INCORPORATING SALINITY CONSIDERATIONS IN WATER AVAILABILITY MODELING

A Thesis

by

GANESH KRISHNAMURTHY

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2005

Major Subject: Civil Engineering

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Approved as to style and content by:

Ralph Wurbs (Chair of Committee)	Anthony Cahill (Member)
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ABSTRACT

Incorporating Salinity Considerations in Water Availability Modeling.

(May 2005)

Ganesh Krishnamurthy, B.E., University of Mumbai, India

Chair of Advisory Committee: Dr. Ralph Wurbs

This research focused on expanding the capabilities of the Water Rights Analysis Package (WRAP) for incorporating salinity considerations in assessments of water availability. A simulation modeling approach was used to address this issue and a generalized simulation model called WRAP-SALT was developed. The Brazos River Basin served as a case study to test the simulation approach adopted by the model.

The simulation model adopts a generalized modeling approach applicable to any river basin system. The model tracks salinity throughout a river basin system over different periods of time for alternative scenarios of water use, reservoir system operating policies, and salt control mechanisms. The model was applied to the Brazos River Basin considering different management scenarios and the results obtained were analyzed.

Reservoir reliabilities were assessed under user imposed salinity constraints. It was observed that the water supply reliabilities decreased significantly if salinity constraints were considered. Salt control dams proposed by the U.S. Army Corps of

Engineers were also incorporated in the simulation of the river basin. It was observed that salinity in the main stem of the Brazos River was significantly reduced. However, no significant improvement was observed in water supply reliabilities.

ACKNOWLEDGEMENTS

This manuscript would have never seen daylight had it not been for the guidance and the support of my advisor, Dr. Ralph Wurbs. He has been a terrific mentor and I consider myself to be privileged to have had the opportunity to work under him. He has been a tremendous source of inspiration, especially when things were going nowhere with my research. His guidance has never been limited to the academic front and he has been very supportive and understanding over personal issues as well. During my graduate studies at Texas A&M, I have always been sure of one thing: that I would never leave Dr. Wurbs's office disappointed. Thanks for everything, Dr. Wurbs.

My family and friends have provided me with selfless love and endless support and I am forever grateful to them.

DEDICATION

To Sumati Sivakumar,

For being there when it mattered most.

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1. INTRODUCTION

1.1 STATEMENT OF THE PROBLEM

Water resources planning and management for any river basin requires proper understanding of the existing and the future demand-supply equations in that region. These equations are dynamic in nature, changing with parameters like economic growth and development, rising population, floods and droughts, and a host of other factors. The emergence of contemporary water uses such as wildlife preservation, habitat enhancement, and recreational requirements also has added to the complexity of the demand problem (Azevedo et al., 2000). Given this nature of the system, planning and decision-making cannot be solely based on historical trends for any given region. The two dominant parameters that influence river basin management and decision policies are: the volume of water demanded and the quality of the water supplied to meet the required demands. Effective management of the highly variable water resources of a river basin requires an understanding of the amount of suitable quality water that can be provided under various conditions within institutional constraints (Wurbs et al., 1994).

Salinity is a major determinant of water supply capabilities in river basins throughout the world, particularly in relatively arid regions. It is particularly prominent

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This thesis follows the style of the *Journal of Hydrologic Engineering.*

in Western Australia and the southwestern part of the United States. Natural salt pollution is a governing constraint to water resources development and management in major river basins of Texas and neighboring states (Wurbs, 2002). Natural salt contamination limits the use of large quantities of water in the Arkansas, Brazos, Canadian, Colorado, Pecos, and Rio Grande Basins of the states of Arkansas, Louisiana, Oklahoma, New Mexico, and Texas. The primary sources of salt loads in these rivers are geologic formations of halite underlying portions of their upper watersheds. Salt springs and salt flats in salt source areas of the upper watersheds are created as water percolates through salt-bearing geologic strata. The mineral pollutants consist largely of sodium chloride with moderate amounts of calcium sulfate and other dissolved solids. Salt concentrations in the downstream reaches of the rivers decrease with dilution from low-salinity tributary inflows. However, salt water encroachment from the Gulf of Mexico increases concentrations near the coast.

During 1997-2003, the Texas Commission on Environmental Quality (TCEQ), its partner agencies, and contractors (consulting firms and university researchers) implemented a Water Availability Modeling (WAM) System based on the Water Rights Analysis Package (WRAP) Model (Wurbs, 2003). Water agencies and their consultants use the modeling system in support of water rights regulatory functions, water resources planning activities, and other water management applications. The TCEQ WAM System has significantly improved capabilities for incorporating complex hydrologic and institutional considerations in assessing water availability. However, water quality is not reflected in the Texas WAM System even though water availability in many of the major river/reservoir systems of the state is severely constrained by water quality problems, particularly natural salt pollution.

Water supply capabilities depend upon water quality as well as the amount of water available. The research documented by this thesis addresses the problem of natural salt pollution in the Brazos River Basin by expanding the generalized WRAP simulation model and Texas WAM System to incorporate salinity considerations in assessments of water availability.

1.2 RESEARCH OBJECTIVES

The overall goal of this research is to expand capabilities for incorporating salinity considerations in assessments of water availability. The objectives of this research are stated below:

1. develop a generalized salinity tracking component for the Water Rights Analysis Package (WRAP) modeling system.
2. investigate methods for developing input data for the model.
3. apply the expanded modeling capabilities to the Brazos River Basin to assess the impacts of natural salt pollution on water supply capabilities.
4. to assess the impact of the salt control dams proposed by the USACE to contain salt pollution in the Brazos River Basin.

A significant contribution of this research will be the development of the generalized WRAP-SALT computer model that can be used to track salinity in regulated streamflow and assess the impact of natural salt pollution on water supply reliabilities for any river basin system.

2. REVIEW OF LITERATURE

2.1 OVERVIEW OF THE WATER RIGHTS ANALYSIS PACKAGE (WRAP)

Drought conditions in Texas during 1995-1996 prompted the State Legislature to enact in 1997 a milestone water management legislation called Senate Bill 1. One major provision of the 1997 Senate Bill 1 was authorization of a project to develop a Water Availability Modeling (WAM) System for all of the river basins of Texas. The Texas Natural Resource Conservation Commission (TNRCC, renamed TCEQ in 2002) was directed to lead this effort. The WAM System was developed during 1997-2003 by the TNRCC/TCEQ in collaboration with the Texas Water Development Board and Texas Park and Wildlife Department, with most of the technical work being performed by consulting engineering firms and university researchers (TNRCC 1998; Sokulsky, Kariann, Dacus, Bookout, Patek 1998; Wurbs 2003).

Under the WAM system, the state is sub-divided into 23 river basins. Datasets for the individual river basins have been developed for input to the WRAP model. WRAP utilizes naturalized river basin hydrology data and water rights data as its input. The model is designed to repeat historical hydrology for user defined water management and usage requirements. The simulation model is set up to follow a monthly time step. The simulation model provides a system to track streamflow sequences, while considering factors like reservoir storage capacities and diversion, in-stream flow requirements and hydropower generation. For each monthly time step, the water balance computations are performed. The simulation results are usually voluminous and provide information about simulation parameters like naturalized flows, regulated flows, unappropriated flows end-of-period reservoir storage capacity, net reservoir evaporation volumes, water supply diversions, hydropower generated and a host of other pertinent simulation information (Wurbs, 2003).

Naturalized flows are defined as those flows that would have occurred under ideal conditions, in the absence of water diversions and reservoir for storage purposes. Naturalized flows are developed by adjusting gaged flows to remove the effects of reservoirs and water use throughout the river basin. Regulated flows can be defined as flows physically present in a given region. Unappropriated flows account for flows that are still available for appropriation (Wurbs, 2003).

The basic components of a WRAP model include a river/reservoir/use system. They have been modeled spatially as a set of control points with each system being assigned to a control point. The relation between each control point and its immediately next downstream control point is represented in the input file. The control points can be represented in any order in the input data sets, irrespective of their spatial positions. However, the relation between a control point and its immediate downstream control point must be explicitly mentioned (Wurbs, 2003).

The simulation model requires a complete description of the historical hydrology over the entire simulation time period. It is modeled as monthly naturalized streamflows over the entire period of simulation, including severe droughts. Hydrology also includes net evaporation less precipitation rates from reservoir water surfaces. The WRAP model treats each water right as a function of water management and usage. A typical water right could include water supply diversion or hydroelectric energy generation requirements and storage in any number of reservoirs. Environmental in-stream flow requirements are modeled as a special type of water right (Wurbs 2003).

WRAP is a generalized computer model that can be applied to inherently complex river/reservoir systems as well as relatively simple systems. There are numerous optional features in WRAP to address complexities in the variety of ways water is managed and utilized by people. The WRAP model allows for the addition of new features and options as need arise (Wurbs, 2003). The WRAP software and documentation, and input data files for each of the river basins is public domain and can be downloaded free of cost from the TCEQ WAM website at:

http:// www.tnrcc.state.tx.us/permitting/waterperm/wrpa/wam.html

The publicly-released WRAP used in the TCEQ WAM System has no water quality modeling features. The natural salt pollution in Texas and neighboring states results in needs for considering salinity in assessing water availability. WRAP-SALT is being developed as a part of the WRAP model for tracking salt concentrations throughout a river/reservoir system for alternative water management/use scenarios. The WRAP-SALT model reads the WRAP-SIM output file along with additional data regarding salt concentrations in incremental naturalized streamflows. The model computes concentrations of these water quality constituents in regulated streamflows and reservoir contents throughout the river basin.

The WRAP-SALT model is described in detail in section 4 of this thesis.

2.2 GENERALIZED WATER ALLOCATION MODELS

Historically, river-basin planning and management has focused more on water quantity than water quality. Over the last decade considerable research has been performed in integrating water quality considerations in water supply planning and management. Although the inseparable interaction of water quantity and quality clearly exists in any water resource system, they are generally managed by different authorities with often conflicting objectives (Dai and Labadie, 2001). Effective management of the highly variable water resources of a river basin requires an understanding of the amount of suitable quality water that can be provided under various conditions within institutional constraints (Wurbs et al., 1994).

Modern day research focuses on the effects of integrated water resource management on a river-basin system by developing simulation models. The remainder of this section is comprised of a review of generic river-basin system management models with integrated water quality features.

WRAP - The Water Rights Analysis Package (WRAP) has been briefly described in section 2.1. The water quality module of the WRAP model, called WRAP-SALT, is being developed as a part of this research and has been described in detail in section 4 of this thesis.

RIBASIM - RIBASIM (River Basin Simulation Model) is a generalized simulation model for assessing the behavior of river basins under different hydrological conditions. Developed at the WL | Delft Hydraulics, the simulation model is a comprehensive and flexible tool which links the hydrological water inputs at various locations with the specific water users in the basin. RIBASIM is based on an interactive GIS based environment for preparation of the basin schematization, the entry of object attribute data and the evaluation of simulation results (Delft Hydraulics, 2004).

A variety of water management and water allocation procedures can be modeled for different stakeholders. It can model single and multiple reservoir systems, lakes and storage basins. RIBASIM can also simulate hydropower generation and ground water management. It also performs water quality analyses by computing the salinity in each river reach and water body, and the salt balance of each irrigation area. The computations are based on the computed flow and water allocation pattern and the relation between the salinity of the abstracted water and the return flow. RIBASIM can be used for long term basin planning, short term water allocation scheduling and in-season operation scheduling (Delft Hydraulics, 2004).

RIVERWARE - RIVERWARE was developed by the Center for Advanced Decision Support for Water and Environment Systems (CADWES) at the University of Colorado, Boulder with funding support from the United States Bureau of Reclamation (USBR), and the Tennessee Valley Authority. RIVERWARE is a generalized tool for modeling complex reservoir systems (Zagona et al., 2001).

RIVERWARE is an object oriented model written in C++. Objects representing various river basin features are used to construct a river basin model. RIVERWARE has a graphical user interface that facilitates easy model formulation. A model is constructed by simply placing the objects on the workspace, naming them and linking them together.

A graphical link editor is provided to link the objects together which enables the formation of the river basin topology. The program also has features to customize the objects as per user defined requirements.

The objects are represented by icons on the workspace which can be opened to show the list of “slots”, which are the variables associated with the physical process model equations for that feature. A reservoir would have Inflow, Outflow, Storage and Pool Elevation amongst its “slots” (Zagona et al., 2001).

The model can also perform water quality simulations. RIVERWARE can model various water quality parameters like total dissolved solids, temperature, dissolved oxygen, etc either individually or in combination. A simple, well-mixed model is available for modeling total dissolved solids alone. Temperature models, Dissolved Oxygen models and discretized reaches in which the water quality equations are coupled with hydraulic routing, either with or without dispersion, use a 2-layer reservoir model (Zagona et al., 2001).

MIKE BASIN - MIKE BASIN was developed at the Danish Hydraulic Institute for addressing various river basin issues like water allocation, reservoir operation, water quality etc. It is coupled with a GIS based environment and is a powerful tool for comprehensive hydrologic modeling to provide basin scale solutions (DHI, 2004).

A river basin model is represented as a network model where the branches represent individual stream sections and the nodes represent confluences, reservoirs, diversions, or water users. The GIS based graphical user interface facilitates easy model formulation. Water allocation is modeled based on a given set of rules; however, new set of rules can be defined within the model with the objective of maximizing the overall benefits. MIKE BASIN also comprises of an inbuilt rainfall-runoff model and a monthly soil moisture accounting model. The model can analyze conjunctive use of surface and groundwater resources. The model has extensive reservoir modeling capabilities and can accommodate multipurpose reservoir systems. MIKE BASIN can model two types of reservoirs, the Standard Reservoir which has a physical storage with all the users drawing water from that same storage and the Allocation Pool Reservoir which has a physical storage with the individual users being allocated a certain storage right. Hydropower generation can be modeled in conjunction with reservoir operation (DHI, 2004).

MIKE BASIN has a separate water quality module which can simulate steady state reactive transport of the substances affecting water quality. Ammonia, nitrate, E-coli, oxygen, total phosphorus, COD, BOD, and a user-defined substance like salinity can be modeled. The user has the option of specifying various rate parameters or using the model default values. Point and non point sources of pollution can be modeled. Water quality in reservoirs and groundwater can also be modeled assuming perfect mixing (DHI, 2004).

IQQM - IQQM (Integrated Quantity and Quality Model) is a hydrologic modeling tool developed at the New South Wales Department of Land and Water Conservation (DLWC) to provide water managers with an analysis tool for water quantity and water quality management. IQQM has been designed for examining long-term behavior under various management scenarios (Simons et al., 1996). The model comprises of a number of modules which includes an instream water quantity module, an instream water quality module and rainfall-runoff modules. The code structure of the model is flexible and allows for the incorporation of new modules to the existing structure or any changes made to the existing structure.

IQQM can be applied to a complex river basin system with numerous reservoirs as well as simple river basin systems without dams. The model operates at a daily time step, however, some processes can be simulated at hourly time steps (Simons et al., 1996).

A river basin system is represented by a series of nodes that are connected by links. Inflows, storage, outflow and other point processes are associated with the nodes. Flow routing and water quality routing is associated with the links. IQQM has a user friendly graphical user interface which allows map layers to be imported from GIS. All river basin system diagrams can be drawn over the imported map (Simons et al., 1996).

Flow routing within the model is based on hydrologic routing techniques and the available alternatives include non-linear routing with lag and Muskingum routing. There are provisions for varying the routing parameters with the depth of flow to allow modeling of overbank flows (Simons et al., 1996).

Reservoir operations can be modeled for various operating rules. The model has an irrigation module which can simulate numerous scenarios and aids farmers as a powerful decision making tool. Urban water supply, wetland and environmental flow requirements, daily climate, water use accounting and resource assessment, and groundwater quantity and quality can also be modeled. The rainfall-runoff module is based on the Sacramento Model developed by the US National Weather Service and California Department of Water Resources (Simons et al., 1996).

The water quality module is based on the program QUAL2E developed for the U.S. Environmental Protection Agency. It is a powerful tool and can model the movement of conservative and non-conservative substances such as pesticides and salinity. A volumetric routing procedure is adopted for modeling the movement of conservative and non-conservative substances under an assumption that fully mixed flow is available in each routing reach. The modified Streeter-Phelps equation is used to model parameters such as DO and BOD. Nitrogen and Phosphorus cycles can be modeled and algal growth can be simulated (Simons et al., 1996).

IRAS - The Interactive River-Aquifer Simulation Program, IRAS, was primarily developed to assist those responsible for planning and managing regional water resource systems (Bennet et al., 1994). It is a generic simulation model which can be applied to a variety of river-aquifer systems under user-defined water management strategies. IRAS addresses the issues of interaction between ground and surface waters, and between water quantity and water quality (IRAS, 2004).

IRAS comprises of a user-friendly graphical user interface which enables the user to construct a schematic of the river-aquifer system to be analyzed. The system schematic is represented by a network of nodes and links. The nodes represent different system components such as aquifers, reservoirs, consumption sites etc. The links can be unidirectional, bi-directional (flows in both directions, as for pumped storage operations) or non-directional (flows possible in either direction depending on surface elevation or pressure head differences), and represent river reaches, diversions and the transfer of water among aquifers and/or wetlands and the surface water system (IRAS, 2004).

IRAS is flexible with regards to the temporal and the spatial resolution of the system simulation. The total duration of the simulation and the time-step within the simulation period is user defined. IRAS also has capabilities to perform water quality constituent simulations. The water quality constituents are user defined along with parameters such as growth, decay, and transformation rate constants and other parameters used in the water quality portion of the model. The simulation of water quality can be limited to only a portion of the entire system being simulated, if desired (IRAS, 2004).

2.3 WATER QUALITY PARAMETERS

The subject of water quality is broad and diverse. The quality of water is relative and its suitability for a particular type of use can be defined by the concentration of one or more quality indicators present in it. There are numerous parameters that are used to define the quality of surface water. Considering the scope of this research, salinity was the only water quality parameter that was taken into consideration for simulation modeling studies of the Brazos River Basin.

In the Brazos River Basin, the groundwater, lithology, climate, relief, degree of urbanization, and other factors greatly influence the quality of surface water (Ganze, 1993). Total dissolved solids (TDS), chlorides, and sulfates are the water quality parameters that have the most pronounced effect on the surface water quality in the basin. This research only considers the impact of the above mentioned water quality parameters on surface water quality in the Brazos River Basin. These water quality parameters collectively reflect the salinity in the Brazos River and its tributaries.

For general purposes, TDS can be defined as the total sum of all the dissolved constituents in water. It is an important water quality indicator and its concentrations define the suitability of water for domestic, industrial and municipal usage. The presence of high TDS concentrations in surface water is an indication of poor quality. TDS plays an important role in diminishing the percentage of dissolved oxygen in a water body. Consequently, the ability of the water body to assimilate wastes is reduced and in some severe cases might lead to the eutrophication of the water body. Drinking water with high TDS concentrations might have a laxative effect on people and in some cases might cause a reverse effect on people whose bodies are not adjusted to them (Sawyer and McCarthy, 1978).

Chloride compounds are present in all surface waters in varying degrees of concentration. Chloride concentrations generally increase with increasing mineral contents (Sawyer and McCarty, 1978). Very high concentrations of chloride compounds in drinking water impart to it a very objectionable taste. Intake of chloride compounds, particularly, sodium chloride (common salt) might pose a health risk for individuals who have salt intake restrictions. Like chlorides, sulfates also occur in all natural surface waters. High concentrations of sulfates might lead to diarrhea (Tate and Arnold, 1990).

Sulfates are also responsible for problems concerning odor due to its reduction to hydrogen sulfide under anaerobic conditions.

The U.S. EPA recommends certain water quality guidelines with regards to the above mentioned parameters. For waters to be used for domestic purposes, the EPA recommends a TDS concentration of less than 500 mg/l, a chloride concentration of less than 250 mg/l, and a sulfate concentration of less than 250 mg/l.

In general, salinity has adverse effects on most domestic, industrial and agricultural activities if it exceeds a certain limiting concentration value. There are various factors that need to be considered while determining the suitability of any water for irrigation. These include: water quality, nature of the crops, sensitivity of the crops to salts, nature of the soil, climactic characteristics in the region etc. Certain crops cannot withstand high salt concentration in the waters used for irrigation and their growth is affected considerably. The potential effects of salinity on industrial processes depend on factors like the nature of the process, the water requirements for the process, the duration of the process, the final produce from the process. The water quality requirements would vary depending on the above mentioned factors. Salinity also hampers certain processes in the industrial sectors resulting in the formation of scales in boilers, pipes, cooling towers etc, which has an adverse economic impact on industrial activities. The use of sub-standard waters for industrial purposes can lead to problems such as product degradation, equipment deterioration and reduction of efficiency or capacity (Montgomery, 1985).

3. NATURAL SALT POLLUTION IN THE BRAZOS RIVER BASIN

3.1 DESCRIPTION OF THE BRAZOS RIVER BASIN

The Brazos River stream system originates in the eastern part of New Mexico near the city of Clovis and flows in a southeasterly direction diagonally across the state of Texas to the Gulf of Mexico near Galveston. The overall length of the basin is approximately 640 miles and it has a width varying from 70 miles in the Upper Basin to 110 miles near the city of Waco to 10 miles near the city of Richmond towards the lower basin near the Gulf. The basin drainage area is approximately 45,600 square miles, of which about 45,000 square miles lies in the state of Texas with the remainder in the state of New Mexico. It accounts for around 16% of the total land area in the state of Texas (Wurbs et al., 1994).

The Brazos River Basin has a typically humid climate in the eastern part while the western region is characterized by semiarid weather. The midsection alternates between humid and dry conditions. The Gulf of Mexico is the principal source of moisture and the warm winds blowing from the Gulf release moisture with lowering temperatures. There is significant variation in the mean annual precipitation characteristics across the basin with the western end of the basin receiving a mean annual precipitation of 16 inches/year to over 50 inches/year in the lower basin towards the Gulf of Mexico (USACE, 1973). Figure 3.1 shows the location of the Brazos River Basin.

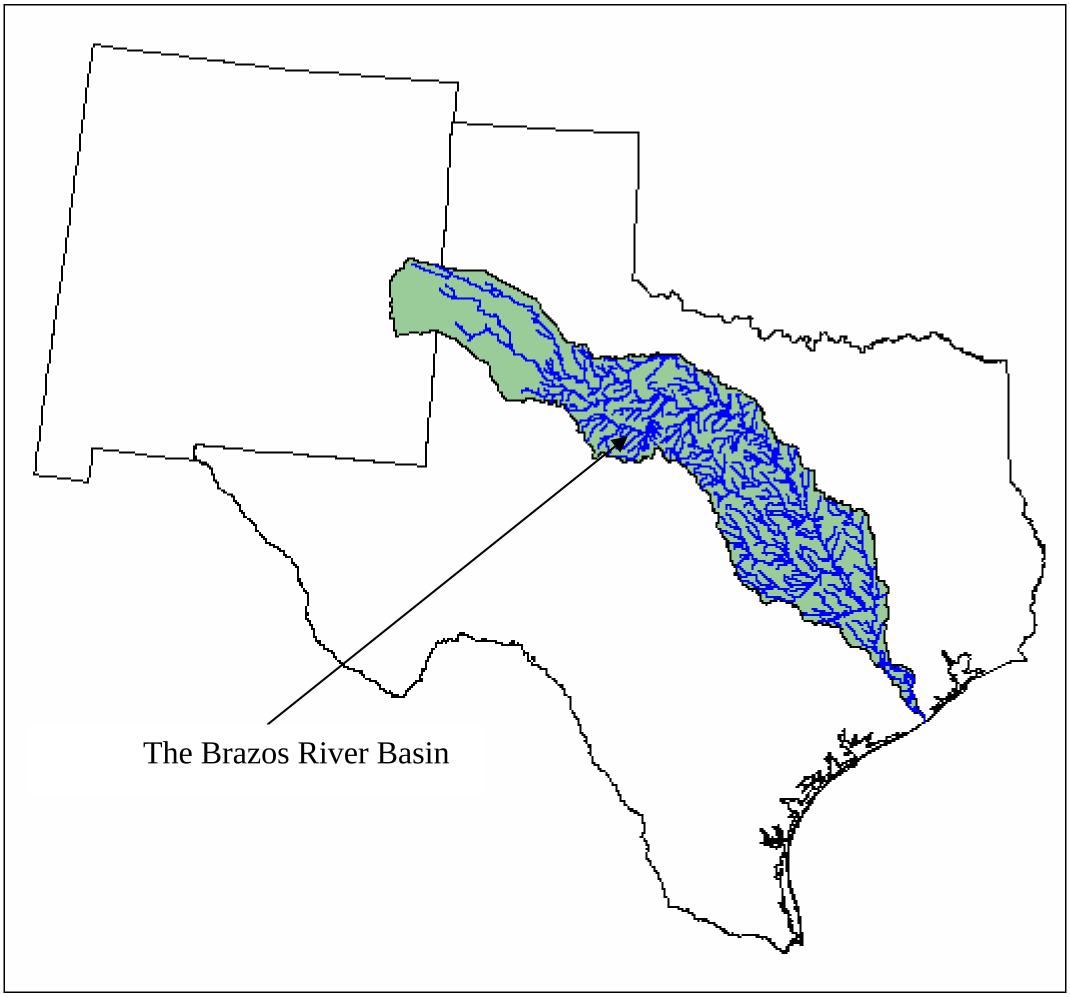

Figure 3.1 Location of the Brazos River Basin

3.2 DESCRIPTION OF THE PROBLEM

Effective management and utilization of the water resources of the Brazos River Basin is severely constrained by natural salt pollution. The water quality is seriously degraded due to the presence of natural mineral pollutants. The quality of the water in the main stem of the Brazos River is particularly degraded by emissions from major salt sources in the Upper Brazos River Basin. These emissions primarily consist of mineral pollutants composed of sodium chloride with moderate amounts of calcium sulfate and other dissolved solids (USACE, 1973). The presence of this natural salt pollution affects the 923-mile main stem stretch from Stonewall County to the Gulf of Mexico. However, due to dilution from good quality tributaries towards the lower basin, the water quality improves considerably when it reaches Richmond Gage (USACE, 1973).

Several universities, state and federal agencies have conducted studies on the natural salt pollution problem in the Brazos River Basin since the mid-1950s (McCrory, 1984). The U.S. Army Corps of Engineers (USACE) conducted natural salt pollution control studies in the Brazos River Basin. These studies are documented by a survey report (USACE, 1973), an environmental impact statement (USACE, 1976a), and draft general design memorandum (USACE, 1983). These studies primarily focused towards determining the most feasible method to control natural salt pollution in the Brazos River Basin and its tributaries. The main objective of these studies was to improve the quality of water in the main stem of the Brazos River to facilitate its full development and utilization.

The study area that was considered by the USACE is located in the Upper Brazos River Basin in the watersheds of the Salt and the Double Mountain Forks of the Brazos River and the North Croton Creek watersheds. It covers an area of approximately 1500 square miles and is sometimes known as the Gypsum Plains subprovince because of the abundance of the gypsum beds in the region. The Permian rock outcrops, with their associated seeps and springs, are the primary source of natural salt contamination affecting the water quality in the Brazos River below this region. Figure 3.2 shows the location of the study area within the Brazos River Basin.

There are numerous, intermittent streams which cut through the predominant rolling plains forming a dendritic drainage system. They transport substantial amounts of silt and sand during floods. The study area is also characterized by the presence of salt flats in several of the creek beds. These salt flats are formed by local widening of the tributary stream valleys where the lower side slopes of the valley were debilitated by salt water seepage and later eroded by runoff and flash flood flows (McCrory, 1984). This process stopped when an erosion resistant bed was encountered leading to the formation of the floor of the salt flat. The evaporation of the saline groundwater emerging from these salt flats leaves behind residues in the dry streambeds which are flushed downstream into the main stem of the Brazos River by occasional runoff or floods.

The major areas contributing to salt water emission in the Upper Brazos River Basin are Croton Creek and Salt Croton Creek. Croton creek includes Hot Springs and

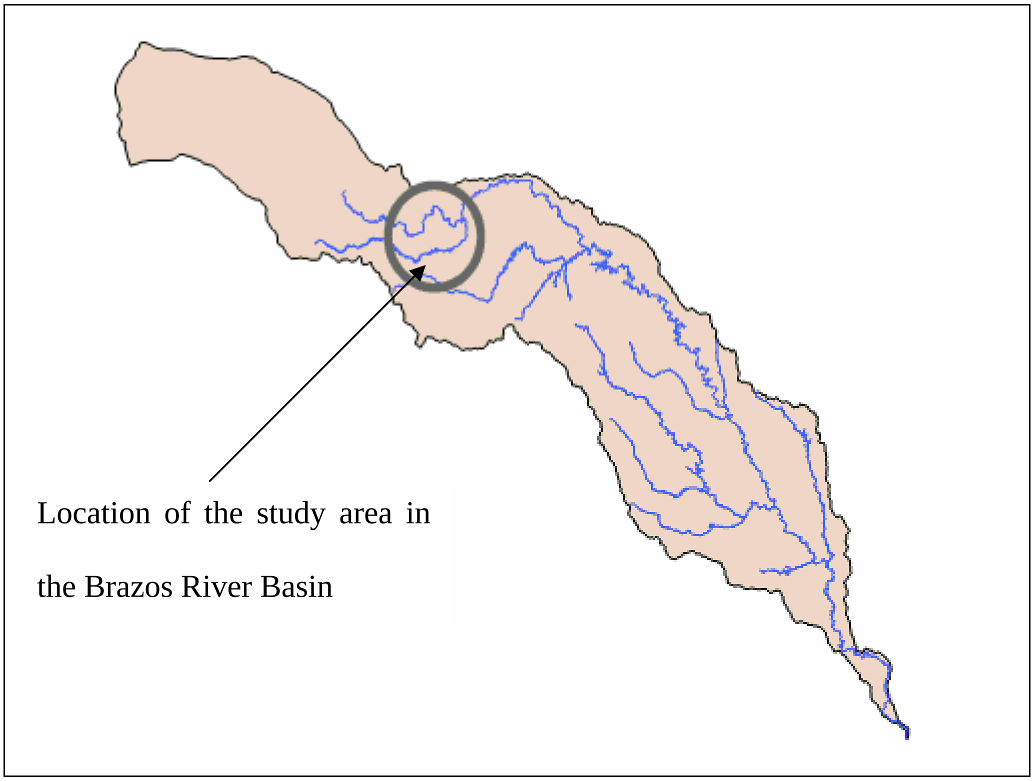

Figure 3.2 Location of the Study Area

the Short Croton salt flats and Salt Croton Creek includes the drainage of Dove Creek, Dove Creek salt flat, and Haystack Creek. McDonald Creek, Verbena Canyon, Salt Creek (Salt Fork), Red Mud Creek, Stinking Creek, and Salt Creek (Double Mountain Fork).

3.3 SALT CONTROL PLANS RECOMMENDED BY THE USACE

The U.S. Army Corps of Engineers (USACE) conducted natural salt pollution control studies in the Brazos River Basin. These studies are documented by a survey report (USACE, 1973), an environmental impact statement (USACE, 1976a), and draft general design memorandum (USACE, 1983). Various alternatives were considered for dealing with the problem posed by the natural salt pollution in the Brazos River Basin. These included suppressing the stream flow, dilution of the stream water, desalination techniques, salt control impoundments and others. Salt control by the use of impoundment structures was found to be the most effective in obtaining acceptable salinity levels in the waters of the Brazos River. There were 11 strategies formulated for salt impoundment and plan 4B was found to offer the best balance between cost, quality and environmental impact (USACE, 1973).

Plan 4B featured three total retention dams and connecting pipelines. The three dams were earthen embankments of the total impoundment type. The proposed dams were large enough to contain all the water, brines, and sediments for a simulated 100-year period.

The three proposed impoundments were: Croton Lake on Croton Creek, Dove Lake on Salt Croton Creek and Kiowa Peak Lake on North Croton Creek. The proposed impoundment structures would dam the runoff from their contributing watersheds and an interconnecting pipeline would be used to transfer the excess water to Kiowa Peak Lake from Croton and Dove Lakes. Figure 3.3 shows the location of the proposed impoundment structures in plan 4B.

The environmental impact of Plan 4B was evaluated and documented in USACE (1976a). Plan 4B was reevaluated and the results (Phase I Advance Engineering and Design, AE&D) were documented in USACE (1983). The study concluded that the recommended salt impoundment plan (Plan 4B) was not economically feasible and recommended that no construction be made. These results are summarized as follows (McCrory, 1984):

1. All of the water of the Brazos River is committed by either contract or water rights. Therefore, based on the USACE’s results, even if the quality of the water was improved, no new municipal, industrial or agricultural irrigation uses would occur.
2. The present and projected water demands are primarily in the lower basin. The quality of the water in this area is the best of the river basin, due to dilution by good quality tributary flows and reservoir releases downstream from the source of pollution. Therefore, any natural salt pollution control in the upper basin (salt study area) would have only a minimal effect on water quality in the lower basin and the benefits attributable to the project.

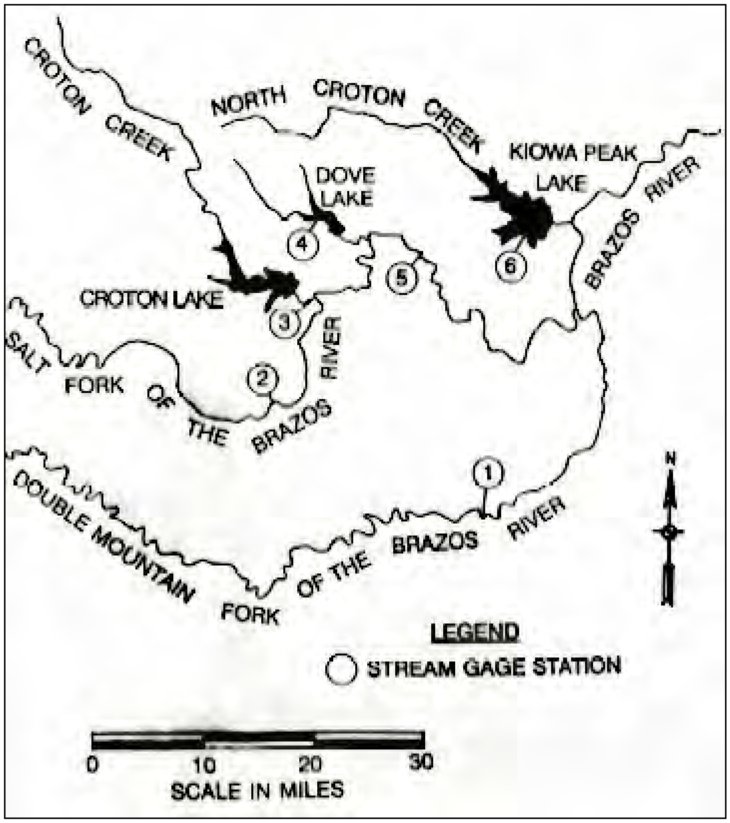

Figure 3.3 Location of the Proposed Salt Control Dams

3. There are less costly alternative sources to Brazos River water in both the Brazos River Basin and adjacent basins.
4. If the water quality were improved and water rights not taken into account, there would be a moderate increase in agricultural irrigation in the upper half of the basin.
5. Minor flood control benefits are associated with the salt control dams because of the small size of the impoundments.
6. Minor recreation benefits are associated with the project.
7. A wildlife habitat migration area would provide benefits to offset the land losses caused by the project.
8. Comparison of the total benefits to the total costs of the project, both based on 1983 prices and interest rate, resulted in a benefit cost ratio of less than 1.0 (McCrory, 1984).

3.4 SALINITY DATA IN THE BRAZOS RIVER BASIN

The U.S. Geological Survey (USGS) operated a daily chemical-quality station on the Brazos River at Waco from December 1906 to November 1907. However, most of the surface water quality data for the Brazos River has been collected only since 1941 (Wurbs and Ganze, 1989). Systematic collection of water quality data was significantly expanded by the USGS after 1964 to assist the USACE in its comprehensive planning study of the Brazos River Basin (Wurbs and Ganze., 1989). Irelan and Mendieta (1964), and Rawson, Flugrath and Hughes (1968) summarized the water quality data for the Brazos River and its tributaries in the early years (Wurbs and Ganze, 1989).

The USGS collected chemical-quality data for 35 daily sampling stations from 1941 through 1963 over varying periods of time. Records for many sampling stations were partial resulting in incomplete data sets. Wurbs and Ganze (1989) compiled the monthly TDS, Cl, and SO_4 loads and discharges for 26 sampling stations for the period 1964-1986. The 26 sampling stations were selected based on their pertinent locations and the availability of gaged data for the period 1964-1986. Table 3.1 lists the 26 sampling stations. Since there was considerable variation observed in the units of the monthly salt load data obtained from the USGS, some data manipulation was performed to maintain consistency in the measurement units. Discharges were cited in units of cubic feet per second (cfs) and salt loads had units of tons/day. The relationship between concentration, load and discharge is shown below:

$$\text{Concentration} = \text{Load} / \text{Discharge}$$

Salt concentration in milligrams of salt solute per liter of water (mg/l) was computed using the following conversion factor:

$$((\text{Tons/day})/ (\text{cubic feet/second})) * 370.8 = \text{mg/l}$$

3.5 TEMPORAL AND SPATIAL VARIATIONS IN SALINITY

There was tremendous variation observed in discharge, salt load and concentration spatially and temporally. It was observed that the patterns in the variations

Table 3.1 Location of the 26 Sampling Stations on the Brazos River

Study Station Number	USGS Station Number	Location
1	8080500	Double Mountain Fork Brazos River Near Aspermont
2	8081000	Salt Fork Brazos River Near Peacock
3	8081200	Croton Creek Near Dayton
4	8081500	Salt Croton Creek Near Aspermont
5	8082000	Salt Fork Brazos River Near Aspermont
6	8082180	North Croton Creek Near Knox City
7	8082500	Brazos River at Seymour
8	8083240	Clear Fork Brazos River at Hawley
9	8085500	Clear Fork Brazos River at Fort Griffin
10	8086500	Hubbard Creek Near Breckenridge
11	8087300	Clear Fork Brazos River at Eliasville
12	8088000	Brazos River Near South Bend
13	8088600	Brazos River at Possum Kingdom Dam Near Graford
14	8090800	Brazos River Near Dennis
15	8092600	Brazos River at Whitney Dam Near Whitney
16	8093360	Aquilla Creek Above Aquilla
17	8093500	Aquilla Creek Near Aquilla
18	8098290	Brazos River Near Highbank
19	8104500	little River Near Little River
20	8106500	Little River at Cameron
21	8109500	Brazos River Near College Station
22	8110000	Yegua Creek Near Somerville
23	8110325	Navasota River Above Groesbeck
24	8111000	Navasota River Near Bryan
25	8114000	Brazos River at Richmond
26	8116650	Brazos River Near Rosharon

were similar for total dissolved solids, chlorides and sulfates. Sampling stations 2, 3, 4, 5, and 6 located in the primary salt pollution source area had high salinity concentrations. The upper watershed area above the Seymour gage contributes only 3.9% of the mean discharge at the Richmond gage. However, this area contributes to 41% of total dissolved solids, 73% of chlorides, and 49 % of sulfates at the Richmond gage. The salt concentrations in the tributaries downstream of Whitney Reservoir were relatively low with tributaries having good water quality entering the Brazos River. Similarly, in the main stem of the Brazos River, the salt concentration decreased significantly in the downstream direction due to fresh water inflows which diluted the salt contents from the upper watershed. The flows at the Little River watershed were in sharp contrast to the Upper Brazos River Basin with very low TDS, chloride and sulfate concentrations respectively. The concentrations of the total dissolved solids, chlorides and sulfates at the Cameron gage on the Little River were 256 mg/l, 31 mg/l and 30 mg/l respectively (Wurbs and Ganze, 1989). Table 3.2 and Table 3.3 shows the mean values of the salt concentrations at the sampling stations during the period of record and for comparable time periods respectively.

Significant variations in the salt concentrations over time were observed in the Brazos River Basin during the period 1964-1986. At the Seymour gage, the concentration of the total dissolved solids ranged from a mean monthly value of 618 mg/l in August 1964 to 15,400 mg/l in May 1984. The chloride concentrations varied from 190 mg/l in June 1975 to 7740 mg/l in May 1984. Sulfate concentrations varied from 112 mg/l in November 1963 to 2225 mg/l in March 1976. At the Richmond gage,

Table 3.2 Mean Values of the Concentrations for the Period of Record

Stn.	Location	Years of Record	Discharge	Load in tons/day			Concentration in mg/l		
				TDS	Cl	S04	TDS	Cl	S04
1	Double Mountain Fork	33	147	562	136	218	1,353	324	570
2	Salt Fork	24	43	680	334	83	5,317	2,585	657
3	Croton Creek	24	13	237	96	58	6,321	2,487	1,677
4	Salt Croton Creek	9	4	673	388	27	56,923	32,856	2,273
S	Salt fork	29	81	1,887	942	217	8,606	4,753	989
6	North Croton Creek	21	17	216	82	60	4,723	1,786	1,323
7	Main Stem	27	292	2,638	1,018	447	3,356	1,295	569
8	Clear Fork	15	46	235	51	94	1,893	411	759
9	Clear Fork	15	151	391	105	116	961	258	286
10	Hubbard Creek	19	93	73	25	4	268	91	20
11	Clear Fork	21	319	614	201	148	715	234	172
12	Main Stem	11	760	2,601	996	561	1,261	486	274
13	Main Stem	45	836	2,959	1,127	636	1,299	493	279
14	Main Stem	19	892	3,103	1,205	622	1,291	501	259
75	Main Stem	38	1,376	3,174	1,120	633	856	302	171
16	Aquilla Creek	3	55	35	2	70	236	14	69
77	Aquilla Creek	14	747	102	6	29	257	14	73
18	Main Stem	18	2,530	4,154	1,287	772	609	189	113
19	Little River	16	912	768	79	67	313	32	25
20	Little River	26	1,544	1,094	729	126	263	31	30
21	Main Stem	22	4,364	5,315	1,379	944	452	117	80
22	Yegua Creek	5	252	174	20	33	167	30	48
23	Navasota River	19	161	56	9	6	131	22	13
24	Navasota River	23	600	232	61	38	144	38	23
25	Main Stem	41	6,545	6,140	1,431	1,020	351	81	58
26	Main Stem	12	7,305	6,462	1,491	1,004	328	76	51

Table 3.3 Mean Values of the Concentrations for Comparable Time Periods

Stn.	Tributary	Years of Record	Discharge	Load in tons/day			Concentration in mg/l		
				TDS	Cl	S04	TDS	Cl	S04
1	Double Mountain Fork	1964-86	126	580	153	209	7,540	416	548
2	Salt fork	1965-86	40	684	339	81	5,782	2,830	698
3	Croton Creek	1964-86	13	225	93	53	6,391	2,541	1,591
4	Salt Croton Creek	1969-77	4	676	425	33	56,923	32,856	2,273
5	Salt Fork	1964-82	60	1,660	1,094	219	12,407	6,066	1,235
6	North Croton Creek	1966-86	17	211	80	58	4,723	1,786	7,323
7	Main Stem	1964-86	269	2,601	1,074	504	3,591	1,482	696
13	Main Stem	1964-86	686	2,795	117	571	1,512	601	309
15	Main Stem	1964-86	1,230	3,075	1,134	591	928	342	178
20	Little River	1964-86	1,481	1,024	123	119	256	31	30
21	Main Stem	1964-83	4,529	5,348	1,368	938	438	112	77
25	Main Stem	1964-86	6,868	6,267	1,466	1,030	339	79	56

the concentration of the total dissolved solids ranged from a mean monthly value of 153 mg/l in November 1984 to 978 mg/l in October 1978. The chloride concentrations varied from 28 mg/l in November 1984 to 355 mg/l in October 1978. Sulfate concentrations varied from 24 mg/l in December 1965 to 185 mg/l in October 1963 (Wurbs and Ganze, 1989).

At the Seymour gage, mean monthly total dissolved solids, chloride, and sulfate concentrations of 11900 mg/l, 5760 mg/l, and 1800 mg/l, respectively, were equalled or exceeded during 10% of the 276 months of the 1964-1986 analysis period and mean monthly total dissolved solids, chloride, and sulfate concentrations of 2420 mg/l, 851 mg/l, and 539 mg/l, respectively, were equalled 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 equalled or exceeded 10% of the time while 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 (Wurbs and Ganze, 1989).

Several attempts were made by Wurbs and Ganze (1989) to isolate trends or long-term changes in salt concentrations which comprised:

1. a linear regression analysis of mean annual concentrations at five major stations
2. a linear regression analysis of 5-year moving averages of mean annual concentrations at the Seymour and the Richmond gages.
3. observing accumulative mass plots to detect changes in slopes.

However, these analyses yielded no clearly defined trends. It was concluded that trends or long-term changes in salt concentrations that may have occurred are very small relative to the tremendous random variability (Wurbs and Ganze., 1989).

4. THE WRAP-SALT SIMULATION MODEL

4.1 MODEL BACKGROUND

Development of the WRAP-SALT simulation model was motivated by the existing natural salt pollution in the southwestern United States. Water usage in the Brazos River is severely constrained by natural salt pollution. The contamination is particularly severe in the Upper Brazos River Basin. The water quality improves significantly towards the lower reaches with good quality inflow from the river tributaries. However, water availability in the basin is constrained by both salt concentrations and water quantities (Wurbs et al. 1994; Sanchez-Torres 1994; Wurbs and Sanchez-Torres 1996). In order to develop a better understanding of the natural salt pollution problem and its impact on water management in the Brazos River Basin, it was felt necessary to develop a river basin system simulation model which would address the issue of natural salt pollution by incorporating salinity considerations.

A salinity version of WRAP was developed by Sanchez-Torres (1994) as a Ph.D. dissertation research project. This model was developed for studying a reservoir/river system reliability considering water rights and water quality. This program was an expanded version of the WRAP3 simulation model. In this model, diversion shortages were based upon water quality and the available water quantity. Diversion shortages were declared if specified maximum allowable salt concentration limits were not satisfied. This salinity model reads a WRAP3 input file and writes an output file identical to the WRAP3 output file. However, unlike WRAP3, this model also reads a naturalized salt load input file and writes an additional output file with salinity related simulation results (Wurbs et al. 1994). The model also had features which provided the user an option of incorporating salinity considerations in multiple-reservoir release decisions.

WRAP was gradually expanded over time with the addition of sophisticated features. However, considering the complexities involved with the coded algorithms and to improve on programming efficiency it was felt necessary to develop an independent salinity model that would proceed with the salt computations working in conjunction with the WRAP program, but being independent otherwise.

4.2 BASIC DIFFERENCES

The principal objective of this research is to expand the capabilities of the WRAP model to incorporate salinity considerations in assessments of water availability. To achieve this goal a generalized salinity tracking component called WRAP-SALT was developed for the Water Rights Analysis Package (WRAP) modeling system.

The WRAP-SALT model focuses mainly on tracking salt concentrations at different control points throughout a river basin system over different periods of time for alternative scenarios of water use, reservoir system operating policies, and salt control mechanisms. Although there are a few similarities between the proposed model, WRAP-

SALT, and the model developed by Sanchez-Torres (1994), they differ in many ways. The major differences are outlined below:

1. Unlike its predecessor, WRAP-SALT is a stand alone program which works in conjunction with the WRAP model.
2. Water supply diversions are not constrained by water quality parameters during a simulation run.
3. The spatial configuration of the control points in a river basin system is tracked directly from the WRAP-SIM input file.
4. The model is programmed in such fashion that the simulation for a network of control points on a river basin system can be executed even with the absence of salinity data for one or more than one control point. For a control point, having limited or no salt data as input, the model simply repeats the salt concentration data from its immediate upstream control point for the entire simulation process.
5. The model can address the issue of reservoir lag time while allocating concentrations for reservoir releases.
6. The model can simulate any river basin system with numerous control points and reservoirs.

4.3 DETAILED DESCRIPTION OF THE WRAP-SALT MODEL

The WRAP-SALT model is essentially designed for computing concentration-duration relationships at user defined locations in a river basin system for alternative water management scenarios. In WRAP, the spatial configuration of the reservoir/river system is represented as a set of control points with system components like reservoirs, diversions, water rights etc assigned to individual control points. WRAP-SALT is based on the same concept of modeling a river basin system configuration as a network of control points.

A salinity simulation study requires development of relevant input datasets. The model primarily requires two types of input – water quantity data and water quality data. A complete simulation can be divided into three phases:

1. Water volumes which are input to the salinity model are obtained from a WRAP-SIM simulation.
2. These volumes are the combined with the water quality/concentration data to perform a WRAP-SALT simulation.
3. The program TABLES is then used to organize and summarize the simulation output results as required by the user.

4.3.1 MODEL INPUT AND OUTPUT

The WRAP-SALT model requires the following files as its input:

1. A WRAP-SIM input file with the file extension (.DAT).
2. A WRAP-SIM output file with the file extension (.OUT).
3. A WRAP-SIM beginning reservoir storages file with the file extension (.BRS).
4. A salinity input file with the file extension (.SIF).
5. A WRAP-SALT beginning reservoir concentrations file with the file extension (.BRC).

The .BRS file and the .BRC file are optional. However, for a salt simulation to begin, the .DAT file, the .OUT file, and the .SIF file are mandatory. The control point records (CP) are read from the .DAT file to identify the spatial configuration of the control points in a river basin system. Water volumes are obtained from the .OUT file and the .SIF file provides pertinent water quality/concentration input data. In a WRAP-SIM input file, the control points can be listed in any order. In the CP record of the WRAP-SIM input file, information regarding a control point and its downstream control point is explicitly mentioned. A WRAP-SIM simulation is based on the priority order of the water rights and is independent of the spatial configuration of the control points in the river basin system. However, the WRAP-SALT model requires that the control points be listed in their natural order; from upstream to downstream.

Any set of units can be adopted for the simulation provided consistency is maintained. The model essentially deals with three types of input: flow volumes, salt loads, and salt concentration. Mathematically, they are related in the following manner, $C = \frac{L}{Q} f_C$, where C represents concentration, L represents load, Q represents flow volumes, and f_c represents the conversion factor to maintain consistency between the input units. The model has a provision wherein the user can define the conversion factor to obtain results in desired units. The default conversion factor in the model is 735.48, which provides concentration in units of milligrams/liter when dealing with concentrations represented in units of tons/acre-feet.

The CP records can be rearranged in a proper sequence by running the program TABLES controlled by the 1CPT record. The rearranged control points can then inserted into a WRAP-SIM input file to generate an output file with control points in the rearranged order. The WRAP-SALT simulation produces three output files which are mentioned below:

1. The main output file with a file extension .SOF; consisting of pertinent simulation results.
2. A message file with a file extension .SMF; consisting of error and warning messages and other optional simulation summary tables.
3. A beginning reservoir concentration file with a file extension .BRC; consisting of end-of-period storage concentrations to be utilized during a subsequent execution of the program under user-defined modeling options.

The main output file provides information regarding the regulated flow volume, load, and concentration; the end-of-period storage volume, load, and concentration, and the diversion target, shortage, and concentration. The message file, besides providing warning and error check messages, also provides comprehensive information about the simulation which includes intermediate simulation results and simulation summary results. A listing of control points showing the spatial configuration may also be created. This information is optional and will only be written to the message file based on user defined modeling options. The beginning reservoir concentration file is optional.

The simulation results may be voluminous depending on the configuration of the river basin system being simulated. The program TABLES summarizes the simulation results based on user defined options. The program creates the following tables:

1. Summary tables for regulated flow volumes, loads, and concentrations.
2. Summary tables for reservoir storage volumes, loads, and concentrations.
3. Frequency tables for regulated flow volumes, loads, and concentrations.
4. Reliability tables that reflect constraints on salt concentrations.

4.3.2 SALINITY SIMULATION

The WRAP-SALT model computes salt loads and concentrations for regulated flows, diversions, and reservoir storage throughout a river basin system for alternative water management scenarios at a monthly time step. The salinity tracking algorithm is based on the assumption that the constituents to be simulated are conservative in nature and do not undergo any chemical or biological transformation during the simulation. It is assumed that the total mass is conserved during a salinity simulation for any river basin system.

Upon execution of the program, the control is transferred from the main program to three sub-routines to initialize the input and the output files and to read and organize relevant input data. A brief description of each subroutine is given below:

1. Subroutine FILEIN – This subroutine is called by the main program to initialize input and output files.
2. Subroutine CHECK – This subroutine is called by subroutine FILEIN to check whether the specified input files exist.
3. Subroutine READIN – This subroutine is called by the main program to read and organize the input data, except for the data related to the time series of input salt loads or concentrations from the WRAP-SALT input file and the flow data from the WRAP-SIM output file. This subroutine performs all pertinent data manipulation and organization within the program.

The WRAP-SALT model is based on a monthly time-step. All salinity and flow balance computations are performed for each month of the entire hydrologic period-of-analysis. The algorithm is based on the premise that the end-of-month concentration at a reservoir serves as the beginning-of-month concentration for the subsequent month. Thus, computations are repeated for each month of the hydrologic period-of-analysis at all control points. Figure 4.1 provides a detailed schematic view of the WRAP-SALT simulation.

The model tracks the spatial configuration of the control points in the river basin system based on the control point sequence in the WRAP-SIM input file. All computations are performed based on the sequence in which the control points are read from the WRAP-SIM input file. The control points have to be specified in an upstream-to-downstream order. All computations for a particular control point are performed only after the completion of the computations for all control points located upstream of that

- Initialization of the WRAP-SALT input and the output files.

  1. The required *SIM* input (DAT) and output (OUT) and *SALT* input (SIF) and output (SOF, SMF) files are initiated.

  2. The optional beginning-of-simulation storage volume (BRS) and concentration (BRC) files are initiated after reading *JC* record specifications from the SIF file.

  3. The identifier of each control point and its next downstream control point are read from the *CP* records in the *SIM* DAT file to establish spatial connectivity.

  4. All data in the SIF file are read except the S records of time series of salt inflows.

- ***Beginning of Salt Constituent Loop***

  1. Salt concentrations or loads are read from the *S* records in the SIF file or constant concentrations from *CS* records are assigned if a SIF file control point has no *S* records.

  2. Beginning-of-simulation reservoir storage concentrations and loads are set.

  3. The initial concentrations are repeated at downstream *SIM* control points that are not included in the SIF file.

  - ***Beginning of Monthly Time Step Loop***

    1. Beginning-of-month reservoir storage volumes, loads, and concentrations are set at beginning-of-simulation values for the first month and thereafter at end-of-month values from the preceding month.

    2. Water quantities are read from the *SIM* simulation results OUT file.

    - ***Beginning of Control Point Simulation Loop***

      1. Lag is set and monthly lag index is updated if the lag options are activated.

      2. Volumes and loads entering the control point are determined.

      3. Concentrations of regulated flows and diversions leaving the control point and the end-of-month storage load and concentration are determined.

      4. Simulation results are written to the SOF and SMF files.

      5. Totals are accumulated for the SMF file total volume and salt balance table.

Figure 4.1 Schematic of a WRAP-SALT Simulation

- ***Control Point Simulation Loop is Repeated***
- ***Monthly Time Step Loop is Repeated***

Volume and load totals are written to the summary table in the SMF file.

- ***Salt Constituent Loop is Repeated***

End-of-simulation storage concentrations are written to the optional BRC file.

Figure 4.1 Continued

control point. The necessary control point configuration in the SIM input file is obtained by executing TABLES as explained earlier in this section. The control points in the WRAP-SALT input file can be organized in any order.

Reservoir storage volume and concentration for each control point must be established for time zero; which is the beginning of the first month of the simulation. The model requires salt input as concentrations of local incremental inflows for each month and the beginning-of-period reservoir storage volumes respectively. Input data must be provided for the most upstream control point on each branch of the river system network where salinity is modeled. For control points which do not have the necessary salinity data as input, input concentrations are repeated from the upstream control point until another control point with input salinity data is encountered in the WRAP-SALT input file.

Flow volumes are read from the WRAP-SIM output file. Total monthly diversion volume at each control point is computed as the difference of the target monthly diversion and the total monthly shortage. The model provides the user three options for allocating the beginning-of-simulation storage volumes at reservoirs. This is controlled by the variable BEGSTO in the 7^{th} column of the JC record in the WRAP-SALT input file. The user can choose to compute the beginning-of-simulation reservoir storage based upon the output flow volumes read from the WRAP-SIM input file. Mathematically, within the model, this equation is represented as:

BSS(CP) = ST - DEP + EP + DT - DS

where,

BSS – beginning-of-simulation reservoir storage volume

DS – diversion shortage

DT – diversion target

EP - evaporation

ST – end-of-period storage volume

DEP – streamflow depletions during the time period

The value computed using this option could be an approximate value as the WRAP-SIM output file might not have all variables on which the beginning reservoir storage volume may depend.

This computed value is overridden if the user opts to manually enter these values in the 11th column of the CP record in the WRAP-SALT input file. The beginning-of-simulation reservoir storage can also be read from the optional beginning reservoir storage file (.BRS file). The corresponding beginning-of-simulation reservoir storage concentration can be provided either as model input in the CP records of the WRAP-SALT input file or can be read from the optional beginning reservoir concentration file (.BRC file).

The salinity simulation takes place within repetitive loops. All computations for a particular water quality constituent are performed for each control point within annual and monthly control loops. Flows and loads entering each control point during the simulation are then accounted for. The incremental naturalized flow and load entering a control point are the amounts at that control point less the corresponding amounts at any control points located immediately upstream. If a control point has no control point located upstream of it, then the incrementals are equal to the totals at that control point. Regulated flow and load entering a control point are computed as the summation of regulated flows and loads from upstream control points adjusted for the effects of channel losses and channel loss credits.

Concentrations for the incremental naturalized flows are provided as input in the WRAP-SALT input file. The concentrations for the entering regulated flows, channel loss credits, and channel losses at a control point are computed during the course of the simulation from upstream control points. Concentration for the return flows can be estimated using any of the following three options:

Column 13 of the CP record can either be left blank in the WRAP-SALT input file which indicates that either the return flow concentration is zero or the concentration is provided by the CC record. A positive value in this column indicates that the simulation adopts a constant return flow concentration for that control point. The third option estimates the concentration of the return flows within the model. The model provides the user two options for computing the total incoming flows and loads at a control point. The user can model the total inflows at a control point by using elementary mass balance methods or compute the inflows as the summation of the total stream inflows and return flows at that control point. If the first option is exercised, then total inflows are estimated in the following manner:

The first estimate of the flow volume entering each control point is computed as the summation of the total incremental naturalized flow, the total upstream regulated flow adjusted for channel losses and channel loss credits, and the return flow at that control point. This water balance equation is represented as:

FIN1 = FNAT + FREG + FCLC - FCL + RET(CP)

where:

FIN1 – first estimate of inflows

FNAT – incremental naturalized flow volume

FREG – sum of regulated flow volumes at upstream control points

FCLC – sum of channel loss credit volumes from upstream control points

FCL – sum of channel loss volumes from upstream control points

RET (CP) – return flow returned to the control point

The first estimate of the loads entering each control point is analogous to that of the flows and is given as:

LIN1 = LNAT + LREG + LCLC - LCL + LRET

where:

LIN1– first estimate of inflow loads

LNAT– load of incremental naturalized flow

LREG– sum of loads of regulated flows at upstream control points

LCLC– sum of loads of channel loss credits from upstream control points

LCL– sum of loads of channel losses from upstream control points

LRET– load of return flow

These computations are performed based on the values read from the WRAP-SIM output file. The above equations do not take into account the constant inflows which enter a control point and are provided in the CI records of the WRAP-SIM input file. Constant inflow records consist of 12 inflows or outflows, for the 12 months of the year, which are repeated each year. Outflows are input as negative inflows. This record is used to model:

1. Return flows not otherwise included in the return flow options, such as return flows from water supply withdrawals from groundwater aquifers
2. Diversions not otherwise included in the water rights
3. Channel losses not otherwise included in the channel loss option
4. Interbasin transfers of water to the control point
5. Interactions between groundwater and streamflow associated with the aquifer pumping (Wurbs 2003).

These inflows and outflows are not reflected in the WRAP-SIM output file. In order to account for these inflows and outflows so as to maintain a consistent water and salt load balance, a second estimate of the flow volume entering each control is made. A second estimate of the flow volume entering each control point is computed as:

$$FIN2 = REG(CP) + DIV + EVAP(CP) - BSS(CP) + STO(CP)$$

where:

FIN2– total inflows with FDIF

REG(CP)– regulated flow

DIV– diversion computed as DT-DS

STO(CP)– reservoir storage volume

BSS(CP)– beginning-of-period storage volume

EVAP– net evaporation less evaporation

The difference in the inflow volumes is computed as

FOTH = FIN2 - FIN1

where:

FOTH-missing component of the water budget such as CI record inflows

An improved value of the load entering a control point is then estimated as:

LIN2 = LIN1 + LOTH

where:

LOTH – loads associated with FOTH

LIN2 – total inflow loads with LOTH

Evaporation volume is not considered as the concentration associated with this volume is assumed to be zero.

For a control point having no storage, the concentration associated with the regulated flow is computed as the ratio of the total incoming load at that control point and the total outflow at that control point. The total outflow at a control point is equal to the sum of the regulated flow and the diversion at that control point. For a reservoir, concentration in the regulated flow and the diversion is modeled as the reservoir outflow concentration. This outflow concentration can either be modeled as the mean storage concentration or the beginning-of-month storage concentration. The user also has the option of modeling reservoir outflow concentration based upon a lag parameter. This is based on the premise that complete mixing takes place within a storage reservoir over a period of time and is not instantaneous. The lag period for each storage reservoir can either be estimated within the model or be provided as input data. Within the model, the lag period is estimated based on a flow retention option which computes lag as a function of storage and outflow.

A key aspect of the WRAP-SALT program is that the user can provide limiting values of concentrations as input to the model. The combination of low flows and high loads and vice-versa can give rise to unreasonable values of concentrations. The limiting values of concentrations aid the user in filtering these unreasonably high or low concentration values by making use of proper engineering judgment.

5. DEVELOPMENT OF SALINITY DATA FOR THE BRAZOS RIVER

One of the objectives of this research is to investigate different methods to develop input salt concentration data for the WRAP-SALT model. Salt concentrations depend on various complex factors besides discharge. They exhibit random variability over time. This research aims at developing a methodology for input data generation which would reflect the real-world random variations in salt concentrations. This section describes the methodology adopted to develop the input dataset which is used to simulate the effects of natural salt pollution in the Brazos River Basin.

The basic data used to develop a complete homogeneous set of monthly salt concentrations for the Brazos River Basin was obtained from the U.S. Geological Survey (USGS). Wurbs and Ganze (1989) compiled the USGS discharge and water quality data into a readily usable format for the USACE. This compiled data was available for a period of record of 24 years, ranging from October 1963 to September 1986. This data is available in electronic format as Lotus 1-2-3 spreadsheets and was exported to Microsoft Excel for further manipulation. Naturalized flows were obtained from the Texas Water Availability Modeling (WAM) dataset for the Brazos River Basin which extends from 1940-1997.

The Brazos WAM dataset extends from January 1940 – December 1997 and salinity data was available for the period October 1963 – September 1986. In order to maintain consistency with the Brazos WAM dataset during simulation modeling studies of the Brazos River Basin, it was required to develop input salinity data for the periods ranging from January 1940 – September 1963 and October 1986 – December 1997. This task was to be achieved using the salinity data available for the period of record. In addition, the salt concentrations developed for the periods January 1940 – September 1963 and October 1986 – December 1997 were to have the same random variability as that of the period of record. The detailed computational procedure followed to develop the input salinity dataset is described in section 5.2.

5.1 SELECTION OF CONTROL POINTS FOR DATA DEVELOPMENT

The Brazos River Basin system has over 3000 control points and salinity data is available only for 26 control points. In addition, the Brazos River Basin exhibits tremendous spatial and temporal variations in salt concentration. Thus, the selection of control points for the development of salinity data was an important aspect of the data development procedure. The selection of control points was based on the:

1. pertinent locations of the control points in the river basin,
2. representation of the spatial variations of salt concentration over the river basin.

Table 5.1 represents the control points for which were used to develop the input salinity data for the WRAP-SALT model with their location on the Brazos River. Figure 5.1 depicts the location of the selected control points on the Brazos River. Based on the selection of the relevant control points for developing the input data set, the following assumptions were made:

Table 5.1 Selected Control Points for Input Data Development

Control Point Name	Location
Seymour Gage	Main Stem
Eliasville Gage	Clear Fork
Whitney Gage	Main Stem
Possum Kingdom Gage	Main Stem
Cameron Gage	Little River
Richmond Gage	Main Stem

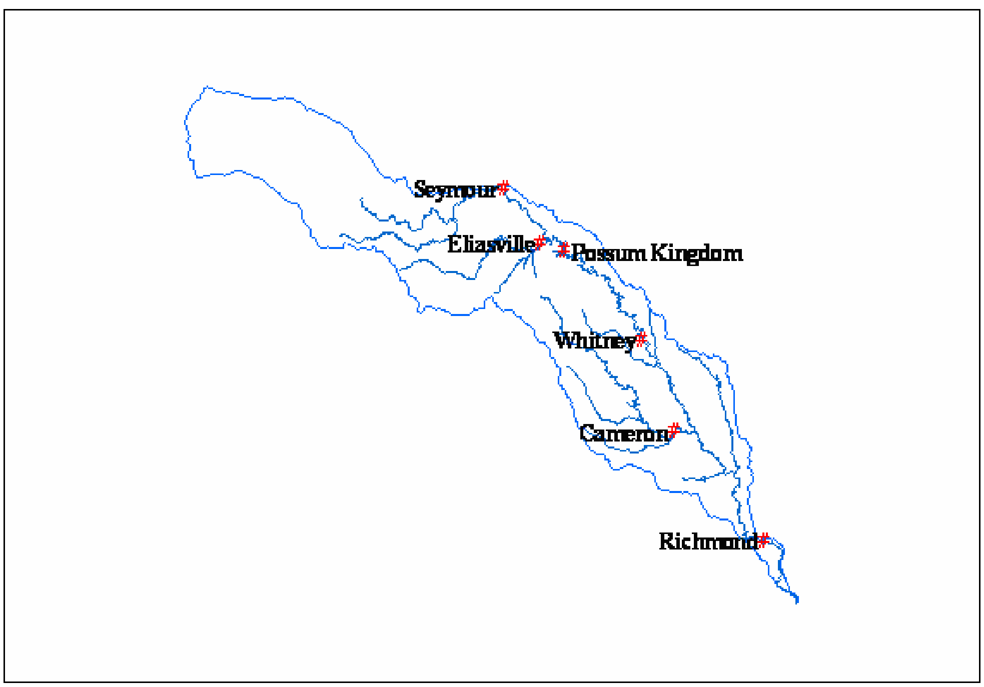

Figure 5.1 Location of the Selected Control Points on the Brazos River

1. Seymour gage would act as an upstream boundary condition. Salt concentration computations for all control points upstream of the Seymour gage would be neglected as there is very minimal use of the waters of the watershed upstream of the Seymour gage.
2. All control points upstream of the Eliasville gage will have the same salt concentrations as that of the flows at the Eliasville gage.
3. All control points upstream of the Cameron gage would have the same salt concentrations as that of the flows at the Cameron gage. This assumption was made considering the approximately constant salt concentrations in the flows from the Little River Watershed at the Cameron gage control point.
4. All control points upstream of the Whitney gage would have the same mean salt concentration as that of the incremental flows between the Possum Kingdom gage and the Whitney gage.
5. All control points lying downstream of the Cameron gage and the Whitney gage would have the same salt concentrations as that of the incremental flows at the Richmond gage.

5.2 BASIC PREMISES

The basic premises involved in the development of input salinity data are outlined below:

1. The loads (L) of the monthly naturalized flows (Q) during the October 1963 – September 1986 period are set equal to the gaged loads (L_G) from the USGS dataset. The historical measured loads at selected gaging stations are assumed to be representative of loads that would have occurred under natural conditions without water resources development. Thus, the total load during the period October 1963 – September 1986 is $\sum L_G$

2. For the period that encompasses both January 1940 through September 1963 and October 1986 through December 1997, for each month, the expected value of L for a given value of Q is computed as $E(L/Q) = aQ^b$, with the coefficients a and b determined by a regression of Q and L_G for the period-of-record ranging from October 1963 – September 1986. The total load during the period January 1940 – September 1963 and October 1986 – December 1997 is the summation of the monthly loads computed as a function of Q. Thus, total load (Jan 1940 - Sep 1963 & Oct 1963 - Dec 1997) is $E(L/Q) = aQ^b$

3. Loads vary randomly from the expected values computed as a function of flow. The random variability of loads during the period of salinity measurements ranging from October 1963 – September 1986 is assumed to be characteristic of the overall January 1940 – December 1997 simulation period. For the periods January 1940 – September 1963 and October 1986 – December 1997, the relation between load and flow is given as

$L_{unadjusted} = E(L|Q) + D \times E(L|Q) = a\,Q^b \times (1.0 + D)$. These loads are adjusted to maintain a total load for the periods January 1940 –September 1963 & October 1986 – December 1997 load equal to the summation $\sum L_{G.}$

The adjustment is defined as $L_{adjusted} = L_{unadjusted}\left(\frac{\Sigma E(L|Q)}{\Sigma L_{adjusted}}\right)$

5.3 METHODOLOGY

The procedure outlined below as Tasks 1-6 results in monthly concentrations for incremental streamflows covering the January 1940 – December 1997 simulation period for all control points located within the watersheds of the Seymour, Eliasville, Cameron, and Richmond Gages. Flows and loads at the Richmond gage represent the incremental watershed below the Cameron, and Whitney gages.

1. The loads (L_G) from the gaged salt data and the naturalized flows (Q) from the WAM dataset are used to perform regression analyses to determine the coefficients 'a' and 'b' for the Seymour, Eliasville, Cameron, and Richmond Gages for the salt period-of-record ranging from October 1963 through September 1986. Hence $E(L|Q) = a\,Q^b$.
2. Fractional load deviations (D) are computed for the Seymour, Eliasville, Cameron, and Richmond Gages for the October 1963 – September 1986 period of salt record and are denoted as $D = \frac{L_G - E(L|Q)}{E(L|Q)}$.

3. The 23 years of monthly fractional load deviations are repeated to cover the January 1940 – September 1963 and October 1986 – December 1997 segments of the January 1940 – December 1997 simulation period for which gaged salt data is not available. This is represented in Table 5.2
4. Loads (L) are computed for each month of the January 1940 – September 1963 and October 1986 – December 1997 segments of the January 1940 – December 1997 simulation period for which gaged salt data is not available as $L_{unadjusted} = \; a\,Q^b \times (1.0 + D)$.
5. Negative values of L, Q, and C may occur at the Richmond gage. The regression analysis is limited to months with positive values of Q. For negative Q (flow losses), the mean concentration C_M is assumed. Therefore, for Q > 0, $E(L|Q) = a\,Q^b$ whereas if Q < 0, $E(L|Q) = C_M\,Q$.
6. Loads and concentrations are adjusted to replace negative values of C caused by either a negative L or a negative Q and to define undefined values of C caused by a Q of zero. If C is undefined because Q = 0, then C = $C_{M.}$ If C is negative because Q is negative while L is positive, C = $C_{M.}$ If C is negative because L is negative while Q is positive, C = 0. No adjustment is required if C is positive regardless of whether L and Q are both positive or are both negative.
7. The loads from Task 4 above, with Task 5 adjustments for the Richmond gage, are adjusted to maintain a total 1940-1963 & 1986-1997 load equal to

the summation ΣE (L|Q). This adjustment is defined as

$$L_{\text{adjusted}} = L_{\text{unadjusted}}\left(\frac{\Sigma E(L|Q)}{\Sigma L_{\text{unadjusted}}}\right).$$

Table 5.2 Salt Load deviations and Their Corresponding Periods

Period	**Period whose deviation was repeated**
January 1940 – September 1940	January 1986 – September 1986
October 1940 – September 1963	October 1963 – September 1986
October 1963 – September 1986	October 1963 – September 1986
October 1986 – December 1997	October 1963 – December 1974

5.4 INPUT DATA REFLECTING THE EFFECTS OF THE SALT CONTROL DAMS

A separate input dataset was also developed for the salt control dam plan proposed by the USACE. Section 3.3 of this thesis describes the proposed salt control plan and its impact on natural salt pollution in the Brazos River Basin. The evaluation of the proposed salt control dam plan involves the estimation of the mean monthly discharge, salt load, and salt concentration at the Seymour gage for the January 1940 – December 1997 period of simulation.

The basic assumption underlying the input data development for the salt control dams was that these dams would contain all the discharge and the salt load at their respective locations. In order to reflect this assumption, pertinent volumes of discharge and salt loads were subtracted from the Seymour gage and the downstream gages on the main stem of the Brazos River. The methodology adopted for the development of the input data considering the effects of the proposed salt control dam plans is same as the one described in section 5.2 and section 5.3

5.5 RESULTS AND DISCUSSION

Discharge and salt loads and salt concentrations vary tremendously over time and with location (Wurbs et. al. 1989). This part of the section describes the spatial and temporal variations that are observed in the salt concentrations.

This section presents relevant statistics for the entire period of simulation from January 1940 - December 1997. The tables also present detailed statistics for the pertinent sub-periods which includes the January 1940 – September 1963, October 1963 – September 1986, and October 1986 – December 1997 periods. Both, arithmatic concentrations and discharge-weighted concentrations are presented for the concerned control points. Means and Standard Deviations are also indicated for the selected control points. Table 5.3 summarizes the means and standard deviations of flows for the concerned control points.

Table 5.3 Means and Standard Deviations of Flows

Gage	**Seymour**	**Eliasville***	**Possum Kingdom**	**Whitney**	**Cameron**	**Richmond**
Means (ac-ft/month)						
1964-86 Gaged Flows	16215.34	18924.38	41382.37	74193.49	89374.78	126426.13
1964-86 Naturalized flows	16840.26	24702.69	53868.11	93760.90	96945.91	258914.62
1940-63&1987-97 Naturalized flows	23470.63	26242.41	74177.22	128826.32	118343.83	265252.50
1940-1997 Naturalized flows	20841.35	25738.02	66123.60	114921.07	109858.44	262739.20
Standard Deviations						
1964-86 Gaged Flows	28936.69	50925.48	82738.97	113123.82	111421.70	162289.50
1964-86 Naturalized flows	29565.37	57715.27	106908.48	145938.20	140903.26	306722.91
1940-63&1987-97 Naturalized flows	49494.66	62861.39	153413.21	234661.55	187048.50	353085.97
1940-1997 Naturalized flows	42816.92	60025.22	137150.91	204743.74	170465.50	335254.66

Concentration-duration analyses were performed for the selected control points for all salt constituents. A summary of the concentration-duration curves for individual salt constituents for the selected control points is also presented. The concentration-duration analyses were also performed taking into consideration the effects of the USACE proposed salt control impoundments. Table 5.4 presents results from the concentration-duration analyses at the Seymour gage under normal conditions while Table 5.5 presents the results from the concentration-duration analyses at the Seymour gage considering the presence of the salt control dams.

Table 5.4 Concentration-Duration Analysis for Seymour

Percent Time Equalled or Exceeded	**TDS (mg/l)**	**Cl (mg/l)**	**SO4 (mg/l)**
10%	10601.0	4967.0	1622.0
25%	8296.0	3606.0	1315.0
40%	6375.0	2648.0	1131.0
50%	5247.0	2095.0	941.0
60%	4196.0	1635.0	828.0
75%	3177.6	1159.7	636.1
90%	1948.8	704.5	410.6
95%	1258.5	425.5	207.5
98%	96.1	31.6	32.4
99%	0.0	0.0	0.0
100%	0.0	0.0	0.0
Mean	5784.8	2503.6	977.7
Standard Deviation	3327.4	1675.3	455.0
Maximum	17103.0	9400.0	2166.0

The variations can be better understood by observing the plots obtained from the developed data. The figures illustrate spatial and temporal variations in salt concentration at the selected control points. At the Seymour gage, the concentration of the total dissolved solids ranged from a mean monthly value of 73 mg/l in August 1987

Table 5.5 Concentration-Duration Analysis for Seymour (with dams)

Percent Time Equalled or Exceeded	**TDS (mg/l)**	**Cl (mg/l)**	**SO4 (mg/l)**
10%	6276.0	2649.0	1285.0
25%	4322.0	1518.0	1014.0
40%	2978.0	1005.0	856.0
50%	2325.0	724.0	709.0
60%	1663.0	403.0	643.0
75%	0.0	0.0	435.7
90%	0.0	0.0	122.3
95%	0.0	0.0	0.0
98%	0.0	0.0	0.0
99%	0.0	0.0	0.0
100%	0.0	0.0	0.0
Mean	2666.5	1041.4	731.0
Standard Deviation	2520.8	1296.1	413.7
Maximum	11056.0	8488.0	1855.0

to 17103 mg/l in October 1943. The chloride concentrations varied from 20 mg/l in August 1987 to 9400 mg/l in October 1943. Sulfate concentrations varied from 28 mg/l in August 1987 to 2166 mg/l in October 1943. At the Richmond gage, the concentration of the total dissolved solids ranged from a mean monthly value of 117 mg/l in October 1984 to 4138 mg/l in August 1941. The chloride concentrations varied from 28 mg/l in October 1984 to 3382 mg/l in August 1941. Sulfate concentrations varied from 22 mg/l in October 1965 to 878 mg/l in August 1941.

At the Seymour gage, mean monthly total dissolved solids, chloride, and sulfate concentrations of 10601 mg/l, 4967 mg/l, and 1622 mg/l, respectively, were equalled or exceeded during 10% of the 696 months of the 1940-1997 analysis period. At the Richmond gage, TDS, Cl, and SO_4 concentrations of 405 mg/l, 112 mg/l, and 68 mg/l were equalled or exceeded 10% of the 696 months of the 1940-1997 analysis period. Figure 5.2 presents concentration-duration curves at the Seymour gage under normal conditions while Figure 5.3 presents concentration-duration curves at the Seymour gage with the salt control dams in place.

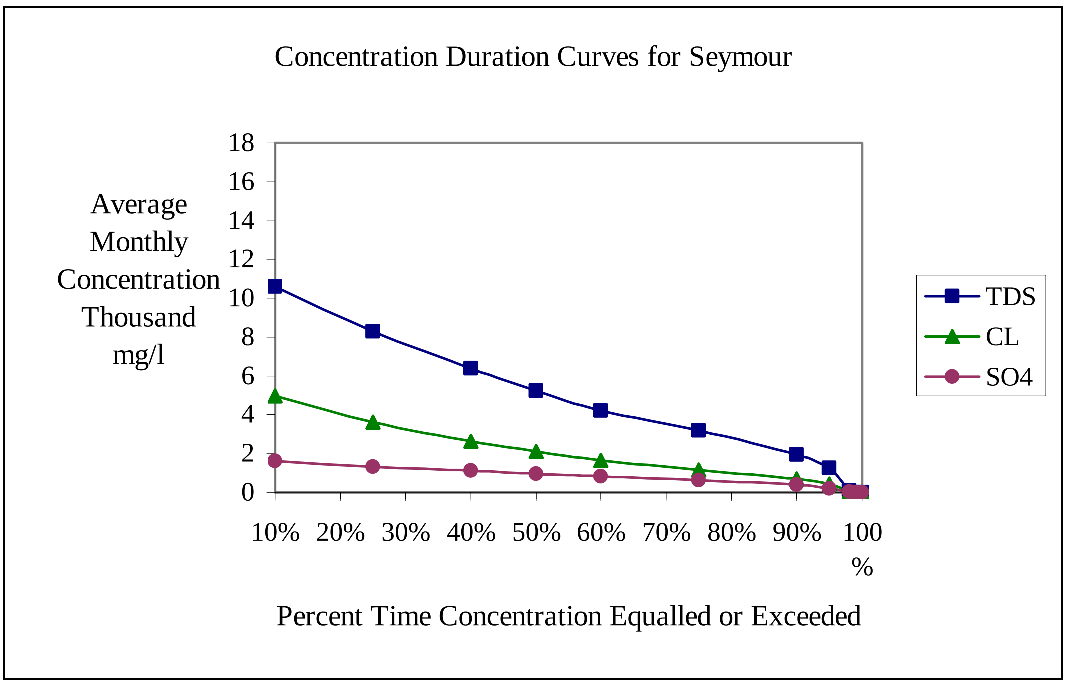

Figure 5.2 Concentration-Duration Curves for Seymour

Considering the salt control dams, we observe that at the Seymour gage, mean monthly total dissolved solids, chloride, and sulfate concentrations of 6276 mg/l, 2649 mg/l, and 1285 mg/l, respectively, were equalled or exceeded during 10% of the 696 months of the 1940-1997 analysis period. At the Richmond gage, TDS, Cl, and SO_4 concentrations of 329 mg/l, 68 mg/l, and 59 mg/l were equalled or exceeded 10% of the 696 months of the 1940-1997 analysis period. Thus, at the Seymour gage, the presence of the salt control dams reduces the TDS concentration, the chloride concentration and the sulfate concentration by 40.79%, 46.66%, and 20.77% respectively. Similarly, at the Richmond gage, the TDS concentration, the chloride concentration and the sulfate concentration are reduced by 18.76%, 39.28%, and 13.23% respectively.

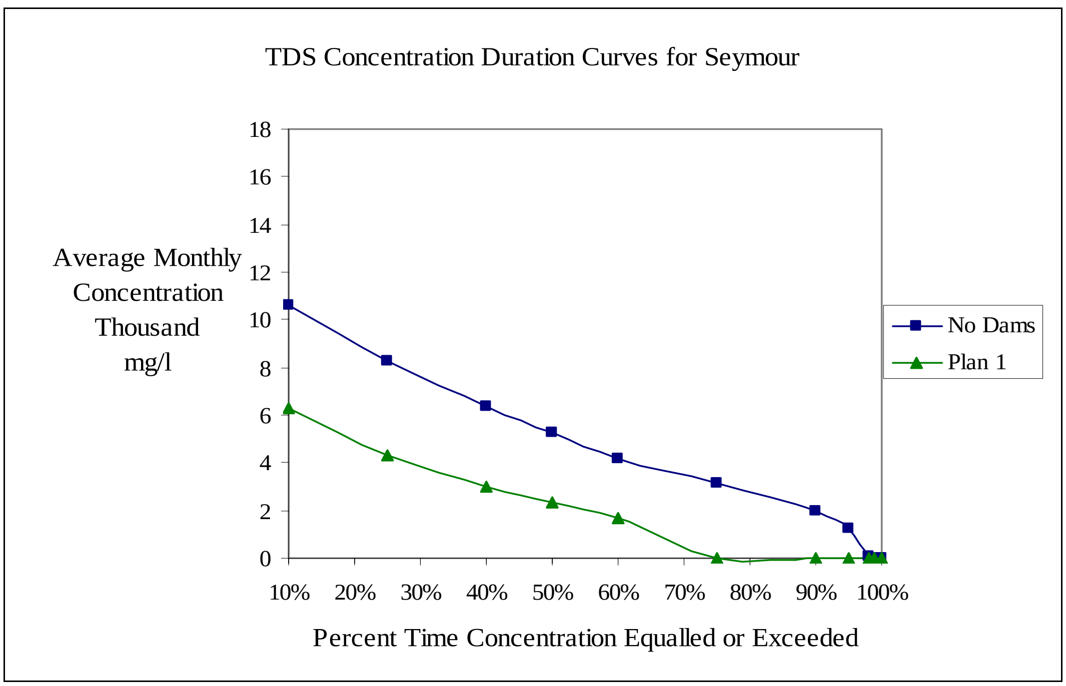

Figure 5.3 TDS Concentration-Duration Curves for Seymour (with dams)

There exists great similarity in the variation patterns of the salt constituents. It is observed that an increase or a decrease in the values of any salt constituent is accompanied by a corresponding increase or a decrease in the concentrations of the other salt constituents. This can be attributed to the fact that salt loads vary in direct proportion with discharge. A flood or a drought event has a direct bearing on the load contained in the flows. This affects the concentration. However, no conclusive relation could be obtained between concentration and discharge while treating concentration as a function of discharge. The results of the data development procedure for the Seymour, Eliasville, Cameron, Whitney, Possum Kingdom and the Richmond gage control points are summarized in Appendix A of this thesis.

6. THE BRAZOS RIVER BASIN SIMULATION STUDY

6.1 SCOPE OF THE STUDY

The Brazos River Basin system has a complex configuration of over 3000 control points, 600 reservoirs, and numerous water rights. In addition, as described in Section 3 of this thesis, the water usage in the Brazos River is severely constrained by natural salt pollution. Thus, to test and verify the salinity simulation modeling capabilities of WRAP-SALT, it was decided that the Brazos River Basin would serve as an ideal case study. The overall goal of this research is to expand capabilities for incorporating salinity considerations in assessments of water availability. The general objectives of the simulation study are as follows:

1. track salt concentrations in the regulated flows at various control points in the Brazos River Basin.
2. study the impacts of the proposed salt control dams on natural salt pollution in the basin.
3. assess water supply reliabilities under various salinity constraints.
4. study the effects of reservoir lag on reservoir outflow concentration and downstream control points.

6.2 ASSUMPTIONS

There were various assumptions adopted during the course of the simulation study. They are listed below:

1. The input salinity data for the river basin was developed based on available historical data. There were certain assumptions made in the development of the input dataset which are described in Section 5 of this thesis. The mathematical manipulations performed in the development of the input dataset to eliminate discrepancies were consistent with the assumptions made.
2. Control points having no salinity input data were considered to have the same salt concentrations as their upstream control point.
3. All salt balance computations are based on the assumption that the salts are conservative in nature and complete mixing occurs in all areas of storage and flow throughout the basin. The total mass of salt in the system is conserved and is not lost or transformed through any physical, chemical, biological process.
4. The diversion shortages declared during the river-basin water supply reliability studies based on salinity constraints were not considered during the original WRAP-SIM simulation. Different values were adopted to serve as levels of salinity constraints to test their impact on the reliability indices.

These values were adopted for research purposes and do not serve as an upper limit on the maximum allowable salt concentration.

The remainder of this section focuses on how the above mentioned objectives were achieved and analyzes the results obtained from the Brazos River Basin simulation study.

6.3 MODEL SETUP AND ORGANIZATION OF INPUT FILES

As described in Section 4 of this thesis, the WRAP-SALT simulation model requires input salinity data and flow data. The salinity data developed for the Brazos River Basin, as described in Section 5, was organized in a format recognized by the simulation model. The input flow and storage volume data were developed by the TCEQ for water availability modeling studies of the Brazos River Basin and can be obtained from the following web-site at no cost:

http://www.tnrcc.state.tx.us/permitting/waterperm/wrpa/wam.html#BJ

The simulation model is based on a monthly time-scale. The simulation extends from January 1940 through December 1997. Thus, there are 696 months in the simulation period. Flow data and salt data for the pertinent control points are provided for 696 months of the simulation period. After the organization of the required input files, simulation runs were made considering alternate scenarios within the scope of the modeling studies.

The WRAP-SALT model provides numerous modeling options for river basin salinity simulation. Proper engineering judgment must be exercised while modeling river basin salinity governed by a particular set of user-defined options. This case study was controlled by the following modeling options for the base scenario:

1. The WRAP-SIM simulation for the Brazos River Basin was performed controlled by an ADJINC value of 4 on the JC record of the WRAP-SIM input file. Under this option, as each water right is considered, upstream negative incremental flow adjustments are applied at the downstream control points but not at the control point of the right (Wurbs 2003).
2. All flow and storage data are in units of “acre-feet/month”. Salt input data at the Seymour gage control point are in units of “tons/month”. Salt input data at all other control points are in units of “milligrams/liter”. In field 15 of the JC record, a conversion factor of 735.48 was selected to maintain consistency in the units of the output data. This is briefly described in Section 4.3.1.1.
3. The beginning-of-simulation reservoir storage volume is obtained from the beginning reservoir storage file (.BRS file) which is an optional output of a WRAP-SIM simulation.
4. Beginning-of-simulation reservoir storage concentrations are adopted from gaged USGS data for the 1964-1986 period under the assumption that values for this period represent the historical ideal.

5. The salinity data in the WRAP-SALT input file was grouped by year with a set of records for each year. For control points without input salt data, data was repeated from control points located upstream.
6. The total inflow into a control point was based on the premise that inflow at a control point equals the summation of the outflow and storage volume change at that control point.
7. At control points having negative total inflows, no adjustments were made to alter the same.
8. Reservoir outflow concentration was modeled based on the mean reservoir storage concentration of the month. Reservoir lag time was not considered in the base simulation run.
9. Limiting values for a control point outflow concentration were assumed to be 1.3 times the minimum and the maximum concentration values observed for that control point in the USGS gaged dataset.
10. Return flow concentration was estimated within the model.
11. Concentration of other inflows was estimated within the model.

6.4 ANALYSES OF THE SIMULATION RESULTS

This section discusses the results obtained from the simulation of the Brazos River Basin. In order to maintain consistency with the results presented in Section 5, the focus of this section is limited to only those control points that were selected for developing the input data. These control points are assumed to be representative of the river basin characteristics. The program TABLES was used to organize the simulation results, perform concentration-duration analyses, and reservoir-reliability analyses.

For the 696 months in the simulation, the Seymour gage control point has a mean regulated TDS concentration of 6303 mg/l. The mean regulated TDS concentration at the control points at Possum Kingdom and Whitney are 2276 mg/l and 1615 mg/l respectively. The EPA has a limiting value of 500 mg/l for TDS concentrations in waters for domestic usage. These values are well above the EPA prescribed standards for domestic usage. Water from the reservoirs at Possum Kingdom and Whitney cannot be utilized for domestic purposes without proper treatment. The Cameron gage control point which lies on the Little River watershed had a mean regulated TDS concentration of 277 mg/l. At the Richmond gage the mean regulated TDS concentration is 359 mg/l. The water quality in the lower basin near the Gulf of Mexico is comparatively better as a result of dilution due to inflows from good quality tributaries.

The mean monthly regulated chloride concentration at Seymour is 2722 mg/l. Chloride concentrations are relatively lower at the Possum Kingdom and the Whitney control points with a mean concentration of 795 mg/l and 684 mg/l respectively. The Cameron gage at the Little River watershed has good quality water with low salt concentrations. Mean monthly sulfate concentrations are again the highest at the Seymour gage with a sulfate concentration of 1066 mg/l. The water quality at Seymour is impaired due to poor quality inflows from the Croton Creek, Salt Croton Creek, and the North Croton Creek tributaries respectively of the Brazos River. The mean monthly regulated sulfate concentration at Richmond is 109 mg/l. From the above mentioned values, it is evident that salt concentrations are higher towards the upper end of the basin and gradually decrease towards the lower end of the basin.

A concentration-duration analysis provides a better picture of the temporal variations in salt concentrations exhibited at the different locations. At the Seymour gage, a regulated TDS concentration of 11,345 mg/l is equalled or exceeded 10 % of the 696 months of the simulation period whereas a concentration of 2043 mg/l is equalled or exceeded 90 % of the 696 months of the simulation period. Mean monthly chloride and sulfate concentrations of 5263 mg/l and 1705 mg/l respectively, are equalled or exceeded during 10% of the 696 months of the 1940-1997 simulation period. At Possum Kingdom, mean monthly TDS, chloride, and sulfate concentrations of 1751 mg/l, 661 mg/l, and 443 mg/l are equalled or exceeded 90 % of the 696 months of the simulation period. Likewise, the water quality at Whitney is poor with a mean monthly TDS, chloride, and sulfate concentration of 1245 mg/l, 589 mg/l, and 364 mg/l being equalled or exceeded 90 % of the 696 months of the simulation period. Table 6.1 shows the results of the concentration-duration analysis at the Seymour gage while Figure 6.1 provides a graphical representation of the same.

The water quality can be classified as good at the Cameron gage on the Little River watershed. At the Cameron gage, mean monthly TDS, chloride, and sulfate concentrations of 252 mg/l, 42 mg/l and 41 mg/l respectively, are equalled or exceeded during 50% of the 696 months during the course of the simulation. At Richmond, the water quality is relatively higher as compared to all the other selected gages lying on the main stem of the Brazos River. At Richmond, mean monthly TDS, chloride, and sulfate concentrations of 587 mg/l, 218 mg/l and 187 mg/l respectively, are equalled or exceeded only during 10% of the 696 months during the course of the simulation.

Table 6.1 Regulated Concentration-Frequency Analysis at Seymour

Percent Time Equalled or Exceeded	TDS (mg/l)	Cl (mg/l)	SO4 (mg/l)
10%	11345.0	5263.0	1705.0
25%	9068.0	4009.0	1439.0
40%	6984.0	2927.0	1205.0
50%	5660.0	2318.0	1032.0
60%	4538.0	1804.0	884.0
75%	3405.0	1255.0	702.0
90%	2043.0	745.0	430.0
95%	1312.0	426.0	250.0
98%	650.0	250.0	250.0
99%	0.0	0.0	0.0
100%	0.0	0.0	0.0
Mean	6303.0	2722.0	1067.0
Standard Deviation	3683.0	1825.0	494.0
Maximum	25000.0	10000.0	2500.0

The variations observed in the salt concentrations at the selected points can be better understood by plotting figures of the same. It is observed that there exists relatively low variation in the salt concentrations at Possum Kingdom and Whitney as compared to the other gaging stations. This is due to the fact that salinity at these gaging stations was modeled as a constant value rather. The variations at Seymour are the most pronounced followed by the variations at Eliasville and Richmond. It can be observed from the plots that an increase or decrease in the concentration of a constituent for any particular year is usually associated with a corresponding change in the concentration of the other constituents. These plots also indicate that water quality in the Brazos River Basin is chiefly affected by the presence of large amounts of total dissolved solids. Chloride and sulfate concentrations are less pronounced as compared to the TDS concentrations towards the lower reaches of the Brazos River.

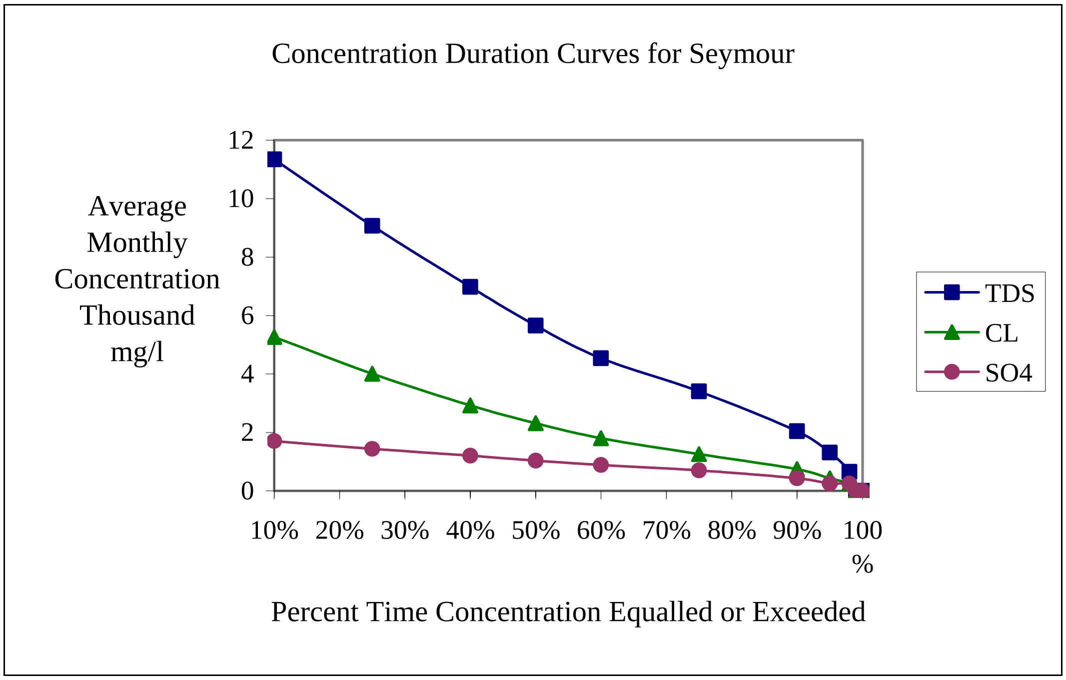

Figure 6.1 Regulated Concentration-Frequency Curves at Seymour

6.5 EFFECTS OF THE SALT CONTROL DAMS

Simulation runs were also made taking into consideration the effects of the proposed salt control impoundments. The water quality in the main stem of the Brazos

River is degraded by emissions from major salt sources in the upper Brazos River Basin. The U.S. Army Corps of Engineers (USACE) conducted natural salt pollution control studies in the Brazos River Basin. These studies primarily focused towards determining the most feasible method to control natural salt pollution in the Brazos River Basin and its tributaries. It was recommended by the USACE that impoundment structures be constructed at specified locations to control and retard salt control emissions into the Brazos River. Separate input data was developed to highlight the effects of the proposed impoundments on streamflow and salt load.

Considering the presence of the salt control dams, we observe that at the Seymour gage, mean monthly TDS, chloride, and sulfate concentrations of 6807 mg/l, 2631 mg/l, and 1245 mg/l, respectively, were equalled or exceeded during 10% of the 696 months of the 1940-1997 analysis period. Thus, at the Seymour gage, the presence of the salt control dams reduces the TDS concentration, the chloride concentration and the sulfate concentration by 40 %, 50 %, and 27 % respectively.

At Possum Kingdom, mean monthly total dissolved solids, chloride, and sulfate concentrations of 1950 mg/l, 577 mg/l, and 479 mg/l, respectively, were equalled or exceeded during 10% of the 696 months of the simulation. Thus, the presence of the salt control dams reduces the TDS concentration, the chloride concentration and the sulfate concentration by 35 %, 41 %, and 26 % respectively. Similarly, at Whitney and Richmond, significant reductions in the salt concentrations were observed. Table 6.2 shows the results of the concentration-duration analysis at the Seymour gage with the salt control dams in effect, while Figure 6.2 provides a graphical representation of the same.

Thus, it was observed that the presence of the salt control impoundments significantly reduce the salt concentrations at the selected control points. However, the mean concentration values still remained significantly higher than the EPA prescribed limiting values for waters to be used for domestic purposes.

Table 6.2 Concentration-Frequency Analysis at Seymour (with dams)

Percent Time Equalled or Exceeded	TDS (mg/l)	Cl (mg/l)	SO4 (mg/l)
10%	6807.0	2631.0	1245.0
25%	5441.0	2005.0	1051.0
40%	4191.0	1464.0	880.0
50%	3396.0	1159.0	754.0
60%	2723.0	902.0	645.0
75%	2043.0	627.0	511.0
90%	1224.0	373.0	314.0
95%	787.0	213.0	180.0
98%	390.0	125.0	180.0
99%	0.0	0.0	0.0
100%	0.0	0.0	0.0
Mean	3783.0	1361.0	779.0
Standard Deviation	2212.0	913.0	361.0
Maximum	15000.0	5000.0	1825.0

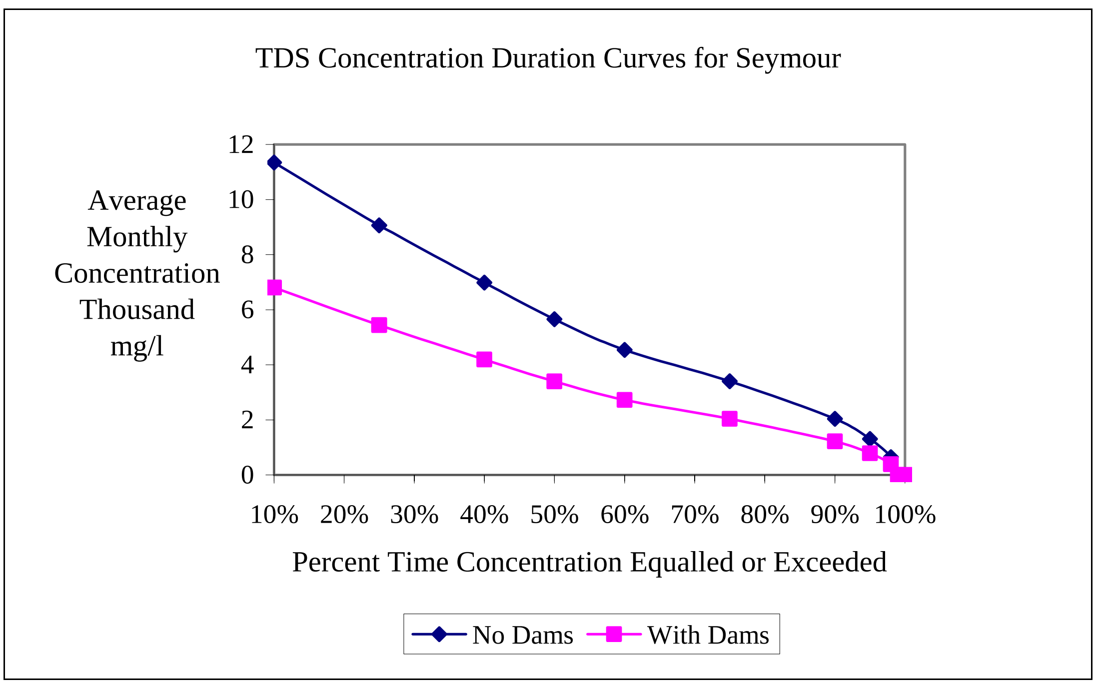

Figure 6.2 Regulated TDS Frequency Curves at Seymour (with dams)

6.6 WATER SUPPLY RELIABILITY UNDER SALINITY CONSTRAINTS

For any river basin system, water supply reliability indices are useful parameters on which planning and management decisions can be made. Period reliability can be defined as the percentage of months in a simulation for which a specified water demand target is met without any shortage (Wurbs 2003). If ‘n’ denotes the number of months in the simulation during which the demand is met without shortages, and if ‘N’ represents the total number of months considered in the simulation then the period reliability is computed as:

$$Rn = (n / N) * 100$$

Volume reliability can be defined as the percentage of the total demand that is actually supplied. It is represented as:

$$Rv = (v / V) * 100$$

This section focuses on how the water supply reliability indices are influenced by salinity constraints in the Brazos River Basin.

Possum Kingdom and Whitney are two major reservoirs lying in the main stem of the Brazos River with large storage capacities. However, water from these reservoirs cannot be utilized for domestic purposes without treatment owing to high salt concentrations in the waters of these reservoirs. Treatment processes such as desalination and dilution are not economically feasible for large volumes of water. An attempt is made to study the water supply reliability indices of these two reservoirs under various user imposed salinity constraints. In case of water utilized for domestic purposes; the EPA standards limit the TDS, chloride, and the sulfate concentrations to 500 mg/l, 250 mg/l, and 250 mg/l respectively. This study extends the constraints imposed on the salt concentrations to 1500 mg/l for TDS and 750 mg/l for both, chlorides and sulfates. Water supply diversions are not governed by water quality constraints in the publicly released version of the WRAP model. Since there is no governing salinity constraint in WRAP, this study assumes the diversions to be made under conditions when salt concentration is at its maximum. In this study, if the salinity concentrations exceed the adopted limits in the water supply diversions, the diversion is set to zero and a diversion shortage is declared. The period and the volume reliabilities are then computed based upon the revised diversion shortages.

For the 696 months in the simulation period, the control point at Possum Kingdom has a volume reliability of 100 % and a period reliability of 100 % without any salinity restrictions. The EPA prescribed TDS concentration of 500 mg/l, if applied as a salinity constraint, reduces the volume and the period reliabilities to 0%. If the constraint is raised to a value of 1000 mg/l, it is observed that the volume and the period reliabilities do not exhibit much difference and increase only marginally to 0.1%. This indicates a tremendous drop from the original values. If the concentration constraint for TDS is raised to 1500 mg/l, we observe that the volume and the period reliabilities increase to 4.89 % and 4.71 % respectively. These reduced values can be attributed to the fact that a TDS concentration of 1500 mg/l is equalled or exceeded 95 % of the times at Possum Kingdom. For chloride concentrations of 250 mg/l, the volume and the period reliabilities are reduced to 0 % respectively. The volume reliability and the period reliability increases to 0.14 % and 0.21 % respectively for a chloride concentration constraint of 500 mg/l. If a chloride concentration constraint of 750 mg/l is considered, then the volume and the period reliabilities increase to 39.51 % and 39.10 % respectively. This can be attributed to the fact that a chloride concentration of 750 mg/l is equalled or exceeded 60 % of the times at Possum Kingdom. If sulfate concentrations are taken into account, then for a sulfate concentration constraint of 250 mg/l, the volume and the period reliabilities are 0%. For sulfate concentrations of 500 mg/l and 750 mg/l, the volume reliabilities are 37.50 % and 98.84 % respectively and the period reliabilities are 37.56 % and 99.02 % respectively. Table 6.3 shows the reliability indices at Possum Kingdom under salinity constraints.

For the 696 months in the simulation period, the control point at Whitney has a volume reliability of 99.20 % and a period reliability of 98.85 %. The EPA prescribed TDS concentration of 500 mg/l, if applied as a salinity constraint, reduces the volume reliability and the period reliability to 0 %. This shows a significant drop from the original values. If the concentration constraint for TDS is raised to 1000 mg/l, we observe that there is not much difference in the reliability indices with the volume and the period reliabilities increasing marginally to 1.01 % and 1.00 % respectively. For a constraint of 1500 mg/l, the volume and the period reliabilities increase significantly to 51.01 % and 52.75 % respectively. This considerable increase can be attributed to the fact that a TDS concentration of 1500 mg/l is equalled or exceeded 40 % of the times at Whitney. For chloride concentrations of 250 mg/l, the volume and the period reliabilities are 0%. The volume reliability and the period reliability increases significantly to 85.63

% and 86.32 % respectively for a chloride concentration constraint of 750 mg/l. If sulfate concentrations are taken into account, then for a sulfate concentration constraint of 250 mg/l, the volume and the period reliabilities are 0 %. For a sulfate concentration constraint of 750 mg/l, the volume and the period reliabilities are 98.85 % and 99.20 % respectively. At Whitney, the maximum sulfate concentration encountered is 634 mg/l during the 696 months of the simulation period. Table 6.4 shows the reliability indices at Whitney under salinity constraints.

Table 6.3 Reliability Indices at Possum Kingdom under Salinity Constraints

Constituent	**Concentration mg/l**	**Reliability (%)**	
		Volume	Period
TDS	500	0.00	0.00
	1000	0.10	0.14
	1500	4.71	4.89
	max	100.00	100.00
Cl	250	0.00	0.00
	500	0.21	0.14
	750	39.10	39.50
	max	100.00	100.00
SO4	250	0.00	0.00
	500	37.56	37.00
	750	98.85	99.02
	max	100.00	100.00

Water-supply reliability indices at Possum Kingdom and Whitney were also assessed taking into account the effects of the proposed salt impoundment structures. At Possum Kingdom, for a TDS concentration constraint of 500 mg/l, no increase was observed in the period and the volume reliabilities with the impoundment structures in effect. However, for a TDS concentration constraint of 1000 mg/l, the volume and the period reliabilities increased to 3.59 % and 3.62 % from their original values. For a TDS concentration constraint of 1500 mg/l, the volume and the period reliabilities increase significantly to 49.43 % and 49.60 % from their original values. Similarly, reliabilities did not show any improvement for a chloride concentration constraint of under 250 mg/l. A volume reliability of 62.79 % and a period reliability of 62.70 % was obtained for a chloride concentration constraint of 500 mg/l. Reliabilities increased significantly under limiting values of sulfate concentrations with a volume reliability of 95.40 % and a period reliability of 95.53 % for a sulfate concentration constraint of 500 mg/l.

Table 6.4 Reliability Indices for Whitney under Salinity Constraints

Constituent	**Concentration mg/l**	**Reliability (%)**	
		Volume	**Period**
TDS	500	0.00	0.00
	1000	1.00	1.01
	1500	52.75	51.01
	max	99.20	98.85
Cl	250	0.00	0.00
	500	0.00	0.00
	750	86.32	85.63
	max	99.20	98.85
SO4	250	0.00	0.00
	500	98.85	99.20
	750	98.85	99.20
	max	98.85	99.20

At Whitney, for a TDS concentration constraint of 500 mg/l, the volume and the period reliabilities did not change from their original values. When the constraint was raised to 1000 mg/l, the volume and the period reliabilities were 57.04 % and 58.26 % respectively as compared to their original values. A TDS salinity constraint of 1500 mg/l produced a high volume reliability of 90.16 % and a high period reliability to 91.14 %. For chlorides, it was observed that the reliabilities increased considerably until a constraint of 500 mg/l was met, beyond which the reliabilities did not show any significant difference from those obtained without the impoundment structures. In the case of sulfates, the volume and the period reliabilities increased remarkably with the control structures in effect. For a sulfate concentration constraint of 500 mg/l, the volume and the period reliabilities increased to 98.85 % and 99.20 % respectively.

6.7 EFFECT OF RESERVOIR LAG ON OUTFLOW CONCENTRATIONS

The simulation modeling of the Brazos River Basin, discussed earlier in this section, does not take into consideration the effects of reservoir lag on salt concentrations throughout the basin. The simulation studies were performed assuming an instantaneous outflow from a reservoir for all inflows. However, in reality a reservoir serves as an impoundment to an entering flow reducing its inflow velocity to zero. Thereafter, a steady mixing of the flow occurs within the reservoir over a period of time before it is discharged. The time period for which an inflow is retained in the reservoir before being discharged is called as reservoir lag time. The salt load entering the reservoir along with the inflow undergoes the same mixing process before being discharged with the flow. An attempt is made to study the effects of reservoir lag time on salt concentrations in the Brazos River Basin using the simulation model WRAP-SALT.

One key aspect of the WRAP-SALT model is its ability to take into consideration the effects of reservoir lag time while modeling salinity in reservoir outflow. The user can model the concentration of the reservoir releases based on the beginning-of-period storage concentration, mean storage concentration, or the storage concentration of the preceding months computed on the basis of reservoir lag time. The lag time, in months, is either provided by the user as input data or computed within the model as a function of storage and outflow. This can be represented as:

$$LM = (STO / OUT) * A$$

where:

LM – Lag period in months

STO – Storage

OUT – Outflow

A – Multiplier used in computing lag

The computer algorithm uses an array variable to record the reservoir concentration for all months during a simulation run. These values are used for allocating release concentrations in future months. If 'n' represents the lag period in months and 'm' represents the current month in the simulation; where m > n, then the release concentration for month 'm' is set equal to the concentration that was computed during the '$(m\text{-}n)^{th}$' month of the simulation. The three main reservoirs lying on the main stem of the Brazos River and affected by salinity are Possum Kingdom, Granbury, and Whitney.

6.7.1 CALIBRATION STUDIES

The calibration studies were performed using the options provided in the WRAP-SALT model to simulate the effects of reservoir lag time. The calibration studies are divided into two phases. In the first phase the reservoir lag time is provided as input data to the simulation model in months. In this case, the lag is fixed for a reservoir throughout a simulation run. The simulation model is executed varying the lag and the results are compared with the gaged data for the corresponding period. The reservoir lag time in months is varied until the modeled concentration values fit with the gaged data.

In the second phase, reservoir lag is computed as a function of storage and outflow within the model. In this case, the lag varies during each month of the simulation process based upon the value of reservoir storage, outflow, and the multiplier used in computing the lag. The simulation model is executed varying the lag multiplier and the results are compared with the gaged data for the corresponding period. The lag multiplier is varied until the modeled concentration values fit with the gaged data.

Calibration studies were performed only for the Possum Kingdom reservoir. This section presents the results obtained during the calibration studies of the Possum Kingdom reservoir based on the procedure described in the preceding paragraphs. The plots of the observed and the modeled values exhibit similar trends over time. The model was executed considering a lag of 5 months, 15 months, 25 months, 30 months, 50 months, 75 months, 100 months, 125 months, and 150 months for Possum Kingdom. The outflow concentration was compared with the observed concentration for the simulation period. It was observed that the correlation coefficient between the modeled and the observed values decreased considerably when the reservoir lag time was greater than 50 months for the Possum Kingdom reservoir. Table 6.5 displays the results of the calibration studies with a constant lag.

Table 6.5 Concentration-Duration Curves at Possum Kingdom (constant lag)

% Time Equalled or Exceeded	No Lag (mg/l)	5 Months (mg/l)	10 Months (mg/l)	15 Months (mg/l)	25 Months (mg/l)
10%	2496.0	2585.0	2586.0	2586.0	2591.0
25%	2287.0	2340.0	2342.0	2344.0	2357.0
40%	2094.0	2114.0	2115.0	2115.0	2170.0
50%	2011.0	1993.0	1994.0	1994.0	2040.0
60%	1930.0	1909.0	1909.0	1909.0	1914.0
75%	1828.0	1792.0	1792.0	1792.0	1807.0
90%	1367.0	1208.0	1208.0	1213.0	1217.0
95%	1137.0	1085.0	1095.0	1095.0	1095.0
98%	1051.0	968.0	968.0	968.0	968.0
99%	967.0	933.0	933.0	933.0	933.0
100%	911.0	827.0	827.0	827.0	827.0
Mean	1979.0	1978.0	1979.0	1980.0	1997.0
Standard Deviation	402.0	465.0	464.0	463.0	465.0
Maximum	2681.0	2802.0	2802.0	2802.0	2802.0

The second phase of the calibration study attempted to model reservoir lag as a function of storage and reservoir outflow. The model was executed considering a lag multiplier of 0.01, 0.025, 0.05, 0.075, 0.1, 0.25, 0.5, 0.75, and 1.0 for Possum Kingdom. Table 6.6 shows the results obtained while modeling reservoir lag as a function of storage and flow.

Table 6.6 Concentration Duration Curves for Possum Kingdom (flow option)

% Time Equalled or Exceeded	No Lag (mg/l)	0.01 (mg/l)	0.03 (mg/l)	0.05 (mg/l)	0.07 (mg/l)
10%	2496.0	2566.0	2709.0	2761.0	2997.0
25%	2287.0	2326.0	2419.0	2441.0	2551.0
40%	2094.0	2151.0	2222.0	2289.0	2382.0
50%	2011.0	2052.0	2108.0	2148.0	2258.0
60%	1930.0	1952.0	2001.0	2036.0	2086.0
75%	1828.0	1850.0	1879.0	1910.0	1946.0
90%	1367.0	1370.0	1375.0	1380.0	1386.0
95%	1137.0	1137.0	1146.0	1146.0	1136.0
98%	1051.0	1053.0	1063.0	1065.0	1058.0
99%	967.0	967.0	980.0	980.0	968.0
100%	911.0	911.0	911.0	911.0	911.0
Mean	1979.0	2018.0	2083.0	2120.0	2202.0
Standard Deviation	402.0	420.0	457.0	475.0	536.0
Maximum	2681.0	2757.0	2877.0	3017.0	3199.0

No significant improvement was observed in the modeled values using this method. The correlation coefficient between the modeled and the observed concentration values decreased considerably as the multiplier value was increased. However, a considerable degree of similarity could be observed in the trends of the modeled and the observed values.

6.7.2 SENSITIVITY STUDIES AT DOWNSTREAM LOCATIONS

This section attempts to check the sensitivity of the downstream control points to reservoir lag time by varying the lag time for several simulation runs at an upstream control point. The Richmond gage control point, located in the Lower Brazos Basin was selected for the sensitivity studies. The lag time for Possum Kingdom was varied for several simulation runs, and the regulated concentrations at Richmond were recorded. Frequency studies were performed and the results were analyzed.

The reservoir lag time for Possum Kingdom was varied using the two options provided in the WRAP-SALT model. Frequency studies were then performed for the Possum Kingdom reservoir and the Richmond gage. It was observed that the regulated concentrations at Richmond remain relatively unaffected by the lag variations at Possum Kingdom. The concentration-duration curves at Possum Kingdom showed little variation when lag was varied without considering the flow retention option. When lag was varied based upon the flow retention option, the variations were further dampened at Possum Kingdom. This shows that the presence of reservoir lag does not have a significant effect on the concentration-duration frequencies at a control point. In addition, reservoir lag does not have a significant impact on downstream regulated concentrations.

6.8 RIVER BASIN VOLUME BALANCE

The WRAP-SALT simulation model provides a volume balance summary for the entire river basin. A water volume and a salt load balance summary table is provide for the entire river basin system for the entire period-of-analysis and is activated by field 12 of the JC record in the WRAP-SIM input file. The summary is based on the principle of a mass/volume balance for a system. Thus, for any given river basin system, the total incoming mass/volume is equal to the summation of the total mass/volume leaving the river basin and the change in storage mass/volume. Figure 6.3 shows a volume balance summary table for the Brazos River Basin. For the Brazos River Basin system, it is observed the difference between the basin inflows and basin outflows is not equal to the storage change for the river basin for the period of simulation. This is attributed to the presence of large negative incremental flows in the river basin and the way these flows are handled in both, the WRAP-SIM model and the WRAP-SALT model.

```
Total Volume and Load Summary for Constituent 1

                              Volume          Load

Naturalized flow           338996320.     146054688.
Regulated boundary          13434595.      76169056.
Return flow                  2208481.        406073.
Other inflows                 717776.       1137208.
Channel loss credits        17676550.      16827112.
Channel losses                267365.        134709.
Regulated at outlet        237291424.     109538840.
Diversions                 114411832.     103717216.
Net evaporation             22129364.             0.
                           ----------     ----------
Inflows - Outflows          -1066263.      27203372.
                           ----------     ----------
Beginning storage            4359602.       4009231.
Ending storage               3780111.       4907794.
                           ----------     ----------
Storage change               -579490.        898564.
                           ----------     ----------
Balance difference           -486773.      26304808.

Negative inflows to control points
                              305337.       1453668.

Negative incremental naturalized flows
                           121719064.
```

Figure 6.3 Volume Balance Summary for the Brazos River Basin

A negative incremental flow usually arises when the streamflow at an upstream gaging station is higher than at a downstream point. Negative incremental flows may result from any one or a combination of causes, some of which are listed below (Wurbs 2003):

1. Channel seepage and evapotranspiration losses
2. Recorded or unrecorded diversions

3. Large travel times causing the effects of precipitation events to reach adjacent control points in different time periods
4. Measuring inaccuracies or data recording errors
5. Computational adjustments in the conversion of gaged flows to naturalized flows which might introduce other inaccuracies that may contribute to negative incremental streamflow.

The WRAP-SIM model has capabilities to handle negative incremental streamflow based on various user-defined options. Thus, in WRAP-SIM naturalized streamflows can be adjusted to remove negative incrementals. WRAP-SALT handles negative inflows differently as compared to WRAP-SIM. There are three options available for handling negative inflows within the model. Option 1 does not perform any adjustments to the negative inflow and all computations are performed based upon this value. Option 2 changes negative inflows to zero. Option 3 limits negative inflow values to not exceed the volume or load in reservoir storage at the beginning of the month.

The Brazos River Basin simulation was performed using Option 1 and no adjustments were made to the negative inflows encountered during computations within the WRAP-SALT model. The presence of these negative inflows gives rise to corresponding negative salt loads and in some cases negative values for salt concentration. It was also observed that the presence of negative inflows gave rise to unreasonably low or high concentrations. This is countered by setting minimum and maximum limiting concentration values for the salt constituents. However, though this may eliminate unreasonable values for salt concentrations, it affects the river basin volume balance. The choice of the limiting values for concentration should be based on sound engineering judgment and a good knowledge of the temporal and spatial variations in the water quality characteristics of the river basin under consideration. Simulation results are presented as tables and figures in Appendix B of this thesis.

7. CONCLUSIONS AND DISCUSSIONS

This section summarizes the research work described in this thesis and draws conclusions using the results obtained from the simulation study of the Brazos River Basin. The goal of this research was to expand capabilities for incorporating salinity considerations in assessments of water availability. This research makes an attempt to attain this goal by addressing several pertinent issues by applying a generalized simulation model to the Brazos River Basin. The simulation model developed and applied in this research is a generalized computer model capable of tracking salinity in any given river basin system. The objectives of this research are stated below:

1. develop a generalized salinity tracking component for the Water Rights Analysis Package (WRAP) modeling system.
2. investigate methods for developing input data for the model.
3. apply the expanded modeling capabilities to the Brazos River Basin to assess the impacts of natural salt pollution on water supply capabilities.
4. assess the impact of the salt control dams proposed by the USACE to contain salt pollution in the Brazos River Basin.
5. study the effects of reservoir lag on reservoir outflow concentration.

The development of the WRAP-SALT model accomplishes the first objective. This model can be considered as a water quality module of the Water Rights Analysis Package (WRAP). The WRAP-SALT model focuses mainly on tracking salt concentrations at different control points throughout a river basin system over different periods of time for alternative scenarios of water use, reservoir system operating policies, and salt control mechanisms. WRAP-SALT reads the relevant discharge and storage data from the WRAP-SIM files and the salt data from a separate input file. All the salt and water balance computations are performed within the model and the output is written to a separate file with the required quantities. The model is user-friendly and provides the user with various flexible modeling options. The WRAP-SALT simulation model is described in detail in Section 4 of this thesis.

There are various issues that need to be addressed which can further refine the capabilities of the WRAP-SALT model. The model is programmed in such fashion that the simulation for a network of control points on a river basin system can be executed even with the absence of salinity data for one or more than one control point. For a control point, having limited or no salt data as input, the model simply repeats the salt load data from its immediate upstream control point for the whole simulation process. This might pose a problem if there is a considerable difference in the values of the salt concentrations at the concerned control points. The user has to make proper engineering judgment while preparing the input dataset to model a river basin system.

Salt loads are considered to be conservative during the whole simulation process. In addition to this, the assumption that the loads are unaffected by physical, chemical, or biological processes simplifies the mathematical computations within the model to a large extent. In reality, salinity is affected by various physical processes. Salinity in affected to a large extent by the chemical composition of the underlying stream bed over which the river water flows. Additional research will be required to identify the various processes that affect salinity in river reaches. The findings can then be incorporated within the WRAP-SALT model.

One of the major issues during the course of the whole study was to develop input salinity data for the Brazos River Basin. The historical data was available for a period of record of 24 years, ranging from October 1963 to September 1986. In order to maintain consistency with the Brazos WAM dataset during simulation modeling studies of the Brazos River Basin, it was required to develop input salinity data for the periods ranging from January 1940 – September 1963 and October 1986 – December 1997 using the available gaged data. Various methods were investigated to develop input data for the Brazos River Basin. There were various assumptions adopted during the course of the data development. In addition, arithmetic manipulations were performed to eliminate certain abnormalities like a negative value for salt concentration. These manipulations were consistent with the assumptions adopted. Development of a complete homogeneous set of salt loads for all control points in a river basin represents an important area for further research.

The research also addressed the issue of the salt control impoundments proposed by the USACE to reduce salinity in the main-stem of the Brazos River. The water quality in the main stem of the Brazos River is degraded by emissions from major salt sources in the upper Brazos River Basin. The U.S. Army Corps of Engineers (USACE) conducted natural salt pollution control studies in the Brazos River Basin. These studies are documented by a survey report (USACE 1973), an environmental impact statement (USACE 1976b), and draft general design memorandum (USACE 1983). These studies primarily focused towards determining the most feasible method to control natural salt pollution in the Brazos River Basin and its tributaries. Salt control by the use of impoundment structures was found to be the most effective in obtaining acceptable salinity levels in the waters of the Brazos River. Separate input datasets were developed to reflect the effects of the salt control dams. It was observed that salinity was considerably reduced along the main stem of the Brazos River. However, the TDS concentration still remained higher than the EPA standards for domestic usage at Possum Kingdom and Whitney along the main stem of the Brazos River. The incorporation of the salt control dams in the modeling study provides useful information regarding the efficacy of the salt impoundment structures. However, this research did not analyze any impact the proposed structures might have on the environment. The results obtained in the simulation of the Brazos River Basin that included the salt control dams were discussed in Section 6 of this thesis. The simulation results reflecting the effects of the impoundment structures were also used to assess water supply reliability indices governed by salinity constraints.

This thesis makes an attempt to calibrate salinity in reservoir outflow by taking into consideration the reservoir lag time. There are various measures that can be adopted to refine the results obtained from the calibration studies. The first phase of the calibration studies assumes a constant lag for a reservoir throughout the simulation. This is not a valid assumption as lag is essentially a function of storage and the timing of the reservoir releases and varies with changing reservoir storage. The second phase of the calibration study was based on this principle. However, it treated lag time as a function of storage and release for individual months. However, reservoir lag is a function of the cumulative storage of the reservoir over a period of time. Another issue that can be investigated is to arrive at a lag time for a reservoir based on its critical period.

When a flow enters a reservoir, it mixes with the volume of water in storage over a long period of time before being discharged. This lag might be of the order of several months or years. The salt load entering with the flow undergoes complete mixing with the salt content of the reservoir over this period of time. Thus, the outflow has a concentration which is not just a function of the storage and release in a month, but a function of these parameters over a period of time. Salt concentration in releases computed as a weighted average of the reservoir concentration over past several months might improve the calibration results.

This research also addresses the issue of water supply reliability indices governed by salinity constraints. Water supply reliability indices serve as important statistical tools which aid river basin planning and management. Water supply diversions in the WRAP model are not governed by water quality criterion. Diversions are made based upon the quantity of water that is available without considering its quality. This research assumes that water supply diversions in the WRAP model are made under conditions that correspond to maximum water pollution. The reliability indices computed by the WRAP model are assumed to be true under conditions where water supply diversions are independent of water quality. The reliability indices of two main reservoirs, Possum Kingdom and Whitney, in the main stem of the Brazos were assessed with and without the salinity constraints. For waters to be used for domestic purposes, the EPA recommends a TDS concentration of less than 500 mg/l, a chloride concentration of less than 250 mg/l, and a sulfate concentration of less than 250 mg/l. These standards were used as base constraints and several runs were made by gradually increasing these values.

The issue of establishing permissible water quality constraints depends upon the type of water use. Water suitable for industrial purposes might not be suitable for irrigation and vice-versa. Acceptable levels of water quality for various types of water use depend on multiple factors and represent an important area of research. It was not within the scope of this research to establish guidelines for permissible salt concentrations for various types of water use. This research focuses in assessing the response of water supply reliability indices in an environment where water supply diversions are controlled by water quality factors.

In this study, if the salinity concentrations exceed the adopted limits in the water supply diversions, the diversion is set to zero and a diversion shortage is declared. The period and the volume reliabilities are then computed based upon the revised diversion shortages. It was observed that the volume and the period reliabilities dropped drastically under the EPA prescribed water quality standards for domestic usage. At Possum Kingdom, for a TDS constraint of 1500 mg/l, a volume reliability of 4.89 % and a period reliability to 4.71 % were obtained. Similarly, at Whitney, for the same constraint, the volume and the period reliabilities are 51.01 % and 52.75 % respectively. These results are discussed in Section 6 of this thesis. It was observed that the reliabilities increased gradually when salinity constraints were relaxed. However, for total dissolved solids, the volume and the period reliabilities remained significantly low for both Possum Kingdom and Whitney.

Water supply reliabilities at Possum Kingdom and Whitney were also assessed taking into account the effect of the salt control dams proposed by the USACE. The presence of the salt control dams did not increase water supply reliabilities significantly. There was a noticeable improvement in the water supply reliabilities; however, the improvements were not as pronounced as the reduction in salt concentrations brought about by the presence of the salt control dams.

The values obtained in this reliability study are approximate and are meant to aid water supply planning and management decisions for a river basin system. These values can be refined significantly if an integrated approach to water resources planning and management is adopted by allocating water supply diversions based on water quality and water use. Integration of WRAP-SALT to the WRAP model provides an area for future research.

Salinity is a very important factor that needs to be considered in the management of the Brazos River Basin. The water in the main stem of the Brazos River is contaminated mainly by the presence of total dissolved solids. Considering the social and growing economic development in the region, the ever increasing demand for good quality surface water might be hard to satisfy. Various alternatives to the proposed salt impoundment structures should be considered to contain the salt pollution originating from small watersheds in the Upper Brazos Basin. An integrated approach considering water quality should be adopted to manage the Brazos River Basin. The WRAP-SALT model can be utilized to address this issue.

This thesis presents a simulation modeling approach to expand capabilities for incorporating salinity considerations in assessments of water availability. The generalized WRAP-SALT model is a useful tool that can be utilized by research agencies to assess the impact of salinity in any river basin system.

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APPENDIX A

Table A - 1 Means of TDS Loads and Concentrations

Gage	Seymour	Eliasville	Possum Kingdom	Whitney	Cameron	Richmond
Means (tons/month)						
1964-86 Gaged Flows	79127.08	18906.32	85018.66	93538.42	31141.75	65948.05
1964-86 Naturalized flows	79127.08	18906.32	-	-	31141.75	64933.81
1940-63&1987-97 Naturalized flows	129357.13	23550.80	-	-	30988.93	61817.83
1940-1997 Naturalized flows	109438.32	22029.33	-	-	31049.53	63053.48
Arithmatic Concentrations (mg/l)						
1964-86 Gaged Flows	6725.03	1470.99	1674.52	950.44	300.57	222.14
1964-86 Naturalized flows	5793.33	1227.94	-	-	383.28	222.14
1940-63&1987-97 Naturalized flows	5779.21	890.52	-	-	310.64	252.95
1940-1997 Naturalized flows	5784.81	1001.05	-	-	339.45	240.73
Discharge-Weighted Concentrations (mg/l)						
1964-86 Gaged flows	3588.91	734.79	1510.99	927.23	256.27	184.45
1964-86 Naturalized flows	3455.79	562.90	-	-	236.26	184.45
1940-63&1987-97 Naturalized flows	4053.56	660.04	-	-	192.59	171.41
1940-1997 Naturalized flows	3862.02	629.50	-	-	207.87	176.50

Table A - 2 Means of Cl Loads and Concentrations

Gage	Seymour	Eliasville	Possum Kingdom	Whitney	Cameron	Richmond
Means (tons/month)						
1964-86 Gaged Flows	32656.89	6226.52	33797.10	34493.40	3743.45	6359.37
1964-86 Naturalized flows	32656.89	6226.52	-	-	3743.45	12033.29
1940-63&1987-97 Naturalized flows	49387.54	6799.80	-	-	3705.27	15056.76
1940-1997 Naturalized flows	42752.97	6612.00	-	-	3720.41	13857.79
Arithmatic Concentrations (mg/l)						
1964-86 Gaged Flows	2988.01	524.76	667.78	351.76	39.07	54.38
1964-86 Naturalized flows	2566.17	423.13	-	-	49.55	54.38
1940-63&1987-97 Naturalized flows	2462.51	331.70	-	-	39.87	82.26
1940-1997 Naturalized flows	2503.62	361.65	-	-	43.71	71.20
Discharge-Weighted Concentrations (mg/l)						
1964-86 Gaged flows	1481.20	241.59	600.66	341.93	30.81	34.18
1964-86 Naturalized flows	1426.25	185.38	-	-	28.40	34.18
1940-63&1987-97 Naturalized flows	1547.62	190.57	-	-	23.03	41.75
1940-1997 Naturalized flows	1508.73	188.94	-	-	24.91	38.79

Table A - 3 Means of SO_4 Loads and Concentrations

Gage	Seymour	Eliasville	Possum Kingdom	Whitney	Cameron	Richmond
Means (tons/month)						
1964-86 Gaged Flows	15345.12	4375.39	17377.35	17989.59	3607.76	9741.21
1964-86 Naturalized flows	15345.12	4375.39	-	-	3607.76	10190.60
1940-63&1987-97 Naturalized flows	25551.16	4294.14	-	-	3512.23	10577.56
1940-1997 Naturalized flows	21503.94	4320.76	-	-	3550.11	10424.11
Arithmatic Concentrations (mg/l)						
1964-86 Gaged Flows	1147.11	372.55	342.69	183.35	36.20	37.21
1964-86 Naturalized flows	989.06	423.13	-	-	46.38	37.21
1940-63&1987-97 Naturalized flows	970.31	331.70	-	-	36.74	42.71
1940-1997 Naturalized flows	977.75	361.65	-	-	40.56	40.53
Discharge-Weighted Concentrations (mg/l)						
1964-86 Gaged flows	696.00	169.62	308.84	178.33	29.69	28.95
1964-86 Naturalized flows	670.18	130.27	-	-	27.37	28.95
1940-63&1987-97 Naturalized flows	800.68	120.35	-	-	21.83	29.33
1940-1997 Naturalized flows	758.86	123.47	-	-	23.77	29.18

Table A - 4 Means and Standard Deviations of TDS Concentrations

Gage	Seymour	Eliasville	Possum Kingdom	Whitney	Cameron	Richmond
Means (tons/month)						
1964-86 Gaged Flows	96547.63	31207.01	136350.75	133729.93	36228.87	83926.02
1964-86 Naturalized flows	96547.63	31207.01	-		36228.87	83926.02
1940 - 63&1987-97 Naturalized flows	268708.89	65496.85	-		42491.35	87934.52
1940-1997 Naturalized flows	218685.71	56615.97	-		40098.09	86319.72
Concentrations (mg/l)						
1964-86 Gaged Flows	3530.54	818.28	443.51	249.32	63.61	250.14
1964-86 Naturalized flows	3156.20	1199.70	-		843.35	250.14
1940-63&1987-97 Naturalized flows	3438.88	832.31	-		259.19	405.23
1940-1997 Naturalized flows	3327.35	980.14	-		568.50	352.11

Table A - 5 Means and Standard Deviations of Cl Loads

Gage	Seymour	Eliasville	Possum Kingdom	Whitney	Cameron	Richmond
Means (tons/month)						
1964-86 Gaged Flows	39242.07	10568.27	54256.13	49308.60	4059.27	18981.03
1964-86 Naturalized flows	39242.07	10568.27	-	-	4059.27	18981.03
1940 - 63&1987-97 Naturalized flows	97516.93	15101.77	-	-	4840.62	39347.53
1940-1997 Naturalized flows	80059.39	13776.70	-	-	4543.86	32835.03
Concentrations (mg/l)						
1964-86 Gaged Flows	1796.37	324.07	186.73	105.05	12.42	117.62
1964-86 Naturalized flows	1594.62	420.28	-	-	105.85	117.62
1940-63&1987-97 Naturalized flows	1726.90	322.62	-	-	32.78	317.80
1940-1997 Naturalized flows	1675.30	359.83	-	-	71.44	257.97

Table A - 6 Means and Standard Deviations of SO_4 Loads and Concentrations

Gage	Seymour	Eliasville	Possum Kingdom	Whitney	Cameron	Richmond
Means (tons/month)						
1964-86 Gaged Flows	20075.22	6445.47	27737.70	25588.88	4222.70	13006.26
1964-86 Naturalized flows	20075.22	6445.47	-	-	4222.70	13006.26
1940 - 63&1987-97 Naturalized flows	58948.25	12189.25	-	-	4787.80	16451.52
1940-1997 Naturalized flows	47742.70	10649.24	-	-	4569.19	15170.40
Concentrations (mg/l)						
1964-86 Gaged Flows	479.32	296.66	98.22	56.96	9.77	50.63
1964-86 Naturalized flows	441.15	391.51	-	-	108.82	50.63
1940-63&1987-97 Naturalized flows	464.24	215.64	-	-	30.60	85.91
1940-1997 Naturalized flows	455.00	292.45	-	-	72.61	73.96

Table A - 7 Concentration-Duration Analyses for Eliasville

Percent Time Equalled or Exceeded	**TDS (mg/l)**	**Cl (mg/l)**	**SO4 (mg/l)**
10%	2078	742	597
25%	1371	480	343
40%	966	339	191
50%	743	268	132
60%	551	210	82
75%	346.5	132.5	47.6
90%	168.2	55.1	20.9
95%	56.1	21	5.1
98%	0	0	0
99%	0	0	0
100%	0	0	0
Mean	1001.1	361.7	236.4
Standard Deviation	980.1	359.8	292.4
Maximum	8317	2747	2820

Table A - 8 Concentration-Duration Analyses for Cameron

Percent Time Equalled or Exceeded	**TDS (mg/l)**	**Cl (mg/l)**	**SO4 (mg/l)**
10%	504.0	81.0	62.0
25%	364.0	45.0	44.0
40%	297.0	35.0	36.0
50%	262.0	30.0	31.0
60%	234.0	28.0	28.0
75%	190.9	26.0	22.3
90%	135.2	21.3	15.2
95%	106.2	15.8	11.4
98%	80.6	10.5	8.4
99%	63.0	3.8	6.1
100%	0.0	0.0	0.0
Mean	339.4	43.7	40.6
Standard Deviation	568.5	71.4	72.6
Maximum	13040.0	1631.0	1695.0

Table A - 9 Concentration-Duration Analyses for Richmond

Percent Time Equalled or Exceeded	TDS (mg/l)	Cl (mg/l)	SO4 (mg/l)
10%	405.0	112.0	68.0
25%	283.0	69.0	48.0
40%	230.0	46.0	36.0
50%	196.0	34.0	30.0
60%	163.0	23.0	26.0
75%	121.1	0.0	16.0
90%	0.0	0.0	0.0
95%	0.0	0.0	0.0
98%	0.0	0.0	0.0
99%	0.0	0.0	0.0
100%	0.0	0.0	0.0
Mean	240.7	71.2	40.5
Standard Deviation	352.1	258.0	74.0
Maximum	4138.0	3382.0	879.0

Table A - 10 Concentration-Duration Analyses for TDS

Percent Time Equalled or Exceeded	Seymour mg/l	Cameron mg/l	Eliasville mg/l	Richmond mg/l
10%	10601.00	504.00	2078.00	405.00
25%	8296.00	364.00	1371.00	283.00
40%	6375.00	297.00	966.00	230.00
50%	5247.00	262.00	743.00	196.00
60%	4196.00	234.00	551.00	163.00
75%	3177.60	190.90	346.50	121.10
90%	1948.80	135.20	168.20	0.00
95%	1258.50	106.20	56.10	0.00
98%	96.10	80.60	0.00	0.00
99%	0.00	63.00	0.00	0.00
100%	0.00	0.00	0.00	0.00

Table A - 11 Concentration-Duration Analyses for Chlorides

Percent Time Equalled or Exceeded	**Seymour mg/l**	**Cameron mg/l**	**Eliasville mg/l**	**Richmond mg/l**
10%	4967.00	81.00	742.00	112.00
25%	3606.00	45.00	480.00	69.00
40%	2648.00	35.00	339.00	46.00
50%	2095.00	30.00	268.00	34.00
60%	1635.00	28.00	210.00	23.00
75%	1159.70	26.00	132.50	0.00
90%	704.50	21.30	55.10	0.00
95%	425.50	15.80	21.00	0.00
98%	31.60	10.50	0.00	0.00
99%	0.00	3.80	0.00	0.00
100%	0.00	0.00	0.00	0.00

Table A - 12 Concentration-Duration Analyses for Sulfates

Percent Time Equalled or Exceeded	**Seymour mg/l**	**Cameron mg/l**	**Eliasville mg/l**	**Richmond mg/l**
10%	1622.00	62.00	597.00	68.00
25%	1315.00	44.00	343.00	48.00
40%	1131.00	36.00	191.00	36.00
50%	941.00	31.00	132.00	30.00
60%	828.00	28.00	82.00	26.00
75%	636.10	22.30	47.60	16.00
90%	410.60	15.20	20.90	0.00
95%	207.50	11.40	5.10	0.00
98%	32.40	8.40	0.00	0.00
99%	0.00	6.10	0.00	0.00
100%	0.00	0.00	0.00	0.00

Table A - 13 Concentration-Duration Analyses for Richmond (dams)

Percent Time Equalled or Exceeded	**TDS (mg/l)**	**Cl (mg/l)**	**SO4 (mg/l)**
10%	329.0	68.0	59.0
25%	234.0	42.0	41.0
40%	189.0	28.0	31.0
50%	162.0	21.0	26.0
60%	134.0	14.0	22.0
75%	98.0	0.0	14.0
90%	0.0	0.0	0.0
95%	0.0	0.0	0.0
98%	0.0	0.0	0.0
99%	0.0	0.0	0.0
100%	0.0	0.0	0.0
Mean	198.6	43.2	35.1
Standard Deviation	293.7	156.5	64.9
Maximum	3334.0	1995.0	741.0

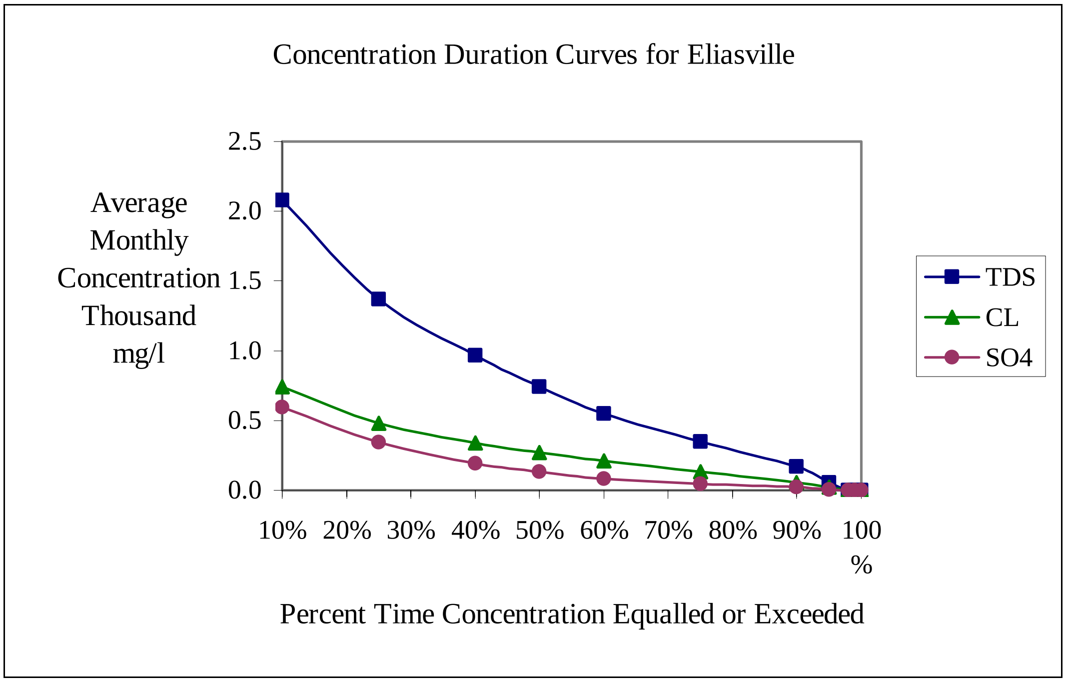

Figure A - 1 Concentration-Duration Curves for Eliasville

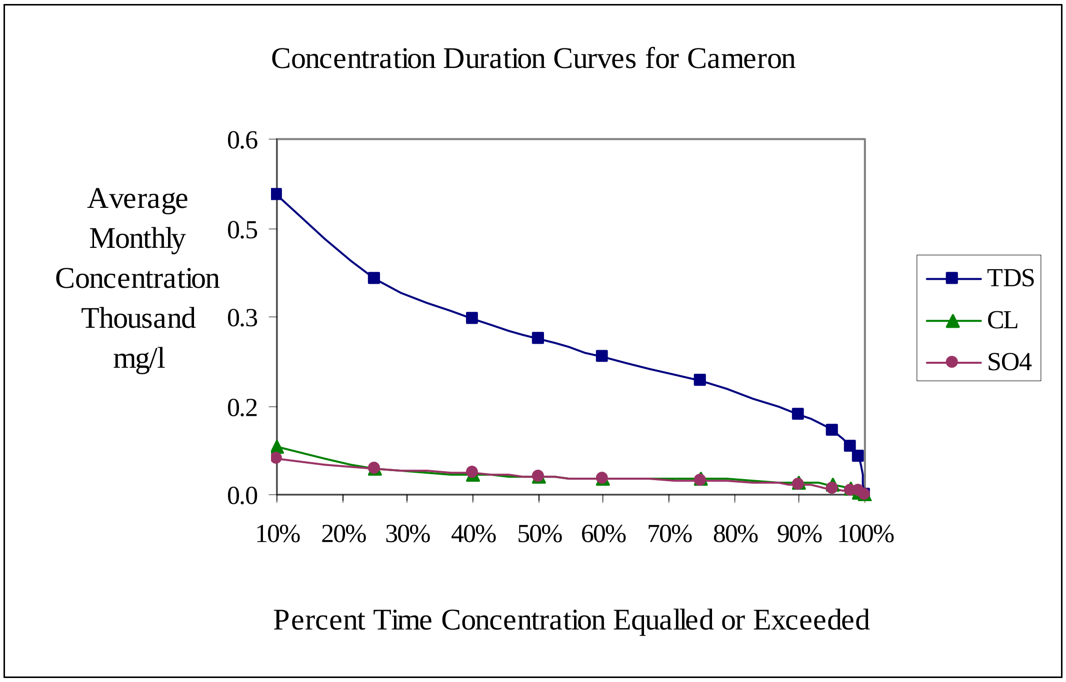

Figure A - 2 Concentration-Duration Curves for Cameron

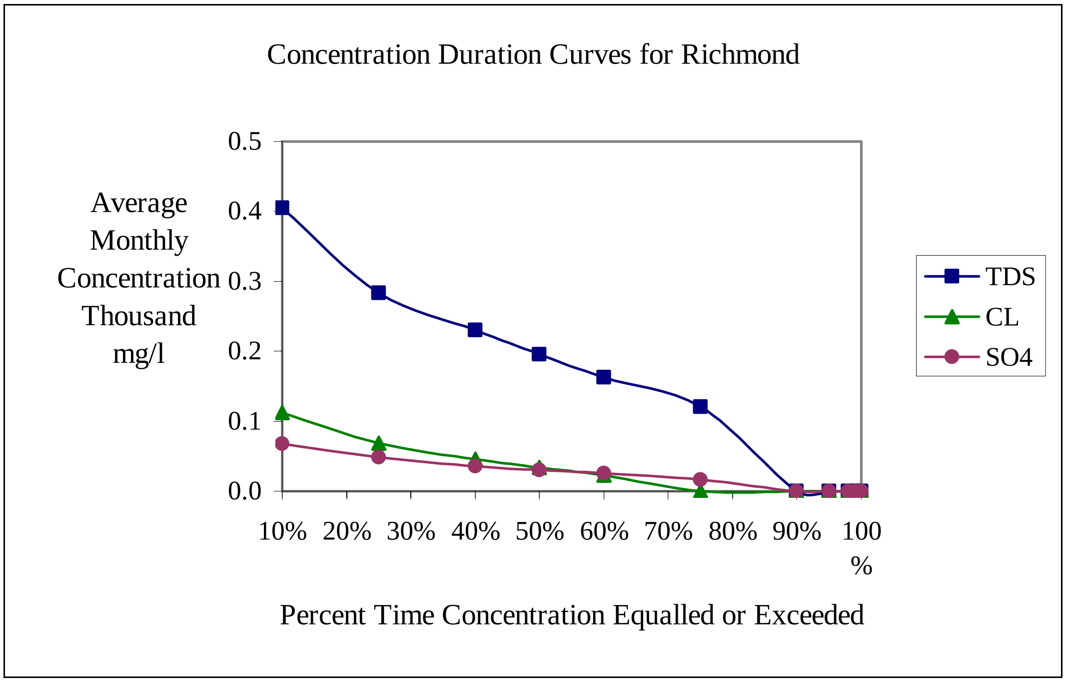

Figure A - 3 Concentration-Duration Curves for Richmond

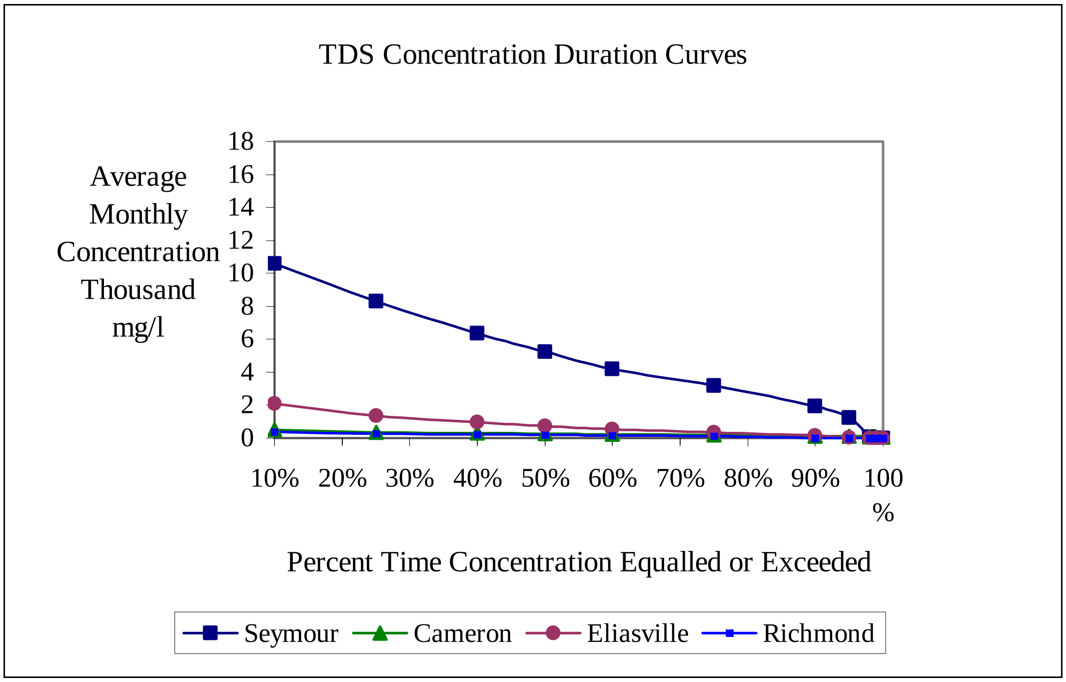

Figure A - 4 Concentration-Duration Curves for TDS

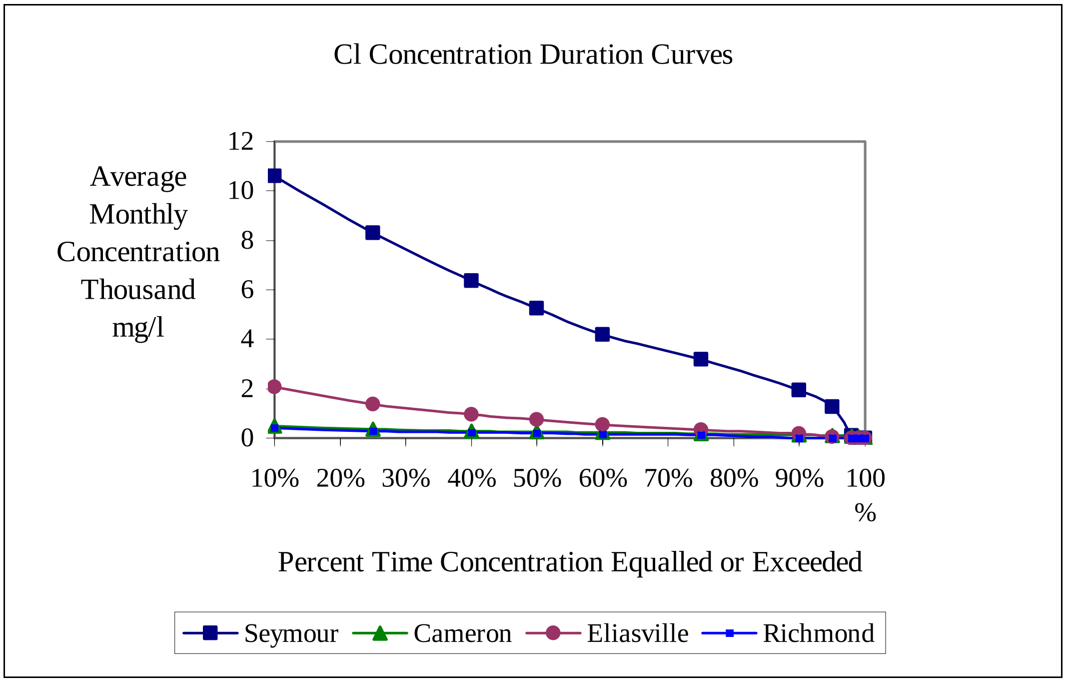

Figure A - 5 Concentration-Duration Curves for Chlorides

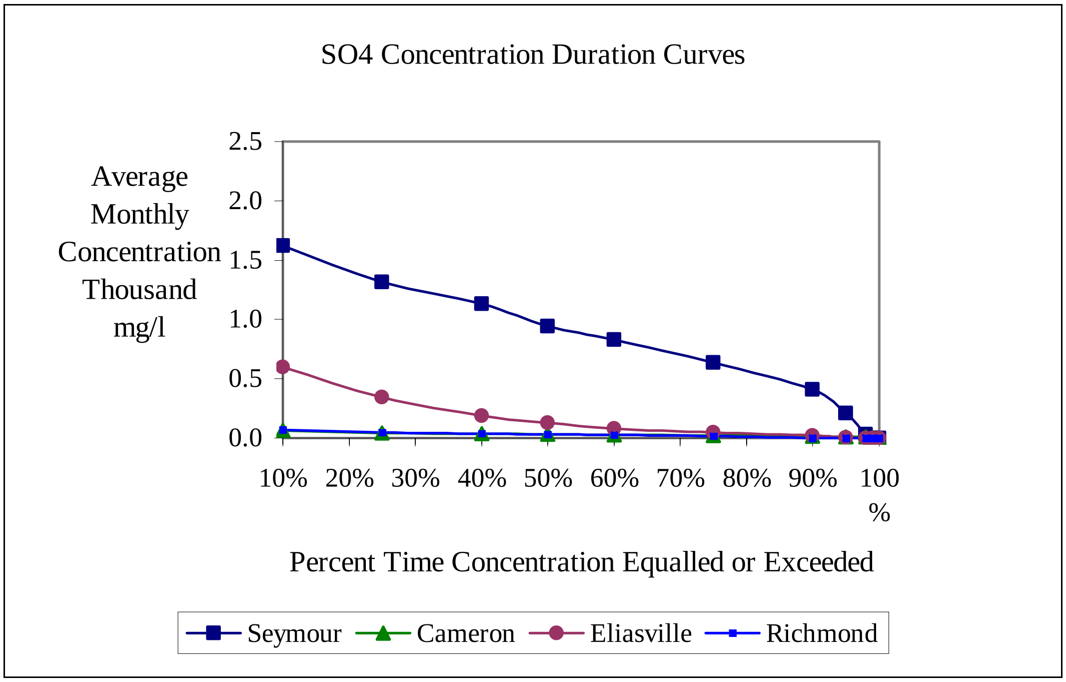

Figure A - 6 Concentration-Duration Curves for Sulfates

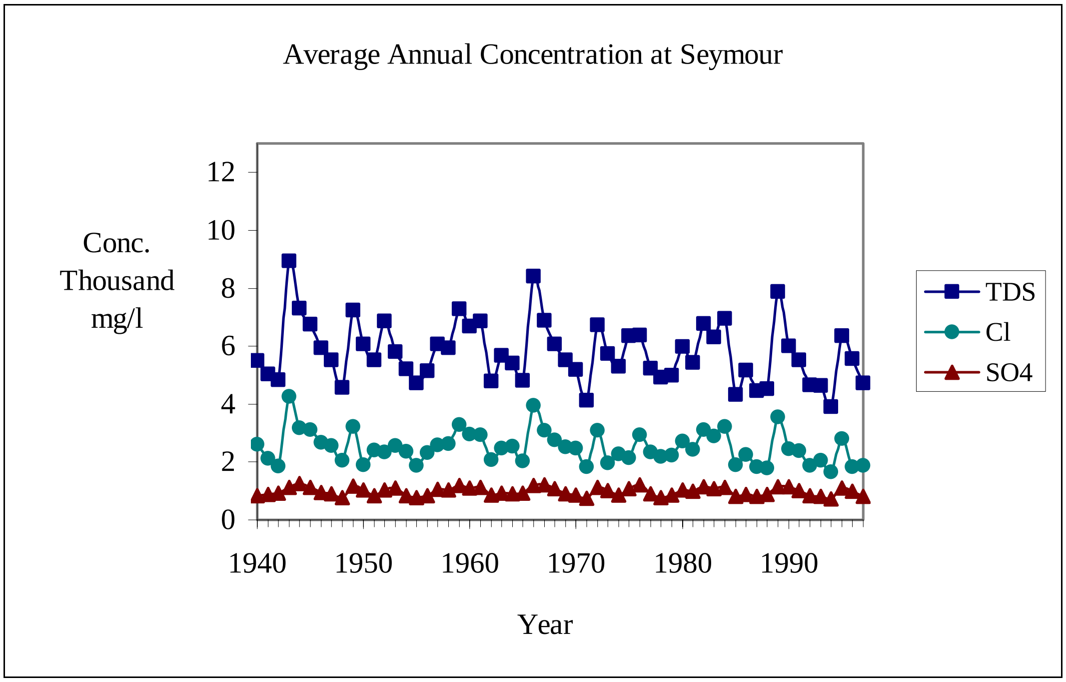

Figure A - 7 Annual Average Concentration at Seymour

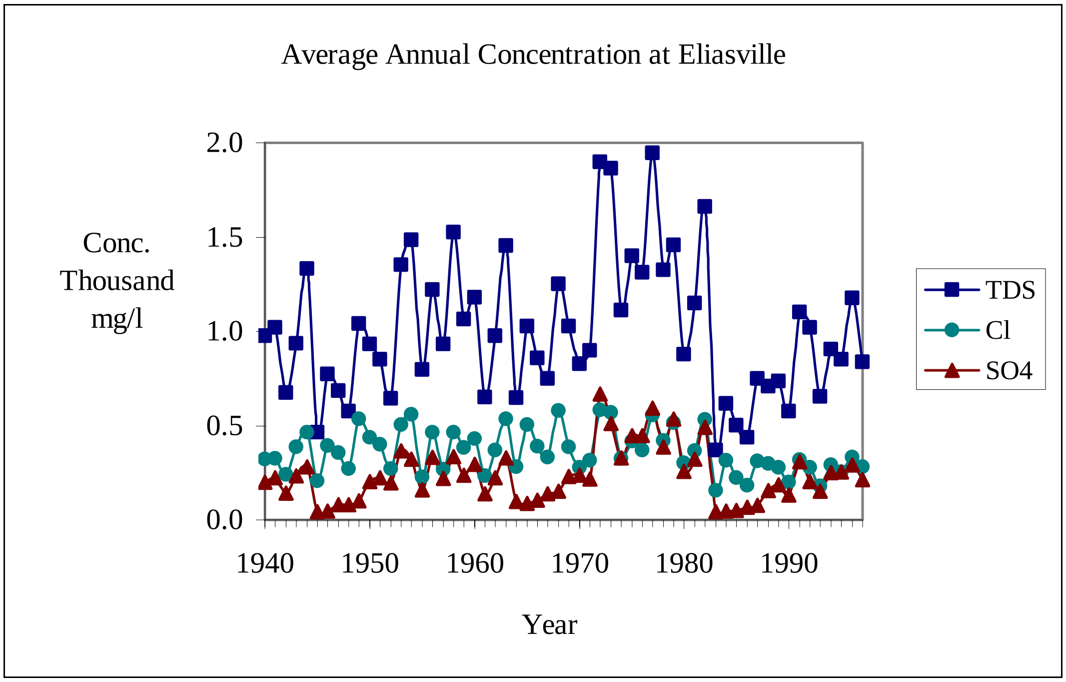

Figure A - 8 Average Annual Concentration at Eliasville

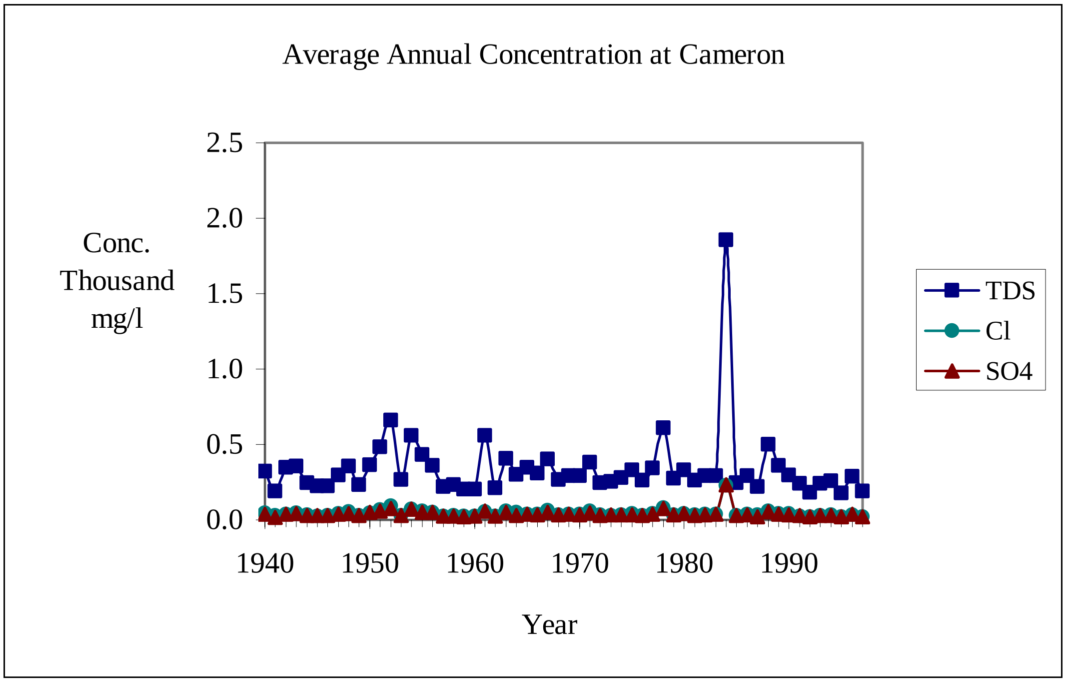

Figure A - 9 Average Annual Concentration at Cameron

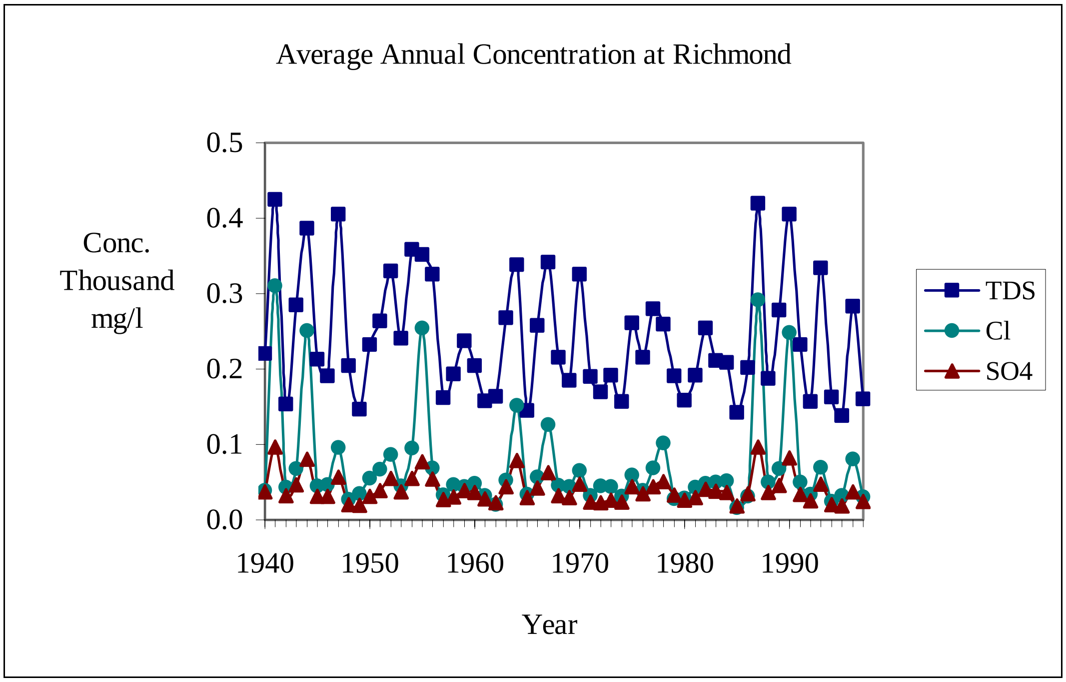

Figure A - 10 Average Annual Concentration at Richmond

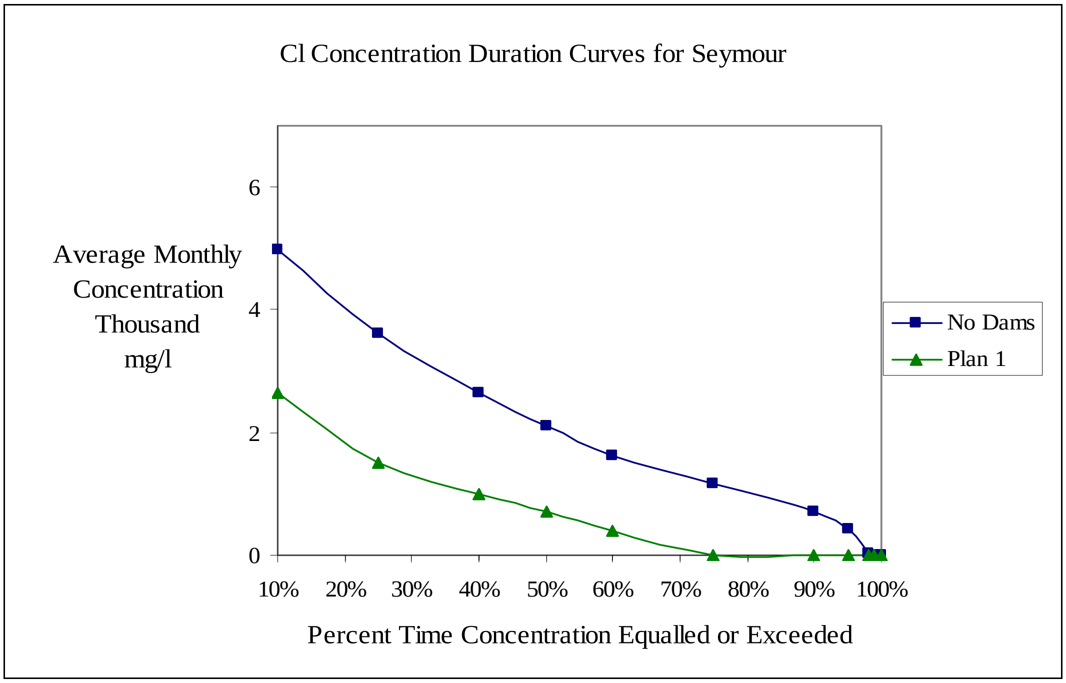

Figure A - 11 Chloride Concentration-Duration Curves for Seymour (dams)

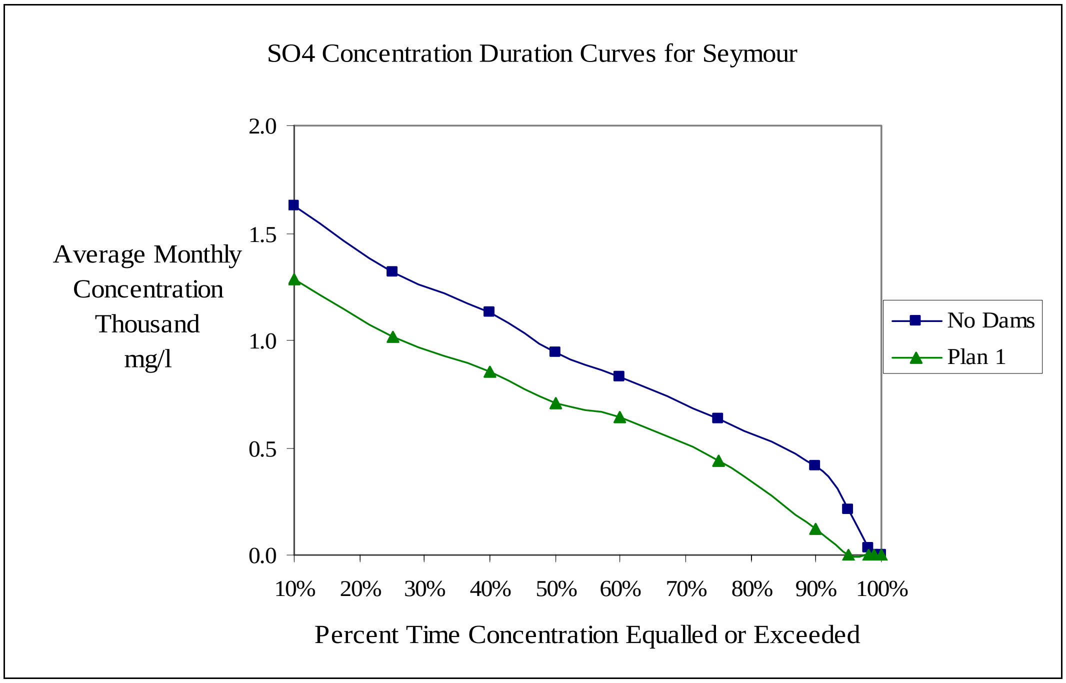

Figure A - 12 Sulfate Concentration-Duration Curves for Seymour (dams)

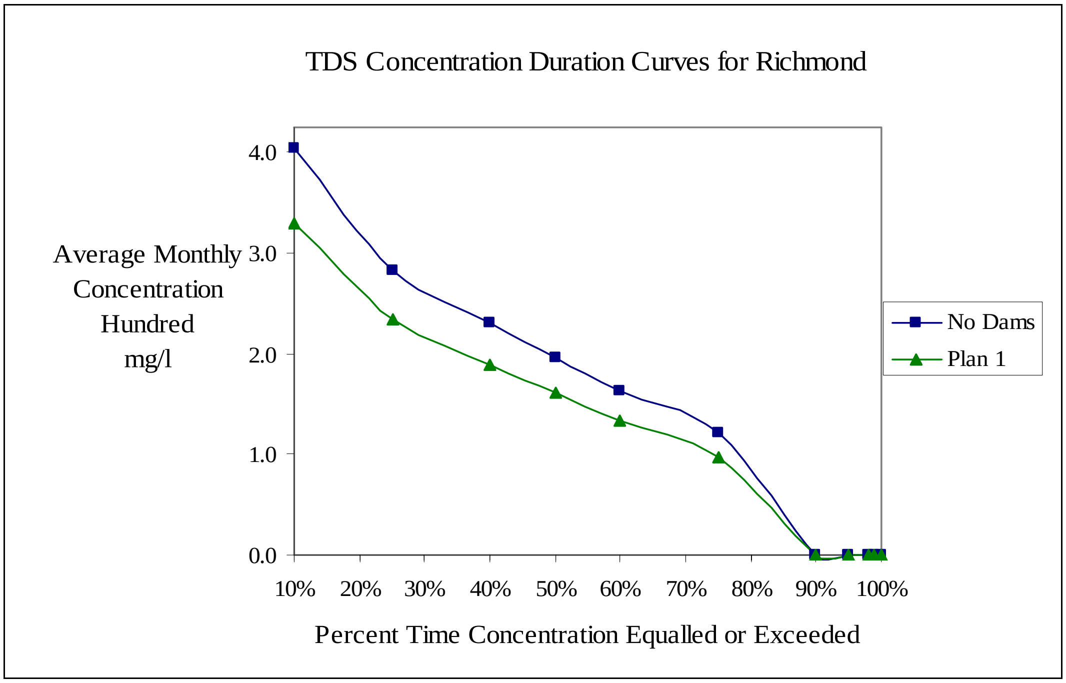

Figure A - 13 TDS Concentration-Duration Curves for Richmond (dams)

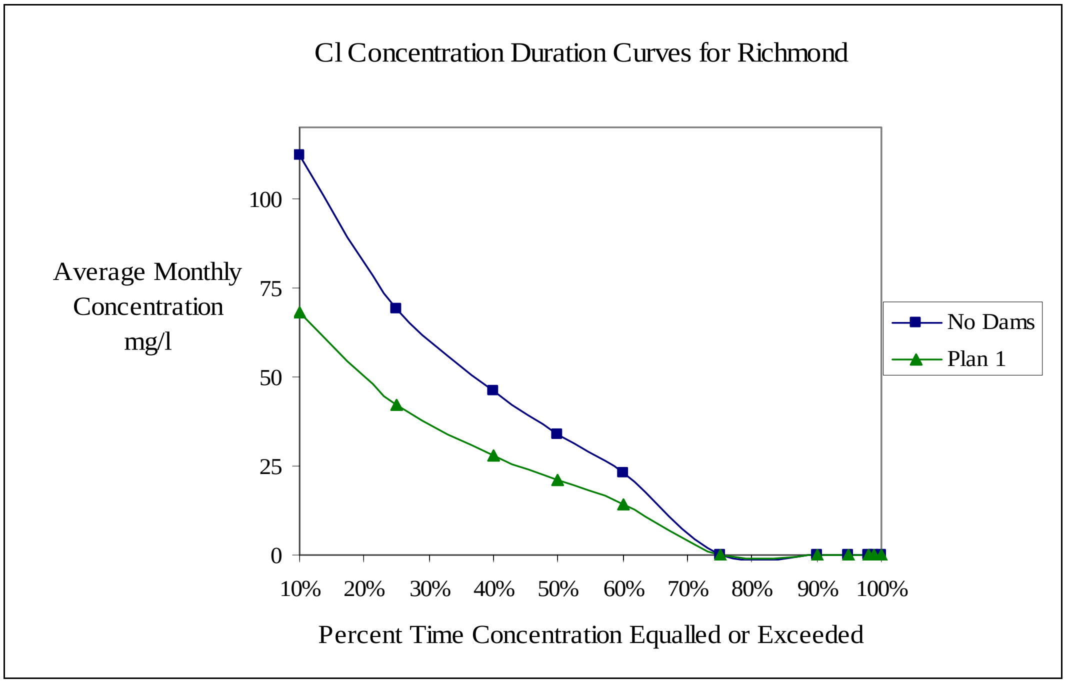

Figure A - 14 Chloride Concentration-Duration Curves for Richmond (dams)

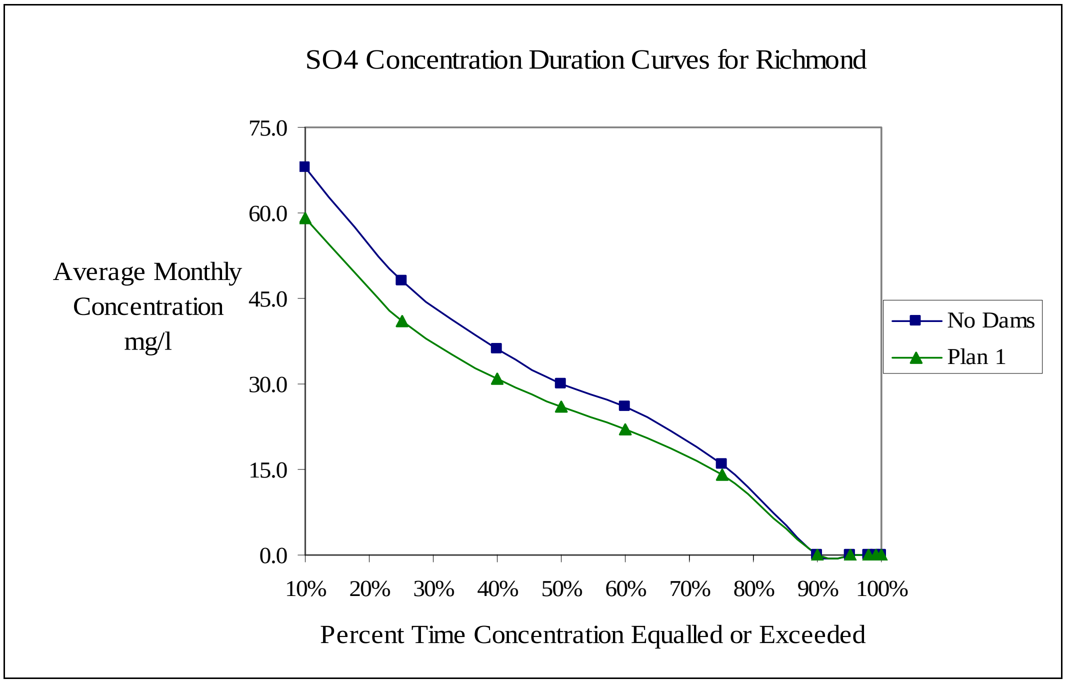

Figure A - 15 Sulfate Concentration-Duration Curves for Richmond (dams)

APPENDIX B

Table B - 1 Means and Standard Deviations of Regulated Flows

Gage	Seymour	Eliasville*	Possum Kingdom	Whitney	Cameron	Richmond
Means (ac-ft/month)						
1940-97	19524.68	17783.40	32627.02	65660.68	82911.03	374309.6
Standard Deviations						
1940-97	40447.48	42904.94	111766.5	173402.02	157175.7	561720.2

Table B - 2 Means of Regulated Concentrations at Eliasville

Percent Time Equalled or Exceeded	TDS (mg/l)	Cl (mg/l)	SO4 (mg/l)
10%	1588.0	537.0	438.0
25%	1157.0	400.0	290.0
40%	901.0	318.0	203.0
50%	768.0	274.0	168.0
60%	640.0	226.0	133.0
75%	469.0	170.0	102.0
90%	250.0	100.0	75.0
95%	0.0	0.0	0.0
98%	0.0	0.0	0.0
99%	0.0	0.0	0.0
100%	0.0	0.0	0.0
Mean	840.0	301.0	214.0
Standard Deviation	527.0	201.0	172.0
Maximum	2978.0	1576.0	1367.0

Table B - 3 Means of Regulated Concentration at Possum Kingdom

Percent Time Equalled or Exceeded	TDS (mg/l)	Cl (mg/l)	SO4 (mg/l)
10%	3016.0	983.0	646.0
25%	2505.0	861.0	576.0
40%	2358.0	807.0	545.0
50%	2246.0	776.0	521.0
60%	2112.0	751.0	505.0
75%	1952.0	720.0	475.0
90%	1751.0	661.0	443.0
95%	1507.0	628.0	394.0
98%	1260.0	596.0	424.0
99%	1000.0	489.0	326.0
100%	1122.0	550.0	368.0
Mean	2276.0	795.0	532.0
Standard Deviation	492.0	118.0	80.0
Maximum	3578.0	1164.0	793.0

Table B - 4 Means of Regulated Concentrations at Whitney

Percent Time Equalled or Exceeded	**TDS (mg/l)**	**Cl (mg/l)**	**SO4 (mg/l)**
10%	2278.0	824.0	485.0
25%	1740.0	711.0	436.0
40%	1565.0	673.0	420.0
50%	1498.0	662.0	410.0
60%	1444.0	640.0	399.0
75%	1368.0	622.0	384.0
90%	1245.0	589.0	364.0
95%	1186.0	567.0	342.0
98%	1080.0	546.0	354.0
99%	953.0	501.0	301.0
100%	1011.0	518.0	330.0
Mean	1615.0	684.0	421.0
Standard Deviation	408.0	107.0	60.0
Maximum	2981.0	1069.0	634.0

Table B - 5 Means of Regulated Concentrations at Cameron

Percent Time Equalled or Exceeded	**TDS (mg/l)**	**Cl (mg/l)**	**SO4 (mg/l)**
10%	425.0	67.0	63.0
25%	323.0	52.0	50.0
40%	277.0	45.0	44.0
50%	252.0	42.0	41.0
60%	234.0	39.0	38.0
75%	201.0	36.0	35.0
90%	151.0	35.0	35.0
95%	123.0	35.0	35.0
98%	83.0	35.0	35.0
99%	48.0	34.0	34.0
100%	0.0	0.0	0.0
Mean	277.0	49.0	48.0
Standard Deviation	135.0	30.0	30.0
Maximum	1000.0	337.0	300.0

Table B - 6 Means of Regulated Concentrations at Richmond

Percent Time Equalled or Exceeded	TDS (mg/l)	Cl (mg/l)	SO4 (mg/l)
10%	587.0	218.0	187.0
25%	431.0	145.0	119.0
40%	340.0	107.0	93.0
50%	306.0	94.0	81.0
60%	270.0	81.0	74.0
75%	234.0	70.0	70.0
90%	200.0	70.0	70.0
95%	200.0	70.0	70.0
98%	200.0	70.0	70.0
99%	200.0	70.0	70.0
100%	0.0	0.0	0.0
Mean	359.0	122.0	109.0
Standard Deviation	179.0	74.0	63.0
Maximum	1000.0	400.0	350.0

Table B - 7 Means of Regulated Concentrations for TDS

% Time Equalled or Exceeded	Seymour	Eliasville	Cameron	Possum Kingdom	Whitney	Richmond
10%	11345.0	1588.0	425.0	3016.0	2278.0	587.0
25%	9068.0	1157.0	323.0	2505.0	1740.0	431.0
40%	6984.0	901.0	277.0	2358.0	1565.0	340.0
50%	5660.0	768.0	252.0	2246.0	1498.0	306.0
60%	4538.0	640.0	234.0	2112.0	1444.0	270.0
75%	3405.0	469.0	201.0	1952.0	1368.0	234.0
90%	2043.0	250.0	151.0	1751.0	1245.0	200.0
95%	1312.0	0.0	123.0	1507.0	1186.0	200.0
98%	650.0	0.0	83.0	1260.0	1080.0	200.0
99%	0.0	0.0	48.0	1122.0	1011.0	200.0
100%	0.0	0.0	0.0	1000.0	953.0	0.0
Mean	6303.0	840.0	277.0	2276.0	1615.0	359.0
Standard Deviation	3683.0	527.0	135.0	492.0	408.0	179.0
Maximum	25000.0	2978.0	1000.0	3578.0	2981.0	1000.0

Table B - 8 Means of Regulated Concentrations for Chlorides

% Time Equalled or Exceeded	**Seymour**	**Eliasville**	**Cameron**	**Possum Kingdom**	**Whitney**	**Richmond**
10%	5263.0	537.0	67.0	983.0	824.0	218.0
25%	4009.0	400.0	52.0	861.0	711.0	145.0
40%	2927.0	318.0	45.0	807.0	673.0	107.0
50%	2318.0	274.0	42.0	776.0	662.0	94.0
60%	1804.0	226.0	39.0	751.0	640.0	81.0
75%	1255.0	170.0	36.0	720.0	622.0	70.0
90%	745.0	100.0	35.0	661.0	589.0	70.0
95%	426.0	0.0	35.0	628.0	567.0	70.0
98%	250.0	0.0	35.0	596.0	546.0	70.0
99%	0.0	0.0	34.0	550.0	518.0	70.0
100%	0.0	0.0	0.0	489.0	501.0	0.0
Mean	2722.0	301.0	49.0	795.0	684.0	122.0
Standard Deviation	1825.0	201.0	30.0	118.0	107.0	74.0
Maximum	10000.0	1576.0	337.0	1164.0	1069.0	400.0

Table B - 9 Means of Regulated Concentrations for Sulfates

% Time Equalled or Exceeded	**Seymour**	**Eliasville**	**Cameron**	**Possum Kingdom**	**Whitney**	**Richmond**
10%	1705.0	438.0	63.0	646.0	485.0	187.0
25%	1439.0	290.0	50.0	576.0	436.0	119.0
40%	1205.0	203.0	44.0	545.0	420.0	93.0
50%	1032.0	168.0	41.0	521.0	410.0	81.0
60%	884.0	133.0	38.0	505.0	399.0	74.0
75%	702.0	102.0	35.0	475.0	384.0	70.0
90%	430.0	75.0	35.0	443.0	364.0	70.0
95%	250.0	0.0	35.0	394.0	342.0	70.0
98%	250.0	0.0	35.0	424.0	354.0	70.0
99%	0.0	0.0	34.0	368.0	330.0	70.0
100%	0.0	0.0	0.0	326.0	301.0	0.0
Mean	1067.0	214.0	48.0	532.0	421.0	109.0
Standard Deviation	494.0	172.0	30.0	80.0	60.0	63.0
Maximum	2500.0	1367.0	300.0	793.0	634.0	350.0

Table B - 10 Frequency Analyses for Possum Kingdom (dams)

Percent Time Equalled or Exceeded	**TDS (mg/l)**	**Cl (mg/l)**	**SO4 (mg/l)**
10%	1950.0	577.0	479.0
25%	1681.0	521.0	430.0
40%	1576.0	497.0	405.0
50%	1511.0	483.0	388.0
60%	1423.0	468.0	373.0
75%	1313.0	434.0	352.0
90%	1181.0	406.0	328.0
95%	1052.0	387.0	293.0
98%	896.0	373.0	312.0
99%	850.0	365.0	270.0
100%	733.0	329.0	240.0
Mean	1516.0	485.0	394.0
Standard Deviation	298.0	65.0	58.0
Maximum	2313.0	719.0	575.0

Table B - 11 Frequency Analyses for Whitney (dams)

Percent Time Equalled or Exceeded	TDS (mg/l)	Cl (mg/l)	SO4 (mg/l)
10%	1449.0	532.0	395.0
25%	1139.0	456.0	319.0
40%	1023.0	440.0	301.0
50%	978.0	430.0	293.0
60%	947.0	423.0	284.0
75%	893.0	414.0	272.0
90%	819.0	399.0	256.0
95%	780.0	389.0	239.0
98%	746.0	379.0	249.0
99%	712.0	370.0	231.0
100%	602.0	351.0	201.0
Mean	1054.0	455.0	304.0
Standard Deviation	256.0	84.0	50.0
Maximum	1927.0	793.0	468.0

Table B - 12 Frequency Analyses for Richmond (dams)

Percent Time Equalled or Exceeded	TDS (mg/l)	Cl (mg/l)	SO4 (mg/l)
10%	476.0	188.0	155.0
25%	354.0	117.0	100.0
40%	285.0	88.0	78.0
50%	255.0	74.0	69.0
60%	229.0	66.0	63.0
75%	196.0	60.0	60.0
90%	162.0	60.0	60.0
95%	160.0	60.0	60.0
98%	160.0	60.0	60.0
99%	160.0	60.0	60.0
100%	0.0	0.0	0.0
Mean	295.0	103.0	92.0
Standard Deviation	143.0	67.0	53.0
Maximum	800.0	360.0	300.0

Table B - 13 Frequency Analyses for TDS (dams)

Percent Time Equalled or Exceeded	**Seymour mg/l**	**Possum Kingdom mg/l**	**Whitney mg/l**	**Richmond mg/l**
10%	6807.0	1950.0	1449.0	476.0
25%	5441.0	1681.0	1139.0	354.0
40%	4191.0	1576.0	1023.0	285.0
50%	3396.0	1511.0	978.0	255.0
60%	2723.0	1423.0	947.0	229.0
75%	2043.0	1313.0	893.0	196.0
90%	1224.0	1181.0	819.0	162.0
95%	787.0	1052.0	780.0	160.0
98%	390.0	896.0	746.0	160.0
99%	0.0	850.0	712.0	160.0
100%	0.0	733.0	602.0	0.0
Mean	3783.0	1516.0	1054.0	295.0
Standard Deviation	2212.0	298.0	256.0	143.0
Maximum	15000.0	2313.0	1927.0	800.0

Table B - 14 Frequency analyses for Chlorides (dams)

Percent Time Equalled or Exceeded	**Seymour mg/l**	**Possum Kingdom mg/l**	**Whitney mg/l**	**Richmond mg/l**
10%	2631.0	577.0	532.0	188.0
25%	2005.0	521.0	456.0	117.0
40%	1464.0	497.0	440.0	88.0
50%	1159.0	483.0	430.0	74.0
60%	902.0	468.0	423.0	66.0
75%	627.0	434.0	414.0	60.0
90%	373.0	406.0	399.0	60.0
95%	213.0	387.0	389.0	60.0
98%	125.0	373.0	379.0	60.0
99%	0.0	365.0	370.0	60.0
100%	0.0	329.0	351.0	0.0
Mean	1361.0	485.0	455.0	103.0
Standard Deviation	913.0	65.0	84.0	67.0
Maximum	5000.0	719.0	793.0	360.0

Table B - 15 Frequency Analyses for Sulfates (dams)

Percent Time Equalled or Exceeded	**Seymour mg/l**	**Possum Kingdom mg/l**	**Whitney mg/l**	**Richmond mg/l**
10%	1245.0	479.0	395.0	155.0
25%	1051.0	430.0	319.0	100.0
40%	880.0	405.0	301.0	78.0
50%	754.0	388.0	293.0	69.0
60%	645.0	373.0	284.0	63.0
75%	511.0	352.0	272.0	60.0
90%	314.0	328.0	256.0	60.0
95%	180.0	293.0	239.0	60.0
98%	180.0	312.0	249.0	60.0
99%	0.0	270.0	231.0	60.0
100%	0.0	240.0	201.0	0.0
Mean	779.0	394.0	304.0	92.0
Standard Deviation	361.0	58.0	50.0	53.0
Maximum	1825.0	575.0	468.0	300.0

Table B - 16 Reliabilities for Possum Kingdom under Constraints (dams)

Constituent	**Concentration mg/l**	**Reliability (%)**	
		Volume	Period
TDS	500	0.00	0.00
	1000	3.62	3.59
	1500	49.60	49.43
	max	100.00	100.00
Cl	250	0.00	0.00
	500	62.70	62.79
	750	100.00	100.00
	max	100.00	100.00
SO4	250	0.21	0.14
	500	95.53	95 .40
	750	100.00	100.00
	max	100.00	100.00

Table B - 17 Reliabilities for Whitney under Constraints (dams)

Constituent	Concentration mg/l	Reliability (%)	
		Volume	Period
TDS	500	0.00	0.00
	1000	58.26	57.04
	1500	91.14	90.06
	max	98.85	99.20
Cl	250	0.00	0.00
	500	98.85	99.20
	750	98.85	99.20
	max	98.85	99.20
SO4	250	6.69	5.89
	500	98.85	99.20
	750	98.85	99.20
	max	98.85	99.20

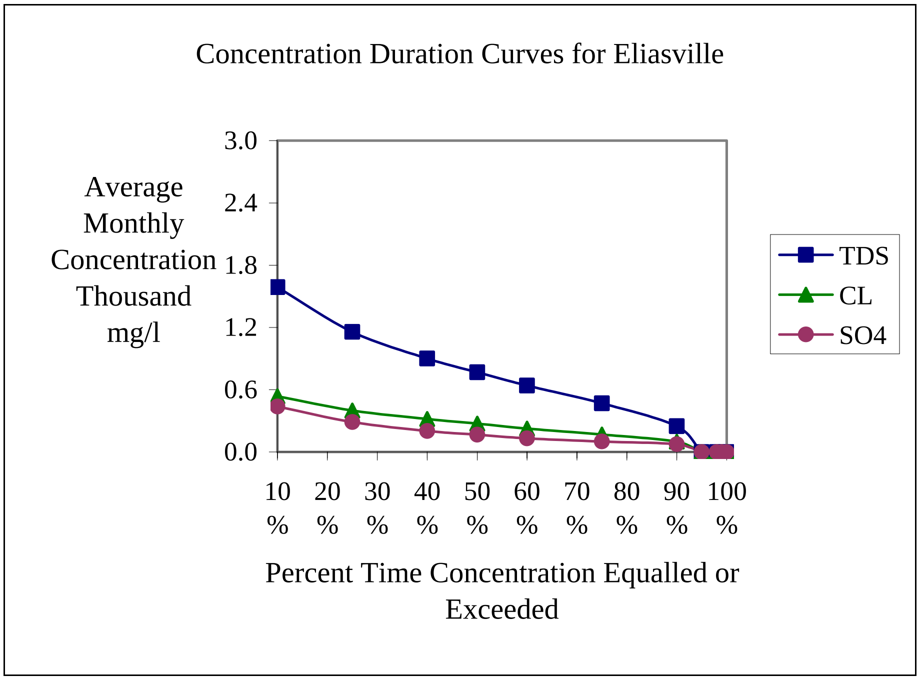

Figure B - 1 Regulated Concentration-Duration curves for Eliasville

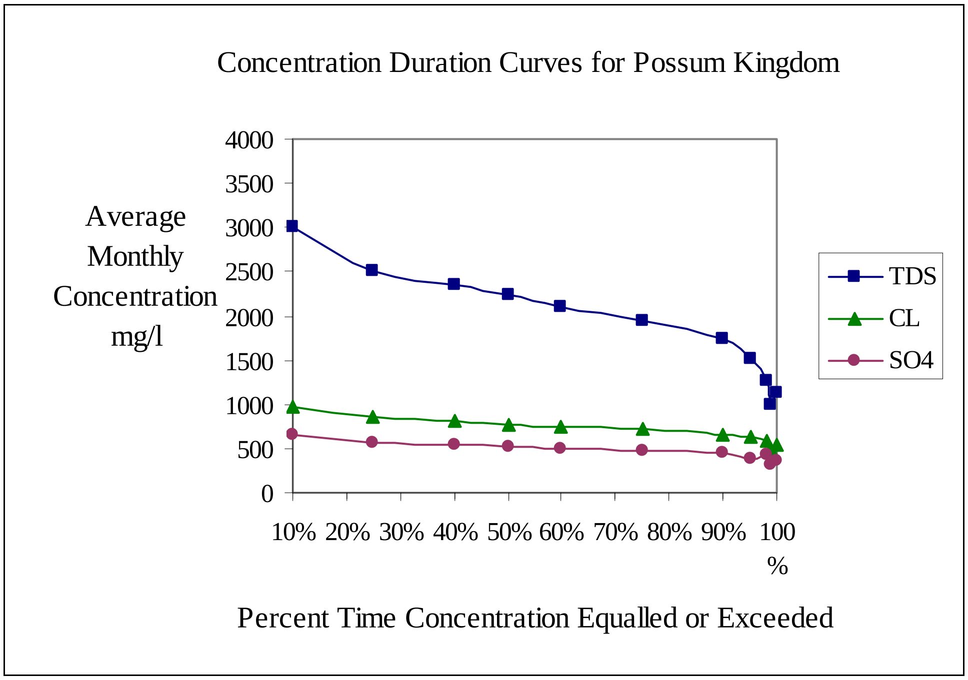

Figure B - 1 Regulated Concentration-Duration Curves for Possum Kingdom

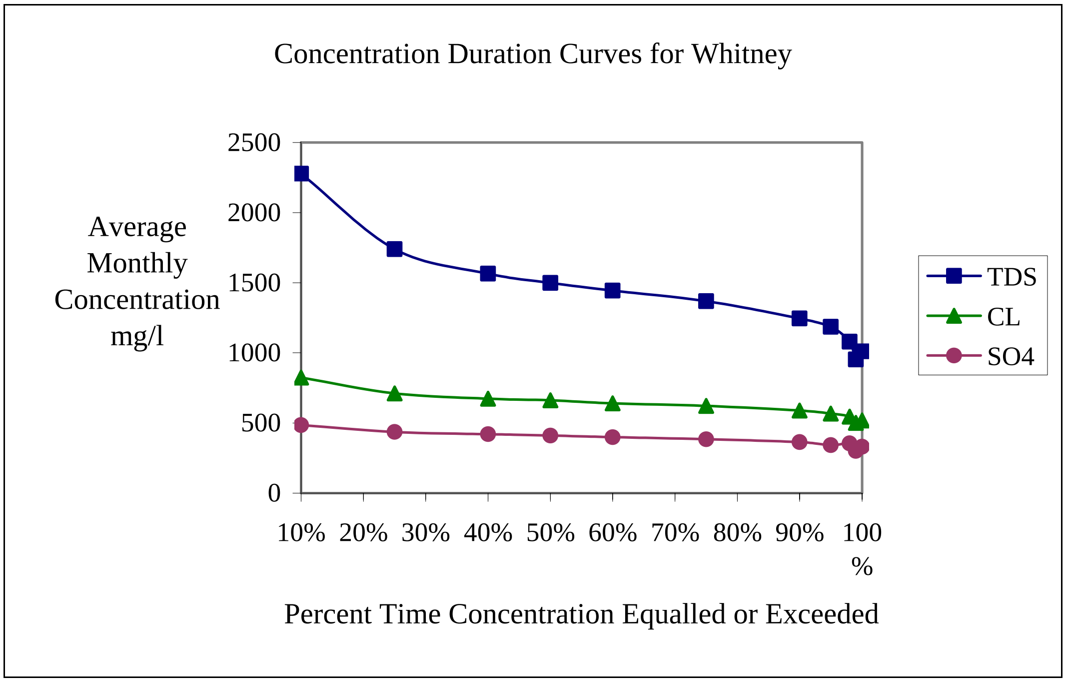

Figure B - 2 Regulated Concentration-Duration Curves for Whitney

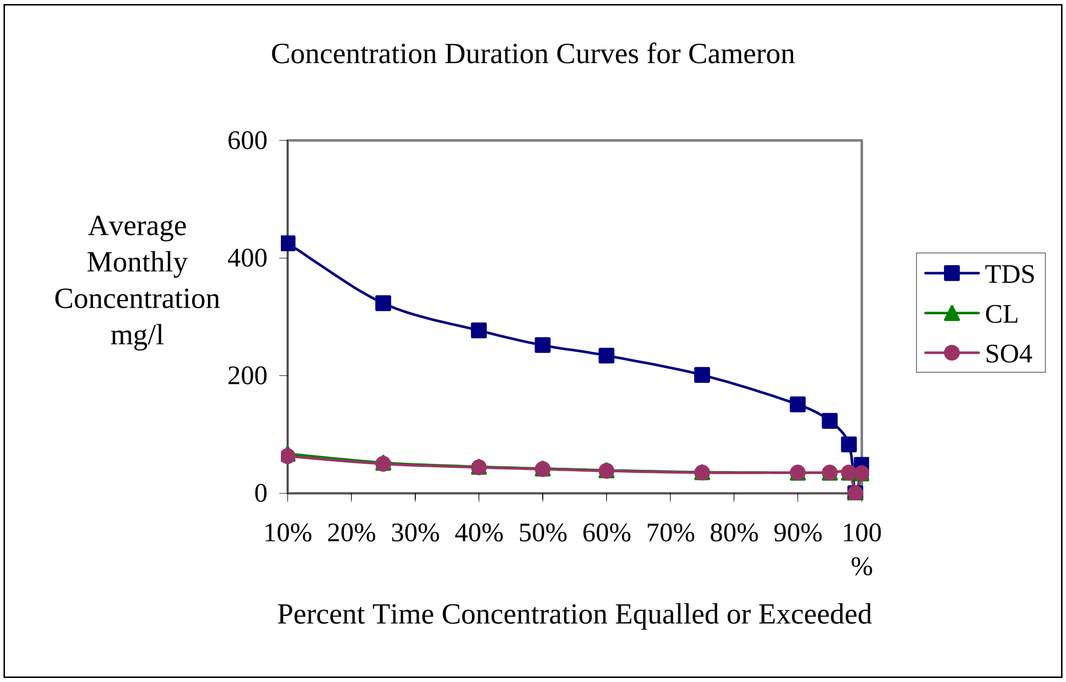

Figure B - 3 Regulated Concentration-Duration Curves for Cameron

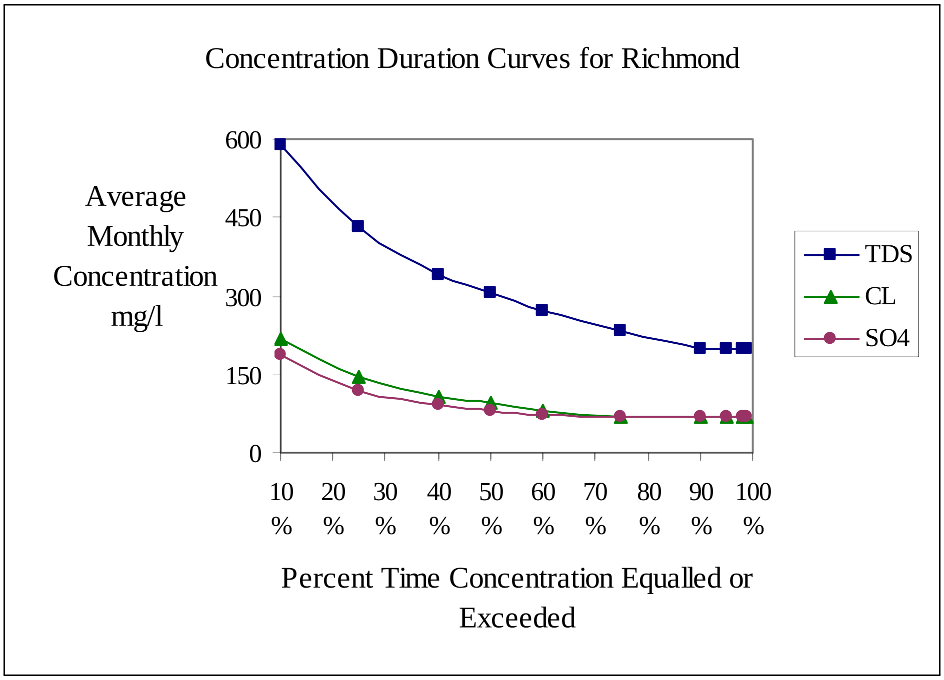

Figure B - 4 Regulated Concentration-Duration curves for Richmond

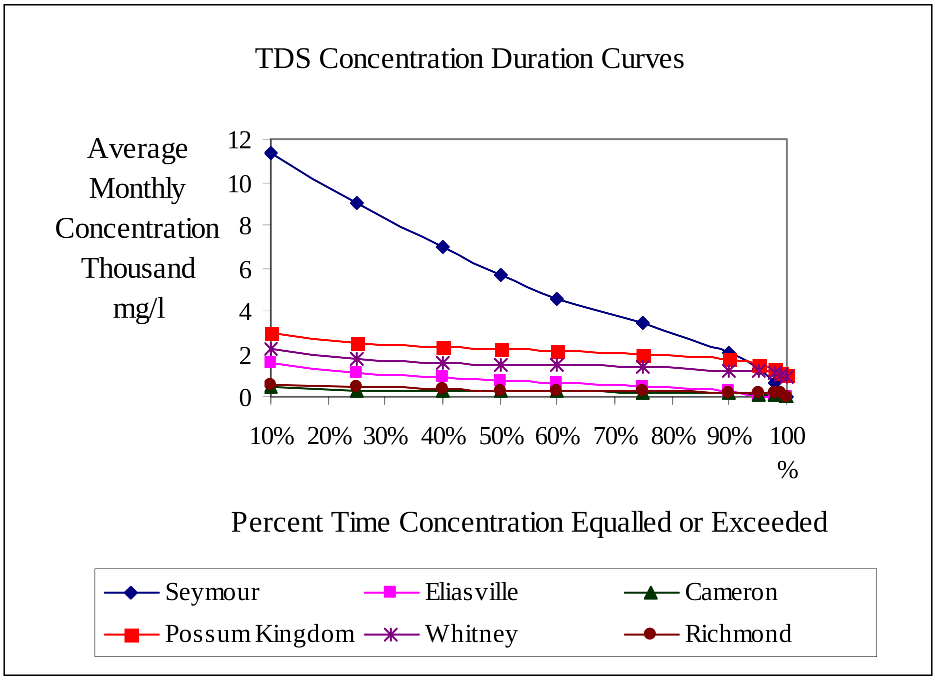

Figure B - 5 Regulated TDS Concentration-Duration curves for the Brazos

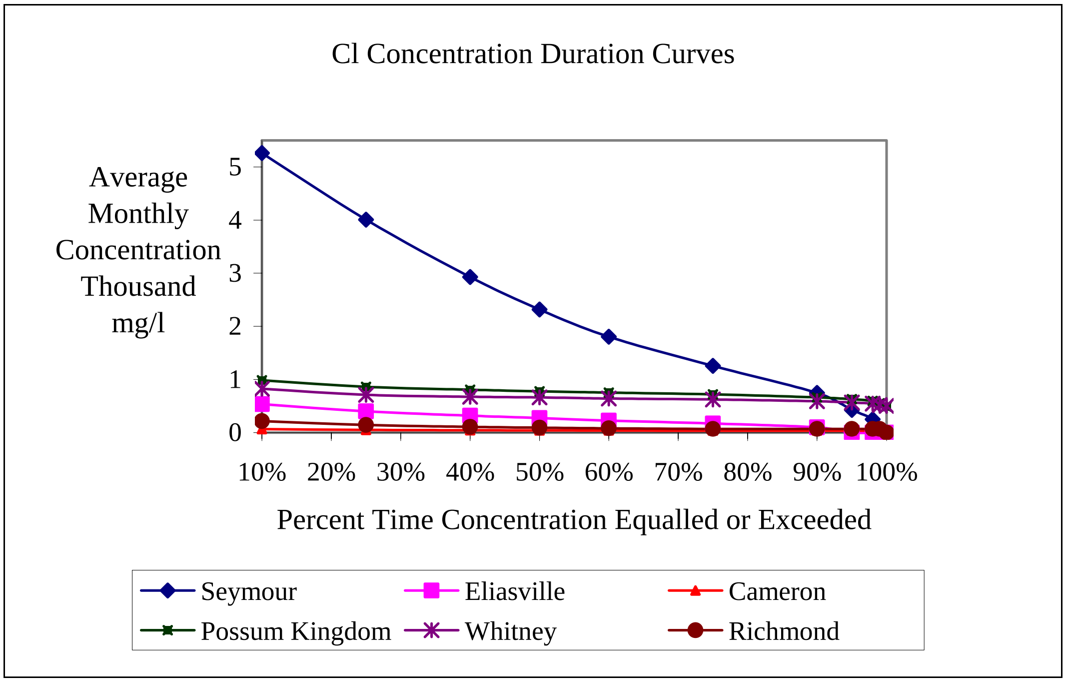

Figure B - 6 Regulated Cl Concentration-Duration curves for the Brazos

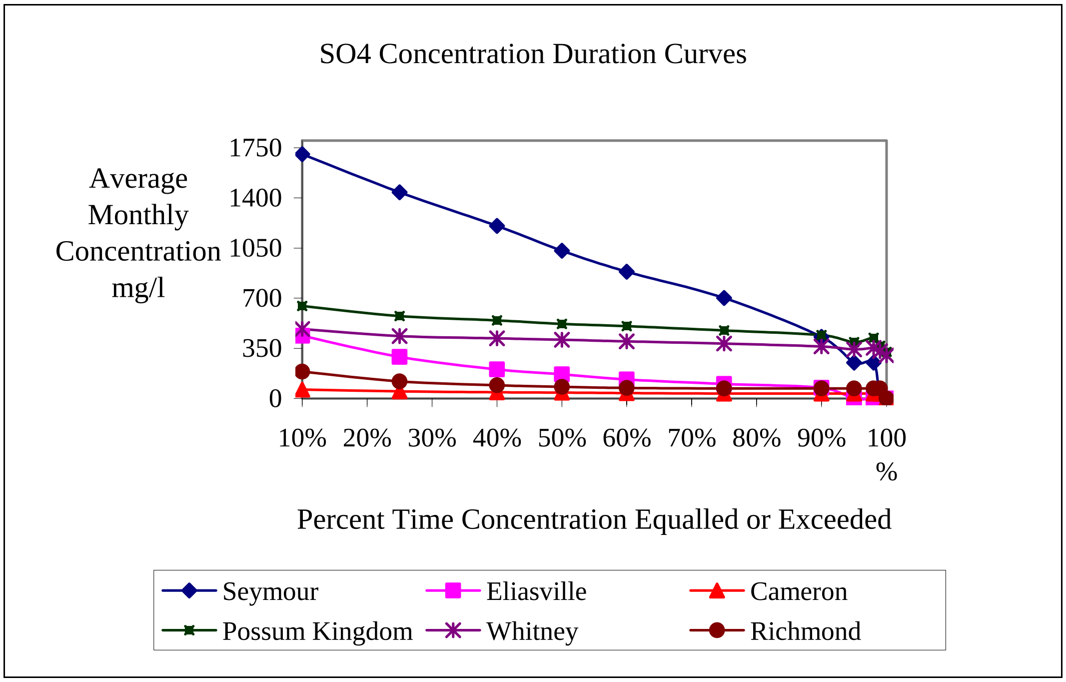

Figure B - 7 Regulated Sulfate Concentration-Duration curves for the Brazos

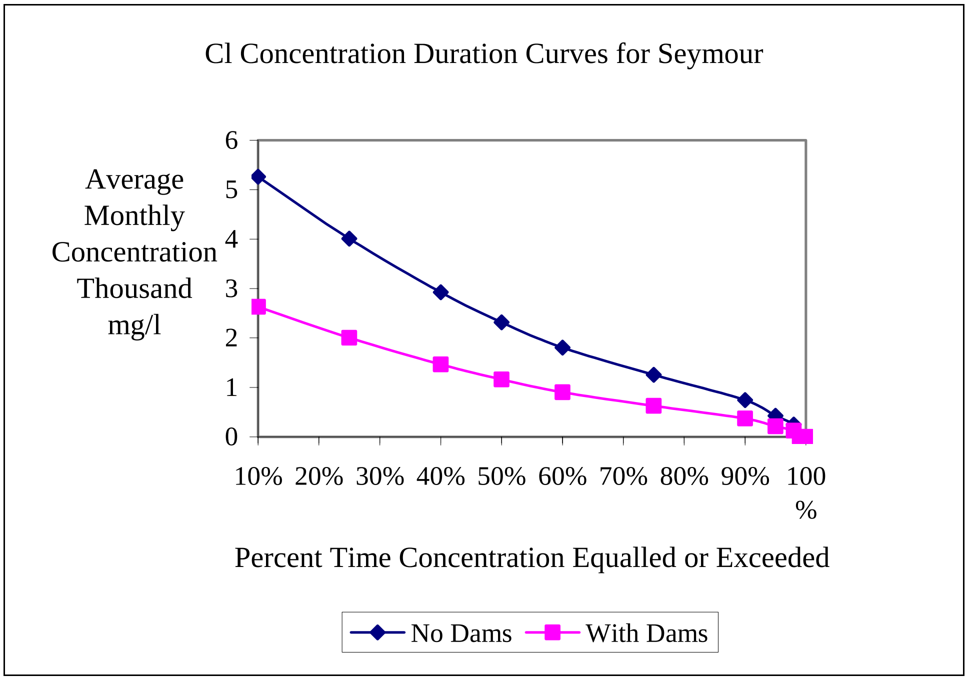

Figure B - 8 Regulated Chloride Concentration Duration curves at Seymour (dams)

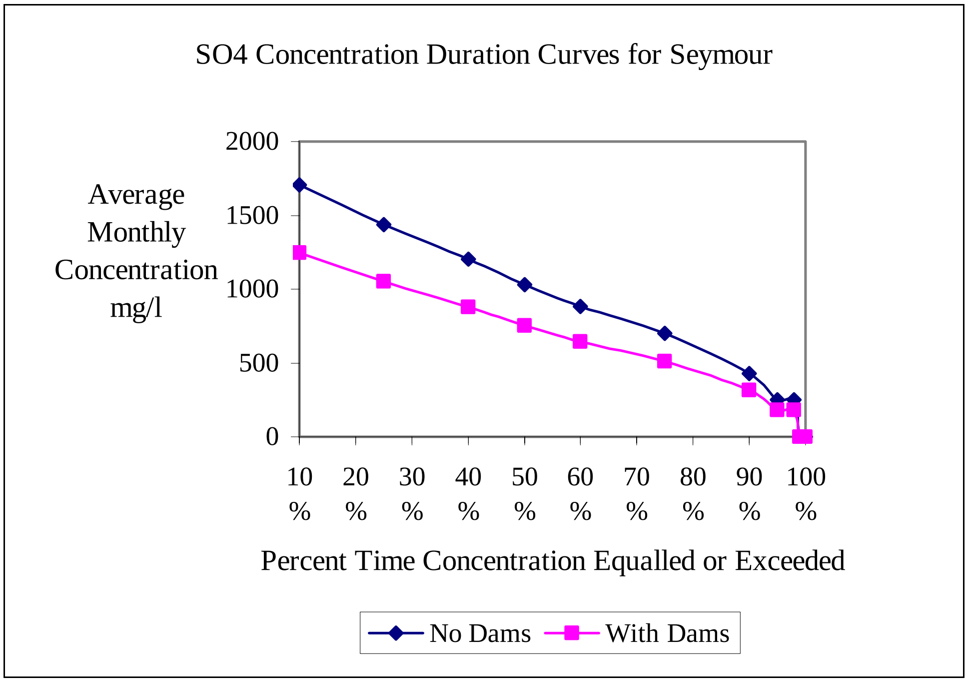

Figure B - 9 Regulated Sulfate Concentration Duration curves at Seymour (dams)

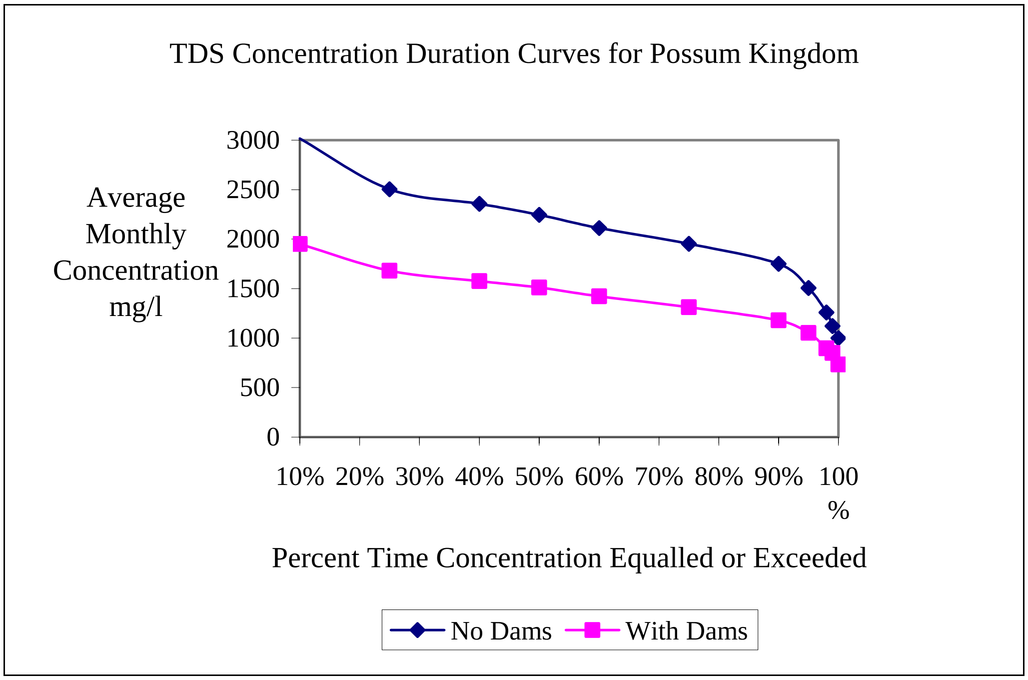

Figure B - 10 Regulated TDS Concentration-Duration curves for Possum Kingdom (dams)

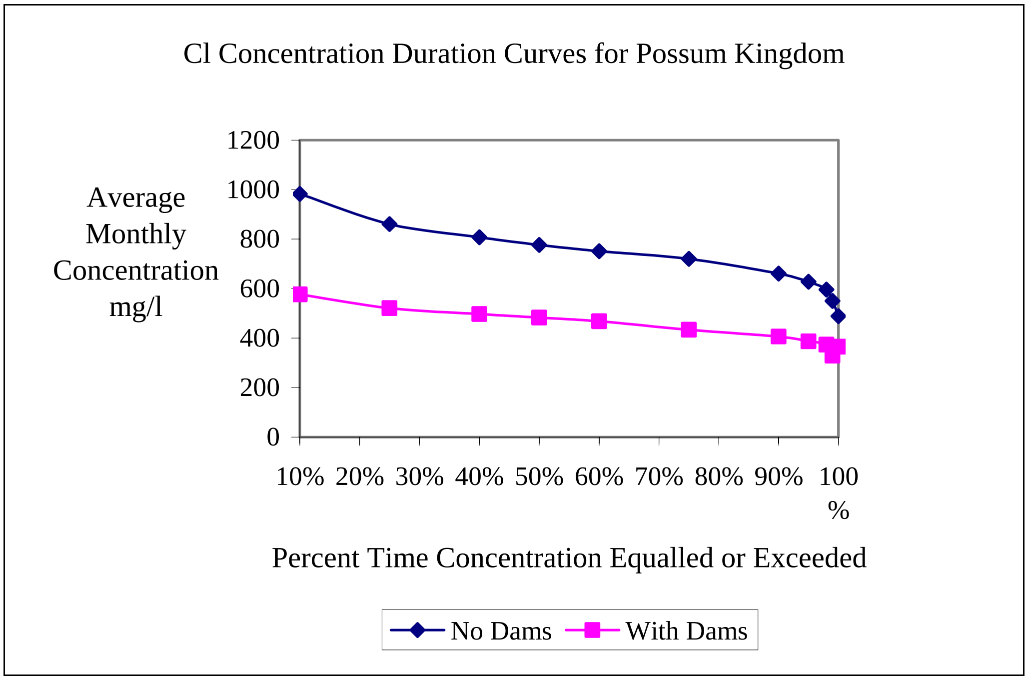

Figure B - 11 Regulated Cl Concentration-Duration curves for Possum Kingdom (dams)

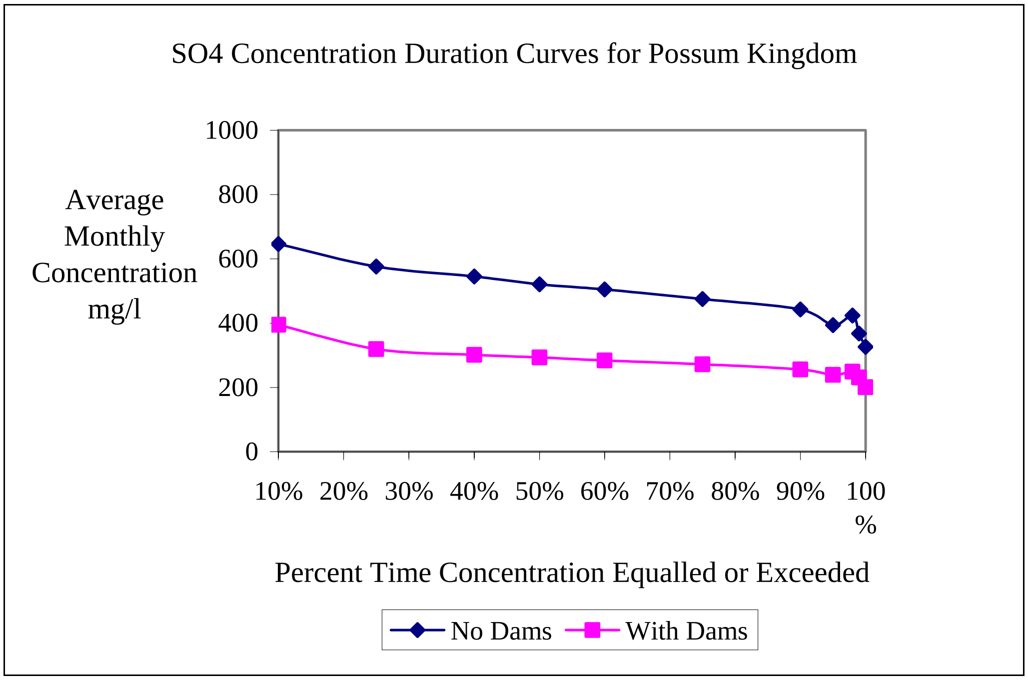

Figure B - 12 Regulated Sulfate Concentration-Duration curves for Possum Kingdom (dams)

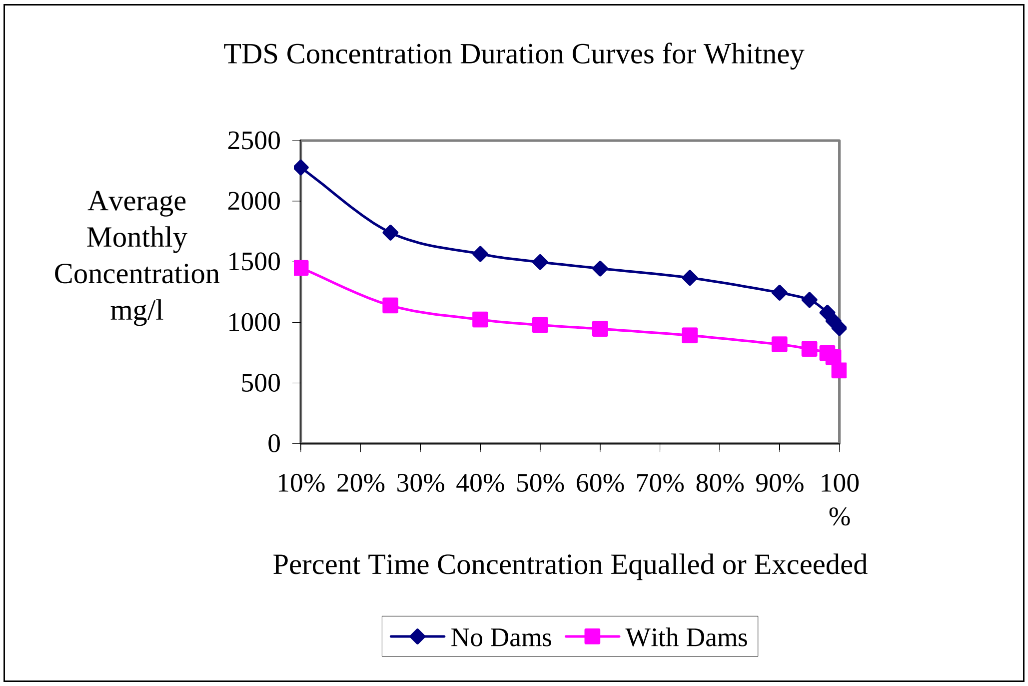

Figure B - 13 Regulated TDS Frequency Curves for Whitney (dams)

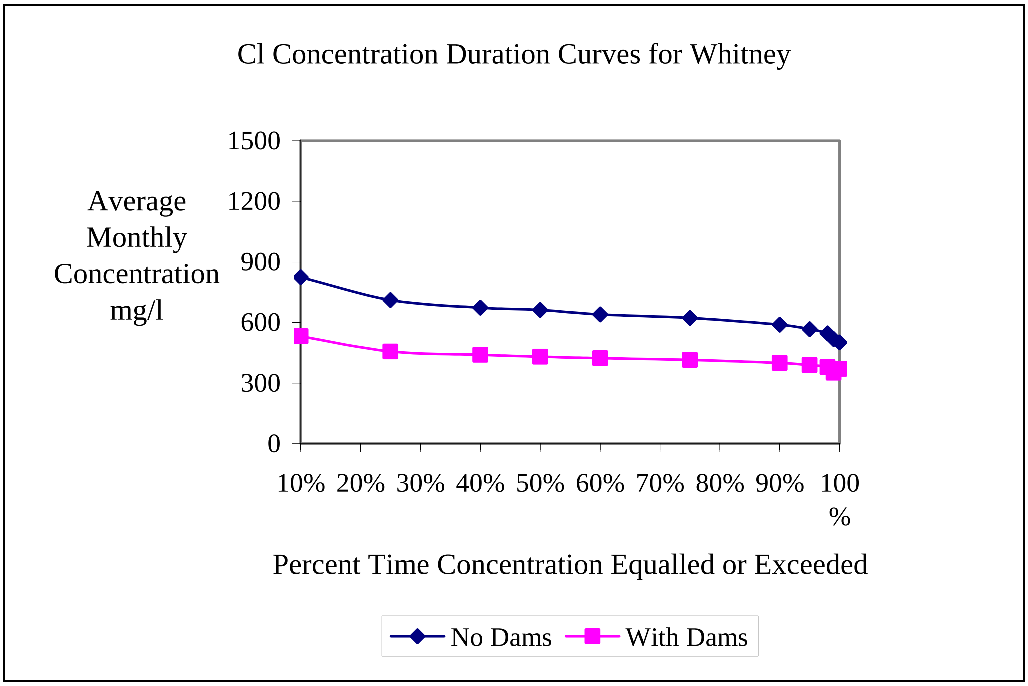

Figure B - 14 Regulated Cl Frequency Curves for Whitney with (dams)

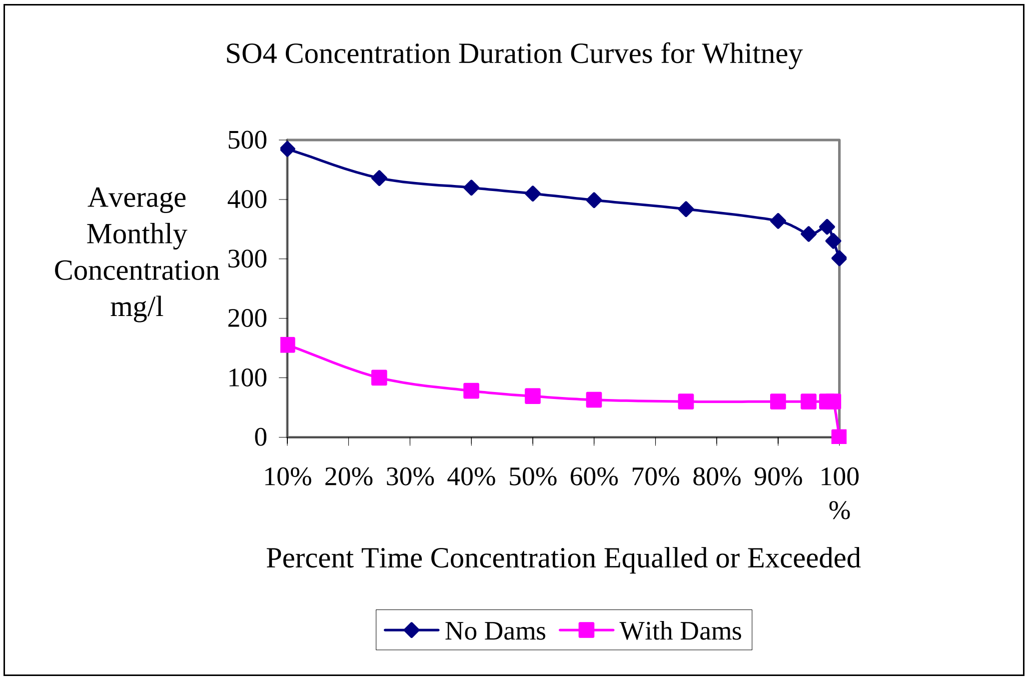

Figure B - 15 Regulated Sulfate Frequency Curves for Whitney (dams)

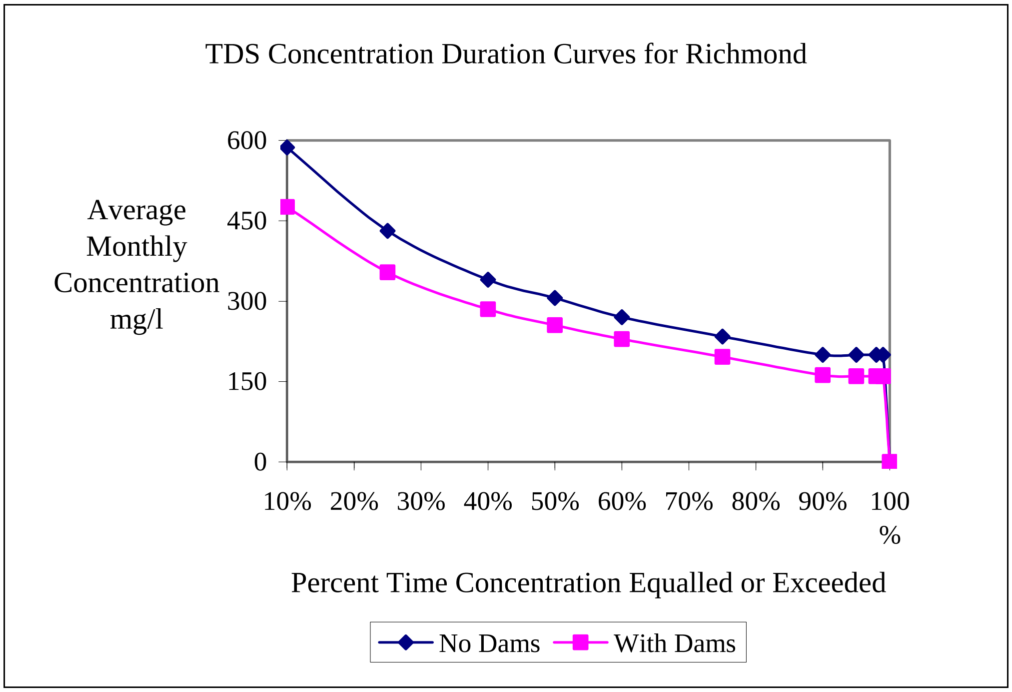

Figure B - 16 Regulated TDS Frequency Curves for Richmond (dams)

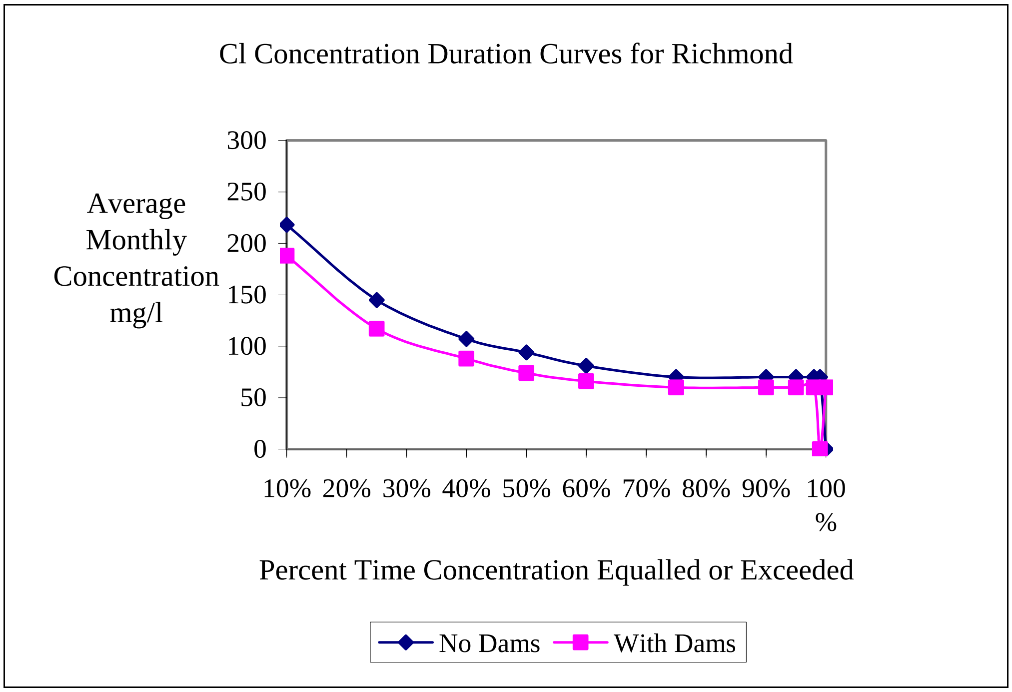

Figure B - 17 Regulated Cl Frequency Curves for Richmond (dams)

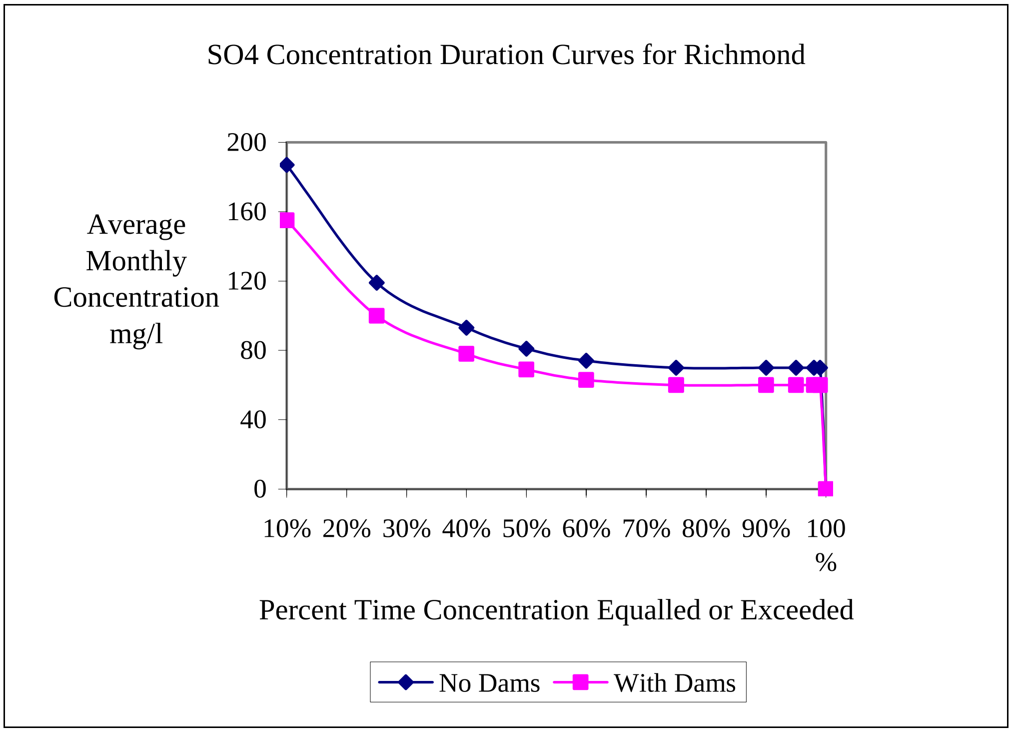

Figure B - 18 Regulated Sulfate Frequency Curves for Richmond (dams)

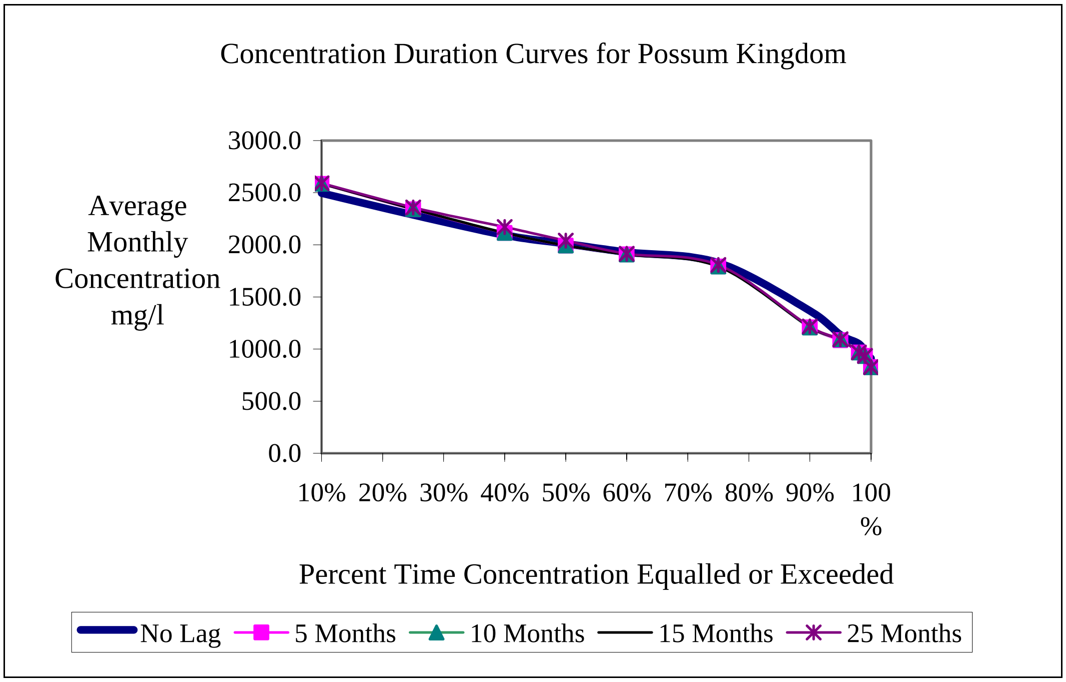

Figure B - 19 TDS Frequency Curves at Possum Kingdom considering a constant lag

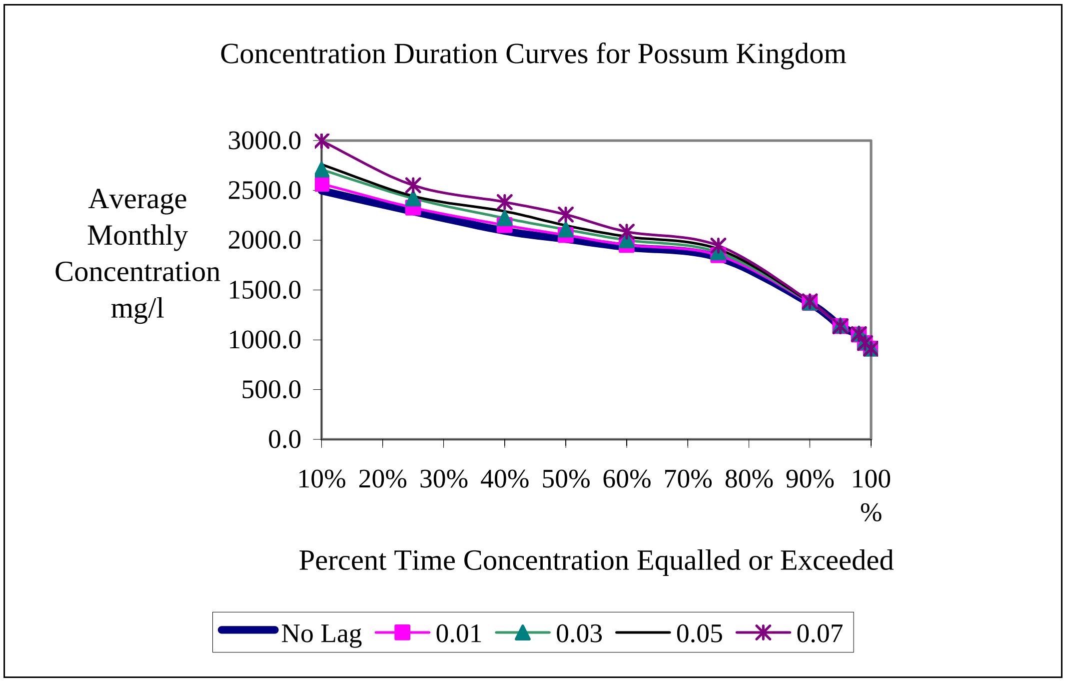

Figure B - 20 TDS Frequency Curves for Possum Kingdom for lag multipliers

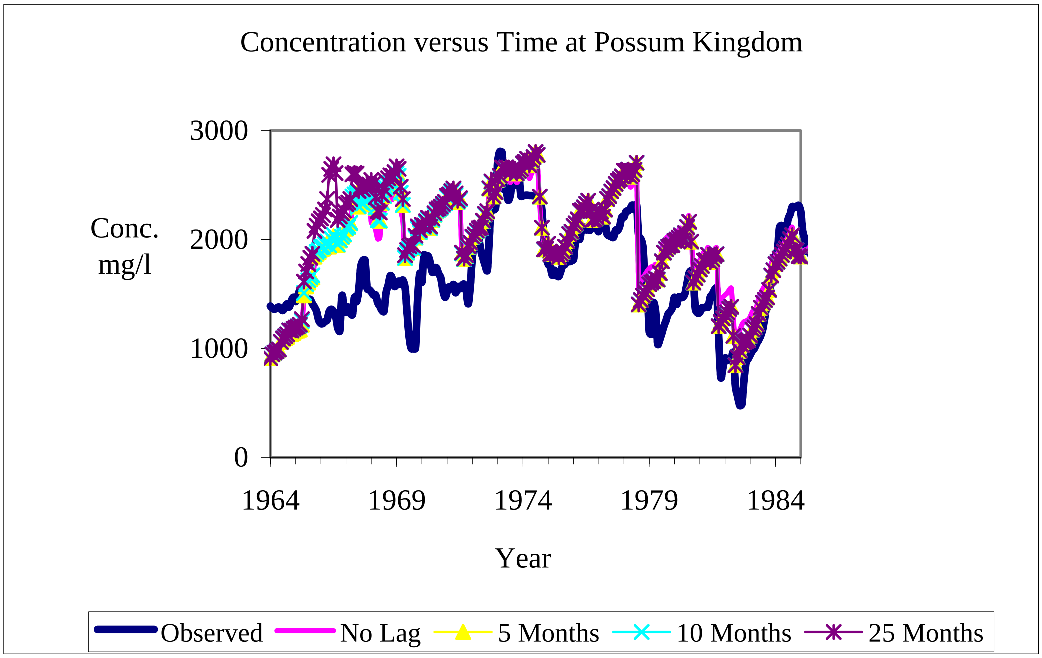

Figure B - 21 Reservoir Outlfow Concentration at Possum Kingdom

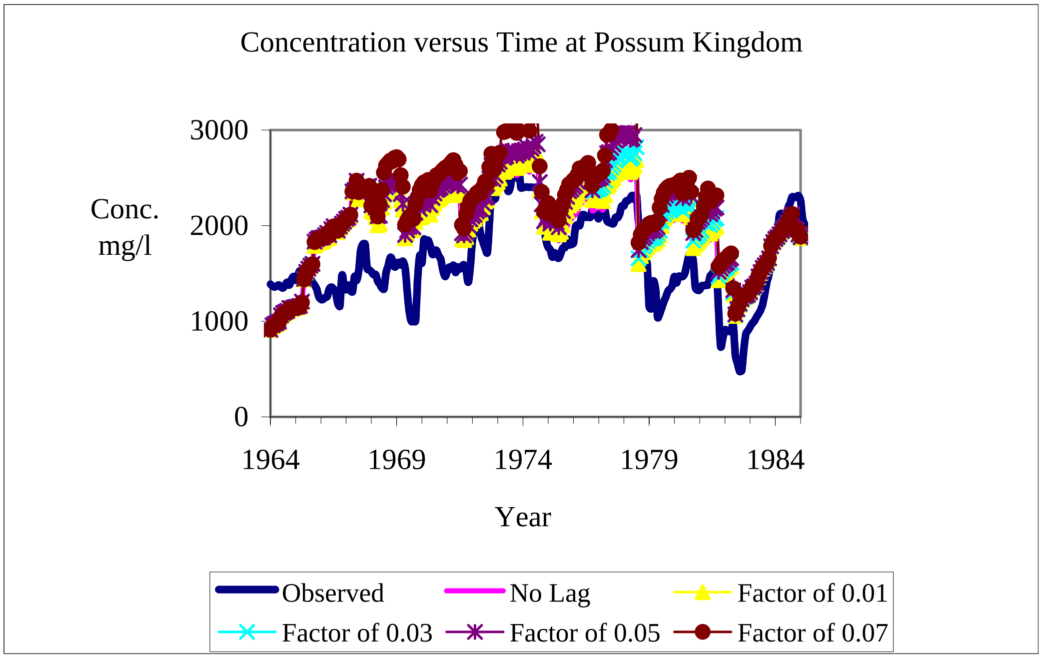

Figure B - 22 Reservoir Outflow Concentration at Possum Kingdom

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