

Figure 5.19 Regulated and Unregulated TDS Concentrations at Station 21 (College Station Gage)

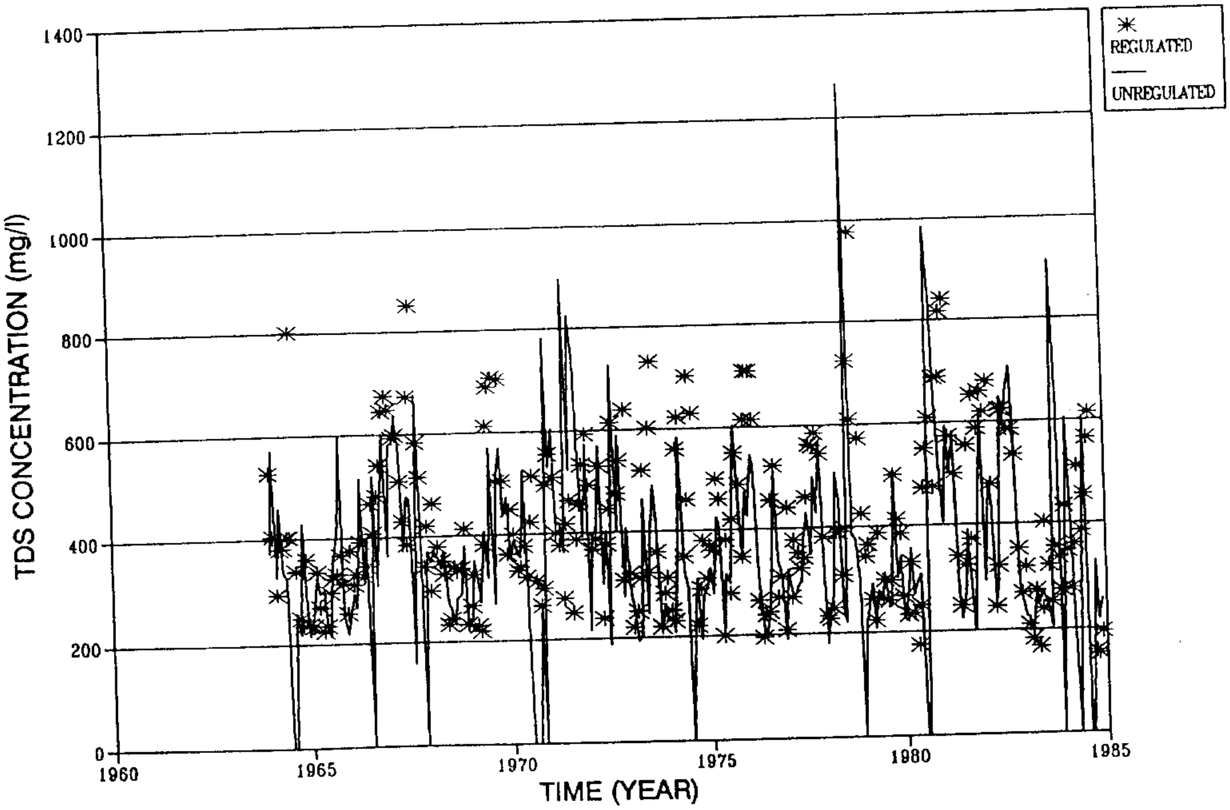

Figure 5.20 Regulated and Unregulated TDS Concentrations at Station 25 (Richmond Gage)

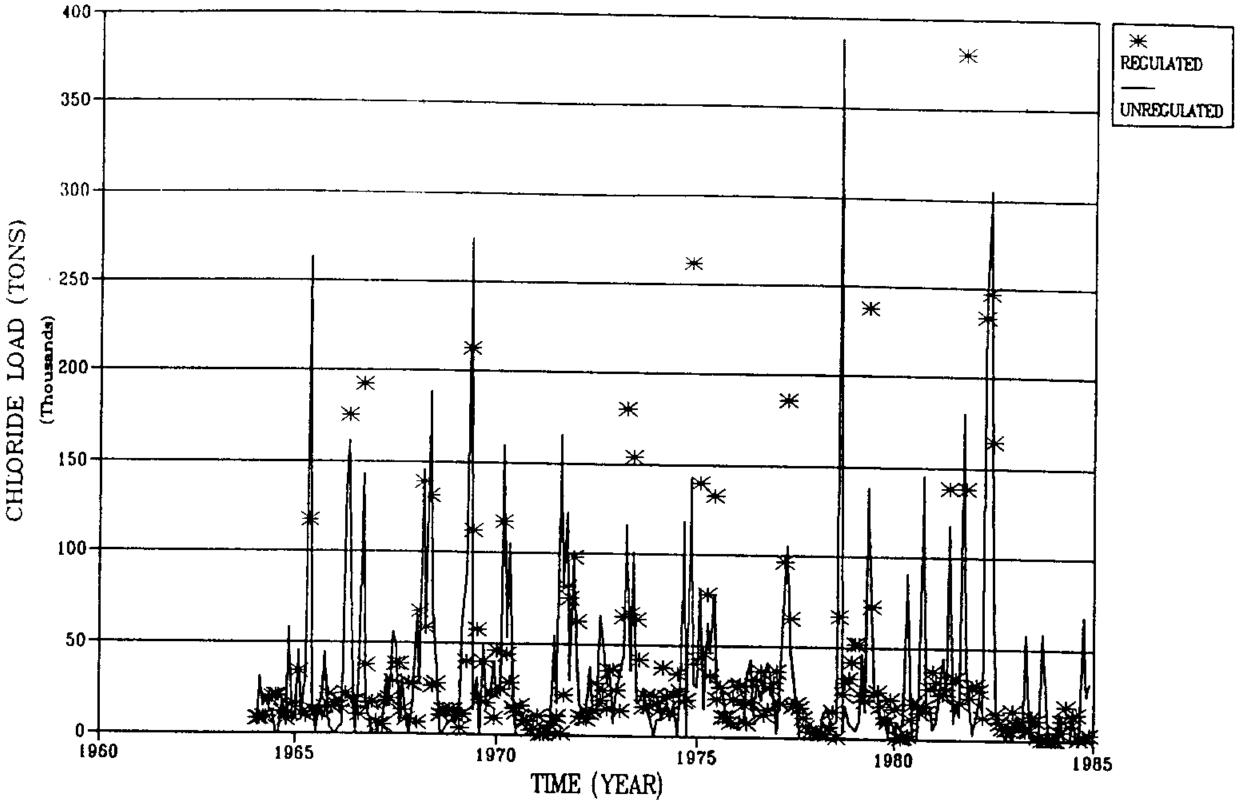

Figure 5.21 Regulated and Unregulated Chloride Loads at Station 15 (Whitney Gage)

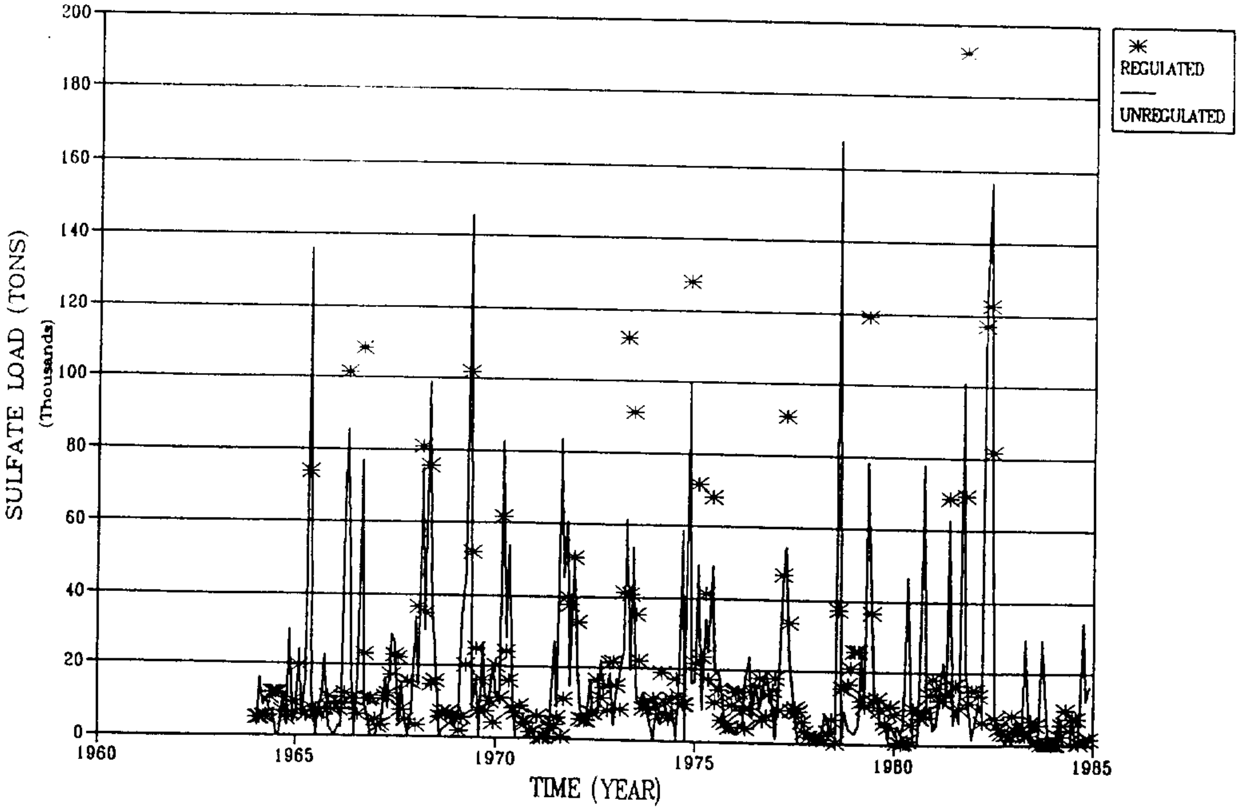

Figure 5.22 Regulated and Unregulated Chloride Concentrations at Station 15 (Whitney Gage)

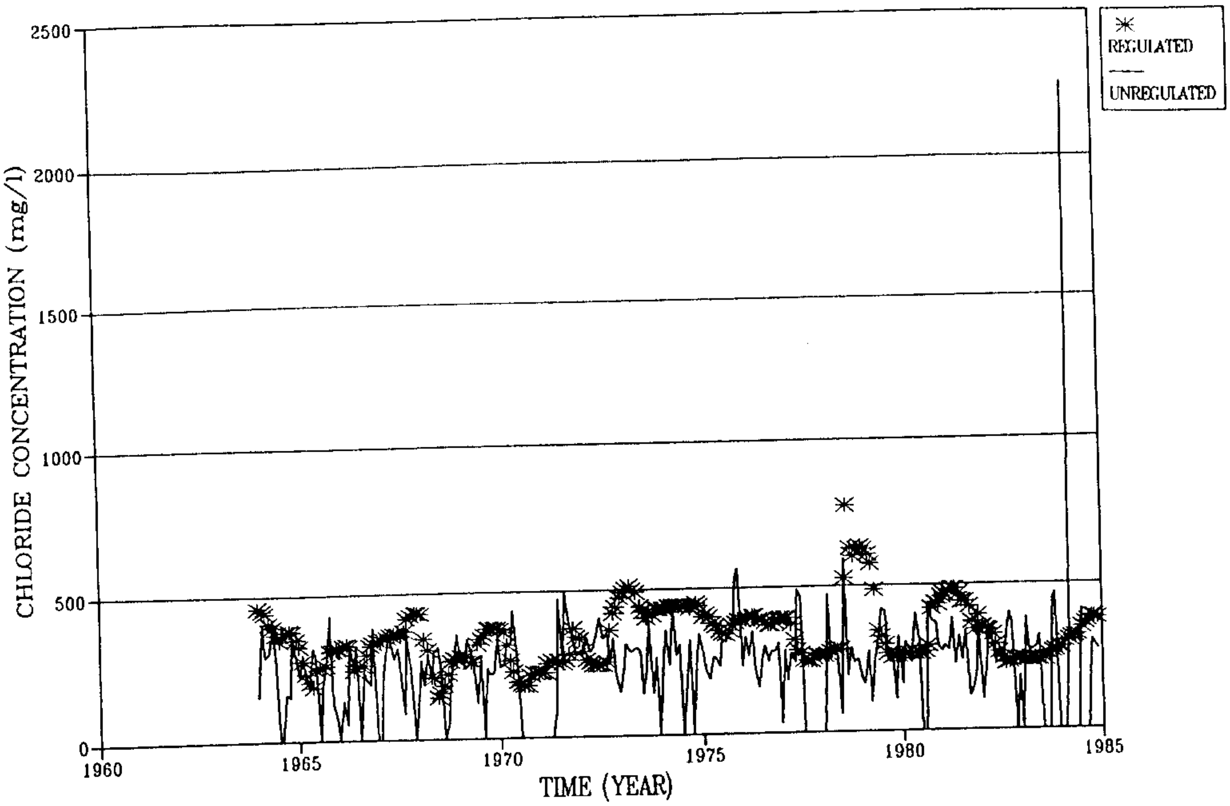

Figure 5.23 Regulated and Unregulated Sulfate Loads at Station 15 (Whitney Gage)

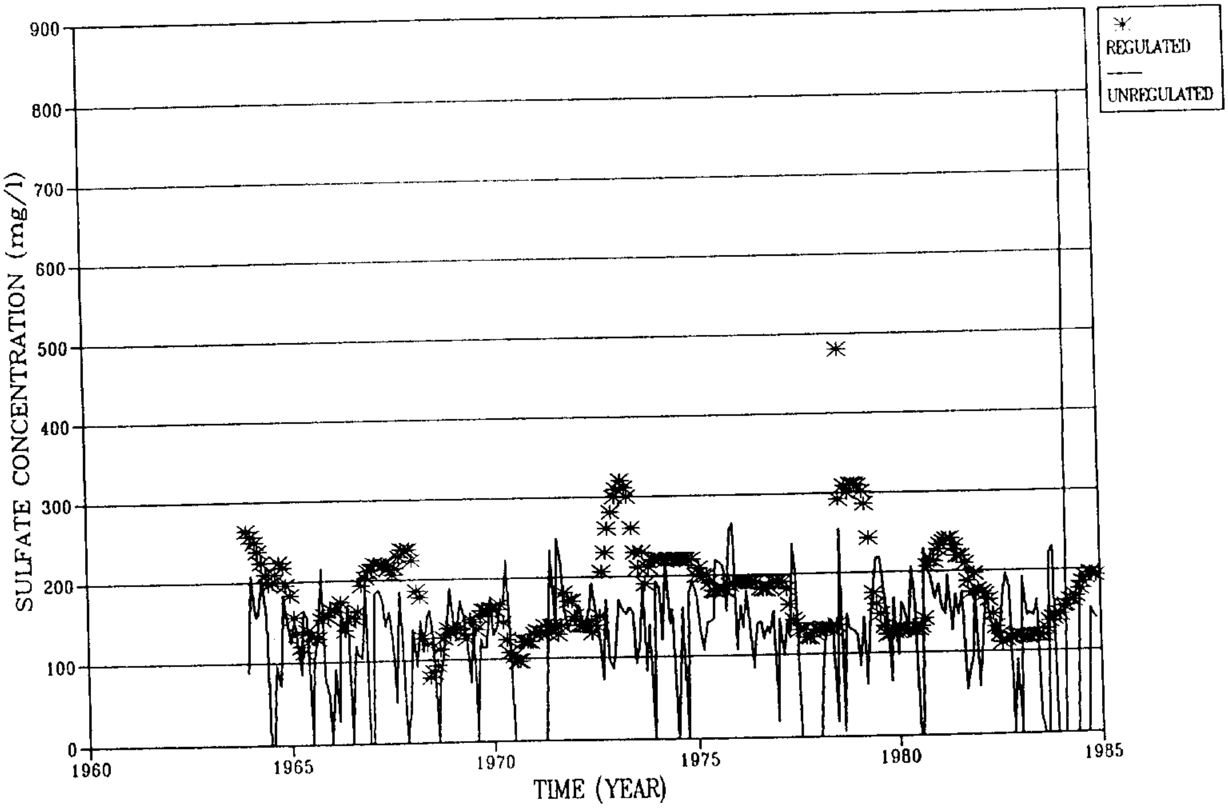

Figure 5.24 Regulated and Unregulated Sulfate Concentrations at Station 15 (Whitney Gage)

Table 5.9
REGRESSION COEFFICIENTS USED TO EXTEND UNREGULATED SALT LOADS

	TDS Load			Chloride Load			Sulfate Load		
Station	a	b	R^2	a	b	R^2	a	b	R^2
10	0.205	1.000	1.000	0.078	1.000	1.000	0.027	1.000	1.000
11	6.23	0.802	0.705	2.94	0.766	0.701	1.157	0.816	0.561
12	74.0	0.681	0.681	54.6	0.626	0.641	10.20	0.717	0.674
13	1.65	1.000	0.981	0.682	1.000	0.980	0.339	1.000	0.979
14	1.41	1.000	0.939	0.573	1.000	0.929	0.281	1.000	0.944
15	1.72	0.951	0.893	0.350	1.000	0.822	0.183	1.000	0.861
18	2.91	0.887	0.867	0.636	0.908	0.738	0.137	1.000	0.859
21	4.33	0.839	0.862	0.531	0.888	0.636	0.527	0.867	0.833
25	3.23	0.848	0.864	0.527	0.867	0.603	0.394	0.869	0.791

Notes:

1. The regression coefficients a and b are for the equation:

   $$\text{salt load} = a * (\text{discharge})^b$$

   where salt load is in tons/month and discharge is in acre-feet/month.

2. R^2 denotes the coefficient of determination. R is the correlation coefficient.

3. The stations are as follows:

10	Hubbard Creek below Hubbard Creek Dam
11	Clear Fork near Eliasville
12	Brazos River near Southbend
13	Brazos River below Possum Kingdom Dam
14	Brazos River near Dennis
15	Brazos River below Whitney Dam
18	Brazos River near Highbank
21	Brazos River near College Station
25	Brazos River near Richmond

Mean Salt Concentrations on Good Quality Tributaries
(Task 3 in Table 5.1)

Constant long-term mean salt concentrations were used in the RESSALT reservoir system simulation model (Chapter 6) for the tributaries which flow into the Brazos River below Whitney Dam. These tributaries have significantly lower salt concentrations than the main stream Brazos River. The concentrations were assumed constant for each month of the 1900-1984 simulation period. Unregulated salt loads were computed by combining the constant mean concentrations with previously developed unregulated flows. Concentrations at stations 19 and 20 on the Little River were adjusted for reservoir evaporation to approximate "unregulated" conditions. At other stations, measured concentrations were used without adjustment.

The period-of-record (1965-1973 & 1980-1986) mean TDS, Cl, and SO_4 concentrations for station 19 on the Little River were adjusted for the evaporation effects of Stillhouse Hollow, Belton, and Proctor Reservoirs. The unregulated mean salt concentrations were approximated as:

measured load / (measured streamflow + evaporation volume)

Thus, the adjustment to "unregulate" the long-term mean concentrations reflects the premise that reservoir evaporation increases concentrations by removing water volume without removing salt load. The "unregulated" mean concentrations for station 20 on the Little River were similarly based on the 1964-84 means adjusted for the evaporation effects of Georgetown, Granger, Stillhouse Hollow, Belton, and Proctor Reservoirs. The regulated and unregulated discharge, load, and concentration means are tabulated in Table 5.10. The unregulated long-term mean concentrations were combined with previously developed unregulated discharges to compute the monthly salt loads required for the RESSALT model.

The measured means shown in Table 3.2 were used without adjustment for the stations on the Navasota River, Aquilla Creek, and Yequa Creek. The measured concentrations on these streams are significantly lower than stations 19 and 20 on the relatively good-quality Little River and much lower than the main stream Brazos River. Also, since Limestone and Aquilla Reservoirs were constructed late in the period-of-record, their evaporation had less impact on the mean salt concentrations.

Combination of Salinity Data with Naturalized Streamflows
(Task 4 in Table 5.1)

The naturalized (unregulated) streamflow data developed by Wurbs et. al (1988) were adopted as the streamflow input for the RESSALT study and are discussed further in Chapter 6. The naturalized monthly flows cover the 1900-1984 simulation period at 23 gaging station locations, of which several are not actually used in the present study. The naturalization adjustments were much more comprehensive, involving numerous reservoirs and diversions, than the adjustments to develop the unregulated flows described above which were limited to removing the effects of four reservoirs. The unregulated salt loads required by RESSALT were developed by combining the previously developed naturalized flows with the: (1) monthly

Table 5.10
MEAN DISCHARGES, LOADS, AND CONCENTRATIONS ON THE LITTLE RIVER

Station	19	20
Period-of-Analysis	65-73 & 80-84	1964-84
<u>Regulated (Measured) Means</u>		
Discharge (ac-ft/month)	50,500	89,900
TDS Load (tons/month)	17,600	31,600
Chloride Load (tons/mouth)	2,310	3,780
Sulfate Load (tons/month)	1,720	3,660
TDS Concentration (tons/ac-ft)	0.349	0.352
Chloride Concentration (tons/ac-ft)	0.0458	0.0420
Sulfate Concentration (tons/ac-ft)	0.0340	0.0408
TDS Concentration (mg/l)	257	259
Chloride Concentration (mg/l)	33.7	30.9
Sulfate Concentration (mg/l)	25.0	30.0
<u>Unregulated Means (Adjusted for Reservoir Evaporation)</u>		
Discharge (ac-ft/month)	101,700	164,800
TDS Load (tons/month)	17,600	31,600
Chloride Load (tons/month)	2,310	3,780
Sulfate Load (tons/month)	1,720	3,660
TDS Concentration (tons/ac-ft)	0.173	0.192
Chloride Concentration (tons/ac-ft)	0.0227	0.0229
Sulfate Concentration (tons/ac-ft)	0.0169	0.0222
TDS Concentration (mg/l)	128	141
Chloride Concentration (mg/l)	16.7	16.9
Sulfate Concentration (mg/l)	12.4	16.3

concentrations computed in Task 1 above; (2) regression equations developed in Task 2; and (3) constant long-term mean concentrations of Task 3.

As discussed further in Chapter 6, the RESSALT model included the 13 reservoirs and four other control points shown in Figure 5.25. The Southbend gage (station 12), also shown in Figure 5.25, is an additional control point included in a number of early RESSALT runs, but was later removed due to problems caused by negative incremental loads and discharges. The 13 reservoirs are each treated as a control point in RESSALT. Stream gaging stations are located relatively short distances downstream of the dams. The other nonreservoir control points in RESSALT are located at stream gaging stations. The USGS water quality sampling program included some but not all of the streamflow gaging station locations adopted in the model. Thus, the locations of the RESSALT control points do not perfectly coincide, in all cases, with the stations for which the data were developed in Tasks 1-3 of Chapter 5. In some cases, salinity data at nearby locations were used for the model control points.

The means, standard deviations, and ranges of the monthly 1900-1984 unregulated discharges and loads included in the RESSALT input file are tabulated in Tables 5.11-5.14. The 1964-1984 means are shown in Table 5.15. These summary statistics are for a basic input data set incorporated in a number of the RESSALT runs. However, a number of other RESSALT runs discussed in Chapters 7 and 8 were based on the two alternative unregulated salt load data sets described in Tasks 5 and 6 below.

Previously Proposed Salt Control Impoundments
(Task 5 in Table 5.1)

The salt control impoundments proposed by the USACE (1973) are discussed in Chapter 4. The locations of the damsites are shown in Figure 4.1. From the perspective of the present study, the salt control impoundment plan is representative of any measure which will contain or remove all salt loads and discharges at stations 3, 4, and 6. The RESSALT simulation study of Chapters 6-8 includes an analysis of the salt control plan. The salt control impoundments are reflected in the RESSALT model by the inputted unregulated streamflows and salt loads. Therefore, in addition to the salt load data set developed in Tasks 1-4 above, an alternative set of otherwise "unregulated" loads and discharges was developed which reflects impoundment and/or removal of all discharges and salt loads at stations 3, 4, and 6. The unregulated salt loads developed in Tasks 1-4 above and the previously developed (Wurbs et al. 1988) naturalized streamflows were adjusted as follows to reflect the impacts of the salt control impoundments on downstream locations on the Brazos River (stations 12, 13, 14, 15, 18, 21, and 25). The adjustment procedure varied between the periods 1964-1984 and 1900-1963.

Missing data during the period 1964-1984 at stations 3, 4, and 6 were synthesized by regression as described in Chapter 4. The 1964-1984 monthly flows and salt loads at stations 3, 4, and 6 were then summed. TDS load, chloride load, sulfate load, and discharge summations (stations 3, 4 & 6 summed) were developed for each of the 252 months of the 1964-84 period. Discharges and loads for 1964-84 at stations 12, 13, 14, 15, 18, 21, and 25 were adjusted by subtracting the corresponding values summed for stations 3, 4, and 6.

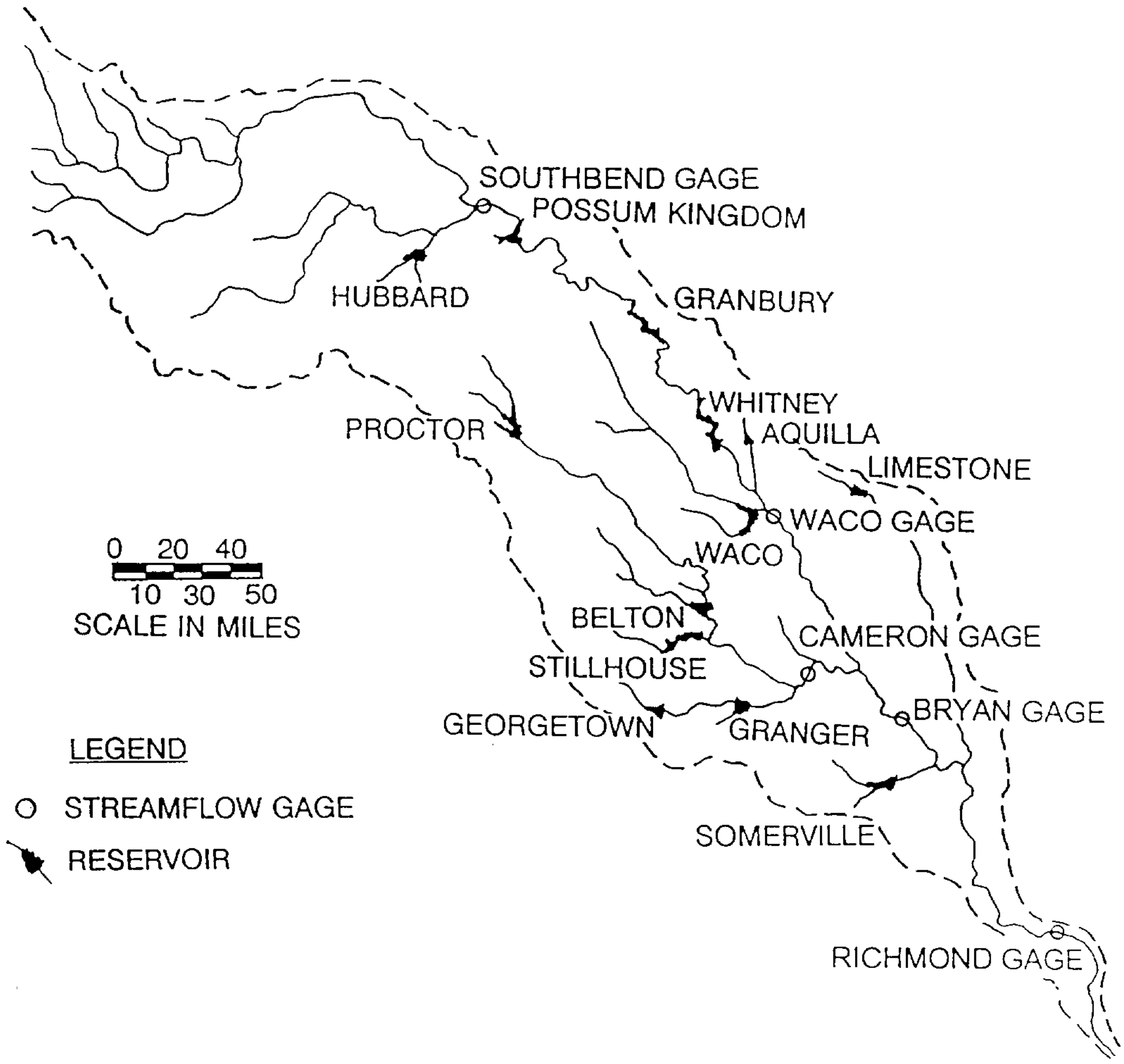

Figure 5.25 Control Points Included in RESSALT Model

Table 5.11
STATISTICS FOR 1900-84 UNREGULATED DISCHARGES

Control Point	Mean Discharge (ac-ft/month)	Standard Deviation (ac-ft/month)	Range	
			Minimum (ac-ft/month)	Maximum (ac-ft/month)
Hubbard Reservoir	9,498	24,235	0	218,243
Brazos River				
Southbend Gage	61,506	122,386	0	1,410,000
Possum Kingdom Res	74,472	143,982	0	1,826,000
Granbury Reservoir	97,050	174,558	0	2,724,000
Whitney Reservoir	138,290	222,842	0	3,363,000
Waco Gage	156,529	245,493	0	3,387,000
Bryan Gage	324,453	473,017	0	4,773,000
Richmond Gage	472,288	641,363	0	7,354,000
Tributaries				
Aquilla Reservoir	7,449	17,326	0	182,916
Waco Reservoir	27,227	51,435	0	588,483
Proctor Reservoir	9,598	24,538	0	355,787
Belton Reservoir	38,976	71,464	0	718,653
Stillhouse Reservoir	18,374	32,193	0	312,711
Georgetown Reservoir	5,403	8,420	0	75,024
Granger Reservoir	14,920	23,658	0	214,404
Cameron Gage	107,225	175,626	0	1,672,000
Somerville Reservoir	19,518	38,218	0	360,985
Limestone Reservoir	26,415	50,173	0	413,723

Table 5.12
STATISTICS FOR 1900-84 UNREGULATED TDS LOADS

Control Point	Mean (tons/month)	Standard Deviation (tons/month)	Range	
			Minimum (tons/month)	Maximum (tons/month)
Hubbard Reservoir	1943	4,959	0	57,545
Brazos River				
Southbend Gage	119,538	161,184	0	1,829,844
Possum Kingdom Res	121,764	236,164	0	3,003,228
Granbury Reservoir	138,239	251,337	0	3,849,350
Whitney Reservoir	131,640	199,964	0	2,758,341
Waco Gage	108,570	146,307	0	1,788,881
Bryan Gage	170,263	208,511	0	1,797,547
Richmond Gage	197,965	223,999	0	2,147,716
Tributaries				
Aquilla Reservoir	2,502	5,819	0	61,431
Waco Reservoir	22,516	36,619	0	379,108
Proctor Reservoir	1,664	4,255	0	61,690
Belton Reservoir	6,758	12,391	0	124,607
Stillhouse Reservoir	3,186	5,582	0	54,221
Georgetown Reservoir	1,037	1,615	0	14,393
Granger Reservoir	2,862	4,539	0	41,131
Cameron Gage	20,570	33,692	0	320,756
Somerville Reservoir	2,598	5,088	0	48,058
Limestone Reservoir	4,705	8,937	0	73,692

Table 5.13
STATISTICS FOR 1900-84 UNREGULATED CHLORIDE LOADS

Control Point	Mean (tons/month)	Standard Deviation (tons/month)	Range	
			Minimum (tons/month)	Maximum (tons/month)
Hubbard Reservoir	739	1,886	0	21,888
Brazos River				
Southbend Gage	48,091	64,391	0	855,855
Possum Kingdom Res	50,498	97,979	0	1,245,641
Granbury Reservoir	55,974	101,959	0	1,560,294
Whitney Reservoir	49,384	79,776	0	1,175,392
Waco Gage	30,934	42,907	0	536,793
Bryan Gage	41,110	55,075	0	516,655
Richmond Gage	43,082	52,511	0	502,621
Tributaries				
Aquilla Reservoir	142	330	0	3,483
Waco Reservoir	6,207	10,390	0	109,640
Proctor Reservoir	218	558	0	8,087
Belton Reservoir	886	1,624	0	16,335
Stillhouse Reservoir	418	732	0	7,108
Georgetown Reservoir	124	193	0	1,720
Granger Reservoir	342	543	0	4,916
Cameron Gage	2,459	4,027	0	38,339
Somerville Reservoir	647	1,267	0	11,963
Limestone Reservoir	790	1,501	0	12,374

Table 5.14
STATISTICS FOR 1900-84 UNREGULATED SULFATE LOADS

Control Point	Mean (tons/month)	Standard Deviation (tons/month)	Range	
			Minimum (tons/month)	Maximum (tons/month)
Hubbard Reservoir	258	659	0	7,652
Brazos River				
Southbend Gage	24,764	38,849	0	324,980
Possum Kingdom Res	25,047	48,679	0	618,209
Granbury Reservoir	27,516	49,924	0	765,869
Whitney Reservoir	25,817	41,498	0	614,807
Waco Gage	21,386	33,541	0	462,752
Bryan Gage	29,860	37,649	0	322,651
Richmond Gage	32,083	37,583	0	362,544
Tributaries				
Aquilla Reservoir	719	1,671	0	17,642
Waco Reservoir	3,720	7,027	0	80,402
Proctor Reservoir	162	414	0	6,006
Belton Reservoir	658	1,206	0	12,131
Stillhouse Reservoir	310	543	0	5,279
Georgetown Reservoir	120	187	0	1,668
Granger Reservoir	332	526	0	4,766
Cameron Gage	2,384	3,904	0	37,169
Somerville Reservoir	448	876	0	8,277
Limestone Reservoir	467	887	0	7,315

Table 5.15
MEANS FOR 1964-84 UNREGULATED DISCHARGES AND SALT LOADS

Control Point	Discharge (ac-ft/month)	1964-84 Mean Load (tons/month) TDS	Chloride	Sulfate
Hubbard Reservoir	13,900	2,844	1,082	378
Brazos River				
Southbend Gage	56,098	159,207	67,483	32,402
Possum Kingdom Res	68,760	110,173	45,671	22,608
Granbury Reservoir	90,522	132,350	53,403	26,379
Whitney Reservoir	128,243	133,678	49,072	25,611
Waco Gage	150,265	105,613	30,020	20,530
Bryan Gage	313,955	181,381	46,921	31,878
Richmond Gage	469,256	211,994	50,454	34,942
Tributaries				
Aquilla Reservoir	7,053	2,369	134	680
Waco Reservoir	23,565	19,909	5,467	3,220
Proctor Reservoir	7,287	1,264	166	123
Belton Reservoir	34,122	5,916	776	576
Stillhouse Reservoir	18,166	3,150	413	307
Georgetown Reservoir	5,527	1,060	127	123
Granger Reservoir	15,552	2,984	357	346
Cameron Gage	101,026	19,381	2,317	2,246
Somerville Reservoir	19,135	2,547	634	439
Limestone Reservoir	27,141	4,834	812	480

Table 5.16
MEANS FOR 1964-84 DISCHARGES AND LOADS AT STATIONS 3, 4, AND 6

Station	Discharge (ac-ft/month)	Load (tons/month) TDS	Chloride	Sulfate
3	794	7,496	3,132	1,766
4	330	22,520	14,158	1,099
6	1,123	7,029	2,665	1,932
total	2,247	37,045	19,955	4,797

Table 5.17
DISCHARGE AND LOAD MULTIPLIERS REPRESENTING THE EFFECTS OF THE SALT CONTROL IMPOUNDMENTS

Control Point	Station Number	Discharge Multiplier	Load Multipliers TDS	Chloride	Sulfate
salt dams	3,4,6	0.000	0.000	0.000	0.000
Southbend gage	12	0.960	0.767	0.704	0.852
Possum Kingdom	13	0.967	0.664	0.563	0.788
Granbury Res	14	0.975	0.720	0.624	0.818
Whitney Res	15	0.982	0.723	0.593	0.813
Waco Gage	18	0.985	0.649	0.335	0.766
Bryan Gage	21	0.993	0.796	0.575	0.850
Richmond Gage	25	0.995	0.825	0.604	0.863

Table 5.18
MEAN UNREGULATED TDS CONCENTRATIONS WITH AND WITHOUT THE SALT CONTROL IMPOUNDMENTS

Control Point	Station Number	Concentration (mg/l) Without Dams 1900-84	Without Dams 1964-84	With Dams 1900-84	With Dams 1964-84
Southbend Gage	12	1,429	2,087	1,149	1,695
Possum Kingdom	13	1,203	1,178	838	832
Granbury Res	14	1,048	1,075	778	812
Whitney Res	15	700	767	518	577
Waco Gage	18	510	517	339	352
Bryan Gage	21	386	425	311	346
Richmond Gage	25	308	332	257	279

Table 5.19
MEAN UNREGULATED CHLORIDE CONCENTRATIONS WITH AND WITHOUT THE SALT CONTROL IMPOUNDMENTS

Control Point	Station Number	Concentration (mg/l) Without Dams 1900-84	Without Dams 1964-84	With Dams 1900-84	With Dams 1964-84
Southbend Gage	12	575	885	427	673
Possum Kingdom	13	499	489	295	305
Granbury Res	14	424	431	275	294
Whitney Res	15	263	281	161	181
Waco Gage	18	145	147	52	59
Bryan Gage	21	93	110	55	68
Richmond Gage	25	67	79	41	51

Table 5.20
MEAN UNREGULATED SULFATE CONCENTRATIONS WITH AND WITHOUT THE SALT CONTROL IMPOUNDMENTS

Control Point	Station Number	Concentration (mg/l) Without Dams 1900-84	Without Dams 1964-84	With Dams 1900-84	With Dams 1964-84
Southbend Gage	12	296	425	264	381
Possum Kingdom	13	247	241	202	200
Granbury Res	14	209	214	176	186
Whitney Res	15	137	147	114	123
Waco Gage	18	100	100	79	80
Bryan Gage	21	68	75	58	65
Richmond Gage	25	50	55	43	48

The discharges and salt loads for 1900-63 were adjusted based on ratios of 1964-84 means. The 1964-84 means for TDS, chloride, and sulfate loads and flows at the pertinent main stream Brazos River locations are included in Table 5.15. The 1964-1984 mean discharges, loads, and concentrations for stations 3, 4, and 6 are presented in Table 5.16. Discharges and loads, reflecting the upstream salt impoundments, were developed by multiplying the unregulated flows and loads of the basic (without salt dams) data set by factors determined as follows:

$$\text{multiplier} = 1 - (M_{3+4+6} / M_i)$$

where M_{3+4+6} denotes the sum of the 1964-84 mean loads or discharges at stations 3, 4, and 6, and M_i denotes the 1964-84 mean at the downstream station. The multipliers are tabulated in Table 5.17.

The mean discharges and loads with and without the salt control impoundments are compared in Tables 5.18-5.20. Reiterating, the "with salt dams" data set represents impoundment or removal of all loads and discharges at stations 3, 4, and 6. The flows and salt loads at stations 3, 4, and 6 are assumed to be removed at all downstream stations on the mainstream Brazos River. "Unregulated" in this case means unregulated except for regulation by the salt control dams.

Addition of a Random Component to the Salt Loads
(Task 6 in Table 5.1)

Real-world salt concentrations vary greatly over time, and the variance is dependent upon other complex factors in addition to discharge. The unregulated salt load data sets described above represent the expected values of the salt loads for the given streamflow discharges. Although the data incorporate the variations of loads and concentrations as a function of discharge, other aspects of variance are not reflected in the computations of Tasks 1-4. The 1900-1963 loads computed with the regression equations of Table 5.9 are fixed by the discharge. The several linear ($b=1$) equations in Table 5.9 reflect the premise of a constant concentration. Likewise, the estimation of loads for the better quality tributaries is based on assuming a constant concentration equal to the mean. The assumption of a constant concentration is also incorporated in the computations to remove the impacts of reservoirs. Therefore, an alternative set of unregulated salt loads was developed with a random component added to better reflect the natural variance of loads and concentrations independently of discharge.

The sole objective in developing the data set outlined in this section is to more realistically reflect the real-world random or unexplained variations in salt concentrations. This represents an advantage over the basic data set developed in Tasks 1-4 above. However, three disadvantages of the Task 6 data, as compared to the Tasks 1-4 basic data, are as follows. Firstly, unlike the Tasks 1-4 loads, the Task 6 computed loads in a given month are not the most likely or expected value of the loads associated with the given discharges for the month. Secondly, random numbers are arbitrary. The computed sequences of unregulated loads would be different if the computations described below were to be repeated with another set of random numbers generated from the same standard normal probability distribution. Thirdly, the random component allows the loads to be negative in many months, which has no physical meaning.

Computational Procedure

The computations involved in developing this alternative unregulated salt load data set are based on the following equation:

$$L = E(L|Q) + k\ S\ (1-R^2)^{0.5}$$

where: L = monthly salt load (tons/month)
Q = monthly discharge (acre-feet/month)
$E(L|Q)$ = expected value of load for a given discharge (tons/month)
$k\ S\ (1-R^2)^{0.5}$ = unexplained variance or random deviation of load from expected value (tons/month)
$S\ (1-R^2)^{0.5}$ = standard error statistic for the load estimate (tons/month)
S = salt load standard deviation (tons/month)
R = correlation coefficient for load (L) versus discharge (Q)
R^2 = coefficient of determination for L versus Q
k = random deviate from a normal probability distribution with mean of zero and variance of one

The loads computed in Tasks 1-4 represent expected values, $E(L|Q)$. With known naturalized discharges, the computational procedures of Tasks 1-4 provide the most likely loads to be expected during each month of the period 1900-1984 at the specified locations. The long-term means of the computed loads and concentrations are realistic, but the variance of the loads and corresponding concentrations are specified solely by the discharges.

The random component of the above equation consists of a normally distributed random number (k) multiplied by the standard error statistic $S(1-R^2)^{0.5}$. The statistic $S(1-R^2)^{0.5}$ is a measure of the variance of the load for a given discharge. Adding this random component to the expected values of the unregulated loads allows the variance as well as mean to be approximately preserved. The 1900-1984 means are not changed by adding the random deviations to the expected values of the monthly loads.

A sequence of 1,020 random numbers (k) was generated covering each month of the period 1900-1984. The same random numbers were used for TDS, chlorides, and sulfates. The random number generation was based on a normal probability distribution with mean and variance of zero and one, respectively. The random number generation algorithm included a simple feature to assure that the 1,020 random numbers (k) summed to zero so that the 1900-84 means of the original data set (Tables 5.11-5.14) would not be changed. After generating an initial 1,020 numbers, additional single random numbers continued to be generated to replace previous numbers until the last 1,020 numbers summed to zero.

The random components of the loads at the Richmond gage (station 25) were computed by multiplying the random numbers (k) by the standard error $(S(1-R^2)^{0.5})$, which is a constant for each salt constituent:

$$\text{random deviation} = k\ S\ (1-R^2)^{0.5}$$

with the 1964-1984 measured loads and discharges being used to estimate the standard deviation (S) of the loads and the coefficient of determination (R^2) for the loads and discharges. The statistics for 1964-84 measured data at the Richmond gage are presented in Table 5.21.

Table 5.21
STATISTICS FOR 1964-84 MEASURED LOADS
AT THE RICHMOND GAGE (STATION 25)

Statistic	TDS	Chloride	Sulfate
mean (tons/month)	192,122	44,884	31,567
standard deviation (tons/month)	196,199	46,715	32,072
coefficient of determination (R^2)	0.835	0.650	0.799
standard error (tons/month)	79,744	27,706	14,422
minimum (tons/month)	24,350	4,930	4,000
maximum (tons/month)	996,000	246,500	163,000

The computations outlined above were applied only at the Richmond gage (station 25). The random components of the loads for all the other stations included in the RESSALT model were developed by simple ratios of 1900-1984 means as follows:

$$\text{random deviation at station } i = (M_i \,/\, M_{25})\,(\text{random deviation at station } 25)$$

where M_i denotes the 1900-84 mean load at station i and M_{25} denotes the 1900-84 mean load at station 25 (Richmond gage), which are tabulated in Tables 5.12-5.14. Thus, the correlation between loads and discharges at the Richmond gage are assumed to be representative of the other locations as well. This approach preserves the correlations between stations. The 1900-84 means, standard deviations, and ranges for the random deviations are presented in Tables 22-24.

The random deviations were added to the loads computed in Tasks 1-4 to develop the alternative set of loads. The monthly TDS, chloride, and sulfate loads cover the period 1900-1984 at all stations included in the RESSALT model.

Resulting Unregulated Salt Loads and Concentrations

The Task 6 alternative set of loads has the same 1900-84 means as the original set developed in Tasks 1-4, but the loads in each individual month vary partially randomly and partially as a function of discharge. The 1900-84 means, standard deviations, and ranges for the unregulated loads are presented in Tables 5.25-5.27. The tables also show the percentage of the 1,020 months during which the load is negative. The expected value (Tasks 1-4) component of the load is always positive. The random deviations are both positive and negative. The load computed by adding the random deviation to the expected value is usual positive but often negative. Load values of less than zero have no physical meaning and represent a disadvantage of this alternative data set.

The same monthly discharge data set is used with both of the alternative salt load data sets. In the individual months of the 1900-84 analysis period, the salt loads vary drastically between the two alternative data sets. However, the 1900-84 summary statistics are quite similar. The major difference between the statistics of Tables 5.12-5.14 and 5.25-5.27 are related to the negative loads in the Tables 5.25-5.27 data set. A comparison of Tables 5.25-5.27 with Tables 5.12-5.14 indicates that the means are the same for the two alternative load data sets, but the standard deviations are a little higher with the random component included in the loads. For example, at the Richmond gage, the standard deviation of 235,908 tons/month for the TDS loads including the random component (Table 5.25) is 6.0% higher than the corresponding standard deviation for the expected value loads (Table 5.12). However, as discussed below the variance of the loads significantly affects the concentrations.

Variations in salt concentrations with the two alternative data sets are compared in Tables 5.28-5.29 and Figures 5.26-5.29. The concentration-duration curves tabulated in Tables 5.28-5.29 and plotted in Figures 5.26-5.29 show the percentage of the 1,020 months (1900-84) for which the salt concentration equalled or exceeded the indicated value, at the Whitney and Richmond gages. The variations between the two alternative data sets are shown to be quite large. For example, with the expected value (Task 4) salt loads, at the Richmond Gage (Table 5.28), TDS concentrations equal or exceed 245 mg/l and 527 mg/l during 95% and 5%, respectively, of the 1,020 months. However, with a random component added to the loads (Task 6 data set), TDS concentration values of -432 mg/l and 1,505 mg/l are equalled or exceeded 95% and 5% of the time. The 10% exceedence probability TDS concentration is 482 mg/l and 925 mg/l, respectively, with the two alternative data sets. With either data set, the mean concentration at the Richmond gage is 308 mg/l.

Concentration-duration relationships for the 1964-1986 measured data are tabulated in Tables 3.4-3.6 and plotted in Figures 3.28-3.30. Unregulated concentrations would be expected to exhibit a greater variation than actual concentrations because the three main stream reservoirs dampen or even out the fluctuations in concentrations. Chapters 3 and 4 point out that the variations of concentrations with time are much more drastic at locations between the primary salt source area and Possum Kingdom Reservoir than at locations below the reservoirs. The two alternative sets of 1900-84 unregulated concentrations reflected in Tables 5.28-5.29 can be compared to the 1964-84 measured data reflected in Tables 3.4-3.6. The expected value (Task 4) unregulated concentrations exhibit significantly less variation than the measured data. The expected value plus random component (Task 6) unregulated concentrations show significantly greater variation. For example the following TDS concentration values for the Richmond gage are taken from Tables 3.4 and 3.29.

exceedence frequency	90%	50%	10%
Task 4 1900-84 unregulated (mg/l)	270	354	482
1964-84 measured (mg/l)	235	382	635
Task 6 1900-84 unregulated (mg/l)	-57	314	925

Table 5.22
STATISTICS FOR RANDOM DEVIATIONS FROM EXPECTED VALUES OF 1900-84 TDS LOADS

Control Point	Mean (tons/month)	Standard Deviation (tons/month)	Range Minimum (tons/month)	Range Maximum (tons/month)	Negative Values (%)
Hubbard	-0.028	791	-2,250	2,400	51
Brazos River					
Southbend	-1.966	48,649	-139,000	147,000	51
Possum Kingdom	1.483	49,565	-141,000	150,000	51
Granbury	0.508	56,262	-160,000	171,000	51
Whitney	1.908	53,573	-153,000	162,000	51
Waco Gage	-0.781	44,186	-126,000	134,000	51
Bryan Gage	-0.869	69,296	-197,000	210,000	51
Richmond	-2.973	80,581	-230,000	244,000	51
Tributaries					
Aquilla	-0.095	1,019	-2,900	3,090	51
Waco	-0.292	9,165	-26,100	27,800	51
Proctor	-0.009	678	-1,930	2,050	51
Belton	0.012	2,751	-7,840	8,340	51
Stillhouse	0.039	1,297	-3,690	3,930	51
Georgetown	0.002	422	-1,200	1,280	51
Granger	-0.023	1,165	-3,320	3,530	51
Cameron	0.075	8,373	-23,800	25,400	51
Somerville	-0.082	1,058	-3,010	3,210	51
Limestone	0.078	1,915	-5,450	5,800	51

Table 5.23
STATISTICS FOR RANDOM DEVIATIONS FROM EXPECTED VALUES OF 1900-84 CHLORIDE LOADS

Control Point	Mean (tons/month)	Standard Deviation (tons/month)	Range Minimum (tons/month)	Range Maximum (tons/month)	Negative Values (%)
Hubbard	0.009	480	-1,370	1,460	51
Brazos River					
Southbend	0.751	31,249	-89,000	94,700	51
Possum Kingdom	-0.112	32,814	-93,500	99,500	51
Granbury	0.471	36,374	-104,000	110,000	51
Whitney	0.767	32,092	-91,400	97,300	51
Waco Gage	-1.657	20,102	-57,300	60,900	51
Bryan Gage	0.358	26,715	-76,100	81,000	51
Richmond	-0.061	27,996	-79,700	84,800	51
Tributaries					
Aquilla	0.001	92	-263	279	51
Waco	0.059	4,033	-11,500	12,200	51
Proctor	0.001	142	-404	430	51
Belton	-0.036	576	-1,640	1,740	51
Stillhouse	0.008	271	-773	823	51
Georgetown	-0.009	81	-229	244	51
Granger	0.004	222	-633	674	51
Cameron	0.014	1,598	-4,550	4,840	51
Somerville	-0.020	420	-1,200	1,270	51
Limestone	-0.022	513	-1,460	1,560	51

Table 5.24
STATISTICS FOR RANDOM DEVIATIONS FROM EXPECTED VALUES OF 1900-84 SULFATE LOADS

Control Point	Mean (tons/month)	Standard Deviation (tons/month)	Range		Negative Values (%)
			Minimum (tons/month)	Maximum (tons/month)	
Hubbard	0.001	117	-334	356	51
Brazos River					
Southbend	-0.566	11,247	-32,000	34,100	51
Possum Kingdom	-0.169	11,377	-32,400	34,500	51
Granbury	0.594	12,498	-35,600	37,900	51
Whitney	0.590	11,726	-33,400	35,500	51
Waco Gage	-0.024	9,712	-27,700	29,400	51
Bryan Gage	0.466	13,563	-38,600	41,100	51
Richmond	0.240	14,574	-41,500	44,200	51
Tributaries					
Aquilla	-0.001	326	-930	989	51
Waco	-0.068	1,690	-4,810	5,120	51
Proctor	-0.001	74	-210	223	51
Belton	0.007	299	-851	906	51
Stillhouse	-0.006	141	-401	427	51
Georgetown	0.002	55	-155	165	51
Granger	-0.012	151	-429	457	51
Cameron	0.004	1,082	-3,080	3,280	51
Somerville	0.006	203	-579	616	51
Limestone	-0.007	212	-604	643	51

Table 5.25
STATISTICS FOR 1900-84 UNREGULATED TDS LOADS WITH RANDOM COMPONENT

Control Point	Mean (tons/month)	Standard Deviation (tons/month)	Range		Negative Values %
			Minimum (tons/month)	Maximum (tons/month)	
Hubbard	1,943	5,031	-2,248	58,911	29
Brazos River					
Southbend	119,598	165,915	-111,652	1,806,079	16
Possum Kingdom	121,764	240,225	-124,232	2,948,245	23
Granbury	138,239	256,535	-139,666	3,786,928	21
Whitney	131,640	206,566	-124,249	2,698,899	18
Waco Gage	108,570	152,162	-103,293	1,739,856	16
Bryan Gage	170,263	218,540	-160,772	1,847,784	14
Richmond	197,964	235,908	-188,256	2,066,548	12
Tributaries					
Aquilla	2,502	5,837	-2,612	60,307	27
Waco	22,515	37,630	-21,427	396,761	19
Proctor	1,664	4,286	-1,904	61,007	26
Belton	6,758	12,688	-7,004	123,642	21
Stillhouse	3,186	5,740	-3,050	55,161	20
Georgetown	1,036	1,652	-1,021	14,028	20
Granger	2,862	4,641	-2,852	40,124	20
Cameron	20,570	34,742	-20,781	325,605	19
Somerville	2,598	5,205	-2,860	48,456	27
Limestone	4,704	9,064	-4,993	71,762	26

Table 5.26
STATISTICS FOR 1900-84 UNREGULATED CHLORIDE LOADS WITH RANDOM COMPONENT

Control Point	Mean (tons/month)	Standard Deviation (tons/month)	Range		Negative Values (%)
			Minimum (tons/month)	Maximum (tons/month)	
Hubbard	739	1,952	-1,365	22,718	32
Brazos River					
Southbend	48,091	69,885	-73,720	840,591	20
Possum Kingdom	50,498	102,636	-82,908	1,209,237	27
Granbury	55,974	107,615	-91,340	1,519,942	25
Whitney	49,383	85,779	-77,985	1,139,791	24
Waco Gage	30,934	47,099	-48,852	514,492	22
Bryan Gage	41,110	60,892	-65,144	562,821	21
Richmond	43,082	59,040	-68,176	551,001	20
Tributaries					
Aquilla	142	336	-236	3,384	30
Waco	6,207	11,098	-9,886	117,409	24
Proctor	218	571	-399	7,944	29
Belton	886	1,722	-1,470	16,133	26
Stillhouse	417	782	-660	7,304	26
Georgetown	124	206	-199	1,650	24
Granger	342	578	-554	4,724	25
Cameron	2,458	4,337	-4,015	40,727	24
Somerville	647	1,338	-1,158	12,121	30
Limestone	790	1,384	-1,384	11,856	31

Table 5.27
STATISTICS FOR 1900-84 UNREGULATED SULFATE LOADS WITH RANDOM COMPONENT

Control Point	Mean (tons/month)	Standard Deviation (tons/month)	Range		Negative Values (%)
			Minimum (tons/month)	Maximum (tons/month)	
Hubbard	258	671	-333	7,854	30
Brazos River					
Southbend	24,764	35,183	-26,461	319,486	18
Possum Kingdom	25,047	49,750	-28,580	605,587	23
Granbury	27,515	51,234	-31,123	752,004	22
Whitney	25,817	43,021	-27,839	601,798	20
Waco Gage	21,386	34,788	-32,075	314,555	16
Bryan Gage	29,859	39,788	-32,075	314,555	16
Richmond	32,082	39,954	-34,608	347,864	13
Tributaries					
Aquilla	718	1,680	-837	17,281	28
Waco	3,720	7,210	-4,131	83,656	23
Proctor	162	418	-207	5,931	27
Belton	658	1,242	-761	12,026	22
Stillhouse	310	562	-334	5,381	22
Georgetown	120	193	-132	1,620	21
Granger	331	541	-370	4,635	21
Cameron	2,383	4,055	-2,696	38,071	20
Somerville	447	901	-552	8,353	27
Limestone	467	904	-557	7,101	27

Table 5.28
CONCENTRATION-DURATION CURVES AT WHITNEY GAGE (STATION 15) FOR ALTERNATIVE DATA SETS

Percent Time: Concentration Equalled or Exceeded	TDS (mg/l)		Chloride (mg/l)		Sulfate (mg/l)	
	Without Random Component	With Random Component	Without Random Component	With Random Component	Without Random Component	With Random Component
1	1,127	16,977	460	9,313	225	3,444
2	1,054	9,098	404	5,218	207	1,947
5	897	4,558	336	2,487	174	965
10	844	2,441	281	1,261	146	501
25	787	1,151	257	504	135	228
50	733	692	257	255	134	135
75	697	329	257	20	134	45
90	661	-860	257	-727	134	-219
95	619	-2,750	218	-1,966	115	-653
100	0	-144,700	0	-86,960	0	-31,740

Table 5.29
CONCENTRATION-DURATION CURVES AT RICHMOND GAGE (STATION 25) FOR ALTERNATIVE DATA SETS

Percent Time: Concentration Equalled or Exceeded	TDS (mg/l)		Chloride (mg/l)		Sulfate (mg/l)	
	Without Random Component	With Random Component	Without Random Component	With Random Component	Without Random Component	With Random Component
1	701	3,455	215	1,155	119	619
2	603	2,557	189	824	106	449
5	527	1,505	135	463	85	262
10	482	925	100	276	74	161
25	416	526	86	135	65	87
50	354	314	74	65	56	50
75	306	201	64	22	49	28
90	270	-57	56	-68	44	-18
95	245	-432	44	-205	38	-88
100	0	-6,563	0	-2,360	0	-1,203

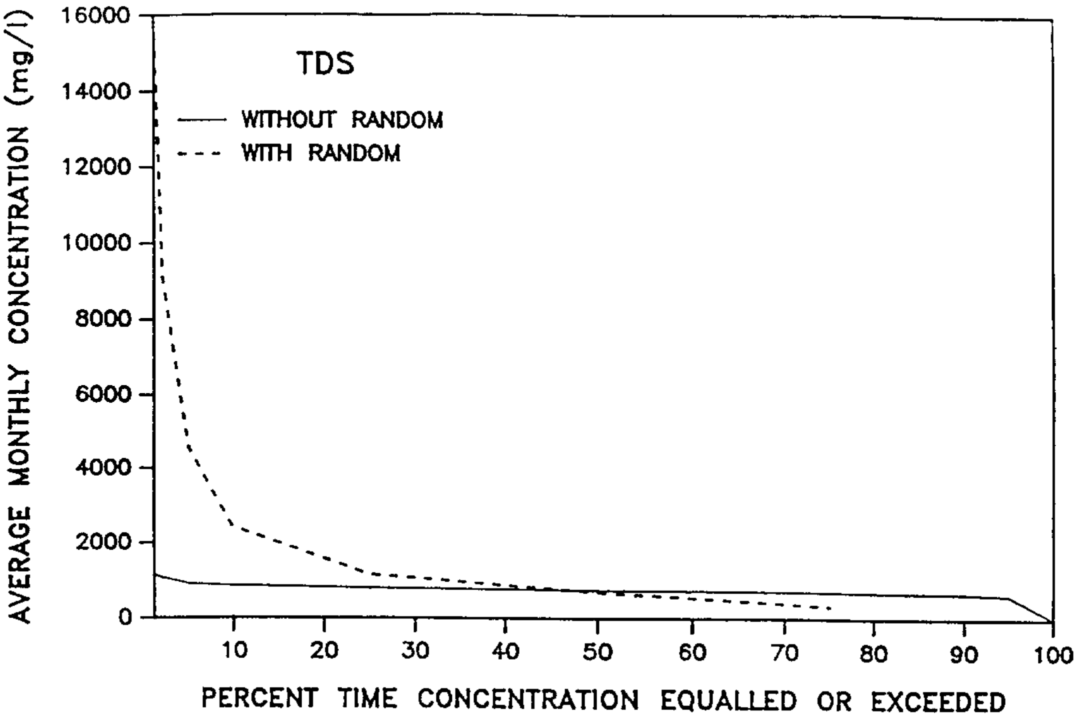

Figure 5.26 TDS Concentration-Duration Curves at Whitney Gage (Station 15) for Alternative Data Sets

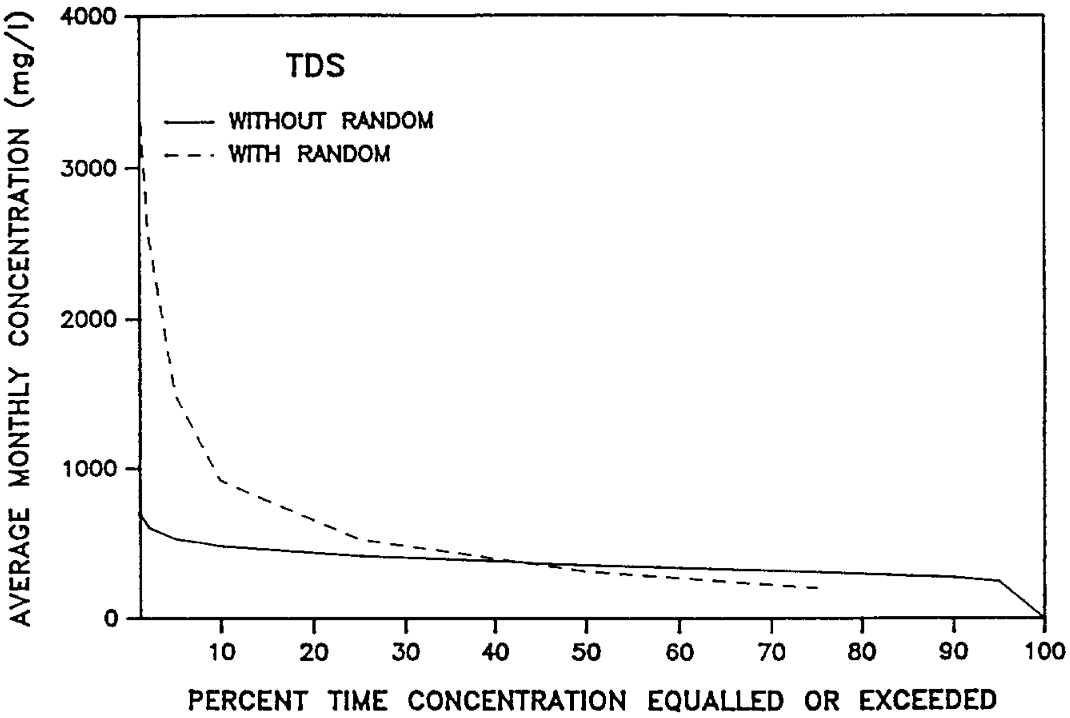

Figure 5.27 TDS Concentration-Duration Curves at Richmond Gage (Station 25) for Alternative Data Sets

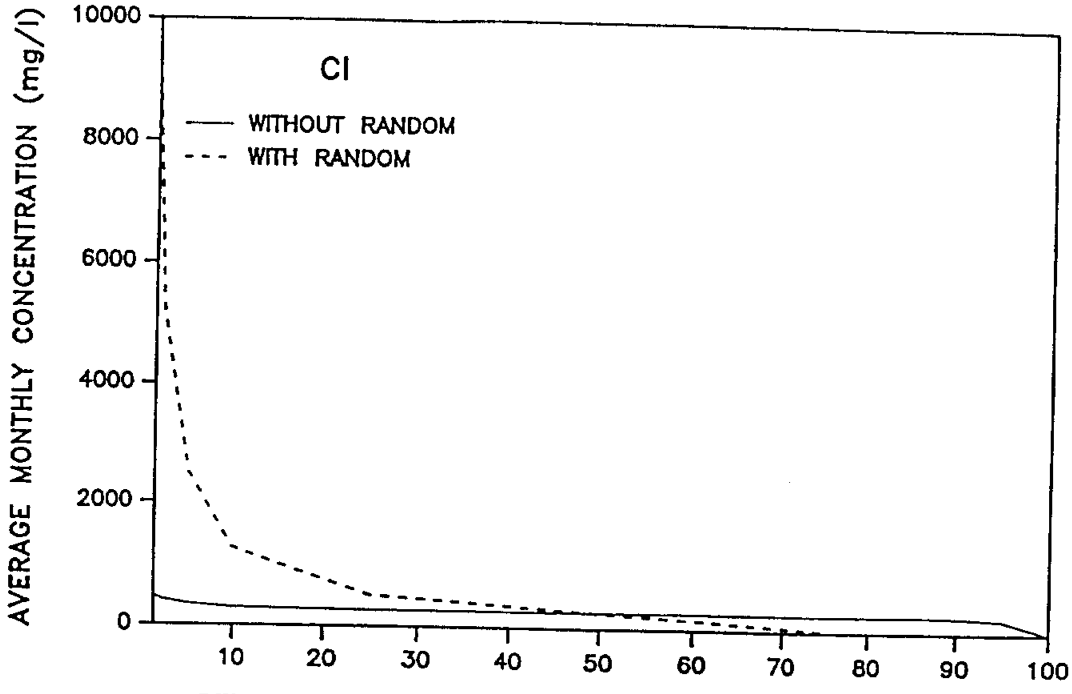

Figure 5.28 Chloride Concentration-Duration Curves at Whitney Gage (Station 15) for Alternative Data Sets

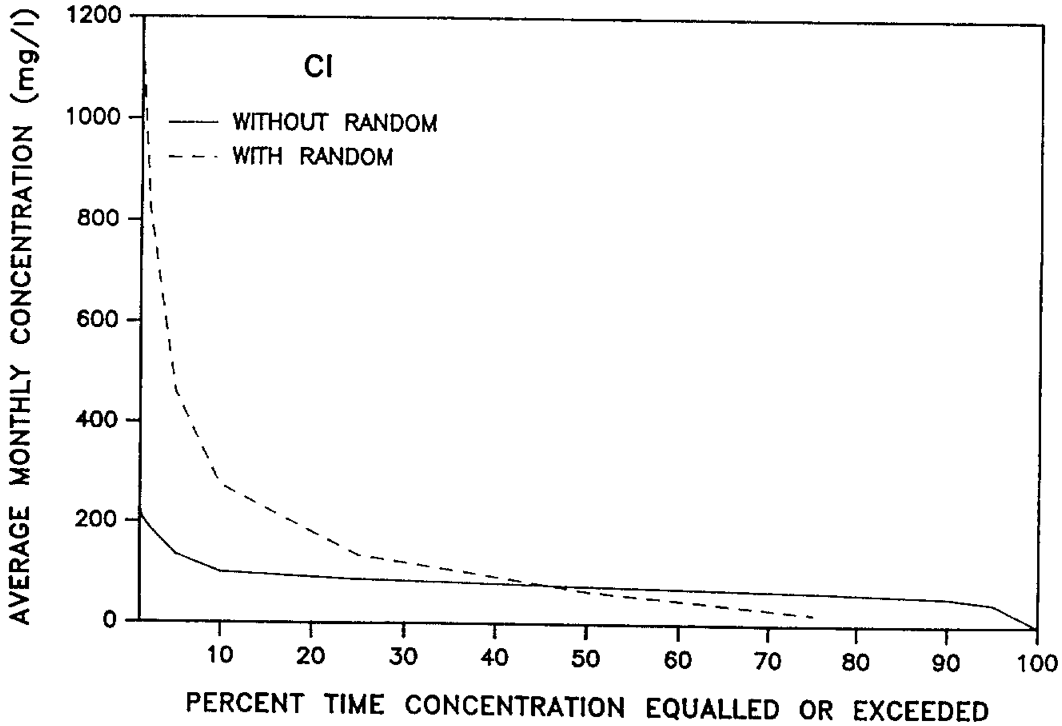

Figure 5.29 Chloride Concentration-Duration Curves at Richmond Gage (Station 25) for Alternative Data Sets

CHAPTER 6
RESERVOIR SYSTEM SIMULATION STUDIES

Chapters 6, 7, and 8 document reservoir system reliability analyses performed using the RESSALT model. The present chapter provides an overview of the simulation study. The results are presented in Chapters 7 and 8. The study is further addressed by Karama (1993).

Scope of Simulation Analyses

The objectives of the simulation study are:

- to quantify the water supply capability of the river/reservoir system,
- to analyze the sensitivity of system reliability to specified allowable salt concentrations,
- to evaluate the effectiveness of alternative reservoir operating policies in improving system reliability,
- to evaluate the effectiveness of salt control impoundments in improving system reliability, and
- to develop expanded generalized modeling and analysis capabilities which can be used in ongoing studies of the Brazos River Basin and other basins as well.

A river basin system consisting of 13 reservoirs and 4 other control points was simulated, using a monthly computational time interval, based on 1900-1984 or 1964-1984 historical sequences of streamflows and salt loads adjusted to represent unregulated conditions. The reservoir system was operated for alternative sets of water use demands and system operating rules during an assumed repetition of historical hydrology. Two alternative approaches were adopted for specifying a set of water use demands. The studies presented in Chapter 7 are based on actual water use in 1984 and projected water use for year 2010. The analyses of Chapter 8 are based on hypothetical yields. Since streamflows, salt loads, and other variables are highly stochastic, water availability is quantified from a reliability perspective.

RESSALT Model

RESSALT (REServoir-SALT), developed and documented by Karama (1993), is a generalized reservoir/river system simulation model which incorporates salinity considerations. The model is generalized for application to a broad range of reservoir system simulation problems in essentially any river basin, but, to date, has been applied only in the Brazos River Basin study reported here. The computer program is coded in FORTRAN77. Model development and the Brazos River Basin simulation study were accomplished using a VAX minicomputer with the VMS operating system.

RESSALT is basically a month-by-month water volume and salt load accounting procedure. Diversion and instream flow requirements are met as long as sufficient streamflow and/or reservoir storage is available and user-specified maximum allowable salt concentrations are not exceeded. Otherwise, shortages are declared. Likewise, hydroelectric energy demands are either met or shortages declared depending upon water availability.

RESSALT is patterned after and is somewhat similar to the generalized computer program "HEC-3 Reservoir System Analysis for Conservation" developed by the USACE Hydrologic Engineering Center (1981). RESSALT does not have all of the optional capabilities of HEC-3 but, unlike HEC-3, does include capabilities for considering salt concentrations. RESSALT can be optionally run with or without the salt features. The input format is patterned after HEC-3 such that the same input data file can be run with either HEC-3 or RESSALT with only minor modifications. The quantity features of RESSALT were tested by running the same input files with HEC-3.

Input and Output Data

In using RESSALT to simulate a system, the locational configuration of reservoirs, diversions, and instream flow requirements are represented as a set of control points. A specified water use scenario and reservoir operating policy is simulated for sequences of monthly streamflows and salt loads inputted for each control point. Input data include:

- mean monthly unregulated streamflows and salt loads, for each salt constituent of interest, for each month of the period-of-analysis for each control point,
- net reservoir evaporation rates for each month of the period-of-analysis for each reservoir,
- reservoir storage characteristics and operating rules,
- hydroelectric power plant characteristics and energy demands for each of the 12 months of the year,
- diversion and instream flow targets for each of the 12 months of the year, and
- maximum allowable salt concentrations for each salt constituent for each type of water use.

Model output, for each month of the simulation period, includes:

- streamflows and salt concentrations for each control point,
- storages, releases, evaporation volumes, and salt concentrations for each reservoir,
- diversions and shortages for each diversion requirement (target),

- instream flows and shortages for each instream flow requirement (target), and
- energy generated and shortages for each hydroelectric power plant.

The monthly output is extremely voluminous. Various output summaries are also provided including:

- means and ranges of pertinent variables,
- period and volume reliabilities for diversion and instream flow targets, and
- and salt concentration versus exceedence frequency relationships for stream locations and reservoirs.

Reservoir Operating Rules

The model-user specifies diversion and instream flow requirements, for each of the 12 months of the year, to be met from streamflow and reservoir storage. Diversions can occur at any or all control points, and multiple diversions can be specified at the same control point. Reservoirs release for diversion and instream flow requirements at downstream locations, as well as supply lakeside diversions. The particular reservoirs from which withdrawals or releases can be made are specified for each diversion and instream flow target. Conservation pools, from which releases and withdrawals are made, are specified by designated inactive and conservation storage levels. Hydroelectric power operations are based on energy demands inputted for each of the 12 months of the year.

Multiple reservoirs may release for a particular diversion or instream flow requirement. Multiple-reservoir release decisions, for a given month, are based on balancing the percent depletion in specified storage zones of the system reservoirs to the extent possible. An optional water quality feature allows release decisions to be based on minimizing shortages while balancing storage depletions to the extent possible. This feature allows shortages, associated with salt concentrations exceeding maximum allowable levels, to be reduced by releasing from reservoirs with lower salinity. Releases are limited to meeting diversion or instream flow quantity targets; no releases are made specifically for dilution. However, the release is made from the reservoir which minimizes shortages for the month, related to both quantity and salt concentration constraints.

Buffer zone reservoir operating rules can also be specified, with diversion and instream flow targets being met only if storage is above specified levels. Storage capacity allocations can also be varied as a function of month of the year to model seasonal rule curve operating policies.

Brazos River Basin System

The locational configuration of the river/reservoir system modeled in the present study is represented by the 13 reservoir and 4 non-reservoir control points shown on the map of Figure

6.1 and schematic of Figure 6.2. Pertinent information describing the reservoirs is provided in Tables 2.1, 2.2, and 2.3.

The Southbend gage (station 12 in Chapters 3-5) was included as a control point in initial RESSALT runs. However, the Southbend control point was removed from the model due to problems with excessive negative incremental flows and loads. The unregulated discharges and loads at the Southbend gage are significantly higher than the corresponding values at the downstream Possum Kingdom gage (station 13) in many months. The Southbend gage is relatively unimportant in the study because no reservoir is there, and its assigned diversions could be reasonably moved to the Possum Kingdom control point. Control points are needed only to indicate the locations of reservoirs, diversions, and/or instream flow requirements. Negative incrementals are discussed further in Chapter 7.

Water Supply Operations

The RESSALT modeling studies focus on the water supply aspects of operation of the multiple-purpose reservoir system. Flood control operations allowing storage in flood control pools to be carried over from one month to the next are not simulated. The model allows the monthly flows to spill downstream whenever the water surface is at or above the designated top of conservation pool. Water supply operations are modeled by specifying diversion targets, for each of the 12 months of the year, at the reservoir and non-reservoir control points, maximum allowable salt concentrations for each type of water use, and rules for making reservoir releases for meeting the targets. As discussed later, various approaches were adopted for specifying alternative water supply plans and scenarios.

Hydroelectric Power Operations

Hydroelectric power plants are located at Whitney and Possum Kingdom Reservoirs. Hydroelectric power generation at Possum Kingdom Reservoir is incidental to water supply, with flows through the turbines being limited primarily to downstream water supply releases. Therefore, power generation at Possum Kingdom was not included in the RESSALT model. Hydroelectric power operations at Whitney Reservoir were included in the modeling studies. Hydropower releases from Whitney Reservoir significantly affect flows in the Brazos River.

The Whitney hydroelectric power operating criteria incorporated into the model are based upon the contract between the Southwestern Power Administration and Brazos Electric Power Cooperative. The contract provides for annual energy of 1,200 kilowatt-hours per kilowatt of peaking power, with the energy not to exceed 200 kilowatt-hours per kilowatt in any one month or 600 kilowatt-hours per kilowatt during four consecutive months. Whitney provides 30,000 kilowatts of peaking power. The monthly energy targets incorporated in the model are 6,000,000 kilowatt-hours in July and August, 2,000,000 kilowatt-hours in June and September, and 2,225,000 kilowatt-hours in each of the eight other months. This totals to 36 gigawatt-hours/year.

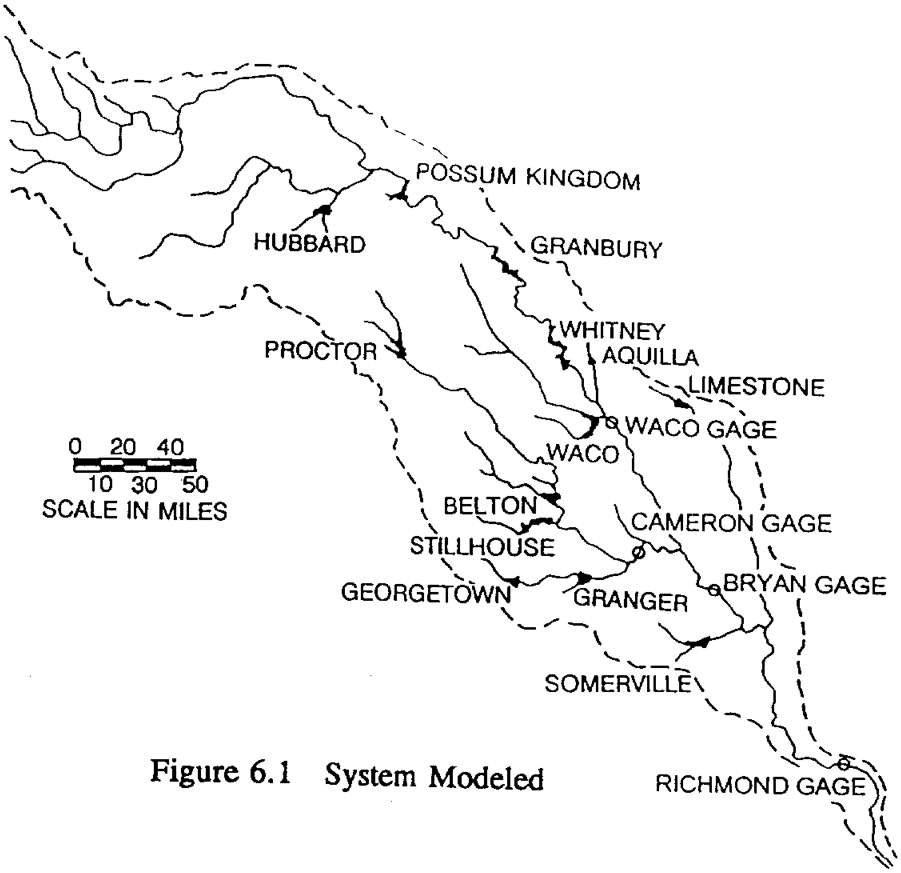

Figure 6.1 System Modeled

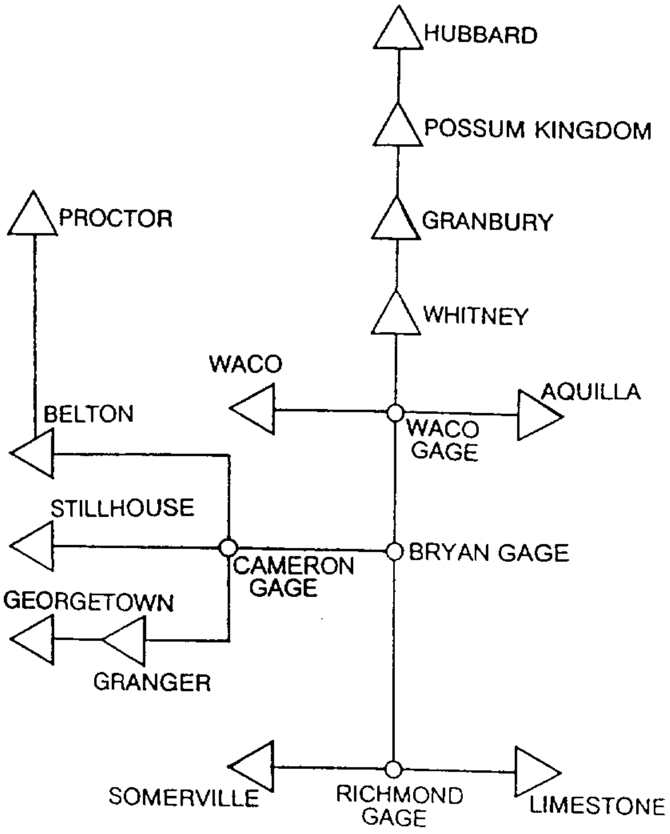

Figure 6.2 System Schematic

Reservoir Elevation/Storage/Area Relationships

A storage volume versus water surface area relationship is inputted to RESSALT for each reservoir, since evaporation volumes are computed as a function of area. An elevation versus storage relationship is required for determining head in the hydroelectric power computations. Storage capacities of the inactive and conservation pools are required for the operating rules. Elevation/storage/area relationships were provided by the Brazos River Authority (BRA) and U.S. Army Corps of Engineers (USACE). Basic data for all the reservoirs except Aquilla and Limestone are also published by the Texas Water Development Board (1973). The same reservoir data were used in the present study as the studies documented by Wurbs, Bergman, Carriere, and Walls (1988) and Wurbs and Carriere (1988).

Reservoir storage capacities change over time due to sedimentation. Water surface elevation versus area and storage volume tables were obtained for both initial, at the time of initial impoundment, and ultimate, at the predicted time for depletion of the sediment reserve, conditions. The sediment reserves tabulated in Table 2.2 correspond to the difference between initial and ultimate area and storage tables. Belton, Whitney, and Possum Kingdom Reservoirs also have elevation versus area and storage relationships updated by surveys conducted since initial impoundment. The years 1984 and 2010 elevation/storage/area tables used in the present study are based on linear interpolation of the initial (or resurveyed) and ultimate data. The 1984 and 2010 sediment condition storage capacities are listed in Table 2.3.

Hydrologic Input Data

Streamflows and salt loads for each month of the 1900-1984 period-of-analysis were inputted for each of the 13 reservoir and 4 non-reservoir control points. The RESSALT input also includes net evaporation rates for each reservoir for each month of the 1900-1984 simulation period. RESSALT computes evaporation volumes each month by multiplying average reservoir surface areas, determined as a function of storage, by the appropriate rates.

The naturalized (unregulated) monthly streamflows documented by Wurbs, Bergman, Carriere, and Walls (1988) and Wurbs and Carriere (1988) were also used in the present study. This naturalized streamflow data set includes streamflows for 1940-1976 developed by the Texas Water Commission and data covering 1900-1939 and 1977-1984 developed at Texas A&M University by Wurbs, Bergman, Carriere, and Walls (1988). The naturalized monthly streamflows were developed by adjusting gaged flows to remove nonhomogeneities caused by the activities of man in the basin. The Texas Water Commission 1940-76 naturalized streamflows include adjustments for water use diversions, return flows, and Soil Conservation Service flood retarding structures, as well as for the numerous major reservoirs. The Texas A&M University data for 1900-39 and 1977-84 include adjustments for 21 major reservoirs and limited diversions. Most of the gaging stations do not have records extending back to January 1900. Records were extended and gaps filled by regression analyses using the MOSS-IV Monthly Streamflow Simulation computer program available from the Texas Water Development Board.

In most cases, the control points used to represent the reservoir/stream system in RESSALT coincide with the stream gaging stations which provided the basic data used in the study. All the non-reservoir control points are stream gaging stations. For twelve of the reservoirs, stream gaging stations are located just below the dams. For the other reservoir, the gage used is some distance downstream of the dam, and the drainage area ratio was used to transfer the streamflow data. The drainage areas at the dams and at the corresponding streamflow gages are included in Table 2.2.

The unregulated total dissolved solids, chloride, and sulfate load input data are described in Chapter 5. For locations on the mainstream Brazos River and Hubbard Creek, for 1964-84, unregulated concentrations (Chapter 5) for each month were multiplied by the naturalized streamflows described above to develop salt loads. For the period 1900-1939, salt loads were developed by applying the regression equations of Table 5.9 to the naturalized streamflows. Alternative RESSALT runs were also made with loads for the entire 1900-84 simulation period developed with the regression equations of Table 5.9. As discussed in Chapter 5, unregulated salt loads on the Little River were developed by multiplying the naturalized streamflows by a constant long-term mean concentration adjusted to remove the effects of upstream reservoir evaporation. Long-term means of measured concentrations, without adjustments, were combined with the naturalized streamflows to develop loads for the better quality tributaries. Most of the control points adopted for the RESSALT model coincide with stream gaging stations, of which some do and others do not have measured salt data. Loads for control points in RESSALT were related to appropriate stations located nearby if measured salt data is unavailable at the control point.

The net reservoir evaporation rates included in the RESSALT input file were from a data base maintained by the TWDB and described by Kane (1967). The data base includes both gross and net reservoir surface evaporation rates. Net evaporation is the gross evaporation loss rate minus the effective rainfall rate, which is rainfall over the reservoir site less the amount of runoff under preproject conditions. The monthly data extends back to January 1940 and were used directly for the 1940-1984 portion of the RESSALT simulation period. For the 1900-1939 portion of the simulation period, 1940-84 averages for each of the 12 months of the year were used. The data is available on a one-degree quadrangle basis. For reservoirs extending across quadrangle boundaries, the evaporation rates for adjacent quadrangles were averaged.

Measures of System Reliability

RESSALT performs sequential month-by-month water and salt load accounting computations. Specified constant annual water use requirements (which vary between the 12 months of the year) are combined with a hypothetical repetition of historical hydrology. The model determines the extent to which the water use requirements (targets or demands) can be met during each month of the simulation period (1900-1984 historical hydrology). Shortages are declared whenever insufficient streamflow and/or reservoir storage amounts, of adequate quality, are available to meet demands. Model output includes: diversions, instream flows, energy generated, and associated shortages for each month for each specified target along with salt concentrations and reservoir storage volumes. The voluminous model output must be reduced to concise measures of system reliability in order to meaningfully analyze and display the simulation results.

Various expressions of reliability can be formulated. The present study uses the concepts of period and volume reliability as defined below. These reliability measures can be applied to either diversion, instream flow, or hydroelectric energy demands. Period reliability is based on counting the number of months of the simulation during which the specified demand target is, and is not, completely met without regard to shortage magnitude. Volume reliability reflects the shortage magnitude as well as frequency.

Period reliability is the percentage of months during the simulation during which a specified demand target is met without shortage. Period reliability (R) is computed from the results of a simulation as:

$$R_{period} = (n/N)\ 100\%$$

where n denotes the number of months during the simulation for which the demand is fully met and N is the total number of months in the simulation (1,020 months during the full 1900-84 simulation period). Thus, reliability is an expression of the percentage of time that the demand can be met. Equivalently, the reliability represents the likelihood or probability of the demand being met in any randomly selected month. Reliability (R) is the complement ($R=1-F$) of the risk of failure (F) that the target will not be met.

Volume reliability is the percentage of the total demand volume which can be actually supplied. The total volume supplied is the demand volume totalled for the entire simulation period minus the sum of the shortages in each month. Volume reliability (R) is the ratio of total volume supplied (v) to volume demanded (V):

$$R_{volume} = (v/V)\ 100\%$$

or, equivalently, the ratio of the mean actual diversion rate to mean target diversion rate.

Firm (dependable or safe) yield is the estimated maximum diversion, instream flow, or hydroelectric energy generation rate which can be maintained continuously during the simulation period, based on specified assumptions regarding various factors. By definition, firm yield and smaller yields have period and volume reliabilities of 100 percent. Yields greater than firm yield have reliabilities of less than 100 percent. The most severe drought of record in the Brazos River Basin occurred during the period 1950-1957. Although historical lowflow periods vary between gaging stations, from a general basinwide perspective, the 1950-1957 critical period controls firm yield estimates.

As discussed below, two alternative approaches are adopted in the study to specify water use requirements: (1) a scenario based on actual water use during some past year or projected future water use and (2) hypothetical yields. The measures of period and volume reliability defined above were applied in both cases. In addition, the concept of firm yield was used with the hypothetical yields.

Organization of the Simulation Study

The simulation study involved numerous executions of the RESSALT model for alternative water use scenarios, reservoir system operating policies, and modeling assumptions. The analyses documented in Chapters 7 and 8 reflect two different strategies for representing water use requirements. The simulations discussed in Chapter 7 incorporate two alternative sets of water demands based on (1) actual estimated water use during 1984 and (2) projected water use for 2010. Chapter 8 is based on the traditional concept of hypothetical yields.

Chapter 7 is based on summarizing and analyzing the results of 18 selected RESSALT runs. The analyses include:

- a summary comparison of various pertinent quantities to develop an overview understanding of the model and the river/reservoir system being modeled,
- comparison of estimated salt concentrations for predevelopment, 1984, and 2010 conditions of river basin development,
- evaluation of the impacts of salt control impoundments on downstream concentrations, and
- various other sensitivity analyses involving alternative management strategies and modeling assumptions.

Chapter 8 is a water supply yield-reliability study for the river/reservoir system, involving numerous runs of RESSALT. Hypothetical yield versus reliability relationships are presented for various situations. The analyses include:

- development of relationships between yield, allowable salt concentrations, and reliability,
- comparison of alternative reservoir system operating plans, and
- evaluation of the impacts of the proposed salt control impoundments.

CHAPTER 7
RESERVOIR SYSTEM SIMULATION FOR ALTERNATIVE WATER USE SCENARIOS

Water Use Requirements and Reservoir Operating Policies

The 1984 and 2010 water use scenarios adopted for the simulation study are simplified approximations of a complex water supply and use system. Over 1,000 public and private entities, owning about 600 reservoirs, hold permits to store, divert, and use the waters of the Brazos River and tributaries for various beneficial purposes. Diversions occur at numerous locations throughout the basin. Groundwater use is also significant. Historical water use records and projections of future use are necessarily approximate. However, the set of diversions aggregated at the control points included in the RESSALT model is considered to be adequately representative of the real system to provide meaningful information within the scope of the study.

The historical 1984 and projected future 2010 water use data sets adopted and described by Wurbs and Carriere (1988) were used again in the present study. Wurbs and Carriere (1988) aggregated, by control point, the Texas Water Development Board water use data which is available by county. Annual water use was distributed to the 12 months of the year, as a function of type of use, using data available from the TWDB and TWC. All water use in the counties in the upper basin above Possum Kingdom and Hubbard Creek Reservoirs was assumed to be supplied by other sources and therefore not included in the model. All other surface water use was assumed to be met by the 13 reservoirs and unregulated streamflow entering the river below the dams. The Texas Water Plan (TWDB 1984) 2010 water use projections used in both the previous and present studies were revised in the recent update of the Texas Water Plan (1990). However, revising the data for the present study was not considered to be warranted.

Return flows were estimated as a fraction of diversions. Return flow factors of 0.40 and 0.35 were used for municipal and manufacturing uses, respectively. All other use types were assumed to have no return flows. Return flow factors were applied to both surface and ground water. No return flows were assigned to inbasin use in the lower basin and diversions to the San Jacinto-Brazos Coastal Basin, which represent a large portion of the total water use. In most cases, return flows were assumed to occur at the same control point as the corresponding diversion. Net diversions, adjusted to reflect return flows, were inputted to RESSALT.

Water use during 1984 is previously summarized in Table 2.4. The annual totals of the monthly net diversion requirements for the 1984 and 2010 water use scenarios, adopted for the simulation study, are presented in Tables 7.1. Demand targets are specified at 16 of the 17 control points. The total annual 1984 and 2010 net water demands are 712,000 ac-ft/yr and 1,960,000 ac-ft/yr, respectively. This includes 1984 demands of 777,000 ac-ft/yr minus return flows of 65,000 ac-ft/yr and 2010 demands of 2,157,000 ac-ft/yr minus return flows of 197,000 ac-ft/yr. The net diversions at the Richmond gage account for 69.5% and 65.8%, respectively, of the total 1984 and 2010 net diversions. The Richmond gage diversions represent water transported to the adjoining coastal basin as well as water use in the lower Brazos River Basin. The monthly distribution of annual water use varies somewhat between control points with

Table 7.1
ANNUAL DIVERSION REQUIREMENTS ADOPTED FOR 1984 AND 2010 WATER USE SCENARIOS

Control Point	1984 Net Diversion (ac-ft/year)	2010 Net Diversion (ac-ft/year)
<u>Hubbard Creek</u>		
Hubbard Creek Reservoir	27,200	77,160
<u>Brazos River</u>		
Possum Kingdom Reservoir	21,470	109,680
Granbury Reservoir	15,840	83,580
Whitney Reservoir	2,960	8,810
Waco Gage	18,400	49,120
Bryan Gage	8,840	28,480
Richmond gage	494,790	1,290,270
<u>Tributaries</u>		
Aquilla Reservoir	1,050	2,070
Waco Reservoir	22,990	71,620
Proctor Reservoir	39,760	125,630
Belton Reservoir	28,250	45,940
Stillhouse Hollow Reservoir	1,310	2,980
Georgetown Reservoir	3,960	11,620
Granger Reservoir	0	0
Cameron Gage	21,970	40,720
Somerville Reservoir	960	3,160
Limestone Reservoir	2,460	9,800
Total	712,190	1,960,620

<u>Notes:</u>

1. The 1984 net diversions of 712,190 ac-ft/year includes diversions of 776,950 ac-ft/year minus return flows of 64,760 ac-ft/year. The 2010 net diversions of 1,960,620 ac-ft/yr include diversions of 2,157,370 ac-ft/year minus return flows of 196,750 ac-ft/year.

2. The monthly diversion targets vary between the 12 months of the year but sum to the annual totals shown.

variations in the mix of types of use. The annual target at the Richmond gage is distributed over the 12 months from January through December as follows: 4.9%, 4.9%, 6.3%, 8.5%, 12.0%, 13.7%, 13.8%, 12.2%, 7.8%, 6.0%, 4.9%, and 4.9%.

In the model, Hubbard, Whitney, Waco, and Proctor Reservoirs are limited to meeting water demands at their own control points. The other nine reservoirs are operated as a system to release for demands at all downstream control points as well as to meet withdrawals at their own control points. Diversions at the four non-reservoir control points are met from available unregulated streamflow supplemented by reservoir releases as needed. Multiple-reservoir release decisions are based on balancing the percent depletion, or percent full, of the active conservation pools. If more than one reservoir can release for a downstream diversion demand, the release for a particular month is made from the reservoir which is most full or least depleted.

As discussed in Chapter 6, Whitney Reservoir is operated for hydroelectric power. The same monthly energy requirements, which total to 36 gigawatt-hours per year, were specified in both the 1984 and 2010 water use scenarios.

As discussed in Chapter 6, reservoir storage characteristics are represented in the model by inputted elevation/storage/area tables. The 1984 and 2010 water use scenarios were combined with alternative reservoir elevation/storage/area data representing 1984 and 2010 conditions of sedimentation. Storage capacities are tabulated in Table 2.3.

The system was simulated alternatively with and without salt concentration constraints. Either way, system operation was based on the same water demand amounts and reservoir operating rules as outlined above. Without designated maximum allowable salt concentrations, demands are met as long as a sufficient volume of streamflow and/or reservoir storage was available. However, with maximum allowable salt concentrations specified, shortages depend on water quality as well as quantity. The maximum allowable salt concentrations were set at 500 mg/l, 250 mg/l, and 250 mg/l, respectively, for total dissolved solids (TDS), chloride (Cl), and sulfate (SO_4), for all demands. The TDS, Cl, and SO_4 limits of 500, 250, and 250 mg/l are the maximum concentrations specified in the Environmental Protection Agency drinking water standards.

Simulation Runs

The simulation study involved numerous executions or runs of RESSALT. The present chapter cites 18 selected runs which are listed in Table 7.2. As indicated in Table 7.2 and discussed above, the alternative runs are based on either 1984 or 2010 conditions of water use and reservoir sedimentation and either do or do not include maximum allowable salt concentrations in the operating criteria. The alternative runs have simulation periods of either 1900-1984 or 1964-1984. As discussed in Chapter 5, the extent to which the salt load input data has been adjusted and synthesized varies significantly between the periods before and after 1964. Also as discussed in Chapter 5, two alternative sets of unregulated flows were incorporated into the model which represent: (1) expected values of salt loads which are dependent upon the discharges (runs 1-12); and (2) the expected values adjusted to included random deviations which are not dependent on discharge (runs 13-16).

Table 7.2
SIMULATION RUNS CITED IN CHAPTER 7

Run	Simulation Period	Water Use Scenario	Salt Constraints	Salt Dams	Random Loads
1	1900-84	1984	no	no	no
2	1900-84	1984	yes	no	no
3	1900-84	2010	no	no	no
4	1900-84	2010	yes	no	no
5	1964-84	1984	no	no	no
6	1964-84	1984	yes	no	no
7	1964-84	2010	no	no	no
8	1964-84	2010	yes	no	no
9	1964-84	1984	no	yes	no
10	1964-84	1984	yes	yes	no
11	1964-84	2010	no	yes	no
12	1964-84	2010	yes	yes	no
13	1900-84	1984	no	no	yes
14	1900-84	1984	yes	no	yes
15	1900-84	2010	no	no	yes
16	1900-84	2010	yes	no	yes
17	1900-84	2010	yes	no	no
18	1964-84	1984	no	no	no

Notes:

1. Runs 1-8 reflect alternative combinations of simulation period (1900-84 or 1964-84), water use scenario and reservoir sedimentation (1984 or 2010), and salt constraints (maximum allowable TDS, Cl, and SO4 concentrations of 500, 250, and 250 mg/l either are or are not specified).

2. Runs 1-4 and runs 5-8 are identical except for the simulation period.

3. Runs 9-12 repeat runs 5-8 with the only change being addition of the three proposed salt control impoundments.

4. Runs 13-16 are identical to runs 1-4 except for the inputted unregulated saltloads. Runs 1-12 & 18 incorporate the unregulated loads, representing expected values for given discharges, which were developed as outlined in Tasks 1-5 or Chapter 5. Runs 13-16 incorporate the unregulated loads, developed in Task 6 of Chapter 5, which include a random deviation from the expected values.

5. Run 17 is identical to runs 4 and 16 except the inputted unregulated loads are based on constant mean consentrations.

6. Run 18 is identical to run 5 except for a different option is used for handling negative incremental streamflows and salt loads.

The alternative runs were made to compare the impacts that alternative management strategies and modeling assumptions have on system reliabilities, streamflows, salt concentrations, and other pertinent variables. Runs 1-8 provide information to evaluate the impacts of salt constraints and compare 1984 versus 2010 conditions. Runs 1-4 versus runs 5-8 demonstrate the sensitivity of model results to the period-of-analysis used. Runs 9-12 were made to evaluate the impacts of the proposed salt control dams discussed in Chapter 4. Runs 13-16 incorporate a different set of salt loads which includes a random component which is not reflected in runs 1-12. Run 17 is unique in that the unregulated salt loads are replaced with loads computed assuming a constant concentration. Run 18 was made to compare alternative options for handling negative incremental streamflows and salt loads.

Simulation results are summarized and various comparative analyses discussed in the following sections. Selected summary-type data from the 18 runs are tabulated in Tables 7.2-7.6.

Overall System Water and Salt Load Balance

Water balances for the basin for the overall 1900-84 or 1964-84 simulation period are presented in Table 7.3. Total dissolved solids (TDS) load balances, corresponding to the water volume balances of Table 7.3, are presented in Table 7.4.

The unregulated flows at the Richmond gage can be viewed as the sum of the incremental flows entering all the river reaches in the basin, or all the control points in the model. The unregulated streamflow at the Richmond gage represents the total cumulative inflow to the basin. As indicated in Table 7.3, the mean 1900-84 and 1964-84 basin inflows (Richmond gage unregulated flows) are 472,290 and 469,260 acre-feet/month, respectively. The simulations begin with all reservoirs full to the top of conservation pool. The end-of-period storages for December 1984 typically represent some drawdown. Thus, the system is provided water from storage as well as from streamflow inflows. However, as shown in Table 7.3, the 1900-84 or 1964-84 storage change is very small compared to inflow.

In the model, all the water available to the river/reservoir/use system is accounted for as either: (1) flow to the Gulf of Mexico (regulated flows below the Richmond gage), (2) net diversions, or (3) net evaporation from the 13 reservoirs. Most of the available water flows to the Gulf. For example, for run 1, the mean flow to the Gulf is 378,700 acre-feet/month or 80% of the available 1900-84 inflow and change in storage (472,290 plus 262 ac-ft/month). The 61,600 ac-ft/month net diversion is 13% of the available water. The 32,260 ac-ft/month 1900-84 mean evaporation accounts for the remaining 7% of the available water.

Table 7.4 accounts for the total system TDS load for the overall simulation period. The 1900-84 and 1964-84 mean TDS loads at the Richmond gage of 197,970 and 211,990 tons/month, respectively, represent the total cumulative system inflow. The salt loads in the reservoirs at the beginning of the simulations were based on the assumptions of: (1) full conservation pools and (2) concentrations of the stored water equal to the 1900-84 mean concentrations. The 1900-84 or 1964-84 net load storage change in the 13 reservoirs is sometimes positive and other times negative depending on tradeoffs between decreases in volume

Table 7.3
SYSTEM WATER BALANCE FOR 18 RUNS

Run	Mean Flows (acre-feet/month)				
	Inflow	Flow to Gulf	Net Diversion	Net Evap	Storage Change
1	472,290	378,700	61,600	32,260	-262
2	472,290	396,980	42,990	32,490	-169
3	472,290	283,400	164,550	25,360	-924
4	472,290	338,980	105,490	28,180	-360
5	469,260	377,060	61,410	31,850	-1,062
6	469,260	397,680	40,260	32,000	-684
7	469,260	280,450	165,540	27,070	-3,741
8	469,260	340,520	101,370	28,830	-1,459
9	467,100	375,060	61,410	31,800	-1,159
10	467,100	390,380	45,570	31,960	-807
11	467,100	278,650	165,540	26,960	-4,037
12	467,100	322,420	117,680	28,500	-1,500
13	472,290	378,700	61,600	32,260	-262
14	472,290	397,800	42,160	32,500	-167
15	472,290	283,400	164,550	25,360	-924
16	472,290	341,060	103,360	28,210	-345
17	472,290	326,060	118,540	28,050	-361
18	469,260	377,430	61,420	31,900	-1,493

Table 7.4
SYSTEM TDS LOAD BALANCE FOR 18 RUNS

Run	Mean TDS Load (tons/month)			
	Inflow	Flow to Gulf	Net Diversion	Storage Change
1	197,970	169,460	28,200	302
2	197,970	169,460	28,000	508
3	197,970	159,270	38,970	-276
4	197,970	154,350	42,860	754
5	211,990	172,950	37,830	1,222
6	211,990	195,220	14,720	2,056
7	211,990	109,230	103,880	-1,113
8	211,990	170,510	38,440	3,051
9	177,300	146,440	31,520	-666
10	177,300	161,970	15,400	-67
11	177,300	94,830	82,530	-67
12	177,300	132,330	45,040	-67
13	197,970	168,700	29,060	207
14	197,970	181,630	15,940	397
15	197,970	148,520	49,820	-373
16	197,970	157,470	39,940	561
17	197,970	149,931	47,670	367
18	211,990	174,970	47,670	-10,650

Table 7.5
RICHMOND GAGE MEANS FOR 18 RUNS

Run	Unregulated			Regulated		
	Flow (ac-ft/mo)	TDS Load (tons/mo)	TDS Conc (mg/l)	Flow (ac-ft/mo)	TDS Load (tons/mo)	TDS Conc (mg/l)
1	472,290	197,970	308	378,700	169,400	329
2	472,290	197,970	308	396,980	181,410	336
3	472,290	197,970	308	283,400	159,270	413
4	472,290	197,970	308	338,980	154,350	350
5	469,260	211,990	332	377,060	172,950	337
6	469,260	211,990	332	397,680	195,220	361
7	469,260	211,990	332	280,450	109,230	287
8	469,260	211,990	332	340,520	170,510	368
9	467,100	177,300	279	375,060	146,440	287
10	467,100	177,300	279	390,380	161,970	305
11	467,100	177,300	279	278,650	94,830	250
12	467,100	177,300	279	322,420	132,240	302
13	472,290	197,970	308	378,700	168,700	328
14	472,290	197,970	308	397,800	181,630	336
15	472,290	197,970	308	283,400	148,520	385
16	472,290	197,970	308	341,060	157,470	340
17	472,290	197,970	308	326,060	149,930	338
18	469,260	211,990	332	377,430	174,970	341

Table 7.6
SYSTEM RELIABILITY FOR 18 RUNS

Run	Target Diversion (ac-ft/mon)	Actual Diversion (ac-ft/mon)	Diversion Shortage (ac-ft/mon)	Volume Reliability (%)	Net Evap (ac-ft/mon)
1	61,740	61,600	141	99.77	32,260
2	61,740	42,990	18,750	69.64	32,490
3	171,600	164,550	7,050	95.89	25,360
4	171,600	105,490	66,110	61.47	28,180
5	61,740	61,410	330	99.47	31,850
6	61,740	40,260	21,480	65.21	32,000
7	171,600	165,540	6,060	96.47	27,070
8	171,600	101,370	70,240	59.07	28,830
9	61,740	61,410	330	99.47	31,800
10	61,740	45,570	16,160	73.82	31,960
11	171,600	165,540	6,070	96.46	26,960
12	171,600	117,680	53,920	68.58	28,500
13	61,740	61,600	141	99.77	32,260
14	61,740	42,160	19,580	68.29	32,500
15	171,600	164,550	7,050	95.89	25,360
16	171,600	103,360	68,240	60.23	28,210
17	171,600	118,540	53,070	60.07	25,355
18	61,740	61,420	320	99.48	31,900

of water stored and increases or decreases in concentration. For example, run 1 has a January 1900 beginning-of-simulation TDS load of 2,442,810 tons and December 1984 end-of-period TDS load of 2,750,830 tons stored in the 13 reservoirs, resulting in a net change of 302 tons/month. Most of the Brazos River salt load flows to the Gulf of Mexico. For example, for run 1, the 1900-84 mean flow to the Gulf (regulated flow below Richmond gage) of 169,460 tons/month accounts for 86% of the total inflow (Richmond gage unregulated loads) of 197,970 tons/month. The run 1 net diversion and storage change, respectively, account for 14% and 0.15% of the inflow.

Comparison of 1900-1984 and 1964-1984 Simulation Periods

Two alternative simulation periods are used, 1900-1984 and 1964-1984. From a basinwide perspective, the most severe drought during the historical period-of-record began in 1950 and was ended by a major flood event in May 1957. Thus, the 1900-1984 period includes the 1950-1957 critical drought period as well as having the obvious advantage of being four times longer. However, the data before 1964 is much more "synthesized" than the 1964-1984 period. All of the salinity measurements used in the study were collected after 1963. The earlier streamflow gaging records are much less complete. A large proportion of the naturalized streamflow data and all the unregulated salt loads before 1964 had to be synthesized by regression analysis.

Runs 1-4 and 5-8 are identical except for the simulation period. A review of Tables 7.3-7.6 shows that the results for runs 1 & 5, runs 2 & 6, runs 3 & 7, and runs 4 & 8 are quite similar, from the perspective of long-term means and reliability statistics. The 1900-84 and 1964-84 simulation periods yield reasonably comparable results.

Comparison of Predevelopment, 1984, and 2010 Conditions of River Basin Development

The unregulated streamflows and salt loads provided as RESSALT input data represent predevelopment conditions without reservoirs or water users. The model computes regulated streamflows representing conditions which would result from hypothetically maintaining the specified 1984 or 2010 water use demand targets constantly during a repetition of historical 1900-1984 hydrology. Regulated flows, loads, and concentrations reflecting 1984 and 2010 conditions, respectively, can be compared with the unregulated flows, loads, and concentrations to evaluate the impacts of basin development, at least the aspects of basin development reflected in the reservoirs and diversions included in the model.

Table 7.5 compares unregulated and regulated flows, loads, and concentrations at the Richmond gage. This provides a measure of the impacts of basin development on river flows in the lower basin. For the alternative runs, the 1900-84 and 1964-84 mean regulated flows range from 60% to 84% of the corresponding mean unregulated flows. The mean regulated TDS loads range from 53% to 92% of the corresponding unregulated means. The mean regulated concentrations range from 86% to 134% of the mean unregulated concentrations. Thus, in the alternative RESSALT runs, the diversions and reservoirs increased the mean

Richmond gage salt concentration under some modeling scenarios and decreased the mean concentration in other situations.

Runs 5 and 7 can be used to evaluate the impacts of basin development. Table 7.7 provides a comparison of results from runs 5 and 7 with the unregulated flows, loads, and concentrations. The mean TDS concentrations for the total system diversions are 453 and 462 mg/l, respectively, for the 1984 (run 5) and 2010 (run 7) water use scenarios, which are significantly greater than the corresponding Richmond gage concentrations of 337 and 287 mg/l. Therefore, diversions of higher salinity water at upstream locations on the Brazos River improve water quality at the Richmond gage. Reservoir evaporation decreases downstream flows and increases concentrations at the Richmond gage. In run 5, the tradeoff between upstream diversions and evaporation had the net effect of increasing the mean concentration at the Richmond gage from 332 to 337 mg/l. In run 7, the tradeoffs between the much higher diversions and lesser evaporation resulted in a mean regulated concentration of 287 mg/l at the Richmond gage compared to a unregulated concentration of 332 mg/l. Likewise, at the Bryan gage the 1984 scenario mean TDS concentration of 456 mg/l is higher than the unregulated mean of 406 mg/l, but the 2010 scenario concentration of 390 mg/l is lower. At the Whitney gage, the mean salinities (873 and 803 mg/l), for the 1984 and 2010 water use and reservoir sedimentation conditions, are both higher than the mean unregulated concentration of 720 mg/l.

Table 7.7
COMPARISON OF PREDEVELOPMENT, 1984, AND 2010
CONDITIONS OF RIVER BASIN DEVELOPMENT

Quantity	Predevelopment (unregulated)	1984 (run 5)	2010 (run 7)
System Means (acre-feet/month)			
inflow	469,260	469,260	469,260
flow to gulf	469,260	377,060	280,450
net diversions	-0-	61,410	165,540
net evaporation	-0-	31,850	27,070
storage change	-0-	-1,062	-3,741
Mean TDS Loads (tons/month)			
inflow	211,990	211,990	211,990
flow to gulf	211,990	172,950	109,230
net diversions	-0-	37,830	103,880
storage change	-0-	1,222	-1,113
Mean TDS Concentrations (mg/l)			
total system diversions	-0-	453	462
below Whitney Reservoir	720	873	803
Bryan gage	406	456	390
Richmond gage	332	337	287

System Reliability for 1984 and 2010 Water Use Scenarios With and Without Salt Constraints

Table 7.6 provides a general overview of system reliability in meeting diversion demands. The mean target and actual diversions, summed for all the control points, for the 1900-84 and 1964-84 simulation periods, are tabulated along with the corresponding shortages and volume reliabilities. The 1984 and 2010 target diversions vary over the 12 months of the year but average 61,740 and 171,600 ac-ft/month, respectively. The volume reliability is computed as the mean of the actual total diversions divided by the corresponding target mean diversion. Reservoir evaporation is a significant demand on the water resource and is also included in Table 7.6.

Runs 1-4 compare system performance for the 1984 and 2010 water use scenarios with and without salt constraints, based on a 1900-1984 simulation period. Runs 5-8 are identical to runs 1-4 except the simulation period is 1964-1984. The salt constraints consist of specification of maximum allowable salt concentrations of 500 mg/l, 250 mg/l, and 250 mg/l for TDS, chlorides, and sulfates, respectively. Volume and period reliabilities for runs 1-4 are tabulated by control point in Tables 7.8 and 7.9.

In addition to the water supply diversions, for which reliabilities are shown in Tables 7.8-7.9, hydroelectric energy is generated at Whitney Reservoir. With the 1984 conditions of water use and reservoir sedimentation reflected in run 1, energy shortages occurred during 63 months scattered over the 1,020 month simulation period, resulting in a period reliability of 93.82%. During four of the months of energy shortage, there were no releases at all through the turbines due to the storage level falling below the top of inactive pool. Energy demands were partially met during each of the other 59 shortage months. For the 2010 conditions of run 3, energy shortages occurred in 147 months resulting in a period reliability of 85.59%. No energy was generated in each of 24 months scattered over the simulation period, with energy targets being partially but not completely met during the other 123 months of shortage.

If maximum allowable salt concentrations are not specified, the 1984 diversion demands can be met with only minimal shortages. As indicated in Tables 7.6 and 7.8, run 1 has a volume reliability of 99.77% for the overall system demand. The only shortages occurred at the Proctor Reservoir and Whitney Reservoir control points. Proctor Reservoir is located on the upper Leon River. Proctor was empty and unable to met demands during 57 months distributed between several different drought periods, for a period reliability of 94.41%. The relatively small diversion at Whitney Reservoir suffered shortages because of drawdowns resulting primarily from hydroelectric power releases rather than the water supply diversion.

Specifying maximum allowable concentrations of 500 mg/l, 250 mg/l, and 250 mg/l for TDS, Cl, and SO_4, respectively, significantly reduces diversion reliabilities. As indicated in Table 7.8, the overall reliability for total system diversions is 69.64% for run 2. The reliabilities are zero for the lakeside diversions from the three mainstream reservoirs. The Richmond gage diversion has volume and period reliabilities of 74.59% and 75.10%, respectively. The lakeside withdrawals from five of the reservoirs on the better quality tributaries are met continuously without shortage.

Table 7.8
VOLUME RELIABILITIES BY CONTROL POINT

Control Point	Volume Reliability (%)			
	Run 1	Run 2	Run 3	Run 4
Hubbard Reservoir	100.00	92.60	90.64	90.64
Brazos River				
Possum Kingdom Reservoir	100.00	0.00	99.12	0.00
Granbury Reservoir	100.00	0.00	99.03	0.00
Whitney Reservoir	97.79	0.00	92.84	0.00
Waco Gage	100.00	12.67	99.30	13.71
Bryan Gage	100.00	49.23	99.87	44.63
Richmond Gage	100.00	74.59	99.20	71.99
Tributaries				
Aquilla Reservoir	100.00	99.02	98.76	99.34
Proctor Reservoir	95.91	95.91	54.32	54.30
Belton Reservoir	100.00	100.00	97.76	99.89
Stillhouse Reservoir	100.00	100.00	99.96	100.00
Georgetown Reservoir	100.00	100.00	96.73	100.00
Cameron Gage	100.00	99.80	99.73	99.71
Somerville Reservoir	100.00	100.00	99.48	100.00
Limestone Reservoir	100.00	100.00	99.34	100.00
System Total	99.77	69.64	95.89	61.47

Table 7.9
PERIOD RELIABILITIES BY CONTROL POINT

Control Point	Period Reliability (%)			
	Run 1	Run 2	Run 3	Run 4
Hubbard Reservoir	100.00	92.55	88.04	88.04
Brazos River				
Possum Kingdom Reservoir	100.00	0.00	98.33	0.00
Granbury Reservoir	100.00	0.00	98.63	0.00
Whitney Reservoir	97.45	0.00	91.86	0.00
Waco Gage	100.00	12.45	99.42	13.24
Bryan Gage	100.00	47.25	99.71	43.82
Richmond Gage	100.00	75.10	99.31	72.40
Tributaries				
Aquilla Reservar	100.00	99.02	98.43	99.31
Proctor Reservoir	94.41	94.41	43.04	42.94
Belton Reservoir	100.00	100.00	96.76	99.80
Stillhouse Reservoir	100.00	100.00	99.90	100.00
Georgetown Reservoir	100.00	100.00	95.00	100.00
Cameron Gage	100.00	99.80	99.41	99.71
Somerville Reservoir	100.00	100.00	99.31	100.00
Limestone Reservoir	100.00	100.00	99.22	100.00

Even though maximum allowable salt concentrations are not specified, the significantly greater 2010 diversion demands of run 3 strains the water supply capabilities of the system. None of the control points have a 100% reliability. However, diversions at most of the control points have reliabilities exceeding 99%, with the lowest reliability being 54.32% at Proctor Reservoir. The overall volume reliability is 95.89% Adding the salt constraints in run 4 lowers the overall system reliability to 61.47%. The Richmond gage diversion has volume and period reliabilities of 71.99% and 72.40%, respectively, in run 4. Lakeside diversions at the three mainstream reservoirs again have zero reliabilities since the reservoir concentrations exceed the allowables during the entire 1,020-month simulation. The reliabilities for lakeside withdrawals from Belton, Stillhouse, Georgetown, Somerville, and Limestone Reservoirs actually improve with addition of the salt constraints (run 4 versus run 3). This is because the shortages at the Richmond and Bryan gages, caused by salt concentrations, reduce the releases from the upstream reservoirs, thus making more water available for lakeside diversions.

Impacts of Proposed Salt Control Impoundments

A system of three salt control impoundments previously proposed by the USACE (1973) is described in Chapter 4. The locations of the impoundments are shown in Figure 4.1. Chapter 4 presents an analysis of the impacts of the salt control dams on concentrations at downstream locations, which is based on adjusting the measured data without actually using a reservoir/river system simulation model such as RESSALT. The analysis of Chapter 4 estimates concentrations which would have occurred historically if the salt control impoundments had existed with nothing else being changed. RESSALT provides the additional modeling flexibility of including the salt control impoundments in the simulation in combination with specified alternative water use scenarios, system operating rules, and other modeling assumptions. The salt control dams are reflected in a RESSALT simulation by the inputted "unregulated" salt loads which, in this case, are actually regulated by the salt control dams. As discussed in Chapters 4 and 5, the salt load input data set reflects the impoundment or removal of all salt loads and discharges at stations 3, 4, and 6.

The salt control impoundments are modeled in runs 9-12. Runs 9-12 are identical to runs 5-8, except all discharges and loads at the sites of the salt control dams have been removed from the inputted loads and flows. With no salt constraints, the reliability is 99.5% for 1984 demands (runs 5 and 9) and 96.5% for 2010 demands (runs 7 and 11), with or without the salt control dams, because salinity causes no shortages at the main stream control points either way. However, for 1984 demands with salt constraints, the salt control impoundments increase the reliability from 65.21% to 73.82%. With salt constraints, the reliability for 2010 demands is increased from 59.07% to 68.58% by the salt control dams.

The proposed salt control impoundments significantly reduce the salt loads and concentrations, particularly chlorides, along the entire length of the main stream Brazos River. The Richmond gage means are tabulated in Table 7.5. The salt control dams reduce the mean unregulated flow, TDS load, and TDS concentration at the Richmond gage by 0.46%, 16%, and 16%, respectively. The corresponding reduction in mean regulated TDS concentration ranges from 13% to 18% for the four runs. The effects of the impoundments are most pronounced for chlorides. The regulated mean chloride concentrations at the Richmond gage for runs 5-8 are

77.1 mg/l, 86.1 mg/l, 55.7 mg/l, and 88.8 mg/l, respectively. The corresponding chloride concentrations for runs 9-12 are 50.6, 56.8, 37.0, and 54.3 mg/l. Thus, the salt control dams reduce the chloride concentrations at the Richmond gage for these pairs of runs by 34.4%, 34.0%, 33.6%, and 33.8%. The corresponding sulfate concentration reductions range from 11.2% to 15.7%.

The mean TDS concentrations in Possum Kingdom Reservoir for runs 5-8 are 1,477 mg/l, 1478 mg/l, 1496 mg/l, and 1533 mg/l, respectively. The salt control impoundments (runs 9-12) reduces these concentrations by 31.6%, 31.5%, 35.6%, and 35.7%. The mean chloride concentrations in Possum Kingdom Reservoir for runs 5-8 are 611, 612, 621, and 636 mg/l, respectively. The impoundments reduce the Possum Kingdom chloride concentrations by 40.1%, 40.1%, 44.6%, and 44.8%, respectively, to 366 mg/l, 367 mg/l, 344 mg/l, and 351 mg/l for runs 9-12.

Alternative Sets of Unregulated Loads

Task 6 of Chapter 5 involved development of an alternative set of unregulated salt loads which include a random component. The basic set of salt loads reflected in runs 1-12 represent the expected or most likely loads for each month for the given discharges. Since the unregulated discharges and salt loads are highly correlated, the corresponding unregulated concentrations are fairly constant. The objective of the Task 6 salt loads is to more realistically represent the variation in concentrations. The addition of a random component to the salt loads still maintains the same 1900-84 means but greatly increases the variance of the concentrations.

Runs 13-16 are identical to runs 1-4 except for the unregulated salt loads included in the RESSALT input data. The unregulated salt loads incorporated in runs 1-4 correspond to Tasks 1-3 of Chapter 5. The loads inputted in runs 13-16 were developed in Task 6 of Chapter 5. Concentration-duration curves at the Richmond gage for runs 1-4 and 13-16 are tabulated in Tables 7.10-7.13 and plotted in Figures 7.1-7.4. The unregulated concentrations are the same as those previously presented in Table 5.29 and Figure 5.27. The other concentrations identified with each individual run in Tables 7.10-7.13 and Figures 7.1-7.4 are the regulated concentrations computed by RESSALT.

As noted in Chapter 5, although the 1900-84 means are the same for the two alternative sets of unregulated concentrations, the set incorporating a random component (runs 13-16) has a much greater variance. The regulated TDS concentration-duration relationships for runs 1-4 versus runs 13-16 are compared in Table 7.10 versus Table 7.11. The corresponding chloride concentrations are presented in Tables 7.12 & 7.13. Interestingly, the regulated concentration-duration curves for runs 13-16 are reasonably similar to the corresponding values for runs 1-4, even though the unregulated concentration-duration curves differ greatly.

The summary statistics presented in Tables 7.3-7.5 are all 1900-84 means. The values for runs 1-4 and 13-16 in these tables are quite similar. The system reliabilities shown in Table 7.6 are also similar. For example, the 1984 and 2010 water use scenarios, with salt constraints, of runs 2 and 4 result in system reliabilities of 69.64% and 61.47%, respectively. With all other

Table 7.10
TDS CONCENTRATION-DURATION CURVES AT RICHMOND GAGE FOR RESSALT SIMULATION RUNS 1-4

Percent Time: Equalled or Exceeded	TDS Concentration (mg/l)				
	Unregulated	Run 1	Run 2	Run 3	Run 4
1	701	960	986	1,157	1,015
2	603	872	902	945	924
5	527	735	758	703	776
10	482	648	673	573	685
25	416	488	497	411	501
50	354	364	382	320	392
75	306	303	314	253	319
90	270	251	268	159	272
95	245	185	210	-51	225
100	0	-123,218	-15,241	-413,385	-13,300

Table 7.11
TDS CONCENTRATION-DURATION CURVES AT RICHMOND GAGE FOR RESSALT SIMULATION RUNS 13-16

Percent Time: Equalled or Exceeded	TDS Concentration (mg/l)				
	Unregulated	Run 13	Run 14	Run 15	Run 16
1	3,455	1,359	1,247	2,010	1,442
2	2,557	1,053	1,043	1,039	1,115
5	1,505	796	847	750	912
10	925	667	701	603	733
25	526	481	505	432	523
50	314	358	380	314	390
75	201	290	305	240	311
90	-57	231	262	115	266
95	-432	155	219	-191	225
100	-6,563	-108,899	-2,206	-365,507	-4,186

Table 7.12
CHLORIDE CONCENTRATION-DURATION CURVES AT RICHMOND GAGE FOR RESSALT SIMULATION RUNS 1-4

Percent Time: Equalled or Exceeded	Chloride Concentration (mg/l)				
	Unregulated	Run 1	Run 2	Run 3	Run 4
1	215	322	335	427	354
2	189	266	280	304	304
5	135	218	235	207	241
10	100	182	194	156	194
25	86	114	123	90	125
50	74	73	79	60	82
75	64	58	64	35	64
90	56	34	41	-19	43
95	44	0	-2	-150	11
100	0	-57,948	-10,200	-269,362	-12,089

Table 7.13
CHLORIDE CONCENTRATION-DURATION CURVES AT RICHMOND GAGE FOR RESSALT SIMULATION RUNS 13-16

Percent Time: Equalled or Exceeded	Chloride Concentration (mg/l)				
	Unregulated	Run 13	Run 14	Run 15	Run 16
1	1,155	537	513	963	546
2	824	429	399	435	424
5	463	286	307	277	329
10	276	227	235	195	244
25	135	124	135	103	137
50	65	71	76	56	80
75	22	47	53	28	55
90	-68	-6	7	-60	19
95	-205	-111	-79	-239	-60
100	-2,360	-4,946	4,582	-259,650	-6,172

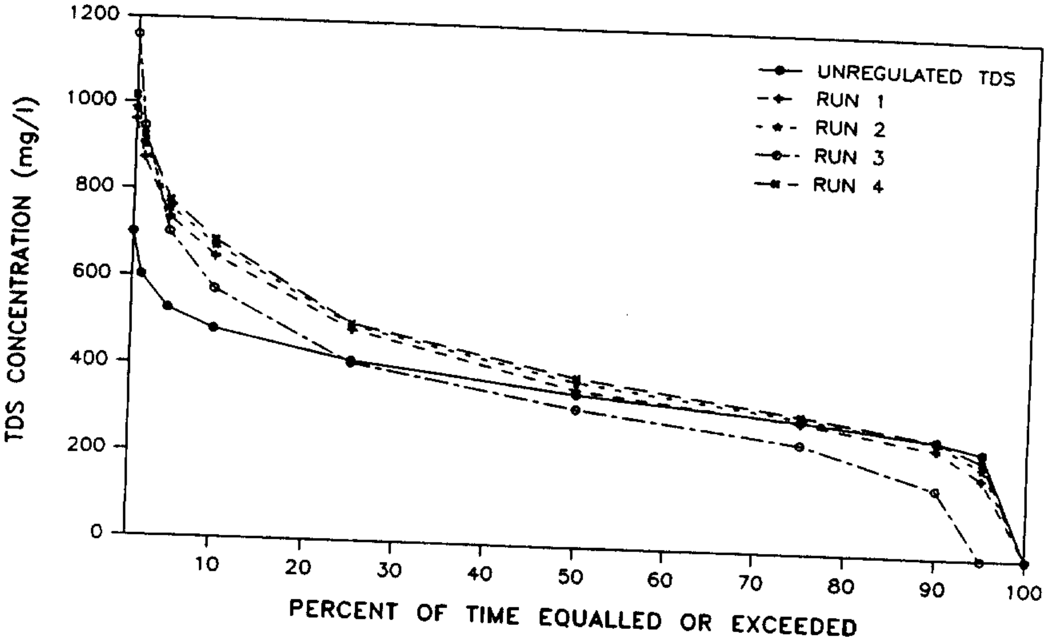

Figure 7.1 TDS Concentration-Duration Curves at Richmond Gage for RESSALT Simulation Runs 1-4

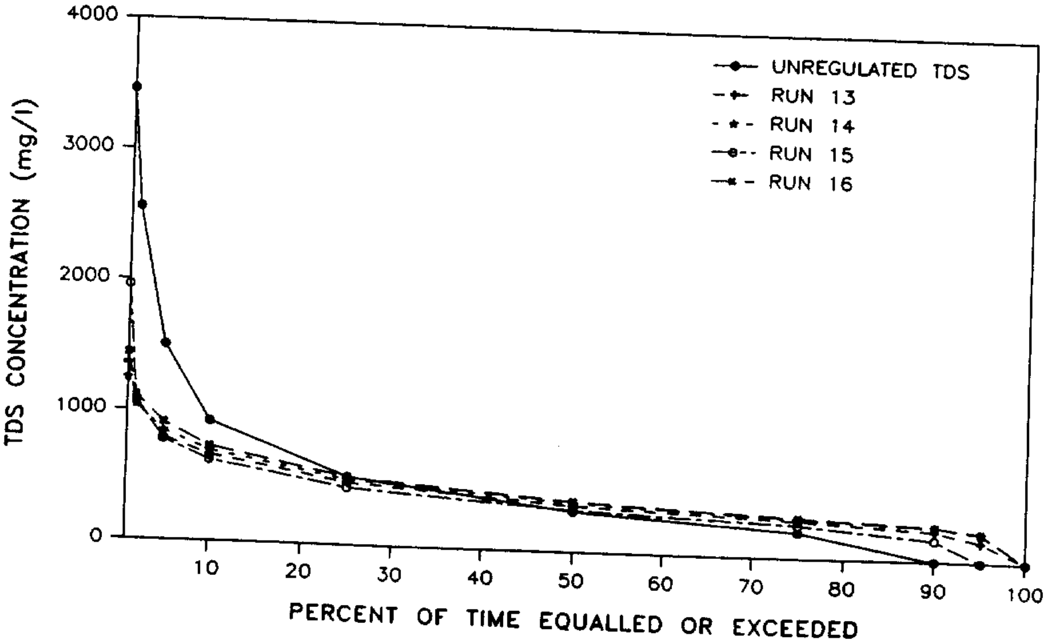

Figure 7.2 TDS Concentration-Duration Curves at Richmond Gage for RESSALT Simulation Runs 13-16

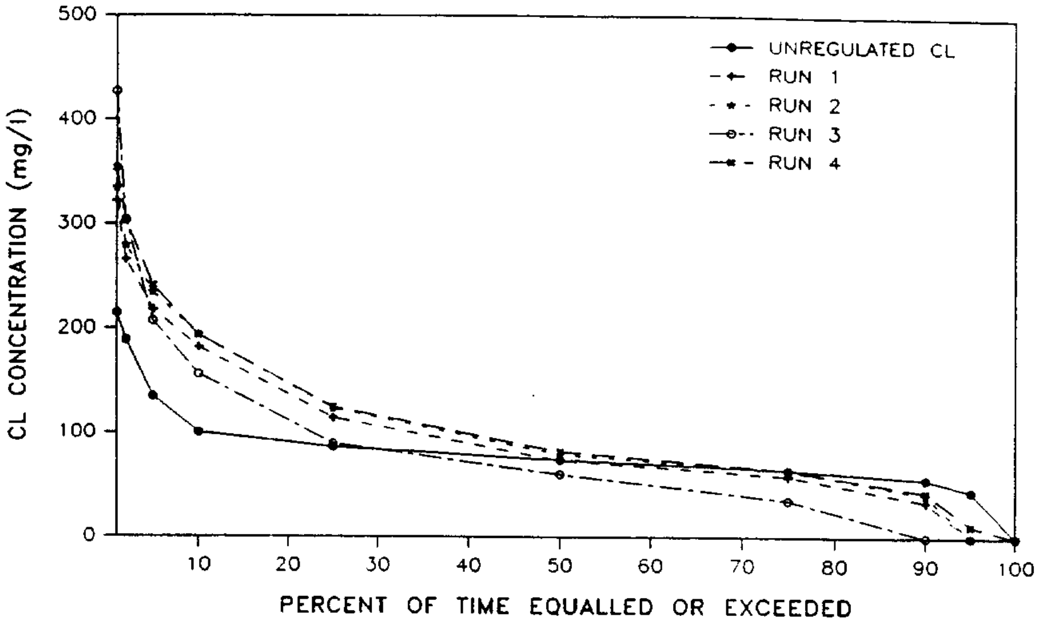

Figure 7.3 Chloride Concentration-Duration Curves at Richmond Gage for RESSALT Simulation Runs 1-4

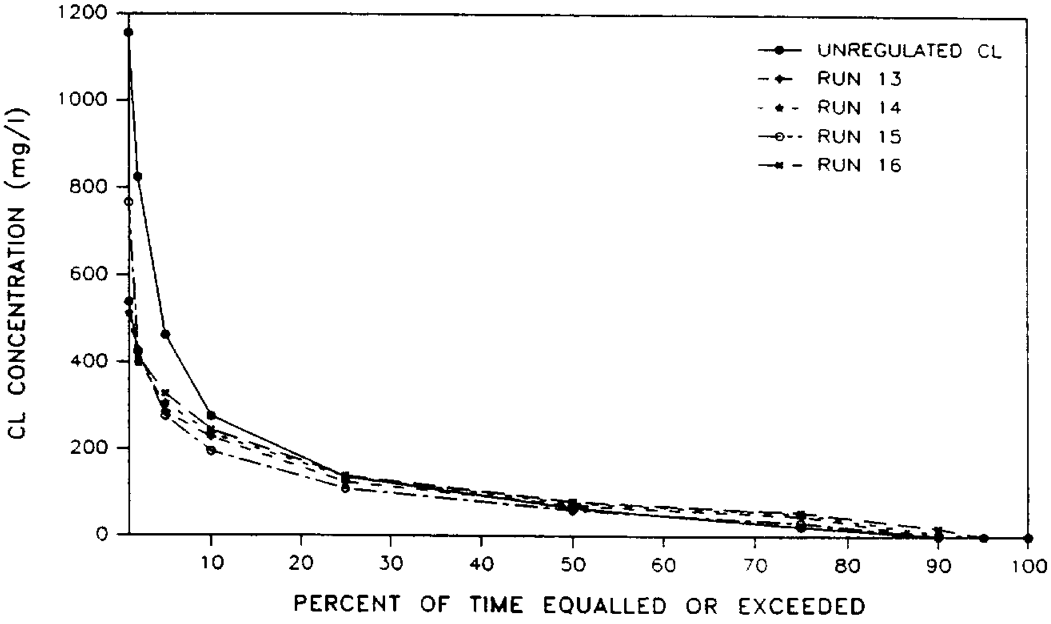

Figure 7.4 Chloride Concentration-Duration Curves at Richmond Gage for RESSALT Simulation Runs 13-16

factors remaining constant, adding the random variation to the unregulated salt loads (runs 14 and 16) decreased these reliabilities to 68.29% and 60.23%.

Run 17 was also made to test the sensitivity of model results to the variance of the inputted salt loads and associated unregulated concentrations. Run 17 is identical to run 4 and run 16 except for the unregulated salt loads. The 1900-84 mean unregulated loads and concentrations at each control point are the same in runs 4, 16, and 17. The month-to-month variations differ between the three runs. Run 17 is unique in that the unregulated concentrations are constant. The unregulated loads inputted to RESSALT for the run 17 simulation were computed by simply multiplying the monthly discharges by the 1900-84 mean concentration at each control point. Thus, for each control point: (1) runs 4, 16, and 17 have the same 1900-84 mean loads and concentrations (197,970 tons/month and 308 mg/l for TDS); (2) run 4 unregulated concentrations are closely correlated with discharges and the variations are unrealistically minimal; (3) run 16 includes a random component in the unregulated salt loads resulting in much greater variations in the unregulated concentration; and (4) run 17 has no variation at all in the unregulated concentrations. Runs 17 and 16 are the extremes, with run 4 falling in between.

System reliabilities (Table 7.6) for runs 4, 16, and 17 are 61.47%, 60.23%, and 60.07%, respectively. A review of the system mean quantities tabulated in Tables 7.3-7.4 indicates that values for run 4 fall in between values for runs 16 and 17, as to be expected. The 1900-84 means of all the quantities in Tables 7.3-7.5 are quite similar for the three alternative runs. The TDS and chloride concentration-duration curves for run 17 presented in Table 7.14 are similar to those for runs 4 and 16 shown in Tables 7.10-7.13.

Table 7.14
TDS AND CHLORIDE CONCENTRATION-DURATION CURVES
AT RICHMOND GAGE FOR RESSALT SIMULATION RUN 17

Percent Time Equalled or Exceeded	Concentration (mg/l)			
	TDS		Chloride	
	Unregulated	Regulated	Unregulated	Regulated
1	308	922	67	181
2	308	789	67	148
5	308	634	67	119
10	308	519	67	94
25	308	414	67	71
50	308	345	67	57
75	308	318	67	51
90	308	274	67	40
95	308	185	67	18
100	308	-1,347	67	-299

As discussed in Chapter 5, the month-to-month variations in the inputted unregulated concentrations for runs 1-12 are not realistic. The variance of the unregulated concentrations are unrealistic even though the corresponding loads and discharges are realistic. The unregulated concentrations are too constant. Consequently, the month-to-month variations in the RESSALT computed regulated concentrations are suspect. However, this modeling concern appears to have relatively little impact on simulation results, at least from the perspective of summary statistics such as reliabilities, long-term mean concentrations, and water and load balances.

Negative Incremental Streamflows and Salt Loads

The unregulated discharges and salt loads provided in the RESSALT input file are total or cumulative values. These represent the total flow and load to pass the control point location during the month. However, the simulation computations use incremental, rather than total, unregulated flows and loads. A RESSALT run begins by computing incremental unregulated discharges and salt loads. The incremental flows and loads at a control point are computed as the inputted cumulative values at the control point minus the corresponding inputted cumulative values at the adjacent upstream control point(s). The incrementals represent the flows and loads entering the river between control points. For the most upstream control point on a tributary, incrementals equal totals. For a given month, the summation of the incrementals at all control points equals the total flow or load at the Richmond gage, which is the most downstream control point or system outlet.

Although usually positive values, incremental unregulated discharges and loads are sometimes negative. In some cases, the negative unregulated incrementals result in negative regulated cumulative flows and/or loads and corresponding concentrations. A negative incremental means that the flow or load upstream is greater than downstream for the month. Negative incrementals may be caused by: (1) natural channel losses due to seepage or evaporation, (2) flood discharges which occur during the later part of a month at a location being delayed until the next month at a downstream location due to travel time in the reach, and (3) measurement and computation inaccuracies.

RESSALT provides three options for handling negative incrementals. The default option allows incrementals to be negative or positive with no special treatment either way. This option was used in all of the runs cited in this report except run 18. The other two options do not allow negative incrementals. Option 2 sets the computed negative incrementals equal to zero and subtracts an equivalent amount from the flow or load in the next month. Option 3 simply sets computed negative incrementals equal to zero, which in effect adds to the amount of water and salt available to the system. Thus, the overall volume and load balance is maintained without increasing the total amounts of water and salt. Option 2 was adopted for run 18.

Runs 5 and 18 are identical except for the option for handling negative incremental unregulated discharges and loads. Significant negative incrementals do occur throughout the Brazos River Basin data set. However, the results for runs 5 and 18 are almost the same from the system overview perspective of Tables 7.3-7.6. Both of the options adopted in runs 5 and 18 preserve the long-term water and salt balances with only the monthly timing being different.

The TDS load storage change cited in Table 7.4 for run 18 is significantly different than for the other runs because of the negative incremental option. Most of the negative incrementals occurred at the three mainstream reservoirs. As indicated above, option 2 sets the negative incrementals equal to zero and subtracts an equivalent amount from the corresponding values for the next month. If the adjusted value for the next month is also negative, the next month in sequence continues to be adjusted until all negatives are removed. The last month in the simulation, which is December 1984 in the study, is the exception. The negatives stay negative since there is no next month. The negative incremental inflows to the reservoirs basically change the timing of storage changes with significant reductions in storage occurring in the last month.

As previously indicated, problems with negative incrementals resulted in the decision to omit the Southbend gage control point from the model. None of the runs cited in this chapter include the Southbend gage as a control point. The negative incrementals occur at the Possum Kingdom gage (station 13), located just downstream, but are caused by the unregulated flows and loads at the Southbend gage (station 12) being greater than at the downstream station 13 in some months. Since measured salinity data were available for only three years at the Southbend gage, most of the loads are synthesized by regression analysis. However, the naturalized streamflows, which are based on adjusted gaged data, also are much greater at the Southbend gage than at the Possum Kingdom gage during many months. The reasons for the negative incrementals have not been determined. However, actual loss of water and salt through bank seepage in Possum Kingdom Reservoir and/or the river reach upstream could possibly play a role.

CHAPTER 8
RESERVOIR SYSTEM YIELD/RELIABILITY ANALYSES

The simulation analyses reported in this chapter demonstrate the sensitivity of yield versus reliability relationships to specified allowable salt concentrations, reservoir system operating strategies, and salt control impoundments. The simulation model necessarily incorporates significant assumptions and simplifications. Consequently, the yield-reliability estimates provide only a rough approximation of the actual water supply capabilities of the real river/reservoir system. However, the yield-reliability estimates do provide a useful index or indicator of the sensitivity or response of the system to various factors of interest. Thus, the information presented in this chapter provides an enhanced overall understanding of the river/reservoir system rather than a single precise measure of water availability.

The concepts of period and volume reliability are discussed in Chapter 6 and applied in Chapters 7 and 8. Yield is specified in Chapter 8 as a demand (diversion or instream flow) target at the Richmond gage. Period reliability, as used in Chapter 8, is the percentage of the 1,020 months of the simulation during which a specified demand target (yield) at the Richmond gage is met fully without shortage. Shortages are the target minus actual diversions (or instream flows). Volume reliability is the percentage of the specified yield (Richmond gage diversion target) volume which is actually diverted. Volume reliability refers equivalently to either 1900-1984 total volume or mean monthly or mean annual volume. Firm yield is the maximum diversion or instream flow demand target with period and volume reliabilities of 100%.

Water Use Requirements and Reservoir Operating Policies

In the analyses addressed in this chapter, water use is represented as a hypothetical yield. A standard system operating plan was adopted for the various simulations. Hubbard, Whitney, Waco, and Proctor Reservoirs are each operated as individual projects to meet demands which are the same in all the simulations. The individual reservoir firm yields for Hubbard, Waco, and Proctor Reservoirs are diverted at the reservoirs. The Hubbard, Waco, and Proctor firm diversions are 57 cfs, 116 cfs, and 30 cfs, respectively, for 1984 sediment conditions, and 56, 106, and 20 cfs for 2010 sediment conditions. Whitney is operated for the hydroelectric energy demands (36 gigawatt-hours/year) outlined in Chapter 6. The other nine reservoirs are operated as a system to meet a diversion or instream flow target at the Richmond gage. The specified demand at the Richmond gage is met by available unregulated streamflows supplemented by reservoir releases as necessary. Alternative model runs were made with 1984 and 2010 conditions of reservoir sedimentation. The locations of the 13 reservoirs and Richmond gage are shown in Figures 6.1 and 6.2. The three other non-reservoir control points included in Figures 6.1 and 6.2 are not used in the simulations of Chapter 8.

Thus, in addition to the demand (yield) at the Richmond gage, which is the focus of the discussions to follow, diversions equal to individual reservoir firm yields are included in the model at Hubbard, Waco, and Proctor Reservoirs. The Hubbard, Waco, and Proctor lakeside diversions are made without consideration of allowable salt concentrations. There are no return flows. These diversions and the Whitney energy demands are the same in all the runs cited in this chapter. The demand at the Richmond gage was the only demand varied for alternative simulations and is the "yield" cited in the tables and figures of this chapter. Since the Richmond gage is the most downstream control point in the model, this yield can be viewed equivalently as representing either a diversion or instream flow target.

The yields are cited as a mean rate in cfs (1 ft^3/sec = 724 ac-ft/year = 60.3 ac-ft/month). However, the demand targets in the model were varied between the 12 months of the year to reflect seasonal water use patterns. Monthly water use distribution factors developed by Wurbs and Carriere (1988) were adopted for the present analyses. Water use records for the city of Waco were used to develop distribution factors for the withdrawals from Hubbard and Waco Reservoirs which are used primarily for municipal water supply. These monthly water use factors vary from 6.2% to 11.7% of the annual use. The monthly distribution factors for the diversion at the Richmond gage represent basinwide averages for all use types. These water use factors vary from 2% of the annual use occurring in January to 27% in July. The seasonal variation in Whitney hydroelectric energy demands are outlined in Chapter 6.

Relationships Between Yield, Allowable Salt Concentrations, and Reliability

With no maximum allowable salt concentration specified, the firm yield at the Richmond gage is 2,235 cfs for 1984 sediment conditions. This firm yield added to the individual reservoir firm yields, totaling 203 cfs, being diverted at Hubbard, Waco, and Proctor Reservoirs results in a total firm yield of 2,438 cfs for the 13-reservoir system operated as outlined above. However, if the Richmond gage diversion is constrained to an allowable TDS concentration of 500 mg/l, the firm yield at the Richmond gage is reduced to zero, and a minimal yield of 100 cfs has a period reliability of only 68.14%. Specifying a maximum allowable TDS concentration of 1,000 mg/l at the Richmond gage results in zero firm yield and a period reliability of 92.45% for a yield of 100 cfs. Thus, with reasonably stringent salt constraints, essentially no yield level can be maintained continuously throughout the simulation without a shortage occurring.

Several numbers are cited in this paragraph simply for comparison to provide a general feel for the relative magnitude of the yields presented in this chapter. The 1900-1984 mean of the unregulated flows at the Richmond gage, which are provided as model input, is 7,890 cfs. This can be viewed as an upper limit on firm yield. The firm (100% reliability) yield would be 7,890 cfs, hypothetically assuming: (1) a reservoir with unlimited storage capacity is located at the Richmond gage and (2) there are no evaporation, other diversions, or specified allowable salt concentrations. Of course in actuality, limited storage capacity, evaporation, and salt constraints reduce firm yield estimates to much less than 7,890 cfs, as indicated by the firm yields of 2,235 cfs and zero cited in the preceding paragraph. As indicated by Table 2.5, an estimated 794,000 acre-feet/year, or 1,100 cfs, was diverted from the Brazos River and tributaries for beneficial use during the year 1984. The 1984 and 2010 net diversions adopted for the simulation runs of the previous Chapter 7 are 983 cfs and 2,710 cfs, respectively (712,000 and 1,960,000 ac-ft/yr). Concentration limits for TDS, chlorides, and sulfates of 500 mg/l, 250 mg/l, and 250 mg/l are recommended in the Environmental Protection Agency drinking water standards.

Volume and period reliabilities, respectively, are tabulated in Tables 8.1-8.2 and plotted in Figures 8.1-8.3 as a function of yield and salt constraint. Each value cited represents a separate run of RESSALT. The yield is a mean annual diversion target at the Richmond gage. The salt constraint is the maximum allowable salt concentration for the diversion. In each month, the diversion is made only if the concentration at the Richmond gage is at or below the allowable. Salt constraints are expressed alternatively in terms of total dissolved solids, chloride, and sulfate. Only one of the salt constituents is included in the allowable limit specified for each simulation.

Tables 8.1-8.2 and Figures 8.1-8.3 demonstrate the sensitivity of reliabilities for a specified yield (or, equivalently, yields for a given reliability) to the allowable salt concentrations specified. For example, if no salt constraint is specified, a diversion target of 2,000 cfs at the Richmond gage can be met continuously, without shortage, during the 1,020-month simulation. However, if a maximum allowable TDS concentration of 500 mg/l is specified, the 2,000 cfs diversion target is fully met during only 70.88% (Table 8.2) of the 1,020 months, and the total or mean volume diverted is 74.11% (Table 8.1) of the target demand. For a demand target (yield) of 1,000 cfs at the Richmond gage, the period reliability decreases from 96.27% to 69.80% with a decrease in the maximum allowable TDS concentration from 1,000 mg/l to 500 mg/l with all other factors remaining constant. With a TDS constraint of 500 mg/l, a minimal yield of 100 cfs has a period reliability of 68.14%. With a TDS constraint of 500 mg/l, reliabilities are controlled by TDS concentrations with the yield levels having only limited effects.

Specifying a constraint of 250 mg/l for chlorides results in period and volume reliabilities of 83.53% and 80.44%, respectively, for the minimal 100 cfs yield. With a chloride constraint of 700 mg/l, firm yield is zero, and yields of 100 cfs, 1,000 cfs, and 2,000 cfs have similar period reliabilities of 99.41%, 99.90%, and 99.41%, respectively. Although reliabilities generally decrease with increasing yield, a higher diversion can decrease reservoir evaporation and actually improve reliabilities slightly. A sulfate constraint of 250 mg/l results in period and volume reliabilities of 97.25% and 94.81% for the 100 cfs yield. The corresponding period and volume reliabilities for a yield of 1,000 cfs are 99.41% and 99.49%, respectively.

Reliabilities are clearly sensitive to salt constraints. The sensitivity decreases with increasing demand levels. The yield-reliability relationships are much more sensitive to total dissolved solids and chloride constraints than to sulfate constraints. If relatively stringent maximum allowable salt concentrations are adopted, water supply capabilities are constrained by salinity rather than available volume of water.

Comparison of Alternative Salt Constraint Operating Plans

The following five operating plans were simulated to compare alternative approaches for dealing with salinity constraints:

Plan 1.- standard operating plan with no allowable concentrations specified.

Plan 2.- same as plan 1 except maximum allowable salt concentrations are specified.

Table 8.1
VOLUME RELIABILITY, YIELD, AND ALLOWABLE SALT CONCENTRATION RELATIONSHIPS FOR 1984 SEDIMENT CONDITIONS

Salt Constituent	Salt Constraint	Yield (cfs)								
		100	1000	2000	3000	4000	5000	6000	7000	8000
	NO	100	100	100.00	95.64	89.94	82.19	74.99	68.66	63.03
	1500	98.35	99.93	99.39	95.47	89.86	82.09	74.97	68.58	62.93
	1000	89.67	97.18	96.06	92.41	88.40	81.40	74.65	68.28	62.72
	900	86.80	93.91	93.28	90.13	86.52	80.88	74.08	67.96	62.47
TDS (ppm)	800	81.62	89.64	90.52	86.55	82.74	78.37	72.68	66.90	61.74
	700	76.99	84.92	86.63	82.60	76.83	73.78	70.95	65.42	60.28
	600	71.41	78.01	81.37	76.41	70.71	65.60	64.21	60.04	57.21
	500	67.11	70.49	74.11	69.05	64.95	58.92	58.86	54.13	52.81
	700	98.85	99.96	99.74	95.49	89.84	82.13	74.99	68.59	62.92
	600	98.00	99.93	99.42	95.49	89.86	82.10	74.97	68.57	62.92
	500	95.07	99.61	98.67	95.15	89.84	82.08	74.95	68.55	62.90
Cl (ppm)	400	91.27	98.24	97.35	94.12	89.10	81.62	74.85	68.48	62.81
	300	85.28	92.34	92.32	88.12	85.32	79.72	73.70	67.71	62.33
	250	80.44	86.77	88.63	83.76	80.46	76.45	72.37	66.62	61.37
	200	76.01	80.66	83.42	79.46	74.69	69.27	65.63	61.33	58.56
	700	100.00	99.96	99.84	95.52	89.85	82.13	74.99	68.59	62.94
	600	100.00	99.96	99.84	95.52	89.85	82.13	74.99	68.59	62.94
	500	100.00	99.96	99.84	95.52	89.85	82.13	74.99	68.59	62.94
SO_4 (ppm)	400	99.62	99.96	99.84	95.52	89.85	82.12	74.99	68.59	62.94
	300	97.53	99.91	99.41	95.47	89.84	82.11	74.99	68.59	62.93
	250	94.81	99.49	98.58	95.09	89.72	82.08	74.96	68.58	62.91
	200	90.59	97.98	96.56	92.86	88.83	81.52	74.71	68.40	62.78

Note

All of the tables in Chapter 8 are tabulations of reliabilities expressed in percent (%).

Table 8.2
PERIOD RELIABILITY, YIELD, AND ALLOWABLE SALT CONCENTRATION RELATIONSHIPS FOR 1984 SEDIMENT CONDITIONS

Salt Constituent	Salt Constraint	Yield(cfs)								
		100	1000	2000	3000	400	5000	6000	7000	8000
	No	100.00	100.00	100.00	94.71	88.63	78.53	69.41	62.65	56.57
	1500	99.12	99.80	99.22	94.31	88.24	78.24	69.51	62.55	56.47
	1000	92.45	96.27	96.47	92.35	87.06	77.45	69.31	62.45	56.47
	900	88.82	92.84	92.35	90.00	85.39	76.57	69.12	62.45	56.86
TDS (ppm)	800	84.22	88.24	89.41	86.47	82.06	75.10	68.33	62.65	56.86
	700	79.71	82.94	84.51	82.06	77.16	72.65	66.47	61.47	57.16
	600	73.73	77.65	78.63	76.47	72.65	67.55	64.90	59.12	55.59
	500	68.14	69.80	70.88	68.92	65.98	61.67	58.82	56.76	53.63
	700	99.41	99.90	99.41	94.31	88.33	78.33	69.41	62.55	56.47
	600	99.02	99.80	99.31	94.31	88.24	78.24	69.51	62.55	56.47
	500	97.55	99.61	98.92	94.22	88.14	78.24	69.61	62.55	56.47
Cl (ppm)	400	94.61	98.14	97.84	93.53	87.75	77.84	69.61	62.45	56.47
	300	87.84	91.75	92.75	88.82	85.39	76.86	69.90	62.45	56.57
	250	83.53	86.37	87.45	84.90	81.59	75.20	68.92	62.55	56.96
	200	78.33	80.59	81.96	79.12	76.57	70.78	66.57	62.06	57.16
	700	100.00	99.90	99.71	94.41	88.33	78.43	69.41	62.55	56.47
	600	100.00	99.90	99.71	94.41	88.33	78.43	69.41	62.55	56.47
	500	100.00	99.90	99.71	94.41	88.33	78.43	69.41	62.55	56.47
SO_4(ppm)	400	99.80	99.90	99.71	94.41	88.33	78.33	69.41	62.55	56.47
	300	98.63	99.71	99.22	94.31	88.33	78.33	69.51	62.55	56.47
	250	97.25	99.41	98.82	94.22	88.24	78.33	69.51	62.55	56.47
	200	93.24	97.25	97.06	92.75	87.35	77.84	69.61	62.45	56.47

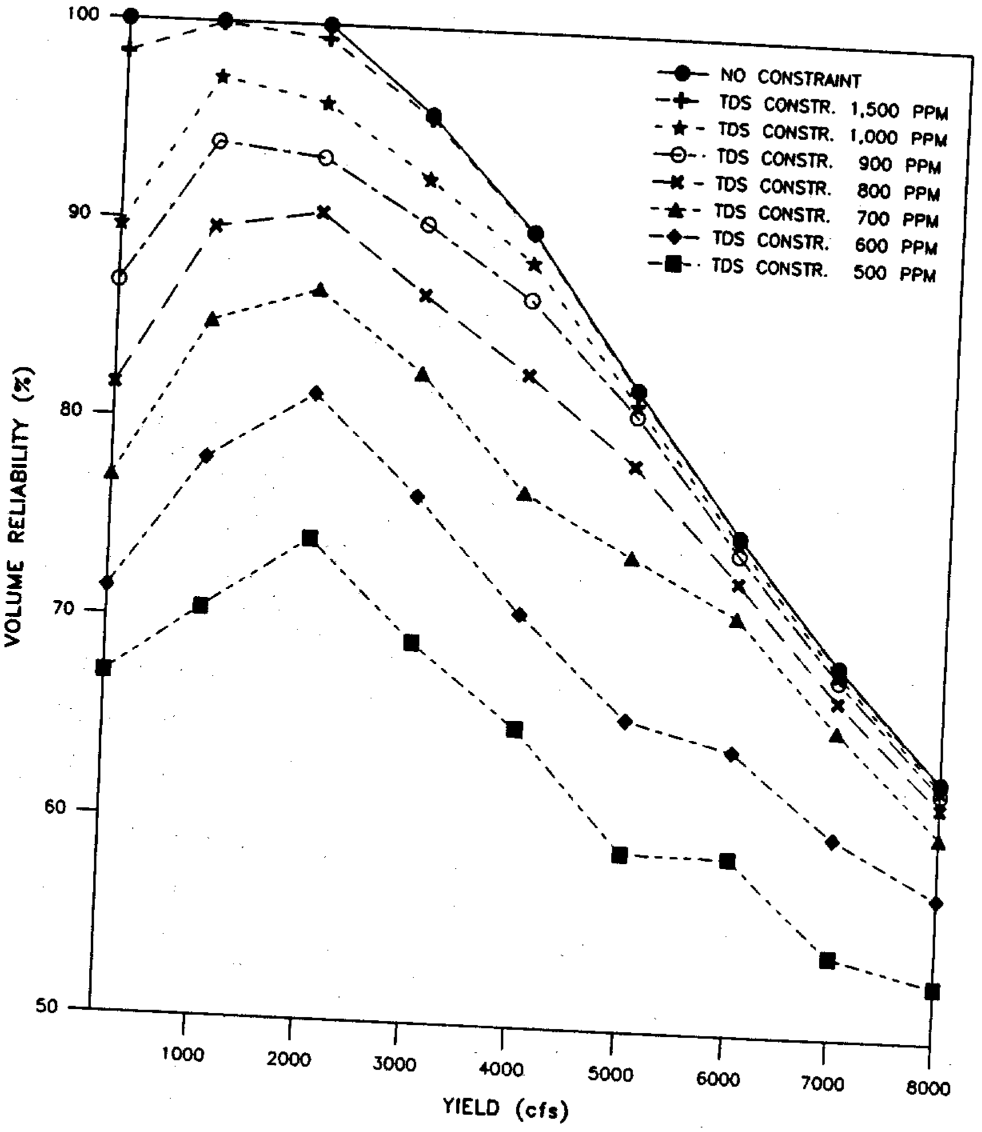

Figure 8.1 Volume Reliability, Yield, and Allowable TDS Concentration Relationships for 1984 Sediment Conditions

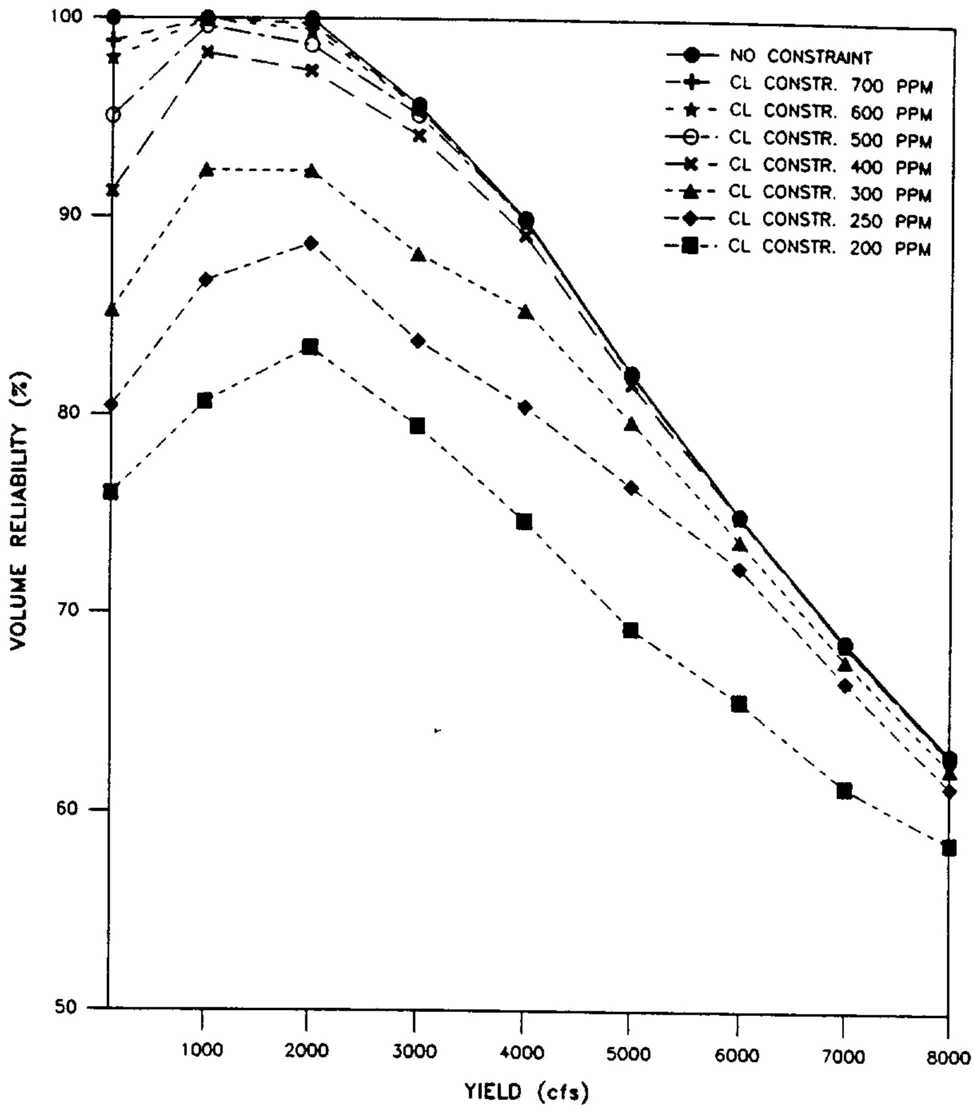

Figure 8.2 Volume Reliability, Yield, and Allowable Chloride Concentration Relationships for 1984 Sediment Conditions

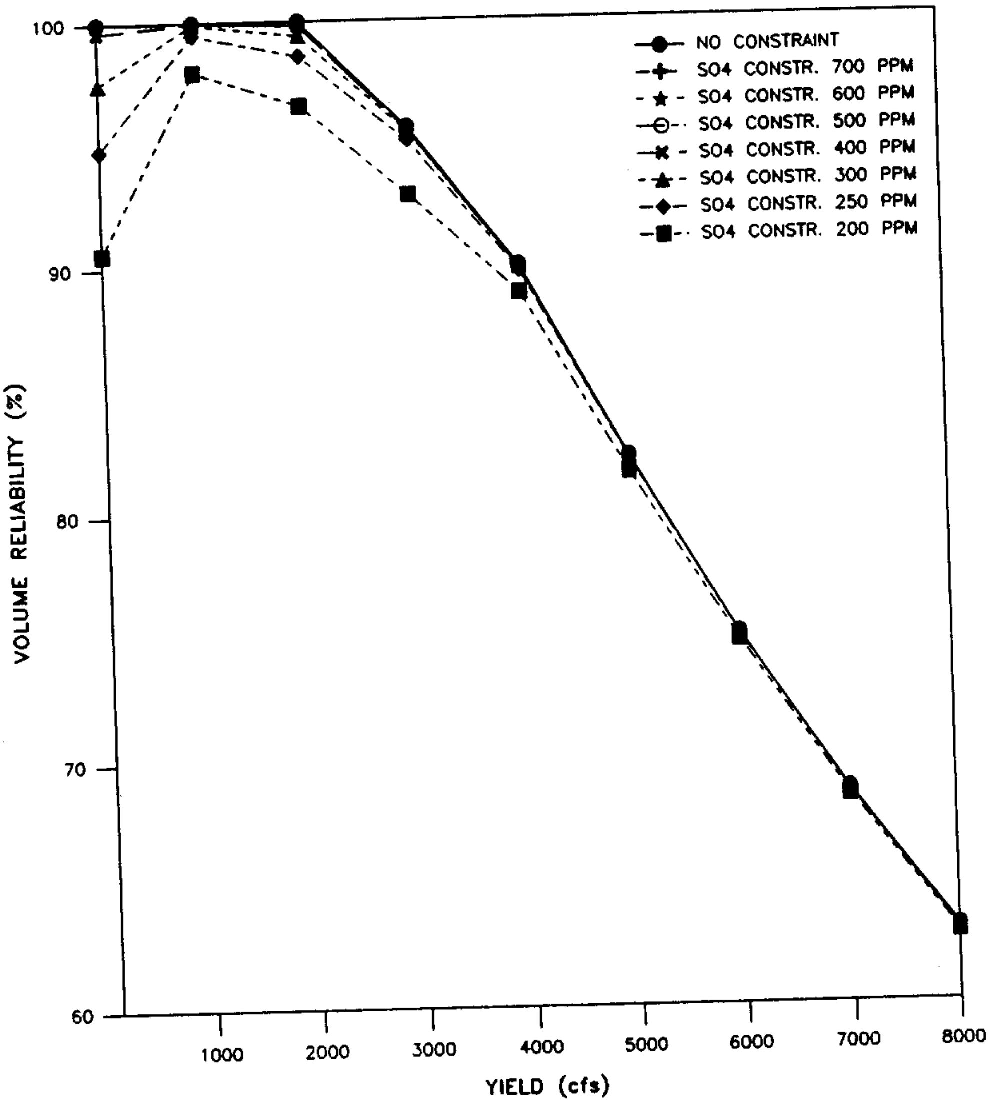

Figure 8.3 Volume Reliability, Yield, and Allowable Sulfate Concentration Relationships for 1984 Sediment Conditions

Plan 3.- same as plan 2 except releases from Possum Kingdom and Granbury Reservoirs are precluded as necessary to minimize shortages on a monthly basis,

Plan 4.- same as plan 2 except releases from Possum Kingdom and Granbury Reservoirs are precluded unless the tributary reservoirs are empty, and

Plan 5.- same as plan 2 except releases from the tributary reservoirs are precluded unless Possum Kingdom and Granbury Reservoirs are empty.

Plan 1 reflects the standard operating plan described in the previous section which includes diversions of 57, 116, and 30 cfs, respectively, at Hubbard, Waco, and Proctor Reservoirs for 1984 sediment conditions or diversions of 56, 106, and 20 cfs for 2010 sediment conditions. Whitney Reservoir is operated for hydroelectric energy demands of 36 gigawatt-hours/year. The varying yield cited in the tables and figures represents the demand at the Richmond gage. Plan 1 does not include specification of allowable salt concentrations. The other four operating plans include maximum allowable salt concentrations. Three alternative levels of allowable concentrations were adopted. Level I consists of TDS, chloride, and sulfate concentrations of 500 mg/l, 250 mg/l, and 250 mg/l, respectively. Alternative levels II and III consist of allowable concentrations of twice and triple this basic level. Level II is 1,000 mg/l, 500 mg/l, and 500 mg/l, respectively, for TDS, chloride, and chloride. Level III is 1,500 mg/l, 750 mg/l, and 750 mg/l.

Plans 2 through 5 differ only in specification of multiple-reservoir release rules for the nine reservoirs operated to meet the demand (yield) at the Richmond gage. Plan 2, as well as plan 1, is based solely on balancing the percentage depletion (or full) of the conservation storage capacity of the nine reservoirs. The release is made from the reservoir that is most full (or least depleted). Plans 3-5 address the fact that Possum Kingdom and Granbury Reservoirs, on the main stream Brazos River, have extremely high salt concentrations compared to the seven other system reservoirs located on good quality tributaries. Shortages are caused by either insufficient water quantity and/or quality. The concentrations at the Richmond gage, in a given month, can be partially controlled by the decision of which reservoir to release from that month, assuming insufficient unregulated flow necessitates a reservoir release.

Plan 3 utilizes a RESSALT option which minimizes total system shortages in a given month. The total shortages in a month are computed alternatively assuming releases from Possum Kingdom and Granbury Reservoirs are allowed versus are not allowed. In precluding or blocking consideration of specific reservoirs in multiple-reservoir release decisions, the alternative options considered by the model each month included blocking either Possum Kingdom or Granbury singly or both together or neither. Subject to precluding or including Possum Kingdom and/or Granbury as possible sources for releases, the release decision is again based on balancing percent storage depletions. The alternative that minimizes shortages is selected for that individual month.

Plan 4 consists of always precluding the high salinity Possum Kingdom and Granbury Reservoirs from consideration in the monthly release decisions unless the other seven reservoirs are completely empty. Plan 5 consists of always precluding the seven good quality tributary reservoirs from consideration in the monthly release decisions unless the conservation storage capacity of Possum Kingdom and Granbury Reservoirs are empty.

Thus, plan 4 consists of not releasing from Possum Kingdom and Granbury unless absolutely necessary as compared to plan 3 which encourages releases from Possum Kingdom and Granbury unless such releases increase shortages. Plans 3 and 4 are both realistic, unlike plan 5 which is not. Plan 5 represents an extremely ineffective approach, demonstrating lower limits to reliabilities, which is included in the analysis for purposes of comparison. Plan 5 consists of making all releases from Possum Kingdom and Granbury until their active conservation pools are emptied.

Simulation Results

Yield versus reliability relationships, with each of the three levels of allowable salt concentrations, for the five operating plans are presented in Tables 8.3-8.6. The reliability/yield/salt constraint relationships are repeated in the four tables for both volume and period reliability and for both 1984 and 2010 conditions of reservoir sedimentation. The sedimentation condition is reflected only in the storage versus area relationships inputted for each reservoir. Each pair of volume and period reliability values in Tables 8.3 & 8.4 and Tables 8.5 & 8.6 reflect a separate execution of RESSALT. The yield represents the demand target at the Richmond gage for which nine reservoirs operate.

A comparison of the reliabilities for plans 1 and 2 again demonstrates sensitivity to salt constraints. Reliabilities (or yields for given reliabilities) are significantly lowered by hypothetically adopting level I allowable TDS, chloride, and sulfate concentrations of 500, 250, and 250 mg/l, respectively. Level II allowable concentrations of 1,000, 500, and 500 mg/l have a much smaller but still somewhat significant impact on reliabilities.

A comparison of plans 2-5 provides an indication of the potential impacts of multiple-reservoir release decisions on concentrations at downstream diversion locations. None of the plans include release of additional water solely for the purpose of dilution. However, releases to meet a quantity requirement can also affect concentrations. Multiple-reservoir release policies can partially mitigate salt constraints. The logical approach is to make releases from the good quality reservoirs.

With salt constraint levels II and III, Plans 2, 3, 4, and 5 result in about the same reliabilities. With salt constraint level I, the reliabilities vary somewhat between Plans 2, 3, 4, and 5. Thus, reliabilities appear to be sensitive to varying multiple-reservoir release policies only if relatively stringent maximum allowable salt concentrations are adopted.

With salt constraint level I, the reliabilities for both plans 3 and 4 are significantly higher than those for plan 2. Volume reliabilities are slightly higher for plan 3 than for plan 4, but plans 3 and 4 period reliabilities are about the same. The difference in plans 3 and 4 is that plan 3 attempts to analyze the tradeoffs between releasing from good versus bad quality reservoirs each month based on minimizing shortages for the month. The idea is to release from Possum Kingdom and Granbury (balance depletions) whenever possible without increasing total shortages

Table 8.3
VOLUME RELIABILITY, YIELD, AND ALLOWABLE SALT CONCENTRATION RELATIONSHIPS FOR ALTERNATIVE OPERATING PLANS FOR 1984 SEDIMENT CONDITIONS

Salt Constraints	Yield	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5
Level I: TDS: 500 mg/l Cl : 250 mg/l SO_4: 250 mg/l	100	100.00	71.63	71.82	71.80	70.96
	1000	100.00	77.11	84.55	84.42	69.73
	2000	100.00	77.59	91.59	89.11	66.05
	3000	95.94	70.85	85.74	83.23	60.34
	4000	89.94	63.91	77.67	75.43	54.43
	5000	82.18	61.88	72.22	69.61	52.53
	6000	75.01	57.80	66.71	64.44	51.51
Level II: TDS: 1000 mg/l Cl : 500 mg/l SO_4: 500 mg/l	100	100.00	98.55	98.74	98.74	98.44
	1000	100.00	98.44	99.64	99.64	97.02
	2000	100.00	96.52	99.93	98.51	95.78
	3000	95.94	95.15	95.95	94.16	96.02
	4000	89.94	89.98	90.15	89.59	89.92
	5000	82.18	83.24	83.20	82.81	83.14
	6000	75.01	76.19	76.26	76.04	76.10
Level III: TDS: 1500 mg/l Cl : 750 mg/l SO_4: 750 mg/l	100	100.00	99.21	99.72	99.72	99.29
	1000	100.00	99.57	99.88	99.96	99.51
	2000	100.00	99.97	100.00	99.84	99.68
	3000	95.94	95.76	96.18	95.68	96.17
	4000	89.94	90.53	90.69	90.06	90.06
	5000	82.18	83.36	83.43	83.19	83.20
	6000	75.01	76.28	76.34	76.12	76.15

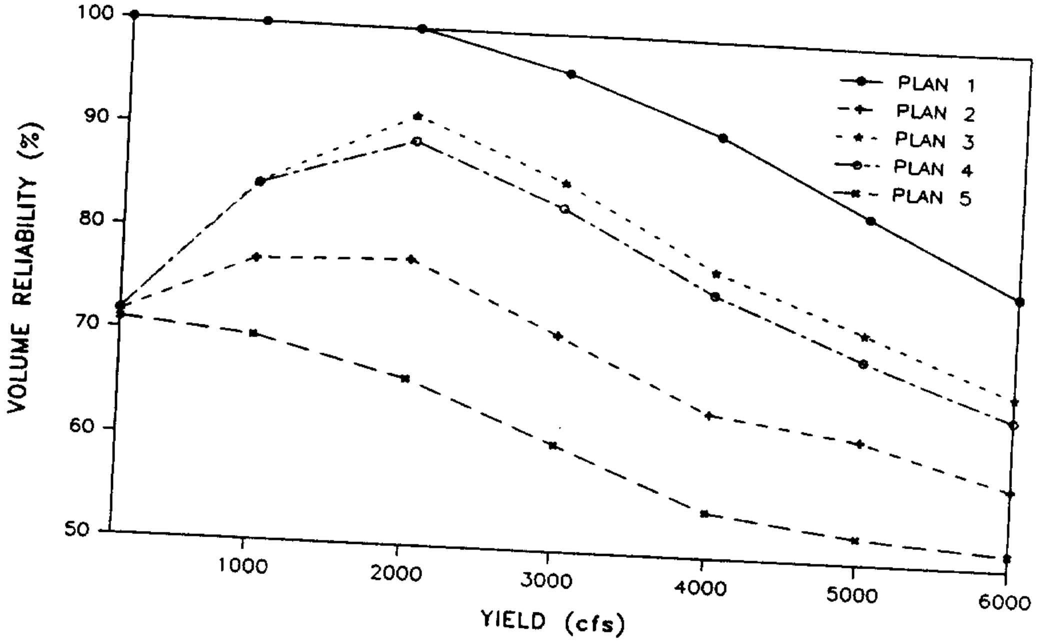

Figure 8.4 Reliability Versus Yield Relationships for 1984 Sediment Conditions for Level I Salt Constraints

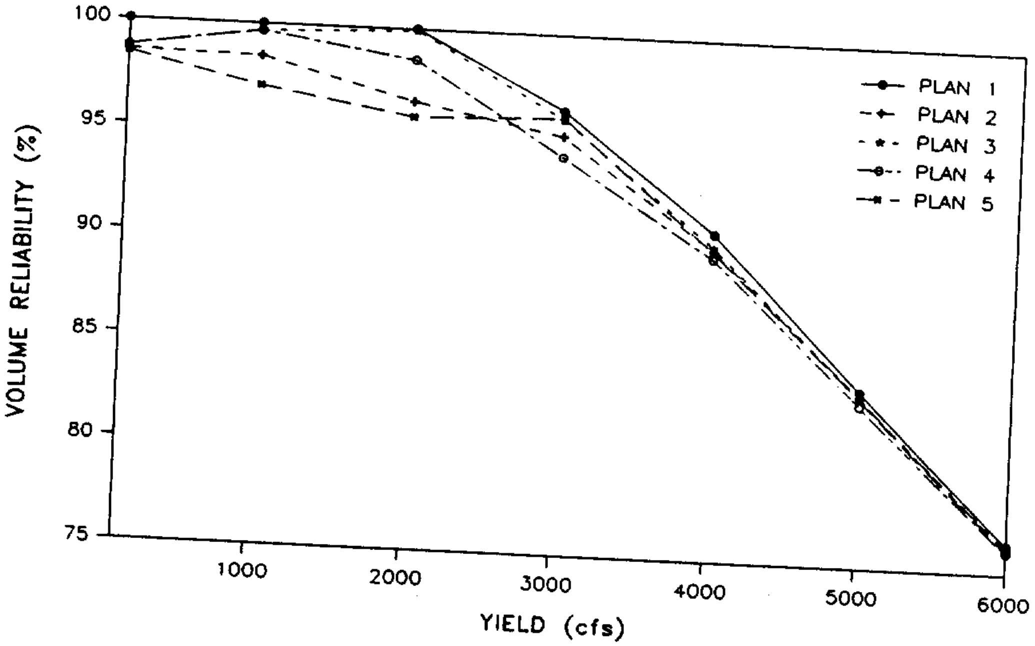

Figure 8.5 Reliability Versus Yield Relationships for 1984 Sediment Conditions for Level II Salt Constraints

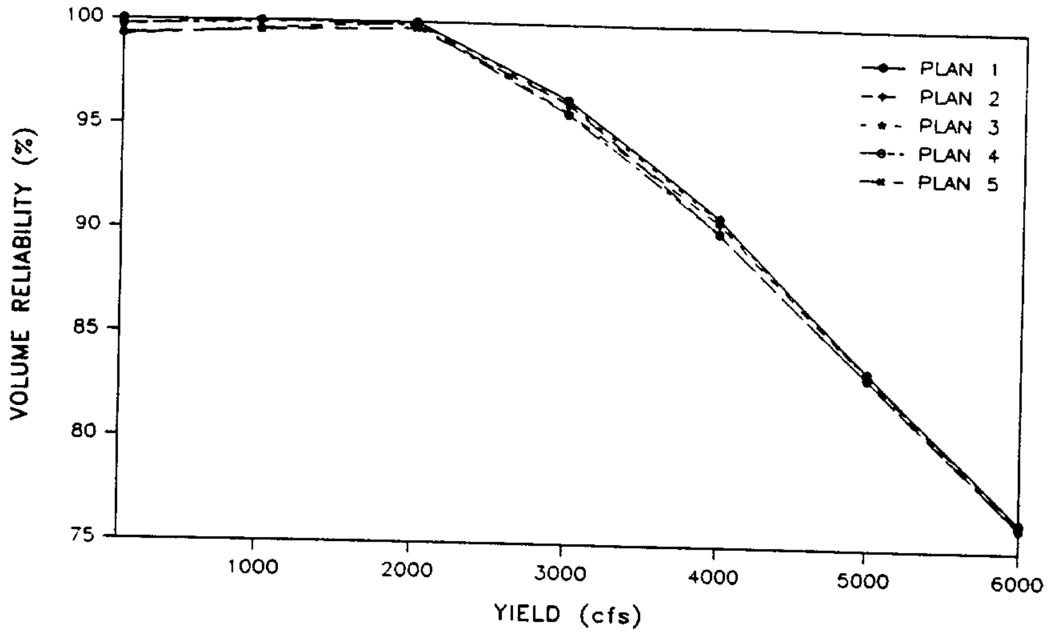

Figure 8.6 Reliability Versus Yield Relationships for 1984 Sediment Conditions for Level III Salt Constraints

Notes:

1. All simulations cited in Chapter 8 are based on operating plans which include nine reservoirs operated to meet a diversion target at the Richmond gage, which is the yield cited in the tables and figures. Reservoir releases are made as needed to supplement streamflows. The other four reservoirs are included in the model but are operated to meet their own individual requirements, consisting of hydroelectric energy demands at Whitney and lakeside diversions at Hubbard, Waco, and Proctor, which are not included in the cited Richmond gage yields.

2. The five alternative operating plan cited in Tables 8.3-8.13 and Figures 8.4-8.6 are defined as follows:

Plan 1.- Multiple(nine)-reservoir release decisions are based on balancing storage. Salt concentrations are not considered.

Plan 2.- Same as Plan 1 except maximum allowable salt concentrations are specified.

Plan 3.- Same as Plan 2 except monthly release decisions are based on minimizing shortages while still balancing storage to the extent possible.

Plan 4.- Same as Plan 2 except releases are made from Possum Kingdom and Granbury Reservoirs only if the seven tributary reservoirs are empty.

Plan 5.- Same as Plan 2 except releases are made from the seven tributary reservoirs only if Possum Kingdom and Granbury Reservoirs are empty.

Table 8.4
PERIOD RELIABILITY, YIELD, AND ALLOWABLE SALT CONCENTRATION RELATIONSHIPS FOR ALTERNATIVE OPERATING PLANS FOR 1984 SEDIMENT CONDITIONS

Salt Constraints	Yield	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5
	100	100.00	76.47	76.57	76.47	76.08
Level I:	1000	100.00	78.24	81.96	81.96	74.71
TDS: 500 mg/l	2000	100.00	78.33	86.37	84.80	71.37
Cl : 250 mg/l	3000	94.51	72.55	81.86	82.25	66.37
SO_4: 250 mg/l	4000	87.94	67.45	71.08	76.37	61.67
	5000	78.73	66.08	67.65	73.14	60.39
	6000	70.00	62.75	62.94	68.53	57.65
	100	100.00	99.12	99.22	99.22	99.12
Level II:	1000	100.00	99.02	99.51	99.51	98.24
TDS: 1000 mg/l	2000	100.00	97.84	99.90	98.73	97.25
Cl : 500 mg/l	3000	94.51	94.80	94.71	95.78	94.71
SO_4: 500 mg/l	4000	87.94	88.63	89.12	89.80	88.14
	5000	78.73	79.90	80.10	80.88	80.00
	6000	70.00	71.76	71.18	71.37	71.18
	100	100.00	99.61	99.80	99.80	99.71
Level III:	1000	100.00	99.71	99.80	99.90	99.51
TDS: 1500 mg/l	2000	100.00	99.90	100.00	99.51	99.31
Cl : 750 mg/l	3000	94.51	95.00	94.80	94.61	94.90
SO_4: 750 mg/l	4000	87.94	89.31	89.35	88.82	88.24
	5000	78.73	79.90	79.80	80.59	80.10
	6000	70.00	71.86	71.27	71.27	71.57

Table 8.5
VOLUME RELIABILITY, YIELD, AND ALLOWABLE SALT CONCENTRATION RELATIONSHIPS FOR ALTERNATIVE OPERATING PLANS FOR 2010 SEDIMENT CONDITIONS

Salt Constraints	Yield	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5
	100	100.00	71.62	71.85	71.82	71.29
Level I:	1000	100.00	77.94	85.71	85.26	70.30
TDS: 500 mg/l	2000	100.00	77.61	91.47	87.15	66.64
Cl : 250 mg/l	3000	95.44	69.13	84.69	81.84	60.43
SO_4: 250 mg/l	4000	89.24	64.98	75.99	73.73	54.03
	5000	81.36	60.12	69.16	67.99	58.64
	6000	74.04	58.91	65.44	62.13	58.17
	100	100.00	98.87	99.08	99.08	98.45
Level II:	1000	100.00	98.49	99.68	99.55	97.27
TDS: 1000 mg/l	2000	100.00	97.16	99.90	98.27	96.72
Cl : 500 mg/l	3000	95.44	94.65	94.92	93.61	94.69
SO_4: 500 mg/l	4000	89.24	88.87	89.02	88.08	88.84
	5000	81.36	81.04	81.20	80.71	80.88
	6000	74.04	73.98	74.08	73.93	73.93
	100	100.00	99.21	99.72	99.72	99.29
Level III:	1000	100.00	99.60	99.92	99.92	99.32
TDS: 1500 mg/l	2000	100.00	99.94	100.00	99.67	99.79
Cl : 750 mg/l	3000	96.44	95.27	95.28	94.72	95.32
SO_4: 750 mg/l	4000	89.24	89.07	89.16	88.39	89.00
	5000	81.36	81.14	81.29	80.86	81.13
	6000	74.04	74.04	74.14	74.00	74.01

Table 8.6

PERIOD RELIABILITY, YIELD, AND ALLOWABLE SALT CONCENTRATION RELATIONSHIPS FOR ALTERNATIVE OPERATING PLANS FOR 2010 SEDIMENT CONDITIONS

Salt Constraints	Yield	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5
Level I: TDS: 500 mg/l Cl : 250 mg/l SO_4: 250 mg/l	100	100.00	76.37	76.57	76.47	76.18
	1000	100.00	78.63	82.75	82.35	74.90
	2000	100.00	78.14	85.78	84.51	71.86
	3000	94.12	72.55	80.98	81.57	65.78
	4000	87.55	67.94	72.16	75.98	61.37
	5000	77.35	65.29	65.29	72.16	63.24
	6000	68.43	62.16	62.65	67.94	59.41
Level II: TDS: 1000 mg/l Cl : 500 mg/l SO_4: 500 mg/l	100	100.00	99.22	99.41	99.41	99.12
	1000	100.00	99.12	99.61	99.41	98.24
	2000	100.00	98.33	99.71	98.33	97.55
	3000	94.12	94.02	93.92	94.80	93.53
	4000	87.55	87.16	87.25	86.37	86.96
	5000	77.35	77.65	77.45	77.94	77.84
	6000	68.43	69.02	68.82	68.92	68.92
Level III: TDS: 1500 mg/l Cl : 750 mg/l SO_4: 750 mg/l	100	100.00	99.61	99.80	99.80	99.71
	1000	100.00	99.80	99.90	99.90	99.41
	2000	100.00	99.80	100.00	99.22	99.61
	3000	94.12	94.02	94.02	94.02	93.92
	4000	87.55	87.45	87.65	86.27	87.25
	5000	77.35	77.75	77.55	77.35	77.94
	6000	68.43	69.02	68.82	68.82	69.12

for the current month. Plan 4 is based simply on releasing from the good quality reservoirs until they are emptied and then using Possum Kingdom and Granbury. The results are about the same in both cases, indicating little opportunity to improve water supply reliability by refining multiple-reservoir operating policies.

Plan 5 is included in the analysis as a representation of an "ineffective" operating strategy which approximates the lower extreme of system reliabilities. Multiple-reservoir system operating plan 2 is based solely on balancing storage depletions without attempting to mitigate salt constraints. Plans 3 and 4 reduce shortages caused by salinity by releasing from the good quality reservoirs. Plan 5, on the other extreme, increases shortages caused by salinity by releasing from the high salinity reservoirs. Tables 8.3-8.6 indicate that reliabilities for plan 5 are significantly, but not necessarily drastically, lower than plans 2-4 for salt constraint level I. With salt constraint level III, all five plans result in quite similar reliabilities.

The simulations reflected in Table 8.3-8.6 were repeated using reservoir storage and surface area data alternatively for years 1984 and 2010 conditions of reservoir sedimentation. The resulting reliabilities are almost the same for either sediment condition. The reliabilities reflect a tradeoff between effects on quantity and quality. The total conservation storage capacity in the 13 reservoirs for 2010 sedimentation is 91.5% of the 1984 storage capacity. The decrease in storage capacity decreases quantity availability and reliability. However, since less water is in storage for 2010 conditions, evaporation tends to be decreased with a corresponding decrease in salt concentrations and possible improvement in reliabilities.

Evaluation of Reservoir Storage Reallocations

Wurbs and Carriere (1988) performed a yield-reliability analysis for alternative storage reallocations without considering salinity. The following presentation extends their work to include salt concentrations. As indicated in Tables 2.1-2.2, the nine USACE reservoirs each contain significant flood control as well as conservation storage capacities. The flood control and conservation pools are set by a designated top of conservation pool elevation. A portion of the flood control storage capacity may be reallocated to conservation purposes by raising the top of conservation pool. Wurbs and Carriere (1988) address storage reallocation in detail. The present discussion is limited to repeating the simulations, which are covered in the previous sections, with the two storage reallocation plans outlined below.

The USACE has discretionary authority to reallocate the lesser of 50,000 acre-feet or 15% of the flood control capacity, as long as project purposes are not significantly impacted. Greater reallocations in federal projects require congressional approval. The first reallocation plan consists of permanent reallocation of this amount of flood control capacity to water supply in each of the following seven USACE/BRA reservoirs: Whitney, Aquilla, Waco, Belton, Stillhouse Hollow, Granger, and Somerville. Storage capacities are tabulated in Tables 2.2-2.3. This reallocation would, of course, adversely impact flood control capabilities. A seasonal rule curve represents an attempt at improving either conservation and/or conservation operations while minimizing adverse impacts on the other purpose. Seasonal rule curve operations, as used here, consist of seasonally varying the designated top of conservation pool. The second storage reallocation plan is the same as the first except the reallocation occurs only during late Spring

Table 8.7
VOLUME RELIABILITY, YIELD, AND ALLOWABLE SALT CONCENTRATION RELATIONSHIPS FOR PERMANENT STORAGE REALLOCATION PLAN FOR 1984 SEDIMENT CONDITIONS

Yield(cfs)	Reliability(%)	Alternative Operating Plans				
		Plan 1	Plan 2	Plan 3	Plan 4	Plan 5
100	Volume	100.00	71.22	71.22	71.20	70.29
	Period	100.00	75.10	75.10	75.00	74.61
1000	Volume	100.00	77.84	84.35	84.35	69.30
	Period	100.00	77.35	81.08	80.98	73.33
2000	Volume	100.00	75.70	91.77	89.01	65.31
	Period	100.00	70.10	83.63	85.49	76.37
3000	Volume	96.56	70.57	86.33	83.22	59.84
	Period	95.88	71.47	81.18	80.88	65.78
4000	Volume	90.83	66.38	77.45	74.59	53.71
	Period	88.92	69.31	72.25	75.78	61.27
5000	Volume	83.39	61.59	71.72	68.92	57.18
	Period	79.90	64.51	68.14	72.45	61.27
6000	Volume	76.14	57.33	65.78	62.57	58.75
	Period	71.96	62.16	61.96	68.04	61.08

Table 8.8
VOLUME RELIABILITY, YIELD, AND ALLOWABLE SALT CONCENTRATION RELATIONSHIPS FOR SEASONAL STORAGE REALLOCATION PLAN FOR 1984 SEDIMENT CONDITIONS

Yield(cfs)	Reliability(%)	Alternative Operating Plans				
		Plan 1	Plan 2	Plan 3	Plan 4	Plan 5
100	Volume	100.00	71.32	71.59	71.56	70.76
	Period	100.00	76.57	76.76	76.76	67.18
1000	Volume	100.00	71.69	87.64	87.20	68.10
	Period	100.00	76.86	83.63	83.24	74.02
2000	Volume	100.00	67.88	92.31	88.06	64.39
	Period	100.00	74.31	87.06	84.51	71.67
3000	Volume	96.06	63.03	85.42	81.97	57.83
	Period	94.80	70.59	81.67	80.69	65.20
4000	Volume	89.93	59.17	76.21	73.22	52.82
	Period	88.14	67.65	71.67	75.00	61.67
5000	Volume	82.26	54.96	69.26	67.70	49.66
	Period	78.82	65.39	64.41	71.67	58.82
6000	Volume	74.86	53.67	64.73	61.41	54.98
	Period	69.41	62.84	60.98	66.76	59.71

and Summer. The amount of storage capacity reallocated from flood control to conservation purposes in each of the seven reservoirs is the lesser of 50,000 acre-feet or 15% of the flood control capacity. The first reallocation plan consists of permanently reallocating the storage capacity. The second plan consists of reallocating the storage capacity from May through August of each year. The seasonal rule curve involves raising the designated top of conservation pool at the beginning of May and lowering it at the end of August. Both the permanent and seasonal reallocation plans are combined with specification of maximum allowable TDS, chloride, and sulfate concentrations of 500, 250, and 250 mg/l, respectively.

Reliabilities for the permanent and seasonal storage reallocations are tabulated in Tables 8.7-8.8, respectively. Except for allocations of storage capacity, the simulations represented in Tables 8.7 and 8.8 are identical to those of Tables 8.3 and 8.4 for salt constraint level I.

Impacts of Proposed Salt Control Dams

The system of three salt control impoundments proposed by the USACE (1973) and reevaluated by the USACE (1983) is described in Chapter 4. The locations of the impoundments are shown in Figure 4.1. The salt control plan is also evaluated in Chapter 7.

The simulations reflected in Tables 8.9-8.12 are identical to those of the previously discussed Tables 8.3-8.6 except for inclusion of the three salt control impoundments. The salt impoundments are represented in RESSALT by the inputted salt loads and discharges, which are discussed in Chapter 5. Representation of the salt dams in RESSALT for the Chapter 8 simulations is the same as for the previously discussed Chapter 7 simulations.

A comparison of Tables 8.3 & 8.9, 8.4 & 8.10, 8.5 & 8.11, and 8.6 & 8.12 indicates that the salt control dams significantly increase reliabilities for salt constraint level I. The improvement in reliabilities is relatively small for salt constraint level II. The salt control impoundments have essentially no impact for salt constraint level III. For example, with salt constraint level I, Table 8.3 indicates reliabilities of 71.80%, 84.42%, and 89.11% for yields of 100 cfs, 1,000 cfs, and 2,000 cfs, respectively, for operating plan 4. The corresponding Table 8.9 reliabilities, with the salt control dams, are 84.96%, 95.41%, and 93.45%. For salt constraint level II, the corresponding 100 cfs, 1,000 cfs, and 2,000 cfs reliabilities are 98.74%, 99.64%, and 98.51%, without the salt control dams, as compared to 99.47%, 99.96%, and 99.60% with the salt control dams.

As noted in Chapters 4 and 7, the proposed salt control impoundments would significantly reduce salinity along the entire length of the Brazos River. However, the effectiveness of the salt control plan in improving water supply reliability depends upon (1) the allocation of water between types of use, (2) the sensitivity of the water uses to salinity, and (3) location of diversions and reservoir releases.

Effects of Alternative Sets of Unregulated Loads

Task 6 of Chapter 5 consists of developing an alternative set of unregulated salt loads which includes partially random load variations. The effects of the alternative sets of unregulated loads are previously discussed in Chapter 7. The 1900-84 mean unregulated loads and concentrations are identical in both data sets. However, the alternative set has greater month to month variations in concentrations.

The Chapter 5 Task 6 unregulated salt loads are included in the RESSALT input for the simulations reflected in Table 8.13. These simulations also incorporate salt constraint level I. The simulations of Table 8.13 are identical to those of Tables 8.3-8.4 (salt constraint level I) except for the unregulated salt loads input to RESSALT. Reliabilities for operating plan 1 are the same in Table 8.13 and Tables 8.3-8.4 because salt concentrations are not considered. The reliabilities for operating plans 2-4 in Table 8.13 are slightly (typically less than one percent) lower than the corresponding values in Tables 8.3-8.4. Thus, the alternative unregulated salt load input data sets result in about the same system reliabilities.

Table 8.9
VOLUME RELIABILITY, YIELD, AND ALLOWABLE SALT CONCENTRATION RELATIONSHIPS FOR ALTERNATIVE OPERATING PLANS FOR 1984 SEDIMENT CONDITIONS WITH SALT CONTROL IMPOUNDMENTS

Salt Constraints	Yield	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5
Level I: TDS: 500 mg/l Cl : 250 mg/l SO_4: 250 mg/l	100	100.00	85.01	85.01	84.96	84.27
	1000	100.00	87.64	95.52	95.41	80.98
	2000	100.00	87.36	96.09	93.45	78.12
	3000	95.82	82.94	91.10	87.42	73.01
	4000	89.71	76.61	84.35	81.37	78.32
	5000	81.89	73.70	77.87	75.43	81.89
	6000	74.72	71.07	72.13	70.03	71.12
Level II: TDS: 1000 mg/l Cl : 500 mg/l SO_4: 500 mg/l	100	100.00	99.15	99.47	99.47	99.24
	1000	100.00	99.80	99.82	99.96	99.80
	2000	100.00	99.47	99.93	99.60	99.62
	3000	95.82	95.50	95.69	94.81	95.74
	4000	89.71	89.42	89.54	88.85	88.87
	5000	81.89	81.73	81.79	81.52	81.69
	6000	74.72	74.61	74.65	74.48	74.43
Level III: TDS: 1500 mg/l Cl : 750 mg/l SO_4: 750 mg/l	100	100.00	99.40	99.72	99.72	99.48
	1000	100.00	99.90	99.91	100.00	99.81
	2000	100.00	99.67	99.93	99.83	99.62
	3000	95.82	95.65	95.70	95.36	95.74
	4000	89.71	89.48	89.59	88.97	88.93
	5000	81.89	81.78	81.84	81.58	81.74
	6000	74.72	74.65	74.69	74.52	74.52

Table 8.10
PERIOD RELIABILITY, YIELD, AND ALLOWABLE SALT CONCENTRATION RELATIONSHIPS FOR ALTERNATIVE OPERATING PLANS FOR 1984 SEDIMENT CONDITIONS WITH SALT CONTROL IMPOUNDMENTS

Salt Constraints	Yield	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5
	100	100.00	88.53	88.53	88.43	88.33
Level I:	1000	100.00	90.00	94.22	93.82	86.96
TDS: 500 mg/l	2000	100.00	90.10	94.51	93.24	83.43
Cl : 250 mg/l	3000	94.31	86.18	90.10	89.71	78.43
SO_4: 250 mg/l	4000	87.75	79.80	81.76	83.92	97.41
	5000	78.53	74.71	74.22	78.14	78.73
	6000	69.61	67.75	67.75	71.67	67.25
	100	100.00	99.50	99.61	99.61	99.61
Level II:	1000	100.00	99.61	99.71	99.90	99.12
TDS: 1000 mg/l	2000	100.00	99.41	99.90	99.31	99.41
Cl : 500 mg/l	3000	94.31	93.73	93.92	93.73	93.82
SO_4: 500 mg/l	4000	87.75	87.75	87.55	86.86	86.86
	5000	78.53	78.53	78.43	78.24	78.82
	6000	69.61	69.71	69.51	69.41	69.02
	100	100.00	99.71	99.80	99.80	99.80
Level III:	1000	100.00	99.80	99.90	100.00	99.61
TDS: 1500 mg/l	2000	100.00	99.51	99.90	99.51	99.41
Cl : 750 mg/l	3000	94.31	93.92	94.02	93.92	93.92
SO_4: 750 mg/l	4000	87.75	87.75	87.65	87.06	86.96
	5000	78.53	78.53	78.53	78.53	78.53
	6000	69.61	69.61	69.51	69.41	69.12

Table 8.11
VOLUME RELIABILITY, YIELD, AND ALLOWABLE SALT CONCENTRATION RELATIONSHIPS FOR ALTERNATIVE OPERATING PLANS FOR 2010 SEDIMENT CONDITIONS WITH SALT CONTROL IMPOUNDMENTS

Salt Constraints	Yield	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5
Level I: TDS: 500 mg/l Cl : 250 mg/l SO_4: 250 mg/l	100	100.00	85.65	85.65	85.60	84.91
	1000	100.00	88.09	95.63	95.78	81.43
	2000	100.00	87.41	96.06	93.82	79.27
	3000	95.37	83.11	90.93	88.34	74.58
	4000	89.06	76.57	84.09	80.94	81.85
	5000	81.13	74.88	77.94	75.74	77.54
	6000	73.89	70.86	71.65	69.52	71.30
Level II: TDS: 1000 mg/l Cl : 500 mg/l SO_4: 500 mg/l	100	100.00	99.15	99.47	99.47	99.24
	1000	100.00	99.82	99.82	99.96	98.81
	2000	100.00	99.29	100.00	99.56	99.71
	3000	95.37	95.14	95.20	94.44	95.16
	4000	89.06	88.81	88.83	88.13	88.34
	5000	81.13	80.87	81.01	80.64	80.82
	6000	73.89	73.72	73.81	73.71	73.64
Level III: TDS: 1500 mg/l Cl : 750 mg/l SO_4: 750 mg/l	100	100.00	99.72	99.72	99.72	99.80
	1000	100.00	99.90	99.91	100.00	99.82
	2000	100.00	99.97	100.00	99.81	99.75
	3000	95.37	95.14	95.20	94.84	95.17
	4000	89.06	88.91	88.92	88.13	88.38
	5000	81.13	80.92	81.06	80.70	80.87
	6000	73.89	73.76	73.85	73.75	73.74

Table 8.12
PERIOD RELIABILITY, YIELD, AND ALLOWABLE SALT CONCENTRATION RELATIONSHIPS FOR ALTERNATIVE OPERATING PLANS FOR 2010 SEDIMENT CONDITIONS WITH SALT CONTROL IMPOUNDMENTS

Salt Constraints	Yield	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5
Level I: TDS: 500 mg/l Cl : 250 mg/l SO_4: 250 mg/l	100	100.00	89.12	89.12	89.02	99.92
	1000	100.00	90.49	94.71	94.41	87.35
	2000	100.00	89.51	94.90	93.63	84.31
	3000	94.12	85.49	89.51	90.59	79.61
	4000	87.35	79.71	81.57	83.63	81.18
	5000	77.45	73.53	74.12	78.04	74.22
	6000	68.43	67.16	67.17	71.57	66.86
Level II: TDS: 1000 mg/l Cl : 500 mg/l SO_4: 500 mg/l	100	100.00	99.51	99.61	99.61	99.61
	1000	100.00	99.71	99.71	99.90	99.12
	2000	100.00	99.61	100.00	99.31	99.41
	3000	94.12	93.82	93.92	93.82	93.24
	4000	87.35	87.06	87.06	85.78	86.57
	5000	77.45	77.65	77.45	76.76	77.94
	6000	68.43	68.63	68.43	68.63	69.12
Level III: TDS: 1500 mg/l Cl : 750 mg/l SO_4: 750 mg/l	100	100.00	99.80	99.80	99.80	99.90
	1000	100.00	99.80	99.90	100.00	99.61
	2000	100.00	99.90	100.00	99.41	99.51
	3000	94.12	93.82	93.92	94.02	93.33
	4000	87.35	87.25	87.25	85.88	86.76
	5000	77.45	77.75	77.55	76.96	77.84
	6000	68.43	68.63	68.43	68.63	69.02

Table 8.13
PERIOD RELIABILITY, YIELD, AND ALLOWABLE SALT CONCENTRATION FOR 1984 SEDIMENT CONDITIONS FOR ALTERNATIVE SALT LOADS

		Alternative Operating Plans				
Yield(cfs)	Reliability(%)	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5
100	Volume	100.00	71.41	71.41	71.39	70.75
	Period	100.00	73.92	73.92	73.82	73.63
1000	Volume	100.00	77.00	85.26	85.17	69.83
	Period	100.00	76.67	81.47	80.88	72.55
2000	Volume	100.00	76.34	91.01	87.44	65.07
	Period	100.00	76.37	84.71	82.94	69.31
3000	Volume	95.94	69.36	84.07	81.31	59.44
	Period	94.51	70.98	79.61	79.71	64.22
4000	Volume	89.94	64.18	75.11	73.14	54.25
	Period	87.94	67.45	70.10	74.61	61.08
5000	Volume	82.18	59.68	68.87	67.67	53.90
	Period	78.73	63.82	63.82	70.49	59.22
6000	Volume	75.01	56.48	63.79	61.68	53.09
	Period	70.00	61.27	60.00	67.06	57.45

CHAPTER 9
SUMMARY AND CONCLUSIONS

Natural Salt Pollution in the Brazos River Basin

The primary source of salinity in the Brazos River is groundwater emissions in the Double Mountain Fork, Salt Fork, and North Croton Creek watersheds located in the upper basin. The river is characterized by extremely high salt concentrations and relatively low streamflows in the headwater tributaries and upper main stream, with flows increasing and concentrations decreasing in a downstream direction. Water quality improves in the lower reaches of the Brazos River due to dilution by tributary inflows. The three main stream reservoirs have salt concentrations which are much too high for municipal, irrigation, and other salinity-sensitive uses without costly desalinization processes or significant dilution. Most of the reservoirs in the basin are located on tributaries with relatively good quality water.

The 1964-86 mean total dissolved solids (TDS) concentration decreases from 3,600 mg/l to 340 mg/l in the approximately 760 river miles from the Seymour gage (150 miles above Possum Kingdom Dam) to the Richmond gage (92 miles above the Gulf). Chlorides constitute a particularly high proportion of the dissolved solids in the primary salt source area. The mean chloride concentrations at the Seymour and Richmond gages are 1,500 mg/l and 79 mg/l, respectively. Salt concentrations on the major tributaries are significantly lower. For example, the 1964-86 mean TDS and chloride concentrations at the Cameron gage on the Little River are 260 mg/l and 31 mg/l, respectively.

Streamflows, salt loads, and concentrations vary greatly over time as well as with location. Temporal variations in salt loads and concentrations are significant at all locations but are particularly drastic near the primary salt source area and in the river reach above Possum Kingdom Reservoir. Fluctuations in salt concentrations are dampened as the salt loads are transported through the three main stream reservoirs. Salt concentrations at upstream locations nearer the primary source area also have a more pronounced pattern of seasonal variation than in the lower reaches of the river.

Any long-term changes or trends over time that may have occurred historically are small relative to the tremendous random variability. Long-term trends or changes in salt concentrations could not be clearly defined by analyses of measured data. The RESSALT simulation studies showed that reservoir evaporation significantly increases salt concentrations, as compared to predevelopment basin conditions, but diversions of highly saline water from the upper reaches and main stream reservoirs can decrease concentrations in the lower basin.

The various salinity data synthesis and analysis procedures adopted in the study rely heavily on regression with discharge. Mean monthly salt concentrations and loads were found to not be as closely correlated with discharge as might be expected. Load versus discharge is much more closely correlated than concentration versus discharge.

Water Supply Reliability

Salinity has been widely recognized as being a controlling constraint in management and utilization of the water resources of the Brazos River Basin. However, water supply reliability in the Brazos River Basin, as well as elsewhere, has traditionally been quantified in terms of firm yield, without considering water quality. The study documented by this report incorporates salinity considerations in evaluating water availability. Water supply reliability estimates are demonstrated to be highly sensitive to specified allowable salt concentrations.

The generalized RESSALT river/reservoir system simulation model was developed in conjunction with the study. RESSALT simulates river basin system capabilities for meeting specified water use requirements during an assumed repetition of historical hydrology. The Brazos River Basin hydrology is represented by monthly streamflows, salt loads, and reservoir evaporation rates at selected locations covering a 1900-84 simulation period. Two alternative approaches were adopted for representing water use in the modeling and analysis exercises: (1) water use scenarios consisting of simplified representations of actual historical water use during the year 1984 and projected future water use for the year 2010; and (2) the traditional concept of hypothetical yields. Numerous simulations were performed to evaluate the effects of alternative management strategies and modeling assumptions.

The extremely high salinity in the three main stream reservoirs almost always preclude lakeside withdrawals when maximum allowable salt concentrations are specified in the model at essentially any reasonable level. Salinity is not a controlling factor for diversions on the better quality tributaries. Diversions from the lower reaches of the Brazos River represent a large portion of the total amount of water withdrawn from the main stream and tributaries for beneficial use. These downstream diversions are very sensitive to the level of maximum allowable salt concentrations specified in the model.

Although shortages occur at isolated upstream locations, the simulation modeling study indicates that, from a basinwide perspective, meeting the demands of the 1984 water use scenario, during an assumed repetition of historical period-of-record hydrology, is well within the water supply capabilities of the river/reservoir system if salinity is not considered. However, adopting maximum allowable TDS, chloride, and sulfate concentration limits of 500 mg/l, 250 mg/l, and 250 mg/l, respectively, for all uses, greatly reduces water supply reliabilities. With the 1984 water use scenario, hypothetically specifying these fairly stringent allowable salt concentration criteria reduces the overall system reliability from about 99.8% to 69.6%. The 2010 water use scenario results in significant shortages even without salt constraints, and specifying allowable salt concentrations significantly lowers the reliabilities. Overall system reliabilities for the 2010 water use scenario are 95.9% and 61.5%, respectively, with and without designation of allowable TDS, chloride, and sulfate concentrations of 500 mg/l, 250 mg/l, and 250 mg/l.

Relationships between yield, allowable salt concentrations, and reliability were developed for a hypothetical diversion target at the Richmond gage, in the lower basin, met by streamflows supplemented by releases from nine reservoirs. With no maximum allowable salt concentration limits specified, the firm yield is about 2,200 cfs. However, specifying a maximum allowable

TDS concentration of 1,000 mg/l reduces the firm (100% reliability) yield to zero. With the 1,000 mg/l TDS constraint, a minimal yield of 100 cfs has a reliability of about 90%, and a yield of 2,000 cfs has a reliability of about 96%. With a maximum allowable TDS concentration of 500 mg/l, yields of 100 cfs and 2,000 cfs have reliabilities of 67% and 74%, respectively. Lower salt concentrations caused by less reservoir evaporation result in a yield of 2,000 cfs having a greater reliability than a minimal yield of 100 cfs. Thus, as relatively stringent salt constraints are incorporated into the analysis, water supply reliabilities are controlled more by water quality than volume availability.

Consideration of water quality as well as quantity is important in evaluating water supply reliability in the Brazos River Basin. For municipal, irrigation, and other salinity-sensitive uses, quality rather than quantity is the limiting factor controlling water availability. Water supply reliability depends upon the (1) allocation of water between types of use, (2) allowable salt concentrations reflecting the sensitivity of the water uses and users to salinity, and (3) location of diversions and reservoir releases.

Management Strategies

The study included evaluation of the effects of two types of management strategies: (1) reservoir system operating policies and (2) impoundment of the runoff from the primary salt source watersheds. Management strategies were evaluated from the perspective of impacts on salt concentrations and water supply reliabilities.

Much of the water withdrawn from the Brazos River and its tributaries for beneficial use is diverted in the lower reach of the Brazos River. Flows in the lower Brazos River are a mixture of highly saline flows from the upper basin and flows from good quality tributaries. The concentrations can be affected by multiple-reservoir release policies. The simulation studies compared three alternative multiple-reservoir system operating policies based on (1) equally balancing the storage (percent storage depletion) in each reservoir, (2) releasing from the main stream reservoirs only if storage in the better quality tributary reservoirs is depleted, and (3) minimizing shortages each month while attempting to balance storage to the extent possible. Reliabilities were found to be only minimally sensitive to operating policies. Potentialities for improving multiple-reservoir system reliability through refinements in operating policies appear to be fairly limited.

Much of the salt load in the Brazos River originates from a relatively small area of the upper basin. The U.S. Army Corps of Engineers has investigated alternative strategies for controlling the natural salt pollution at its source. A plan consisting of three salt control impoundments was proposed by the USACE but later concluded to be economically infeasible. The present report includes an evaluation of the impacts of removing the loads and flows at the sites of the proposed salt dams. The sum of the mean discharges at gaging stations near the proposed salt control dam sites is only about 0.4% of the mean flow at the Richmond gage in the lower basin. However, the mean TDS, chloride, and sulfate loads at the salt control impoundments are 14%, 32%, and 11%, respectively, of the mean loads at the Richmond gage and much higher percentages of the mean loads flowing into the three main stream reservoirs. The proposed salt control impoundments or other equivalent measures would significantly reduce salt concentrations along the entire length of the Brazos River. Overall system reliabilities of 69.6% and 61.5%, respectively, are cited above for the 1984 and 2010 water use scenarios with the salt constraints indicated. These reliabilities are increased to 73.8% and 68.6% by the salt control impoundments.

Reallocation of water between uses and users has become a major focus in water resources planning and management nationwide in recent years. Water reallocations would be required to fully realize the potential benefits of the types of measures cited above. The types of modeling and analysis capabilities addressed here will be important in future evaluations of water reallocations and other associated water management plans.

Generalized Modeling and Analysis Capabilities

The RESSALT model, data files, and analysis methodologies developed in the research reported here are pertinent to other studies of the Brazos River Basin and other river basins as well. RESSALT is generalized for application to essentially any river basin. The simulation model provides flexible capabilities for a broad range of river/reservoir system modeling applications. The general modeling and analysis approach adopted here should be applicable to investigations of other major river basins in the Southwest and elsewhere in which natural salt pollution is of concern. The testing of alternative modeling assumptions and methods should be useful in other studies. The extensive Brazos River Basin data files, which include unregulated streamflows and salt loads, evaporation rates, and reservoir characteristics, will be very useful in continuing studies. The basic data files are also being used in another component of the present research study which involves integration of water rights and salinity considerations.

REFERENCES

Environmental Protection Agency, "Salinity Control, Interim Report for Water Supply and Water Quality Control Study, Brazos River Basin, Texas," EPA Region VI, Dallas, Texas, March 1973.

Ganze, C.K., "Analysis of Salt Concentrations in the Brazos River Basin," Master of Science Thesis, Texas A&M University, August 1990.

Ganze, C.K., and Wurbs, R.A., "Compilation and Analysis of Monthly Salt Loads and Concentrations in the Brazos River Basin," Prepared for U.S. Army Corps of Engineers Fort Worth District under Contract DACW63-88-M-0793, January 1989.

Irelan, B. and Mendieta, H.B., "Chemical Quality of Surface Waters in the Brazos River Basin in Texas," Water-Supply Paper 1779-K, U.S. Geological Survey, 1964.

Kane, J.W., "Monthly Reservoir Evaporation Rates for Texas, 1940 through 1965," Texas Water Development Board,' Report 64, October 1967.

Karama, A.S., "Analysis of Reservoir System Reliability Constrained by Natural Salt Pollution," Ph.D. Dissertation, Texas A&M University, August 1993.

Rawson, J., "Study and Interpretation of Chemical Quality of Surface Waters in the Brazos River Basin, Texas," Report 55, Texas Water Development Board, July 1967.

Rawson, J., Flugrath, M.W., and Hughes, L.S., "Sources of Saline Water in the Upper Brazos River Basin, Texas," Open File Report No. 108, U.S. Geological Survey, March 1968.

Saleh, I., "Synthesis of Streamflow and Salt Loads," Master of Science Thesis, Texas A&M University, August 1993.

Texas Department of Water Resources, "Water for Texas, A Comprehensive Plan for the Future," GP-4-1, November 1984.

Texas Water Development Board, "Water of Texas, Today and Tomorrow," GP-5-1, December 1990.

U.S. Army Corps of Engineers, Fort Worth District, "Natural Salt Pollution Control Study, Brazos River Basin, Texas," December 1973.

U.S. Army Corps of Engineers, Fort Worth District, "Final Environmental Impact Statement, Natural Salt Pollution Control Study, Brazos River Basin, Texas," January 1976.

U.S. Army Corps of Engineers, Fort Worth District, "Brazos Natural Salt Pollution Control, Brazos River Basin, Texas, Design Memorandum No. 1, General, Phase I - Plan Formulation," April 1983.

Wurbs, R.A., Bergman, C.E. Carriere, P.E., and Walls, W.B., "Hydrologic and Institutional Water Availability in the Brazos River Basin," TR-144, Texas Water Resources Institute, August 1988.

Wurbs, R.A., and Carriere, P.E., "Evaluation of Storage Reallocation and Related Strategies for Optimizing Reservoir System Operations," TR-145, Texas Water Resources Institute, August 1988.

Wurbs, R.A., and Walls, W.B., "Water Rights Modeling and Analysis," Journal of Water Resources Planning and Management, ASCE, Vol. 115, No. 4, July 1989.