IMPACTS OF NATURAL SALT POLLUTION ON WATER SUPPLY CAPABILITIES OF RIVER/RESERVOIR SYSTEMS

A Dissertation

by

CHI HUN LEE

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

DOCTOR OF PHILOSOPHY

May 2010

Major Subject: Civil Engineering

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Approved by:

Chair of Committee,	Ralph Wurbs
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ABSTRACT

Impacts of Natural Salt Pollution on Water Supply

Capabilities of River/Reservoir Systems.

(May 2010)

Chi Hun Lee, B.S., M.S., Hongik University, Korea

Chair of Advisory Committee: Dr. Ralph A. Wurbs

Salinity is a major determinant of where and how water resources are used worldwide. Natural salt pollution severely constrains the beneficial use of large amounts of water in Texas and neighboring states. High salinity loads in several major river/reservoir systems, including the Brazos River, originate largely from salt seeps and springs in isolated areas of the upper river basins located in the Permian Basin geologic region.

Research objectives were (1) to improve salinity simulation capabilities of the Water Rights Analysis Package (WRAP) modeling system, and (2) to develop a better understanding of the occurrence, transport, and impacts of salinity in the Brazos River and Lakes Possum Kingdom, Granbury, and Whitney. Water volume budgets and total dissolved solids load budgets were developed for five river reaches covering 405 miles of the upper Brazos River. Methodologies were developed for creating and applying WRAP salinity input datasets. The WRAP modeling system was expanded and applied

to the entire Brazos River Basin to investigate alternative modeling premises and impacts of salinity and salinity control measures on water supply capabilities.

Water and salinity budget analyses of the Brazos River system based primarily on measured stream flow, reservoir storage, and total dissolved solids data compiled by the U.S. Geological Survey were performed to explore the characteristics of flow and storage volumes and salinity loads and concentrations in the river/reservoir system. WRAP salinity input datasets were developed based on results from the salinity budget study. One dataset was designed and applied specifically for testing salinity routing methods and calibrating salinity routing parameters. A second complete basin salinity dataset was developed and applied to simulate the Brazos River Basin for alternative management strategies. The results of the simulations demonstrate, for example, that previously proposed salt control impoundments can significantly reduce salinity loads and concentrations in the three reservoirs and at all locations on the Brazos River from the impoundments downstream to the Gulf of Mexico.

The WRAP salinity simulation features are designed to provide flexibility in combining water quantity simulation datasets from the Texas Water Availability Modeling System or other sources, which may be very complex, with available salinity data which varies in extent and format between different river basins. The modeling capabilities demonstrated by the Brazos River Basin study can be applied in other river basins as well.

DEDICATION

This dissertation is dedicated to the late Dr. Chae Kwan Lim

who was an outstanding scholar,

the best friend and mentor in my study abroad life.

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First of all, I would like to give my best thanks to God. God is always looking after me and giving me infinite and endless love. I absolutely believe only God rules my life and leads me right way.

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Finally, I am sincerely grateful to my wife, my life, my immortal beloved, Jin-Sung Park who has encouraged me to come this far. Thank you and I love you.

The study in Texas A&M University is ended, but the study in my life just began. Around me many people helped me and led me to this way. From now on I know the time is beginning for repaying them for their infinite love. I would like to be someone who supports people and who is needed for the human society.

So help me God.

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CHAPTER I

INTRODUCTION

1.1 Statement of the Problem

Natural salt pollution from geologic formations in the upper watersheds of the Brazos and other river basins in the Southwestern United States severely constrains the use of otherwise available major water supply sources. The Water Rights Analysis Package (WRAP) modeling system has been routinely applied in Texas since the late 1990s in regional and statewide planning studies and administration of the state's water rights permit system, but without consideration of water quality. However, water supply capabilities depend upon water quality as well as quantity. This dissertation explores natural salt pollution in the Brazos River Basin, which is similar to salinity problems in other neighboring river basins, from the perspective of WRAP modeling system assessments of water supply capabilities. Total dissolved solids (TDS) load budget and water volume budget studies are combined with WRAP simulation studies to develop a better understanding of natural salt pollution and its impacts on water resources development, management, allocation, and use.

Salinity in soil, groundwater, and surface water is a major problem in managing river basins worldwide. Salinity results in a decrease in agricultural productivity and a decline in the quality of supplies for drinking, irrigation, and industrial use.

This dissertation follows the style of *Water Resources Planning and Management.*

In the Permian Basin geologic region of the Southwestern United States, natural salt contamination originates from geological formations underlying portions of the upper watersheds of the Arkansas, Canadian, Red, Brazos, Colorado, and Pecos Rivers in the states of Kansas, Colorado, Oklahoma, New Mexico, and Texas (Rought 1984). The Brazos River of Texas is typical of these river systems. Most of the water supply diversions from the main-stem Brazos River occur either in the lower reaches after dilution from low-salinity tributary inflows or at Lake Granbury where the water is treated at a desalination plant operated by the Brazos River Authority.

1.2 Scope of the Research

The TDS load budget and volume budget studies and simulation studies of the Brazos River Basin described in this dissertation build upon and combine the Texas Commission on Environmental Quality (TCEQ) Water Availability Modeling (WAM) System and salinity data collected by the U.S. Geological Survey (USGS). The WAM System consists of the generalized WRAP river/reservoir system simulation model and input datasets for the 23 river basins of Texas, including the Brazos. The WAM System deals with water quantity, not water quality. However, a salinity modeling component called WRAP-SALT has been recently added to the WRAP modeling system. The research described in this dissertation included testing, improving, and applying WRAP-SALT. The effects of salinity on water supply capabilities were assessed based on WRAP simulation studies with input data for the Brazos River Basin from the WAM System combined with a WRAP-SALT salinity input file developed from the USGS dataset described below.

The USGS conducted an extensive salinity data collection program from October 1963 through September 1986 in support of natural salt pollution control studies performed by the U.S. Army Corps of Engineers. This dataset of water year 1964-1986 monthly salt loads and concentrations was adopted for the studies presented in this dissertation along with limited additional available more recent USGS reservoir salinity data. Volume and load budget studies were performed for five sub-reaches of a 405-mile reach of the upper Brazos River extending from the Seymour gage located 160 miles upstream of Morris Sheppard Dam to the Whitney gage located just downstream of Whitney Dam. The volume and load budget studies provide insight into salinity characteristics of the Brazos River independently of the WRAP simulation study. The volume and load budget studies for the upper Brazos River supplemented with salinity data at other locations throughout the river basin also supported development of a WRAP-SALT salinity input file for the WRAP simulation studies.

Thus, the research supports improvement and application of salinity simulation features that have been developed for the WRAP modeling system to incorporate consideration of water quality, particularly natural salt pollution, in assessments of water supply capabilities. The studies also provide insight into the salinity characteristics of the Brazos River Basin and impacts of salinity on water supply capabilities.

The objectives of the research are to:

1. to develop an improved understanding of the occurrence, transport, and characteristics of salinity in the Brazos River and Lakes Possum Kingdom, Granbury, and Whitney
2. test and improve the salinity simulation capabilities of the WRAP modeling system
3. formulate, test, and apply methods for routing salinity through reservoirs in the WRAP-SALT model and determining parameters for the salinity routing methods
4. formulate, test, and apply methods for developing a salinity input dataset for WRAP-SALT for use in water availability and water supply reliability assessments for the Brazos River Authority reservoir system
5. perform a WRAP simulation study to evaluate the impacts of salinity and salinity mitigation measures on water supply capabilities of the Brazos River Authority system

CHAPTER II

LITERATURE REVIEW

This dissertation addresses both the characteristics of salinity in river/reservoir systems and the incorporation of salinity in river/reservoir system analysis models. Thus, the literature review focuses on two topics; (1) salinity problems and related studies in water resources management, (2) water quality considerations in reservoir system analysis models.

2.1 Salinity Problems and Related Studies in Water Resources Management

Natural salt pollution causes serious problems in many river basins of the world, including regions where the climate is humid (e.g., Holland, Sweden, and Hungary), as well as arid or semiarid regions (e.g., southwestern United States, Australia, India, and the Middle East) (Yaron 1981). According to Williams (1987), a world-wide area of about 950 million ha is now affected by salinity. High salinity in a river basin severely constrains the use of water for agriculture, municipal activities, industry, and environmental needs. High salinity concentrations cause losses in cultivated lands, decreases in crop yields, increases in municipal and industrial water treatment costs, and corrosion of facilities and pipelines. Environmental losses may occur with changes of plant, animal, and aquatic life in response to changes in salinity. Salinity problems are often an important consideration in the planning and management of river basins.

Severe salinity problems are well documented in the Western and Southwestern regions of the United States. The quality of water in the main streams of a number of river systems in the Southwestern United States is seriously degraded by salt emissions from major salt sources in the upper portion of these basins that were created by a large inland sea during the Permian age (Rought 1984, Wurbs 2002). For example, according to Miyamoto (1995), the highest salinity of the Rio Grande included in this major salt source area occurs in the section from Fort Quitman to Presidio (2,000 to 5,000 mg/l) and at the Pecos River (2000 to 4000 mg/l). Salinity of the Rio Grande is increasing at an annual rate of 15 to 18 mg/l.

The development of water balance and salinity budgets has been found to be useful in examining the characteristics of the hydrological cycle of water and salinity. In order to develop water and salt budgets, collection of stream flow and salinity data is required. Many investigations have been performed to collect and analyze salinity data. Periodically, since 1961, the U.S. Geological Survey (USGS), in collaboration with state, federal, and local agencies, has collected water quality records for selected reservoirs in Texas (Andrews 1988; Andrews and Strause 1982; Flugrath and Chitwood 1982; Kunze and Rawson 1972; Leibbrand et al. 1987; Rawson et al 1979a; Rawson et al. 1975; Rawson et al. 1979b; Rawson et al. 1973; Strause et al. 1984). These reports include the results of on-site determinations of specific conductance, dissolved oxygen, temperature, and laboratory analyses of samples collected from 17 reservoirs including Lakes Texoma, Sam Rayburn, Hubbard Creek, Possum Kingdom, Whitney, Proctor, Belton, Red Bluff, Meredith, Greenbelt, Arlington, Lewisville, Livingston, Conroe, Granbury, Town, and Canyon. The USGS operates the National Water Data Storage and Retrieval System (WATSTORE) to support convenient access to collect the data. Even though specific conductance and discharges can be obtained as a WATSTORE compute file, the monthly salt loadings and concentrations are not stored in the computer system. Ganze (1990) compiled and analyzed mean monthly and mean annual discharges, loadings, and concentrations of total dissolved solids (TDS), dissolved chloride (Cl), and dissolved sulfate (SO4) at 26 selected gaging stations in Brazos River Basin, Texas.

Inosako et al (2006) suggested three simple methods for estimating outflow salinity from inflow salinity and quantity, and reservoir storage on a monthly time step. Three scenarios were considered. The first scenario is that the data available are limited to quantity and salinity of inflow, and the initial reservoir storage and its salinity. The second scenario is that the reservoir storage is known on a monthly basis or can be computed from monthly inflow and outflow data. The third scenario is that the complete water balance is known, including evaporation, rainfall, and percolation losses.

(Miyamoto et al. 2007) examined water balance and salt loading of Red Bluff Reservoir in Texas. They explained that at least two other factors which increase salinity of Red Bluff. One is significant reduction in incoming flow of low salinity water for dilution. The other factor is washout of salt from the watershed. Even though they constructed a water balance of Red Bluff Reservoir, a salinity budget was not developed because of missing data of salinity between inflow, outflow, and reservoir storage.

Kerachian and Karamous (2006; 2007) developed optimal operating rules for water quality management in reservoir-river systems using a methodology combining a water quality simulation model and a stochastic genetic algorithm-based conflict resolution technique. They showed that the proposed model for reservoir operation and waste load allocation can reduce the salinity of the allocated water demands as well as the salinity build-up in the reservoir.

Imberger (1981) examined the response of the Wellington Reservoir to changes in streamflow salinity and outflow strategies by using the dynamic reservoir simulation model DYRESM. In this research, the effects of the increase of salt of Wellington Reservoir were synthesized and the usefulness of a salinity diversion dam was evaluated. The result of the examination represents the prediction of the exact nature of the salinity variations is not important as the mixing in the reservoir acts as a strong filter.

The spatial and temporal variability of salt concentrations represent another dimension in assessing water availability for various water users and types of use under specified water resources development and management scenarios. The salinity simulation component of WRAP called WRAP-SALT (Wurbs 2009; Wurbs et al. 2006) was developed for computing concentration frequency statistics at locations of interest throughout a river system for alternative water management plans. Early research studies in incorporating salinity considerations in WRAP modeling are reported by Wurbs et al (1995; 1993; 2009; 1994), Sanchez-Torres (1994), Karama (1993), Krishnamurthy (2006) and Ha (2007).

Sanchez-Torres (1994) developed a model to simulate reservoir/river system operations based on a priority data algorithm for the allocation of water resources among numerous water users, incorporating water salinity constraints in the simulation process. Eighty-three simulation runs were performed to consider various management alternatives of the reservoir system. The results represent the incorporation of salinity constraints into the simulation model affects greatly on the reliabilities and yields of the reservoir/river system.

Water quality is a relative concept (Dzurik and Theriaque 1996). Different purposes of water use may require different levels of quality. The standard of water quality for public drinking might be higher than for irrigation or industry. For example, The U.S. Environmental Protection Agency suggests secondary drinking water standards based on health effects and taste preferences because conventional water treatment process do not remove salinity. The limits for TDS, chloride, and sulfate concentrations are 500, 250, and 250 mg/l, respectively. In these reasons, salinity control is a complicated problem that includes not only technical considerations but also economical, environmental, and political problems. Because of these complexities, there are controversies and different opinions for designing plans for salinity control. In the Brazos River Basin, the natural salt pollution studies were performed by the U.S. Army Corps of Engineers (USACE) with several other agencies (USACE 1977). A project consisting of three salt impoundments was proposed as the most effective solution for controlling natural salt pollution in the Brazos River Basin. However, the plan of building three impoundments was not performed because it was not economically feasible based on economic evaluation methods and considerations.

The Texas Commission on Environmental Quality (TCEQ) operates Total Maximum Daily Load (TMDL) Program to improve water quality in impaired or threatened water bodies in Texas. The TMDL program includes the followings:

1) determination of the maximum loadings of a pollutant that a water body can receive and still attain and maintain its water quality standards
2) allocation of this allowable loading to point and non-point source categories in the watershed

TMDL defines an environmental target by determining the extent to which a certain pollutant must be reduced. There are many projects of the TMDL program and databases of the projects are opened at TCEQ website (http://www.tceq.state.tx.us).

There are many research studies about salinity control in water resources management (Franson and Lopez 1984; Jonez 1984; McCrory 1984; Riding 1984). These studies include the following salinity control plans: (1) reuse of saline water, (2) planning and constructing required subsurface and surface drainage facilities for intercepting saline water, (3) irrigation source control by improving irrigation practices to reduce salt pickups, (4) disposal by means of injection well. However, these plans were definitely projected by considering the circumstance of each river basin. Appropriate salinity control plans should consider the characteristics of different river basin of interest. The typical salinity control problems are the conflicting interest of the upstream and downstream water users, the competing water users, and conflicting water users in the river basin. These problems are mainly based on the assessment of the water and the salinity mitigation and control costs (Karama 1993).

2.2 Water Quality Considerations in Reservoir System Analysis Models

Most water quality models perform the prediction of water pollution using mathematical simulation techniques. Also, many of these models are used to support planning and management including tracking of pollutants in surface water or groundwater and control of treatment of wastewater discharges.

2.2.1 QUAL2E (The Enhanced Stream Water Quality Model)

Enhanced Stream Water Quality Models (QUAL2E) (Brown et al. 1987) can model the movement of conservative and non-conservative substances such as pesticides and salinity. The model uses a finite difference solution to the one-dimensional longitudinal advective-dispersive mass transport and reaction equation. 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. However, even though this model can be used to biologically sensitive systems, it might be best suited for evaluating mean monthly salt loads and discharges (Ganze 1990).

2.2.2 WASP (Water Quality Analysis Simulation Program)

The Water Quality Analysis Simulation Program (WASP) is a generalized compartment modeling framework for simulating water quality and contaminant fate and transport in surface waters. This program can be used to interpret and predict water quality for analyzing a wide variety of pollution in almost any type of water body. Time series of Advection-dispersion, point and diffuse mass loading, and boundary exchanges can be represent in this program. Water quality processes are modeled in special kinetic subroutines that are either selected form a library or supplied by the user. WASP consists of two stand-alone computer programs. DYNHYD and WASP, that can be run in conjunction or separately. The hydrodynamics program DYNHYD simulates the movement of water. The water quality program WASP models the movement and interaction of pollutants within the water. EUTRO and TOXI are sub-models which can be incorporated into the water quality program (Ambrose 1988).

WASP7 is recently upgraded version. (Ambrose et al. 2006). WASP7 includes various variables: ammonia, nitrate, orthophosphate, phytoplankton, detrital carbon, detrital nitrogen, detrital phosphorous, dissolved oxygen, dissolved organic nitrogen, dissolved organic phosphorous, salinity, and inorganic solids. WASP calculates mass leaving and determines boundaries to user specified flow paths, user specified dispersion paths, and read from hydrodynamic interface file. Also, users should supply initial concentration of algal biomass and cell nitrogen and phosphorous content by segment. A new spatially variable parameter in WASP7 represents the fraction of bottom area suitable for growth. Loading originates from atmospheric deposition, groundwater infiltration, municipal, industrial discharge and watershed runoff and erosion. The results can be analyzed by steady, seasonal, monthly, daily and hourly intervals.

2.2.3 MIKE BASIN

MIKE BASIN (Danish Hydrologic Institute) was developed at the Danish Hydraulic Institute for addressing various river basin issues such as water allocation, reservoir operation, water quality issues, conjunctive use and . It is coupled with a GIS based environment and is a powerful tool for comprehensive hydrologic modeling to provide basin scale solutions. MIKE BASIN provides a network model where river stems represent individual stream section. Also, confluences, diversion, reservoir, and water users can be provided by the nodes. MIKE BASIM assumes purely advective transport for water quality solution and the groundwater description uses the linear reservoir equation.

2.2.4 SWMM (Storm Water Management Model)

The original version of the Storm Water Management Model (SWMM) was developed as a single-event model specifically for the analysis of combined sewer overflows, but its scope has vastly broadened since the original release (Huber et al. 1986). Version 4 of the model performs both continuous and single event simulation throughout the whole model, can simulate backwater, surcharging, pressure flow, and water quality. The current edition, Version 5, is a complete re-write of the previous version. SWMM 5 is operated under Windows and provides an integrated environment for editing input data of study area, running hydrologic, hydraulic and water quality simulations (EPA). SWMM can estimate pollutant loads connected to runoff. The following processes can be modeled for any number of water quality constituents:

- dry-weather pollutant buildup over different land uses
- pollutant washoff from specific land uses during storm events
- direct contribution of rainfall deposition
- reduction in dry-weather buildup due to street cleaning
- reduction in washoff load due to BMPs
- entry of dry weather sanitary flows and user-specified external inflows at any point in the drainage system
- routing of water quality constituents through the drainage system
- reduction in constituent concentration through treatment in storage units or by natural processes in pipes and channels

Huber et al (1986) presented a bibliography of SWMM usage and provided many references of case studies. SWMM software can be downloaded at EPA website (http://www.epa.gov/ednnrmrl/models/swmm/).

2.2.5 RiverWare

RiverWare is a generalized tool for reservoir and river basin simulation. RiverWare provides streamflow inflows routing of a river/reservoir system based on hydrologic information. River system nodes are input data included in watershed runoff.

The main process depends on volume mass balance; reservoir, river reaches based on hydrologic routing, evaporation, diversion, return flows and other losses. The model can also be combined with a groundwater model and electric power generation. RiverWare is a customizable modeling environment in which the user creates a basin network model and selects appropriate methods for simulating the physical processes on each basin feature. Operating policies are expressed via rules that are interpreted during the simulation process. Its user-friendly interface and data processing and graphical output utilities simplify communicating technical information to stakeholders. RiverWare simulates water quality along with water quantity processes. Also, temperature, total dissolved solids (TDS), and dissolved oxygen in reservoirs and reaches can be simulated within RiverWare. TDS concentration is simulated based on water quantity constituents such as inflow, diversion, and return flow in the reservoir. There are three options of reservoir mixing models; a simple, well-mixed reservoir or a two-layered reservoir model (Zagona et al. 2001).

2.2.6 MODSIM

MODSIM is a generalized river basin network simulation model for hydrologic and water rights analyses of complex water management systems. The recent version, MODSIM-DSS (Decision Support System) was designed specifically to meet the growing demands and pressure on river basin management. Water is allocated based on user-specified priorities. The user assigns relative priorities for meeting diversion, instream flow, and storage target, as well as lower and upper bounds on flows and storages. The model computes values for all flows and storage.

Originally, MODSIM was conceived in 1978 at Colorado State University based on modifying and updating the Texas Water Development Board SYMYLD-II model (Wurbs and U.S. Army Engineer Institute for Water Resources. 1994). MODSIM is designed for developing basin-wide strategies for short-term water management, long-term operational planning, drought contingency planning, water rights analysis and resolving conflicts between urban, agricultural, and environmental concern (Shafer and Labadie 1978).

Upgraded version, MODSIM-DSS is developed under the MS.NET Framework and is comprised entirely of native code written in MS Visual C++.NET (Labadie 2005). This program provides a graphical user interface (GUI) system allowing users to create any river basin system topology. Data structures included in each model object are controlled by a data base management system.

2.2.7 IQQM (Integrated Quantity/Quality Model)

A generic integrated water quantity and quality simulation model (IQQM) was developed at the New South Wales Department of Land Water Conservation (DLWC) to provide water managers with an analysis tool for water quantity and water quality management. In IQQM, river systems are simulated by a series of nodes connected by links. The model comprises of a number of modules which includes an instream water quantity module, an instream water quality module and rainfall-runoff modules. Water quality module in IQQM is based on QUAL2E program (Brown et al. 1987). Temperature, arbitrary conservative and non-conservative constituents, biochemical oxygen demand, coliforms, nitrogen, phosphorus algae could be simulated by water quality module. In order to trace the conservative solutes, IQQM uses a volumetric routing procedure based on the assumption that flows are fully mixed (Metcalf & Eddy Boston. 1972). IQQM can be applied to a complex river basin system with numerous reservoir as well as simple river basin systems without dams. The model operates at a daily time steps, however, some processes can be simulated at hourly time steps.

2.2.8 HEC-5

The HEC-5 was developed at the Hydrologic Engineering Center by Bill S. Eichert (USACE 1998). An initial version released in 1973 has been subsequently expanded to include operation for conservation purposes and for period-of-record routings. HEC-5Q is the expanded version of HEC-5. HEC-5Q analyzes water flows and water quality in reservoirs with downstream river reaches. The model operates regulating outflows through gates and turbines and vertical temperature gradients in reservoir. The water quality module uses system flows generated by the flow module and computes the vertical distribution of temperature and other constituents in the reservoirs and the water quality in the associated downstream reaches. The water quality module also includes an option for selecting the gate opening for reservoir selective withdrawal structures to meet user-specified water quality objectives at downstream control points (Wurbs and U.S. Army Engineer Institute for Water Resources. 1994).

The decision criteria are programmed to consider flood control, hydropower, instream flow, and water quality requirements. HEC-5 can simulate a reservoir system of up to ten reservoirs and up to thirty control points.

HEC-5Q can simulate up to 3 conservative constituents, and non-conservative constitutes with restriction, and dissolved oxygen. Various constituents such as Water temperature, total dissolved solids (TDS), nitrate nitrogen, phosphate phosphorus, phytoplankton, carbonaceous BOD, ammonia nitrogen, and dissolve oxygen can be simulated by HEC-5Q.

CHAPTER III

RESERVOIRS AND NATURAL SALT POLLUTION IN THE BRAZOS RIVER BASIN

3.1 Brazos River Basin

The Brazos River Basin shown in Figure 3.1 forms a continuous watershed 1,050 miles long, which extends from New Mexico to the Gulf of Mexico and comprises 44,620 square miles, 42,000 of which are in Texas. It is the longest river in Texas and the one with the greatest discharge (Hendrickson 2006). The Brazos River Basin extends from eastern New Mexico southeasterly across Texas to the Gulf of Mexico. The basin area is abut 16% of the land are in Texas. Figure 3.1 represents the Brazos River Basin map. The upper watershed tributaries of the Brazos River originating in the High Plains and Caprock Escarpment area of Texas are salty intermittent streams. The main stem Brazos River begins at the confluence of the Salt Fork and Double Mountain Fork and flows in a meandering path approximately 923 miles to the Gulf of Mexico at the city of Freeport. Possum Kingdom, Granbury, and Whitney Reservoirs are located on the main stem. Detailed information of the Brazos River Basin are provided by the Texas Department of Water Resources (TDWR 1984) and the U.S. Army Corps of Engineering (USACE 1977).

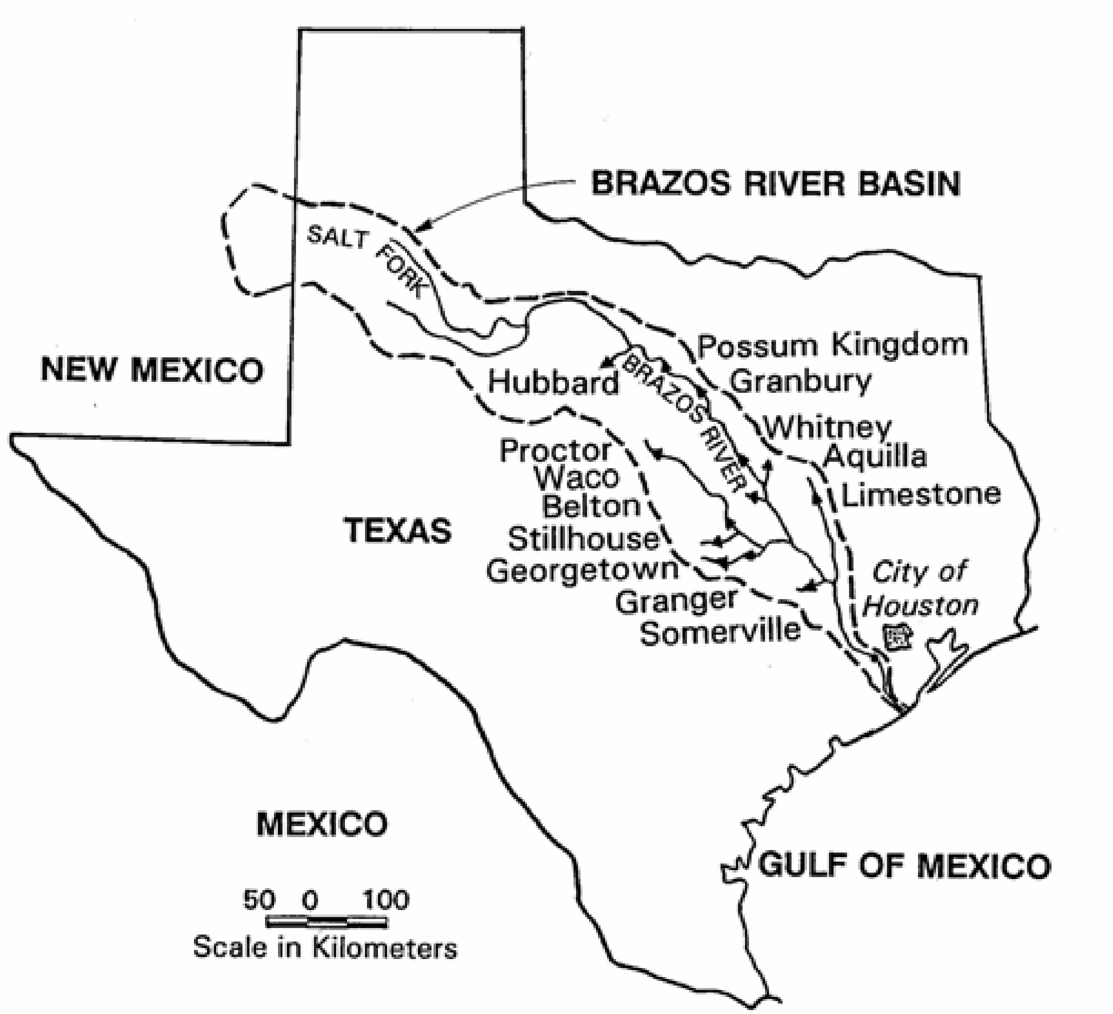

Figure 3.1 Brazos River Basin with Hubbard Reservoir and 12 BRA Reservoirs

3.2 Reservoirs in the Brazos River Basin

Reservoirs in Texas vary tremendously in size. Several hundred thousand natural lakes, farm and stock ponds, flood retarding and stormwater detention structures, recreation lakes, and small water supply reservoirs vary in size from less than an acre-feet to 5,000 acre-feet (Wurbs et al. 1985). There are 196 major reservoirs in Texas with storage capacities of at least 5,000 acre-feet and about 3,500 other smaller reservoirs with storage capacities ranging between 200 and 5,000 acre-feet.

The Brazos River Basin has 43 major reservoirs with storage capacities of at least 5,000 acre-feet and several hundred other smaller reservoirs with storage capacities ranging between 200 and 5,000 acre-feet. Possum Kingdom Lake has the largest conservation storage capacity in the Brazos River Basin, and Lake Whitney has the second largest conservation storage capacity. Considering the combined total of both flood control and conservation storage capacity, Lake Whitney is the largest reservoir in the Brazos River Basin and the seventh largest reservoir in Texas. Lakes Whitney, Granbury, and Possum Kingdom are the only major reservoirs on the main stream of the Brazos River. The multiple-purpose Whitney Reservoir is a component of the federal nine-reservoir system operated by the Fort Worth District of the U.S. Army Corps of Engineers (USACE) for flood control. Whitney Reservoir is also a component of the multiple-reservoir system operated by the BRA for water supply that includes the nine USACE reservoirs and three other non-federal reservoirs. Possum Kingdom and Granbury Reservoirs are non-federal conservation storage projects owned and operated by the Brazos River Authority.

Pertinent data for these three reservoirs are tabulated in Table 3.1 and Table 3.2 and their locations are presented on the Figure 3.1. Also, the information of these three reservoirs is provided by 3.2.1 through 3.2.3.

Table 3.1 Possum Kingdom, Granbury, and Whitney Reservoirs on the Brazos River

Name of Reservoir	Name of Dam	Initial Impoundment Date	Permitted Storage (acre-feet)	Permitted Diversions (ac-ft/yr)	WAM 1988-1997 Diversions (acre-feet/year)
Possum Kingdom	Morris Sheppard	March 1941	724,739	230,750	57,483
Granbury	De Cordova Bend	September 1970	155,000	64,712	36,025
Whitney	Whitney	December 1951	50,000	18,336	18,336

Table 3.2 Reservoir Storage Capacity

Reservoir	Initial Storage Date	Sediment Survey Update	Inactive Pool (acre-feet)	Top of Conservation Pool			Flood Control (acre-feet)
				Original (acre-feet)	Surveyed (acre-feet)	WAM 2000 (acre-feet)	
PK	1941	1974	221,000	724,740	570,240	552,010	−0−
Granbury	1970	−	52,500	153,490	−	132,820	−0−
Whitney	1951	1959	379,100	642,180	627,100	549,790	1,372,400

The Brazos River Authority (BRA) holds water right permits to store and divert the amounts of water noted in Table 3.1 for municipal, industrial, and agricultural uses. The Brazos River Authority water right permits provide flexibility for multiple-reservoir and multiple-purpose reservoir/river system operations. The majority of the water released from these three reservoirs for water supply purposes is diverted from the lower reaches of the Brazos River many miles below Whitney Dam for use in the lower Brazos River Basin and adjoining San Jacinto-Brazos Coastal Basin. Actual water use is typically significantly less than permitted diversion amounts. The last column of Table 3.1 shows the diversion amounts associated with the water rights attached to each reservoir included in the TCEQ WAM System current use scenario dataset, which reflects the maximum actual use in any year during the ten-year period 1988-1977.

Storage capacity data for Lakes Possum Kingdom, Granbury, and Whitney are shown in Table 3.2. Inactive pools at Lake Whitney and Possum Kingdom provide dead storage for hydropower. The inactive pool at Lake Granbury is set to accommodate lakeside withdrawals of cooling water for a steam-electric power plant. Reservoir storage capacity is lost over time due to sedimentation. The total storage capacity below the top of conservation pool elevation at the completion of construction (date of initial impoundment) is shown in the fifth column of Table 3.2. Sediment surveys of Lake Possum Kingdom and Whitney in 1974 and 1959 resulted in the revised storage capacity estimates in the sixth column. The TCEQ WAM System current use dataset includes approximate estimates of storage capacities of all major reservoirs as of the year 2000. These capacity estimates for the Brazos River reservoirs are also included in Table 3.2.

3.2.1 Lake Possum Kingdom

Possum Kingdom Reservoir is on the Brazos River in Palo Pinto, Stephens, Jack, and Young counties. It has a capacity of 724,739 acre-feet, a surface area of 19,800 acres, and a shoreline of 310 miles. Morris Sheppard Dam impounds 1,500,000 acre-feet of water annually for municipal, industrial, mining, irrigation, flood control, recreational, and power-generation uses (Dowell et al. 1971). Hydroelectric power is generated at Possum Kingdom and Whitney Reservoirs. The southwest Poser Administration is responsible for marketing hydroelectric power generated at Lake Whitney, which it sells to the Brazos Electric Power cooperative. The Brazos River Authority sells the power generated at Possum Kingdom also to the Brazos Electric Power cooperative. No water rights exist specifically for hydropower at the two Brazos River reservoir/hydropower projects. Hydropower is generated by excess flow (spills) and releases for downstream water supply diversions.

3.2.2 Lake Whitney

Whitney Reservoir is in the Brazos River Basin two miles from Whitney on the western edge of Hill County on the Bosque county line. The reservoir, which supplies water for municipal purposes, irrigation, and power production, is owned by the United States Government and operated by the United States Corps of Engineers, Fort Worth District. It has a capacity of 379,100 acre-feet and a surface area of 23,500 acres. Storage capacity for flood control is 1,372,400 acre-feet between elevations of 520 and 571 feet above mean sea level. The drainage area above the dam is 17,620 square miles (Dowell et al. 1971). The Corps of Engineers operates the 1,372,400 acre-feet flood control pool of Lake Whitney as a component of the system of nine federal flood control reservoirs to reduce downstream flooding. The flood control pool is emptied as quickly as feasible after flood events while not contributing flows exceeding specified non-damaging levels at downstream gaging stations. The bottom of the flood control pool is the top of the conservation pool. Flood control operations are in effect whenever the lake water surface rises above the top of conservation pool elevation.

3.2.3 Lake Granbury

Lake Granbury is located on the Brazos River and extends through much of the eastern half of Hood County. The Brazos River Authority proposed construction of a dam on the Brazos River in Hood County in the late 1950s. Impoundment of water began on September 15, 1969. Lake Granbury has a total capacity of 153,490 acre-feet and 103 miles of shoreline (Dowell et al. 1971).

3.3 Natural Salt Pollution in the Brazos River Basin

3.3.1 Sources of Natural Salt Pollution

Salts consisting largely of sodium chloride with moderate amounts of calcium sulfate and other dissolved solids contaminant surface waters in the Brazos River Basin. Salinity concentrations vary widely from one stream to another, from location to location on the same stream, and from time to time at any specified location. Geologic factors, runoff and stremflow characteristics, and activities of man largely determine the nature and amount of salinity transported by the Brazos River and its tributaries (Rawson et al. 1967). Geological formations in the Permian Basin geologic region are the primary source of the salinity and Figure 3.2 represents major rivers affected by Permian Basin salt. Salt springs and seeps and salt flats in the upper watersheds of the Brazos, Colorado, Pecos, Red, Canadian, and Arkansas Rivers contribute large salt loads to there river.

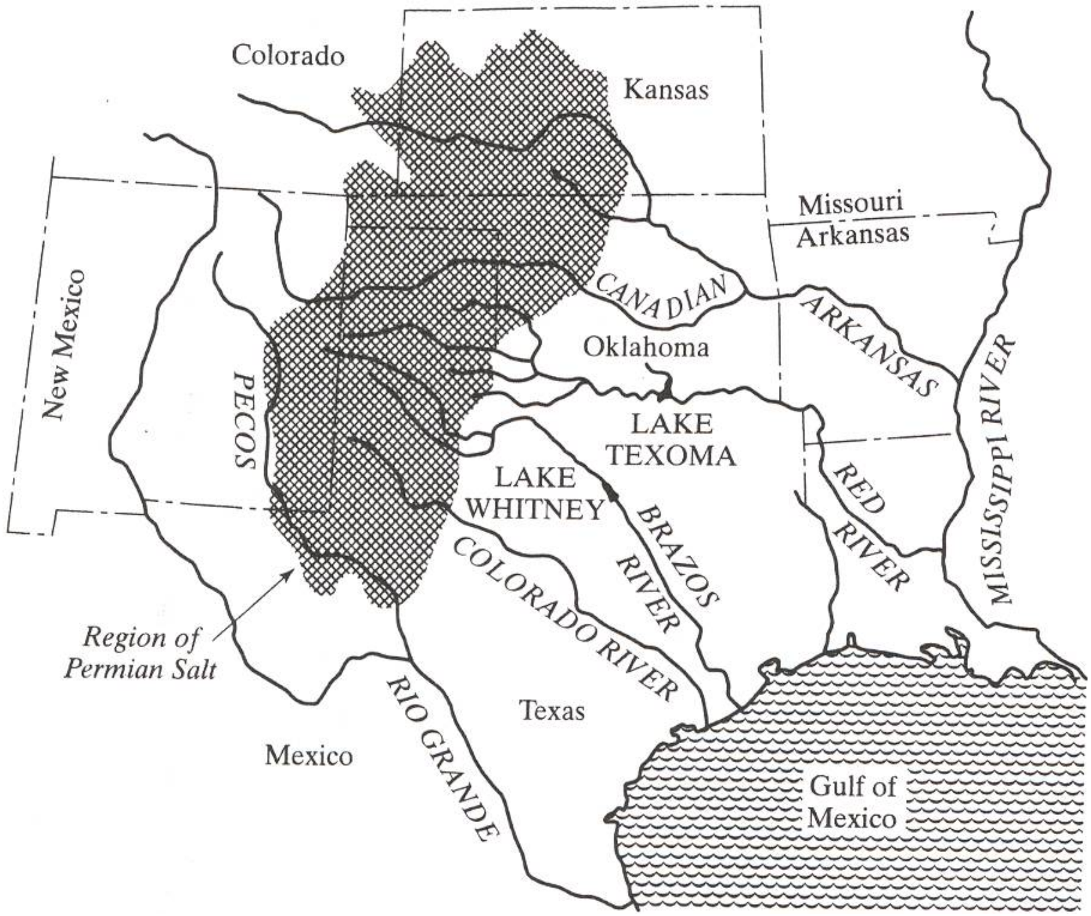

Figure 3.2 Major Rivers Affected by Permian Basin Salt

The upper Brazos River consists of three main branches, the Salt Fork, the Double Mountain For, and the Clear Fork. The salts of natural origin in the Salt Fork upstream from Peacock are produced from sources that may be classified as either diffuses or point. Diffuses natural sources are characterized by salt accretions from large drainage streams that flow from a small area. Point sources include seeps or springs and highly mineralized streams that flow from a small area. Salt Fork Brazos River, McDonald Creek, Verbena Canyon, Red Mud Creek, Duck Creek, Salt Creek, Croton Creek, Salt Croton Creek, Stinking Creek, North Croton Creek, Double Mountain Fork

Brazos River, and Clear Fork Brazos River are known as the sources of salt found in the upper Brazos River Basin. The detailed descriptions of there sources area are provided by the U.S. Army Corps of Engineering (USACE 1977).

3.3.2 Dataset from USACE/USGS Natural Salt Pollution Studies

The Fort Worth District (FWD) of the U.S. Army Corps of Engineers (USACE) in collaboration with the U.S. Geological Survey (USGS), U.S. Environmental Protection Agency (USEPA), and other agencies conducted extensive Brazos River Basin natural salt pollution studies during the 1960's-1980's (Wurbs 2002). The USGS conducted an extensive water quality data collection program from October 1963 through September 1986 in support of USACE salt pollution control studies. The USACE-sponsored USGS salinity measurement program was discontinued in 1986. The USACE later contracted with Texas A&M University to compile the USGS salinity data in a more conveniently usable format and to perform various analyses (Wurbs et al. 1993).

USGS water quality sampling activities in the Brazos River Basin date back to 1906 and continue to the present. However, the salinity data collection program during October 1963 through September 1986 was much more extensive than salinity measurement activities before or since. A total of 39 stations in the basin have monthly salinity data for at least three years during 1964-1986. The 26 stations listed Table 3.3 and Table 3.4 with locations shown in Figure 3.3 were selected for the compilation and analyses of Wurbs et al. (Wurbs et al. 1993) because of their record length and pertinent locations. The water quality measurements occurred at or near stream flow gaging stations included in the regular USGS stream flow data collection program. The USGS continues to measure flow rates at most of the gaging stations even though water quality measurements ended in 1986.

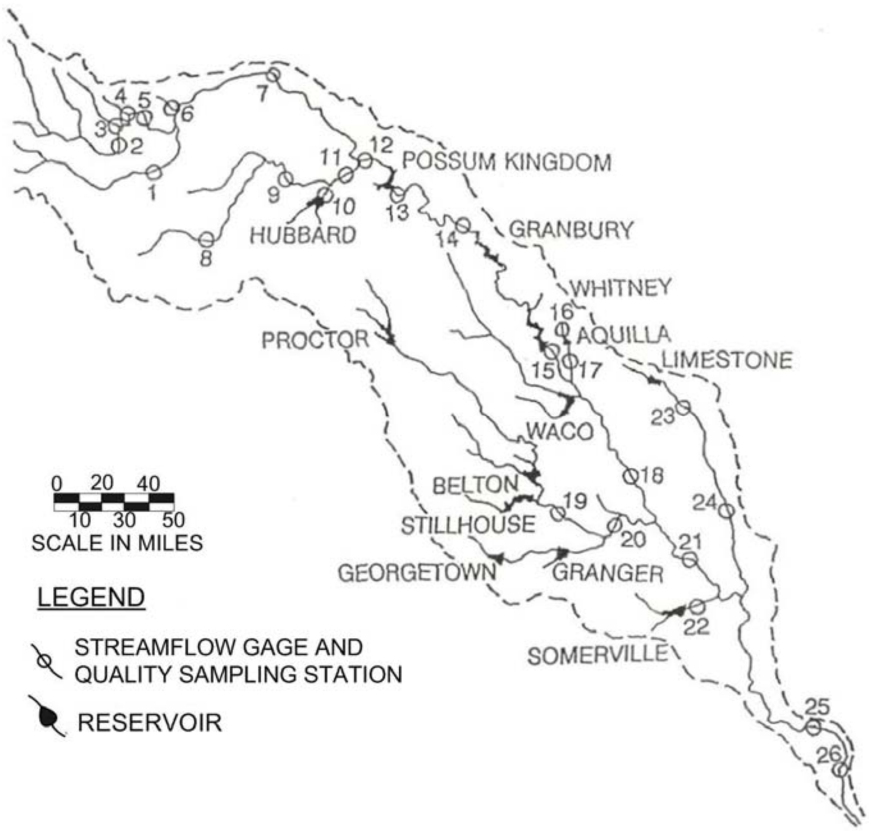

Figure 3.3 USGS Stream Flow and Water Quality Stations (Wurbs et al. 1993)

The USGS aggregated daily flow and concentration observation into mean monthly flows and monthly concentrations and loads of total dissolved solids (TDS), chloride, and sulfate. Chloride and sulfate are major constituents of total dissolved solids (salinity) in the Brazos River. Discharged and salt loads are cited by the USGS in units of cubic feet second (cfs) and tons/day, respectively.

Table 3.3 USGS Stream Flow Gaging and Water Quality Sampling Stations (Wurbs et al. 1993)

Map No.	Station Number	Station Name (nearest town)	Stream	Drainage Area (mile^2)	Period-of Record
1	08080500	Aspermont	Double Mountain Fork	8,796	1964-86
2	08081000	Peacock	Salt Fork of Brazos	4,619	1965-86
3	08081200	Jayton	Croton Creek	290	1966-86
4	08081500	Aspermont	Salt Croton Creek	64	1969-77
5	08082000	Aspermont	Salt Fork of Brazos	5,130	1964-82
6	08082180	Knox City	North Croton Creek	251	1966-86
7	08082500	Seymour	Brazos River	15,538	1964-86
8	08083240	Hawley	Clear Fork of Brazos	1,416	1968-79,82-84
9	08085500	Fort Griffin	Clear Fork of Brazos	3,988	1968-76,79,82-84
10	08086500	Breckenridge	Hubbard Creek	1,089	1968-75
11	08087300	Eliasville	Clear Fork of Brazos	5,697	1964-82
12	08088000	South Bend	Brazos River	22,673	1978-81
13	08088600	Graford	Brazos River	23,596	1964-86
14	08090800	Dennis	Brazos River	25,237	1971-86
15	08092600	Whitney	Brazos River	27,189	1964-86
16	08093360	Aquilla	Aquilla Creek	255	1980-82
17	08093500	Aquilla	Aquilla Creek	308	1968-81
18	08098290	Highbank	Brazos River	30,436	1968-79,81-86
19	08104500	Little River	Little River	5,228	1965-73,80-86
20	08106500	Cameron	Little River	7,065	1964-86
21	08109500	College Station	Brazos River	39,599	1967-83
22	08110000	Somerville	Yegua Creek	1,009	1964-66
23	08110325	Groesbeck	Navasota River	239	1968-86
24	08111000	Bryan	Navasota River	1,454	1964-81
25	08114000	Richmond	Brazos River	45,007	1964-86
26	08116650	Rosharon	Brazos River	45,339	1969-80

Table 3.4 Period-of-Record Mean Discharge and Salt Loads and Concentrations

	USGS Gaging Station (nearest town, stream)	Flow (cfs)	Load (tons/day) TDS	Chloride	Sulfate	Concentration (mg/l) TDS	Chloride	Sulfate
1	Aspermont, Double Mountain	126	580	153	209	1,540	416	548
2	Peacock, Salt Fork Brazos	40	684	339	81	5,782	2,830	698
3	Jayton, Croton Creek	13	225	93	53	6,391	2,541	1,591
4	Aspermont, Salt Croton Cr	4	676	425	33	56,923	32,856	2,273
5	Aspermont, Salt Fork	60	1,660	1,094	219	12,407	6,066	1,235
6	Knox City, North Croton Cr	17	211	80	58	4,723	1,786	1,323
7	Seymour, Brazos River	269	2,601	1,074	504	3,591	1,482	696
8	Hawley, Clear Fork Brazos	46	235	51	94	1,893	411	759
9	Fort Griffin, Clear Fork	151	391	105	116	961	258	286
10	Breckenridge, Hubbard Cr	93	73	25	4	268	91	20
11	Eliasville, Clear Fork Brazos	319	614	201	148	715	234	172
12	South Bend, Brazos River	760	2,601	996	561	1,261	486	274
13	Graford, Brazos River	712	2,947	1,127	571	1,534	601	309
14	Dennis, Brazos River	892	3,103	1,205	622	1,291	501	259
15	Whitney, Brazos River	1,230	3,075	1,134	591	928	342	178
16	Aquilla, Aquilla Creek	55	35	2	10	236	14	69
17	Aquilla, Aquilla Creek	147	102	6	29	257	14	73
18	Highbank, Brazos River	2,530	4,154	1,287	772	609	189	113
19	Little River, Little River	912	768	79	61	313	32	25
20	Cameron, Little River	1,544	1,094	129	126	256	31	30
21	College Station, Brazos	4,529	5,348	1,368	938	438	112	77
22	Somerville, Yequa Creek	252	114	20	33	167	30	48
23	Groesbeck, Navasota River	161	56	9	6	131	22	13
24	Bryan, Navasota River	600	232	61	38	144	38	23
25	Richmond, Brazos River	6,868	6,267	1,466	1,030	339	79	56
26	Rosharon, Brazos River	7,305	6,462	1,491	1,004	328	76	51

Monthly discharges and loads cited in this dissertation in acre-feet/month and tons/month are based on summations of daily amounts. Salt concentrations are cited in units of milligrams of salt solute per liter of water (mg/l). Assuming a liter of water has a mass of one kilogram, the units mg/l and parts of salt solute per million parts of water (ppm) are equivalent.

CHAPTER IV

DEVELOPMENT OF SALINITY BUDGET FOR THE BRAZOS RIVER

4.1 Salinity Budget Study for the Brazos River/Reservoir System

The objectives for developing and analyzing river flow and reservoir storage volume budgets, total dissolved solids (TDS) load budgets, and associated TDS concentrations are to:

1. Develop an understanding of the magnitude, timing, variability, and other characteristics of salinity moving through the river/reservoir system.
2. Develop a salinity input dataset for use in applying WRAP-SALT in assessing water supply capabilities for the Brazos River Authority reservoir system.

This research directly provides insight regarding the physical processes of salinity being transported through the river/reservoir system. For each of the river reaches, the volume and load budgets were developed for each month of the October 1963 through September 1986 period-of-analysis of:

- flow volumes and TDS loads entering the reach during the month
- flow volumes and TDS loads leaving the reach during the month
- volumes and TDS loads in reservoir storage at the end of each month

Concentrations are computed for given loads and volumes. Some components of the volume and load budget inflows and outflows consist of observed data. Estimates for other components are computed form available data based on formulating reasonable assumptions and premises. Computation of TDS loads and volume-weighted mean TDS concentrations of the water stored in the three reservoirs is a key aspect of the analyses.

4.2 River Reaches and Gaging Stations

The five reaches of the Brazos River adopted for the water and salinity budget study are defined by the USGS stream flow gaging and/or water quality stations listed in Table 3.3 with locations shown in Figure 3.3. The most upstream reach defined by the Seymour and South Bend gages lies between the primary salt source watersheds and the most upstream reservoir. Three of the other four reaches contain Lakes Possum Kingdom, Granbury, and Whitney, respectively.

The six USGS gaging stations defining the five river reaches are listed in Table 4.1. The USGS salinity dataset includes monthly flows as well as monthly loads and concentrations. The monthly flows from the salinity dataset are used in the analyses. Although the salinity data collection program was terminated in 1986, stream flow data continued to be collected at five of the gages. The flow gaging stations near the towns of Seymour, South Bend, Graford, and Dennis also served as water quality stations during the USACE-sponsored USGS salinity data collection program. The flow gage near Glen Rose was not included in the salinity data collection program. Although another stream flow gage is located nearby, gage 08092600 near the City of Whitey below Whitney Dam was used to collect flow and salinity data during the 1964-1986 salinity program but was not continued as a regular flow gage.

Table 4.1 Gaging Stations Defining Volume and Load Balance Reaches

Station	Fig. 3.3	USGS Number	WAM CP ID	Flow-Only Gage Record	Salinity and Flow	River Mile	Drainage Area ($mile^2$) Total	Contrib	Increm
Seymour	7	08082500	BRSE11	1923-present	1964-86	847	15,538	5,972	5,972
South Bend	12	08088000	BRSB23	1938-present	1978-81	687	22,673	13,107	13,107
Graford at PK	13	08088600	SHGR26	1976-present	1964-86	614	23,596	14,030	923
Dennis	14	08090800	BRDE29	1968-present	1971-86	571	25,237	15,671	1,641
Glen Rose	−	08091000	BRGR30	1923-present	none	524	25,818	16,252	581
Whitney	15	08092600	−	−	1964-86	442	27,189	17,623	1,371

The portion of the Brazos River Basin shown in Figure 4.1 includes the reach of the Brazos River extending from the Seymour gage at river mile 847 downstream to the Whitney gage at river mile 442 above the Gulf of Mexico. The Seymour gage is about 76 miles below the origin of the main-stem Brazos River at the confluence of the Salt For and Double Mountain Fork. The river miles in Table 4.1 are measured from the river's mouth at the Gulf of Mexico. The river miles of the Whitney and Graford gages are from USGS studies. The river miles for the other four gages were estimated in the present study from GIS maps available from the WAM System dataset. Drainage areas are from published USGS data. A 9,566 square mile flat arid portion of the river basin in and near New Mexico is considered by the USGS to no contribute to flows in the Brazos River.

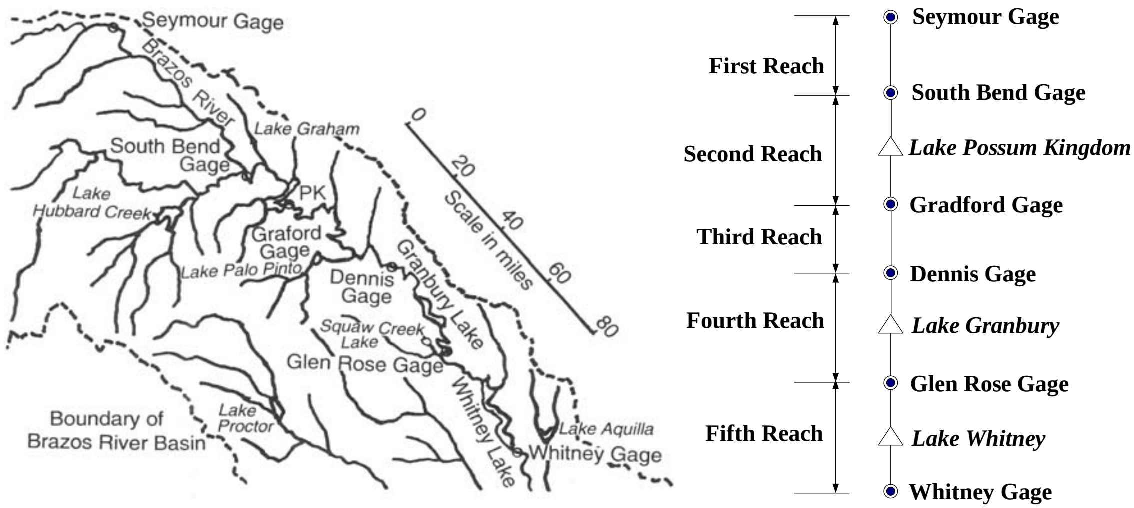

Figure 4.1 Map and Schematic of Volume and Load Balance Reaches and Vicinity

Table 4.2 Availability of Observed Monthly Stream Flows, Storage, and Salinity Data

Gage or Lake	Volume Observations	Salinity Observations
Seymour Gage	Oct 1963 − Sep 1986	Oct 1963 − Sep 1986
South Bend Gage above Lake Possum Kingdom	Oct 1963 − Sep 1986	Nov 1977 − Sep 1981
Graford Gage below Lake Possum Kingdom	Oct 1963 − Sep 1986	Oct 1963 − Sep 1986
Dennis Gage above Lake Granbury	Jun 1968 − Sep 1986	Oct 1970 − Sep 1986
Glen Rose Gage between Granbury & Whitney	Oct 1963 − Sep 1986	−
Whitney Gage below Lake Whitney	Oct 1963 − Sep 1986	Oct 1963 − Sep 1986
Lake Possum Kingdom	Oct 1963 − Sep 1986	−
Lake Granbury	Oct 1963 − Sep 1986	−
Lake Whitney	Oct 1963 − Sep 1986	−

Table 4.2 represents availability of observed monthly stream flows, storage, and salinity data for each of the five river reaches and three reservoirs. The salinity observations cover the complete period-of-analysis at the Seymour, Graford, and Whitney gages and portions of the period-of-analysis at the South Bend gage. Observed data were used where available. Additional data were synthesized as required to develop

complete sequences of flows and loads at all of the gages and end-of-month storage loads for the three reservoirs.

4.3 Water and Salinity Balance Relationships

The water and salt budgets are based on the following relationships which are valid for each of the 276 individual months or the overall 23 year period-of-analysis. The mass balance equation 4.1 is used for routing streamflows through the reservoir as follows:

$$S_t = S_{t-1} + I - O - E +/- F_{other} \tag{4.1}$$

where

S_t = storage at the end of the current month (ac-ft)

S_{t-1} = storage at the end of the previous month (ac-ft)

I = inflow volume during the month (ac-ft)

O = outflow volume during the month (ac-ft)

E = net evaporation during the month (ac-ft)

F_{other} = other gains or losses during the month (ac-ft)

The equation for load balance follows the same concept as the mass balance equation for streamflows. The load balance equation is as follows:

$$L_{S(t)} = L_{S(t-1)} + L_I - L_O +/- L_{Diff} \tag{4.2}$$

where

$L_{S(t-1)}$ = salt loads in reservoir storage at the end of the current month (tons)

$L_{S(t)}$ = salt loads in reservoir storage at the end of the previous month (tons)

L_I = inflow loads during the month (tons)

L_O = outflow loads during the month (tons)

L_{Diff} = load difference (tons)

The concentration and salt loads are computed as follows:

$$C = \frac{L}{V}F \tag{4.3}$$

where,

C = salt concentration (mg/l)

L = salt loads (tons)

V = streamflows or storage (ac-ft)

F = conversion factor

Acre-feet, tons, and mg/l are the units adopted in this dissertation. With concentration in milligrams per liter (mg/l), load in tons, and volume in acre-feet, the conversion factor is 735.48 in the equation above. The conversion factor is derived as follows:

$$\frac{\text{tons}}{\text{ac-ft}}\,\frac{2{,}000\text{ pounds}}{\text{tons}}\,\frac{453\text{ g}}{\text{pound}}\,\frac{1{,}000\text{ mg}}{\text{gram}}\,\frac{\text{ac-ft}}{43{,}560\text{ ft}^3}\,\frac{\text{ft}^3}{28.316\text{ liters}} = \frac{\text{mg}}{\text{liter}}$$

4.4 Flow and Load Components

In this dissertation, the following notation is used to define the components of the volume and load budgets.

F = flow volume in acre-feet/month

L = loads in tons/months

C = concentration in milligrams/liter

Subscripts: US = upstream gage representing river inflow to reach

DS = downstream gage representing river outflow from reach

WS = water supply diversion

OI = other inflow volume and associated load entering reach

OO = other outflow volume and associated load leaving reach

X = other load required to balance load budget

EP = net evaporation less precipitation volume in acre-feet/month

S = storage volume in acre-feet

SL = loads in storage in tons

ΔS = change in storage volume during the month in acre-feet

ΔSL = change in loads in storage during the month in tons

Subscripts: B = storage at the beginning of month or period-of-analysis

E = storage at the end of month or period-of-analysis

The following inflow and outflow components are included in the volume budgets and salinity load budgets for each of the 276 months of the water year 1964-1986 period-of-analysis.

F_{US}: observed or synthesized flows at the upstream gage are the river flows into the reach

F_{DS}: observed or synthesized flows at the downstream gage are the river flows leaving the reach

EP: net evaporation from the water surface less precipitation falling on the water surface at reservoirs

F_{WS}: water supply diversions at Lake Granbury are the only recorded data adopted for lakeside withdrawals of water

F_{OI}: both F_{OO} and F_{OI} are computed together as the amounts required to balance volumes each month, with positive results for other flows in a particular month being adopted as F_{OI} and negative results as F_{OO}. Other inflows represent rainfall runoff from the local incremental watershed entering the reach between the upstream and downstream gages and subsurface base flow as well as possible effect of hydrograph timing and measurement inaccuracies

F_{OO}: other outflows are the negative values from a volume balance. F_{OO} represents water supply diversion, seepage, and other losses.

L_{US}: observed or synthesized loads at the upstream gage which are entering to the reach

L_{DS}: observed or synthesized loads at the downstream gage which are leaving the reach

L_{WS}: lads of water supply diversions at Lake Granbury. The Lake Granbury diversion loads are estimated based on estimated storage concentrations

L_{OI}: Loads associated with other inflow volumes F_{OI}

L_{OO}: Loads associated with other outflow volumes F_{OO}

L_X: L_X is the load required to balance the long-term 1964-1986 load budget. These other loads (L_X) represent inaccuracies in the other load budget terms and additional inflows and outflow not otherwise reflected in the other load budget terms. The total 1964-1986 L_X is computed as the load needed to zero-out the summation when all known loads are summed.

4.5 Volume and Load Budget Procedures

4.5.1 Reach from the Seymour Gage to the South Bend Gage

The most upstream of the five reaches of the Brazos River considered in the water and salinity balance analyses extends from the USGS gaging station near Seymour downstream to the USGS gaging station near South Bend which is located just upstream of Possum Kingdom Reservoir. A key objective of the water and salinity budget computations for this first reach is estimating missing loads at the South Bend gage which serve as the load inflows to the second reach containing Possum Kingdom Reservoir.

Seymour – South Bend Volume Budget

The volume budget is represented by the following equation which is applicable to each of the individual 276 months as well as to the overall 1964-1986 period-of-analysis.

South Bend flow = Seymour flow + other inflows – other outflows

$$F_{DS} = F_{US} + F_{OI} - F_{OO} \tag{4.4}$$

Complete monthly flow volume data for water years 1964-1986 are available from the USGS database for the Seymour and South Bend gages (F_{DS} and F_{US}). Other inflow (F_{OI}) and outflows (F_{OO}) are assigned based on balancing the above equation. The other inflows or outflows are the differences of F_{DS} minus F_{US} occurring each month. Incremental inflows may reflect subsurface base flow entering the river between the gages and precipitation runoff from the incremental local watershed. Incremental outflows may include water supply diversions, evapotranspiration, and seepage losses. In any month, the flow differences may be actually caused by a combination of both inflows and outflows along with storage effects and measurement inaccuracies. However, due to data limitations, other flows in each individual month are assigned as either other inflows (F_{OI}) if positive or other outflows (F_{OO}) if negative, with either F_{OI} or F_{OO} being zero and the other being either a positive quantity or possibly also zero.

The volume budget for the reach of the Brazos River between the Seymour and South Bend gages described above is very simple. The volume budget is reformulated slightly as outlined below to support the load budget computations in regard to extending the load record at the South Bend gage. The Eliasville gage is incorporated in the determination of other flows and loads entering or leaving the Brazos River between the Seymour and South Bend gages. The Eliasville gage on Hubbard Creek is labeled map number 11 in Figure 3.2 and Table 3.3. The refinement in determining other inflow and outflow volumes and loads is reflected in the following expanded volume budget representation.

South Bend flow = Seymour flow + Eliasville flow +or– incremental inflow or outflow

$$F_{South\ Bend} = F_{Seymour} + F_{Eliasville} \text{ +or– (Incremental inflow or outflow)} \quad (4.5)$$

where:

incremental inflow or outflow = $F_{South\ Bend} - F_{Seymour} - F_{Eliasville}$

If ($F_{Eliasville}$ + incremental inflow or outflow) is positive:

$F_{OI} = F_{Eliasville}$ + (incremental inflow or outflow)

$F_{OO} = 0.0$

If ($F_{Eliasville}$ + incremental inflow or outflow) is negative:

$F_{OI} = 0.0$

$F_{OO} = F_{Eliasville}$ + (incremental inflow or outflow)

<u>Seymour – South Bend Load Budget</u>

The load budget for the reach of the Brazos River from the Seymour gage to the South Bend gage was developed based on the following equation. The equation for the load budget follows the same concept of the volume budget computation.

South Bend load = Seymour load + other inflow load – other outflow load

$$L_{DS} = L_{US} + L_{OI} - L_{OO} \quad (4.6)$$

Flow and load data at the Eliasville gage are also used to estimate the other load (L_{OI} and L_{OO}) terms. The key aspect of the Seymour –to–South Bend volume and load budget computation is estimation of loads at South Bend for the missing portions of the 1964-1986 period-of-analysis. Table 4.3 represents the period of flow volume and load record for three gaging stations.

Table 4.3 Period of flow volume and load records for three gaging stations

Gage	Flow Volume and Record	TDS Load Record
Seymour	Oct 1963 – Sep 1986	Oct 1963 – Set 1986
Eliasville	Oct 1963 – Sep 1986	Oct 1963 – Sep 1982
South Bend	Oct 1963 – Sep 1986	Nov 1977 – Sep 1981

Observed TDS loads at the Eliasville gage cover the period October 1963 through September 1982. Loads at Eliasville for the missing period October 1982 through September 1986 were synthesized by a regression analysis with flow volumes at Eliasville. TDS loads at the South Bend gage for the period November 1977 through September 1981 are available in the USGS dataset. Loads for October 1963 through October 1977 and October 1981 through September 1986 are estimated as follows. In the equation 4.6, L_{OI} and L_{OO} are determined by combining loads at the Eliasville gage with incremental loads between the Eliasville, Seymour, and South Bend Gages as follows.

$$L_{incremental} = L_{South\ Bend} - L_{Eliasville} - L_{Seymour}$$

Incremental loads were determined for each month of the period November 1977 through September 1981 for which loads are available for the South Bend gage as well as for the Seymour and Eliasville gage. The incremental flows and loads between the Eliasville, Seymour, and South Bend gages for the 47 months during the period November 1977 through September 1981 were used to determine an inflow concentration and outflow concentration as follows. The 47 months were divided between months in which the computed incremental flow is positive (representing net inflows) versus negative (representing net outflows). Volume-weighted concentrations for each of these two groups of months were computed by dividing the total load by the total volume. The incremental flows were positive in 34 months. The flow volume-weighted mean TDS concentration during these 34 months was computed as 1,312 mg/l. The incremental flows were negative during 13 months. The volume-weighted mean concentration during these 13 months is 2,099 mg/l. The incremental load between the Eliasville, Seymour, and South Bend gages for each month of the periods October 1963 through October 1977 and October 1981 through September 1986 was computed as follows.

$$\text{If } F_{incremetnal} > 0 \qquad L_{incremental} = (1{,}312 \text{ mg/l})(F_{incremental})/(735.48)$$

$$\text{If } (F_{incremetnal} < 0 \qquad L_{incremental} = (2{,}099 \text{ mg/l})(F_{incremental})/(735.48)$$

$$\text{If } F_{incremetnal} = 0 \qquad L_{incremental} = 0.0$$

The other inflow load L_{OI} and other outflow load L_{OO} terms for each month of the 1964-1986 period-of-analysis were computed as follows.

$$L_{other} = L_{incremental} + L_{Eliasville}$$

$$\text{If } L_{other} > 0 \qquad L_{OI} = L_{other} \text{ and } L_{OO} = 0.0$$

$$\text{If } L_{other} < 0 \qquad L_{OO} = L_{other} \text{ and } L_{OI} = 0.0$$

4.5.2 Reach from the South Bend Gage to the Graford Gage

The water and salinity balance reach that contains Possum Kingdom Reservoir extends from the USGS gaging station near South Bend to the USGS gaging station near Graford. A key aspect of the load budget for this reach is a significant excess load represented by the term L_X and its distribution over the 1964-1986 period-of-analysis. Alternative methods for dealing with L_X are compared in Appendix A.

South Bend – Graford Volume Budget

The volume budget is represented by the following equation which is applicable to each of the individual 276 months as well as to the overall 1964-1986 period-of-analysis.

Δ Possum Kingdom storage = South Bend flow – Graford flow + other inflow – other outflow – net reservoir evaporation-precipitation

$$\Delta S = F_{US} - F_{DS} + F_{OI} - F_{OO} - EP \tag{4.7}$$

Monthly volumes are available from existing datasets for ΔS, F_{US}, F_{DS}, and EP. Other inflows (F_{OI}) and outflows (F_{OO}) are assigned based on balancing the above equation.

A complete 1964-1986 record of end-of-month storage volume of Possum Kingdom Reservoir is available from the USGS. However, the storage volume data are significantly affected by the 1974 sediment survey. Published observed storage volumes are derived by combining water surface managements with an elevation versus storage volume relationship, which as indicated in Table 3.2 changed significantly for Possum

Kingdom Lake in 1974. For purposes of the 734,400 acre-feet in March 1941 to 570,240 acre-feet in October 1973 to obtain a 14.8 percent decrease by September 1963. The Possum Kingdom storage volumes for October 1963 through September 1973 were adjusted by multiplying by a factor of 0.852. Net evaporation-precipitation volumes were obtained from the HDR work files (HDR 2001) associated with the WAM dataset. These monthly net evaporation-precipitation depths are also found in the TCEQ WAM System WRAP input dataset. The other inflow (F_{OI}) and outflow (F_{OO}) are computed from the equation 4.7. Thus, the water balance equation 4.6 is automatically balanced in each month. These computations completed the volume budget, with inflows, outflows, and storage changes summing to zero in each month.

South Bend – Graford Load Budget

The load budget for the South Bend to Graford reach was developed after completion of the volume budget. Upon completion of the load budget, computed Possum Kingdom Reservoir storage loads are combined with storage volumes from the volume budget to compute storage concentrations.

Δ Possum Kingdom storage load = South Bend load – Graford load + other inflow load – other outflow load + other load

$$\Delta SL = L_{US} - L_{DS} + L_{OI} - L_{OO} + L_X \quad (4.8)$$

Incremental flow volumes from the volume budget are used in estimating the incremental loads for the load budget. The other load term L_X in the load balance is the loads required to make the load budget balance. The other load L_X represents the net total of all other inflow and outflow loads not otherwise accounted for in the load budget and any inaccuracies in other terms.

The other inflow loads L_{OI} were determined by combining the F_{OI} from the volume budget with a constant concentration of 270 mg/l, adopted based on concentrations at gages with similar neighboring watersheds. Mean TDS concentrations at Breckenridge (Fig. 3.2 map number 10), Little River (map number 19), and Aquilla (map number 17) gages are 268 mg/l, 313 mg/l, and 257 mg/l. The other outflow loads L_{OO} associated with the other outflow F_{OO} from the volume budget were determined by combining the F_{OO} with the concentration of the downstream flows at the Graford gage each month.

The unknown concentrations of the water in storage in Possum Kingdom Reservoir at the beginning and the end of the 1964-1986 period-of-analysis were set based on the corresponding observed outflow concentrations. This is the storage concentration at the beginning of October 1963 and the end of September 1986. The October 1963 beginning concentration was set equal to the mean outflow concentration during the first 21 months beginning in October 1963. The first 21 months represent the retention period during which the outflows sum to approximately the storage volume at the beginning of October 1963. The September 1986 storage concentration was set equal to the September 1986 outflow concentration.

The other load term L_X makes the load balance sum to zero. L_X represents all loads not reflected in the other load budget terms and inaccuracies in the other terms.

The 1964-1986 mean load difference was computed based on the equation 4.8. The 1964-1986 mean load difference was found to be a negative value indicating an unexplained loss in load. The monthly other loads (L_X) were computed by allocating the 1964-1986 mean load difference between months using alternative methods compared in Appendix B. The load budget results for this reach between the South Bend and Graford gages are sensitive to the methodology adopted for distributing the total other loads ($\sum L_X$) to individual months.

Upon completion of the load budget, the end-of-month concentration of the water in storage in Possum Kingdom Reservoir was computed by combining the storage loads computed in the load budget with the observed storage volumes.

4.5.3 Reach from the Graford Gage to the Dennis Gage

The Graford to Dennis reach has no reservoir on the Brazos River. The volume and load balances were developed as follows:

<u>Graford – Dennis Volume Budget</u>

$$\text{Graford flow} = \text{Dennis flow} + \text{other outflow} - \text{other inflow}$$

The volume budget of the Graford to Dennis reach was computed by equation 4.4 like the case of the volume budget computation of the Seymour to South Bend gage. The complete 1964-1986 record of monthly flows at the Graford gage are outflows from the South Bend-to-Graford reach and inflows to the Graford-to-Dennis reach.

Incremental flows for September 1963 through April 1968 were computed as the naturalized flows form the WAM dataset at the Dennis gage minus naturalized flows at the Graford gage adjusted for Lake Palo Pinto. In any month during September 1963 through April 1968 in which the storage in Lake Palo Pinto increased, the storage increase was subtracted from the incremental naturalized flows. If Lake Palo Pinto was full to capacity at the end of the month, the net evaporation-precipitation volume was subtracted from the incremental naturalized flows.

<u>Graford – Dennis Load Budget</u>

Like the procedure of the volume budget computation, the load budget of the Graford-to-Dennis reach was developed by using the equation 4.6.

Graford load = Dennis load – other inflow load + other outflow load

The USGS salinity data includes loads for the complete 1964-1986 period-of-analysis at the Graford gage which were adopted for the load budget. The incremental loads for the period from October 1970 through October 1986 were computed by subtracting Graford loads from Dennis loads. The incremental loads for the period from September 1963 through September 1970 were computed by multiplying incremental volumes by the mean concentration computed for the October 1970 through October 1986 incremental flows and load. The loads at the Dennis gage during September 1963 through September 1970 were computed as the summation of the Graford loads plus incremental loads.

4.5.4 Reach from the Dennis Gage to the Glen Rose Gage

The Dennis to Glen Rose reach contains Lake Granbury which was constructed during the first several years of the 1964-1986 period-of-analysis. The load budget computations are different than for the other three reaches largely because there are no salinity data at the Glen Rose gage defining the downstream limit of the reach. Also, this reach has the only data for water supply diversions.

<u>Dennis – Glen Rose Volume Budget</u>

Δ Granbury storage = Dennis flow – Glen Rose flow + Dennis-to-Granbury incremental flow + Granbury-to-Glen Rose other inflow – Granbury-to-Glen Rose other outflow – water supply diversions – Granbury evaporation-precipitation

$$\Delta S = F_{US} - F_{DS} + F_{OI} - F_{OO} - F_{WS} - EP \qquad (4.9)$$

The complete record of observed storage volumes in Lake Granbury are available, but the dam and reservoir project was constructed during the early years of the 1964-1986 period-of-analysis. An initial small non-zero volume of 270 acre-feet was stored during October 1968 but the total storage volume did not exceed inflows each month until November 1969. September 1970 has been cited as the official initial impoundment data for the completed project.

The incremental flows were divided between the two sub-reaches upstream and downstream of the dam in proportion to drainage area. Of the total incremental drainage area between the Dennis and Glen Rose gages of 581 square miles, 442 square miles (76.1 percent) is above De Cordova Bend Dam (Lake Granbury) and the remaining 139 square miles (23.9 percent) is below. The incremental flows were divided 76.1 and 23.9 percent.

Dennis – Glen Rose Load Budget

Incremental loads were determined by combining the incremental flows (F_{OI}) from the volume budget with a constant concentration of 270 mg/l. Incremental loads entering Lake Granbury were assumed to be 76.1 percent of the total, with the remaining 23.9 percent entering the Brazos River between the dam and Glen Rose gage. During the period from October 1963 through September 1968, construction of Lake Granbury had not been completed and reservoir storage was zero. The loads at Glen Rose were computed as the summation of Dennis loads plus total incremental loads. From October 1968 through September 1986, the load budget computations were performed following an algorithm that combines the following premises:

- Flow volumes at the Glen Rose gage are the Lake Granbury outflow volume plus 23.9 percent of incremental flows. Lake Granbury outflow volumes are computed as observed flow at the Glen Rose gage less 23.9 percent of incremental flows.

• Water supply diversion loads are estimated based on assuming the diversion concentration during a month is equal to the storage concentration at the beginning of the month.

• A net inflow load to Lake Granbury is defined as consisting of the load at the Dennis gage plus 76.1 percent of incremental load less the diversion load. In each month, this net inflow load is divided between Granbury change-in-storage load and Granbury outflow load in direct proportion to the change-in-storage volume and outflow volume.

Lake Granbury storage loads are computed based on the following relationships.

end-of-month storage load = [beginning-of-month storage load + Dennis load + 76.1 percent of other inflow load – 76.1 percent of other outflow load – diversion load] [assigned proportion]

$$SL_E = [SL_B + L_{US} + L_{OI} - L_{OO} - L_{WS}]\left[\frac{F_{DS}}{F_{US} + S_{US}}\right] \tag{4.10}$$

4.5.5 Reach from the Glen Rose Gage to the Whitney Gage

The most downstream of the five reaches contains Lake Whitney. The volume and load balances were developed as follows, which is similar to the procedure applied to the South Bend to Graford reach which contains Possum Kingdom Lake except an additional adjustment is added to the load budget to match the observed Whitney storage concentrations from USGS reservoir water quality survey (Strause et al. 1984). This is the only reach for which the salinity budget includes adjustments for volume-weighted storage concentrations determined by the USGS from actual reservoir water quality survey measurements.

Glen Rose – Whitney Volume Budget

The volume budget computation was performed by the equation 4.7 used to develop the volume budget of the South Bend-to-Graford reach. A complete 1964-1986 record of monthly flows at both the Glen Rose and Whitney gages available from the USGS was adopted. Net evaporation-precipitation volumes, end-of-month storage volume of Whitney Reservoir were obtained from the HDS work files (HDR 2001) associated with the WAM dataset.

Glen Rose – Whitney Load Budget

Upon completion of the load budget, computed Lake Whitney storage loads are combined with storage volumes from the volume from the volume budget to compute storage concentrations. After completion of an initial load budget, further adjustments are performed to for Lake Whitney storage concentrations to equal observed values at selected points in time based actual measurements.

The procedure of the load budget computation of the Glen Rose-to-Whitney reach is similar to the case of the South Bend-to-Graford reach. Equation 4.8 was used to develop the load budget of the Glen Rose-to-Whitney reach. The unknown concentrations of the water in storage in Whitney Reservoir at the beginning and the end of the 1964-1986 period-of-analysis were set based on the corresponding observed outflow concentrations. The October 1963 beginning concentration was set equal to the mean outflow concentration during the October 1963 through August 1964. These first 11 months represent the retention period during which the outflows sum to approximately the storage volume at the beginning of October 1963. The September 1986 storage concentration was set equal to the September 1986 outflow concentration. The computational algorithm for storage loads is the same for both the Possum Kingdom Lake and Whitney Lake reaches.

Additional Adjustments to Match Observed Lake Whitney Storage Concentration

The U.S. Geological Survey conducted water quality surveys of Lake Granbury (Strause et al. 1983) and Lake Whitney (Strause et al. 1984). Surveys were performed at 16 sites in Lake Granbury 28 times during water years 1970-1979 and at 27 sites in Lake Whitney 30 times during water years 1970-1980. From these measurements, the USGS computed volume-weighted mean storage concentrations. The volume-weighted mean storage concentrations for Lake Granbury determined by the USGS are compared with the value developed in the present salinity budget study but are not used to actually adjust the salinity budget.

The monthly time step salinity budget covers each of the 276 months of the 1964-1986 period-of-analysis. The volume-weighted mean concentrations of storage in

Lake Whitney reported by Strause and Adrews (Strause et al. 1984) represent 30 point in time spaced at somewhat irregular intervals between September 23, 1970 and May 6, 1980. The following procedure was adopted for adjusting the salinity budget to match the results of the 30 water quality surveys of Lake Whitney.

- The storage volume, loads, and concentrations in the salinity budget are end-of-month amounts. Each of the 30 reservoir survey dates were assigned to the nearest end-on-month date.

- The TDS load in storage for each of the 30 months was determined by combining the storage concentration reported by Strause and Adrews (Strause et al. 1984) with the known storage volume.

- The storage concentration adjustment load (L_{SCA}) is the difference between the previously computed storage load and the storage load based on the storage concentration mentioned by Strause and Andrews (Strause et al. 1984). The computed L_{SCA} for each of the 30 months is the additional inflow or outflow load required to make the storage concentration match the value reported by Strause and Andrews (Strause et al. 1984) while continuing to maintain a load balance.

4.6 Volume and Load Budget Results

The river flow volume budgets and total dissolved solids (TDS) load budgets for the five river reaches were developed for each of the 276 months of the October 1963 through September 1986 period-of-analysis. Concentrations are determined by applying a conversion factor to load divided by volume. The results of the volume and load budget analyses are displayed in the form of the summary tables and plots.

Various computational strategies and methods were investigated during the development of the volume and load budgets for the five river reaches. The results presented here are based upon those premises and methods that were adopted as being most realistic. Results derived with alternative premises addressing key issues are presented in Appendix A for comparison. The comparative evaluation of alternative methods presented in Appendix A highlight the following two particularly significant issues dealing with estimating TDS loads.

- TDS loads at the South Bend gage for the period November 1977 through September 1981 are available in the USGS dataset. Loads for October 1963 through October 1977 and October 1981 through September 1986 are estimated.

- The other load L_X term required to balance the load budget is relatively large. Load budget results vary significantly depending upon the method adopted to allocated L_X between individual months.

4.6.1 Volume and Load Budget Summary Tables

The 1964-1986 means of the components of the volume and load budgets are tabulated in Table 4.4 and Table 4.5. Each of the volume and load budgets sums to zero. Mean concentrations corresponding to the Table 4.4 and Table 4.5 load and flow means are represented in Table 4.6. The concentration in Table 4.6 are derived directly from Table 4.4 and Table 4.5 by dividing loads by volumes and multiplying by the unit conversion factor of 735.48.

The last two columns of Table 4.5, Table 4.6 and Table 4.7 summarize salinity budget results for the two alternative versions of the load budget for the reach between the Glen Rose and Whitney gages. The first version of the salinity budget was developed without incorporating the data from USGS water quality surveys of Lake Whitney (Strause et al. 1984). The second refined salinity budget reflects storage concentration adjustments (SCA) in which Lake Whitney storage loads were modified to match the storage concentrations provided by Strause and Andrews (Strause et al. 1984).

Table 4.4 1964-1986 Mean Monthly Flow Volumes (Acre-Feet/Month)

Components of Volume Balance	Seymour to South Bend	South Bend to Graford	Graford to Dennis	Dennis to Glen Rose	Glen Rose to Whitney
			(acre-feet/month)		
Upstream river flow (F_{US}, +)	16,215	38,712	42,999	57,077	61,670
Downstream river flow (F_{DS}, −)	38,712	42,999	57,077	61,670	74,193
Other inflow (F_{OI}, +)	22,913	10,240	15,280	8,350	19,447
Other outflow (F_{OO}, −)	416	1,967	1,202	1,020	2,233
Water supply diversions (F_{WS}, −)	−0−	−0−	−0−	924	−0−
Net evaporation-precipitation (EP, −)	−0−	3,731	−0−	1,272	3,603
Change in storage volume (ΔS, −)	−0−	255	−0−	541	1,088

Table 4.5 1964-1986 Mean Monthly Loads (Tons/Month)

Components of Load Balance	Seymour South Bend	South Bend Graford	Graford Dennis	Dennis Glen Rose	Glen Rose to Whitney Initial	Glen Rose to Whitney After SCA
			(tons/month)			
Upstream river flow (L_{US}, +)	79,127	105,068	89,712	91,475	90,017	90,017
Downstream river flow (L_{DS}, −)	105,068	89,712	91,475	90,017	93,538	93,538
Other inflow load (L_{OI}, +)	28,069	3,759	6,939	3,065	7,139	7,139
Other outflow load (L_{OO}, −)	2,128	4,416	5,177	1,517	3,103	3,103
Water supply diversions (L_{WS},−)	−0−	−0−	−0−	1,855	−0−	−0−
Load to balance budget (L_X, +)	−0−	− 12,787	−0−	−0−	1,298	1,298
Change in storage load (ΔSL, −)	−0−	1,911	−0−	1,149	1,813	1,857
Lake Whitney storage concentration adjustment (SCA) loads						
SCA inflow load (L_{SCA}, +)	−0−	−0−	−0−	−0−	−0−	5,446
SCA outflow load (L_{SCA}, −)	−0−	−0−	−0−	−0−	−0−	5,402

Table 4.6 1964-1986 Mean TDA Concentrations (Milligrams/Liter)

Components of Load Balance	Seymour South Bend	South Bend Graford	Graford Dennis	Dennis Glen Rose	Glen Rose to Whitney Initial	Glen Rose to Whitney After SCA
			(mg/l)			
Upstream river flow	3,589	1,996	1,534	1,204	1,073	1,073
Downstream river flow	1,996	1,534	1,204	1,073	927	927
Other inflows	901	270	444	270	270	270
Other outflows	3,762	1,651	3,389	1,102	1,022	1,022
Water supply diversions	−0−	−0−	−0−	1,477	−0−	−0−
Reservoir storage change	−0−	5,512	−0−	1,562	1,226	1,255

The 1964-1986 means of end-of-month storage volumes and loads and 1964-1986 mean concentrations for Possum Kingdom, Granbury, and Whitney Reservoir are summarized in Table 4.7. The storage volume, load, and concentration at the beginning of October 1963 and end of September 1986 are also included in Table 4.7. Reservoir storage concentrations are volume-weighted mean (spatially averaged) concentrations for the entire reservoir.

Table 4.7 Reservoir Volumes, TDS Loads, and TDS Concentrations

	Possum Kingdom	Granbury Reservoir	Whitney Reservoir Initial	Whitney Reservoir After SCA
276-month mean storage volume (acre-feet)	517,008	107,420	475,928	475,928
276-month mean storage load (tons)	1,142,683	190,115	717,672	686,969
276-month mean storage concentration (mg/l)	1,626	1,302	1,109	1,062
276-month mean outflow concentration (mg/l)	1,534	1,073	927	927
Storage volume beginning of Oct 1963 (ac-ft)	477,802	−0−	332,300	332,300
Storage volume at end of Sept 1986 (ac-ft)	548,300	149,200	632,500	632,500
Load at the beginning of October 1963 (tons)	938,630	−0−	491,069	491,069
Load at the end of September 1986 (tons)	1,466,130	317,040	1,039,626	1,054,472
Concentration beginning October 1963 (mg/l)	1,445	−0−	1,199	1,199
Concentration end of September 1986 (mg/l)	1,967	1,563	1,209	1,226

The means of flows, loads, and concentrations at the six gaging stations and two other downstream gages (College station and Richmond gages) are tabulated in Table 4.8 along with the means expressed as a percentage of the means at the Whitney gage. The last three columns of Table 4.8 show the dramatic decrease in salinity concentrations in ad downstream direction caused by dilution from low-salinity tributary inflows.

Table 4.8 1964-1986 Mean Flows, Loads, and Concentrations at Gages on the Brazos River

USGS Gaging Station	Fig. 3.2 No.	River Mile	Mean Flow (ac-ft/yr)	Mean Load (tons/yr)	Mean Concen (mg/l)	Mean Flow	Mean Load	Mean Concen
						Percentage of Whitney Gage		
Seymour	7	847.4	194,600	949,500	3,589	21.9%	84.6%	387%
South Bend	12	686.5	464,500	1,260,800	1,996	52.2%	112%	215%
Graford	13	614.2	516,000	1,076,500	1,534	58.0%	95.9%	165%
Dennis	14	571.0	684,900	1,097,700	1,179	76.9%	97.8%	127%
Glen Rose	–	523.6	740,000	1,080,096	1,073	83.1%	96.2%	116%
Whitney	15	442.4	890,300	1,122,500	927	100%	100%	100%
College Station	21	281.1	3,279,000	1,952,000	438	368%	174%	47%
Richmond	25	92.0	4,972,000	2,287,000	339	558%	204%	37%

The means of the other inflow volumes (F_{OI}) from Table 4.4 are expressed as an equivalent depth of runoff from the local incremental watershed with drainage areas shown in Table 4.9 as a check on the reasonableness of the computed amounts. The 1964-1986 mean flow volume as an equivalent depth over the watershed is computed by dividing F_{OI} in acre-feet/month by the watershed area and applying conversion factors. The F_{OI} volume equivalents of 3.9, 2.5, 2.1, 3.2, and 3.2 inches/year listed in the last column of Table 4.9 appear to be reasonable amounts when viewed as rainfall runoff from the local incremental watersheds above the gages. For comparison, the Aquilla Creek at Aquilla and Little River at Little River gages (map number 17 and 19 in Figure 3.2) have mean flows of 147 and 912 cfs and drainage area of 308 and 5,228 mile^2, which translate to 6.5 and 2.4 inches/year, respectively.

Table 4.9 Other Inflow Volumes as a Watershed Runoff Depth Equivalent

Reach	Watershed Area (square miles)	Other Inflow (F_{OI}) (acre-feet/month)	Other Inflow Depth (inches/year)
Seymour to South Bend	13,107	22,913	3.9
South Bend to Graford	923	10,240	2.5
Graford to Dennis	1,641	15,280	2.1
Dennis to Glen Rose	581	8,350	3.2
Glen Rose to Whitney	1,371	19,447	3.2

4.6.2 Time Series Plots of Volume, Load, and Concentrations

The October 1963 through September 1986 monthly river flow volumes, TDS loads, and TDS concentrations at the six gaging stations are plotted in Figure 4.2 through Figure 4.19. The volumes, loads, and concentrations of water stored in Possum Kingdom, Granbury, and Whitney Reservoirs are plotted in Figure 4.20 through Figure 4.28. All of the plots cover the 276 months of the October 1963 through September 1986 period-of-analysis.

The Lake Whitney storage loads and concentrations without the storage concentration adjustment (SCA) are plotted in Figure 4.25 and Figure 4.28 The storage concentration adjustments (SCA) modify the load budget as necessary to match the storage concentrations determined in 30 reservoir water quality surveys of Lake Whitney (Strause et al. 1984).

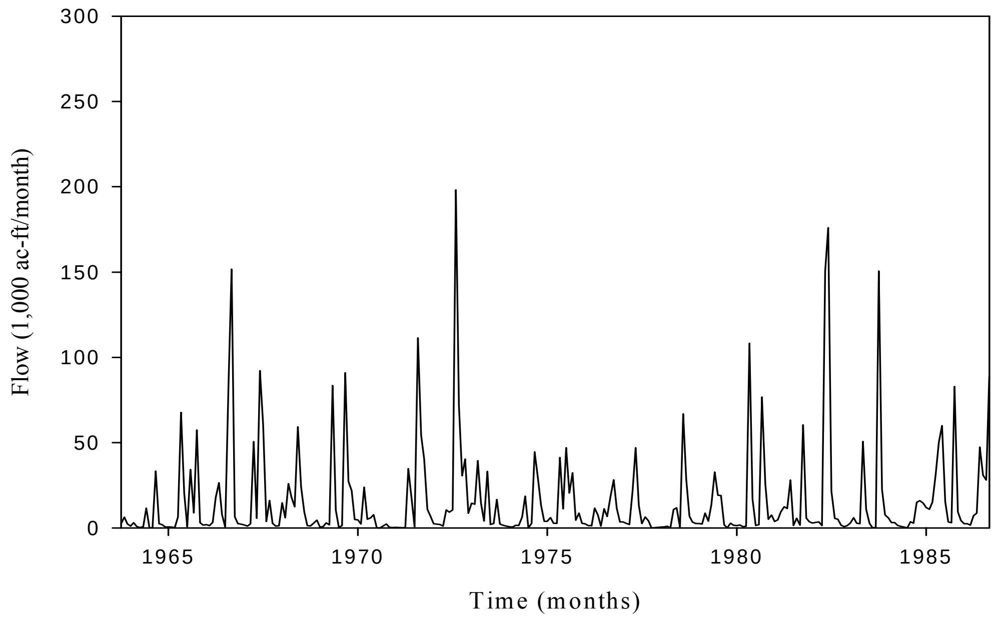

Figure 4.2 Monthly Flows at the Seymour Gage

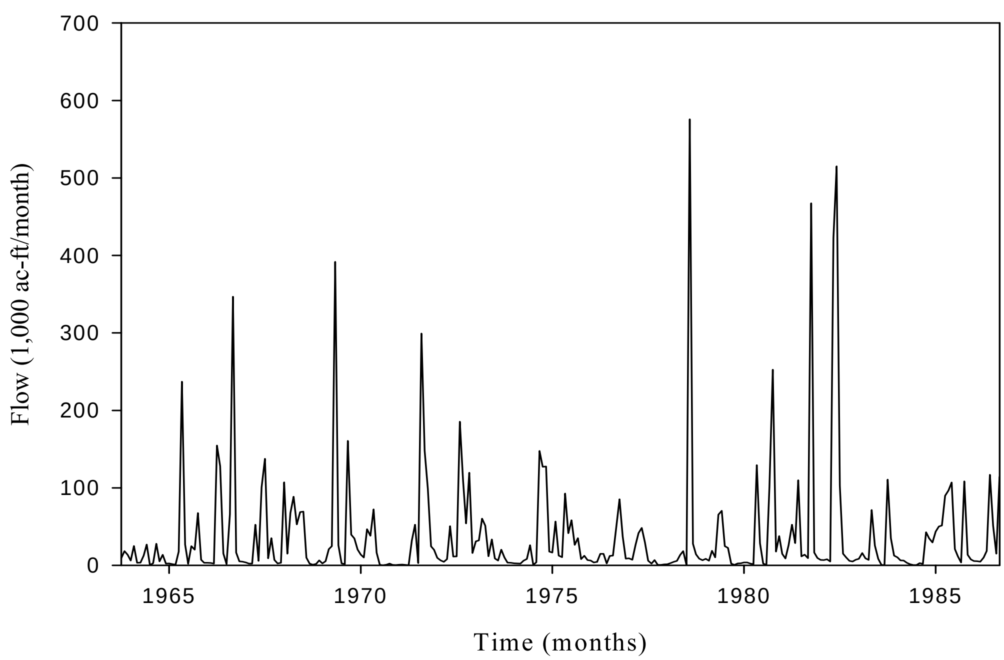

Figure 4.3 Monthly Flows at the South Bend Gage

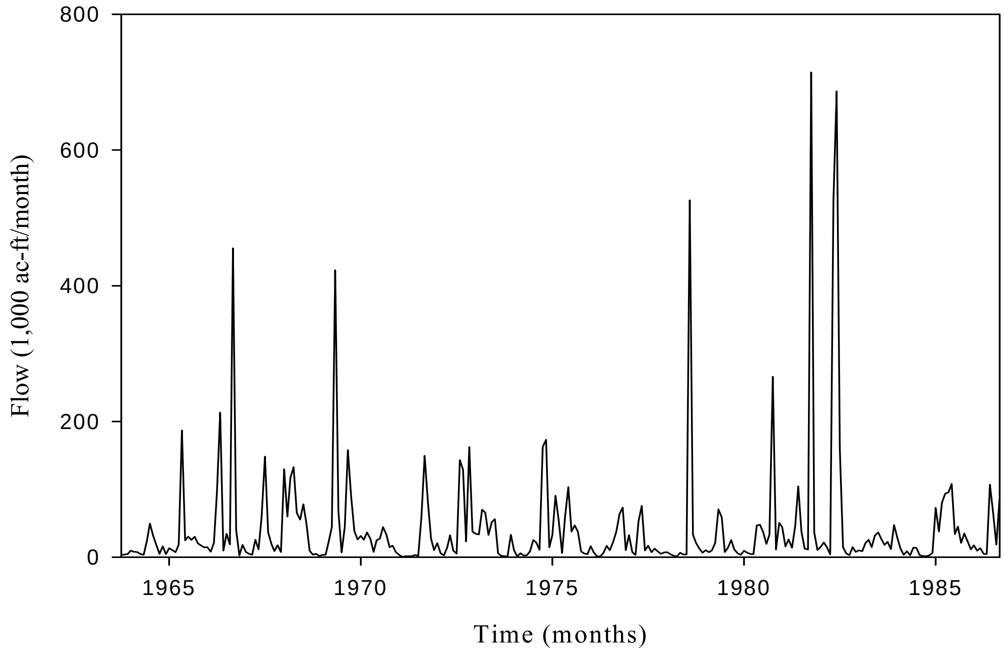

Figure 4.4 Monthly Flows at the Graford Gage

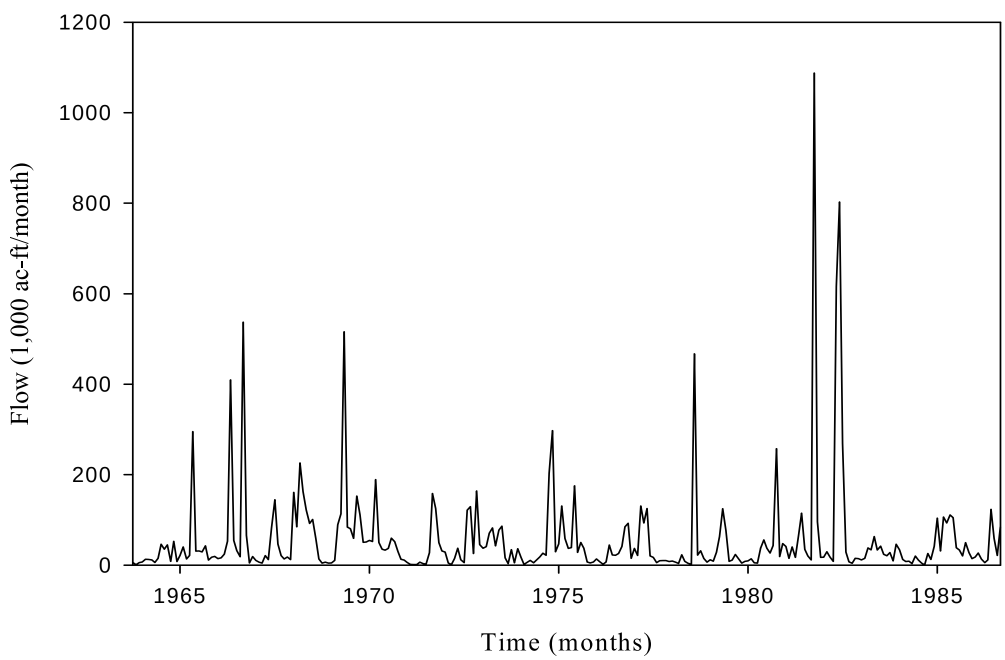

Figure 4.5 Monthly Flows at the Dennis Gage

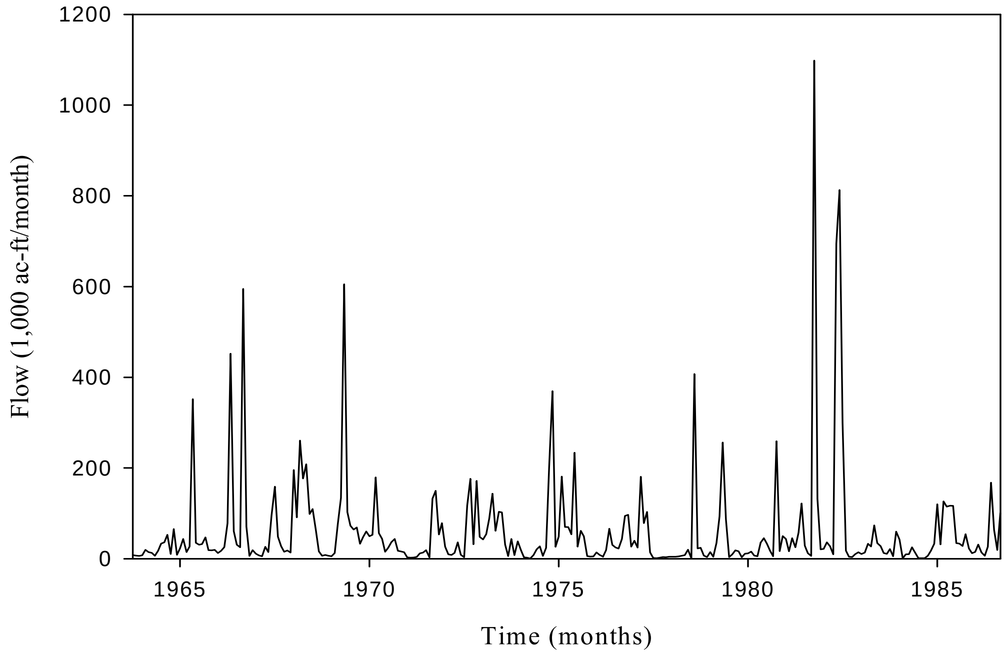

Figure 4.6 Monthly Flows at the Glen Rose Gage

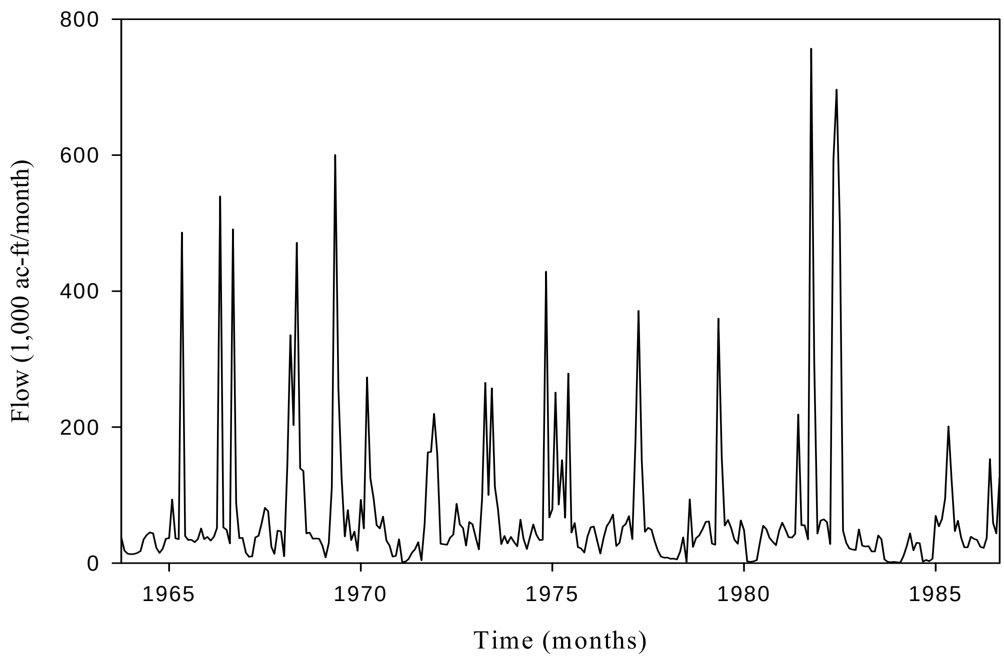

Figure 4.7 Monthly Flows at the Whitney Gage

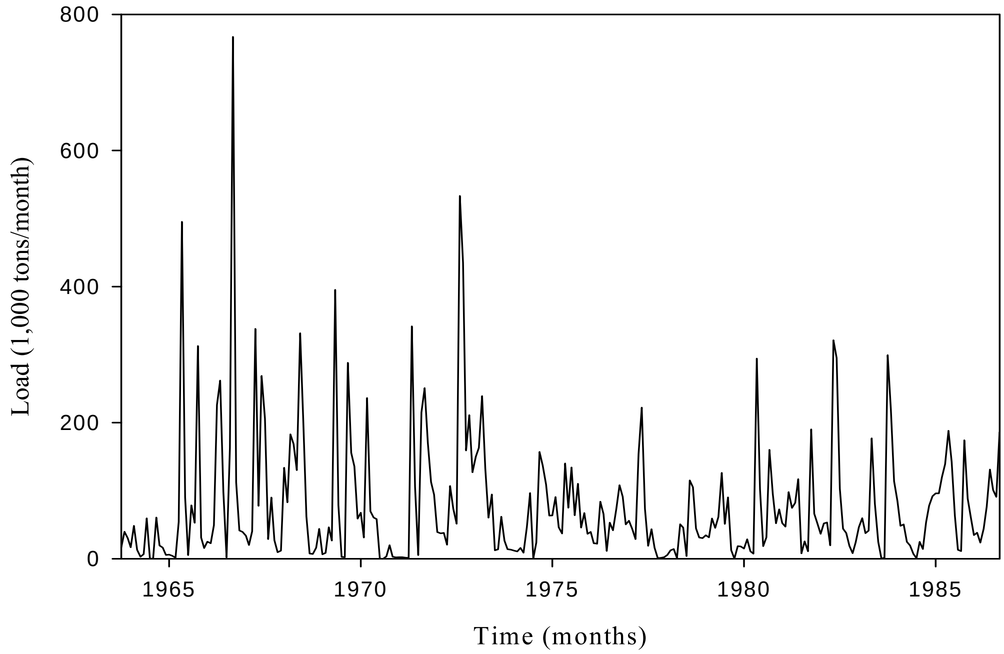

Figure 4.8 Monthly TDS Loads at the Seymour Gage

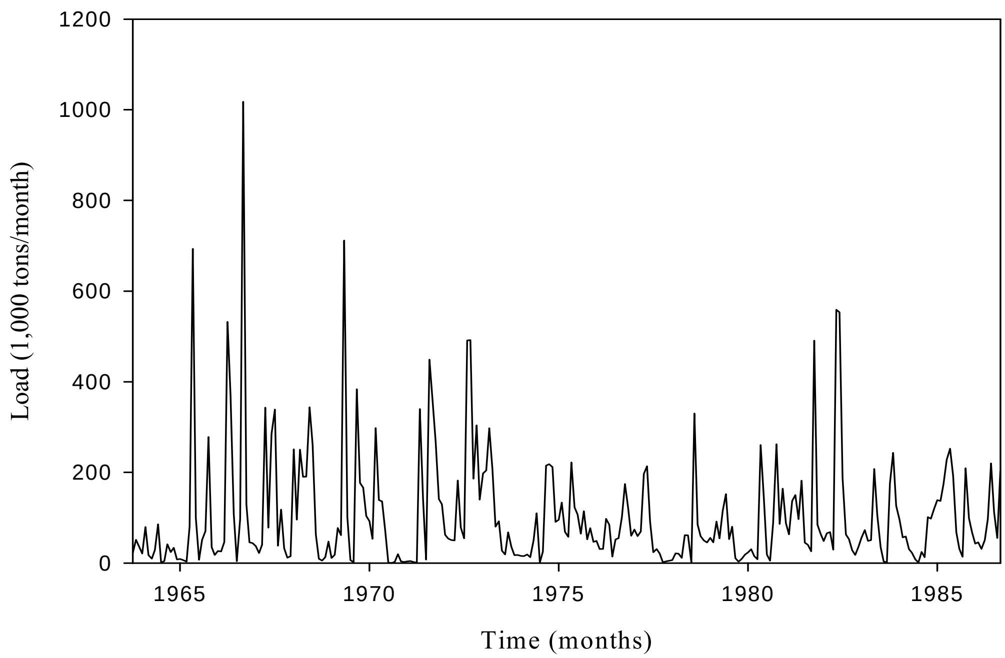

Figure 4.9 Monthly TDS Loads at the South Bend Gage

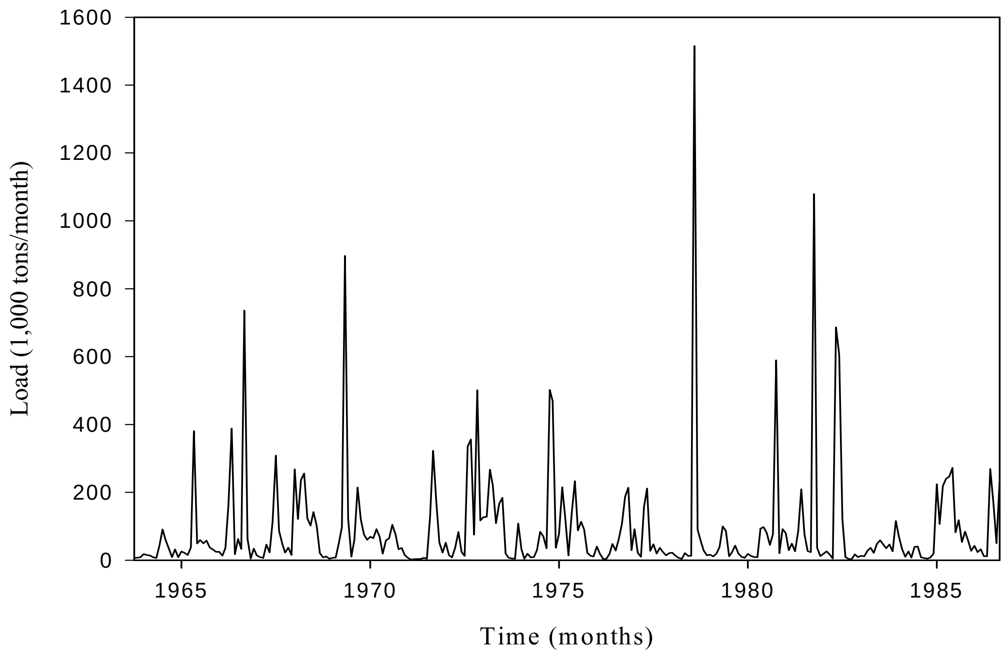

Figure 4.10 Monthly TDS Loads at the Graford Gage

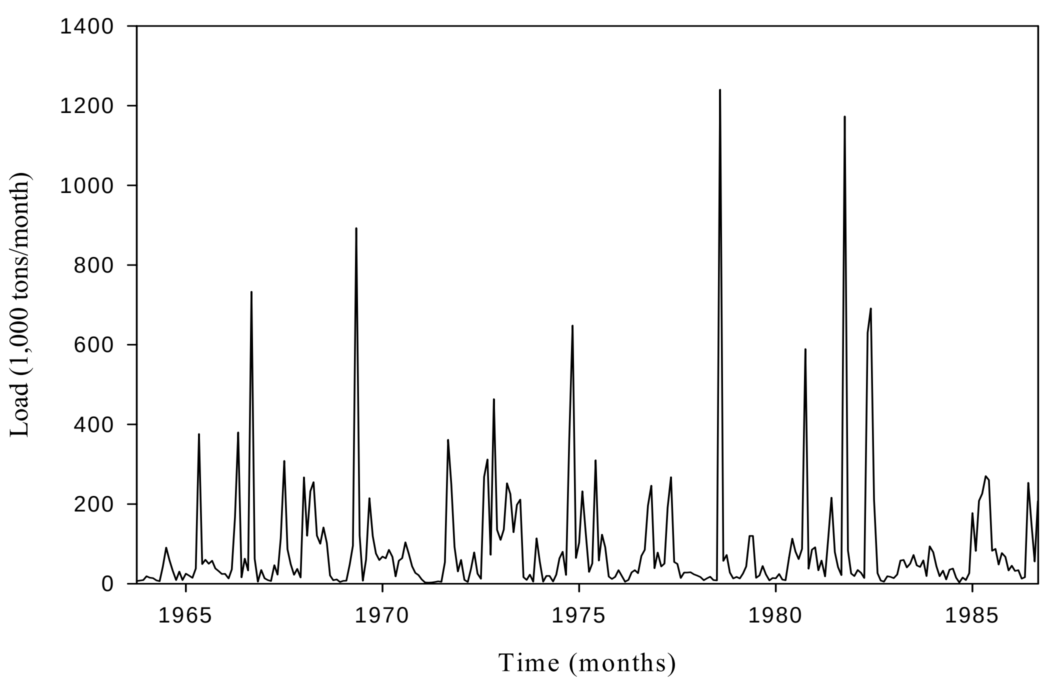

Figure 4.11 Monthly TDS Loads at the Dennis Gage

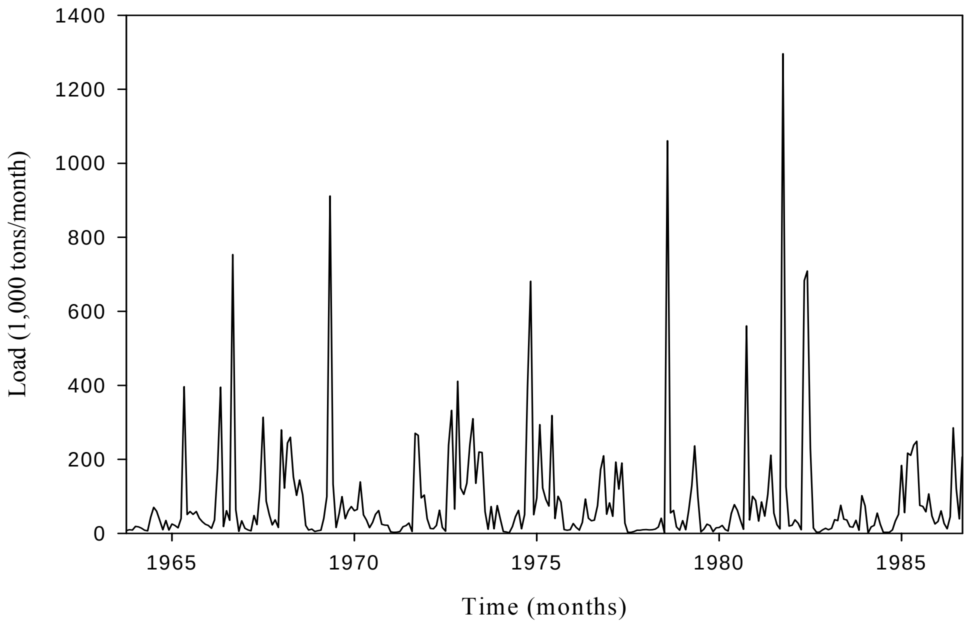

Figure 4.12 Monthly TDS Loads at the Glen Rose Gage

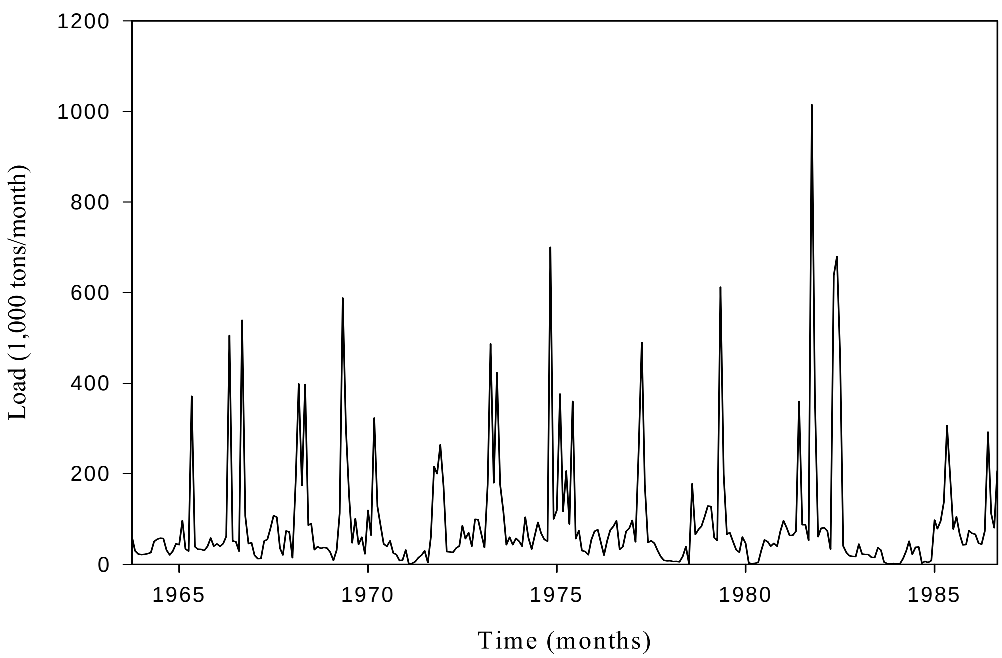

Figure 4.13 Monthly TDS Loads at the Whitney Gage

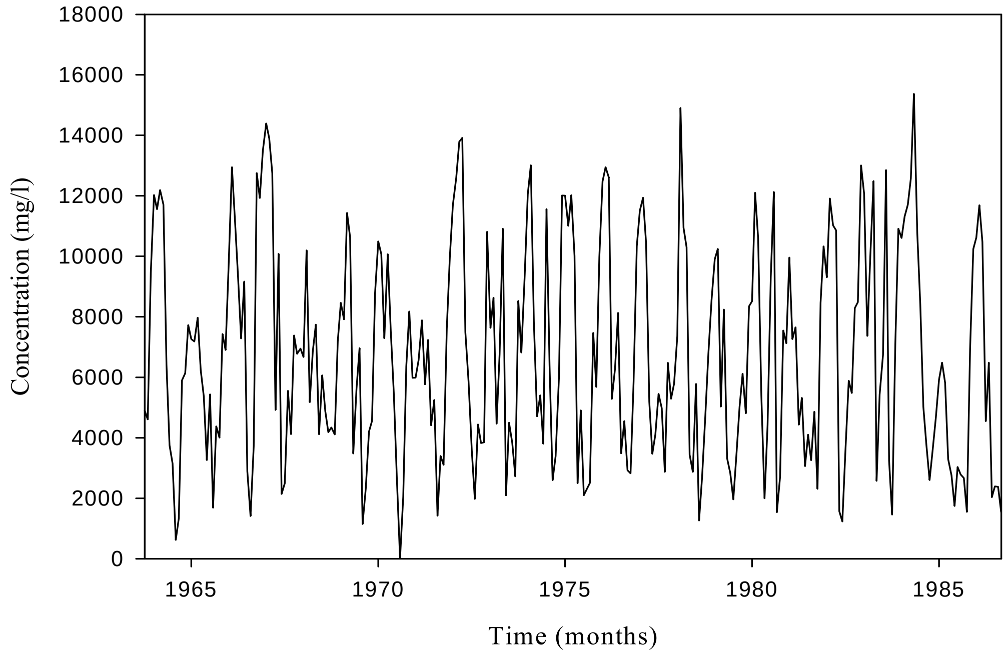

Figure 4.14 Monthly TDS Concentrations at the Seymour Gage

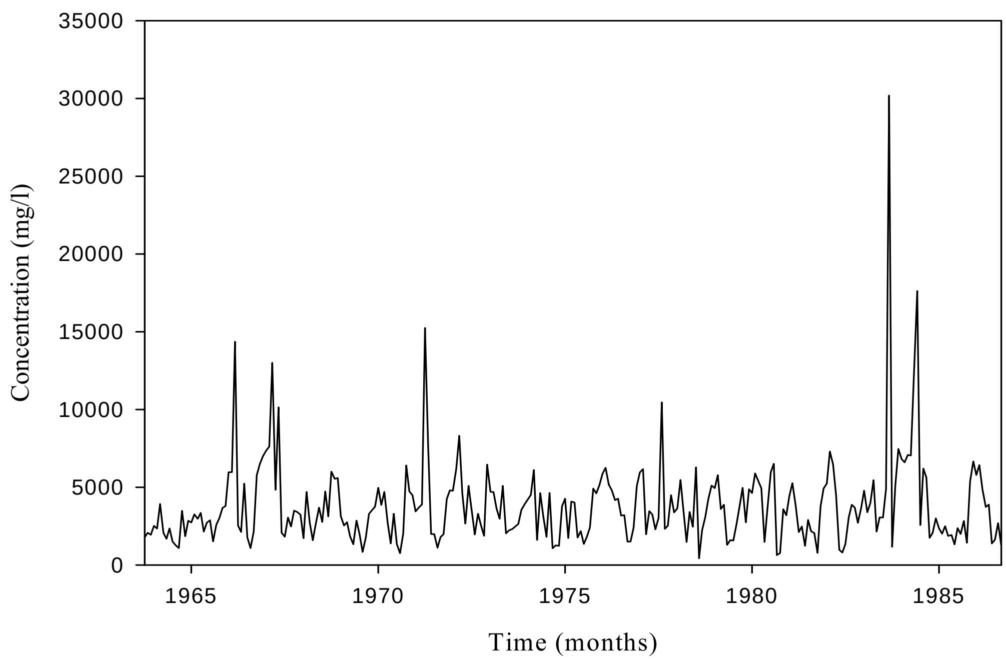

Figure 4.15 Monthly TDS Concentrations in South Bend Gage

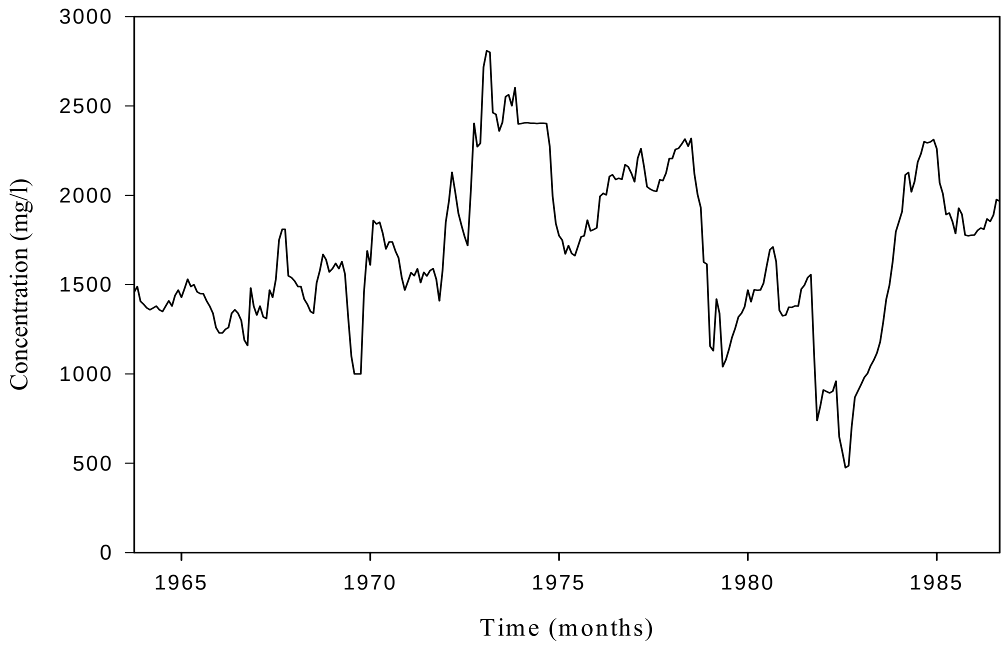

Figure 4. 16. Monthly TDS Concentrations at the Graford Gage

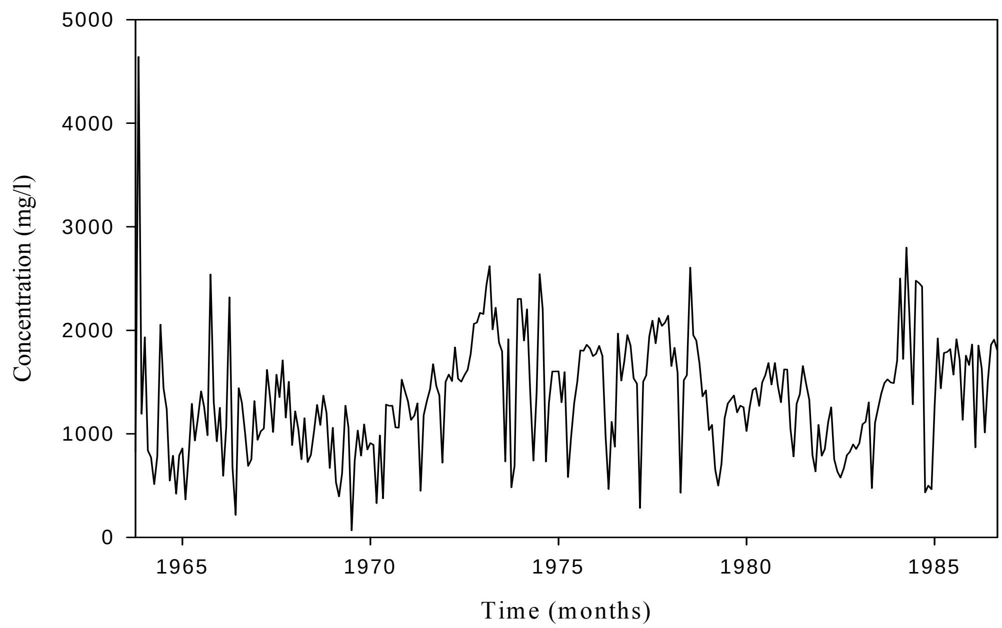

Figure 4.17 Monthly TDS Concentrations at the Dennis Gage

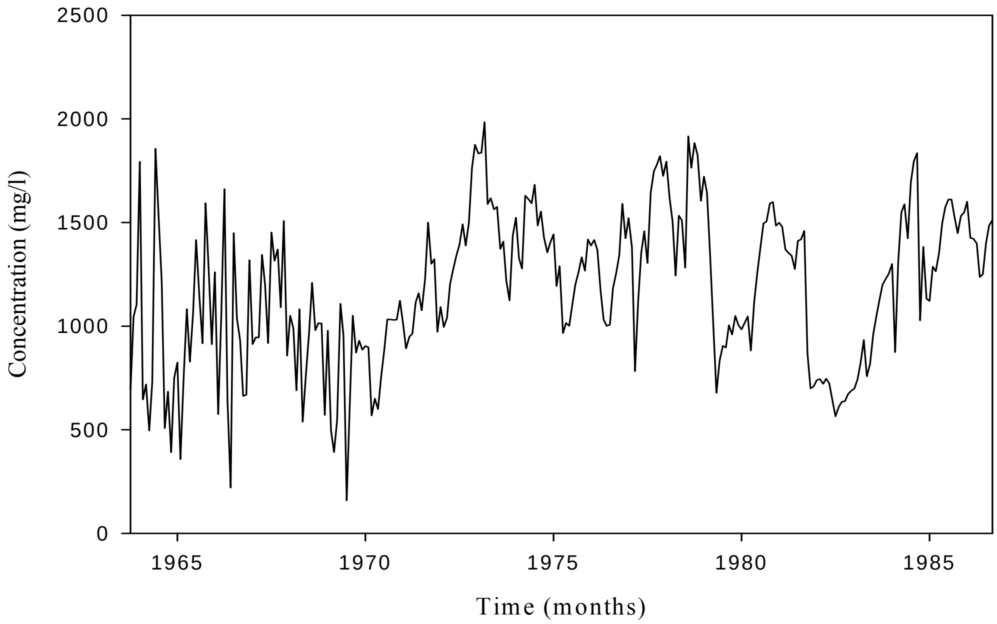

Figure 4.18 Monthly TDS Concentrations at the Glen Rose Gage

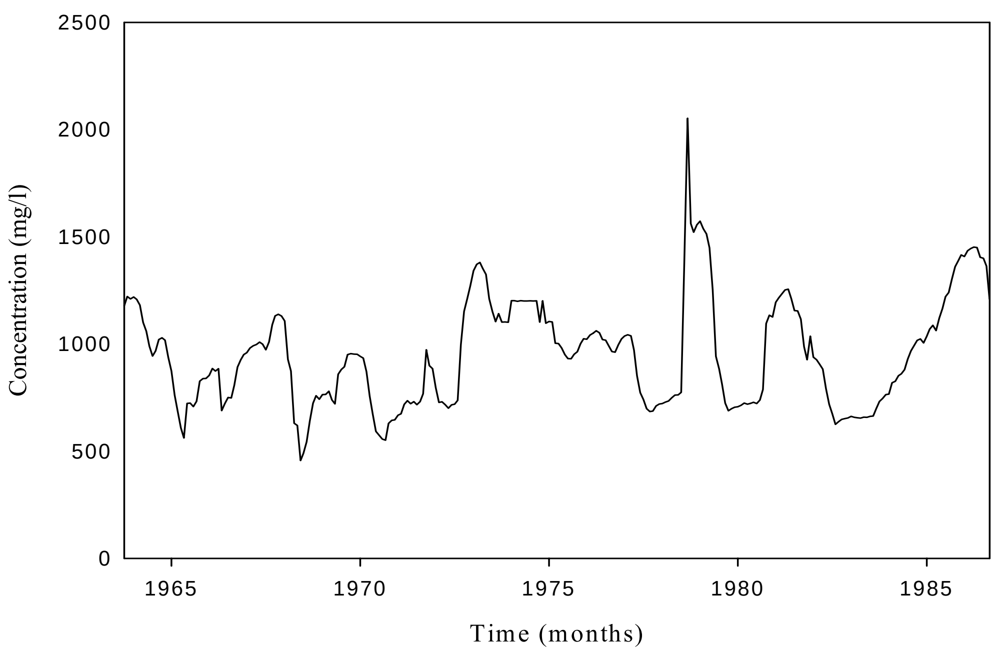

Figure 4.19 Monthly TDS Concentrations at the Whitney Gage

Figure 4.20 Storage Volumes in Possum Kingdom Reservoir

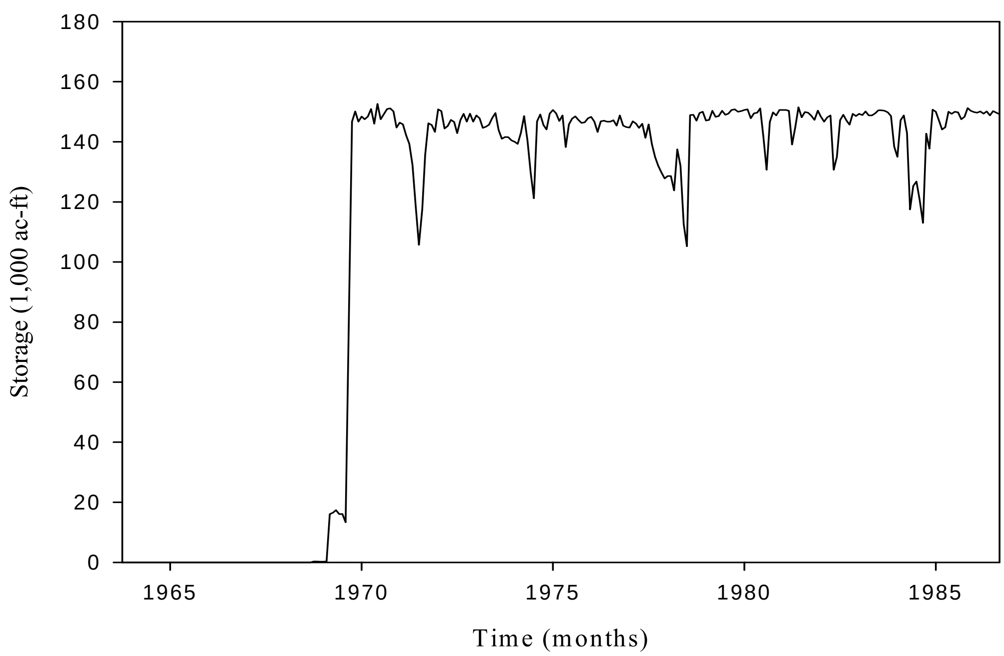

Figure 4.21 Storage Volumes in Granbury Reservoir

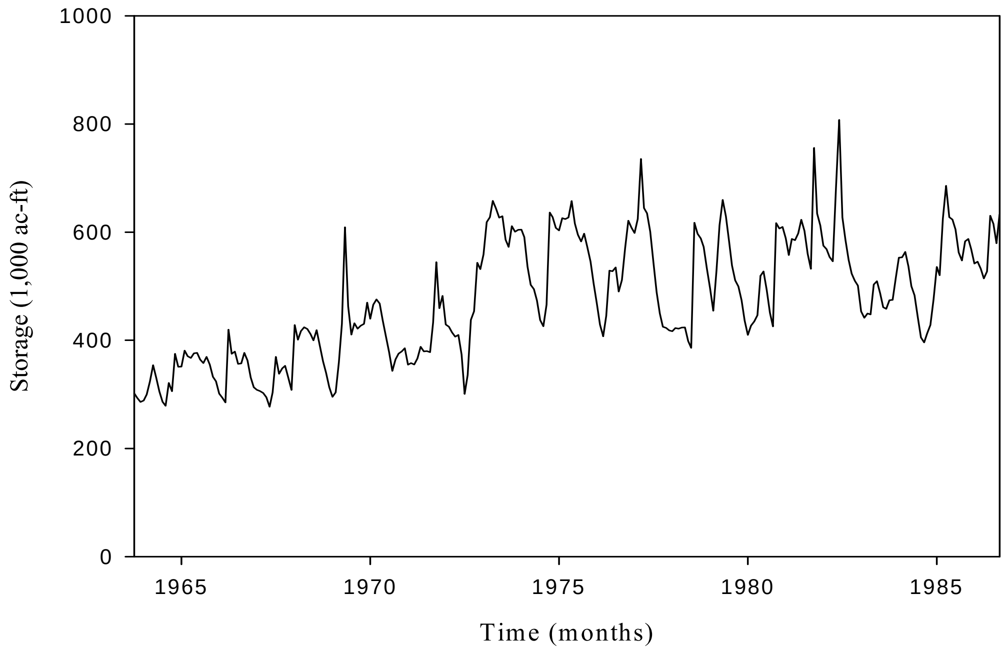

Figure 4.22 Storage Volumes in Whitney Reservoir

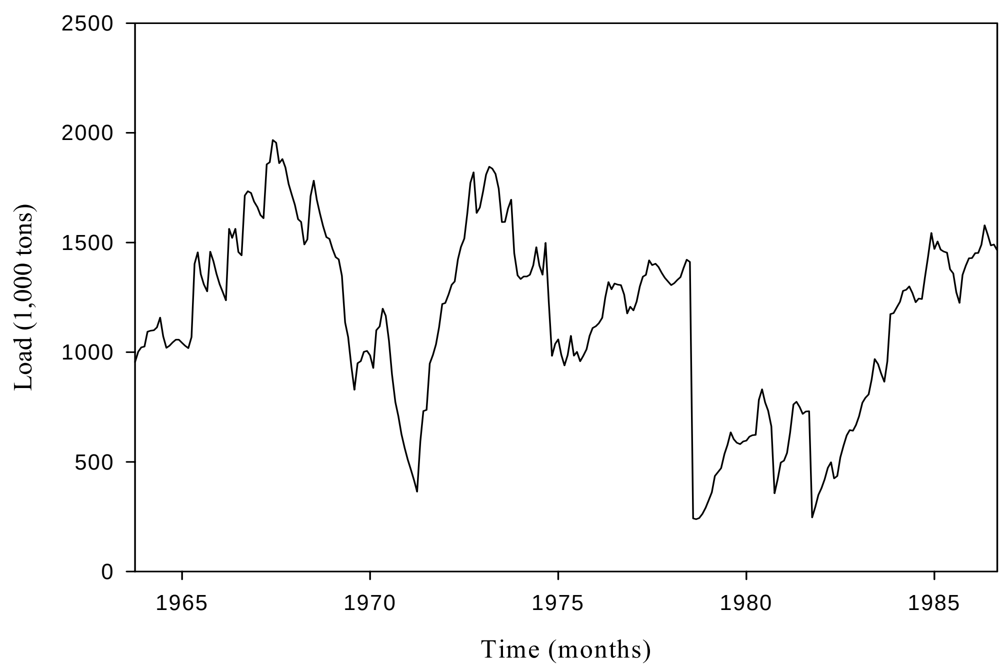

Figure 4.23 Storage Loads in Possum Kingdom Reservoir

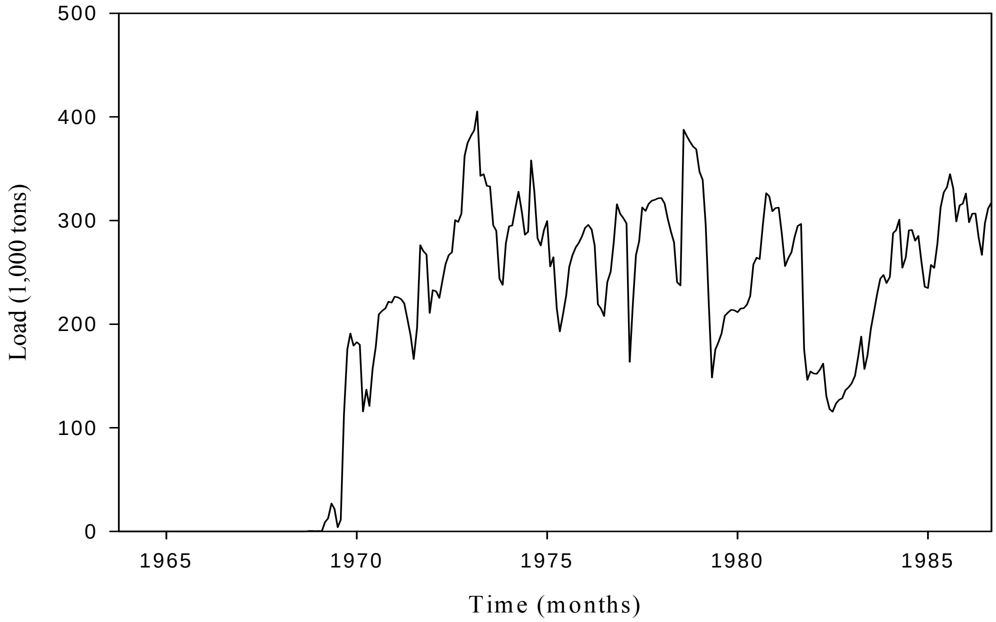

Figure 4.24 Storage Loads in Granbury Reservoir

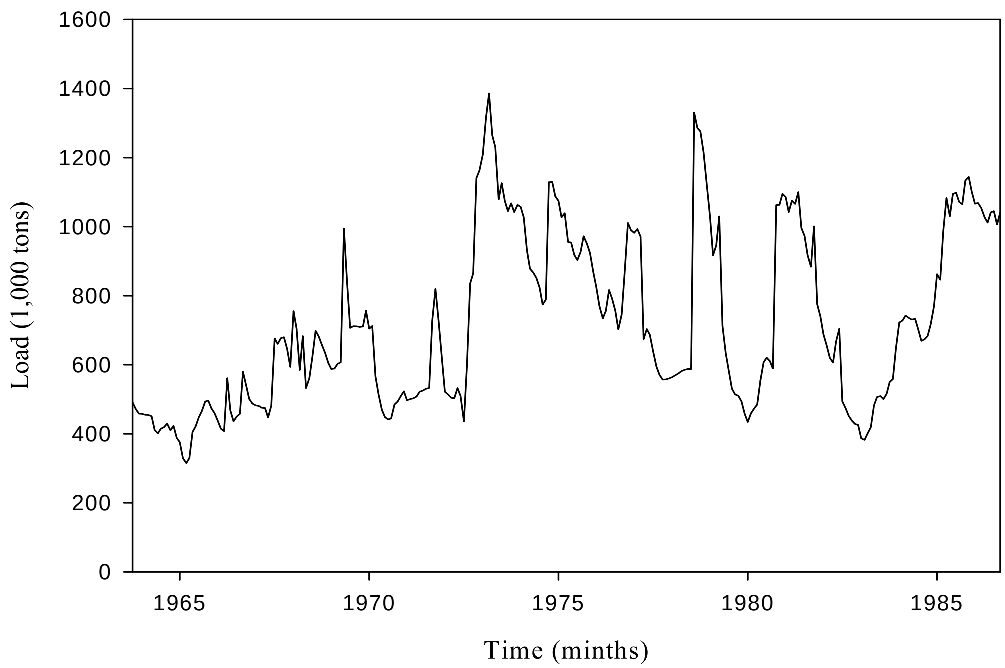

Figure 4.25 Storage Loads in Whitney Reservoir (without SCA)

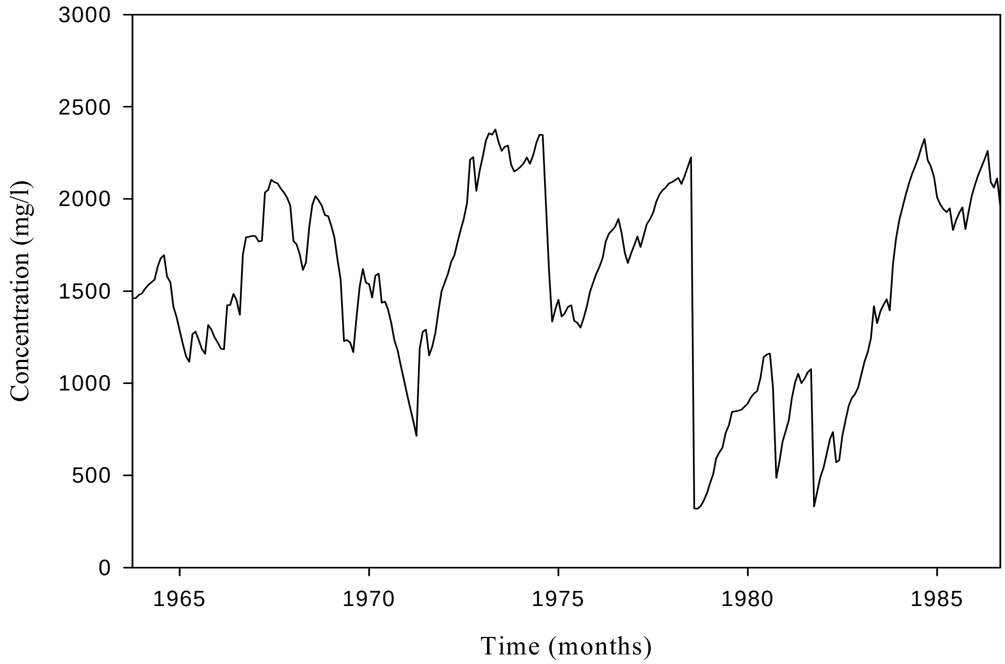

Figure 4.26 Storage Concentration in Possum Kingdom Reservoir

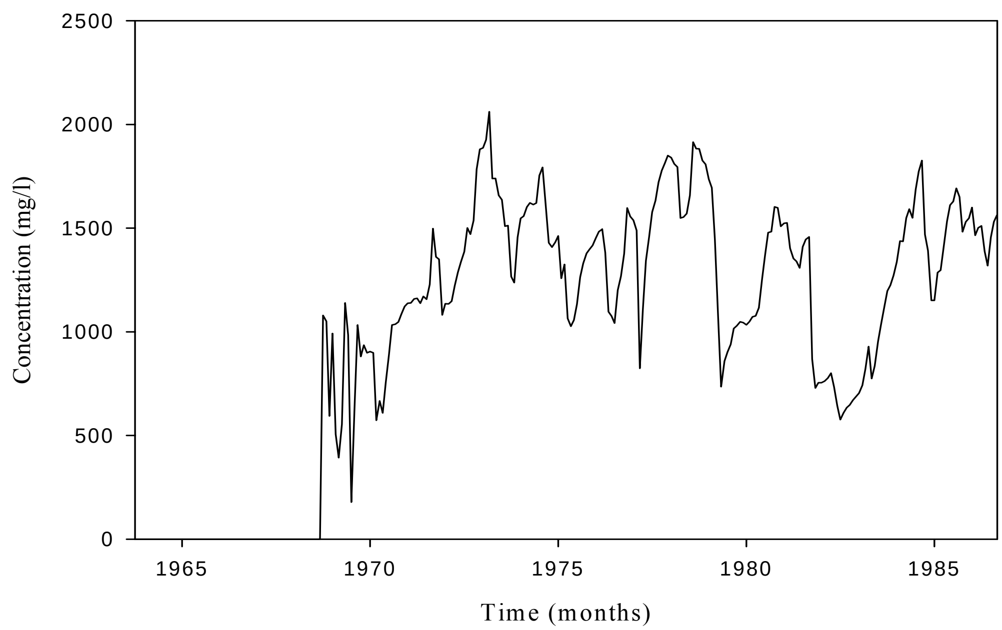

Figure 4.27 Storage Concentration in Granbury Reservoir

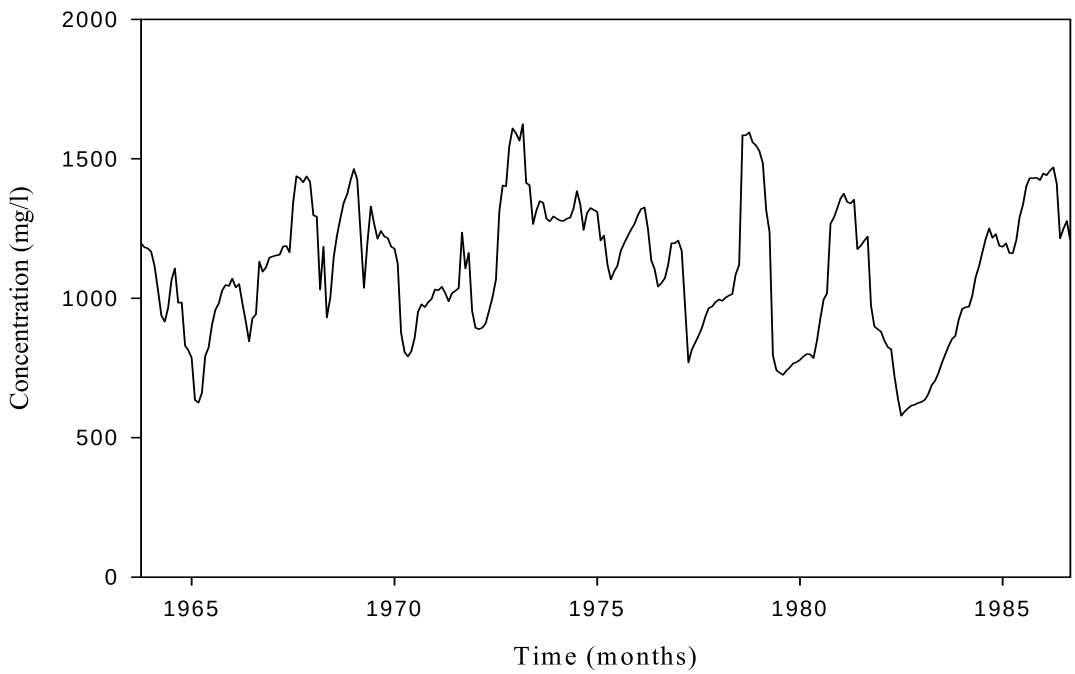

Figure 4.28 Storage Concentration in Whitney Reservoir (without SCA)

The 1964-1986 volume and load budget results represent tremendous apparently random variations over time. The variability in TDS concentration is affected by the spatial distribution of rainfall during flood events over primary salt source subwatersheds versus other subwatersheds with less salt. Reservoirs have the effect of soothing out the variations in concentrations somewhat. A seasonal pattern of concentration variation is more pronounced for the Seymour gage and other upper basin gages than for the gages located downstream of reservoir which exhibit essentially no seasonal patterns.

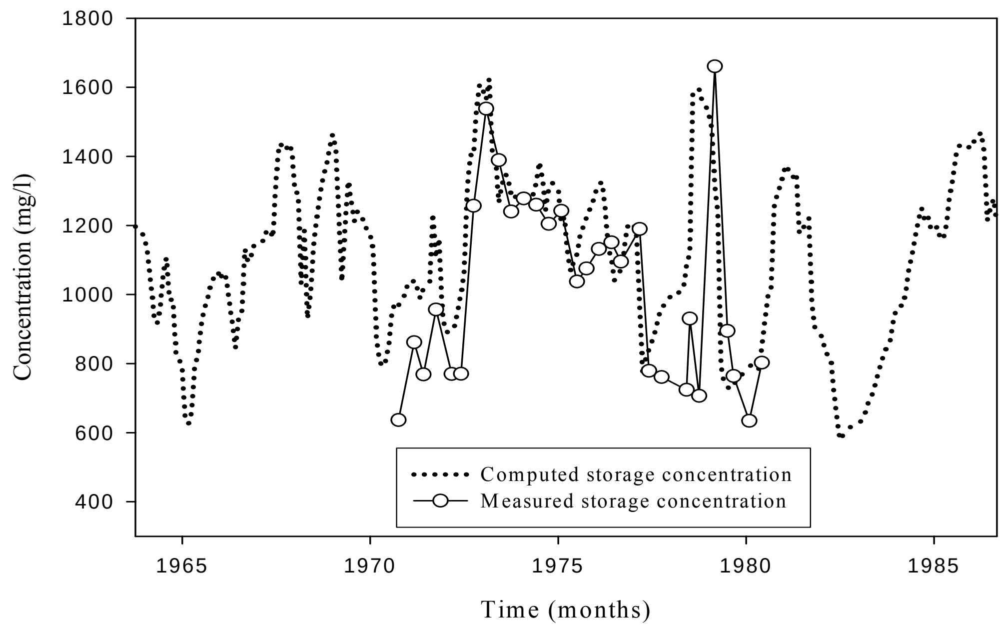

Figure 4.29 Comparison of Whitney Computed and Measured Storage Concentration

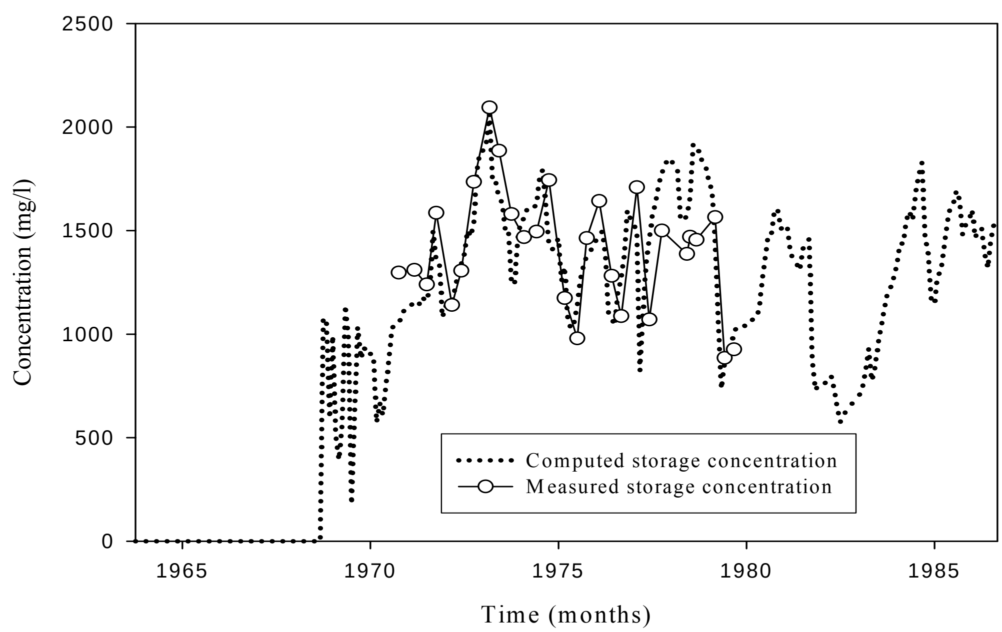

Figure 4.30 Comparison of Granbury Computed and Measured Storage Concentration

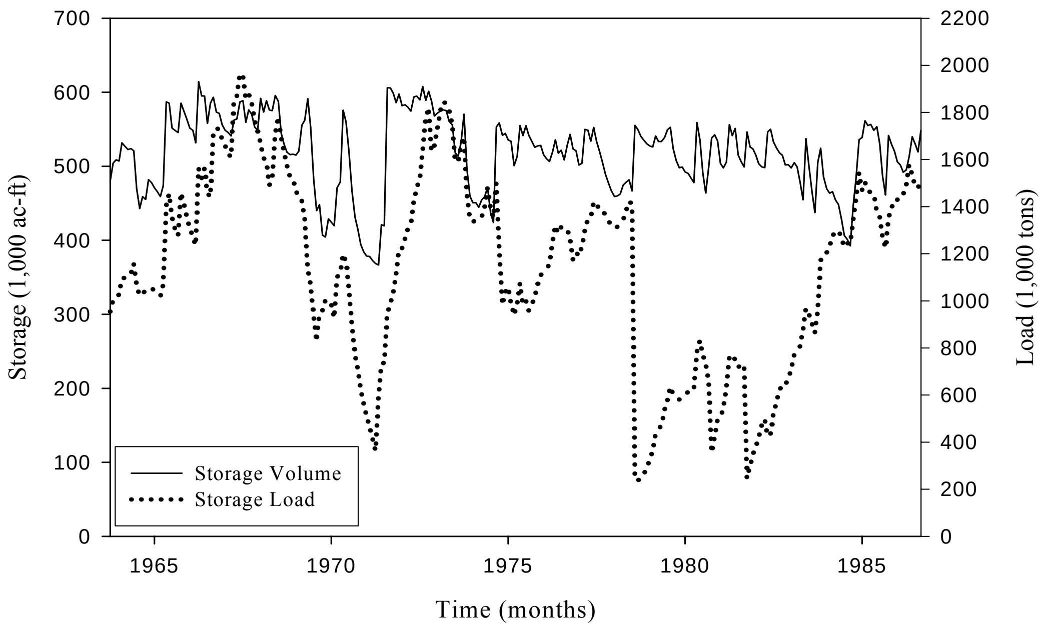

Figure 4.31 Comparison of Possum Kingdom Storage Volume and Load

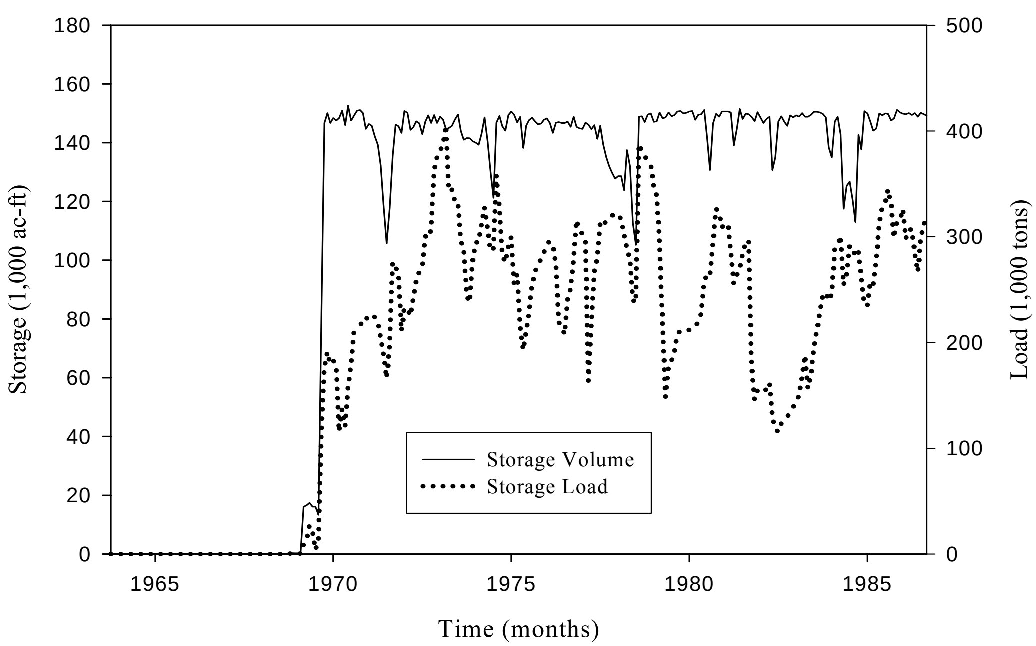

Figure 4.32 Comparison of Granbury Storage Volume and Load

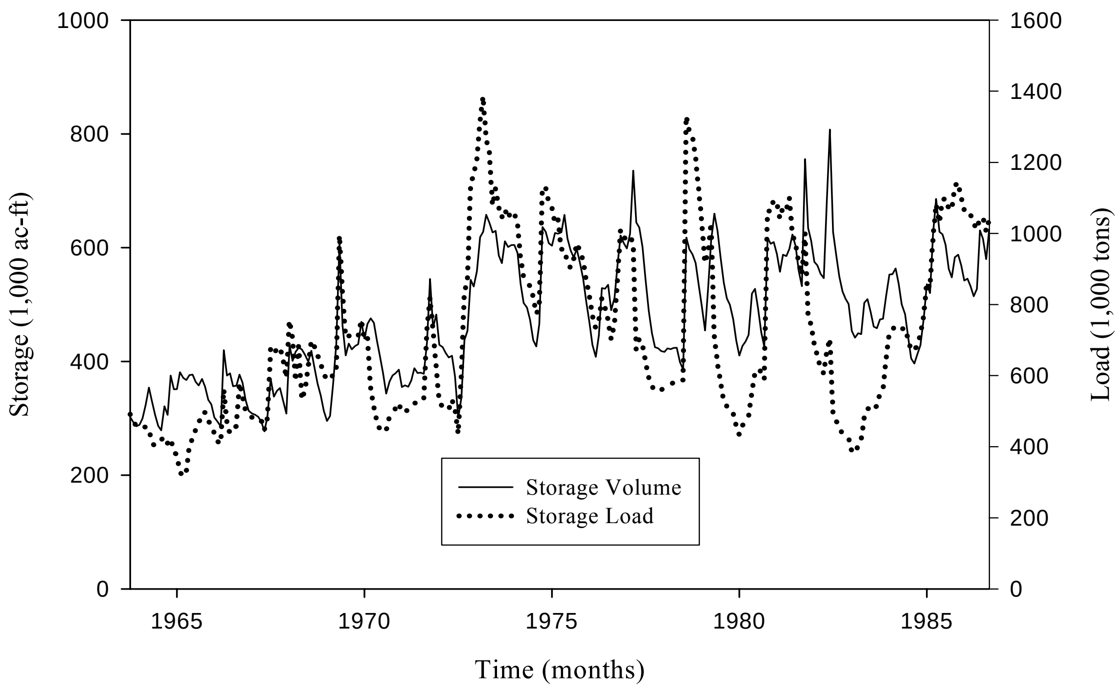

Figure 4.33 Comparison of Whitney Storage Volume and Load

Lake Whitney storage loads and concentrations computed in the salinity budget analyses without the storage concentration (SCA) are plotted in Figure 4.28 and comparison of Whitney storage concentrations before and after SCA is plotted in Figure 4.29. The 28 Lake Granbury measurement-based storage concentrations are plotted in Figure 4.30 along with the storage concentrations computed in the salinity budget analysis. The comparisons between measured and computed reservoirs concentrations of the Lake Whitney and Granbury represent similar patterns and values of TDS concentrations. The USGS computed volume-weighted mean dissolved solids concentrations of Lake Whitney based on surveys performed on the 30 dates. Likewise, volume-weighted mean dissolved solids concentrations of storage in Lake Granbury were developed by the USGS based on 28 water quality surveys during water years 1970-1979. The salinity budget for the reach between the Glen Rose and Whitney gages was adjusted to match the 30 measurement-based mean storage concentrations available for Lake Whitney. These TDS load budget adjustments are referenced here as storage concentration adjustments (SCA).

4.6.3 Comparisons of Reservoir Storage and Outflow Quantities

Figures 4.34, 4.35, and 4.36 compare storage concentrations developed by the salinity budget computations versus outflow concentrations for the three reservoirs. The outflow concentrations for Lakes Possum Kingdom and Whitney are the USGS observed concentrations at the Graford and Whitney gages. The outflow concentrations for Granbury plotted in Figure 4.18 are the concentrations at the Glen Rose gage computed in conjunction with developing the salinity budget.

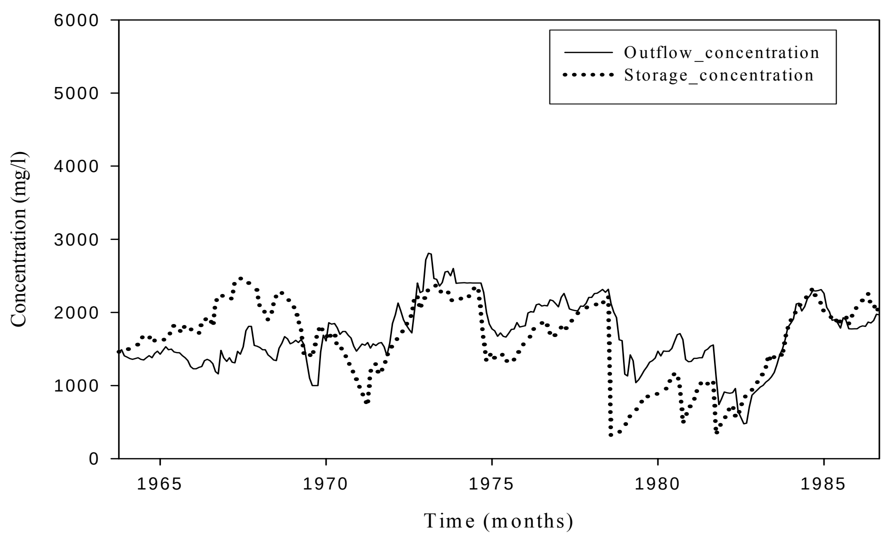

Figure 4.34 Comparison of Possum Kingdom Storage and Outflow Concentrations

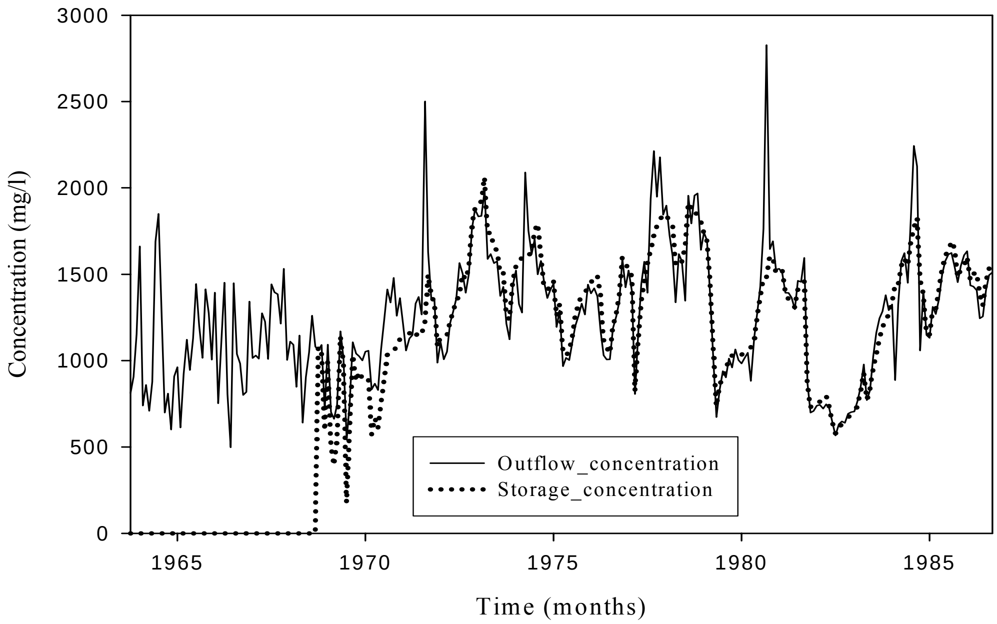

Figure 4.35 Comparison of Granbury Storage and Outflow Concentrations

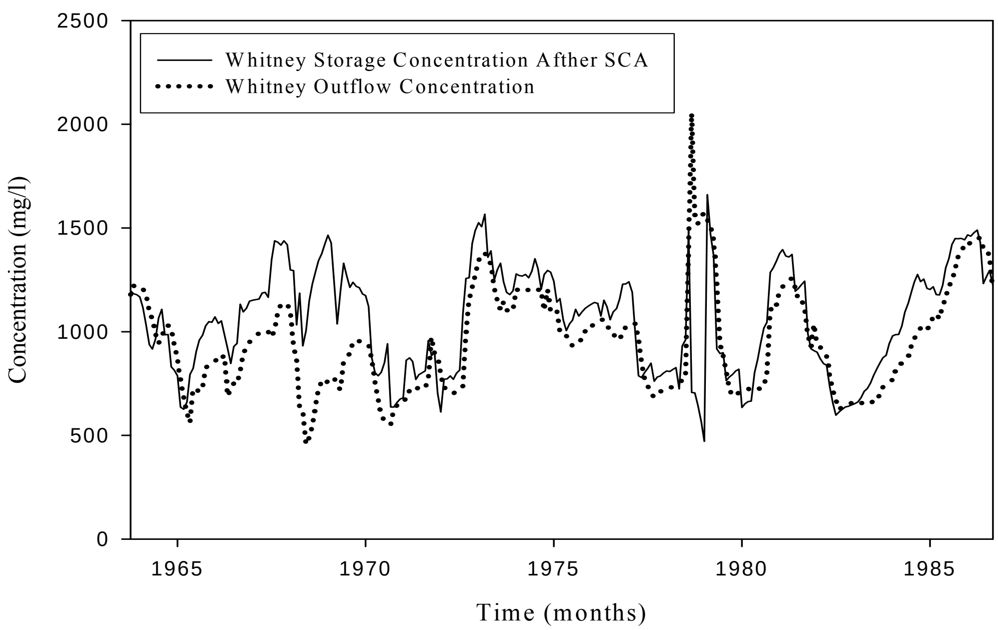

Figure 4.36 Comparison of Whitney Storage Concentrations after SCA and Outflow Concentrations

CHAPTER V

RELATIONSHIPS BETWEEN CONCENTRATIONS OF RESERVOIR OUTFLOW AND STORAGE

One of the objectives of this research is formulating, testing, and applying methods for routing salinity through reservoirs and determining parameters for the salinity routing methods. In this chapter, the investigation of the relationships between reservoir storage concentration and outflow concentration was performed to provide better understanding of the movement of the salinity between the reservoir and downstream gage located just below the reservoir.

The concentration of the reservoir outflow should be representative of the concentration of water stored in the reservoir near the outlet structure, which is different than the volume-weighted storage concentration. In reality, salt concentrations vary spatially, temporally throughout a reservoir. Streams carry salinity to the inlet of reservoir, and mixing occurs over time through a reservoir. A significant lag time may be required for the salt entering the reservoir to be mixed and transported to the reservoir outlet.

5.1 Relationships of Outflow Concentrations to Possum Kingdom and Whitney Reservoirs Storage Concentrations

As described in Table 3.1 and Table 3.2 of the Chapter III, Possum Kingdom and Whitney are very large reservoirs. Spatial variations in concentrations throughout the reservoirs at any instant in time may be significant. Likewise, long-term mean concentrations also vary spatially at different locations in the reservoir.

The reservoir outflow concentration refers to the TDS concentration in the Brazos River just below Morris Sheppard Dam (Possum Kingdom Lake) and Whitney Dam. The concentration of water flowing at these two locations on the river fluctuates over time and may vary significantly during the course of a month. The long-term 1964-1986 mean reservoir outflow concentration can be expected to be different than the long-term 1964-1986 mean volume-weighted storage concentration because inflows and outflows with different concentrations occur along the length of each reservoir. Concentrations in the Brazos River reservoirs are generally decreased by precipitation runoff from the local incremental watersheds entering the reach between the gages defining the upstream and downstream ends of the reach. Precipitation falling directly on the reservoir water surface also decreases the concentration of the water in storage. Evaporation from the reservoir water surface increases storage concentration. For each of the Brazos River reservoirs, river flows entering the reservoir have higher concentrations than the river flows below the dam.

The long-term 1964-1986 volume-weighted mean concentration of water stored in Possum Kingdom is 1,626 mg/l and the corresponding volume-weighted outflow concentration at the Graford gage is 1,534 mg/l. Thus, the mean outflow concentration is 94.3 percent of the storage concentration.

Whitney Reservoir volume-weighted storage concentration is 1,062 mg/l and the corresponding streamflow concentration at the Whitney gage is 927 mg/l. The mean flow concentration in the river below the dam is 87.3 percent of the Lake Whitney volume-weighted storage concentration.

Regression analyses were performed to examine relationships between reservoir storage concentration and outflow concentration for Possum Kingdom and Whitney Reservoir. Granbury Reservoir is not included in this chapter because of differences in the load budget analyses associated with differences in data availability and the later initial impoundment and size of Lake Granbury. The results from the investigation of the relationships between outflow concentration and reservoir storage concentration are used to examine the parameters for routing salinity through reservoirs in WRAP-SALT simulation.

Table 5.1 Correlation Coefficients and Regression Equations for Possum Kingdom and Whitney Outflow Concentration versus Storage Concentration

	Possum Kingdom		Whitney	
Lag Time (months)	Correlation Coefficient R	Linear Regression Equation	Correlation Coefficient R	Linear Regression Equation
0	0.966	F(X) = 0.9813 X	**0.979**	**F(X) = 0.8881 X**
1	0.968	F(X) = 0.9845 X	0.977	F(X) = 0.8858 X
2	**0.969**	**F(X) = 0.9865 X**	0.973	F(X) = 0.8826 X
3	0.968	F(X) = 0.9874 X	0.969	F(X) = 0.8785 X
4	0.966	F(X) = 0.9877 X	0.966	F(X) = 0.8759 X
5	0.964	F(X) = 0.9873 X	0.962	F(X) = 0.8730 X
6	0.961	F(X) = 0.9862 X	0.958	F(X) = 0.8705 X
7	0.959	F(X) = 0.9855 X	0.954	F(X) = 0.8684 X
8	0.956	F(X) = 0.9847 X	0.951	F(X) = 0.8664 X
9	0.953	F(X) = 0.9832 X	0.947	F(X) = 0.8646 X

The end-of-month storage is compared with the flow concentration at the downstream gaging station (Graford or Whitney) for the same month or a later month. The lag is the number of months for which the outflow concentration follows the storage concentration in the regression analyses and the plots.

Table 5.1 represents the linear regression equation and corresponding correlation coefficient (R) for the regression analyses. The character X denotes the reservoir storage concentration and F(X) represents the outflow concentration. A high value of the correlation coefficient may be perceived as implying high relationship between two variables. The linear regression analyses for Possum Kingdom Reservoir storage concentration and Graford gage outflow concentration provide the best fitting results (R=0.969) when the lag time is 2 months. With no lag time, correlation coefficient value for Whitney Reservoir storage and outflow concentration has the highest value (0.979). Even though correlation coefficients show decreasing trend when the lag time increases, lagging the outflow concentration was found to have little effect on the storage concentration versus outflow concentration relationship. The plots of the fitted linear regression line are provided in Appendix C.

5.2 Relationships of Outflow Concentrations to Storage Concentrations for Other Reservoirs in Texas

The main objective of this research is to investigate the impacts of salinity on water resources capabilities in Brazos River Basin. The previous section of this chapter described relationships of reservoir storage and outflow concentrations at Possum Kingdom and Whitney Reservoirs on the Brazos River. In this section, other selected reservoirs in Texas are analyzed to examine the movement of the salinity through the reservoir.

The best way to inspect the variation of the salinity concentrations throughout the reservoir is collecting the water quality data by field measurement. Even though the U.S. Geological Survey continues to collect the water quality data of numerous gaging stations in the U.S.A., only limited reservoir storage concentration data is available.. The salinity data of Kemp Reservoir in the Red River Basin, Red Bluff Reservoir in the Rio Grande Basin, Livingstone and Cedar Creek Reservoirs in the Trinity River Basin were collected and compared with the salinity data of downstream gaging stations.

5.2.1 Cedar Creek Reservoir in Trinity River Basin

Cedar Creek Reservoir is located in Henderson and Kaufman Counties, Texas. The project is owned and operated by the Tarrant Country Water Control and Improvement District No. 1 for municipal water supply. The storage capacity of Cedar Creek Reservoir is 679,200 acre-feet and surface area is 34,000 acres at operation elevation of 332 feet. Water is diverted from the reservoir for municipal and industrial uses by the cities of Arlington, Fort Worth, Mansfield, Kemp, Trinidad, and Mabank (Leibbrand et al. 1987). The drainage area above the dam is 1,007 square miles (Hendrickson 2006). Figure 5.1 represents the location and shape of Cedar Creek Reservoir.

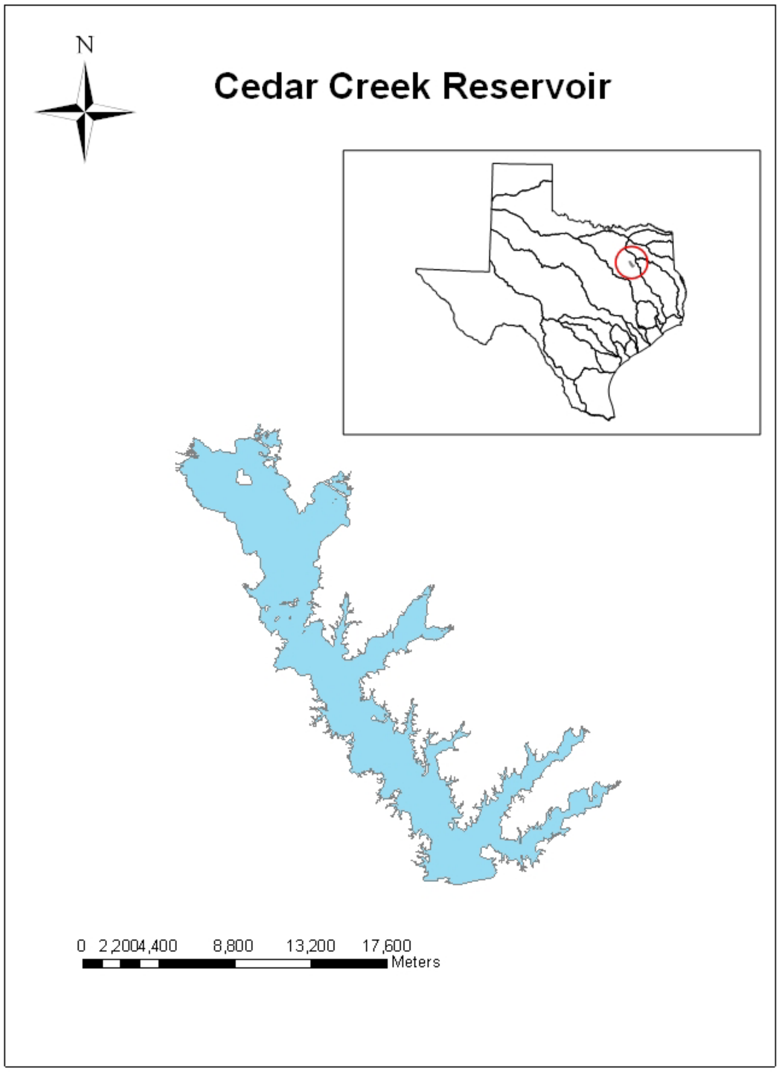

Figure 5.1 Geographic map of Cedar Creek Reservoir in Trinity River Basin

The U.S. Geological Survey has made comprehensive water-quality surveys of Cedar Creek Reservoir seasonally since January 1977, in cooperation with the Tarrant County Water Control and Improvement District No. 1 and the Texas Department of Water Resources. Water samples were collected and analyzed for the major dissolved chemical constituents, total nitrogen and phosphorus, and dissolved iron. In this research, TDS concentration data of Cedar Creek Reservoir were used to compare with TDS concentration of the downstream gaging station. The downstream gaging station is located at Cedar Creek Reservoir near Trinidad. USGS gaging station number is 08063010. Period-of-analysis is from January 1977 to June 1984.

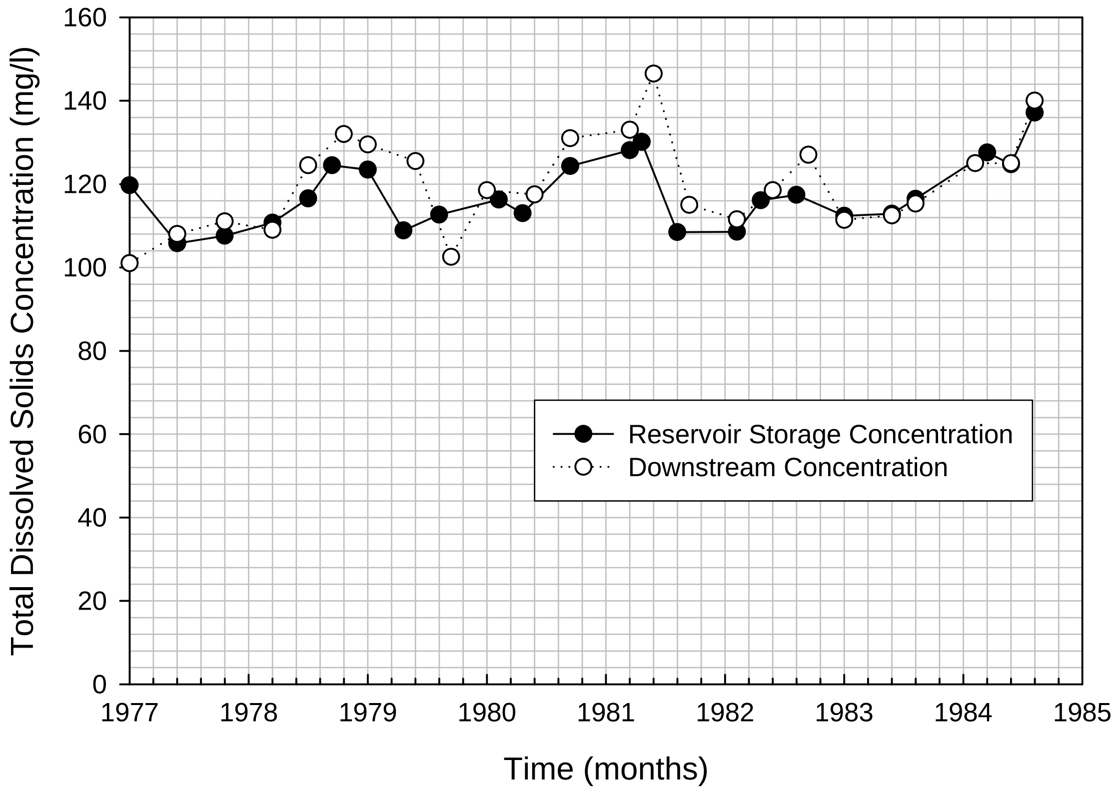

Figure 5.2 Comparison of Cedar Creek Reservoir Storage Concentration and Outflow Concentration

Cedar Creek Reservoir storage concentration and outflow concentration are compared in Figure 5.2. Data in Figure 5.2 indicate that from calendar year 1977 to 1984 the volume-weighted concentration of Cedar Creek Reservoir was less than 140 mg/l for total dissolved solids. Because there is no continuous data of both storage and outflow concentration during period-of-analysis and also, period of data collection is relatively short, it is difficult to exactly define the relationship between reservoir storage and outflow concentration. Figure 5.2 does not indicate significant trend of variation nor does it indicate an increasing trend in dissolved solids for Cedar Creek Reservoir. Arithmetic mean of TDS concentration of Cedar creek is 117.4 mg/l. Even though the outflow concentrations in some months were higher than the storage concentration, the trend of the changes of the concentration follows the storage concentration. The arithmetic mean of the outflow concentration is 120.5 mg/l and significant lag time was not detected between Cedar Creek Reservoir and outflow concentration.

5.2.2 Livingston Reservoir in Trinity River Basin

Livingston Dam is on the Trinity River about 6 miles southwest of Livingston in southeastern Texas. The reservoir extends across parts of Polk, San Jacinto, Trinity, and Walker Counties. Livingston Reservoir is owned and operated by the city of Houston and Trinity River Authority and was designed to conserve water for municipal supply, industrial use, and irrigation (Rawson et al. 1979). The reservoir has a normal capacity of 1,788,000 acre-feet, covers 82,600 acres, and drainage area is 16,616 square miles. The reservoir is used for municipal, industrial, and irrigation purposes. The geographical location and shape of Livingston Reservoir is represented in Figure 5.3.

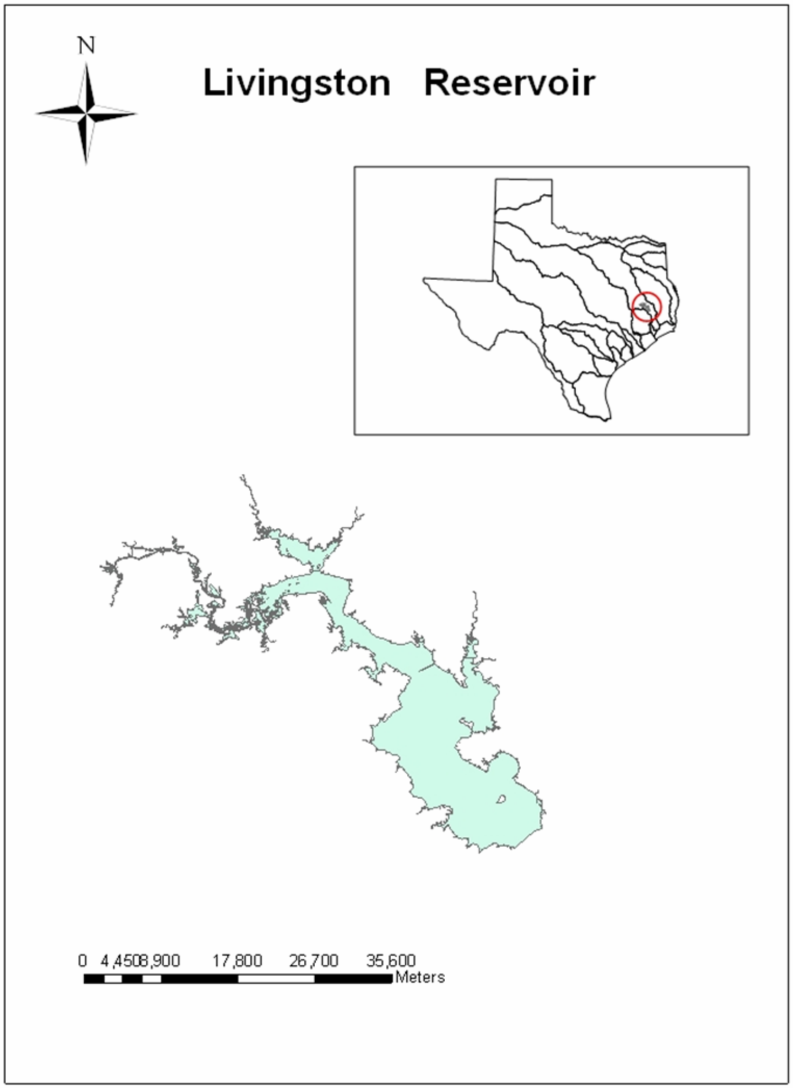

Figure 5.3 Geographic map of Livingston Reservoir in Trinity River Basin

U.S. Geological Survey published streamflow and water-quality data annually as the U.S. Geological Survey series Water Resources Data for Texas: Part 1. Surface-Water Records and Part 2. Water-Quality Records. Rawson (1979) complied and analyzed these data of the concentrations of dissolved solids, chloride, and sulfate in Livingston Reservoir on the Trinity River Basin. In this research, the data of total dissolved solids concentrations of Livingston Reservoir were obtained from this report. The downstream gaging station is located at Trinity River near Goodrich and USGS gaging station number is 08066250. The data of downstream gaging station were obtained from published USGS reports (Geological Survey (U.S.). Water Resources Division).

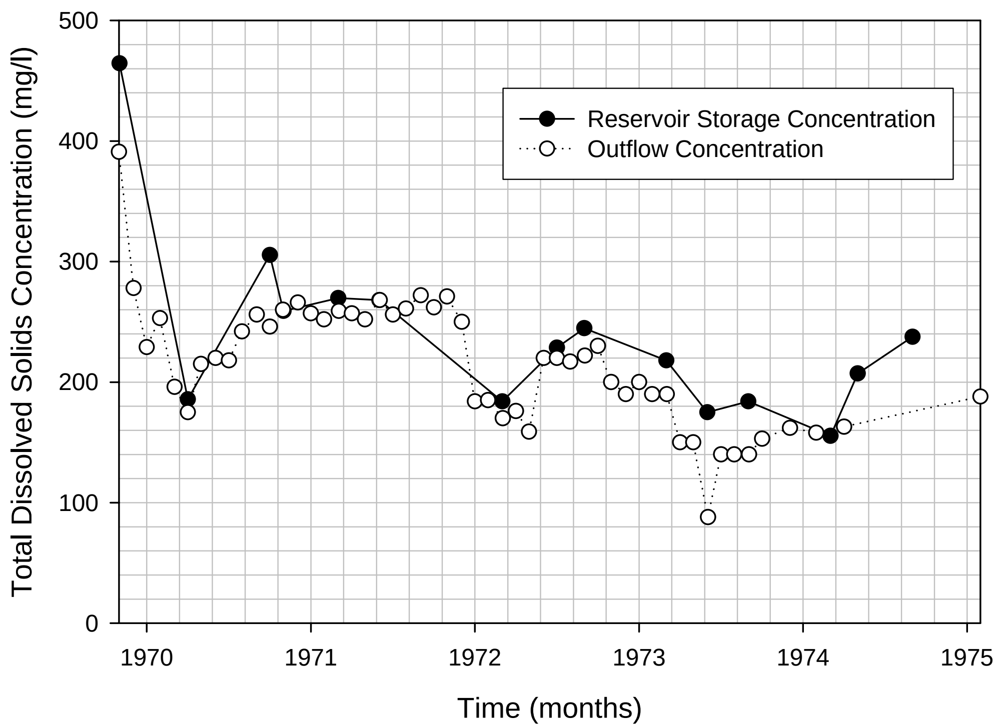

Figure 5.4 Comparison of Livingston Reservoir Storage Concentration and Outflow Concentration

Figure 5.4 compares the observed reservoir storage concentration with outflow concentration at Livingston Reservoir. Period-of-analysis is from October 1969 to July 1975. Arithmetic means of total dissolved solids concentration of Livingston Reservoir storage and outflow are 225.82 mg/l and 209.25, respectively. Data on Figure 5.4 show that outflow concentrations represent the trend of the changes of TDS concentrations in Livingston Reservoir. The seasonal variation in concentrations of dissolved solids of both storage and outflow represents that TDS concentrations during summer and fall season are higher than during spring season because evaporation is high and inflow is low. No significant lag time is detected.

5.2.3 Texoma Reservoir in Red River Basin

Denison Dam which forms Lake Texoma was built in 1942 by the U.S Army Corps of Engineers for flood control and hydroelectric power. Increasing needs for water have caused Lake Texoma to be considered as a source of water for public supply even though it has generally been too highly mineralized for this use. Water from Lake Texoma is pumped to Lake Randall to augment the municipal supply for the city of Denison (Leifeste et al. 1971).

Figure 5.5 represents the shape and location of Lake Texoma. Lake Texoma is on the Red River between Texas and Oklahoma in Grayson and Cooke counties, Texas, and Marshall Johnson, Bryan, and Love counties, Oklahoma. It spreads over 89,000 acres and is protected by Denison Dam, five miles northwest of Denison, Texas. Lake Texoma had a storage capacity of 2,722,000 acre-feet and a surface area of 91,200 acre (Dowell and Breeding 1967).

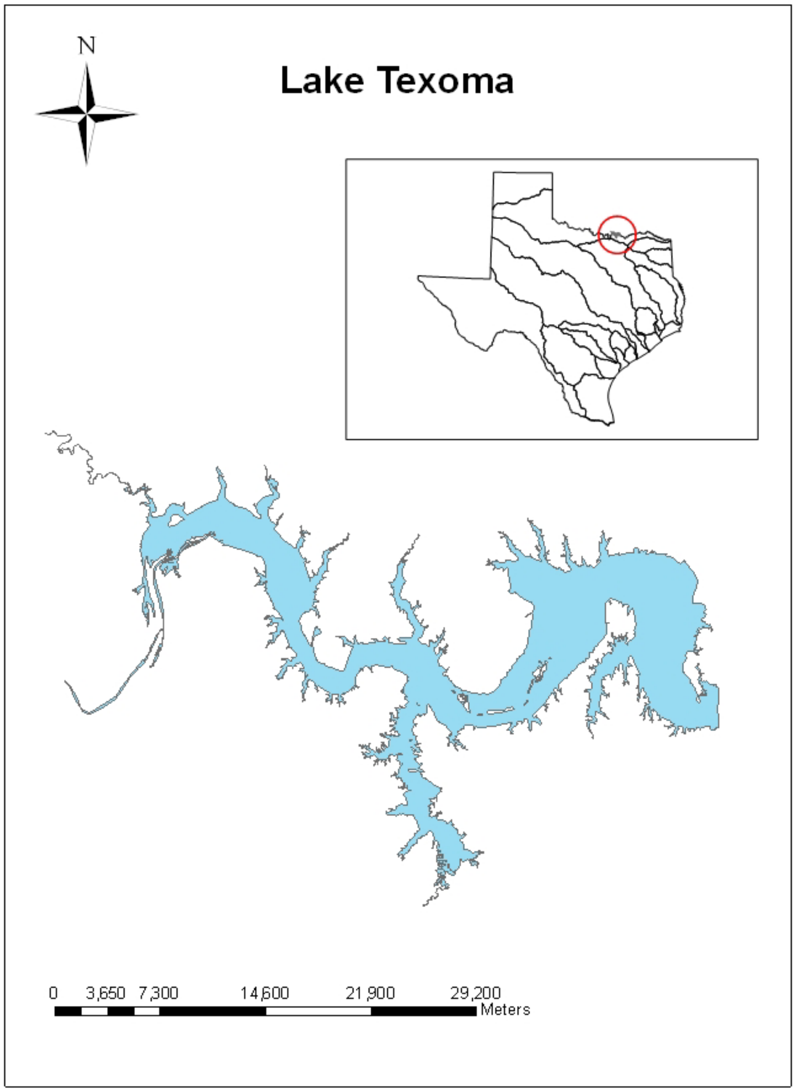

Figure 5.5 Geographic map of Lake Texoma in Red River Basin

The TDS concentration data of Lake Texoma has been collected since impoundment began in 1944 and ended in 1967. The downstream gaging station of Lake Texoma is located at Red River at Denison Dam near Denison, Texas. USGS gaging station number is 07331600.

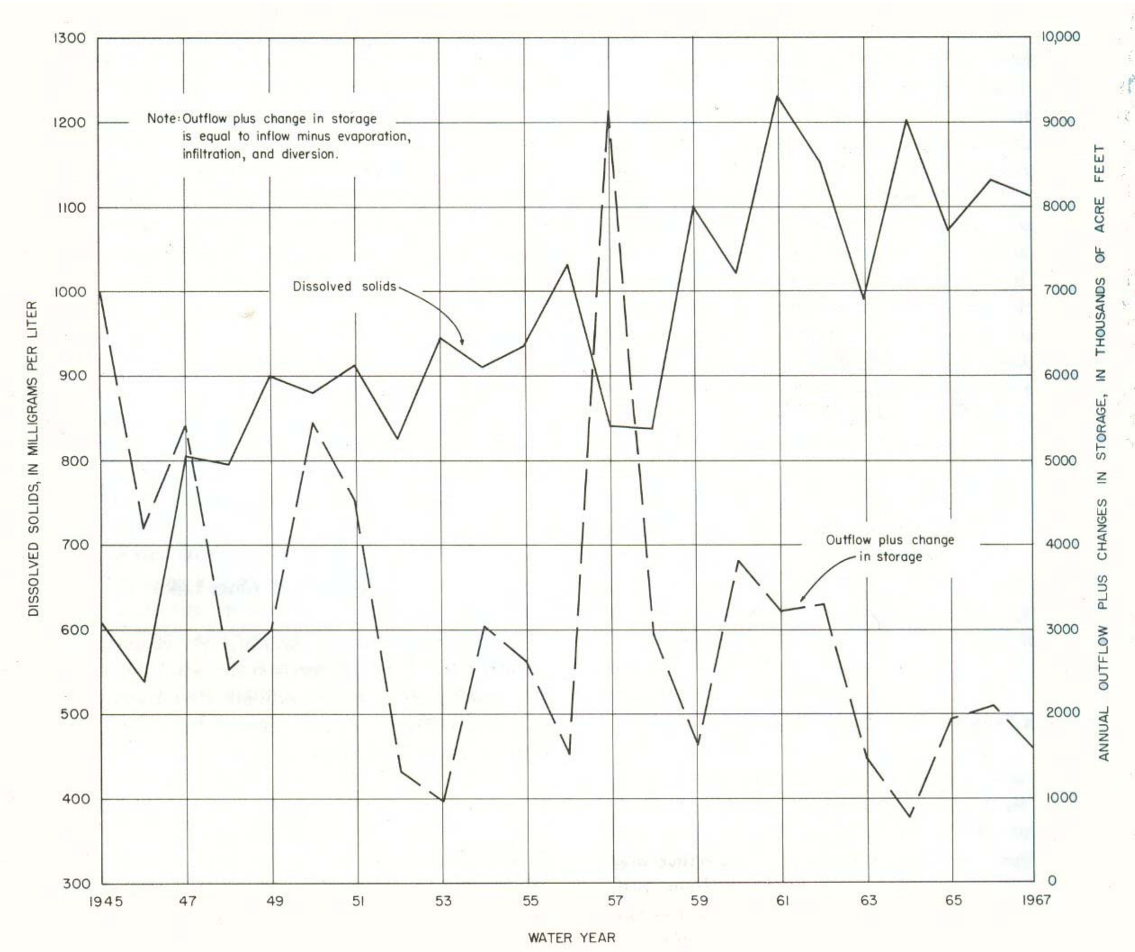

Figure 5.6 Graph Showing Dissolved-Solids Content and Quantity of Water in Lake Texoma, 1945-1967 (Leifeste et al. 1971)

Figure 5.6 represents dissolved solids concentrations in Lake Texoma during 1945 to 1967. The dissolved solids concentration has ranged from 989 to 1,230 mg/l. Data on Figure 5.6 show that 23 year of records of dissolved solids collected since impoundment began in 1944 have a significant trend of increasing concentrations. Even though the data collection for downstream gaging station (07331600) has been continued to the present since 1964, the work of data collection in Lake Texoma was ended in 1967.

Period-of-analysis is from 1964 to 1967 selected by considering the constraints of period-of-record.

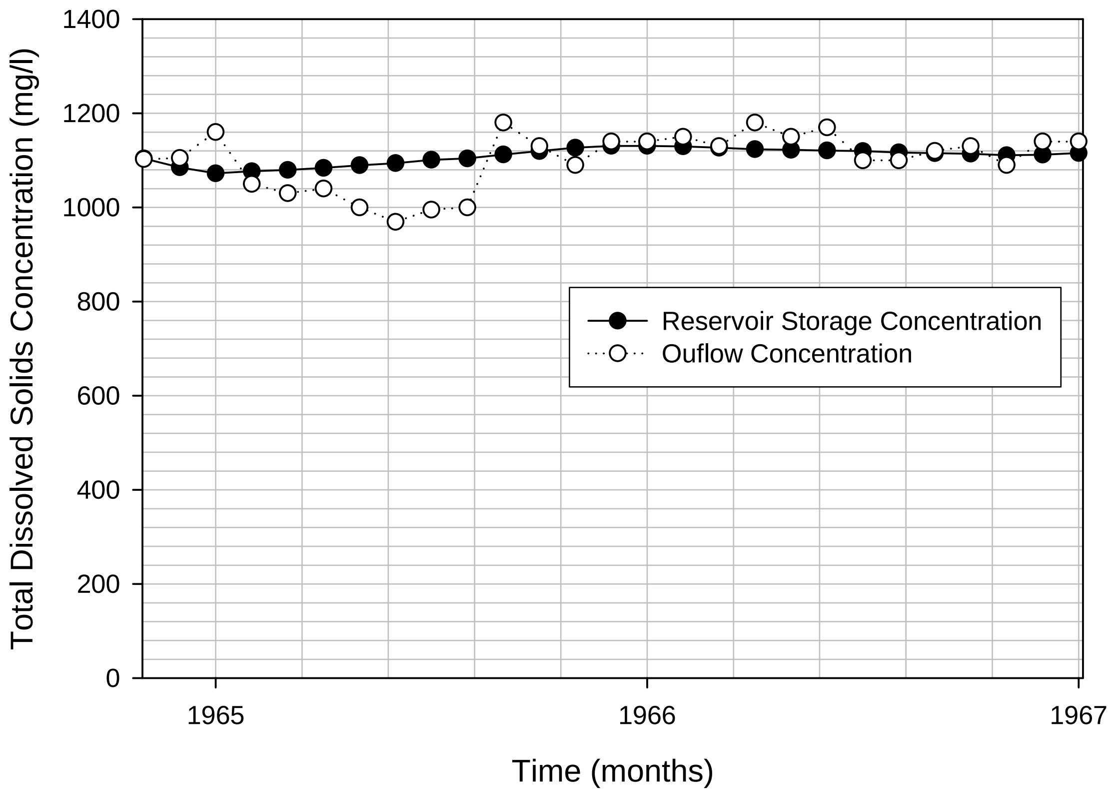

Figure 5.7 Comparison of Denison Reservoir Storage Concentration and Outflow Concentration

Data on Figure 5.7 represent the comparison of reservoir storage and outflow concentrations in Lake Texoma. Arithmetic mean of reservoir storage concentration during period-of-analysis is 1,118.3 mg/l and is little higher than the concentration of outflow concentration of 1,112.6 mg/l. The concentrations of the downstream gaging station and reservoir show similar trend in variation. There is no notable seasonal variation and lag time between reservoir storage concentration and outflow concentration.

5.2.4 Red Bluff Reservoir in Rio Grande River Basin

Red Bluff Reservoir is on the Pecos River in Reeves and Loving Counties, 45 miles north of Pecos. The drainage area of the reservoir is 20,720 square miles, with usable storage of 307,000 acre-feet. The reservoir is used for irrigation of 145,000 acres and for two hydroelectric units with a combined capacity of 2,300 kilowatts (Dowell and Breeding 1967). The location and geographic map are presented in Figure 5.8.

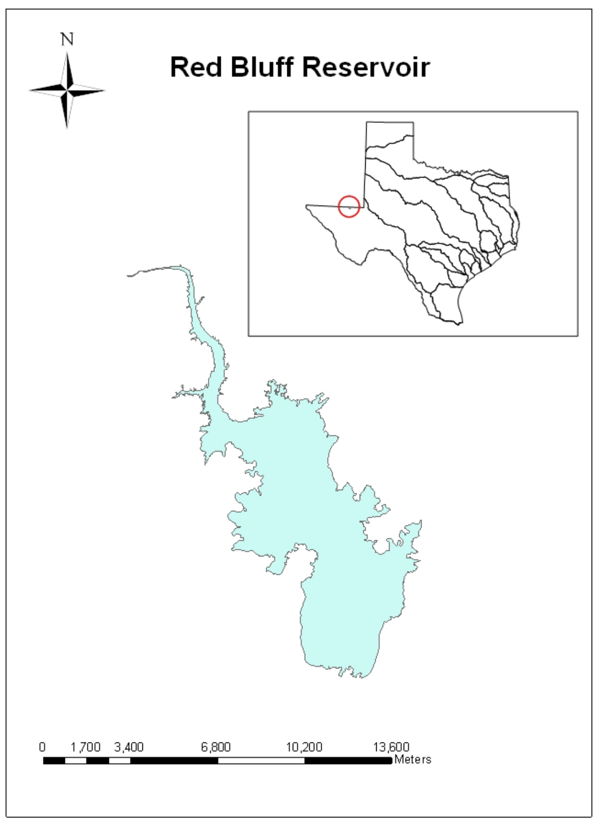

Figure 5.8 Geographic map of Red Bluff Reservoir in Rio Grande River Basin

Miyamoto (Miyamoto et al. 2007) complied the salinity data of Red Bluff Reservoir and developed water balance, salt loading, and salinity control options of Red Bluff Reservoir. The data of Red Bluff Reservoir storage concentration used in this research were obtained from the study of Miyamoto (Miyamoto et al. 2007).

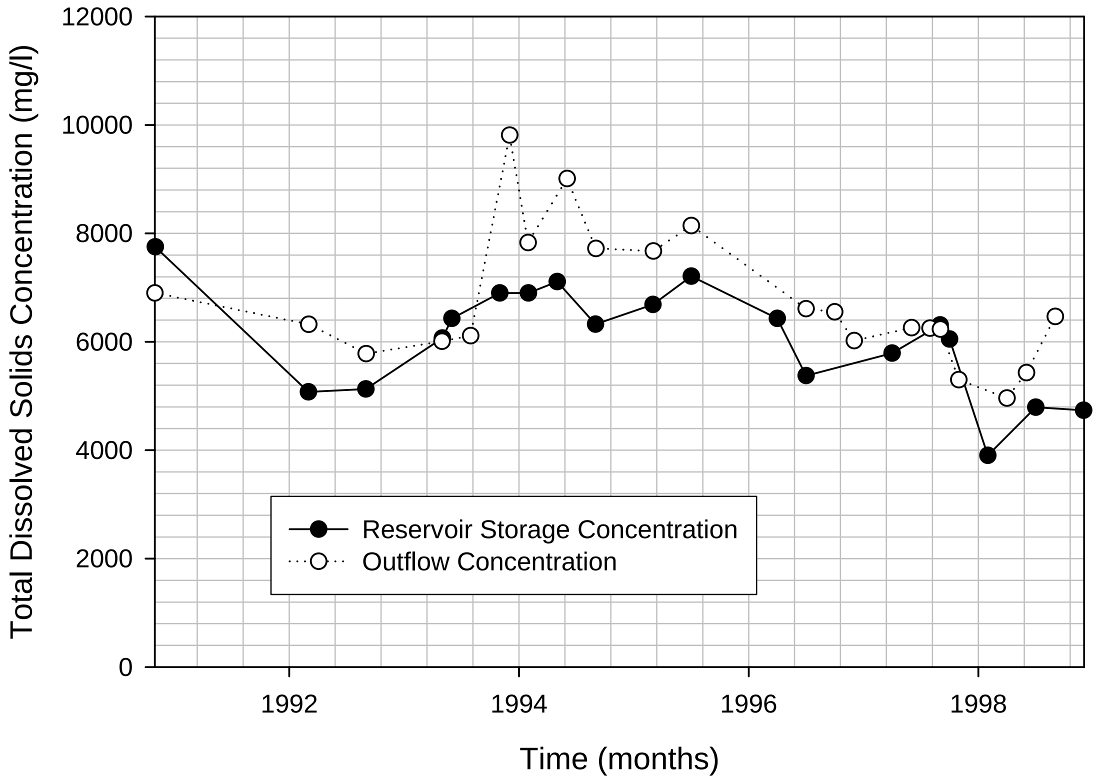

Figure 5.9 Comparison of Red Bluff Reservoir Storage Concentration and Outflow Concentration

Downstream gaging station of Red Bluff Reservoir is located at Pecos River near Orla (USGS station number, 08412500). Selected period-of-record is October 1990 through December 1998 for comparison with Red Bluff Reservoir storage concentration. As presented in Figure 3.1, Pecos River is affected by Permian Basin salt. Collected dataset of the TDS concentration at downstream gaging station shows higher values of concentration than the concentrations of the other river basins. Mean TDS concentration value of downstream gaging station is 6,732.1 mg/l. 6,732.1 mg/l is 188% higher than mean concentration of the Seymour gage in Brazos River Basin. 6,732.1 mg/l is about 14 times of second drinking water standard at TDS of 500 mg/l. Pecos River is affected directly by Permian Basin salt and relatively low streamflow might cause high concentration of Red Bluff Reservoir and downstream gaging station.

The comparison between observed storage concentration and outflow concentration is shown in Figure 5.9. Unlike the comparison results from Cedar Creek and Livingston Reservoirs, outflow concentrations are little higher than reservoir storage concentration. Arithmetic means of Red Bluff Reservoir storage and outflow concentration during period-of-analysis are 6,051.1 mg/l and 6,732.1 mg/l, respectively. The reason of high concentrations in outflow might be caused by the impact of surface inflow or groundwater of high salinity concentration between Red Bluff Reservoir and downstream gaging station. Because Texoma Reservoir is located at Permian salt source area as shown in Figure 3.1, surface streamflow from the tributary or seepage of subsurface groundwater of high concentration could affect on the downstream concentration.

CHAPTER VI

SALNITY ROUTING THROUGH RESERVOIRS

The salinity budget analyses presented in Chapter IV provide an enhanced understanding of the characteristics of dissolved solids moving through a river/reservoir system. The present Chapter VI investigates computational methods for routing salinity through reservoirs for incorporation into WRAP-SALT simulation routines and methods for determining values for the parameters of the routing methods.

6.1 Salinity Routing Methodology

The salinity budget study provides a dataset used to investigate salinity routing methods. The WRAP-SALT simulation includes computation of end-of-month reservoir storage concentrations and mean monthly reservoir outflow concentrations for each month of the simulation. The model computes reservoir storage loads and concentrations based on load balance accounting algorithms and computes concentrations of water released and withdrawn from a reservoir as a function of the volume-weighted mean concentration of the water stored in the reservoir in the current month or previous months. A load budget accounting of the various component load inflows and outflows entering and leaving a reservoir is performed. A time history of storage concentrations computed for previous months is maintained for use in the lag procedure.

Reservoir outflow concentration refers to the monthly concentration of the regulated streamflow in the river downstream of the dam and the monthly concentration of the water withdrawn from the reservoir as lakeside diversions. The computed downstream river flows and lakeside diversions may have either the same or different concentrations. Reservoir storage concentration is the volume-weighted concentration of the water stored in the reservoir either at the end of a month or the average of the beginning-of-month and end-of-month concentrations. The following statements represent two methods of routing reservoir.

1. The first component is a lag routine incorporating Equation 6-1 and 6-3. The outflow concentration for a particular month is computed as a function of the storage concentration in that month or 1, 2, 3, or more months earlier. The lag procedure relates the outflow concentration to the storage concentration that occurred some integer number of months earlier. The lag time in months may be entered as an input parameter or computed automatically within WRAP-SALT based on flow retention time and a multiplier factor input parameter.
2. The second component of the routing methodology is based on Equation 6-2 which is used to compute outflow concentration as a function of storage concentration in the current month or a previous month. The outflow concentration may exceed, be less than, or equal the storage concentration.

The outflow concentration is computed as a function of storage concentration.

$$OC_M = SC_{M-L} \tag{6-1}$$

OC_M denotes outflow concentration in month M, and SC is the storage concentration in month M-L (L months before month M). Lag L is an integer number of months. Equation 6.2 is an expanded version of Equation 6-1 with SC_{M-L} multiplied by a factor computed as a function of the two input parameters F_1 and F_2. With F_1 and F_2 defaults of 1.0, Equation 6-2 reduces to Equation 6-1. With a zero for the lag L, and 1.0 for F_1 and F_2, the reservoir outflow concentration equals the storage concentration. The parameter F_1 and F_2 allows the outflow concentration to differ from the storage concentration.

$$OC_M = SC_{M\text{-}L} \times F_1 \left[1.0 + \left(\frac{V}{V_C} \right) \left(F_2 - 1.0 \right) \right] \tag{6.2}$$

V_C in Equation 6.2 is a storage volume entered as an input parameter which is typically the storage capacity of the reservoir. V is the average storage contents of the reservoir during the current month computed within WRAP-SALT. The ration V/V_C represents storage contents as a fraction of capacity or other specified volume.

The lag (L) in months may be entered directly as an input parameter. Alternatively, the lag L may be computed internally within WRAP-SALT based on the concept of retention time.

$$\text{retention time } T_R \text{ in months} = \frac{\text{reservoir storage volume}}{\text{outflow volume per month}}$$

WRAP-SALT includes an algorithm for summing reservoir storage volume and outflow volume over multiple months for use in computing a retention time T_R. The lag time L is computed by WRAP-SALT as the following function of retention time T_R. L is truncated to an integer number of months. The multiplier factor F_L is an input parameter with a default of 1.0.

$$L = T_R (F_L) \tag{6.3}$$

Two approaches are available for setting the lag parameter L. The first option is for L to be a constant integer provided by the model-user as an input parameter. The second option is for L to be computed within WRAP-SALT based on Equation 6-3 with the parameter F_L provided by the user as an input parameter. With the second option, the lag is allowed to vary from month to month.

6.2 Development of Input Dataset of WRAP-SALT for Validating and Calibrating Salinity Routing Methods

An input dataset of WRAP-SALT was developed for purposes of calibrating salinity routing parameters based on the volume and load budgets and validating salinity routing methods. The reservoir storage and release concentrations computed by WRAP-SALT with alternative values for salinity routing parameters are then compared with the corresponding concentrations from the salinity budget. The volume budget results are adopted as a fixed given. The load budget results were used to develop the salinity input file of WRAP-SALT.

The SIM output file (treated by WRAP-SALT as an input file) and the WRAP-SALT salinity input file model the salinity budget study system of six river reaches and three reservoirs as mentioned at Chapter IV.

All quantities in the WRAP-SIM output file are monthly values for each of the 276 months of the October 1963 through September 1986 simulation period-of-analysis. The WRAP-SIM output file was simplified to include only the following variables:

- naturalized streamflows at all control points
- regulated streamflows at all control points
- diversion targets for the Granbury control point
- reservoir storage volumes for the Possum Kingdom, Granbury, and Whitney
- reservoir evaporation volumes for the Possum Kingdom, Granbury, and Whitney

For purposes of the simulation, naturalized flows are defined as the flows that would occur without the storage/release/evaporation effects of the three reservoirs. Regulated flows are the actual observed flows. The difference between regulated and naturalized flows is the volume changes associated with the storage/release/evaporation effects of the three reservoirs. The diversion targets at the Granbury control points are the actual recorded diversions at Lake Granbury. Zero is entered in the WRAP-SIM output file for diversion shortages, making the diversion targets equal actual diversions. The end-of-month storage volumes for each of the three reservoirs and monthly reservoir surface net evaporation-precipitation volumes are also included in the WRAP-SIM output file.

In developing input dataset, all volume inflows and outflows between control points were aggregated in a single 1964-1986 series of incremental flows. Likewise, all load inflows and outflows were aggregated into 1964-1986 sequences of incremental loads.

Salt loads entering the river system at the Seymour control point are the observed salt loads at the Seymour gaging station since the Seymour control point is the most upstream control point. The salt loads entering at the other control points are the net aggregated incremental loads between that control point and the next upstream control point.

Table 6.1 Mean Monthly Flow Volumes (acre-feet/month) of WRAP-SIM Simulation

Control Point	Naturalized Flow	Regulated Flow	Incremental Flow Volume			Storage Change	Net Evap	Diversion
			Inflow	Outflow	Net			
Seymour	16,215	16,215				-0-	-0-	-0-
			22,913	416	22,497			
South Bend	38,712	38,712				-0-	-0-	-0-
			10,240	1,967	8,273			
PK Graford	46,985	42,999				255	3,731	-0-
			15,280	1,202	14,078			
Dennis	61,063	57,077				-0-	-0-	-0-
			6,354	776	5,578			
Granbury	66,641	59,919				541	1,272	924
			1,996	244	1,752			
Glen Rose	68,393	61,670				-0-	-0-	-0-
			19,447	2,233	17,214			
Whitney	85,607	74,193				1,088	3,603	-0-

The volume and load budget summaries presented in Table 4.4 through 4.6 of Chapter IV are rearranged as Table 6.1, Table 6.2, and Table 6.3 to support the explanation of the procedure adopted for creating a WRAP-SALT input dataset to validate and calibrate salinity routing methods. Table 6.1 and Table 6.2 are tabulations of mean flow volumes in acre-feet/month and the corresponding mean TDS loads in tons/month. Table 6.3 shows the concentrations obtained by dividing the Table 6.2 loads by the Table 6.1 flow volumes.

Table 6.2 Summary of Mean Monthly Loads (tons/month) in WRAP-SALT Input File

Control Point	Naturalized Flow	Regulated Flow	Incremental Flow Load			Storage Change	Diversion
			Inflow	Outflow	Net		
Seymour	79,127	79,127				-0-	-0-
			28,069	2,128	25,941		
South Bend	105,068	105,068				-0-	-0-
			3,759	17,203	−13,444		
PK Graford	91,624	89,712				1,911	-0-
			6,939	5,177	1,762		
Dennis	93,386	91,475				-0-	-0-
			2,332	1,154	1,178		
Granbury	94,564	89,649				1,149	1,855
			733	365	368		
Glen Rose	94,932	90,017				-0-	-0-
			13,883	8,506	5,377		
Whitney	100,309	93,538				1,856	-0-

Table 6.3 Concentrations for Quantities in Table 6.1 and 6.2 (milligrams/liter)

Control Point	Naturalized Flow (mg/l)	Regulated Flow (mg/l)	Incremental Flow			Storage Change (mg/l)	Diversion (mg/l)
			Inflow (mg/l)	Outflow (mg/l)	Net (mg/l)		
Seymour	3,589	3,589				-0-	-0-
			901	3,762	848		
South Bend	1,996	1,996				-0-	-0-
			270	6,432	-1,195		
PK Graford	1,434	1,534				5,512	-0-
			334	3,168	92		
Dennis	1,125	1,179				-0-	-0-
			270	1,094	155		
Granbury	1,044	1,100				1,562	1,476
			270	1,100	154		
Glen Rose	1,021	1,074				-0-	-0-
			525	2,801	230		
Whitney	862	927				1,254	-0-

The TDS loads in Table 6.2 correspond to the volumes in Table 6.1. The net incremental flow loads are provided as input in the WRAP-SALT salinity input file. These are the salt loads entering the river/reservoir system.

6.3 Simulation Results of Validating the Salinity Routing Methodology

WRAP-SALT computes reservoir outflow concentrations as a function of storage concentration. There are two options to compute reservoir outflow concentrations by the input parameter TM.

TM option 1

Reservoir outflow concentration = mean storage concentration during month

TM option 2

Reservoir outflow concentration = storage concentration at beginning of month

Simulation results are presented here alternatively with TM option 1 and 2. The lag L defined in Equation 6-1 is set at zero and the parameters F_1 and F_2 in Equation 6-3 are set at the defaults of 1.0. The retention-based lag option represented by Equation 6-2 is not applied in these simulations.

Mean concentrations resulting from the WRAP-SALT simulation are compared with the mean observed concentration from the salinity budget study in Table 6.4. For the 276 months in the 1964-1986 simulation, the Seymour gage control point has a mean regulated TDS concentration of 3,589 mg/l. The mean regulated TDS concentration at the South Bend gage is 1,996 mg/l. Due to the manner in which the WRAP-SALT input dataset was created, with none of the three reservoirs located upstream, the concentrations at the Seymour and South Bend gages must be exactly the same in the WRAP-SALT results and salinity budget study. The reservoir storage and outflow concentrations vary between the WRPA-SALT simulation results and salinity budget study affecting simulation results at the control point of each reservoir and downstream control points.

Table 6.4 Comparison of Simulated and Observed 1964-1986 Mean Concentrations

Control Points and Reservoirs	Simulated Concentrations TM Option 1 (mg/l)	Simulated Concentrations TM Option 2 (mg/l)	Observed Concentration (mg/l)
Stream Flow Concentrations			
Seymour gage	3,589	3,589	3,589
South Bend gage	1,996	1,996	1,996
Graford gage	1,539	1,540	1,534
Dennis gage	1,195	1,196	1,204
Lake Granbury	1,109	1,110	-
Glen Rose gage	1,076	1,077	1,073
Whitney gage	928	929	927
Reservoir Storage Concentrations			
Lake Possum Kingdom	1,689	1,611	1,626
Lake Granbury	1,271	-	1,302
Lake Whitney	923	962	1,062

Flow and storage concentration from the water and salinity budget study and WRAP-SALT simulations with TM option 1 and 2 activated are compared in the plots of Figure 6.1 through Figure 6.24. The reservoir storage and outflow concentration results are almost the same with either of the two alternative TM options.

Figure 6.10 – Figure 6.12 and Figure 6.19 – Figure 6.21 compare simulated end-of-month reservoir storage concentrations with the observed concentrations of flow during the month at the nearest gage located downstream of the dam. These plots provide a means to visualize the time lag between storage concentration and outflow concentration. However, the plots do not appear to display a pronounced lag effect. As a minor note, the timing is off by about half of a month in the plots since the end-of-month storage concentration is plotted with the mean flow concentration during the month.

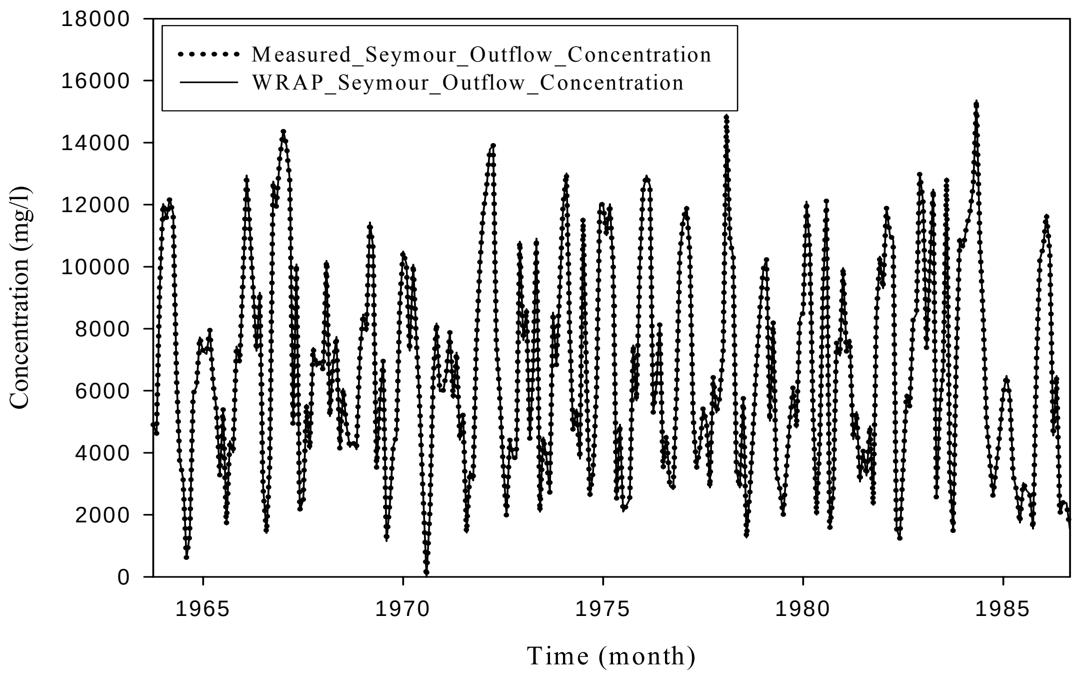

Figure 6.1 Observed and Simulated Concentrations at Seymour Gage (TM option 1)

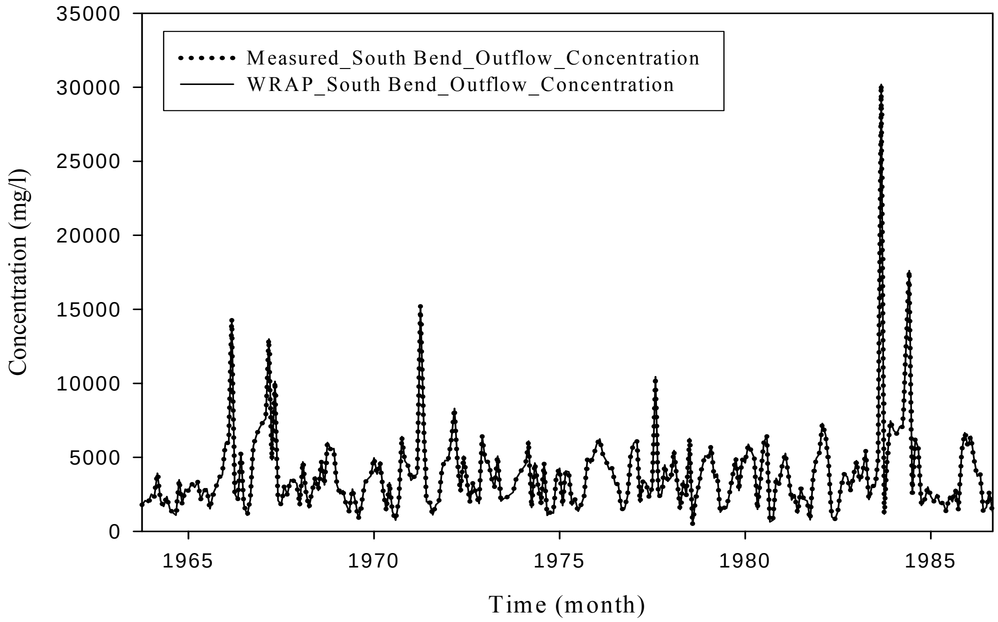

Figure 6.2 Observed and Simulated Concentrations at South Bend Gage (TM option 1)

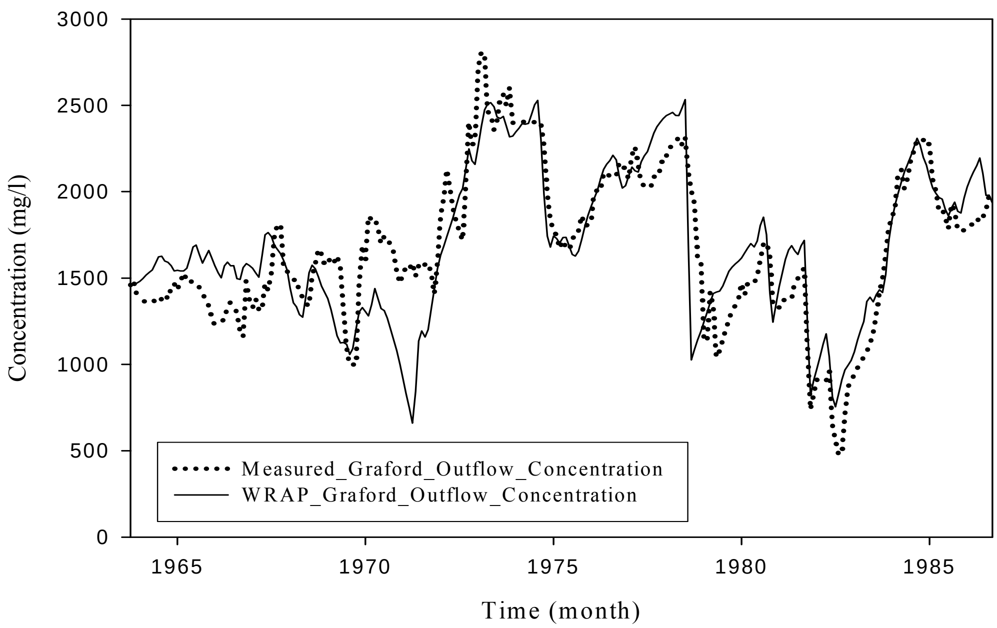

Figure 6.3 Observed and Simulated Concentrations at Graford Gage (TM option 1)

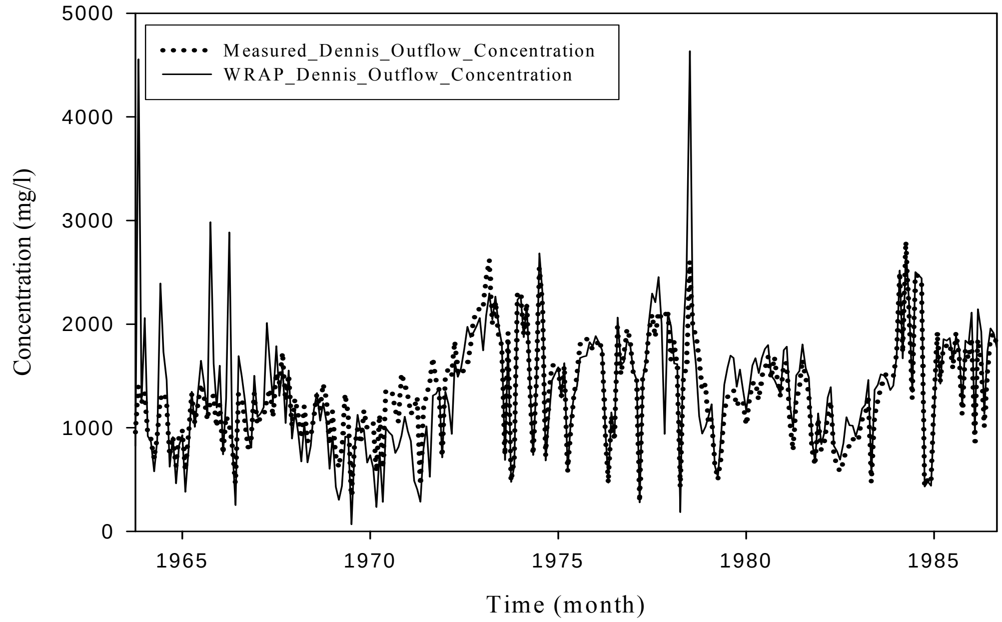

Figure 6.4 Observed and Simulated Concentrations at Dennis Gage (TM option 1)

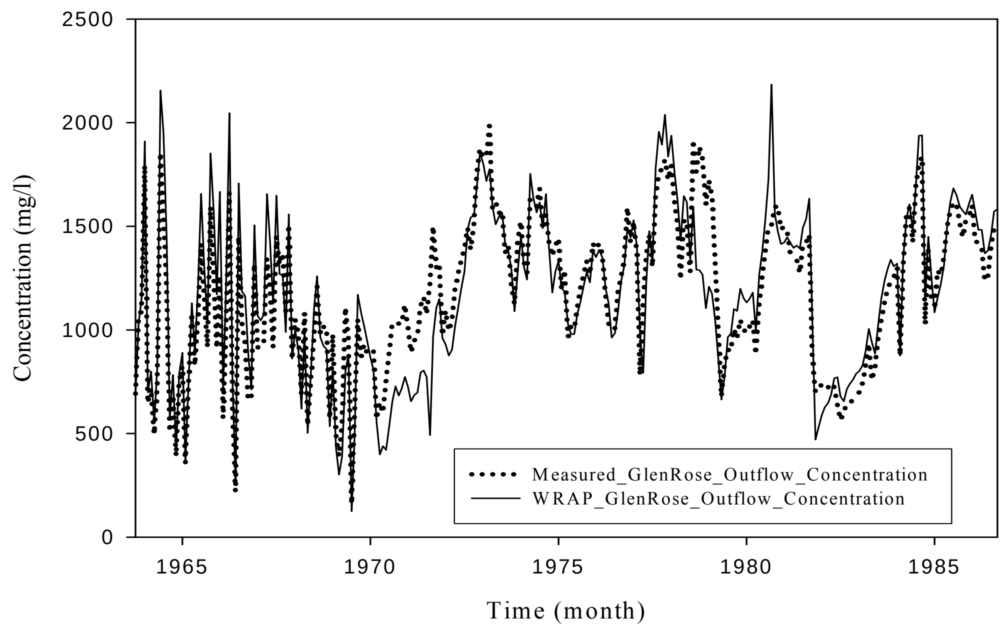

Figure 6.5 Observed and Simulated Concentrations at Glen Rose Gage (TM option 1)

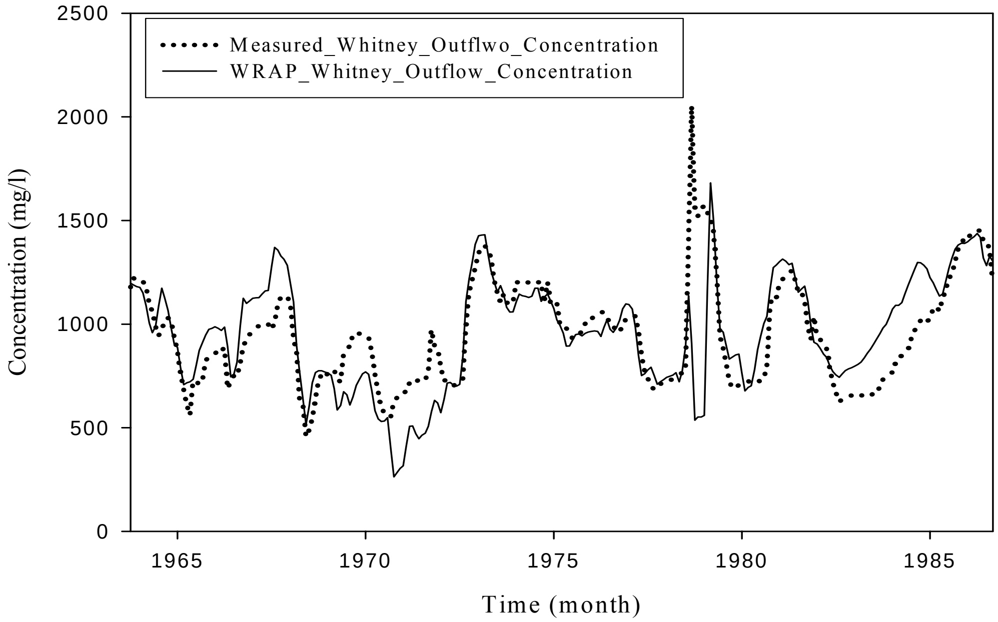

Figure 6.6 Observed and Simulated Concentrations at Whitney Gage (TM option 1)

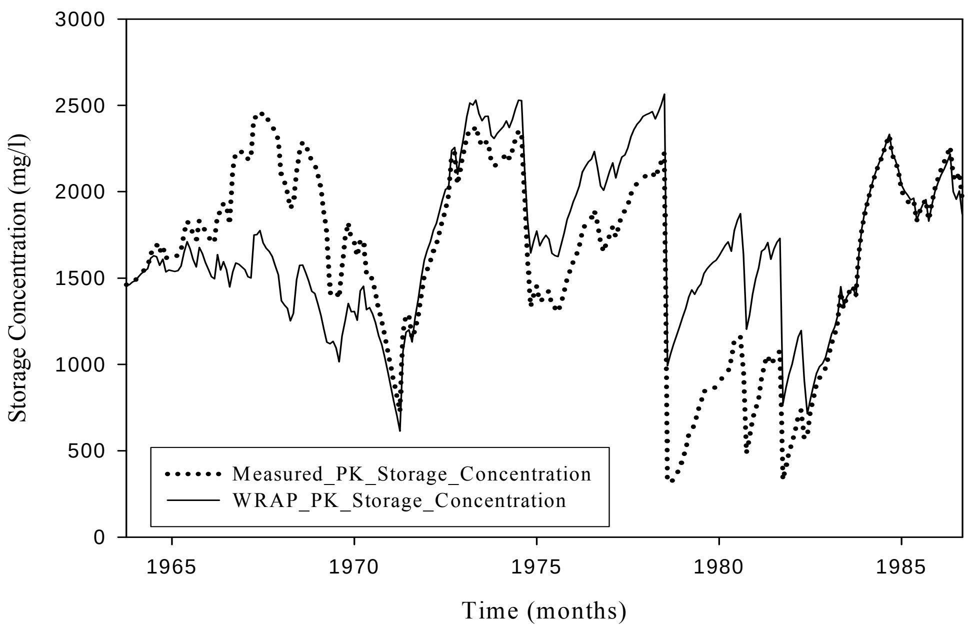

Figure 6.7 Possum Kingdom Reservoir Storage Concentration (TM option 1)

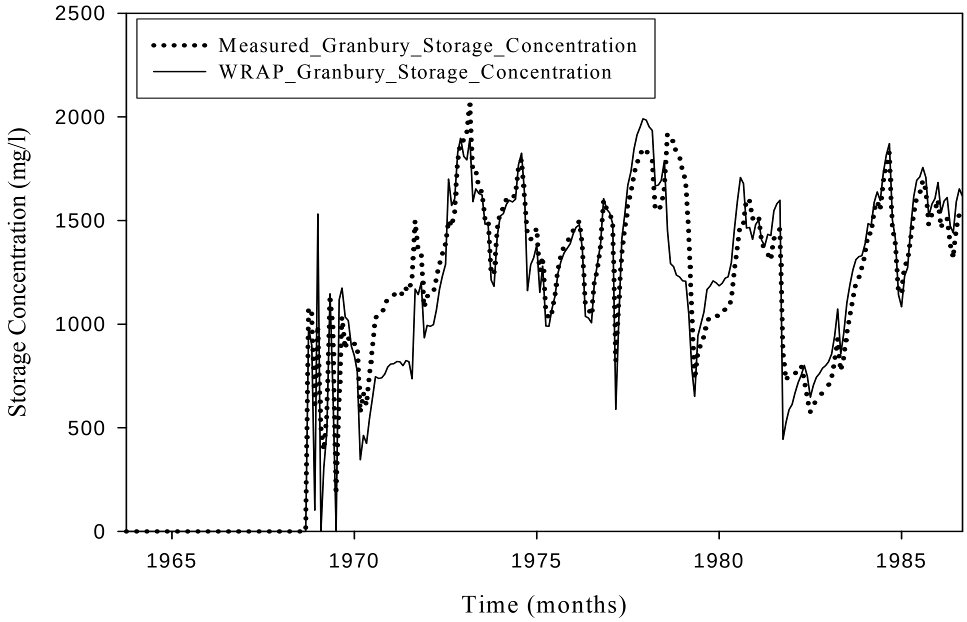

Figure 6.8 Granbury Reservoir Storage Concentration (TM option 1)

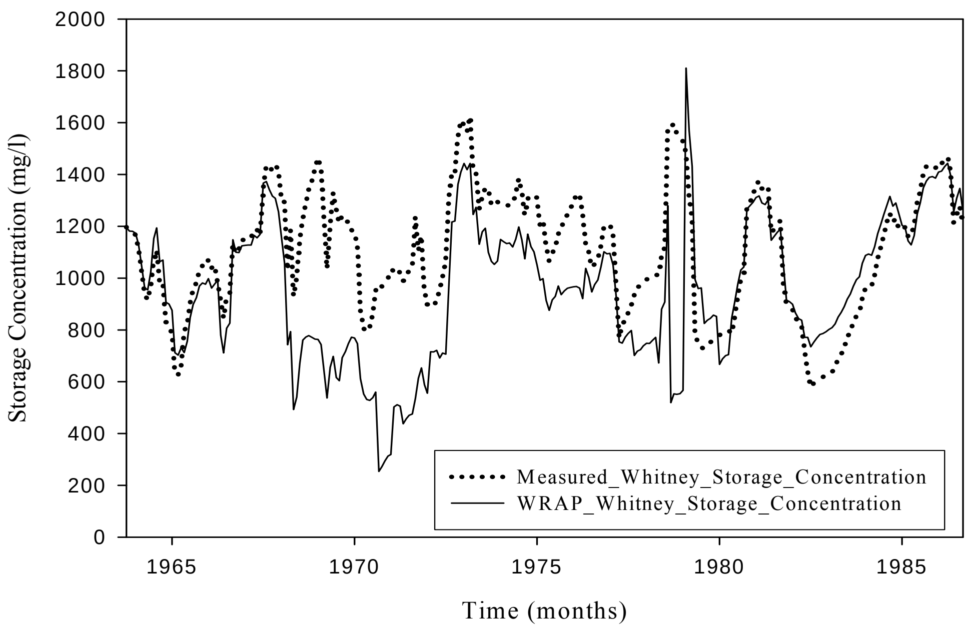

Figure 6.9 Whitney Reservoir Storage concentration (TM option 1)

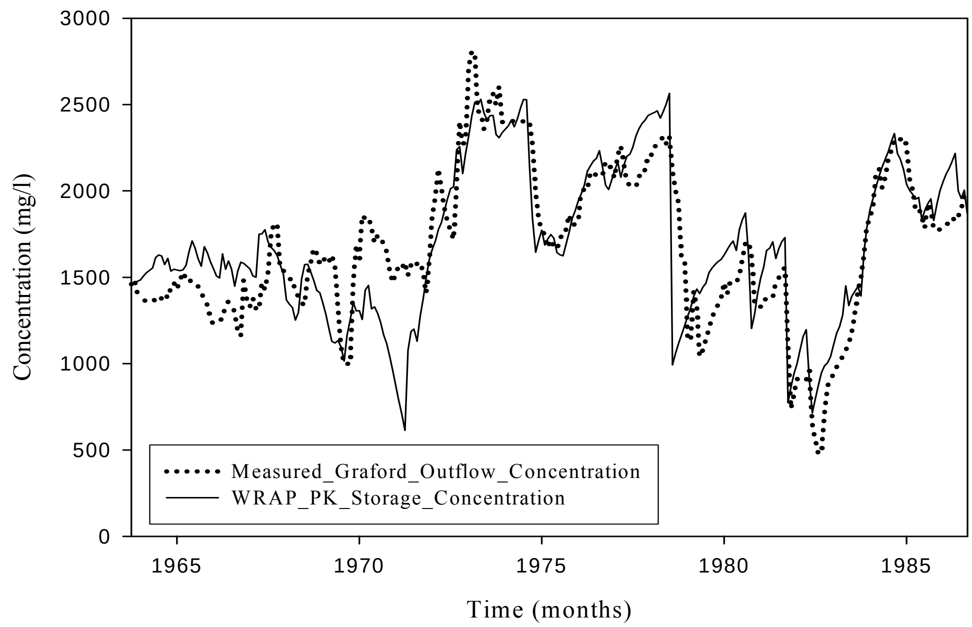

Figure 6.10 Possum Kingdom Simulated Storage Concentration and Graford Gage Observed Flow Concentration (TM option 1)

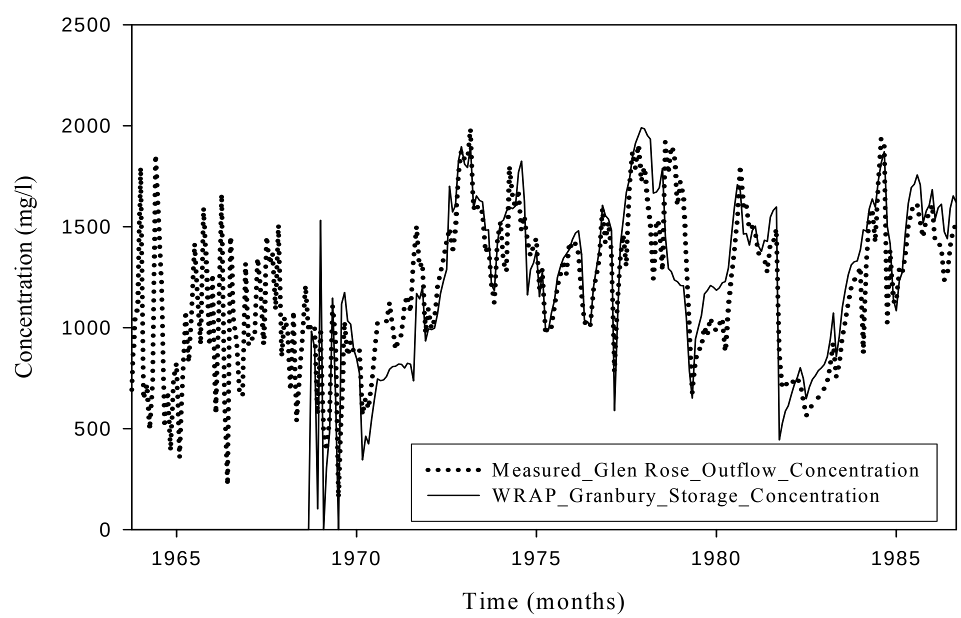

Figure 6.11 Granbury Simulated Storage Concentration and Glen Rose Gage Observed Flow Concentration (TM option 1)

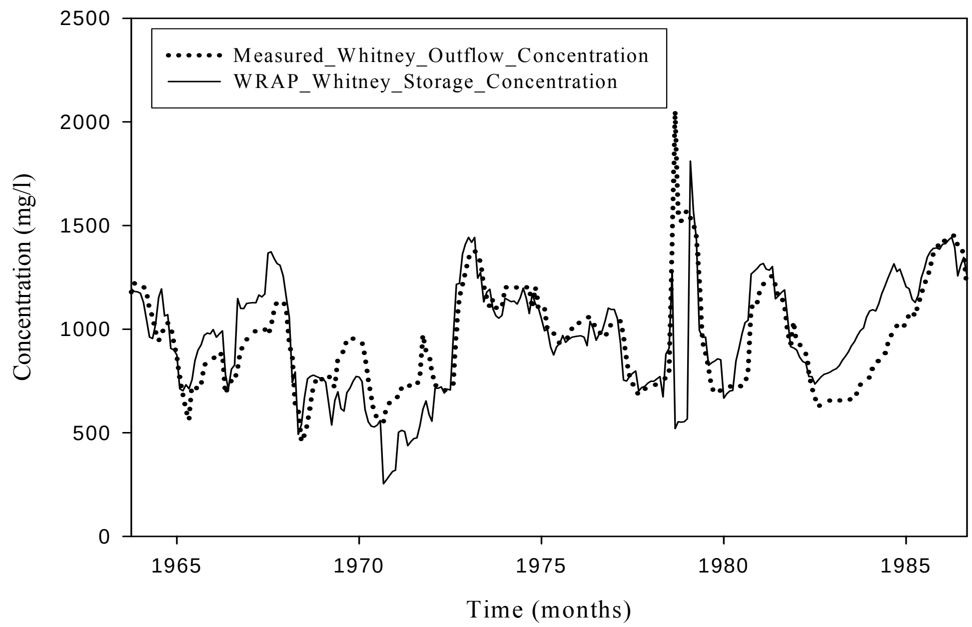

Figure 6.12 Whitney Simulated Storage Concentration and Whitney Gage Observed Flow Concentration (TM option 1)

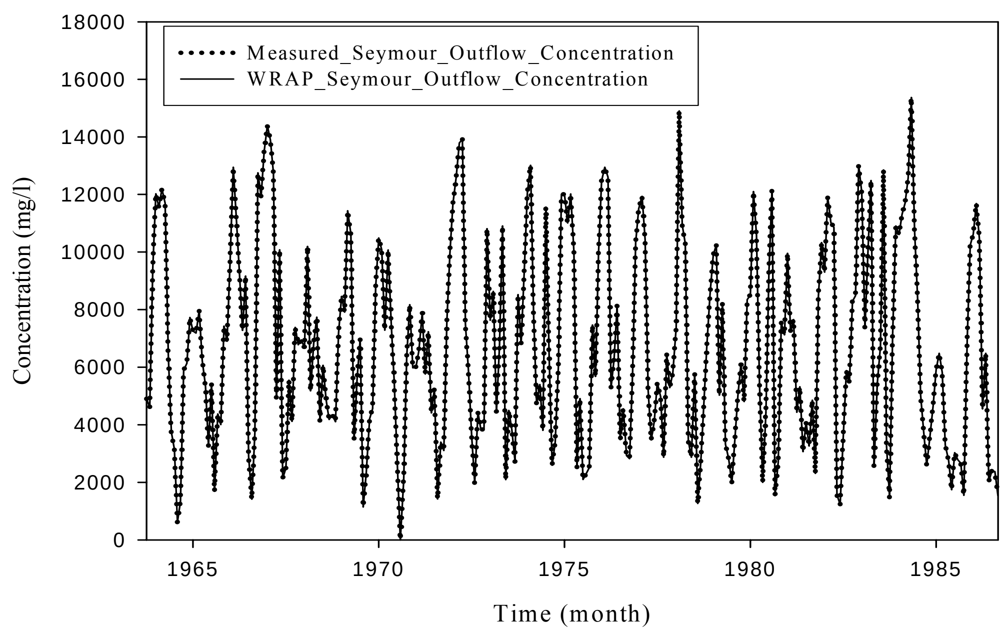

Figure 6.13 Observed and Simulated Concentrations at Seymour Gage (TM option 2)

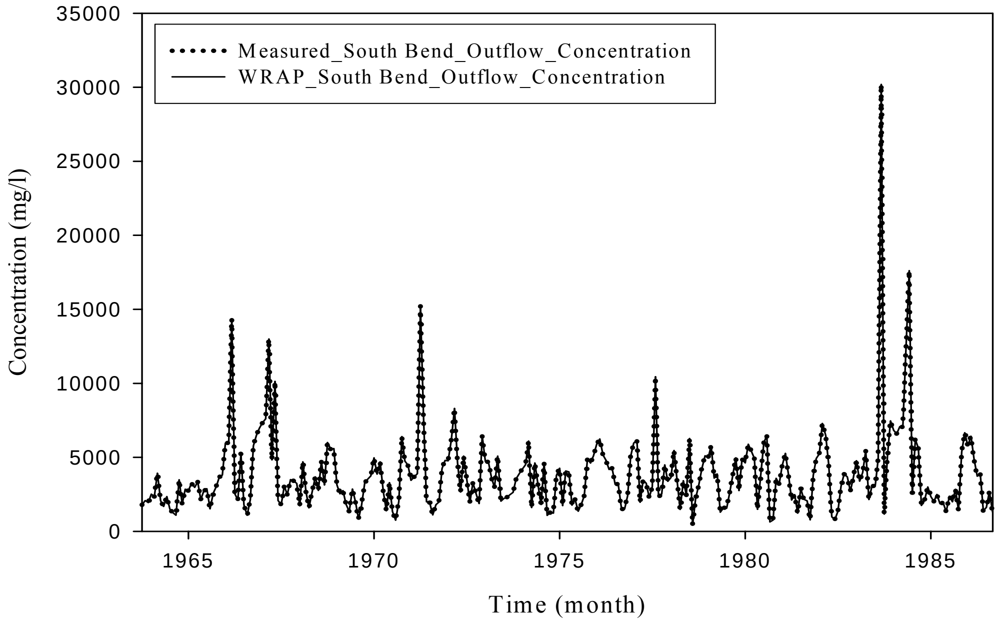

Figure 6.14 Observed and Simulated Concentrations at South Bend Gage (TM option 2)

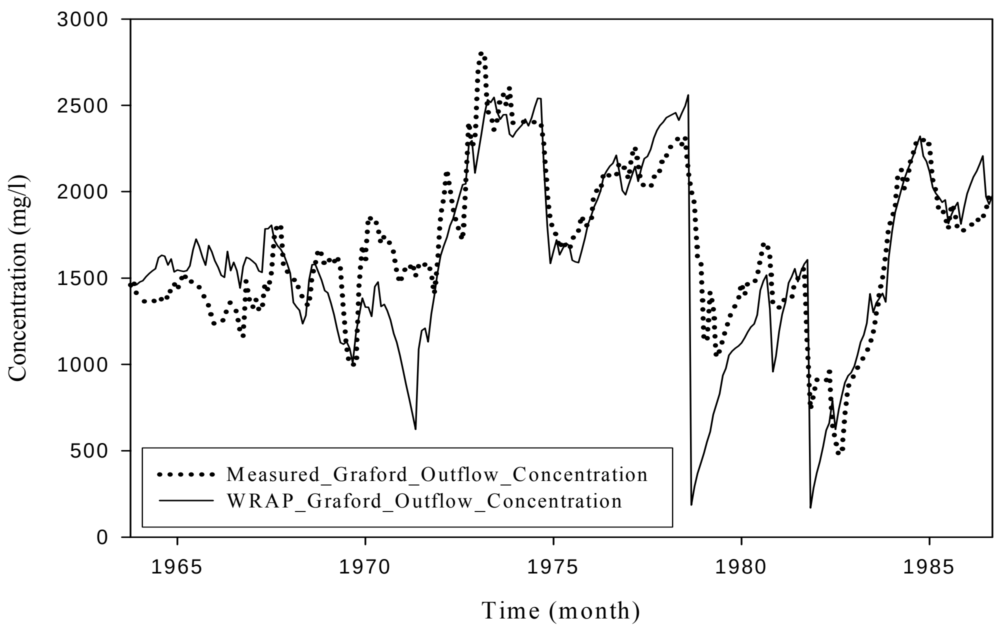

Figure 6.15 Observed and Simulated Concentrations at Graford Gage (TM option 2)

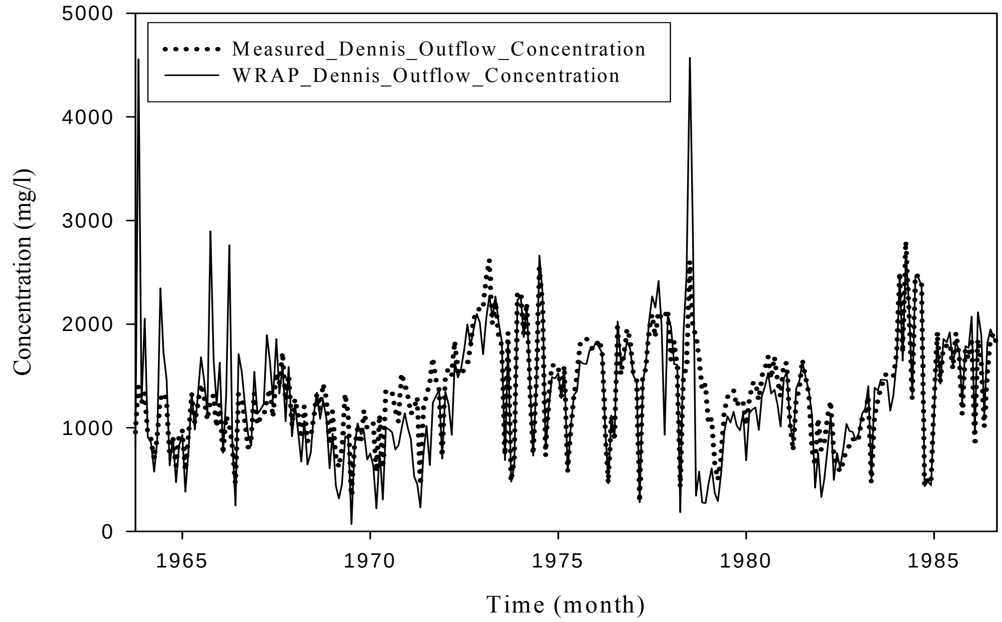

Figure 6.16 Observed and Simulated Concentrations at Dennis Gage (TM option 2)

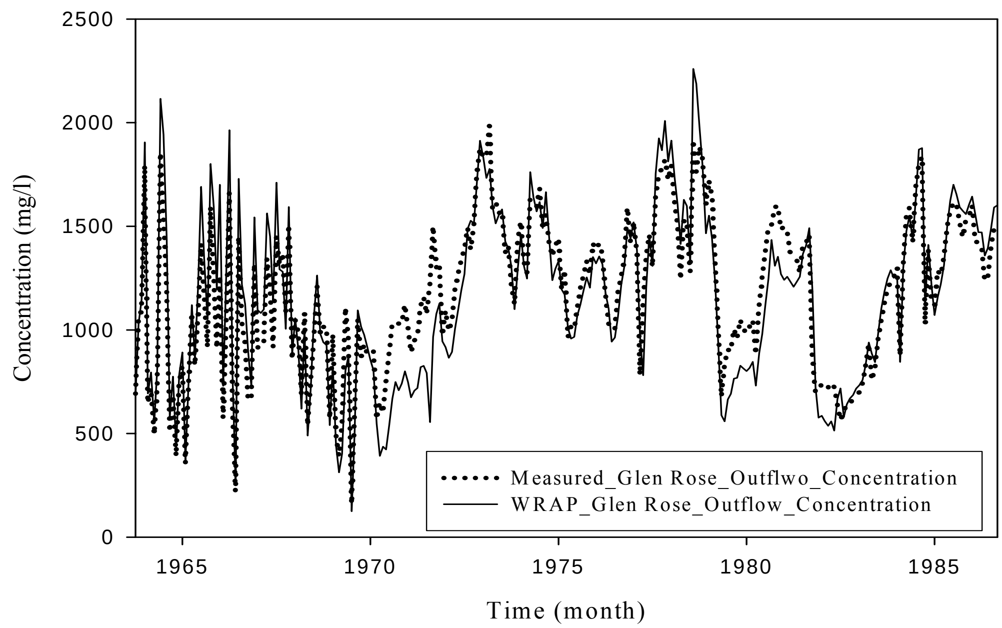

Figure 6.17 Observed and Simulated Concentrations at Glen Rose Gage (TM option 2)

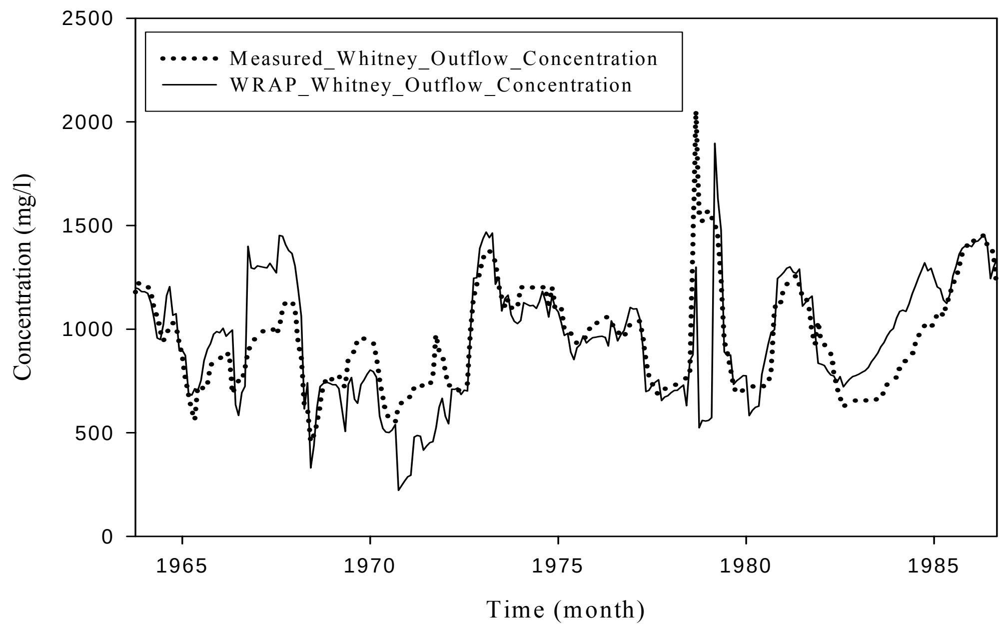

Figure 6.18 Observed and Simulated Concentrations at Whitney Gage (TM option 2)

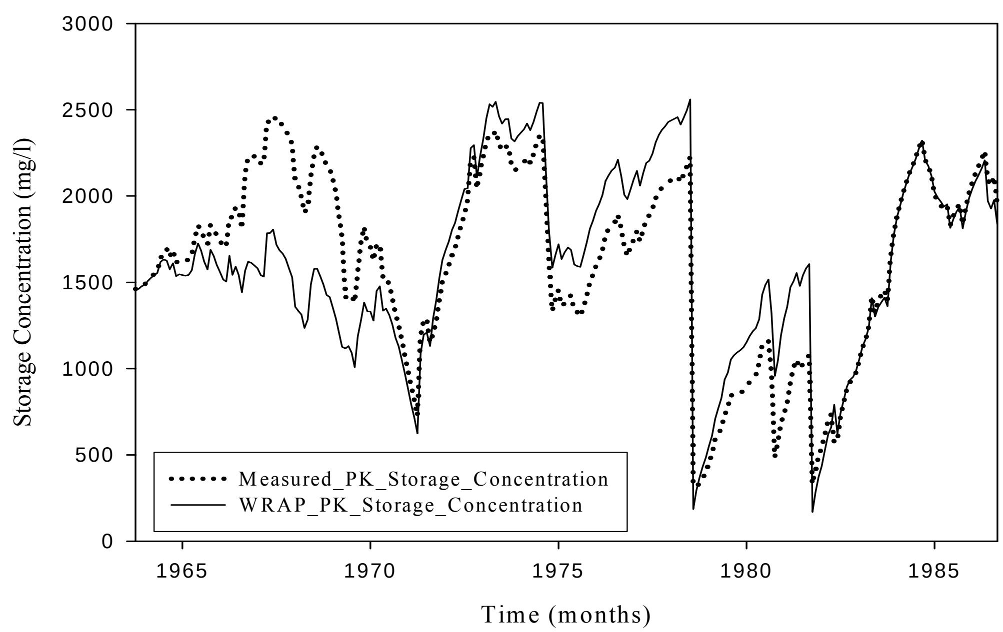

Figure 6.19 Possum Kingdom Reservoir Storage Concentration (TM Option 2)

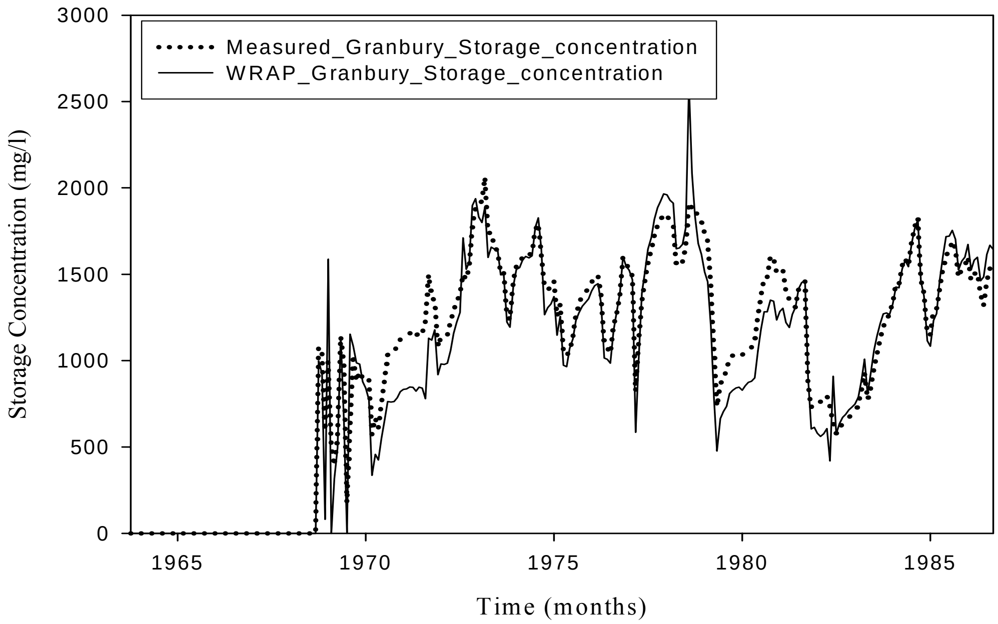

Figure 6. 20 Granbury Reservoir Storage Concentration (TM option 2)

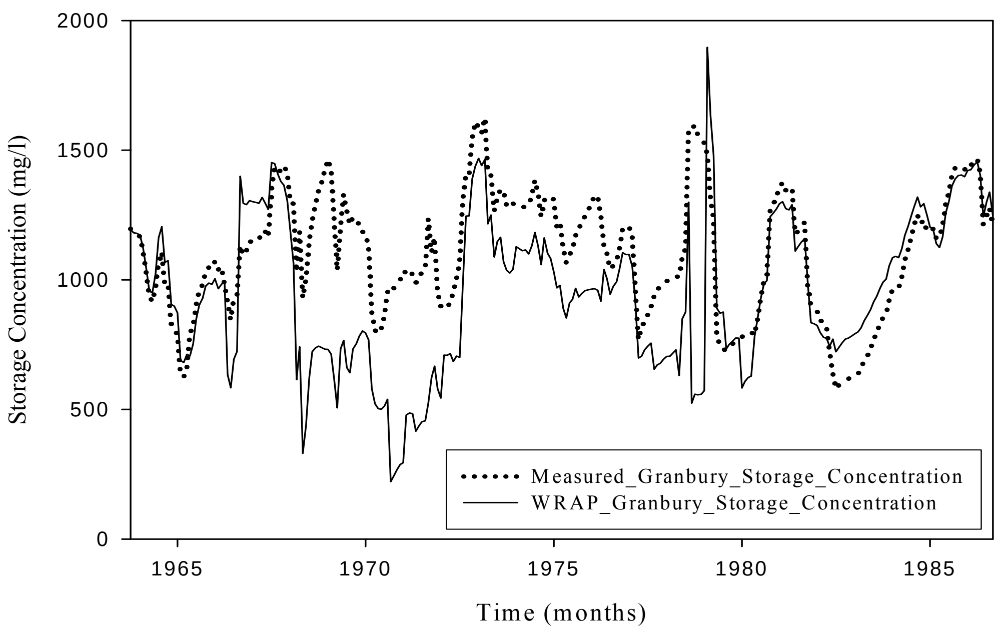

Figure 6.21 Whitney Reservoir Storage Concentration (TM Option 2)

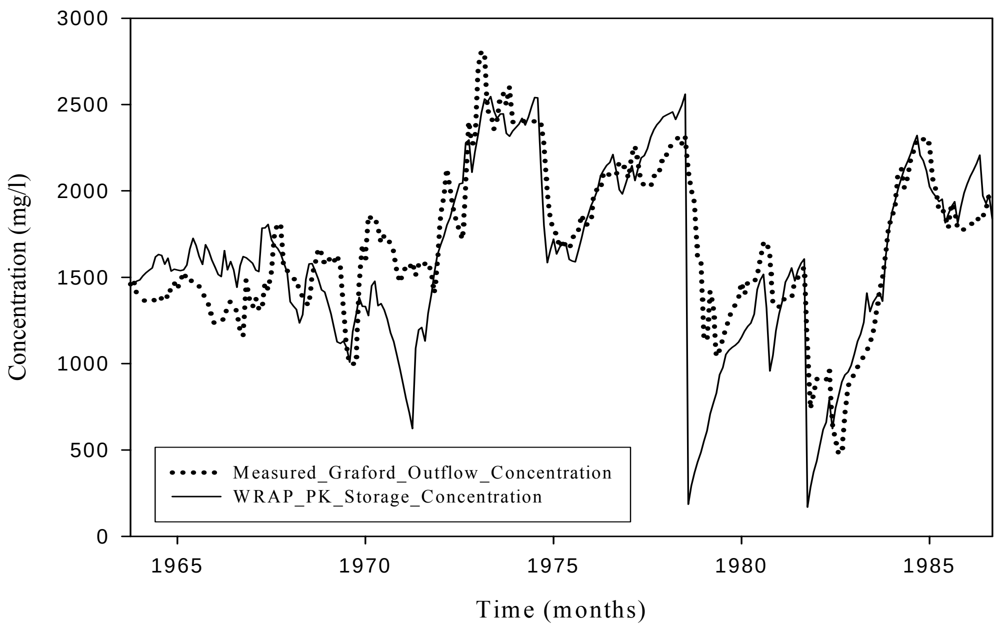

Figure 6.22 Possum Kingdom Simulated Storage Concentration and Graford Gage Observed Flow Concentration (TM option 2)

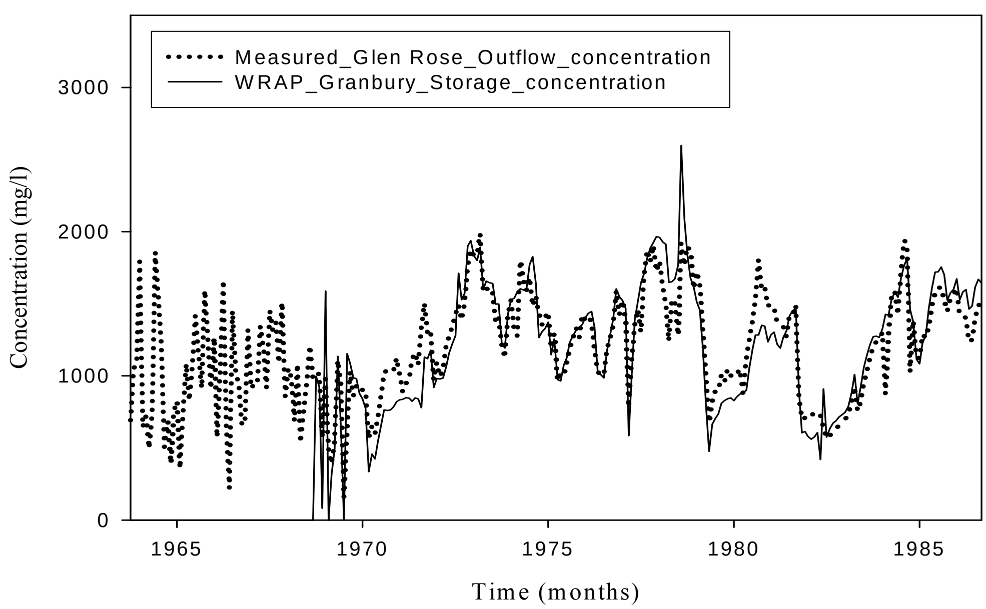

Figure 6.23 Granbury Simulated Storage Concentration and Glen Rose Gage Observed Flow Concentration (TM option 2)

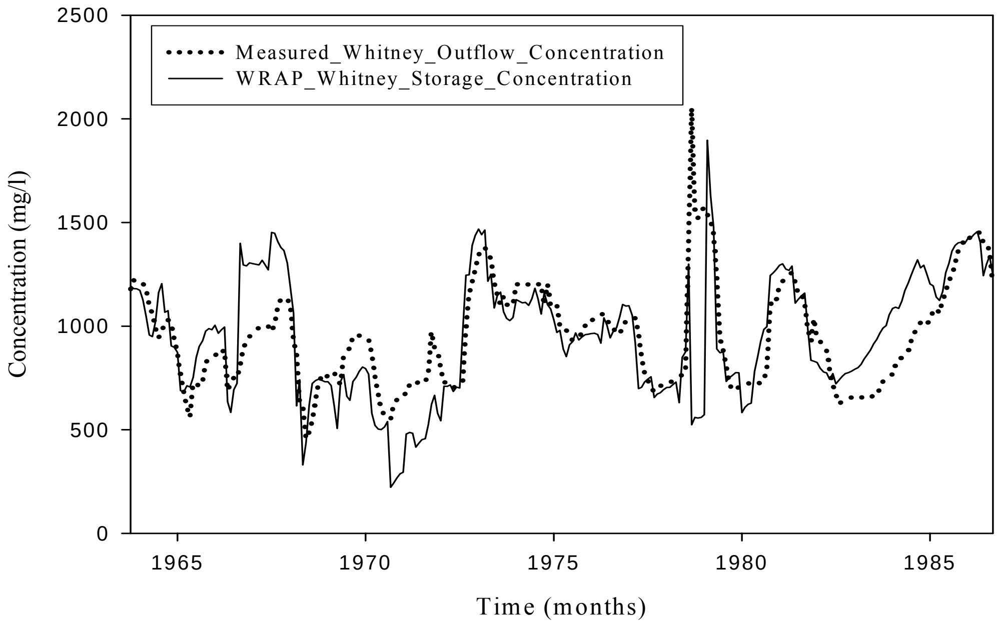

Figure 6.24 Whitney Simulated Storage Concentration and Whitney Gage Observed Flow Concentration (TM option 2)

6.4 Simulation Studies to Explore Salinity Routing through Reservoirs and Calibrate Parameters

In the real-world, salt loads are carried by streamflows into the upper reaches of a reservoir, and mixing occurs over time. Salt loads may require long periods of time to move through a reservoir and reach the outlet. The lag options in WRAP-SALT represent physically the time required for the salt loads to reach the reservoir outlet after entering the reservoir in a particular month. In this part, WRAP-SALT simulation studies focused on storage and outflow concentration at Possum Kingdom and Whitney

Reservoirs designed to investigate the alternative routing methods and develop values for the lag parameters.

The general methodology for salinity routing through reservoir was introduced in Section 6.1. Routing is based on Equation 6-1, 6-2, and 6-3. As previously mentioned, there are two LAG options for routing salinity through reservoir. LAG option 1 is for the lag L to be a constant integer provided by the model-user as an input parameter. With LAG option 2, the lag L is computed within WRAP-SALT based on Equation 6-2 with the multiplier factor F_L provided by the user as an input parameter. With the second option, the lag is allowed to vary from month to month.

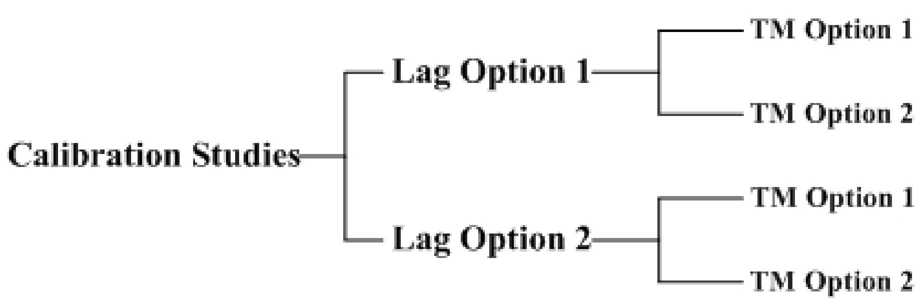

Figure 6.25 Lag Options Applied for Possum Kingdom and Whitney Reservoir

The subheadings 6.4.1 through 6.4.4 in Chapter VI present results of applying the two lag options at each of the two reservoirs as outlined in Figure 6.25. The subheading 6.4.5 in Chapter VI provides calibration statistics and an overall summary and conclusions for the salinity routing study. Simulation results are presented in various tables and plots for comparison. Streamflow and reservoir storage concentrations from the WRAP-SALT simulation results are compared with the observed streamflow concentrations and reservoir storage concentrations from the salinity budget study results from Chapter IV.

6.4.1 Possum Kingdom Reservoir with Lag Option 1

Streamflows at the Graford gage located downstream of the dam are comprised of outflows from Possum Kingdom Reservoir. Storage and outflow concentrations from WRAP-SALT simulations are compared with storage concentrations computed in the salt budget analysis and USGS observed streamflow concentrations at the Graford gaging station.

The results of alternative simulations with lag option 1 with constant lags (L in Equation 6-1) of 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, and 20 months are presented in this section. The simulations with lag option 1 were repeated with TM option 1 and 2 dictating whether monthly mean versus beginning-of-month storage concentrations are sued to compute outflow concentrations.

Linear correlation and regression coefficients are tabulated in Table 6.5 as indices for comparing pairs of 276 month (1964-1986) sequences of monthly TDS concentrations. The label *observed* refers to the salinity budget dataset of Chapter IV. *Simulated* means computed in the WRAP-SALT simulation. The following pairs of sequences of Possum Kingdom Reservoir outflow and/or storage concentrations are compared in Table 6.5.

Column 2 – Observed outflow (flows at Graford gage) versus simulated outflow concentrations. TM option 1 (mean concentration) is activated.

Column 3 – Observed (computed in salinity budget) versus simulated storage concentrations. TM option 1 (mean concentration) is activated.

Column 4 – Observed outflow (flows at Graford gage) versus simulated outflow concentrations. TM option 2 (beginning-of-month) is activated.

Column 5 – Observed (computed in salinity budget) versus simulated storage concentrations. TM option 2 (beginning-of-month) is activated.

Column 6 – Observed outflow (flows at Graford gage) versus simulated outflow concentrations. TM option 1 (mean concentration) is activated.

Column 7 – Observed (computed in salinity budget) versus simulated storage concentrations. TM option 1 (mean concentration) is activated.

Column 8 – Observed outflow (flows at Graford gage) versus simulated outflow concentrations. TM option 2 (beginning-of-month) is activated.

Column 9 – Observed (computed in salinity budget) versus simulated storage concentrations. TM option 2 (beginning-of-month) is activated.

The relative closeness of the correlation and regression coefficients to 1.0 provides an index for comparing the results of the simulations to the storage and outflow concentrations from the salinity budget analysis of Chapter IV. A value of precisely 1.0 for the correlation coefficient and regression coefficient would be an indication that the 1964-1986 sequences of simulated and observed concentrations are identical.

Table 6.5 Linear Correlation and Regression Coefficients for Alternative Lags

(1) Observed Simulated TM option	(2) Outflow Outflow 1	(3) Storage Storage 1	(4) Outflow Outflow 2	(5) Storage Storage 2	(6) Outflow Outflow 1	(7) Storage Storage 1	(8) Outflow Outflow 2	(9) Storage Storage 2
Lag	Correlation Coefficient (R)				Regression Coefficient (a) for Y = aX			
(months)								
0	0.990	0.972	0.984	0.982	0.9944	0.9917	0.9612	0.9739
1	0.985	0.974	0.971	0.982	1.0740	1.1278	1.0202	1.0868
2	0.977	0.972	0.961	0.973	1.1061	1.1858	1.0323	1.1214
3	0.973	0.970	0.955	0.972	1.1160	1.2458	1.0405	1.1792
4	0.969	0.970	0.951	0.974	1.1274	1.3105	1.0570	1.2516
5	0.965	0.971	0.946	0.976	1.1409	1.3414	1.0688	1.2834
6	0.961	0.970	0.936	0.974	1.1413	1.3987	1.0592	1.3302
7	0.954	0.967	0.927	0.973	1.1335	1.4519	1.0386	1.3702
8	0.946	0.963	0.912	0.962	1.1307	1.5061	1.0505	1.4398
9	0.938	0.959	0.903	0.959	1.1290	1.5291	1.0429	1.4568
10	0.932	0.958	0.898	0.959	1.1209	1.5749	1.0349	1.5033
15	0.926	0.954	0.890	0.954	1.0862	1.7581	1.0022	1.6908
20	0.932	0.952	0.902	0.948	1.1048	1.6335	1.0289	1.5753

Table 6.5 includes WRAP-SALT simulations with the alternative lag times tabulated in column 1 and the two alternative options. The statistical analysis summarized in Table 6.5 implies that zero lag (no lag) is the optimal choice if lag option 1 is adopted for Possum Kingdom Reservoir. The correlation coefficient decreases with increases in the lag. Likewise, the regression coefficient departs from 1.0 as the value for the lag entered in the WRAP-SALT input is increased. TM option 1 appears to provide a little closer fit than TM option 2 through the differences between the TM option 1 and 2 statistics in Table 6.5 are minimal.

Plots of the observed and simulated reservoir storage and outflow concentrations are provided in Figure D.1 through D.12 of Appendix D for simulations with no lag and lags of 1 month and 2 months. The plots show significant differences between in magnitudes of the observed and simulated concentrations. However, the differences in magnitudes are not greatly influenced by timing or lag. The differences between the two 1964-1986 sequences of monthly concentrations plotted in each of the graphs are dominated by vertical differences (concentration magnitudes) rather than horizontal (timing pattern) differences.

Statistics for the 1964-1986 sequences of end-of-month storage concentrations for Possum Kingdom Reservoir and the monthly mean concentrations at the Graford gage are tabulated in Table 6.6 through Table 6.10. Statistics are provided in Table 6.6 for the dataset developed in the salinity budget study of Chapter IV. The same statistics for the WRAP-SALT simulation results for alternative lags and TM options are tabulated in Table 6.7, Table 6.8, Table 6.9, and Table 6.10 for comparison. The tables reflect lag option 1 applied with alternative simulations representing a range of different lags. The statistics include mean and standard deviation of the concentrations and a frequency relationship with concentration tabulated for specified exceedance frequencies.

Table 6.6 Statistics for Possum Kingdom Reservoir Storage and Outflow Concentrations from the Salinity Budget Dataset

Exceedance Frequency or Other Statistic	PK Storage Concentration (mg/l)	Graford Flow Concentration (mg/l)
10 %	2,230	2,294
25 %	2,078	2,008
40 %	1,837	1,773
50 %	1,717	1,615
60 %	1,562	1,509
75 %	1,278	1,379
90 %	798	1,130
95 %	572	940
98 %	402	739
99 %	331	562
100%	319	475
Mean	1,626	1,534
Standard Deviation	544	466
Maximum	2,464	2,809

Table 6.7 Statistics for Concentrations at Graford Gage (TM option 1, Lag option 1)

Lag (months)	0	1	2	3	4	5	6	7	8	9	10	15	20
Exceed Fr	Concentration (mg/l)												
10 %	2,350	2,585	2,735	2,828	2,904	3,005	2,951	2,885	2,927	3,017	3,086	3,250	2,971
25 %	2,014	2,140	2,212	2,280	2,327	2,317	2,337	2,375	2,422	2,446	2,417	2,262	2,233
40 %	1,686	1,917	2,005	2,013	2,042	2,098	2,094	2,012	1,971	1,883	1,856	1,772	1,854
50 %	1,585	1,792	1,871	1,849	1,825	1,841	1,776	1,730	1,693	1,660	1,602	1,571	1,617
60 %	1,520	1,677	1,704	1,652	1,642	1,654	1,645	1,590	1,531	1,486	1,445	1,445	1,475
75 %	1,289	1,512	1,503	1,481	1,471	1,445	1,435	1,352	1,294	1,239	1,208	1,105	1,348
90 %	946	1,304	1,235	1,133	1,033	1,022	938	923	900	924	929	823	960
95 %	624	1,126	1,011	860	839	799	814	720	716	729	670	706	638
98 %	401	952	794	711	635	673	539	517	493	453	459	528	415
99 %	290	904	618	428	460	363	389	424	463	430	437	293	299
100 %	169	551	331	174	198	192	200	275	435	266	134	250	223
Mean	1,609	1,833	1,882	1,887	1,895	1,913	1,906	1,886	1,879	1,874	1,857	1,795	1,846
SD	528	458	549	628	686	731	778	826	875	919	946	956	903
Max	2,560	2,795	3,212	3,522	3,810	4,064	4,251	4,403	4,594	4,769	4,911	5,535	4,897

Table 6.8 Statistics for Concentrations at Graford Gage (TM option 2, Lag option 1)

Lag (months)	0	1	2	3	4	5	6	7	8	9	10	15	20
Exceed Fr	Concentration (mg/l)												
10 %	2,350	2,580	2,707	2,800	2,907	2,917	2,956	2,899	3,037	3,029	3,115	3,201	2,922
25 %	2,014	2,165	2,209	2,220	2,274	2,316	2,252	2,258	2,380	2,344	2,339	2,177	2,204
40 %	1,686	1,866	1,912	1,919	1,966	2,008	2,018	1,856	1,837	1,741	1,688	1,654	1,673
50 %	1,585	1,713	1,731	1,727	1,684	1,720	1,654	1,596	1,532	1,521	1,445	1,445	1,469
60 %	1,520	1,582	1,588	1,549	1,542	1,500	1,482	1,445	1,394	1,335	1,282	1,205	1,407
75 %	1,289	1,364	1,276	1,269	1,214	1,231	1,158	1,084	1,004	938	901	878	1,017
90 %	946	897	690	661	723	674	477	370	438	445	368	448	610
95 %	624	529	404	386	342	265	120	162	136	27	40	127	311
98 %	401	292	138	33	0	0	0	0	0	0	0	47	0
99 %	290	132	0	0	0	0	0	0	0	0	0	0	0
100 %	169	0	0	0	0	0	0	0	0	0	0	0	0
Mean	1,609	1,712	1,721	1,721	1,742	1,757	1,731	1,687	1,710	1,694	1,677	1,621	1,692
SD	528	623	710	776	822	867	920	962	1,029	1,066	1,085	1,089	1,023
Max	2,560	2,980	3,259	3,578	3,846	4,089	4,267	4,408	4,623	4,808	4,941	5,601	5,063

Table 6.9 Statistics for Possum Kingdom Storage Concentrations
(TM option 1, Lag option 1)

Lag (months)	0	1	2	3	4	5	6	7	8	9	10	15	20
Exceed Fr	Concentration (mg/l)												
10 %	2,350	2,607	2,771	2,920	3,050	3,072	3,182	3,318	3,459	3,633	3,752	4,460	4,457
25 %	2,014	2,256	2,411	2,548	2,654	2,700	2,798	2,918	3,083	3,209	3,309	3,648	3,297
40 %	1,687	2,008	2,131	2,249	2,377	2,464	2,599	2,686	2,793	2,868	2,943	3,222	2,898
50 %	1,590	1,860	1,993	2,082	2,207	2,300	2,410	2,510	2,563	2,564	2,616	2,842	2,686
60 %	1,526	1,776	1,839	1,899	1,980	2,020	2,110	2,185	2,234	2,227	2,315	2,553	2,299
75 %	1,289	1,603	1,632	1,680	1,769	1,802	1,849	1,913	1,973	1,956	2,015	2,277	1,867
90 %	946	1,429	1,456	1,490	1,540	1,535	1,560	1,613	1,622	1,616	1,637	1,789	1,601
95 %	624	1,302	1,317	1,367	1,452	1,461	1,508	1,528	1,530	1,523	1,555	1,595	1,527
98 %	401	1,158	1,156	1,212	1,309	1,354	1,443	1,461	1,468	1,441	1,482	1,507	1,415
99 %	290	1,035	1,032	1,079	1,222	1,257	1,363	1,430	1,438	1,404	1,458	1,474	1,322
100 %	169	798	793	839	984	1,087	1,253	1,331	1,353	1,309	1,307	1,446	1,196
Mean	1,610	1,930	2,028	2,128	2,237	2,286	2,383	2,476	2,572	2,611	2,688	2,994	2,749
SD	528	436	491	542	576	596	629	670	727	780	816	978	1,022
Max	2,560	2,810	3,070	3,241	3,462	3,581	3,760	3,974	4,189	4,332	4,547	5,358	5,221

Table 6.10 Statistics for Possum Kingdom Storage Concentrations
(TM option 2, Lag option 1)

Lag (months)	0	1	2	3	4	5	6	7	8	9	10	15	20
Exceed Fr						Concentration (mg/l)							
10 %	2,350	2,599	2,754	2,898	3,011	3,032	3,146	3,210	3,523	3,626	3,719	4,485	4,494
25 %	2,014	2,270	2,390	2,505	2,606	2,649	2,754	2,856	3,106	3,176	3,261	3,567	3,225
40 %	1,687	1,954	2,077	2,189	2,314	2,400	2,480	2,508	2,712	2,746	2,834	3,143	2,805
50 %	1,590	1,777	1,803	1,905	2,079	2,225	2,285	2,300	2,392	2,356	2,474	2,635	2,557
60 %	1,526	1,648	1,654	1,697	1,800	1,836	1,905	1,952	1,990	2,009	2,100	2,375	2,106
75 %	1,289	1,465	1,461	1,488	1,573	1,577	1,640	1,665	1,692	1,663	1,747	1,950	1,686
90 %	946	1,080	1,087	1,132	1,190	1,151	1,209	1,285	1,314	1,303	1,405	1,547	1,356
95 %	624	681	648	703	870	840	983	1,008	984	980	1,137	1,359	944
98 %	401	383	361	394	516	477	545	522	492	438	438	609	424
99 %	290	270	244	285	384	360	357	335	306	252	252	426	252
100 %	169	142	97	106	172	104	101	80	52	0	0	170	0
Mean	1,610	1,804	1,859	1,952	2,074	2,119	2,199	2,266	2,390	2,417	2,496	2,812	2,589
SD	528	597	657	702	722	749	783	817	910	952	974	1,128	1,174
Max	2,560	2,950	3,105	3,239	3,438	3,543	3,755	3,971	4,190	4,330	4,565	5,391	5,224

Table 6.7, Table 6.8, Table 6.9, Table 6.10 include tabulations of TDS concentrations in mg/l associated with the exceedance frequencies listed in the first column. Mean, standard deviations, and maximum values of the concentrations are also tabulated at the bottom of the tables. These statistics are for the results of WRAP-SALT simulations with the lag times in months cited in the first row of the tables.

6.4.2 Possum Kingdom Reservoir with Lag Option 2

Lag option 2 is based on Equations 6-1, 6-2, and 6-3 with the lag time in months being computed within WRAP-SALT as a function of detention time. The lag is computed for each month of the simulation. The input parameters are multiplier factor

F_L defined by Equation 6-3 and an upper limit on the lag. The user-specified upper limit on the lag is adopted in any particular month if the computed lag exceeds the limit. Multiplier factors (F_L) of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0 were adopted for Possum Kingdom Reservoir. Since the results of applying lag option 1 presented in the preceding section indicates that the lag should be zero or relatively small, an upper limit of 3 months was placed on the lag.

Table 6.11 is comparable to the previously discussed Table 6.5. The second column of Table 6.11 representing no lag was copied from Table 6.5. The correlation and regression coefficients for the simulation with no lag are closer to 1.0 than the correlation and regression coefficients with lag option 2 activated with any of the multiplier factor values tabulated in Table 6.11. Plots of observed (salinity budget) versus WRAP-SALT simulated concentrations of reservoir storage and streamflows below the dam are provided as Figure D.13 through D.24 in Appendix D.

Table 6.11 Linear Correlation and Regression Coefficients for Alternative Values for Multiplier Factor

(1) Observed Simulated TM	(2) Outflow Outflow 1	(3) Storage Storage 1	(4) Outflow Outflow 2	(5) Storage Storage 2	(6) Outflow Outflow 1	(7) Storage Storage 1	(8) Outflow Outflow 2	(9) Storage Storage 2
F_L	Correlation Coefficient (R)				Regression Coefficient (a) for Y = aX			
No Lag	0.990	0.972	0.984	0.982	0.9944	0.9917	0.9612	0.9739
0.1	0.970	0.858	0.954	0.862	0.8824	2.8372	0.8150	2.7801
0.2	0.983	0.939	0.967	0.941	1.0527	1.2969	0.9880	1.2405
0.3	0.977	0.965	0.961	0.968	1.0986	1.1724	1.0289	1.1110
0.4	0.974	0.959	0.959	0.963	1.0937	1.2487	1.0228	1.1860
0.5	0.974	0.962	0.958	0.964	1.106	1.2441	1.0317	1.1778
0.6	0.980	0.954	0.963	0.953	1.0733	1.3167	0.9919	1.2458
0.7	0.979	0.955	0.963	0.953	1.0767	1.3230	0.9997	1.2560
0.8	0.974	0.965	0.957	0.967	1.1135	1.2643	1.0378	1.1991
0.9	0.974	0.965	0.957	0.967	1.1141	1.2644	1.0385	1.2014
1.0	0.974	0.965	0.957	0.967	1.1139	1.2668	1.0385	1.2019

Table 6.12 Statistics for Possum Kingdom Storage Concentrations (TM option 1, Lag option 2)

Factor (F_L)	No Lag	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Exceed Freq	Concentration (mg/l)										
10 %	2,350	8,469	3,510	2,716	2,937	2,962	3,404	3,404	3,030	3,033	3,033
25 %	2,014	6,557	2,713	2,482	2,682	2,683	2,788	2,800	2,679	2,679	2,682
40 %	1,687	6,123	2,261	2,128	2,251	2,233	2,263	2,272	2,281	2,286	2,286
50 %	1,590	5,663	2,049	1,901	2,049	2,019	2,046	2,052	2,056	2,057	2,063
60 %	1,526	4,870	1,900	1,787	1,915	1,888	1,900	1,904	1,909	1,909	1,909
75 %	1,289	2,812	1,640	1,585	1,643	1,628	1,630	1,630	1,657	1,659	1,659
90 %	946	1,866	1,436	1,413	1,481	1,461	1,472	1,476	1,479	1,481	1,481
95 %	624	1,568	1,278	1,240	1,355	1,304	1,319	1,321	1,344	1,361	1,361
98 %	401	1,528	960	1,103	1,237	1,156	1,178	1,181	1,205	1,220	1,220
99 %	290	1,484	750	903	1,028	947	969	971	1,007	1,040	1,040
100 %	169	1,461	501	659	788	704	727	730	766	800	800
Mean	1,610	5,125	2,229	2,007	2,146	2,129	2,237	2,247	2,160	2,164	2,164
Stand Dev	528	2,380	781	532	586	595	745	749	592	588	588
Maximum	2,560	10,642	4,519	3,426	3,650	3,576	4,221	4,221	3,518	3,518	3,518

Table 6.13 Statistics for Concentrations at Graford Gage (TM option 1, Lag option 2)

Factor (F_L)	No Lag	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Exceed Freq	Concentration (mg/l)										
10 %	2,350	2,096	2,606	2,719	2,757	2,774	2,676	2,689	2,815	2,815	2,818
25 %	2,014	1,800	2,075	2,185	2,207	2,214	2,168	2,187	2,204	2,204	2,208
40 %	1,686	1,628	1,877	1,978	1,979	1,982	1,892	1,896	2,008	2,013	2,015
50 %	1,585	1,565	1,740	1,887	1,872	1,853	1,747	1,714	1,861	1,862	1,864
60 %	1,520	1,446	1,638	1,714	1,673	1,681	1,598	1,598	1,662	1,666	1,666
75 %	1,289	1,218	1,460	1,480	1,460	1,462	1,430	1,430	1,461	1,467	1,467
90 %	946	853	1,154	1,239	1,193	1,225	1,208	1,192	1,186	1,197	1,197
95 %	624	562	908	902	910	955	859	861	999	940	940
98 %	401	368	646	673	679	744	582	587	800	811	811
99 %	290	191	324	363	366	368	347	347	636	646	646
100 %	169	77	84	99	99	99	85	85	99	99	99
Mean	1,609	1,497	1,777	1,866	1,857	1,877	1,804	1,808	1,888	1,889	1,888
Stand Dev	528	497	536	565	579	593	589	598	602	602	603
Maximum	2,560	2,663	3,184	3,246	3,270	3,417	3,468	3,513	3,516	3,519	3,519

Table 6.14 Statistics for Possum Kingdom Storage Concentrations
(TM option 2, Lag option 2)

Factor (F_L)	No Lag	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Exceed Freq	Concentration (mg/l)										
10 %	2,350	8,432	3,474	2,688	2,914	2,948	3,376	3,376	3,019	3,020	3,020
25 %	2,014	6,480	2,731	2,433	2,650	2,624	2,734	2,762	2,632	2,636	2,636
40 %	1,687	5,806	2,097	2,035	2,196	2,181	2,200	2,233	2,217	2,217	2,220
50 %	1,590	5,301	1,860	1,765	1,865	1,845	1,847	1,859	1,884	1,888	1,888
60 %	1,526	4,377	1,666	1,630	1,674	1,661	1,663	1,668	1,698	1,698	1,698
75 %	1,289	2,711	1,492	1,431	1,473	1,461	1,462	1,465	1,478	1,478	1,478
90 %	946	1,770	1,019	1,022	1,145	1,059	1,061	1,061	1,096	1,124	1,124
95 %	624	1,571	747	623	778	695	696	697	712	713	713
98 %	401	1,529	541	337	498	441	433	432	434	434	434
99 %	290	1,484	449	218	378	322	316	316	318	318	318
100 %	169	1,461	331	86	240	185	185	183	185	185	185
Mean	1,610	4,970	2,070	1,842	1,978	1,955	2,054	2,069	1,986	1,990	1,991
Stand Dev	528	2,390	891	677	723	739	879	889	742	739	740
Maximum	2,560	10,619	4,480	3,390	3,615	3,541	4,180	4,180	3,482	3,482	3,482

Table 6.15 Statistics for Concentrations at Graford Gage (TM option 2, Lag option 2)

Factor (F_L)	No Lag	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Exceed Freq	Concentration (mg/l)										
10 %	2,350	2,093	2,619	2,680	2,721	2,762	2,675	2,701	2,785	2,785	2,788
25 %	2,014	1,740	2,035	2,143	2,139	2,145	2,055	2,055	2,147	2,147	2,155
40 %	1,686	1,556	1,792	1,921	1,930	1,925	1,780	1,782	1,904	1,904	1,906
50 %	1,585	1,431	1,648	1,772	1,745	1,745	1,618	1,618	1,727	1,718	1,726
60 %	1,520	1,296	1,517	1,586	1,576	1,563	1,486	1,489	1,552	1,555	1,549
75 %	1,289	933	1,288	1,334	1,271	1,266	1,234	1,229	1,259	1,259	1,259
90 %	946	470	654	670	670	676	679	680	708	711	711
95 %	624	285	279	299	301	355	360	358	399	399	399
98 %	401	0	0	0	0	0	0	0	35	35	35
99 %	290	0	0	0	0	0	0	0	0	0	0
100 %	169	0	0	0	0	0	0	0	0	0	0
Mean	1,609	1,350	1,630	1,712	1,700	1,714	1,632	1,641	1,722	1,723	1,723
Stan Dev	528	609	690	715	728	741	721	737	752	752	753
Maximum	2,560	2,672	3,285	3,247	3,304	3,437	3,482	3,571	3,573	3,576	3,576

Table 6.12 through Table 6.15 contain the same statistics as Table 6.7 through Table 6.10. These statistics from the WRAP-SALT simulations results can be compared with the statistics from the salinity budget study tabulated in Table 6.6.

6.4.3 Whitney Reservoir with Lag Option 1

The same lag options were applied to both Whitney and Possum Kingdom Reservoirs. The following presentation of the study results for Whitney Reservoir is organized in the same format as the preceding discussion of Possum Kingdom Reservoir.

Streamflows at the Whitney gage located on the Brazos River below Whitney Dam near Aquilla are comprised of outflows from the reservoir. Storage and outflow concentrations from WRAP-SALT simulations are compared with storage concentrations computed in the salt budget analysis and USGS observed streamflow concentrations at the Whitney (Aquilla) gaging station.

Linear correlation and regression coefficients for alternative lags were tabulated in Table 6.16. Simulation results without activation of lag features (zero lag) provide the best fit to the observed outflow and storage concentrations. The correlation coefficients decrease with increases in lag time for Whitney Reservoir as well as Possum Kingdom Reservoir. Plots of the observed and simulated reservoir storage and outflow concentration with different lag times are provided in Figure D.25 through D.36 in Appendix D.

Table 6.16 Linear Correlation and Regression Coefficients for Alternative Lags

(1) Observed Simulated TM	(2) Outflow Outflow 1	(3) Storage Storage 1	(4) Outflow Outflow 2	(5) Storage Storage 2	(6) Outflow Outflow 1	(7) Storage Storage 1	(8) Outflow Outflow 2	(9) Storage Storage 2
Lag	Correlation Coefficient (R)				Regression Coefficient (a) for Y = aX			
(months)								
0	0.979	0.985	0.976	0.982	0.9887	0.9040	0.9858	0.9006
1	0.954	0.975	0.940	0.917	1.1133	1.1209	1.0799	1.0842
2	0.921	0.963	0.902	0.960	1.1801	1.2947	1.1277	1.2367
3	0.899	0.962	0.883	0.963	1,2107	1.4405	1.1474	1.3662
4	0.885	0.961	0.865	0.959	1.2352	1.5614	1.1907	1.5092
5	0.873	0.957	0.850	0.952	1.2533	1.6485	1.1976	1.5816
6	0.864	0.954	0.835	0.948	1.2514	1.6874	1.1909	1.6130
7	0.854	0.949	0.826	0.942	1.2558	1.7034	1.1977	1.6271
8	0.838	0.942	0.802	0.928	1.2711	1.8113	1.2150	1.7329
9	0.817	0.929	0.775	0.909	1.3006	1.9179	1.2698	1.8666
10	0.803	0.921	0.773	0.913	1.3288	1.9964	1.2862	1.9447
15	0.767	0.903	0.728	0.894	1.3161	2.1595	1.2489	2.0839
20	0.773	0.794	0.741	0.773	1.2649	1.2642	1.2057	1.2117

Table 6.17 Statistics for Whitney Reservoir Storage and Outflow Concentrations from the Salinity Budget Study

Exceedance Frequency or Other Statistic	Whitney Storage Concentration (mg/l)	Whitney Flow Concentration (mg/l)
10 %	1,389	1,256
25 %	1,242	1,104
40 %	1,157	997
50 %	1,075	942
60 %	983	858
75 %	820	730
90 %	705	664
95 %	646	638
98 %	626	561
99 %	598	544
100%	472	456
Mean	1,062	927
Standard Deviation	253	250
Maximum	1,661	2,052

Storage and outflow concentration statistics for Whitney Reservoir from the salinity budget dataset are reproduced in Table 6.17. The mean, standard deviation, and exceedance frequency relationships are for the 1964-1986 sequences of end-of-month storage concentrations for Whitney Reservoir and the monthly mean flow concentrations at the Whitney gage. The simulation results statistics in Table 6.18 through Table 6.21 can be compared with the Table 6.17 statistics of the observed data from the load budget studies of Chapter IV.

Table 6.18 Statistics for Concentrations at Whitney Gage (TM option 1, Lag option 1)

Lag (months)	0	1	2	3	4	5	6	7	8	9	10	15	20
Exceed Fr	Concentration (mg/l)												
10 %	1,299	1,530	1,834	1,938	2,029	2,065	2,131	2,240	2,492	2,605	2,547	2,546	2,266
25 %	1,154	1,325	1,401	1,512	1,671	1,711	1,712	1,795	1,833	1,811	1,863	1,733	1,459
40 %	1,059	1,188	1,223	1,248	1,311	1,330	1,344	1,316	1,285	1,305	1,308	1,239	1,199
50 %	965	1,098	1,126	1,179	1,191	1,199	1,153	1,150	1,116	1,132	1,138	1,165	1,127
60 %	892	1,009	1,072	1,044	1,050	1,033	1,020	994	981	976	958	849	852
75 %	760	901	920	894	819	816	812	754	722	694	626	579	711
90 %	609	663	657	618	562	490	363	367	343	324	400	377	435
95 %	527	545	497	434	345	278	267	267	261	281	329	269	276
98 %	430	444	367	268	241	214	206	204	213	244	295	207	197
99 %	313	399	292	222	182	191	195	185	208	220	212	162	147
100 %	263	331	190	156	165	182	157	128	124	147	105	147	101
Mean	956	1,098	1,181	1,219	1,245	1,263	1,260	1,264	1,281	1,317	1,352	1,334	1,273
SD	263	326	439	517	576	630	664	701	761	846	905	1,031	984
Max	1,681	1,891	2,217	2,575	2,897	3,408	3,643	3,709	3,481	4,003	4,152	4,999	5,265

Table 6.19 Statistics for Concentrations at Whitney Gage (TM option 2, Lag option 1)

Lag (months)	0	1	2	3	4	5	6	7	8	9	10	15	20
Exceed Fr	Concentration (mg/l)												
10 %	1,310	1,584	1,820	1,881	1,990	2,029	2,099	2,239	2,549	2,671	2,669	2,741	2,249
25 %	1,173	1,317	1,403	1,508	1,662	1,718	1,728	1,774	1,796	1,859	1,913	1,775	1,460
40 %	1,038	1,129	1,182	1,228	1,289	1,267	1,284	1,272	1,267	1,356	1,336	1,199	1,199
50 %	959	1,066	1,088	1,139	1,139	1,159	1,128	1,149	1,104	1,093	1,114	1,044	984
60 %	849	987	1,018	1,015	1,009	1,001	964	928	917	927	973	779	780
75 %	732	865	842	826	782	752	724	684	637	530	516	406	615
90 %	580	606	542	491	400	207	169	135	44	119	197	221	277
95 %	498	402	382	0	0	0	0	0	0	0	13	10	78
98 %	375	307	0	0	0	0	0	0	0	0	0	0	0
99 %	283	0	0	0	0	0	0	0	0	0	0	0	0
100 %	222	0	0	0	0	0	0	0	0	0	0	0	0
Mean	948	1,065	1,125	1,150	1,193	1,197	1,190	1,194	1,216	1,282	1,304	1,258	1,215
SD	292	376	493	556	637	698	739	779	860	976	986	1,122	1,041
Max	1,896	1,846	2,382	2,543	3,014	3,694	3,800	3,894	4,033	4,514	4,325	5,096	5,376

Table 6.20 Statistics for Whitney Storage Concentrations (TM option 1, Lag option 1)

Lag (months)	0	1	2	3	4	5	6	7	8	9	10	15	20
Exceed Fr	Concentration (mg/l)												
10 %	1,308	1,598	1,958	2,125	2,277	2,393	2,467	2,495	2,742	3,205	3,448	4,059	2,995
25 %	1,155	1,438	1,687	1,841	2,019	2,144	2,189	2,257	2,451	2,625	2,728	2,925	1,956
40 %	1,051	1,316	1,482	1,667	1,793	1,913	1,941	1,952	2,065	2,124	2,182	2,403	1,459
50 %	964	1,204	1,373	1,560	1,713	1,799	1,822	1,817	1,866	1,952	1,995	2,136	1,251
60 %	884	1,145	1,298	1,473	1,620	1,666	1,673	1,682	1,776	1,850	1,902	1,971	962
75 %	756	997	1,120	1,219	1,375	1,466	1,532	1,542	1,565	1,634	1,689	1,783	508
90 %	598	737	896	988	1,023	1,009	986	967	1,003	1,030	1,058	1,033	78
95 %	526	659	728	788	831	867	888	836	868	893	946	842	0
98 %	448	507	587	674	733	769	774	725	788	836	827	693	0
99 %	309	387	485	591	680	752	766	717	751	772	769	565	0
100 %	253	356	463	580	665	716	739	701	728	715	674	450	0
Mean	956	1,201	1,397	1,559	1,691	1,784	1,825	1,843	1,965	2,090	2,182	2,363	1,363
SD	271	330	407	448	487	545	583	616	688	795	866	1,060	1,056
Max	1,811	1,986	2,285	2,552	2,967	3,477	3,730	3,787	3,934	4,208	4,643	5,284	4,359

Table 6.21 Statistics for Whitney Storage Concentrations (TM option 2, Lag option 1)

Lag (months)	0	1	2	3	4	5	6	7	8	9	10	15	20
Exceed Fr	Concentration (mg/l)												
10 %	1,310	1,623	1,921	2,030	2,209	2,345	2,390	2,422	2,820	3,371	3,491	4,082	3,049
25 %	1,173	1,447	1,599	1,768	1,971	2,068	2,137	2,228	2,465	2,632	2,679	2,844	1,814
40 %	1,038	1,249	1,434	1,580	1,757	1,842	1,898	1,923	1,971	2,036	2,106	2,315	1,380
50 %	959	1,130	1,291	1,464	1,644	1,716	1,727	1,735	1,778	1,859	1,933	2,047	1,169
60 %	849	1,078	1,206	1,368	1,489	1,530	1,586	1,617	1,682	1,768	1,845	1,849	942
75 %	732	926	1,044	1,202	1,308	1,346	1,347	1,290	1,327	1,396	1,557	1,686	376
90 %	580	708	780	904	952	944	918	873	898	921	1,034	945	11
95 %	498	601	686	728	763	770	755	700	746	818	903	721	0
98 %	375	476	550	626	675	695	708	657	704	720	802	461	0
99 %	283	348	437	530	614	675	690	629	676	685	674	417	0
100 %	222	315	416	515	591	617	523	402	356	439	587	332	0
Mean	949	1,161	1,332	1,476	1,628	1,704	1,739	1,753	1,875	2,036	2,124	2,278	1,304
SD	292	341	415	428	505	577	609	653	756	894	898	1,091	1,089
Max	1,896	1,934	2,342	2,518	3,060	3,673	3,795	3,835	3,985	4,589	4,662	5,376	4,401

6.4.4 Whitney Reservoir with Lag Option 2

This section presents the results of applying WRAP-SALT alternatively with values for the multiplier factor (F_L) of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0 adopted for Whitney Reservoir. The format of the presentation is the same as the previous comparable section on Possum Kingdom Reservoir. Table 6.22 is comparable to Table 6.11. The correlation and regression coefficients for the simulation with no lag are closer to 1.0 than the correlation and regression coefficients with lag option 2 activated with any of the multiplier factor values in Table 6.22.

Plots of comparison of observed and simulated flow concentrations for multiplier factors of 0.3, 0.4, and 0.5 and the two TM options are provided as Figure D.25 through D.36 and Figure D.37 through Figure D.48 in Appendix D.

Table 6.22 Linear Correlation and Regression Coefficients for Alternative Values for Multiplier Factor

(1) Observed Simulated TM	(2) Outflow Outflow 1	(3) Storage Storage 1	(4) Outflow Outflow 2	(5) Storage Storage 2	(6) Outflow Outflow 1	(7) Storage Storage 1	(8) Outflow Outflow 2	(9) Storage Storage 2
F_L	Correlation Coefficient (R)				Regression Coefficient (a) for Y = aX			
No Lag	0.979	0.970	0.976	0.982	0.9887	0.9040	0.9858	0.9006
0.1	0.853	0.883	0.832	0.883	0.7719	8.3071	0.7222	8.2529
0.2	0.928	0.856	0.904	0.852	0.9063	4.7564	0.8355	4.6727
0.3	0.934	0.903	0.917	0.901	0.9959	3.7229	0.9477	3.6662
0.4	0.938	0.921	0.922	0.918	1.0210	2.5160	0.9695	2.4548
0.5	0.930	0.940	0.917	0.939	1.0855	2.1723	1.0385	2.1191
0.6	0.930	0.946	0.916	0.944	1.0948	2.1379	1.0463	2.0831
0.7	0.903	0.960	0.886	0.959	1.1577	2.1610	1.1104	2.1067
0.8	0.906	0.961	0.890	0.959	1.1688	1.7321	1.1146	1.6716
0.9	0.907	0.960	0.893	0.959	1.1803	1.5814	1.1233	1.5146
1.0	0.935	0.979	0.918	0.977	1.1250	1.5128	1.0856	1.4626

Table 6.23 Statistics for Whitney Storage Concentrations (TM option 1, Lag option 2)

Factor (F_L)	No Lag	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Exceed Freq					Concentration (mg/l)						
10 %	1,308	14,188	9,970	6,818	4,814	3,742	3,601	3,168	2,595	2,400	2,148
25 %	1,155	12,461	6,269	4,946	2,855	2,782	2,659	2,740	2,201	2,041	1,890
40 %	1,051	10,818	5,456	4,326	2,598	2,298	2,258	2,465	1,955	1,806	1,763
50 %	964	9,787	5,001	3,971	2,497	2,168	2,143	2,340	1,845	1,672	1,659
60 %	884	8,830	4,685	3,720	2,424	2,072	2,077	2,242	1,752	1,556	1,556
75 %	756	7,217	3,640	3,078	2,026	1,861	1,833	2,057	1,584	1,366	1,394
90 %	598	1,548	1,377	1,489	1,535	1,505	1,504	1,562	1,215	1,044	1,044
95 %	526	1,180	1,163	1,161	1,166	1,175	1,175	1,175	1,143	962	962
98 %	448	1,006	960	951	968	978	978	978	978	831	831
99 %	309	941	889	881	909	921	925	925	925	817	817
100 %	253	840	751	746	769	780	788	788	788	788	788
Mean	956	9,302	5,289	4,103	2,732	2,362	2,322	2,360	1,888	1,716	1,627
Stand Dev	271	4,152	2,870	1,760	1,139	824	780	607	495	487	384
Maximum	1,811	17,543	13,138	8,822	6,088	4,594	4,404	3,638	3,041	2,780	2,148

Table 6.24 Statistics for Concentrations at Whitney Gage (TM option1, Lag option 2)

Factor (F_L)	No Lag	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Exceed Freq					Concentration (mg/l)						
10 %	1,299	1,404	1,364	1,454	1,454	1,590	1,590	1,904	1,908	1,909	1,632
25 %	1,154	1,115	1,184	1,213	1,243	1,341	1,341	1,394	1,384	1,469	1,375
40 %	1,059	847	993	1,086	1,097	1,185	1,193	1,205	1,206	1,203	1,199
50 %	965	739	892	988	1,007	1,072	1,102	1,133	1,129	1,128	1,121
60 %	892	647	757	864	924	996	1,024	1,046	1,040	996	1,003
75 %	760	324	474	675	759	813	813	856	878	872	869
90 %	609	134	253	414	519	580	596	596	643	653	660
95 %	527	81	155	191	290	453	442	427	491	495	536
98 %	430	35	48	116	155	182	183	190	280	283	303
99 %	313	28	31	82	122	146	149	171	186	186	241
100 %	263	26	22	32	93	88	89	119	117	110	110
Mean	956	756	857	958	997	1,075	1,086	1,161	1,175	1,185	1,119
Stand Dev	263	468	443	424	390	400	398	489	476	481	381
Maximum	1,681	1,902	2,343	2,258	2,184	2,220	2,192	2,442	2,442	2,424	2,231

Table 6.25 Statistics for Whitney Storage Concentrations (TM option 2, Lag option 2)

Factor (F_L)	No Lag	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Exceed Freq	Concentration (mg/l)										
10 %	1,310	14,120	9,899	6,812	4,762	3,698	3,544	3,061	2,576	2,344	2,036
25 %	1,173	12,345	6,151	4,915	2,739	2,593	2,480	2,698	2,075	1,935	1,885
40 %	1,038	10,720	5,398	4,292	2,561	2,284	2,235	2,414	1,881	1,737	1,719
50 %	959	9,706	4,962	3,979	2,472	2,153	2,112	2,300	1,790	1,597	1,597
60 %	849	8,786	4,673	3,663	2,369	2,046	2,035	2,220	1,703	1,498	1,498
75 %	732	7,174	3,631	3,033	1,974	1,779	1,767	2,002	1,518	1,298	1,298
90 %	580	1,364	1,190	1,260	1,327	1,325	1,405	1,411	1,177	992	992
95 %	498	1,167	1,091	1,114	1,133	1,141	1,149	1,149	1,075	912	912
98 %	375	971	932	928	948	954	956	956	956	796	796
99 %	283	876	759	751	768	776	841	841	841	779	779
100 %	222	801	726	683	731	728	761	761	761	761	761
Mean	949	9,235	5,190	4,034	2,658	2,299	2,258	2,299	1,821	1,642	1,576
Stand Dev	292	4,163	2,890	1,780	1,155	826	777	612	496	476	379
Maximum	1,896	17,524	13,047	8,741	6,039	4,559	4,368	3,626	3,011	2,751	2,310

Table 6.26 Statistics for Concentrations at Whitney Gage (TM option 2, Lag option 2)

Factor (F_L)	No Lag	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Exceed Freq	Concentration (mg/l)										
10 %	1,310	1,394	1,387	1,480	1,485	1,544	1,551	1,831	1,829	1,830	1,652
25 %	1,173	1,081	1,161	1,227	1,249	1,335	1,334	1,429	1,422	1,454	1,432
40 %	1,038	805	897	1,103	1,077	1,173	1,195	1,199	1,202	1,199	1,197
50 %	959	682	798	932	980	1,056	1,094	1,094	1,107	1,101	1,093
60 %	849	601	678	828	877	968	971	988	996	978	973
75 %	732	256	406	630	674	780	805	826	864	831	831
90 %	580	30	104	172	387	476	486	500	523	531	537
95 %	498	0	0	0	0	0	0	0	161	211	254
98 %	375	0	0	0	0	0	0	0	0	0	0
99 %	283	0	0	0	0	0	0	0	0	0	0
100 %	222	0	0	0	0	0	0	0	0	0	0
Mean	948	702	781	904	939	1,026	1,036	1,113	1,121	1,124	1,080
Stan Dev	292	486	464	463	433	434	433	527	507	515	432
Maximum	1,896	1,803	1,791	1,967	1,786	1,900	1,885	2,421	2,423	2,395	1,917

6.4.5 Reservoir Salinity Routing Parameter Calibration Summary

Calibration statistics are tabulated in Table 6.27 through Table 6.30 for TDS concentrations in mg/l of the end-of-month storage in Possum Kingdom and Whitney Reservoirs and mean monthly streamflows at the Graford and Whitney gaging stations for the 276-month period-of-analysis extending from October 1963 through September 1986. The plan identifier listed in column 1 of the tables refers to the combination of parameters in columns 2, 3, 4, and 5. The calibration statistics for each plan are tabulated in column 6 through 13 of each of the four tables.

The calibration statistics presented in the following Tables 6.27–6.30 were developed from simulation results for Possum Kingdom and Whitney Reservoirs for selected combinations of the following routing parameters. The previously discussed TM option 1 was adopted for all of these simulations. The descriptions of the tables are as follows:

Columns 1-5 – The plan identifier in column 1 refers to the combination of the four calibration parameters LAG1, LAG2, RCF1, and RCF2 listed in column 2-5. As described in previous section, LAG1 and LAG2 are abbreviated forms of two options (Lag option 1 and Lag option 2) for salinity routing through reservoir. RCF1 and RCF2 are the factors of F_1 and F_2 in Equation 6-2.

Column 6 – MO (Mean Observed) is the mean of the 276 observed monthly flow concentrations or end-of-month storage concentration in mg/l.

Column 7 – MS (Mean Simulated) is the mean of the 276 simulated monthly flow concentrations or end-of-month storage concentration in mg/l.

Column 8 – MD (Mean Difference) is the mean of the 276 differences between observed less simulated flow concentrations or storage concentrations in mg/l.

Column 9 – MD+ is the mean of the 276 differences between observed less simulated monthly flow concentrations or end-of-month storage concentrations that are positive numbers.

Column 10 – MD– is the mean of the 276 differences between observed less simulated monthly flow concentrations or end-of-month storage concentrations that are negative numbers.

Column 11 – MDS (Mean of Differences Squared) is the mean of the square of the 276 differences between observed less simulated monthly flow concentrations or end-of-month storage concentrations.

Column 12 – Max+ is the maximum of the 276 differences between observed less simulated monthly flow concentrations or end-of-month storage concentration in mg/l,

Column 13 – Max– is the minimum of the 276 differences between observed less simulated monthly flow concentrations or end-of-month storage concentrations in mg/l.

The parameters LAG1 and LAG2 control the timing (lag time) features of the WRAP-SALT algorithms for routing salinity through reservoirs. The parameters RCF1 and RCF2 (F_1 and F_2) address differences between the long-term levels of volume-weighted outflow concentrations versus volume-weighted storage concentrations reflecting losses or gains of salinity load in the reservoir.

Plans 1, 2, 3, 4, and 5 consist of activating the lag option in which a constant lag is entered as the LAG1 parameter. Plans 6 and 7 activate the retention based option with a maximum lag limit of 3 months. Of these seven salinity routing plans, the optimal for both Whitney and Possum Kingdom Reservoir is plans 1 or 2 which represent an lag of either zero or one month.

Plans 8, 9, 10, and 11 consist of making outflow concentration less than the corresponding storage concentrations by entering values than the default of 1.0 for RCF1 or RCF2. The lag options are not activated, thus the lag is zero. Observed reservoir storage and outflow volume-weighted TDS concentrations are shown in Table 6.4 and Tables 6.27-6.30 and repeated in Table 6.31. The 1964-1986 mean outflow concentrations are 94.3 percent and 87.3 percent of the 1964-1986 mean storage concentrations of Possum Kingdom and Whitney Reservoirs. These percentages are adopted for the parameters RCF1 and RCF2.

Table 6.27 Parameter Calibration Statistics for Concentrations of Flows at Graford Gage

1 Plan	2 LAG1	3 LAG2	4 RCF1	5 RCF2	6 MO	7 MS	8 MD	9 MD+	10 MD−	11 MDS	12 Max+	13 Max−
1	0	0	1.0	1.0	1,534	1,539	-4	234	-166	20	978	-425
2	1	0	1.0	1.0	1,534	1,530	4	235	-296	20	1,055	-1,044
3	2	0	1.0	1.0	1,534	1,525	10	258	-391	93	1,214	-1,351
4	3	0	1.0	1.0	1,534	1,519	16	320	-429	253	1,161	-1,381
5	6	0	1.0	1.0	1,534	1,507	27	327	-549	751	1,285	-1,847
6	3	1.0	1.0	1.0	1,534	1,507	27	306	-418	749	1,195	-1,585
7	3	0.5	1.0	1.0	1,534	1,506	28	286	-409	793	1,203	-1,585
8	0	0	0.943	1.0	1,534	1,534	1	229	-161	1	911	-448
9	0	0	0.9	1.0	1,534	1,529	5	220	-164	29	861	-466
10	0	0	1.0	0.943	1,534	1,534	1	239	-160	0	919	-449
11	0	0	1.0	0.90	1,534	1,530	5	226	-166	24	876	-469

Table 6.28 Parameter Calibration Statistics for Storage Concentrations
in Possum Kingdom Reservoir

1 Plan	2 LAG1	3 LAG2	4 RCF1	5 RCF2	6 MO	7 MS	8 MD	9 MD+	10 MD−	11 MDS	12 Max+	13 Max−
1	0	0	1.0	1.0	1,626	1,689	-63	307	-314	3,964	783	-820
2	1	0	1.0	1.0	1,626	1,931	-305	204	-484	93,288	506	-1,002
3	2	0	1.0	1.0	1,626	2,028	-402	179	-591	161,583	429	-1,165
4	3	0	1.0	1.0	1,626	2,127	-501	149	-689	251,388	389	-1,331
5	6	0	1.0	1.0	1,626	2,380	-755	48	-884	569,361	152	-1,539
6	3	1.0	1.0	1.0	1,626	2,162	-537	168	-750	288,295	416	-1,495
7	3	0.5	1.0	1.0	1,626	2,127	-501	168	-810	251,287	477	-1,540
8	0	0	0.943	1.0	1,626	1,792	-166	295	-384	27,606	670	-954
9	0	0	0.9	1.0	1,626	1,878	-252	274	-451	63,572	577	-1,066
10	0	0	1.0	0.943	1,626	1,789	-164	289	-385	26,822	664	-945
11	0	0	1.0	0.90	1,626	1,873	-248	269	-446	61,297	566	-1,050

Table 6.29 Parameter Calibration Statistics for Concentrations of Flow at Whitney Gage

1 Plan	2 LAG1	3 LAG2	4 RCF1	5 RCF2	6 MO	7 MS	8 MD	9 MD+	10 MD−	11 MDS	12 Max+	13 Max−
1	0	0	1.0	1.0	927	928	-1	147	-117	1	1,146	-360
2	1	0	1.0	1.0	927	924	4	190	-286	14	1,049	-941
3	2	0	1.0	1.0	927	920	8	225	-450	59	1,389	-1,563
4	3	0	1.0	1.0	927	915	12	269	-545	142	1,377	-1,924
5	6	0	1.0	1.0	927	911	16	343	-710	268	1,145	-2,645
6	3	1.0	1.0	1.0	927	909	18	249	-387	340	1,422	-1,281
7	3	0.5	1.0	1.0	927	865	62	273	-354	3,854	1,481	-1,261
8	0	0	0.873	1.0	927	923	5	153	-126	21	1,148	-336
9	0	0	0.9	1.0	927	924	3	155	-121	11	1,148	-341
10	0	0	1.0	0.9	927	924	4	158	-129	13	1,154	-378
11	0	0	1.0	0.8	927	918	10	166	-164	91	1,160	-480

Table 6.30 Parameter Calibration Statistics for Storage Concentrations in Whitney Reservoir

1 Plan	2 LAG1	3 LAG2	4 RCF1	5 RCF2	6 MO	7 MS	8 MD	9 MD+	10 MD−	11 MDS	12 Max+	13 Max−
1	0	0	1.0	1.0	1,062	956	105	167	-71	11,058	701	-150
2	1	0	1.0	1.0	1,062	1,217	-155	173	-235	24,121	451	-854
3	2	0	1.0	1.0	1,062	1,414	-353	149	-394	124,344	322	-1,547
4	3	0	1.0	1.0	1,062	1,576	-515	83	-550	265,045	259	-1,914
5	6	0	1.0	1.0	1,062	1,838	-776	62	-797	602,016	212	-2,575
6	3	1.0	1.0	1.0	1,062	1,651	-589	13	-587	347,151	53	-1,402
7	3	0.5	1.0	1.0	1,062	2,407	-1,345	2	-1,323	1,809,568	3	-3,410
8	0	0	0.873	1.0	1,062	1,136	-74	271	-143	5,523	537	-367
9	0	0	0.9	1.0	1,062	1,097	-36	213	-116	1,286	577	-315
10	0	0	1.0	0.9	1,062	1,097	-36	213	-116	1,286	577	-315
11	0	0	1.0	0.8	1,062	1,255	-193	265	-260	37,351	512	-641

The concept of lag time addresses the issue of the time required for entering salt loads to be transported through a large reservoir. Lag options have been extensively investigated in this study based on the initial premise that lag time is an important key consideration in salinity routing. However, this was found to not be the case for the two reservoirs analyzed. Lag times of zero or one month were found to be optimal for Possum Kingdom and Whitney Reservoirs. These reservoirs can probably be best simulated without activation of the lag options (zero lag). If the lag option is activated, the optimal lag is one month. A reasonable approach is to adopt the beginning-of-month TM option combined with zero lag.

CHAPTER VII

DEVELOPMENT OF WRAP-SALT SALINITY INPUT DATASET FOR THE BRAZOS RIVER BASIN

This chapter outlines the approach adopted in developing the salinity inflow input data for the Brazos River Basin using data from the volume and salinity budget study. The WRAP-SALT salinity input file contains data defining the salt loads entering the river/reservoir system. These inflow data account for most of the salinity input file read by WRAP-SALT along with the WRAP-SIM simulation results.

7.1 WRAP-SIM Input Dataset

Simulations are performed using a single WRAP-SALT salinity input dataset combined with the following alternative WRAP-SIM input datasets:

1. The Texas Commission on Environmental Quality (TCEQ) Water Availability Modeling (WAM) System dataset for the Brazos River Basin and San Jacinto-Brazos Coastal Basin with the authorized use scenario (run 8) consists of SIM input files with the following filenames: Bwam8.DAT, Bwam8.FLO, Bwam8.EVA, and Bwam8.DIS. These files are called the Bwam8 dataset.

2. The Brazos River Authority Condensed (BRAC) dataset with the authorized use scenario (run8) consists of SIM input files with the filenames BRAC8.DAT, BRAC8.FLO, BRAC8.EVA, and BRAC8.RUF. Development of the BRAC dataset is described by Wurbs and Kim (Wurbs and Kim 2008).
3. The Brazos River Authority Condensed 2008 Actual Use (BRAC2008) dataset is a variation of the BRAC8 dataset in which the water use data in the DAT file represents actual water use by Brazos River Authority customers during the year 2008. The BRAC2008 dataset was adopted in the study presented in this chapter to model the impacts of natural salt pollution on water supply capabilities and the potential effects of salinity control measures and alternative reservoir system operating strategies.

The WRAP-SALT reads a salinity input (SIN) file along with simulation results from an output (OUT) file created by the WRAP program SIM. A single WRAP-SALT salinity input SIN file is discussed in this chapter that is designed for use with either of the several available versions of the Brazos WRAP-SIM input datasets (DAT, FLO, EVA, DIS, and RUF files).

The TCEQ Water Availability Modeling (WAM) System WRAP-SIM input dataset for the Brazos River Basin, last updated in August 2007, contains over 3,800 control points. Wurbs and Kim (Wurbs and Kim 2008) document development of a condensed WRAP-SIM Brazos River Basin input dataset at Texas A&M University based on reducing the full TCEQ WAM System DAT file to essentially those river/reservoir water management/allocation/use features that are directly connected to the Brazos River Authority (BRA) reservoir system. The TCEQ Brazos WAM (Bwam) and Brazos River Authority Condensed (BRAC) datasets both include authorized use scenario (Bwam 3 and BRAC3) and current use scenario (Bwam8 and BRAC8) versions. The number of control points, primary control points, and reservoir contained in each of these four datasets are shown in Table 7.1.

Table 7.1 Number of Control Points and Reservoirs in Brazos River Basin WRAP-SIM Input Datasets

	Number of		
Brazos River Basin WRAP-SIM Input Dataset	Control Points	Primary Control points	Reservoirs
Bwam3 Authorized Use (August 2007)	3,830	77	670
Bwam8 Current Use (August 2007)	3,834	77	711
BRAC3 Authorized Use (December 2008)	48	48	15
BRAC8 Current Use (December 2008)	48	48	14

The purpose for developing the condensed BRAC dataset is to have a much simpler model that facilitates operational planning studies and other decision support activities for the Brazos River Authority System (Wurbs and Kim 2008). The 12 BRA reservoirs, which include Possum Kingdom, Granbury, Whitney, and nine others, are included in the dataset along with the non-BRA Hubbard Creek and Squaw Creek Reservoirs. The number of control points is reduced from over 3,800 to 48. The streamflow inflows in the BRAC3 and BRAC8 input datasets are flows available to the BRA after consideration of all the other water users and management/use features in the river basin that have been removed from the Bwam3 and Bwam8 datasets.

7.2 Outline of WRAP-SALT Salinity Input Dataset

The hydrologic period-of-analysis for the TCEQ WAM System Brazos River Basin dataset is January 1940 through December 1997. Wurbs and Kim (Wurbs and Kim 2008) extended the hydrologic period-of-analysis to 1900-2007. The 1964-1986 salinity data were used to develop a WRAP-SALT salinity input SIN file that covers 1900-2007.

7.2.1 USGS Gaging Stations Used in Developing Salinity Input Dataset for the Brazos River Basin

Data in the salinity input (SIN) file describing total dissolved solids (TDS) concentrations or loads of inflows to the river system are assigned to six key control points representing the five USGS gaging stations listed in Table 7.2 and the basin outlet where the Brazos River flows into the Gulf of Mexico. Salt loads entering the river system at other control points are computed within WRAP-SALT based on repetition of concentration data from the salinity input file entered for these selected control points. Table 7.2 represents the control point identifiers used in Bwam and BRAC datasets and the 1964-1986 mean monthly flows volumes, loads, and concentrations from the observed USGS dataset.

Table 7.2 1964-1986 Mean Flows, Loads, and Concentrations at Selected Control Points

USGS Gaging Station (Control Point Location)	Fig. 3.2 Map No.	WAM CP ID	Mean Flow (ac-ft/mon)	Mean Load (tons/month)	Mean Concentration (mg/l)
Brazos River at Seymour gage	7	BRSE11	16,215	79,127	3,589
Gage at Graford below Possum Kingdom	13	SHGR26	42,999	89,712	1,534
Gage near Aquilla below Whitney Dam	15	BRAQ33	74,193	93,538	927
Little River at Cameron gage	20	LRCA58	89,374	33,276	256
Brazos River at Richmond gage	25	BRRI70	414,328	190,628	338

The locations of the USGS gaging stations listed in Table 7.2 are shown in Figure 3.2 of Chapter III. The Cameron gage on the Little River represents the largest low-salinity tributary sub-basin of the Brazos River Basin. Lakes Proctor, Belton, Stillhouse Hollow, Georgetown, and Granger are Brazos River Authority reservoirs located above the Cameron gage. The Richmond gage is on the lower Brazos River. Salinity concentrations at the Richmond gage represent a mixture of high-salinity flows passing through the Whitney gage, low-salinity flows from the Little River sub-basin which pass through the Cameron gage, and low-salinity inflows entering the river system above the Richmond gage and below the Cameron and Whitney gages.

Salinity inflow data in the SIN file dataset is assigned to the six control points representing the five gaging stations listed in Table 7.2 and the Brazos River outlet at the Gulf of Mexico. Additional otherwise unaccounted for salinity outflows (losses) were developed for Lakes Possum Kingdom, Granbury, and Whitney. The reservoirs are assigned control point identifiers 515531, 515631, 515731 in the Brazos WAM dataset.

7.2.2 Concentrations of Inflows to the River System

The WRAP-SALT input SIN file includes total dissolved solids (TDS) loads at control point BRSE11, a mean regulated flow TDS concentration at LRCA58, and concentrations of river inflows assigned to the five other control points listed in Table 7.3. Concentrations are repeated within the WRAP-SALT simulation computations for all other control points, except those sites located upstream of the Seymour gage and Cameron gage control points (BRSE11 and LRCA58).

Table 7.3 Total Dissolved Solids (TDS) Data Entered in Salinity Input SIN File

Control Point ID	Control Point Location	Components of Input Dataset
BRSE11	Brazos River at Seymour gage	load series for total regulated flows
SHGR26	Brazos River at Graford gage	concentration series for incremental inflows
BRAQ33	Brazos River at Aquilla gage	concentration series for incremental inflows
LRCA58	Little River at Cameron gage	constant 256 mg/l for total regulated flows
BRRI70	Brazos River at Richmond gage	concentration series for incremental inflows
BRGM73	Brazos River at Gulf of Mexico	constant 339 mg/l for incremental inflows

The Seymour gage (BRSE11) and Cameron gage (LRCA58) control points are treated as upstream boundaries. The SIM simulation includes computation of water quantities for all control points including those located upstream of the Seymour and Cameron gage. However, the WRAP-SALT simulation begins at the Seymour and Cameron control points and extends downstream to the outlet of the Brazos River at the Gulf of Mexico. Salinity loads and concentrations are computed within a WRAP-SALT simulation for all control points except those located upstream of the Seymour and Cameron gages.

The term *inflows* as used in Table 7.3 is defined differently for WRAP-SIM simulations with the Brazos Water Availability Model (Bwam) versus Brazos River Authority Condensed (BRAC) datasets. The *inflows* on the WRAP-SIM input datasets for the Bwam datasets are naturalized flows. The *inflows* to the river system for the BRAC model represent flows available to the primary system that reflect the effects of the numerous secondary water rights in the Bwam3 and Bwam8 DAT files that are removed in the BRAC3 and BRAC DAT files.

7.2.3 Volume and Load Balance Summaries

The schematic of Figure 7.1 shows the six USGS gaging stations that define the salinity budget reaches of Chapter III and the five USGS gaging stations adopted for developing the WRAP-SALT salinity input file dataset.

The 1964-1986 volume and salinity budget is summarized in Tables 4.4, 4.5 and 4.6 of Chapter IV. Table 7.4 is a reorganized summary of the volume and salinity budget structured to represent the WRAP-SALT salinity input SIN file dataset. The 1964-1986 means of the incremental flow volumes and loads from the salinity budget study dataset used to develop the WRAP-SALT salinity input for each of the five control points are tabulated in Table 7.4. The load outflow (losses) from Tables 4.4 and 4.5 are assigned to the three reservoirs and also summarized in Table 7.4.

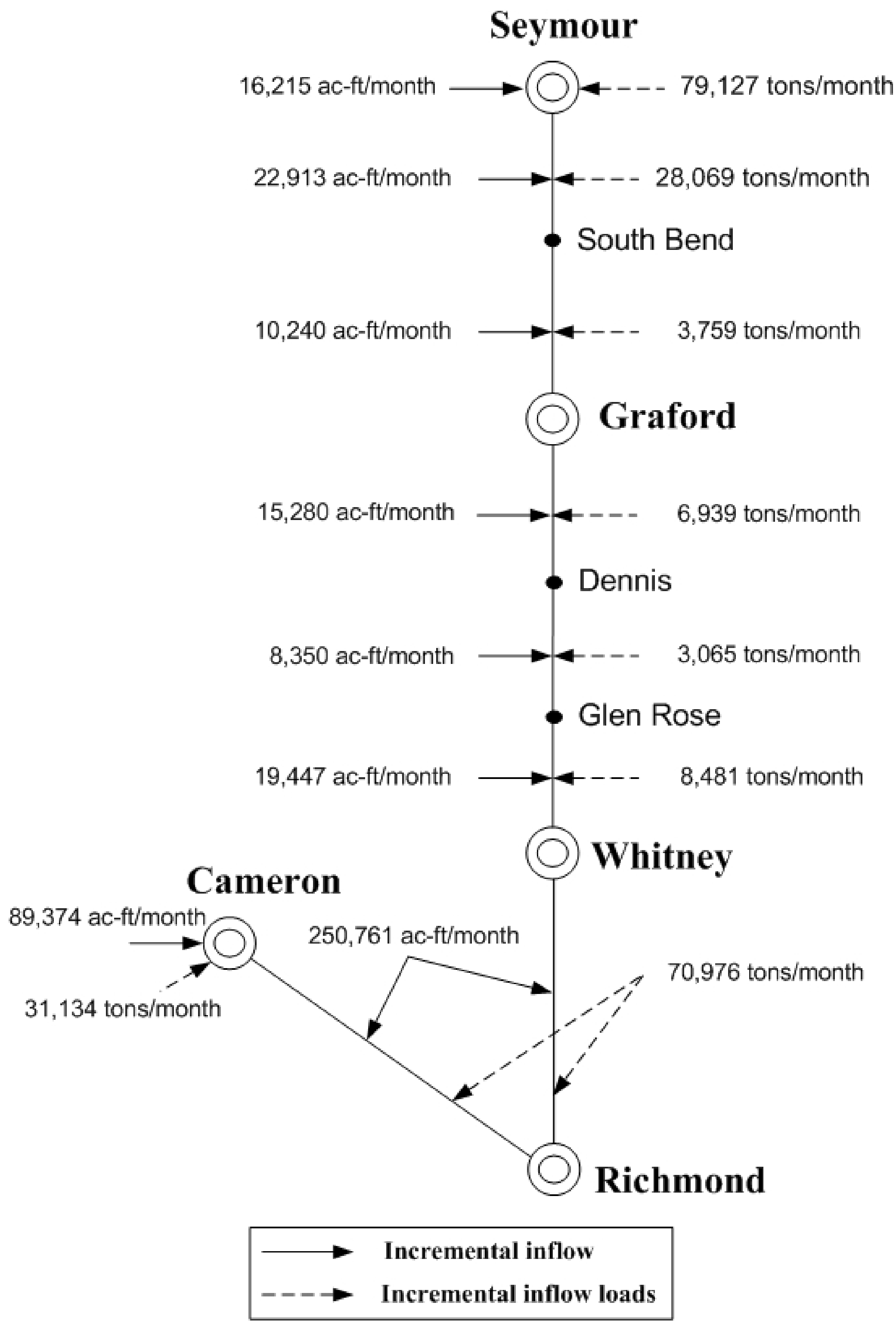

Figure 7.1 1964-1986 Mean of Incremental Inflow Volumes and Loads

Table 7.4 Means of Incremental Volumes, Loads, and Concentrations of Inflow and Losses

Control Point	Figure 1.3 Map Number	Mean Volume (ac-ft/month)	Mean Load (tons/month)	Mean Load (percentage)	Mean Concentration (mg/l)
		Inflows Entering the River System			
Seymour gage	7	16,215	79,127	34.9	3,589
Graford gage	13	33,153	31,828	14.1	706
Whitney gage	15	43,077	18,485	8.2	316
Cameron gage	20	89,374	31,134	13.7	256
Richmond	25	251,443	65,956	29.1	193
Subtotal		432,262	226,530	100.0	385
		Losses Leaving the River System			
Lake Possum Kingdom		2,383	19,331	66.4	5,966
Lake Granbury		2,222	6,694	23.0	2,216
Lake Whitney		2,233	3,103	10.6	1,022
Subtotal		6,838	29,128	100.0	3,140
		Total Net Inflows Less Losses			
Brazos River Basin Total		440,100	197,402		330

Basin totals are provided at the bottom of Table 7.4. The WRAP-SATL input dataset has a 1964-1986 mean total TDS load of 197,396 tons/month entering the Brazos River and its tributaries above the Richmond gage control point. Of course, the 276 monthly inflows loads at each control point are highly variable, fluctuating greatly from the mean loads. The 1964-1986 mean total load of 190,628 ton/month at the Richmond gage shown in Table 7.2 is the mean of the observed flows from the original USGS dataset. The 197,402 tons/month is the mean TDS load of the river flows at the Richmond gage that are entered in the WRPA-SALT input SIN file dataset. The difference is 6,774 tons/month as shown below.

Total basin load in Table 7.4	=	197,402 tons/month
Actual load at Richmond gage in Table 7.2	=	190,628 tons/month
Difference	=	6,774 tons/months
Change in storage in the three reservoirs	=	4,917 tons/month
Granbury water supply diversions	=	1,855 tons/month
Total	=	6,772 tons/month

The main difference is the increase in the amount of water in storage in Possum Kingdom, Granbury, and Whitney Reservoirs between the beginning of September 1963 and end of October 1986 which averaged over 276 months is 4,917 tons/month from Table 4.5. The Granbury water supply diversion accounts for the remaining 1,855 tons/month of the difference.

Salt concentrations through the Brazos River and its tributaries exhibit extreme variability both spatially and temporally. The concentrations tabulated in the last column of Table 7.4 illustrate the spatial variability of salinity concentrations. A governing objective of the methodology outlined here is to reasonably accurately capture the variability of TDS concentrations with time as well as location.

7.3 Methodology for Developing WRAP-SALT Input Dataset

The strategy for developing the salt inflows for the WRAP-SALT salinity input (SIN) file consists of applying the following methods at each of the six control points listed in Table 7.3. The methods differ at the different control points. The dataset is designed based on salinity computations not being performed in WRAP-SALT for any control points located upstream of the Seymour gage (BRSE11) and Cameron gage (LRCA58) control points. The TDS load inflows for all other control points are computed automatically within WRAP-SALT by repeating concentrations entered for control points SHGR26, BRAQ33, BRRI70, and BRGM73. The loads or concentrations of Seymour, Graford, Aquilla, and Richmond gages for the remainder of the 1900-2007 simulation are synthesized as a function of monthly WRAP-SIM inflow volumes using the methodology described later in this chapter.

7.3.1 Seymour Gage

The Seymour gage serves as an upstream boundary in WRAP-SALT. Although the WRAP-SIM simulation computes water quantities at control points located upstream of the Seymour gage control point, the WRAP-SALT salinity begins at this control point. The observed loads for October 1963 through September 1986 are included in the SIN file without modification. The January 1900 through December 2007 monthly loads represent salinity loads of regulated flows entering the river upstream of the Seymour gage and reaching the Seymour gage. The corresponding regulated flow volumes are computed by WRAP-SIM.

7.3.2 Graford Gage

The concentrations provided in the SIN file for the Graford gage represent the concentrations of incremental flows entering the river between the Seymour and Graford gages. The loads are the difference in inflow loads between the Seymour and Graford gages each month adjusted to remove the timing effects of storage in Possum Kingdom Lake. The volumes are the differences in flow volumes between the Seymour and Graford gages adjusted to remove net evaporation and storage effects of Possum Kingdom Lake. Incremental inflow volumes and loads are computed as follows.

<u>Incremental inflow volume</u>

= other inflow Seymour-to-South Bend + other inflow South Bend-to-Graford

= 22,913 + 10,240 = 33,153 acre-feet/month

<u>Incremental inflow load</u>

= other inflow Seymour-to-South Bend + other inflow South Bend-to-Graford

= 28,069 + 3,759 = 31,828 tons/month

Concentrations for each of the 276 months during 1964-1986 are determined by combining the incremental loads and volume from the salinity and volume budget data.

7.3.3 Whitney Gage

The concentrations provided in the SIN file for the Whitney gage represent the concentrations of incremental flows entering the river/reservoir system between the Graford and Whitney gages. Incremental inflow volumes and loads are computed as follows.

<u>Incremental inflow volume</u>

= other inflow Graford-to-Dennis + other inflow Dennis-to-Glen Rose + other inflow Glen Rose-to Whitney

= 15,280 + 8,350 + 19,447 = 43,077 acre-feet/month

<u>Incremental inflow load</u>

= other inflow load Graford-to-Dennis + other inflow load Dennis-to-Glen Rose + other inflow load Glen Rose-to Whitney + other load (L_X) + SCA inflow load – SCA outflow load

= 6,939 + 3,065 + 7,139 +1,298 + (5446-5402) = 18,485 tons/month

7.3.4 Cameron Gage

The Cameron gage control point is treated as an upper boundary in the WRAP-SALT simulation above which salinity concentration are not computed. A single constant concentration provided in the SIN file for the Cameron gage control point represents the concentration of regulated flows flowing through the Cameron gage control point. The volume-weighted mean concentration of 256 mg/l from the observed 1964-1986 USGS data was adopted for the entire simulation period-of-analysis.

Another alternative option for modeling salinity in the river system above the Cameron gage was also investigated. The alternative option is based on developing a 1900-2007 sequence of monthly TDS concentrations for the Cameron gage applying the same methodology used for the other gaging stations. The results for the Cameron gage are presented later in this chapter along with the results for the other gaging stations. The concentration series is designed to be applied to the inflows at all control points located upstream of the Cameron gage. This modeling approach was found to work fine. However, applying a constant concentration to regulated flows was concluded to be more realistic and better served the purpose of anticipated modeling applications. Salinity concentrations in the Little River sub-basin are small relative to the Brazos River.

7.3.5 Richmond Gage

The concentrations provided in the SIN file for the Richmond gage represent the concentrations of incremental flows entering the river above the Richmond gage at locations that are not above the Cameron and Whitney gages. The incremental loads are the loads at the Richmond gage less the loads at the Cameron and Whitney gages. Incremental loads and volumes and corresponding concentrations for 1964-1986 were computed using available USGS data.

7.3.6 Basin Outlet

The mean concentration of naturalized flows in the Brazos River is assumed to be the same from the Richmond gage downstream to the outlet at the Gulf of Mexico and is set at the 1964-1986 volume-weighted mean of the observed concentrations at the Richmond gage. The 1964-1986 mean of total regulated flows at the Richmond gage of 339 mg/l is provided in the SIN file for control point BRGM73 representing the point where the Brazos River flows into the Gulf of Mexico. The constant concentration is applied within the WRAP-SALT simulation to all incremental inflow between the Richmond gage (BRRI70) and outlet (BRGM73) control points.

7.3.7 Load Losses in Reservoirs

WRAP-SIM computes channel losses and channel loss credits associated with water supply diversions, return flows, reservoir storage, and other water management operations that affect river flows. Channel losses and loss credits in WRAP are the increases (losses) and decreases (loss credits) in channel losses that result from water control and use. Naturally occurring channel losses are assumed to already be reflected in the naturalized stream flows provided to WRAP-SIM as input data. Likewise, the salinity loads defined in the WRAP-SALT input file are assumed to already reflect naturally occurring losses. WRAP-SALT computes loads associated with water quantities derived from WRAP-SIM reservoir system operations and other water management practices, including loads associated with channel losses and channel loss credits.

The losses of loads addressed below represent additional other losses not associated with the WRAP-SIM channel losses and channel loss credits. These are loads that are not associated with any component of the volume budget. These other losses at the three reservoirs were developed as follows and are expressed in the WRAP-SALT input as percentages of inflow loads. In Table 7.4, outflow loads (losses) were assigned to control points 515531, 515631, and 515731 representing Lakes Possum Kingdom, Granbury, and Whitney in the WRAP-SALT input dataset. The 1964-1986 mean TDS load quantities in Table 7.5 are computed from quantities in Table 7.4.

The inflow load to Possum Kingdom Lake shown in Table 7.5 is computed from the quantities in Table 7.4 as the cumulative total inflows to the Graford gage:

$$\text{inflow load to PK} = 79{,}127 + 31{,}828 = 110{,}955 \text{ tons/month}$$

Losses (outflow loads) of 19,331 tons/day are assigned to control point 51531 representing Possum Kingdom Lake. The mean losses of 19,331 tons/day are 17.4 percent of the mean inflow loads to the reservoir of 110,955 tons/day before removing the losses. The net inflow load to Possum Kingdom Lake after removing these losses is 91,624 tons/day.

Table 7.5 1964-1986 Mean TDS Load Losses Not Associated with Volumes

Reservoir	WAM CP Identifier	Inflow Load (tons/month)	Load Losses (tons/month)	Net Inflow (tons/month)	Before Losses (tons/month)	Load Losses (percentage)
Possum Kingdom	515531	110,955	19,331	91,624	110,955	17.422
Granbury	515631	10,004	6,694	94,934	101,628	6.587
Whitney	515731	8,481	3,103	100,312	103,415	3.0005
Total		129,440	29,128	100,312		

7.4 Extending Salinity Data to 1900-2007 Based on Relationships Between Flow Volumes and Loads

The salinity budget study described in Chapters III and IV was based on data from a major salinity data collection program conducted by the USGS from October 1963 through September 1986. The salinity budget data were used to develop a dataset that include the following data:

- Total TDS loads and flow volumes at the Seymour and Cameron gages for each of the 276 months of USGS water years 1964-1986
- Incremental loads and volumes at the Graford, Whitney, and Richmond gages for the 276 months of USGS water years 1964-1986

These data were then combined with naturalized flow volumes for 1900-1963 and 1987-2007 to develop the salinity input SIN file data extending from January 1900 through December 2007.

As described in Section 7.1, recent work for the WAM system dataset extended the period-of-analysis to January 1900 through December 2007. The WRAP-SALT salinity input file (SIN) provides TDS concentrations for the period from January 1900 through December 2007. A methodology for extending the salinity data from 1964-1986 to 1900-2007 based on relating loads to naturalized flow volumes is outlined as follows.

7.4.1 SALIN

A utility program called SALIN was developed to assist in developing time series of salinity loads or concentrations for inclusion in a WRAP-SALT input file (SIN) as S records. Program SALIN provides capabilities for extending the time period covered by the salt concentrations or loads recorded on the SIN file S records. SALIN provides the following alternative approaches for synthesizing either concentrations or loads to extend the period-of-analysis covered by available salinity data:

- conventional least-squares linear or non-linear regression of monthly loads or concentrations as a function of flow volume
- direct linear interpolation of a flow volume versus load or concentration table

The regression analysis alternative may be advantageous over the direct interpolation alternative from the perspective of providing a better estimate of the expected value of monthly concentration or load for a given monthly volume. However, variations in concentration are lost in the regression approach. The direct interpolation option is advantageous compared to regression from the perspective of better preserving the variability in concentrations (Wurbs 2009). The computational methods described in

7.4.2 are incorporated in SALIN. The program was applied to develop the salinity data for the SIN file for the Brazos River Basin. SALIN also computes the data statistics presented later in this chapter.

7.4.2 Extension of Salinity Data

Observed loads, volumes, and/or concentrations adopted for 1964-1986. The monthly loads were extended to cover the complete 1900-2007 period-of-analysis as follows. The October 1963 through September 1986 loads and flows from the salinity budget dataset provide a flow volume versus load table which can be read numerically by a linear interpolation routine. The monthly naturalized flows from the Brazos WAM dataset for January 1900 through September 1963 and from October 1986 through December 2007 were combined within program SALIN with the volume-load table to synthesize loads. The monthly loads are divided by corresponding monthly naturalized flow volumes to obtain concentrations.

The observed loads at the Seymour gage for 1964-1986 are included in the SIN file without modification. The loads at the Seymour gage for the remainder of the 1900-2007 period-of-analysis were synthesized as a function of naturalized flow volumes. Unlike the Cameron gage, 1964-1986 observed flows at the Seymour gage closely approximate naturalized flows. The SIN file loads at the Seymour gage are treated in WRAP-SALT as the total loads of the regulated flows at this site.

The 1964-1986 observed concentrations in mg/l were adopted for the WRAP-SALT input dataset for the control points at the Graford, Whitney, and Richmond gages.

The naturalized flows from the Bwam dataset were converted to incremental flows as necessary in SALIN program and then combined with the flow-load relationship to synthesize loads. The synthesized loads and naturalized flows were combined to compute concentrations. This resulted in sequences of concentrations in mg/l for each month from January 1900 through December 2007 at the Graford, Whitney, and Richmond gages. As previous discussed in 7.3.4, a constant concentration to regulated flows was applied to the Cameron gage control point. However, the methodology described in above, was also applied to the Cameron gage control point for comparison.

The conventional approach for defining a flow volume versus load relationship is to apply least squares liner or non-linear regression. The expected value of load is expressed as function of flow volume. This approach work fine in preserving mean values of loads and concentrations but variability is lost. The resulting computed concentrations exhibit little or no variability. Plots found in Chapter IV of observed monthly TDS concentrations at the various gaging stations demonstrate the great variability in concentrations that are characteristic of flows in the Brazos River and its tributaries. The volume-load table interpolation approach was applied to better model the high degree of variability exhibited by salinity loads and concentrations.

7.4.3 Statistics and Plots of Streamflow Volumes, Loads, and Concentrations

The salinity data for the WRAP-SALT salinity input file (SIN) was developed by applying the methodology outlined in above. A table of salt loads and flow volumes is read as input by program SALIN file for a longer simulation period. The October 1963 through September 1965 monthly TDS loads and flow volumes were used to synthesize loads and concentrations for January 1900 through December 2007 by linear interpolation and alternatively by linear regression.

This chapter consists of plots and tables of statistics for the flow and salinity data for the five gaged control points. The program SALIN develops salinity data based on linear interpolation of volume-load tables, performs linear regression, and develops tables containing the following statistics:

- Number of months
- Means of volumes, loads, and concentrations
- Standard deviations of volumes, loads, and concentrations
- Autocorrelation coefficients for volumes, loads, and concentrations
- Correlation coefficients for volumes and loads, and concentrations
- Smallest and greatest concentrations

Seymour Gage

Statistics for the results from volume-load table interpolation and regression methods are presented in Table 7.6 and Table 7.7. The 1964-1986 mean load and concentrations at the Seymour gage is 79,127 tons/month and 3,589 mg/l. Means of 1900-1963 and 1987-2007 loads synthesized by the volume-load table interpolation method are 94,196 and 82,164 tons/month, and the corresponding concentrations are 2,862 and 3,441 mg/l. Means of 1900-1963 and 1987-2007 loads generated by linear regression are 79,579 and 57,724 tons/month, and the mean concentration is 2,418 mg/l for both periods. The 1900-2007 data includes 1900-1963 and 1987-2007 naturalized flow volumes and synthesized loads and concentrations and 1964-1986 observed flow volumes, loads, and concentrations.

Table 7.6 Statistics for the Results from the Volume-Load Table Interpolation Method for the Seymour Gage

Period	1964-1986 Observed	1900-2007	1900-1963	1987-2007
Number of months	276	1,296	765	255
Mean of volume (ac-ft/month)	16,215	21,199	24,210	17,561
Mean of load (tons/month)	79,127	88,620	94,196	82,164
Mean of concentrations (mg/l)	3,589	3,075	2,862	3,441
Standard deviation of volume	28,937	42,261	48,773	31,251
Standard deviation of load	96,548	116,006	129,311	89,385
Standard deviation of concentration	4,725	4,639	4,681	4,172
Autocorrelation coefficient for volume	0.921	0.284	0.287	0.196
Autocorrelation coefficient for load	0.714	0.319	0.316	0.326
Autocorrelation coeff. for concentration	0.697	0.603	0.525	0.614
Smallest concentration (mg/l)	0	0	0	0
Greatest concentration (mg/l)	15,375	15,375	15,290	15,008

Table 7.7 Statistics for the Results from Linear Regression Method for the Seymour Gage

Period	1964-1986 Observed	1900-2007	1900-1963	1987-2007
Number of months	276	1,296	765	255
Mean of volume (ac-ft/month)	16,215	21,199	24,210	17,561
Mean of load (tons/month)	79,127	75,183	79,579	57,725
Mean of concentrations (mg/l)	3,589	2,608	2,418	2,418
Standard deviation of volume	28,937	42,261	48,773	31,251
Standard deviation of load	96,548	138,876	160,317	102,722
Standard deviation of concentration	4,725	2,547	546	0
Autocorrelation coefficient for volume	0.921	0.284	0.287	0.196
Autocorrelation coefficient for load	0.714	0.284	0.287	0.196
Autocorrelation coeff. for concentration	0.697	0.813	0.231	0.934
Correlation coeff. for linear regression	0.776	-	-	-
Smallest concentration (mg/l)	0	0	0	0
Greatest concentration (mg/l)	15,375	15,375	2,418	2,418

Monthly flow volumes, loads, and concentrations at the Seymour gage are plotted in Figure 7.2 through Figure 7.6. A dashed line is used in the plots for the period from October 1963 through September 1986 for which the USGS observed volumes, loads, and concentrations are adopted. The solid lines are the monthly naturalized flow volumes from the Brazos WAM dataset and the synthesized TDS loads and concentrations. Figure 7.2 is a plot of the 1900-1963 and 1987-2007 naturalized streamflows and 1964-1986 observed flows.

The solid lines in Figure 7.5 and Figure 7.6 are the January 1900 through September 1963 and October 1986 through December 2007 loads and concentrations synthesized by linear regression. The regression loads in Figure 7.5 exhibit great variability. However, Figure 7.6 shows the lost of variability that occurs in monthly concentrations synthesized based on linear regression. The synthesized concentrations are a constant value for all non-zero loads volumes and undefined for zero volume.

Relationships between 1964-1986 monthly flow volumes versus TDS loads and concentrations are shown in Figure 7.7 and Figure 7.8. Relationships between 1900-1963 and 1987-2007 monthly naturalized flow volumes versus loads and concentrations synthesized by volume-load table interpolation are presented in Figure 7.9 and Figure 7.10. The corresponding relations for the results of the regression based synthesis are shown in Figure 7.11 and Figure 7.12.

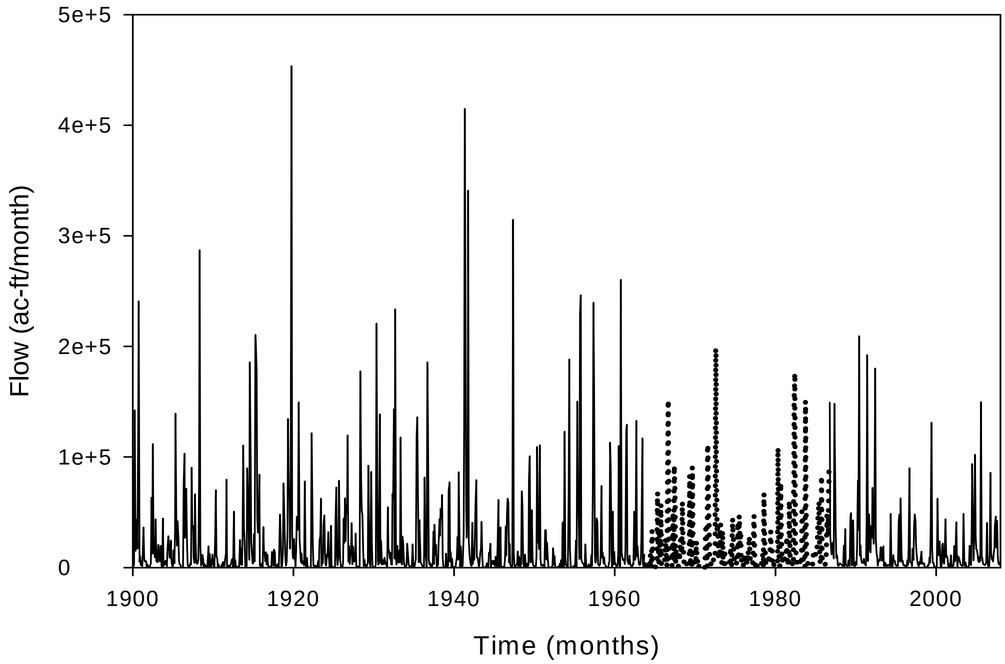

Figure 7.2 Streamflow at the Seymour Gage

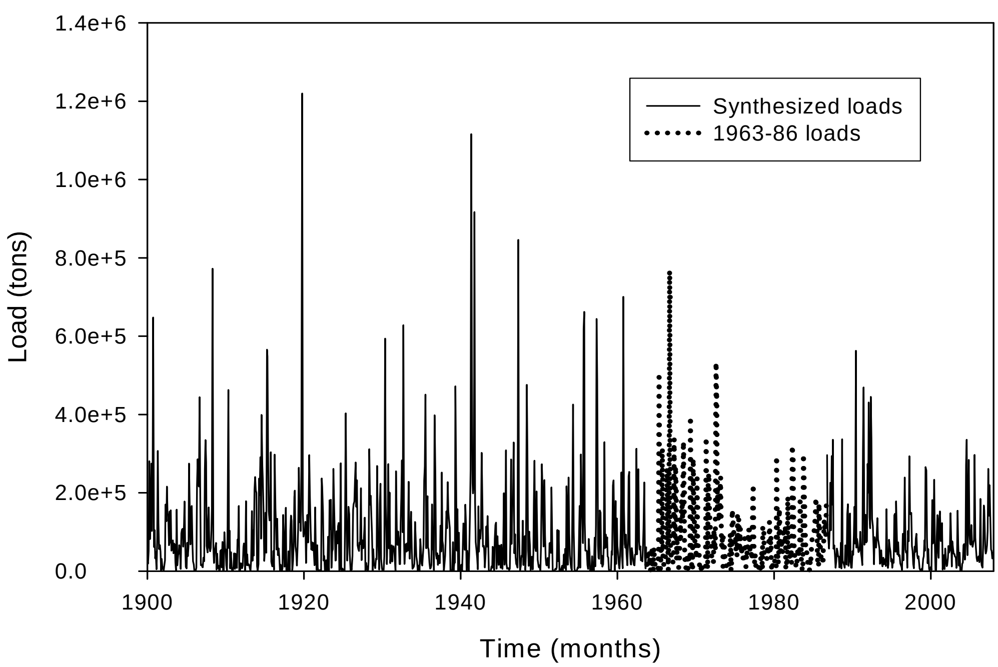

Figure 7.3 Loads at the Seymour Gage Synthesized by Volume-Load Interpolation Method

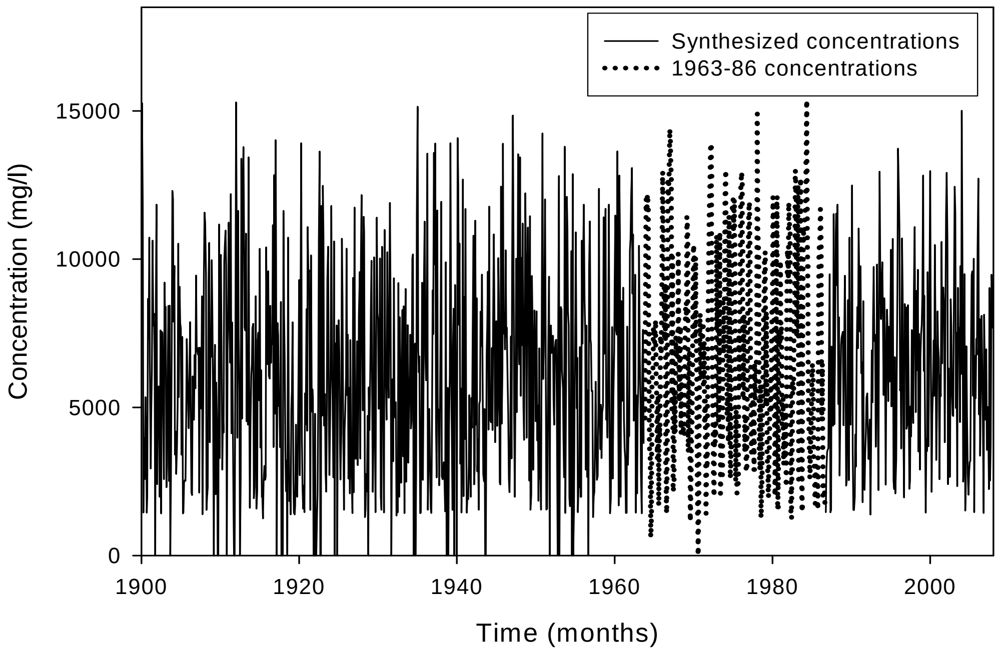

Figure 7.4 Concentrations at Seymour Gage based on by Volume-Load Interpolation Method

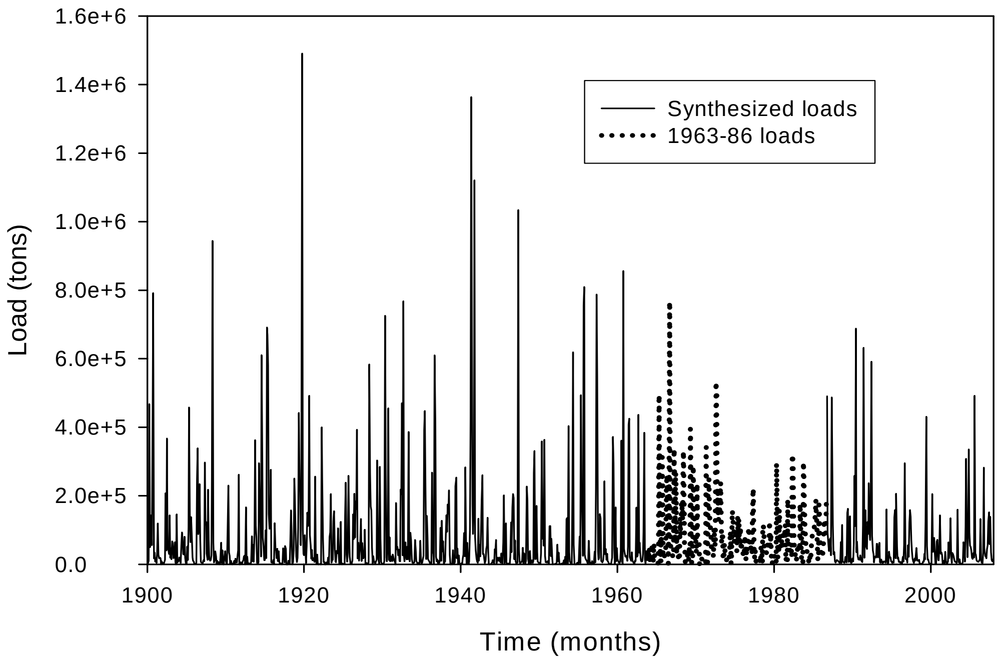

Figure 7.5 Loads at Seymour Gage Synthesized by Volume-Load Interpolation Method

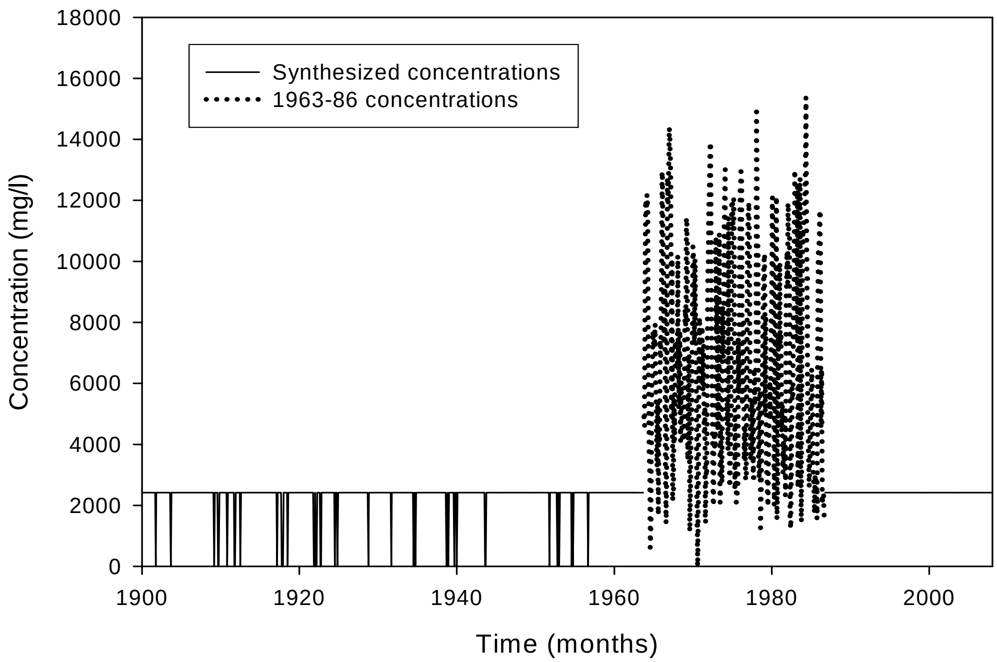

Figure 7.6 Concentrations at Seymour Gage Synthesized by Linear Regression

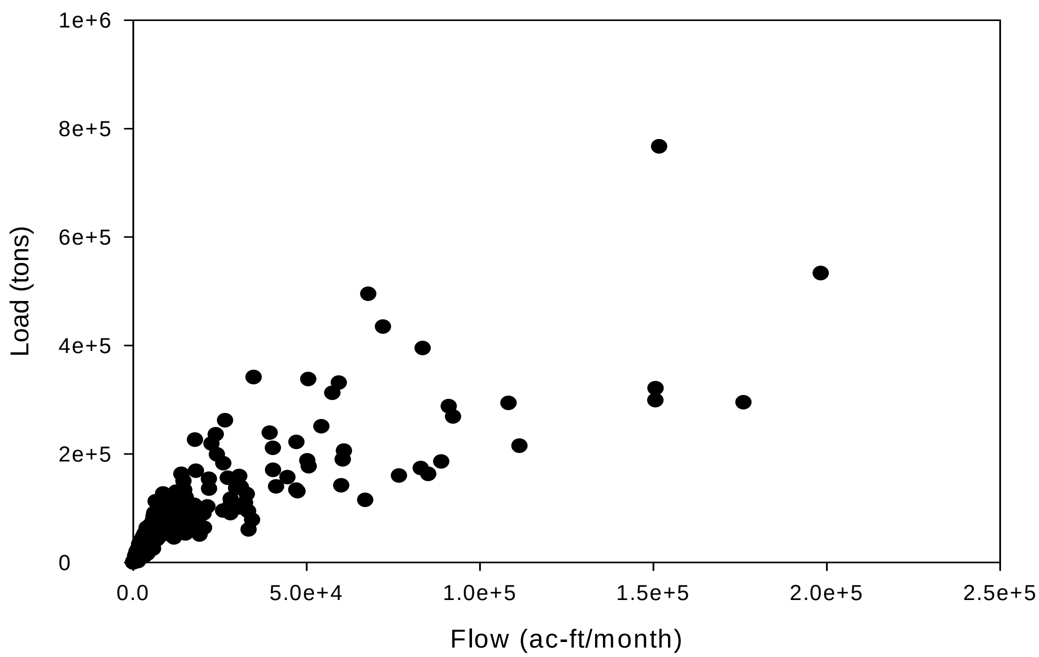

Figure 7.7 Monthly Flow versus Load from 1964-1986 at Seymour Gage

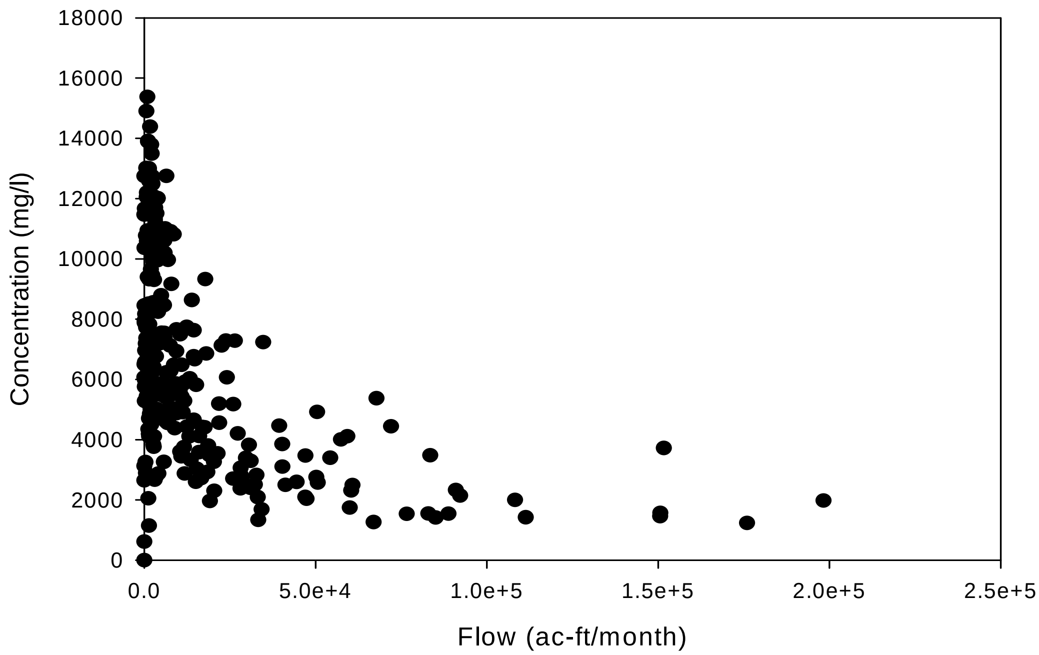

Figure 7.8 Monthly Flows versus Concentration from 1964-1986 at Seymour Gage

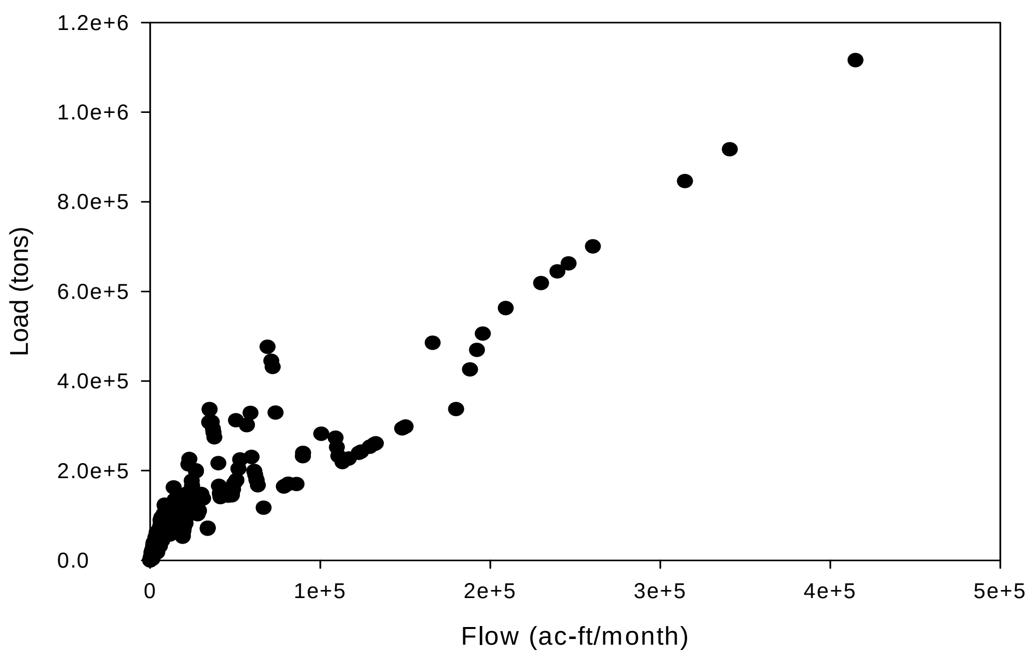

Figure 7.9 Monthly Flow versus Load from 1900 to 1963 and from 1987 to 2007 at Seymour Gage (Volume-Load Interpolation Method)

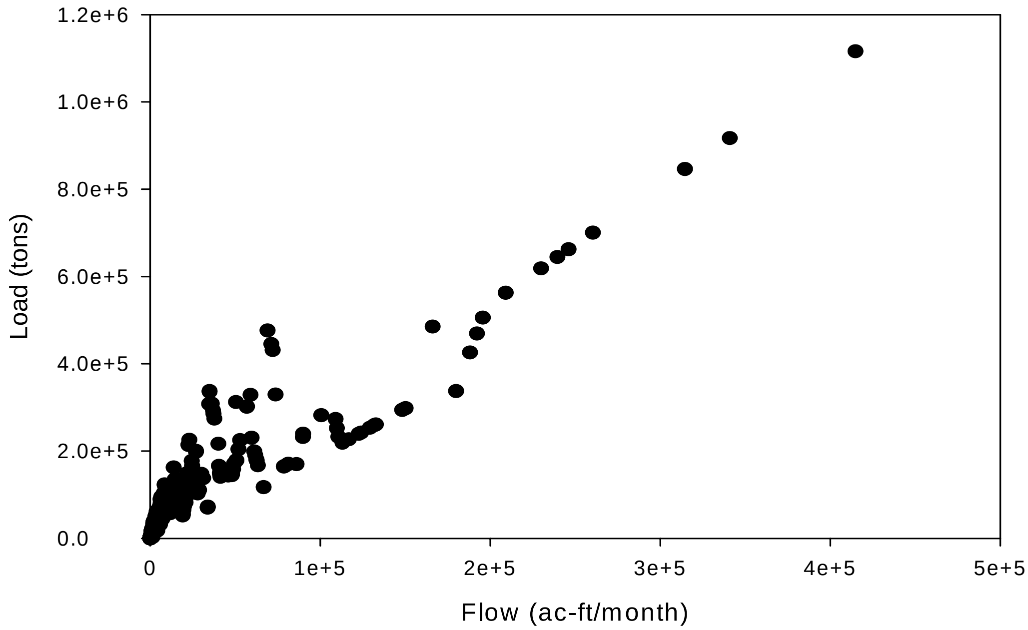

Figure 7.10 Monthly Flow versus Concentration from 1900 to 1963 and from 1987 to 2007 at Seymour Gage (Volume-Load Interpolation Method)

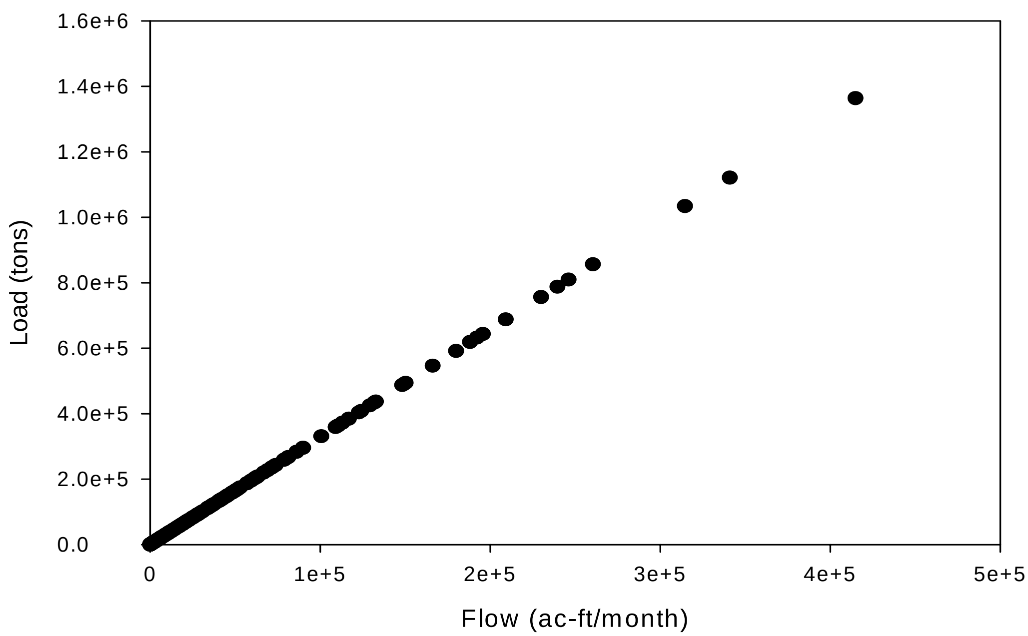

Figure 7.11 Monthly Flow versus Load from 1900-1963 and from 1987 to 2007 at Seymour Gage (Linear Regression Method)

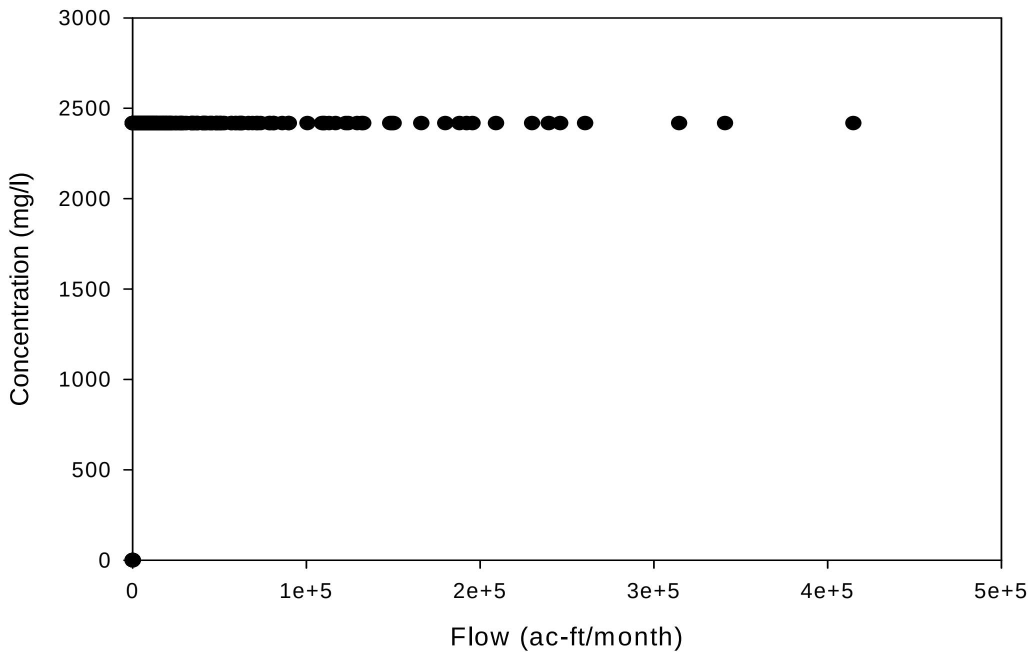

Figure 7.12 Monthly Flow versus Concentration from 1900 to 1963 and from 1987 to 2007 at Seymour Gage (Linear Regression Method)

<u>Graford Gage</u>

The WRAP-SALT salinity input file contains 1900-2007 monthly TDS concentrations at the Graford gage that represent the concentrations of incremental flows entering the river between the Seymour gage and Graford gage. The naturalized flows from the Brazos WAM dataset at the Seymour gage and Graford gage were entered in the program SALIN input SAI file to compute the incremental natural inflows between the Seymour gage and Graford gage.

Statistics for the results from the volume-load interpolation and linear regression methods are tabulated in Table 7.8 and Table 7.9. The 1900-1963 mean of loads synthesized by volume-load interpolation is 46,184 tons/months with a concentration of

683 mg/l. The 1987-2007 mean of the interpolated loads is 43,041 tons/month with a concentration of 711 mg/l. The 1964-1986 mean of the concentrations is 706 mg/l.

TDS loads and concentrations at the Graford gage are plotted in Figure 7.14 through Figure 7.17. A dashed line is used in the plots for the period from October 1963 through September 1986 during which USGS observed volumes, loads, and concentrations are available. The solid line represents the monthly TDS loads and concentrations for January 1900 through September 1963 and October 1986 through December 2007 that were synthesized based on either volume-load interpolation or linear regression. Relationships between monthly flow volumes versus TDS loads and concentrations are shown in Figure 7.18 through Figure 7.23.

Table 7.8 Statistics for the Results from the Volume-Load Interpolation Method for the Graford Gage

Period	1964-1986	1900-2007	1900-1963	1987-2007
Number of months	276	1,296	765	255
Mean of volume (acre-feet/month)	33,153	45,195	49,761	44,532
Mean of load (tons/month)	31,828	42,508	46,184	43,041
Mean of concentrations (mg/l)	706	692	683	711
Standard deviation of volume	78,260	96,948	106,421	83,681
Standard deviation of load	57,452	71,539	77,594	65,152
Standard deviation of concentration	719	602	580	511
Autocorrelation coefficient for volume	0.161	0.300	0.298	0.425
Autocorrelation coefficient for load	0.188	0.284	0.278	0.363
Autocorrelation coeff. for concentration	0.455	0.310	0.259	0.249
Smallest concentration (mg/l)	0	0	2	0
Greatest concentration (mg/l)	4,166	4,166	4,109	3,926

Table 7.9 Statistics for the Results from the Linear Regression Method for the Graford Gage

Period	1964-1986	1900-2007	1900-1963	1987-2007
Number of months	276	1,296	765	255
Mean of volume (acre-feet/month)	33,153	45,195	49,761	44,532
Mean of load (tons/month_	31,828	34,171	35,743	31,987
Mean of concentrations (mg/l)	706	556	528	528
Standard deviation of volume	78,260	96,948	106,421	83,681
Standard deviation of load	57,452	69,718	76,442	60,108
Standard deviation of concentration	719	362	53	33
Autocorrelation coefficient for volume	0.161	0.300	0.298	0.425
Autocorrelation coefficient for load	0.188	0.301	0.298	0.425
Autocorrelation coeff. for concentration	0.455	0.579	0.232	0.000
Correlation coeff. for linear regression	0.907	-	-	-
Smallest concentration (mg/l)	0	0	528	0
Greatest concentration (mg/l)	4,166	4,166	706	706

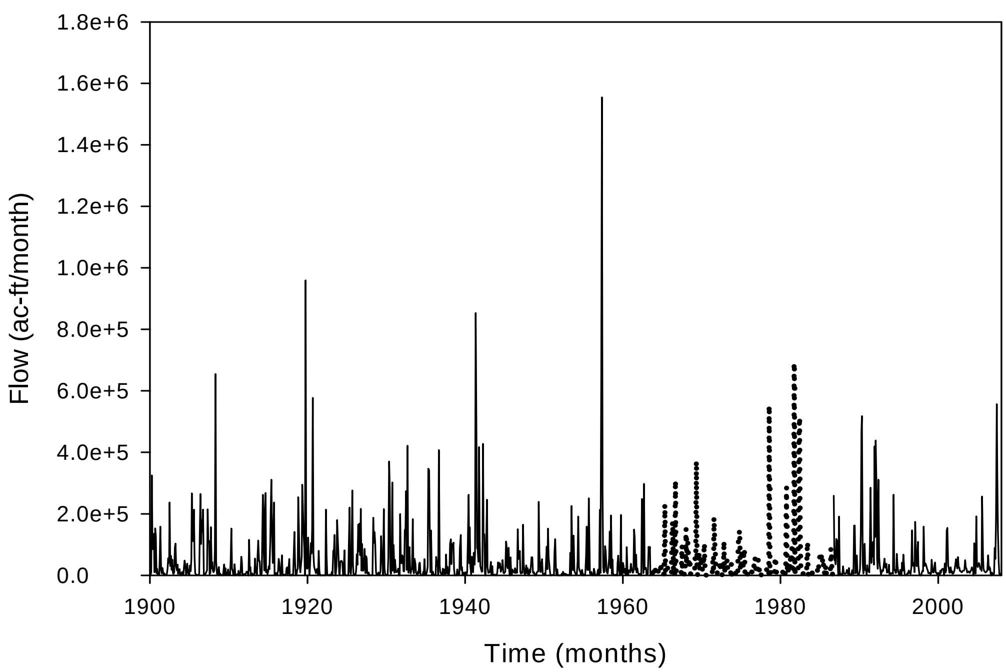

Figure 7.13 Incremental Streamflows at the Graford Gage

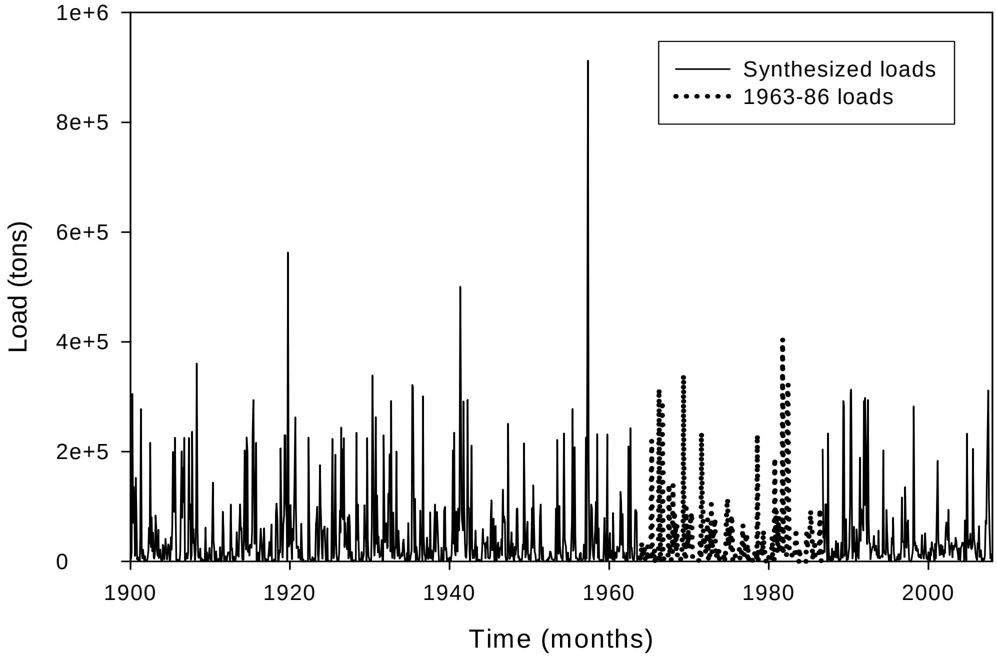

Figure 7.14 Loads at Graford Gage Synthesized by Volume-Load Interpolation Method

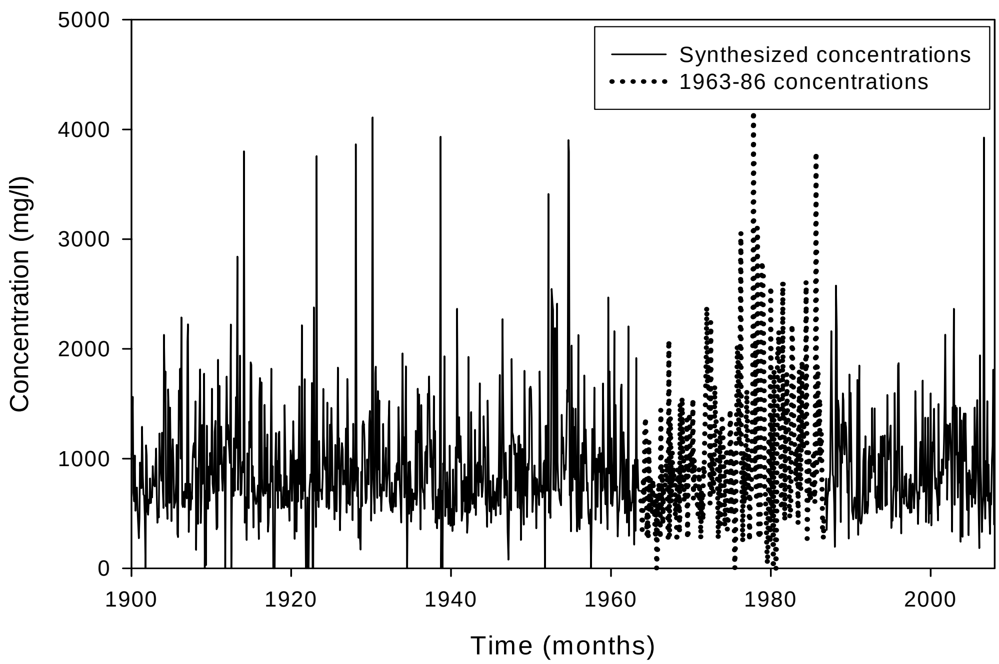

Figure 7.15 Concentrations at Graford Gage based on by Volume-Load Interpolation Method

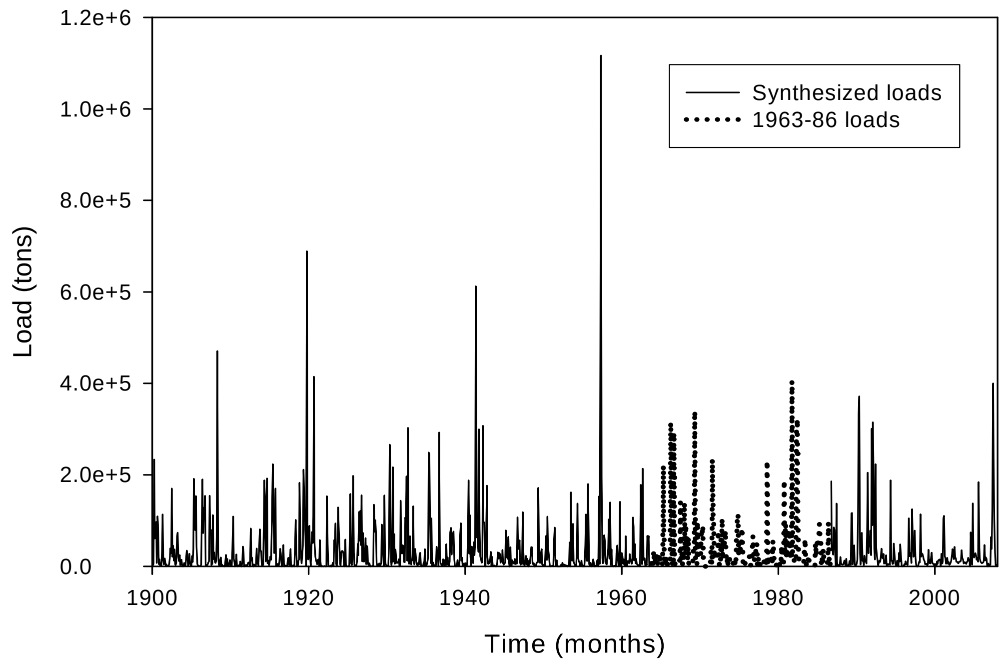

Figure 7.16 Loads at Graford Gage Synthesized by Linear Regression

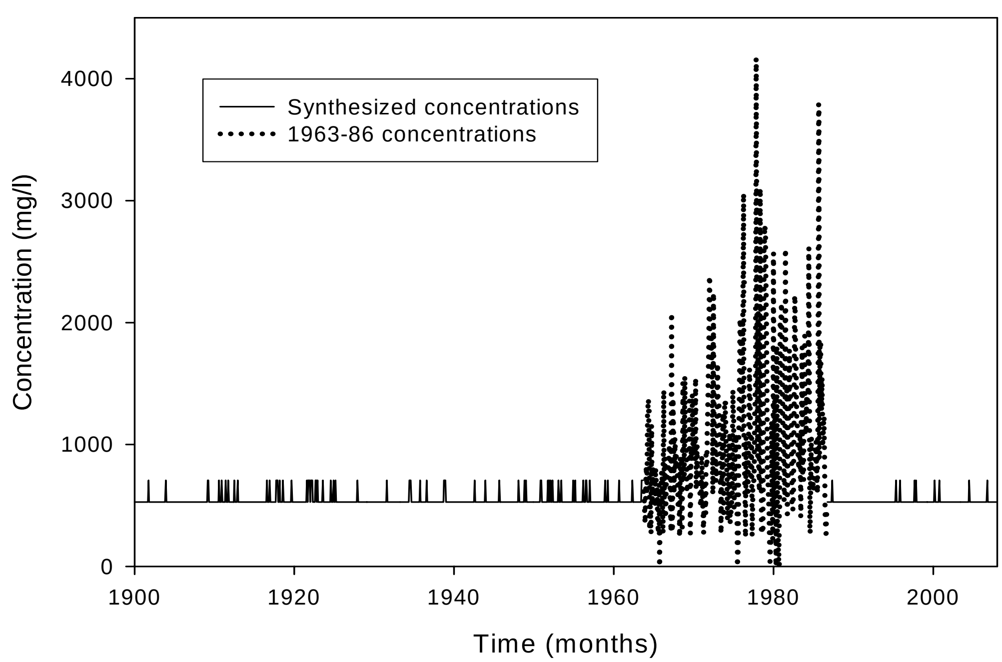

Figure 7.17 Concentrations at Graford Gage Synthesized by Linear Regression

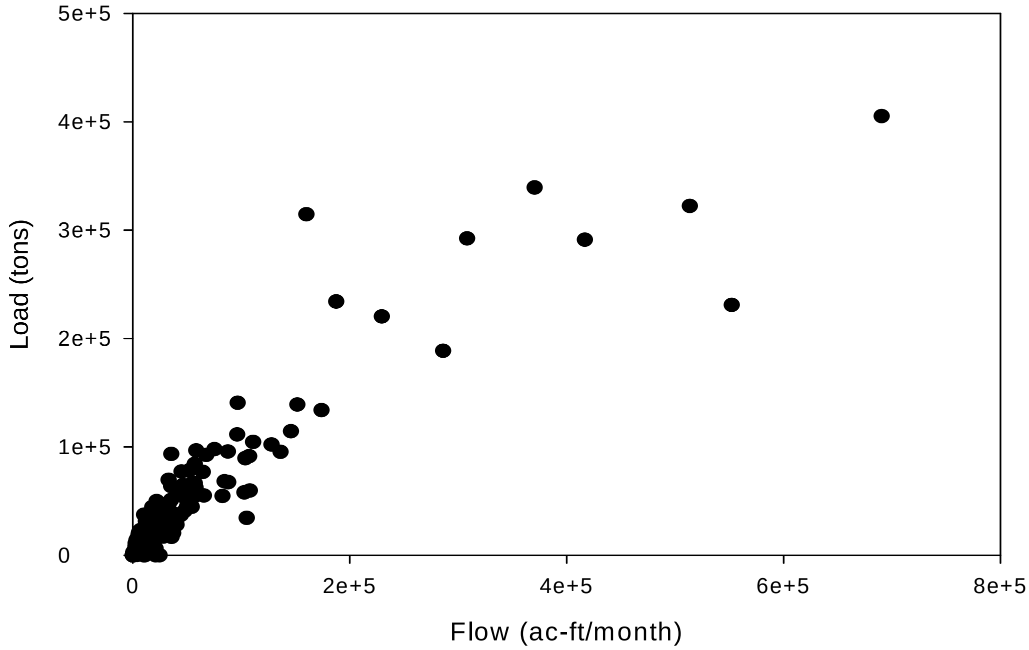

Figure 7.18 Monthly Incremental Inflow versus Load from 1964 to 1986 at Graford Gage

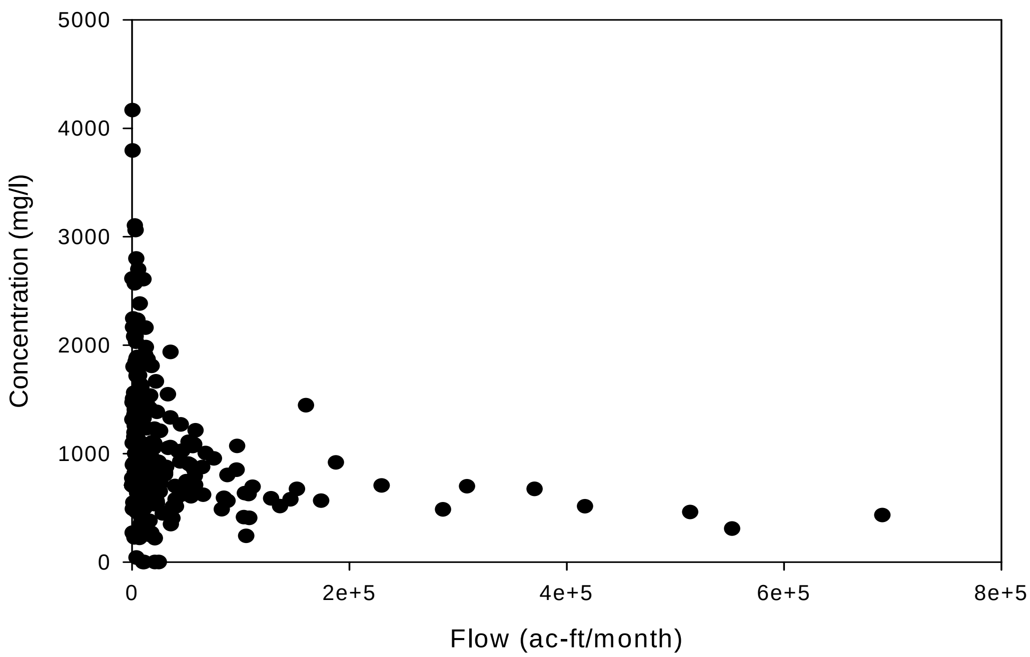

Figure 7.19 Monthly Incremental Inflow versus Concentration from 1964 to 1986 at Graford Gage

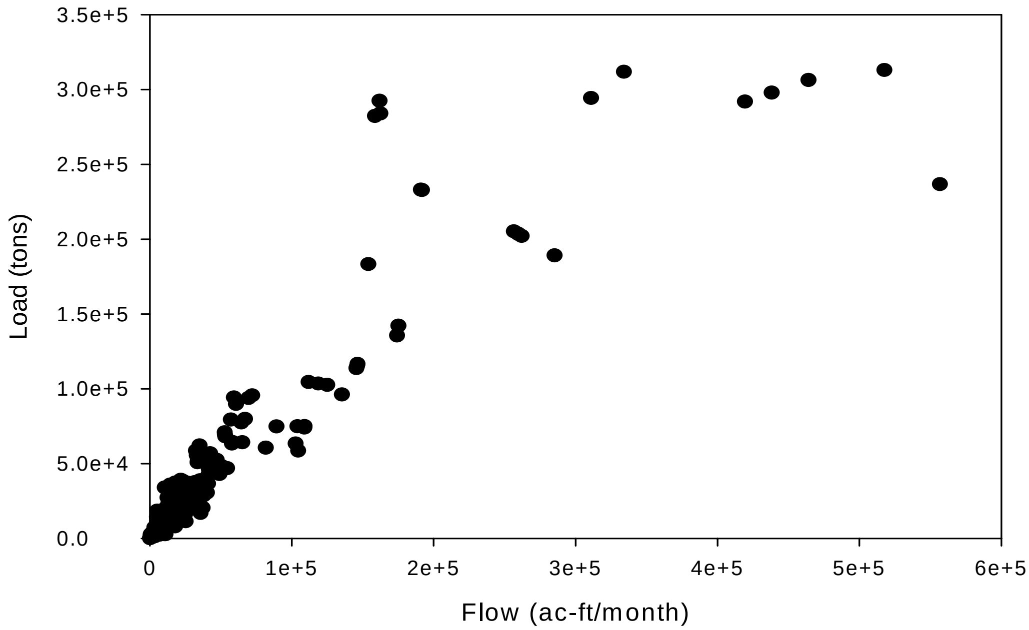

Figure 7.20 Monthly Incremental Inflow versus Load from 1900 to 1963 and from 1987 to 2007 at Graford gage (Volume-Load Interpolation Method)

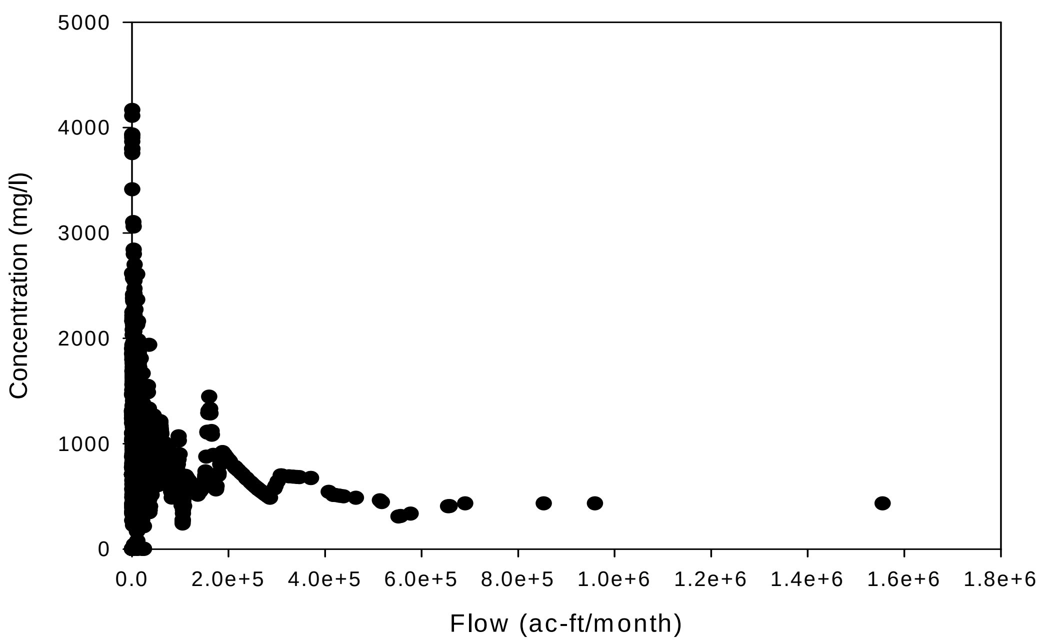

Figure 7.21 Monthly Incremental Inflow versus Concentration from 1900 to 1963 and from 1987 to 2007 at Graford gage (Volume-Load Interpolation Method)

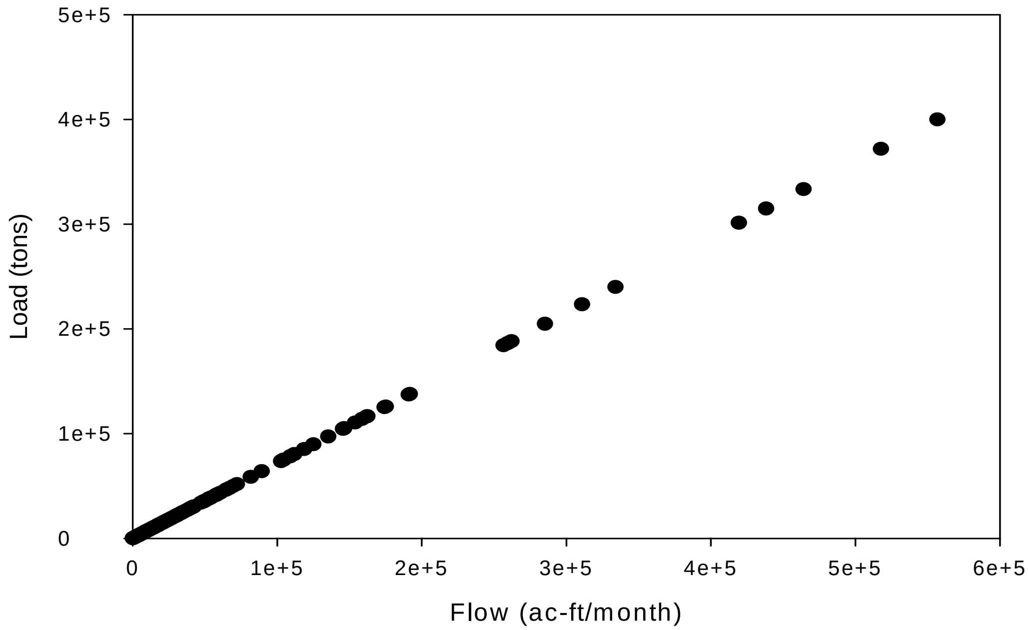

Figure 7.22 Monthly Incremental Inflow versus Load from 1900 to 1963 and from 1987 to 2007 at Graford gage (Linear Regression Method)

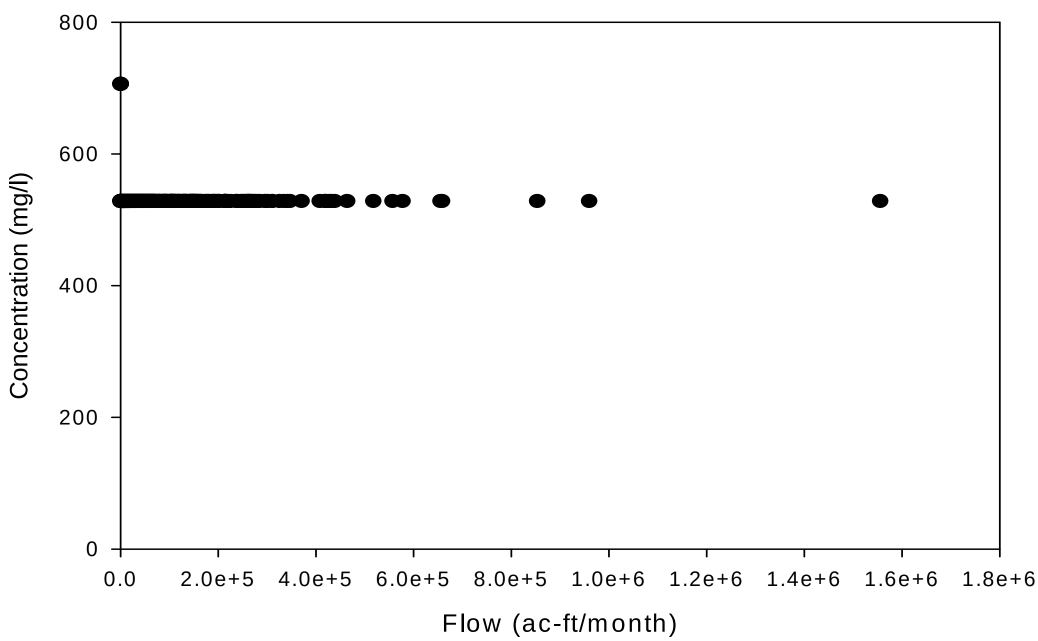

Figure 7.23 Monthly Incremental Inflow versus Concentration from 1900 to 1963 and from 1987 to 2007 at Graford gage (Linear Regression Method)

Whitney Gage

The WRAP-SALT salinity input file contains 1900-2007 monthly TDS concentrations at the Whitney gage located below Whitney Dam that represents the concentrations of incremental flows entering the river between the Graford gage and Whitney Dam. The naturalized flow volumes from the Brazos WAM dataset at the Graford gage and Whitney gage were entered in the program SALIN input SAI file to compute the incremental natural inflows. These incremental monthly inflow volumes are plotted in Figure 7.24. The USGS water year 1964-1986 incremental flow TDS loads entering the river/reservoir system were computed by considering the Graford-to-Dennis, Dennis-to-Glen Rose, and Glen Rose-to-Whitney load inflows.

The statistics of the results from the volume-load interpolation and linear regression methods are represented in Table 7.10 and Table 7.11. The 1900-1963 mean of load synthesized by volume-load interpolation is 23,149 tons/month with a concentration of 308 mg/l. The mean load value for 1987-2007 is 29,980 tons/month and mean concentration is 306 mg/l. Figure 7.25 and Figure 7.26 show the loads and concentrations developed using the volume-load interpolation method. The loads and concentrations synthesized by linear regression are plotted in Figure 7.27 and Figure 7.28.

Table 7.10 Statistics for the Results from Volume-Load Interpolation Method for the Whitney Gage

Period	1964-1986	1900-2007	1900-1963	1987-2007
Number of months	276	1,296	765	255
Mean of volume (acre-feet/month)	43,078	55,968	55,232	72,127
Mean of load (tons/month)	18,487	23,500	23,149	29,980
Mean of concentrations (mg/l)	316	309	308	306
Standard deviation of volume	68,403	108,030	112,366	126,542
Standard deviation of load	71,934	54,679	47,647	52,371
Standard deviation of concentration	2,682	3,727	4,542	974
Autocorrelation coefficient for volume	0.947	0.32	0.244	0.489
Autocorrelation coefficient for load	0.058	0.153	0.15	0.34
Autocorrelation coeff. for concentration	0.085	0.024	0.019	0.082
Smallest concentration (mg/l)	0	0	55	0
Greatest concentration (mg/l)	35,295	86,109	86,109	10,524

Table 7.11 Statistics for the Results from Linear Regression Method for the Whitney Gage

Period	1964-1986	1900-2007	1900-1963	1987-2007
Number of months	276	1,296	765	255
Mean of volume (acre-feet/month)	43,078	55,968	55,232	72,127
Mean of load (tons/month)	18,488	21,290	20,482	26,747
Mean of concentrations (mg/l)	316	280	273	273
Standard deviation of volume	68,403	108,030	112,366	126,542
Standard deviation of load	71,930	50,626	41,670	46,926
Standard deviation of concentration	2,682	1,239	14	8
Autocorrelation coefficient for volume	0.292	0.320	0.244	0.489
Autocorrelation coefficient for load	0.055	0.207	0.244	0.489
Autocorrelation coeff. for concentration	0.052	0.060	0.171	0.125
Correlation coeff. for linear regression	0.328	-	-	-
Smallest concentration (mg/l)	0	22	273	0
Greatest concentration (mg/l)	35,295	35,295	316	316

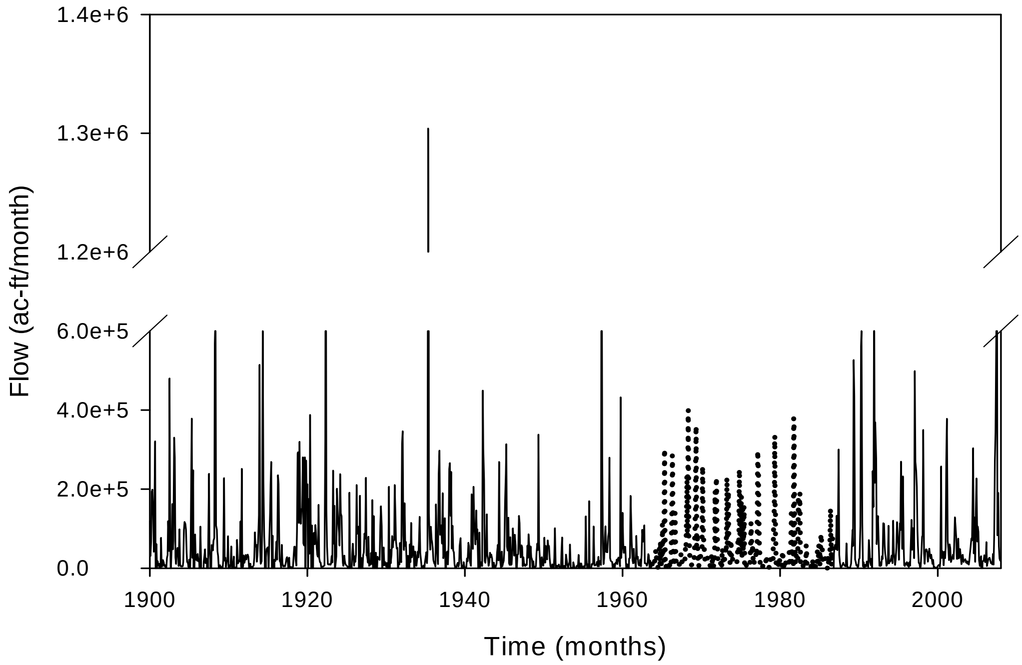

Figure 7.24 Incremental Streamflows at the Whitney Gage

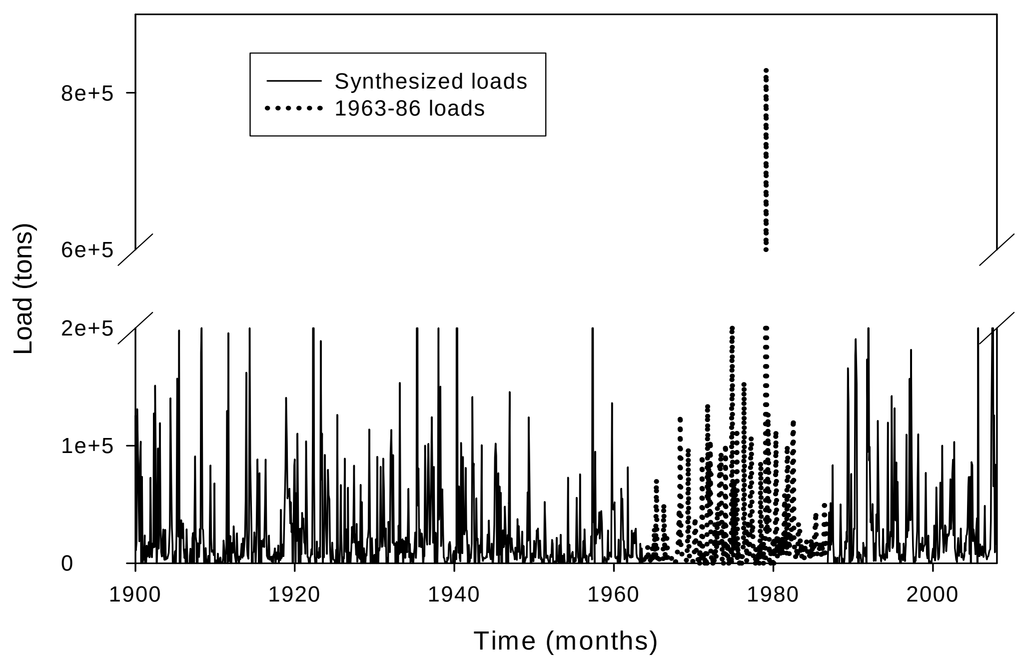

Figure 7.25 Incremental Loads at Whitney Gage Synthesized by Volume-Load Interpolation Method

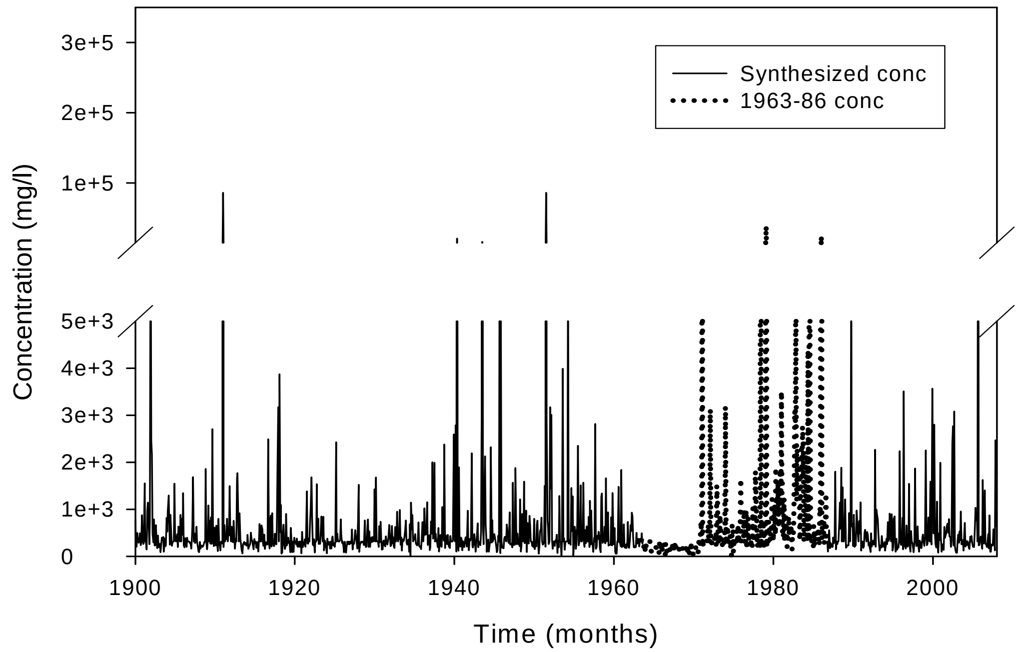

Figure 7.26 Incremental Inflow Concentrations at Whitney Gage based on by Volume-Load interpolation Method

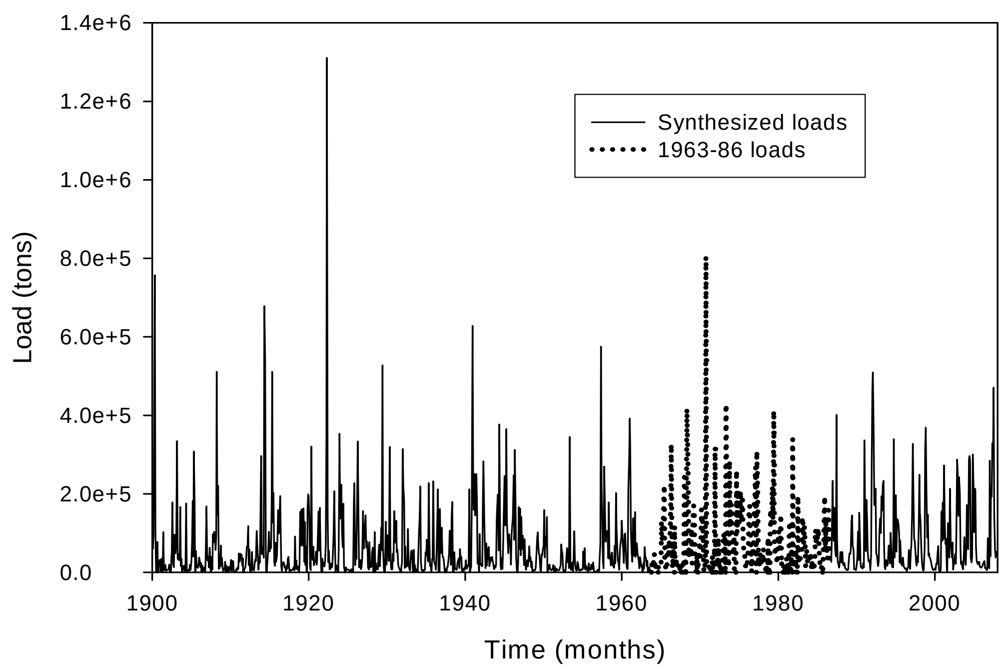

Figure 7.27 Incremental Loads at Whitney Gage Synthesized by Linear Regression

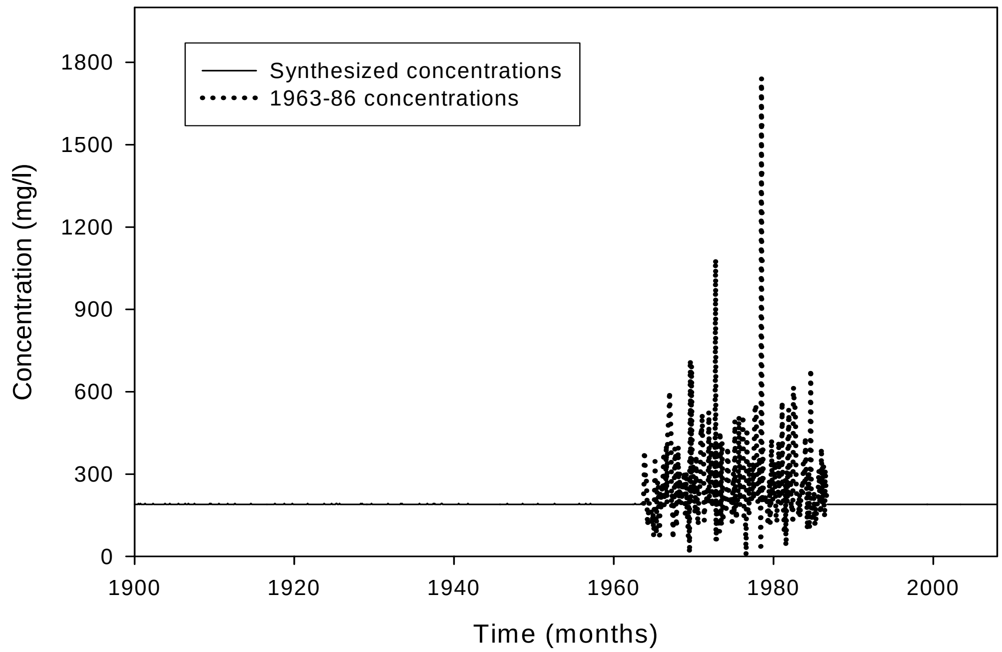

Figure 7.28 Incremental Inflow concentrations at Whitney Gage by Linear Regression

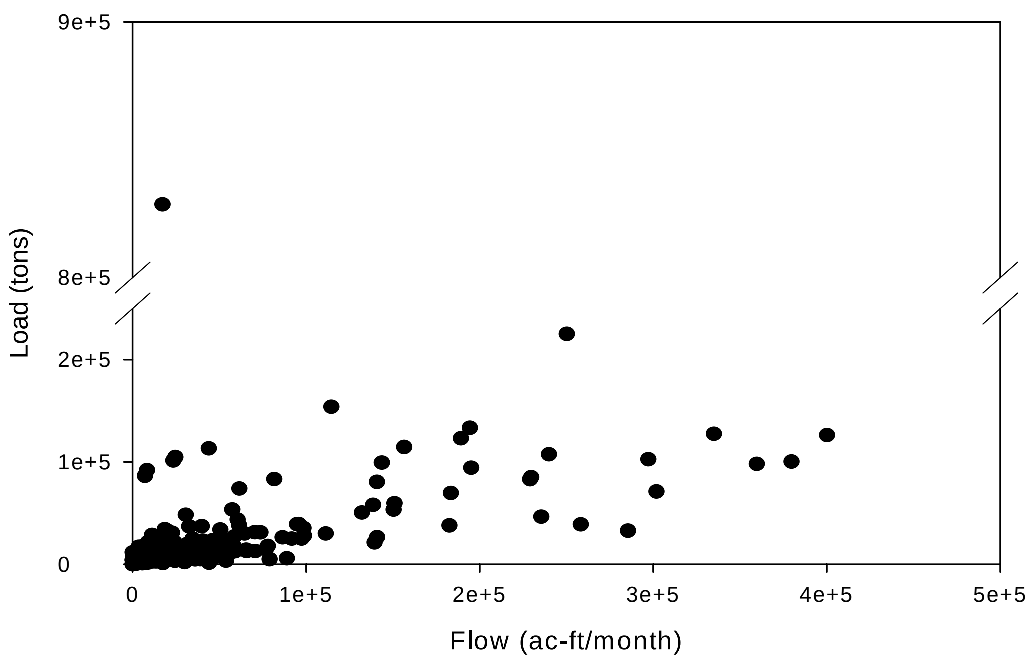

Figure 7.29 Monthly Inflow Volumes versus Loads from 1967 to 1986 at Whitney Gage

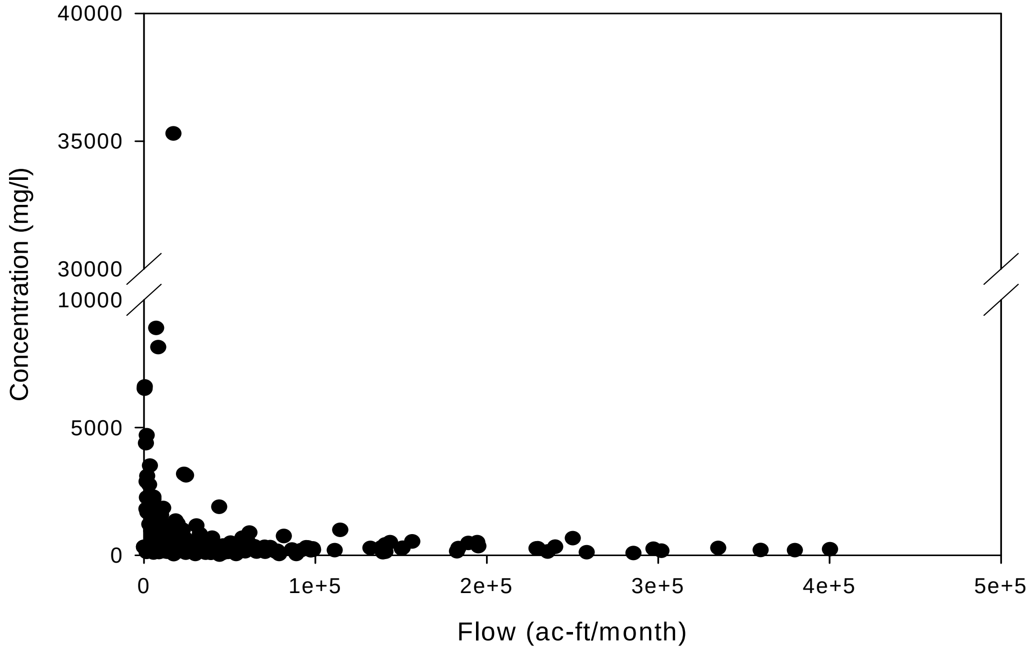

Figure 7.30 Monthly Flows versus Concentrations from 1967 to 1986 at Whitney Gage

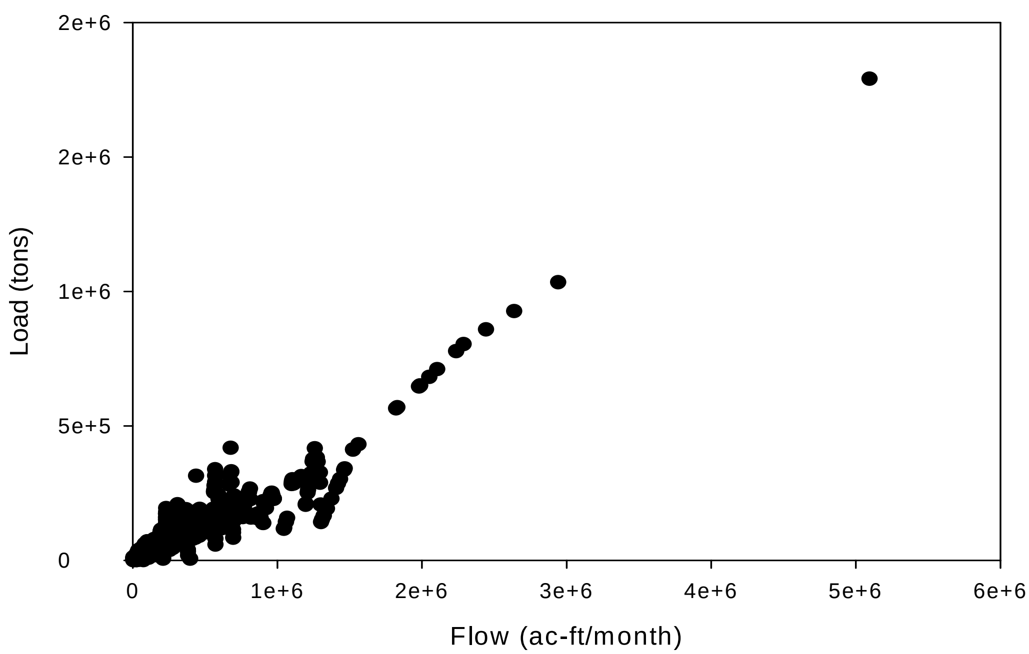

Figure 7.31 Monthly Flows Versus Loads from 1900 to 1963 and from 1986 to 2007 at Whitney Gage (Volume-Load Interpolation Method)

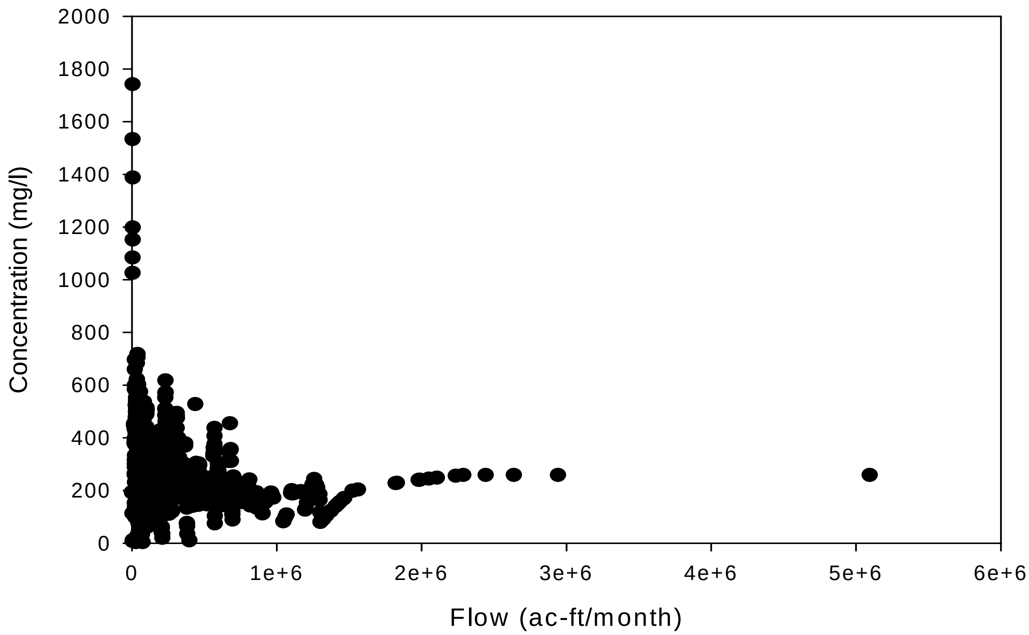

Figure 7.32 Monthly Flows Versus Concentrations from 1900 to 1963 and from 1986 to 2007 at Whitney Gage (Volume-Load Interpolation Method)

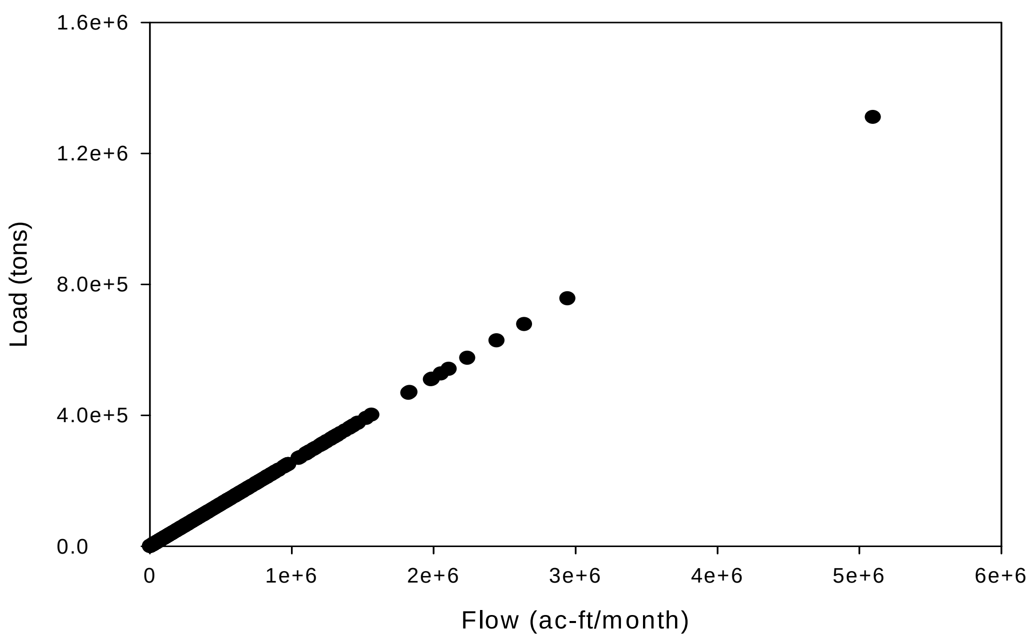

Figure 7.33 Monthly Flows Versus Loads from 1900 to 1963 and from 1986 to 2007 at Whitney Gage (Linear Regression Method)

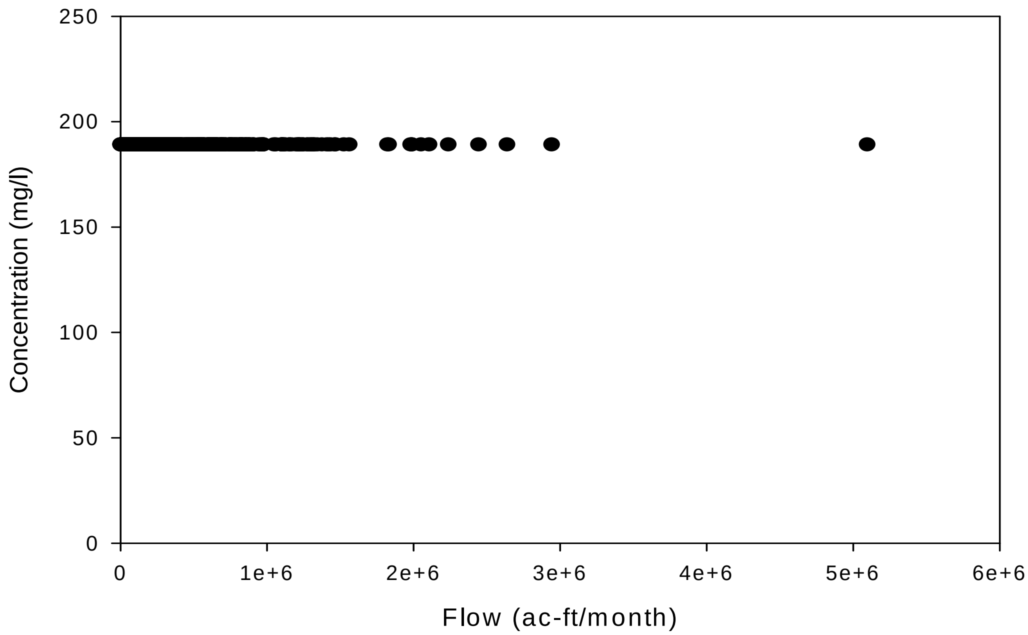

Figure 7.34 Monthly Flows Versus Concentrations from 1900 to 1963 and from 1986 to 2007 at Whitney Gage (Linear Regression Method)

Cameron Gage

Two alternative methods for modeling loads and concentrations in the Little River sub-basin above the Cameron gage were investigated. The alternative adopted was to treat the Cameron gage as an upstream boundary with the observed 1964-1986 mean concentration of 256 mg/l applied to the entire 1900-2007 simulation period. The TDS loads entering at this upstream boundary location are computed within WRAP-SALT by combining 256 mg/l concentration with the regulated flow at the Cameron gage during each month of the 1900-2007 simulation period.

The second alternative simulation approach investigated was to treat the Cameron gage similarly to the other gage locations, with a 1900-2007 time series of inputted monthly concentrations applied to flows at all locations in the Little River sub-basin at an above the Cameron gage. The concentrations of flows entering the river above the Cameron gage were synthesized as follows alternatively applying the volume-load interpolation and linear regression methods.

The 1900-2007 naturalized flows at Cameron gage are plotted in Figure 7.35. Since these are total flows, there are no negative incremental flows to deal with. The statistics from the datasets resulting from applying the volume-load interpolation and linear regression methods are presented in Table 7.12 and Table 7.13 respectively. The 1900-1963 means of loads and concentrations synthesized by the volume-load interpolation method are 37,136 tons/month and 250 mg/l. The 1987-2007 mean loads and concentrations from Table 7.12 based on the volume-load interpolation method are 52,107 tons/month and 244 mg/l.

Table 7.12 Statistics for the Results from Volume-Load Interpolation Method for the Cameron Gage

Period	1964-1986	1900-2007	1900-1963	1987-2007
Number of months	276	1,296	765	255
Mean of volume (acre-feet/month)	89,374	114,370	109,243	156,807
Mean of load (tons/month)	31,134	38,804	37,136	52,107
Mean of concentrations (mg/l)	256	250	250	244
Standard deviation of volume	111,421	180,924	183,597	222,470
Standard deviation of load	36,202	59,008	60,081	72,291
Standard deviation of concentration	77.6	79	82	68
Autocorrelation coefficient for volume	0.916	0.489	0.392	0.633
Autocorrelation coefficient for load	0.863	0.474	0.379	0.605
Autocorrelation coeff. for concentration	0.737	0.638	0.587	0.629
Smallest concentration (mg/l)	0	0	0	0
Greatest concentration (mg/l)	474	474	474	436

Table 7.13 Statistics for the Results from Linear Regression Method for the Cameron Gage

Period	1964-1986	1900-2007	1900-1963	1987-2007
Number of months	276	1,296	765	255
Mean of volume (acre-feet/month)	89,374	114,370	109,243	156,807
Mean of load (tons/month)	31,134	38,183	36,155	51,897
Mean of concentrations (mg/l)	256	246	243	243
Standard deviation of volume	111,421	180,924	183,597	222,470
Standard deviation of load	36,202	59,749	60,764	73,629
Standard deviation of concentration	77.6	42	20	0
Autocorrelation coefficient for volume	0.592	0.489	0.392	0.633
Autocorrelation coefficient for load	0.626	0.491	0.392	0.633
Autocorrelation coeff. for concentration	0.753	0.713	0.200	0.993
Correlation coeff. for linear regression	0.982	-	-	-
Smallest concentration (mg/l)	0	0	0	0
Greatest concentration (mg/l)	474	474	243	243

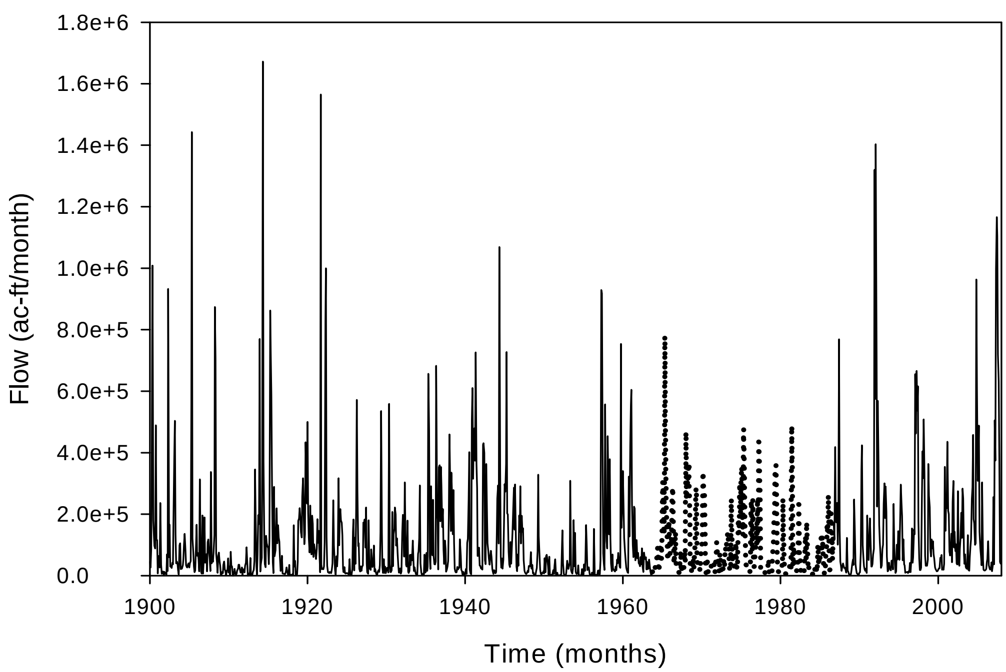

Figure 7.35 Streamflows at the Cameron Gage

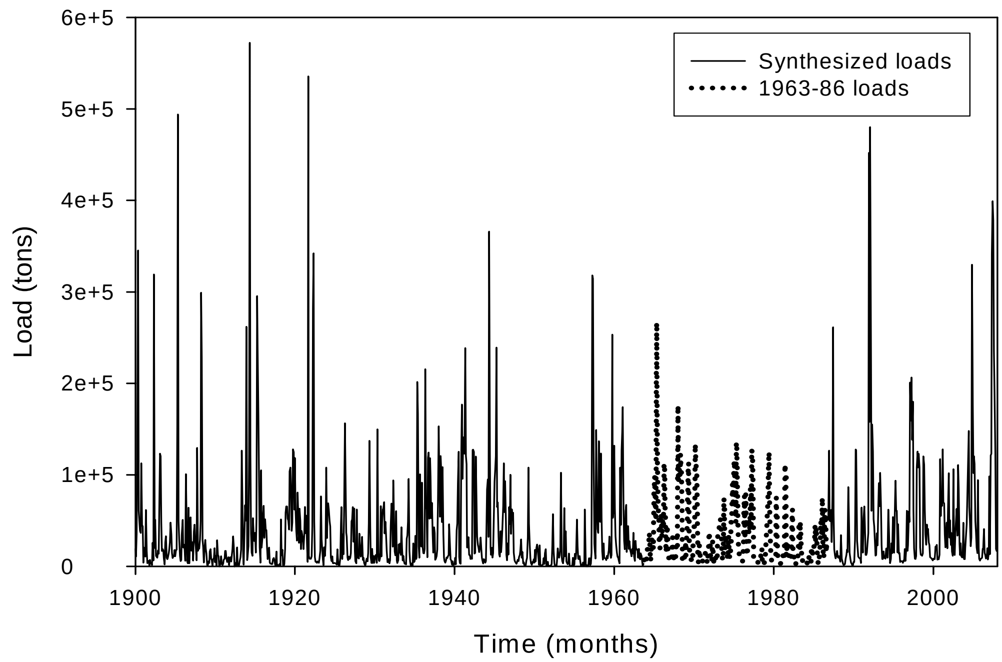

Figure 7.36 Loads at Cameron Gage Synthesized by Volume-Load Interpolation Method

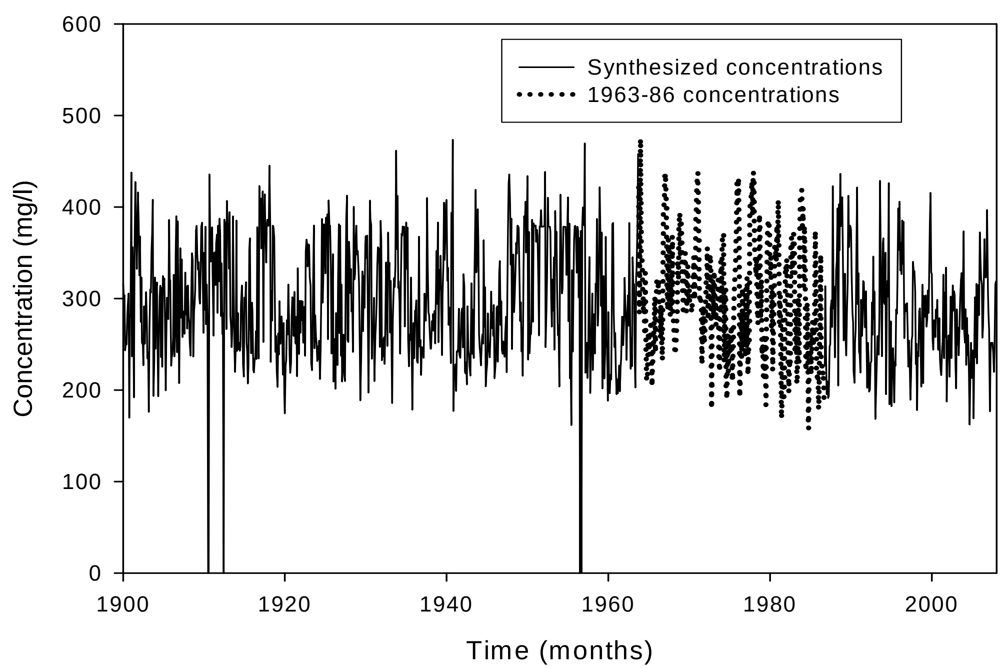

Figure 7.37 Concentrations at Cameron Gage Synthesized by Volume-Load Interpolation Method

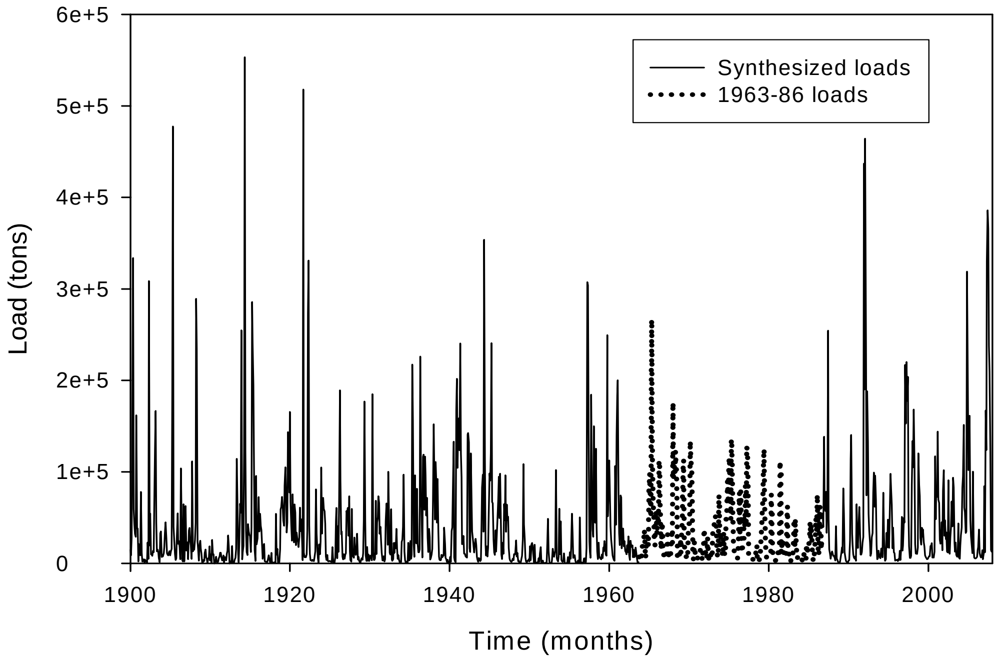

Figure 7.38 Loads at Cameron Gage Synthesized by Linear Regression

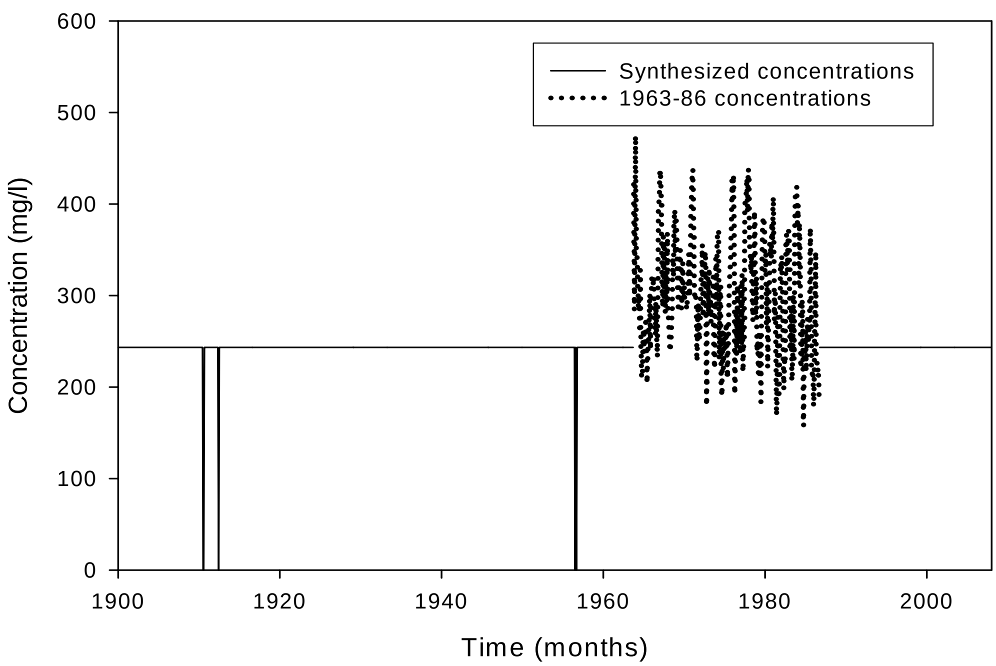

Figure 7.39 Concentrations at Cameron Gage Synthesized by Linear Regression

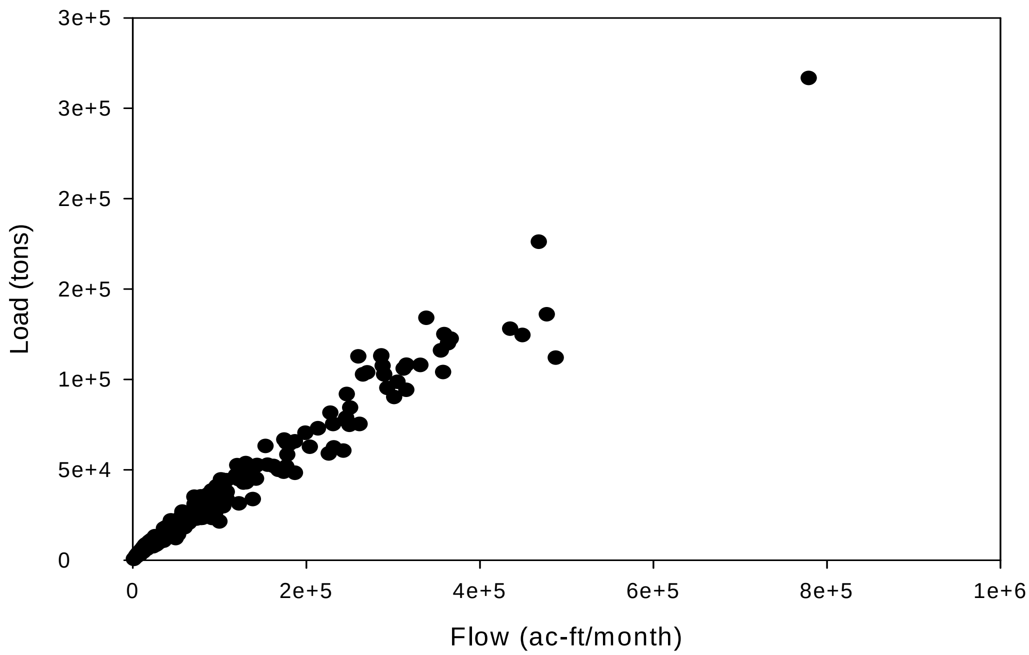

Figure 7.40 Monthly Flows versus Loads from 1967 to 1986 at Cameron Gage

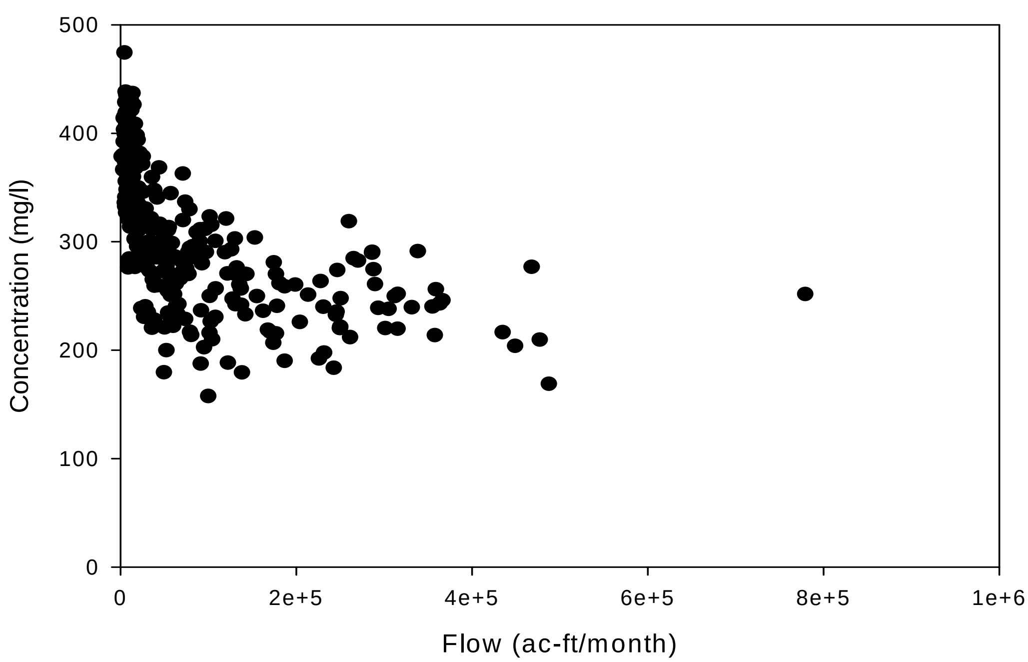

Figure 7.41 Monthly Flows versus Concentrations from 1967 to 1986 at Cameron Gage

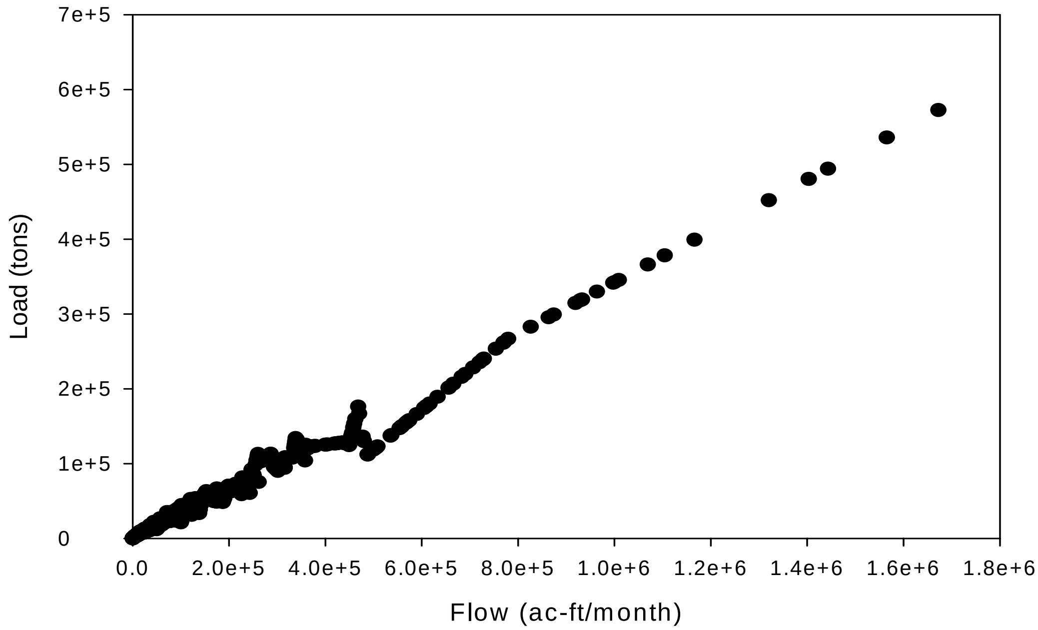

Figure 7.42 Monthly Flows versus Loads from 1900 to 1963 and from 1986 to 2007 at Cameron Gage (Volume-Load Interpolation Method)

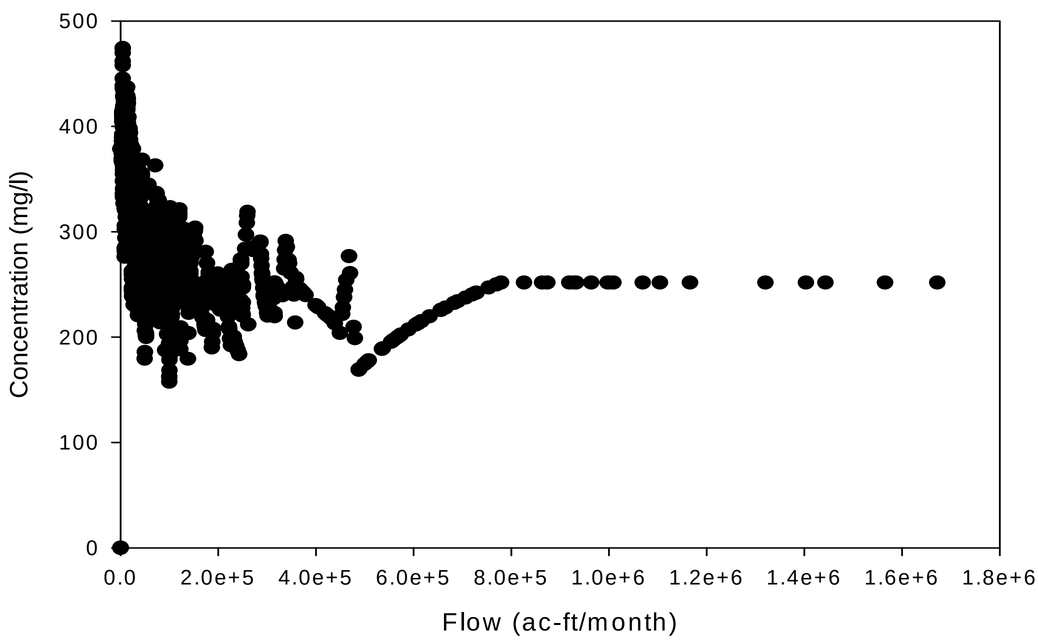

Figure 7.43 Monthly Flows versus Concentrations from 1900 to 1963 and from 1986 to 2007 at Cameron Gage (Volume-Load Interpolation Method)

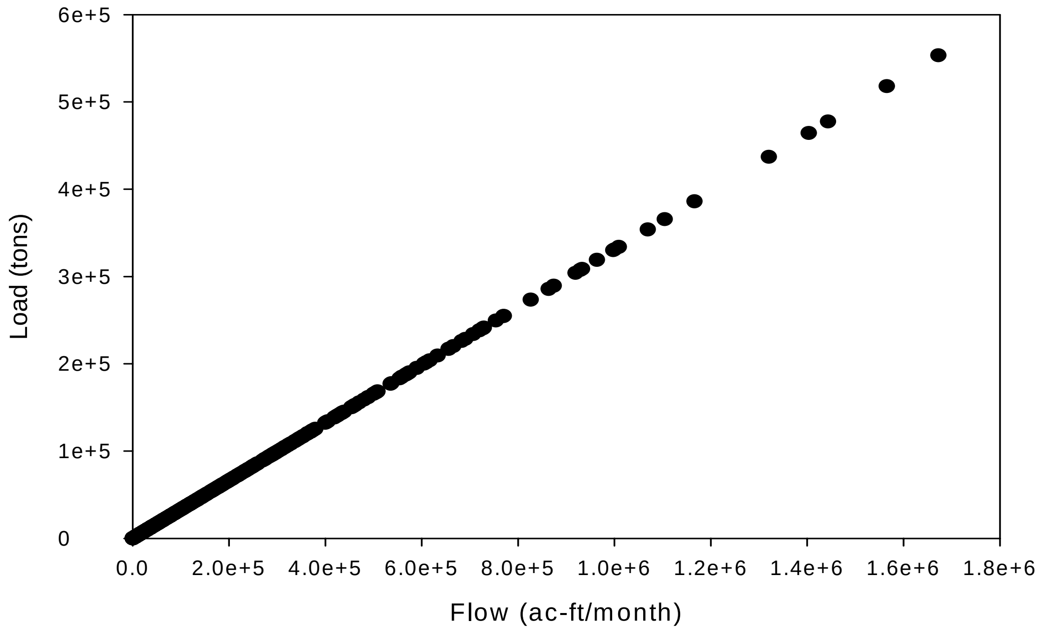

Figure 7.44 Monthly Flows versus Loads from 1900 to 1963 and from 1986 to 2007 at Cameron Gage (Linear Regression Method)

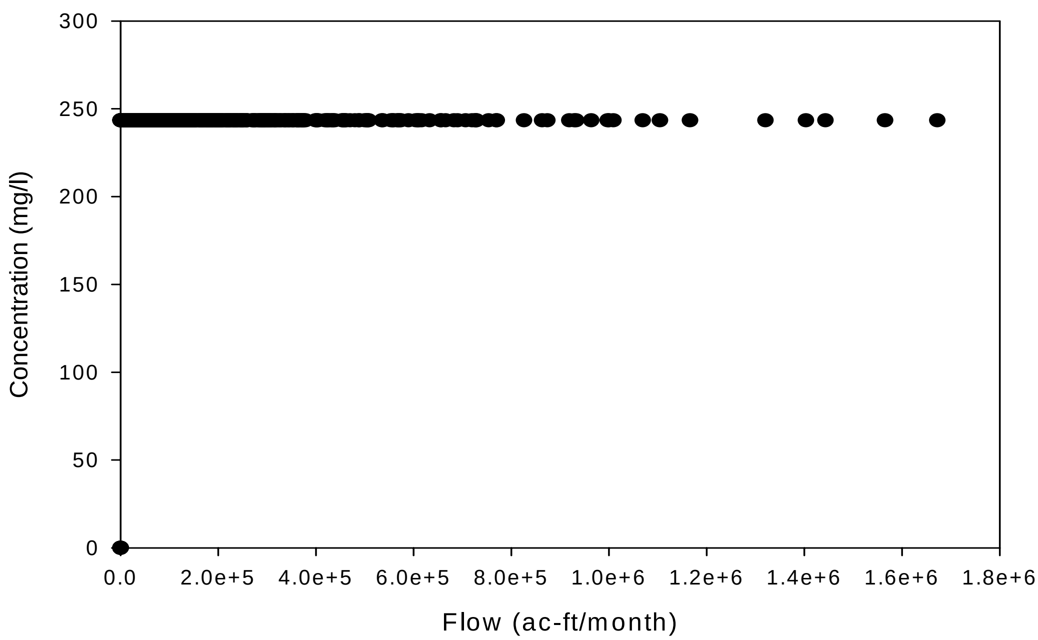

Figure 7.45 Monthly Flows versus Concentrations from 1900 to 1963 and from 1986 to 2007 at Cameron Gage (Linear Regression Method)

<u>Richmond Gage</u>

The WRAP-SALT salinity input file contains January 1900 through December 2007 monthly TDS concentrations at the Richmond gage that represents the concentrations of incremental flows entering the river upstream of the Richmond gage but downstream of the Whitney and Cameron gage. The naturalized flows from the Brazos WAM dataset at the Richmond, Whitney, and Cameron gages were entered in the program SALIN to compute the incremental inflows as the flows at the Richmond less the flows at the Whitney and Cameron gages. These incremental monthly inflow volumes for 1900-1963 and 1987-2007 naturalized flows and 1964-1986 observed flows are plotted in Figure 7.46.

The observed 1964-1986 monthly incremental TDS loads and flow volumes were used in combination with 1900-1963 and 1987-2007 naturalized flows to synthesize concentrations for 1900-1963 and 1987-2007 alternatively by volume-load interpolation and linear regression. The 1900-1963 and 1987-2007 loads are synthesized by using the relationship between incremental inflow volumes and incremental inflow loads for 1964-1986.

Statistics for the results from volume-load interpolation and linear regression methods are tabulated in Table 7.14 and Table 7.15. The 1900-1963 mean of incremental loads synthesized by volume-load interpolation method is 65,121 tons/month with a concentration of 205 mg/l. 1987-2007 mean of the interpolated load is 88,044 tons/month with a mean concentration of 198 mg/l.

Table 7.14 Statistics for the Results from Volume-Load Interpolation Method for the Richmond Gage

Period	1964-1986	1900-2007	1900-1963	1987-2007
Number of months	276	1,296	765	255
Mean of volume (acre-feet/month)	251,443	255,956	233,671	327,695
Mean of load (tons/month)	65,955	69,801	65,121	88,004
Mean of concentrations (mg/l)	193	201	205	198
Standard deviation of volume	321,302	379,503	395,169	382,268
Standard deviation of load	97,383	116,211	124,208	108,479
Standard deviation of concentration	190	152	150	123
Autocorrelation coefficient for volume	0.914	0.409	0.364	0.557
Autocorrelation coefficient for load	0.593	0.309	0.278	0.497
Autocorrelation coeff. for concentration	0.046	0.166	0.141	0.170
Smallest concentration (mg/l)	0	4	8	0
Greatest concentration (mg/l)	1,742	1,742	1,533	705

Table 7.15 Statistics from the Results from Linear Regression Method for the Richmond Gage

Period	1964-1986	1900-2007	1900-1963	1987-2007
Number of months	276	1,296	765	255
Mean of volume (acre-feet/month)	251,443	255,956	233,671	327,695
Mean of load (tons/month)	65,955	66,114	60,110	84,297
Mean of concentrations (mg/l)	193	190	189	189
Standard deviation of volume	321,302	379,503	395,169	382,268
Standard deviation of load	97,383	100,466	101,654	98,336
Standard deviation of concentration	190	83	1	0
Autocorrelation coefficient for volume	0.368	0.409	0.364	0.557
Autocorrelation coefficient for load	0.202	0.374	0.364	0.557
Autocorrelation coeff. for concentration	0.082	0.224	0.042	0.991
Correlation coeff. for linear regression	0.838	-	-	-
Smallest concentration (mg/l)	0	4	189	0
Greatest concentration (mg/l)	1,742	1,742	193	189

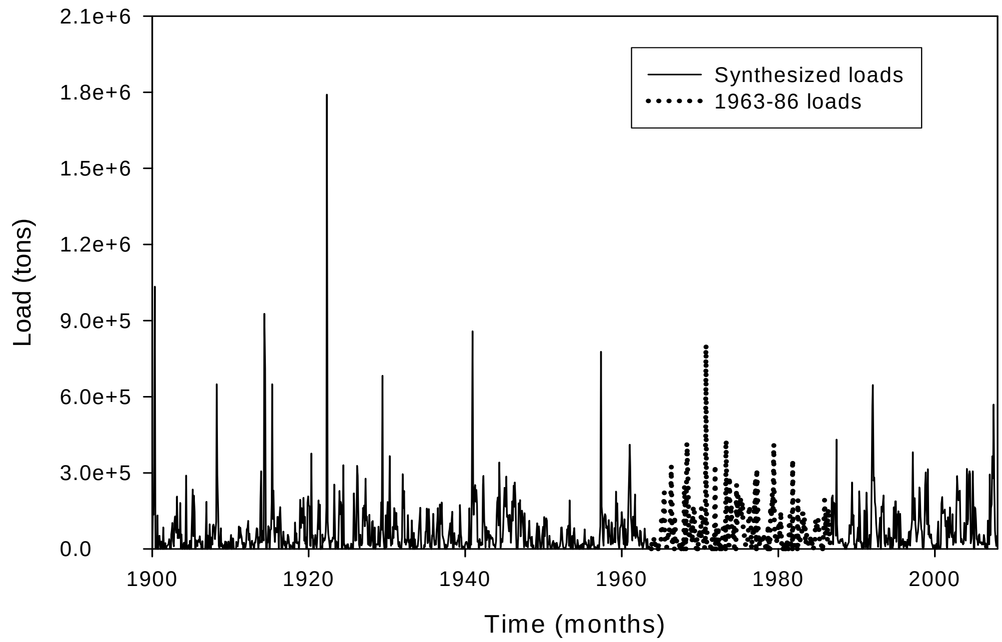

Figure 7.46 Incremental Loads at Richmond Gage Synthesized by Volume-Load Interpolation Method

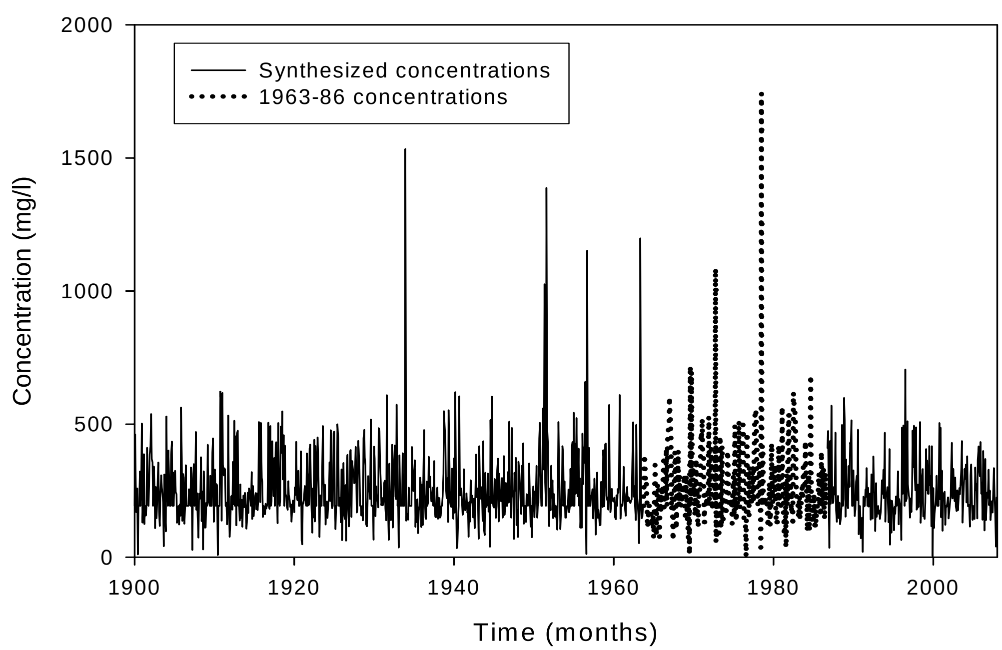

Figure 7.47 Incremental Loads at Richmond Gage Synthesized by Linear Regression Method

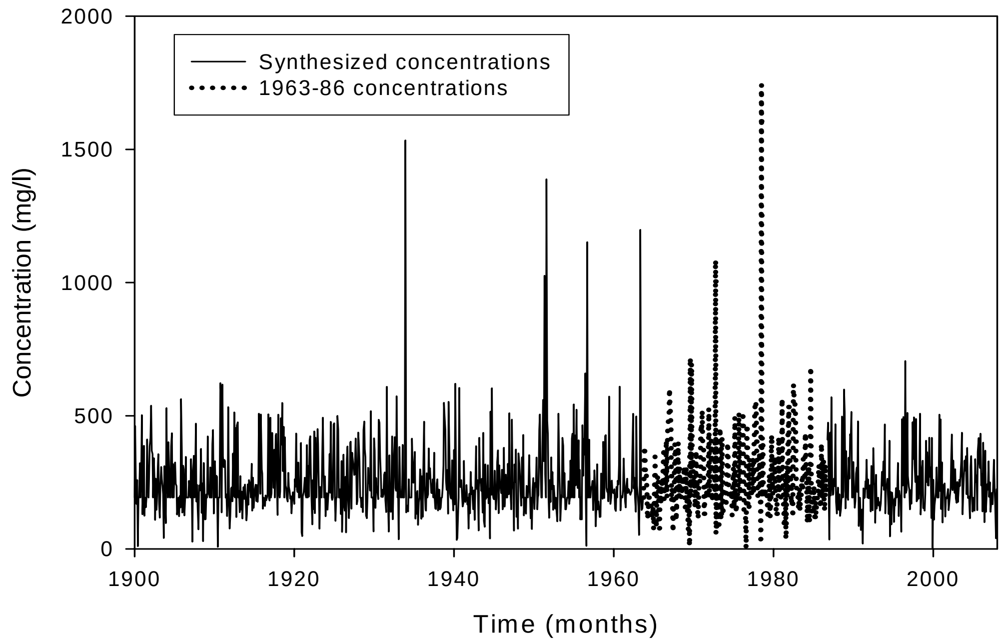

Figure 7.48 Incremental Inflow Concentrations at Richmond Gage by Volume-Load Interpolation Method

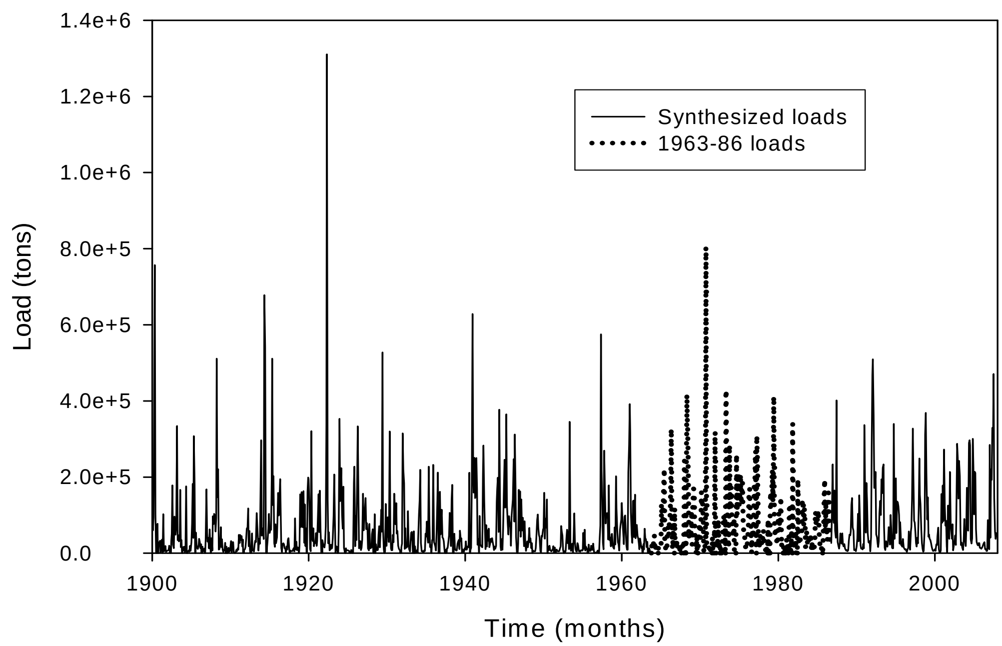

Figure 7.49 Incremental Inflow Loads at Richmond Gage by Linear Regression Method

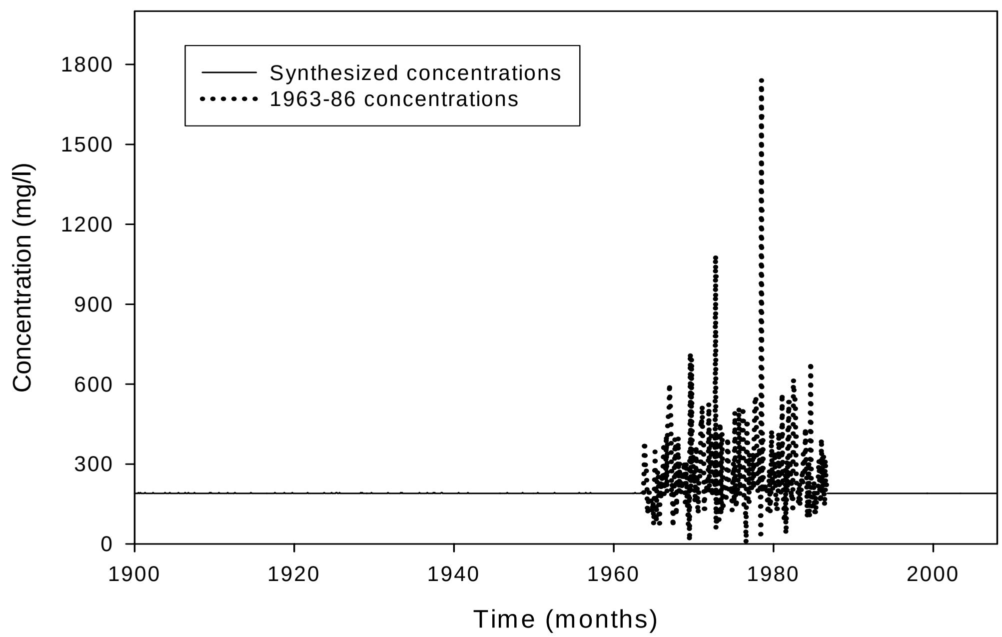

Figure 7.50 Incremental Inflow Concentrations at Richmond Gage by Linear Regression Method

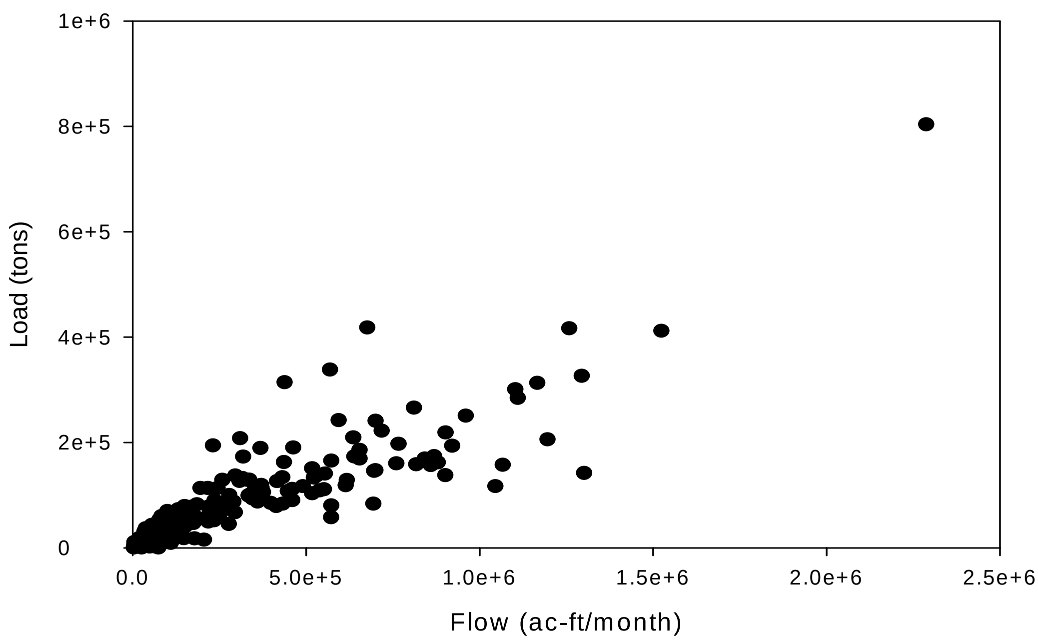

Figure 7.51 Monthly Flows versus Loads from 1967 to 1986 at Richmond Gage

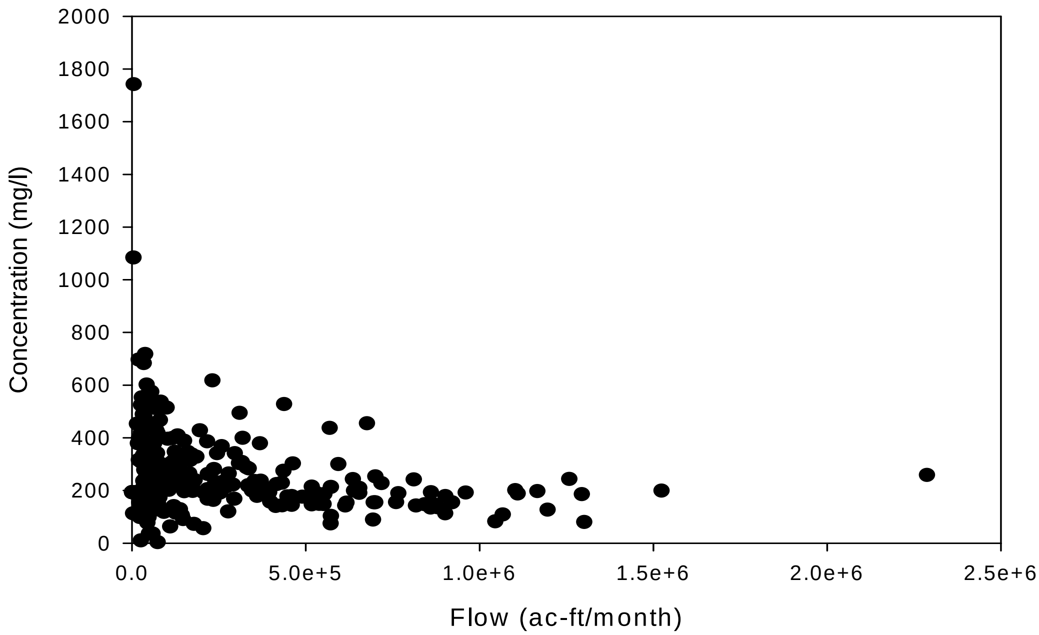

Figure 7.52 Monthly Flows versus Concentrations from 1967 to 1986 at Richmond Gage

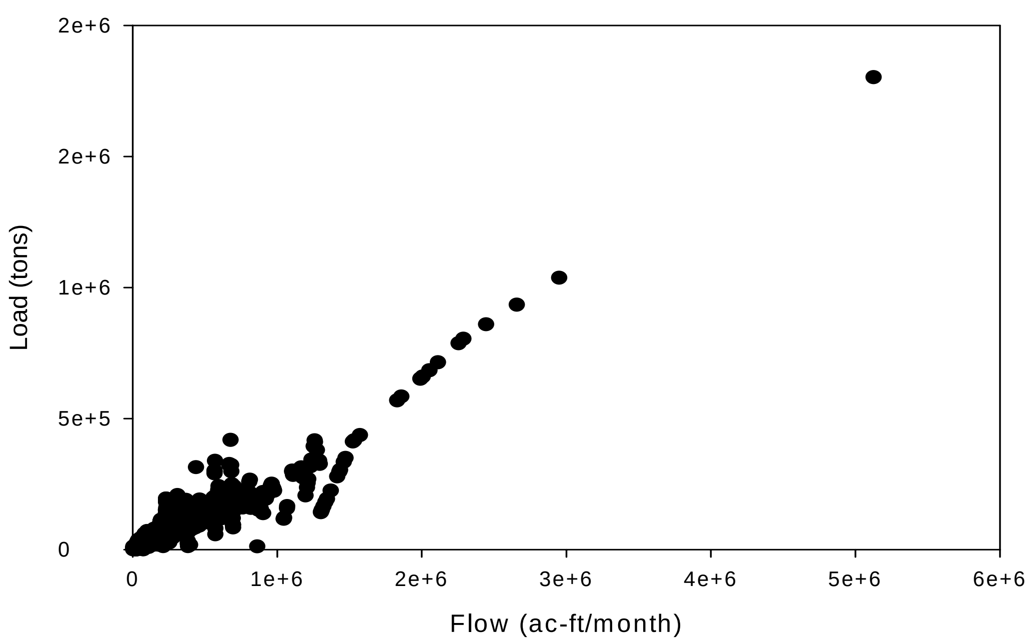

Figure 7.53 Monthly Flows versus Loads from 1900 to 1963 and from 1986 to 2007 at Richmond Gage (Volume-Load Interpolation Method)

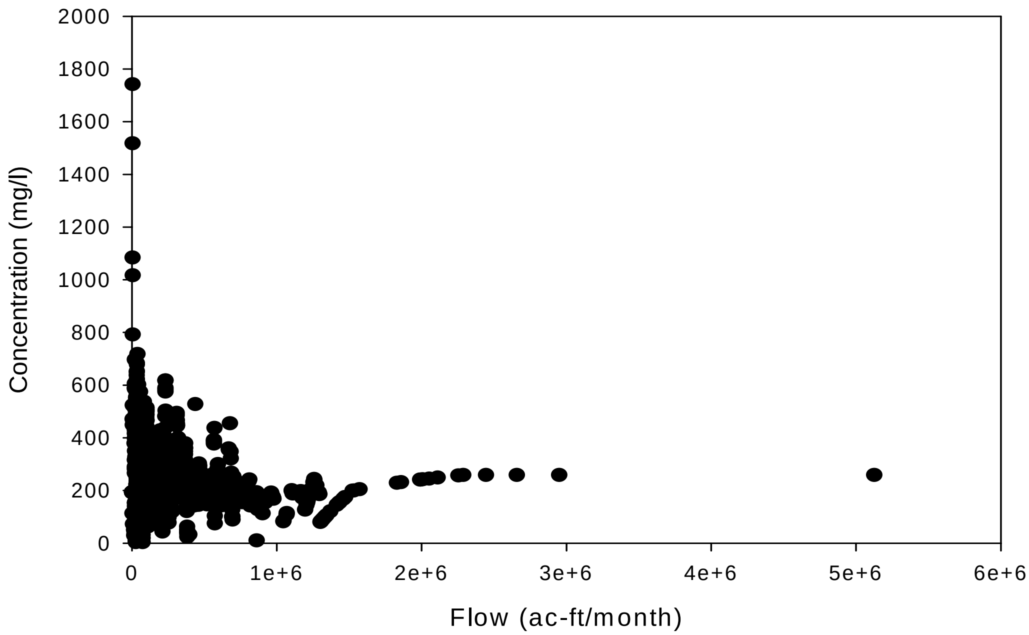

Figure 7.54 Monthly Flows versus Concentrations from 1900 to 1963 and from 1986 to 2007 at Richmond Gage (Volume-Load Interpolation Method)

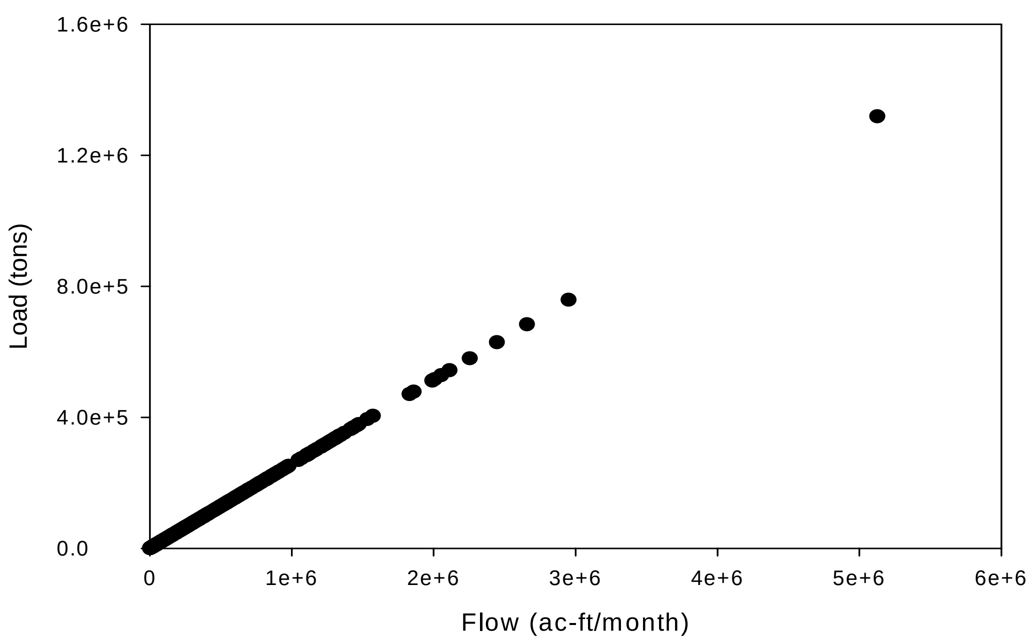

Figure 7.55 Monthly Flows versus Loads from 1900 to 1963 and from 1986 to 2007 at Richmond Gage (Linear Regression Method)

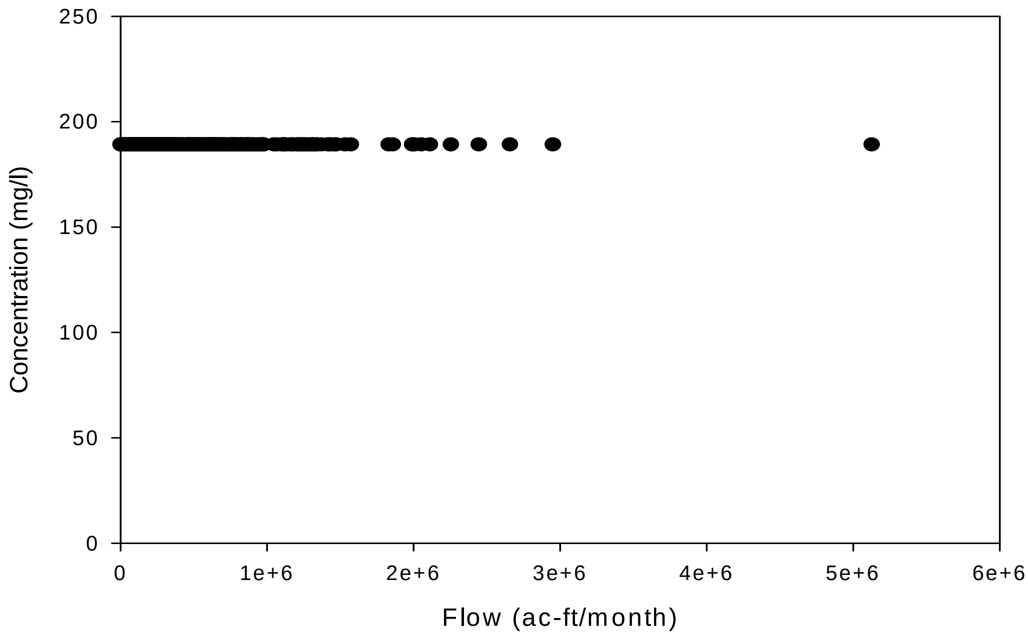

Figure 7.56 Monthly Flows versus Concentrations from 1900 to 1963 and from 1986 to 2007 at Richmond Gage (Linear Regression Method)

7.5 Summary of WRAP-SALT Input Dataset

Previously described in this chapter, WRAP-SALT input dataset was developed based on the volume and load budget study. Also, the parameters used in salinity input file SIN were developed through the study of routing salinity through the reservoirs in Brazos River Basin. A WRAP-SALT input dataset consists of the following input files:

- simulation results OUT and beginning reservoir storage BRS files created with SIM

- salinity input SIN file that includes the data developed in the preceding Chapters VI and VII along with additional salinity information described in this chapter

7.5.1 WRAP-SIM OUT and BRS Files

The WRAP-SIM simulation results output file, with filename extension OUT, is required by WRAP-SALT and must contain output records for all control points included in the input DAT file. WRAP-SALT reads only control point output records. The various quantities from the OUT file serve as the basis for the WRAP-SIM monthly volume accounting computations.

WRAP-SALT has alternative options for inputting beginning-of-simulation reservoir storage contents. The most convenient option for large dataset is to include a BRS file created with SIM in the SALT input dataset. Beginning reservoir storage files, with the filename extension BRS, were developed in the study based on the cycling approach of matching beginning and ending storage. Three BRS files were created for use with Bwam8, BRAC8, and BRAC2008 simulations.

Preliminary SIM simulations were performed to determine beginning-of-simulation (beginning of January 1900 or January 1940) storage volumes for each reservoir that are approximately equal to end-of-simulation (end of December 2007) storage volumes. SIM simulations for 1940-2007 were performed with the beginning of January 1940 storage contents set at capacity in all reservoirs. The end of December 2007 storage contents for each reservoir were recorded in a BES file. These ending storage volumes were adopted as beginning-of-simulation storage contents recorded in a BRS file. The Bwam8, BRAC8, and BRAC2008 beginning reservoir storage (BRS) files from the 1940-2007 simulation are also applied with 1900-2007 simulation since the December 2007 storage volumes are essentially the same with either period-of-analysis.

7.5.2 WRAP-SALT Salinity Input SIN File

WRAP-SALT reads a salinity input file with the filename extension SIN which contains information controlling the salinity simulation and describing the salt loads entering the river system. The SIN file contains salinity inflows to the river system, parameters controlling routing of salinity through reservoirs, and data controlling concentrations of diversions, return flows, and other components of the volume and load budgets. The same SIN file is applied with the SIM simulation results from either the Bwam8, BRAC8, or BRAC2008 datasets. Developed SIN file is represented in Table 7.16.

Development of the total dissolved solids (TDS) inflows incorporated into the Brazos SIN file. TDS loads or concentrations were developed for the six control points listed in Table 7.3. These data are assigned to the seven control points listed in Table 7.17. The locations of the control points are shown in Figure 3.2. Concentrations provided for these locations are repeated within the WRAP-SALT simulation at upstream control points as necessary to provide salinity inflows at all control points below the two specified upstream boundaries.

Table 7.16 WRAP-SALT Salinity Input SIN File for Use with Bwam8, BRAC8, and BRAC2008 Dataset

```
**  WRAP-SALT Input File Brazos.SIN
**  Accompanying WRAP-SIM Datasets Bwam8, BRAC8, and BRAC2008
**       1         2         3         4         5         6         7         8
**345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345
678
**     !       !       !       !       !       !       !       !       !       !
  !
SC  1940  68   1   0   0   0   1   0   2   1   2   2   0             0.1
**
CO     3  BRSB23  BRBR59  BRHE68
CO     5  421331  515831  509431  516531  516431
**     !       !       !       !       !       !       !       !       !       !
  !
**   Seymour gage on Brazos River
CPBRSE11   0   3
**   Possum Kingdom Reservoir on Brazos River
CP515531   0   0   0   2       0       0       0   1626.  0.1742
CC                  800.     -1.     -1.     -1.      0.  10000.      0.   5000.
1626.
**   Granbury Reservoir on Brazos River
CP515631   0   0   0   2       0       0       0   1302. 0.06587
CC                  400.     -1.     -1.     -1.      0.   8000.      0.   5000.
1302.
**   Whitney Reservoir on Brazos River
CP515731   5   0   0   2       0       0       0   1062.  0.0300
CC                  300.     -1.     -1.     -1.      0.   6000.      0.   4000.
1062.
**   Cameron gage on Little River
CPLRCA58   2   4   0   2       0       0       0
CC          256.             -1.     -1.     -1.      0.   2000.
**   Richmond gage on Brazos River
CPBRRI70   0   0   0   2       0       0       0
CC                  250.     -1.     -1.     -1.      0.   2000.      0.   2000.
339.
**   Outlet at Gulf of Mexico
CPBRGM73   2   0   0   2       0       0       0
CC          339.    250.     -1.     -1.     -1.      0.   2000.      0.   2000.
339.
ED
**     1       2       3       4       5       6       7       8       9       1
**34567890123456789012345678901234567890123456789012345678901234567890123456789012345678901
2
S1BRSE11    1940      0.  16683.     17.  56128. 121810. 116720.  54327. 169760. 121700.     69.  52160.  35593.
S1515531    1940    530.    542.    340.    901.    395.    567.    614.   1104.    517.   2365.   1109.   1005.
S1515631    1940    761.    316.   2787.    102.  20932.    359.    118.   1895.    256.    207.    403.    351.
S1BRRI70    1940    372.    166.    620.    233.     33.     41.    144.    193.    605.    233.    232.    259.
S1BRSE11    1941   1725.  39100. 147470. 258900.1115700. 505460. 224790. 198110. 230130. 916940. 177100.  74173.
S1515531    1941   1378.    966.   1205.    993.    432.    504.    798.    613.    949.    513.    676.    833.
S1515631    1941    127.    323.    206.    196.    344.    408.    283.    207.    972.    316.    127.    376.
S1BRRI70    1941    205.    159.    172.    330.    184.    176.    194.    241.    166.    193.     77.    208.
```

Table 7.17 Total Dissolved Solids (TDS) Entered in Salinity Input SIN File

Control Point ID	Control Point Location	Monthly Sequences on *S1* Records or Constant Concentration on *CC* Record
BRSE11	Brazos River at Seymour gage	load series for total regulated flows
515531	Possum Kingdom Dam (Graford gage)	concentration series for incremental inflows
515631	Granbury Dam	concentration series for incremental inflows
515731	Whitney Dam (Aquilla gage on Brazos)	concentration series for incremental inflows
LRCA58	Little River at Cameron gage	constant 256 mg/l for total regulated flows
BRRI70	Brazos River at Richmond gage	concentration series for incremental inflows
BRGM73	Brazos River Outlet at Gulf of Mexico	constant 339 mg/l for incremental inflows

Salinity inflow data for control points SHGR26 and BRAQ33 at the Graford and Aquilla gages on the Brazos River are assigned to control points 515531, 515631, and 515731, representing Lakes Possum Kingdom, Granbury, and Whitney. The same sequences of concentrations of incremental flows between control points SHGR26 and BRAQ33 are entered for control points 515631 (Lake Granbury) and 515731 (Lake Whitney).

Control points BRSE11 (Seymour gage) on the Brazos River and LRCA58 (Cameron gage) on the Little River are treated as upper boundaries in WRAP-SALT, upstream of which the salinity simulation is not extended. The SIM simulation includes computation of water quantities for all control points including those located upstream of the Seymour and Cameron gages. However, the WRAP-SALT salinity tracking simulation begins at the Seymour gage and Cameron gages and extends downstream to the Brazos River outlet at the Gulf of Mexico. Salinity loads and concentrations are computed within the WRAP-SALT simulation for all control points except those located at and upstream of the control points located upstream of control points 515531, 515631, 515731, BRRI70, and BRGM73 but not upstream of BRSE11 and LRCA58.

Alternative options provided in WRAP-SALT for specifying beginning-of-simulation reservoir storage concentrations were investigating including application of the beginning reservoir concentration (BRC) file with recycling. Unlike the beginning-ending-storage (BES) file feature, the end-of-simulation concentrations are sensitive to beginning concentrations. Due to this issue, the approach of developing a BRC file based on recycling was not adopted.

The beginning-of-simulation storage concentrations tabulated in Table 7.18 were adopted. The beginning-of-simulation concentrations of 1,626 mg/l, 1,302 mg/l, and 1,062 mg/l adopted for Lakes Possum Kingdom, Granbury, and Whitney are the mean 1964-1986 storage concentrations at these three reservoirs from the salinity budget study of Chapter III and IV.

Table 7.18 Beginning-of-Simulation Reservoir Storage Concentration

Control Point	Reservoir	Concentration (mg/l)	
		Reservoir at Control Point	Upstream Reservoirs
515531	Possum Kingdom	1,626	800
515631	Granbury	1,302	400
515731	Whitney	1,062	300
BRRI70	−	−	250
BRGM73	−	−	250

Application of the WRAP-SALT salinity routing capabilities to Possum Kingdom and Whitney Reservoirs is investigated in Chapter VI. Based on the studies, the lag feature controlled by LAG1 and LAG2 in CP record fields 7 and 8 was not adopted. The beginning-of-month TM option (CP record field 6) is combined with zero lag.

WRPA-SALT provides alternative options for assigning concentrations to water supply diversion, return flows, CI record constant inflows, channel losses, and channel loss credits which are activated on CC records. These concentrations are specified in the Brazos SIN file as follows. Concentrations of run-of-river diversions are set at the concentration of reservoir storage. Concentrations of run-of-river diversions are the same as the regulated flow leaving the control point. Concentrations of return flows, CI record constant inflows, channel losses, and channel loss credits are based on outflow concentrations at upstream control points. Outflow volumes and concentration at the upstream control points may be zero in some months, in which case the concentrations of return flows, CI record constant inflows, channel losses, and channel loss credits are set at the values entered in CC record columns 81-88. Maximum concentration limits are also specified on the CC records shown in Table 7.16.

Components of salinity loads are normally connected to specific components of the flow and storage volume budget in WRAP-SALT. For example, TDS loads are associated with streamflows, water supply diversion, and return flows. However, options activated by the parameters LLI(cp) and LLS(cp) in control point CP record filed 10 and 11 allow specification of additional salinity load losses or gains that are not associated with flow or storage volumes. These otherwise unaccounted for loads, not connected to any particular component of the volume budget, are computed in WRAP-SALT by multiplying either reservoir inflow loads or storage loads by the factors LLI(cp) and LLS(cp). The load and volume budget of Chapter III and IV include such losses of TDS loads at Lakes Possum Kingdom, Granbury, and Whitney. The parameter LLI(cp) is computed in Table 7.5 for Possum Kingdom, Granbury, and Whitney Reservoirs as 0.17420, 0.06587, and 0.03000.

CHAPTER VIII

WRAP SIMULATION OF THE BRAZOS RIVER BASIN

This chapter presents a simulation study in which the WRAP computer program SALT is applied in combination with the WRAP program SIM and TABLES to model the Brazos River Basin. Impacts of natural salt pollution on water supply capabilities are investigated with the simulation model. The impacts of multiple-reservoir system operations and salinity control measures on salinity concentrations throughout the river system are also explored.

8.1 Introductory Overview

Ten simulations listed in Table 8.1 were performed to investigate the impacts of salinity on water resources capabilities in the Brazos River Basin. The first two simulations use the TCEQ Water Availability Modeling (WAM) System dataset (Bwam8) alternatively with the 1940-2007 and 1900-2007 hydrologic periods-of-analysis. The 1940-2007 period-of-analysis is adopted for the other simulations. The third simulation is based on the Brazos River Authority Condensed (BRAC8) dataset.

The Bwam8 and BRAC8 datasets reflect the current use scenario originally labeled simulation run8 in the TCEQ WAM System. The current use scenario includes the maximum annual water supply diversion amount of any year during the period 1898-

1997 for each water right permit and best estimates of return flows. Reservoir storage capacities are adjusted to reflect year 2000 conditions of reservoir sedimentation.

The Brazos River Authority Condensed 2008 Actual Use (BRAC2008) dataset was adopted for more detailed salinity simulation studies. BRAC2008 is a revised version of the BRAC8 model that incorporates BRA water supply diversions recorded during the year 2008. Simulation 5, 6, 7, 8, and 9 apply the BRAC2008 dataset to explore impacts on salt concentrations of alternative multiple-reservoir system operating strategies. Flows and loads are adjusted in simulation 10 to model a natural salt pollution control impoundment plan previously proposed by the Corp of Engineers.

Table 8.1 Alternative Simulations

Simulation	WRAP-SIM Input Data	Simulation Period	Description
1	Bwam8	1940-2007	Original basic WAM dataset.
2	Bwam8	1900-2007	Original basic WAM dataset.
3	BRAC8	1940-2007	Original basic BRAC8 dataset.
4	BRAC2008	1940-2007	Original basic BRAC2008 dataset.
5, 6, 7, 8, 9	BRAC2008	1900-2007	Multiple-reservoir system operations.
10	BRAC2008	1940-2007	Natural salt pollution control impoundments.

8.2 Salinity Simulations with the BWAM8 Dataset (Simulations 1 and 2)

The Bwam8 dataset contains 3,834 control point *CP* records, 1,725 water right WR records, 711 reservoirs, 144 instream flow IF records, along with other input records.

Naturalized flows are provided in the FLO file for 77 primary control points. Flows are distributed to the 3,757 other secondary control points based on information provided in the flow distribution DIS file. The EVA file contains net reservoir surface evaporation less precipitation rates for 67 different areas of the river basin. The original Bwam8 dataset has a 1940-1997 hydrologic period-of-analysis. Alternative periods-of-analysis of 1940-2007 and 1900-2007 were adopted for the salinity simulation study. Also, the original Bwam8 dataset sets the beginning-of-simulation storage contents at capacity. The present study includes a BRS file developed based on setting the beginning-of-simulation storage contents at the initially simulated end-of-simulation storage contents.

The simulation results OUT file and beginning reservoir storage BRS file are created with WRAP-SIM with Bwam8 DAT, FLO, EVA, and DIS input files. WRAP-SALT reads the OUT and BRS files along with the salinity SIN file reproduced in Table 7.16.

8.2.1 Bwam8 Simulation for 1940-2007 Hydrologic Period-of-Analysis

The total volume and load summary reproduced as Table 8.2 is from the message SMS file created by WRAP-SALT. Table 8.3, Table 8.4, and Table 8.5 reflect an 816-month simulation extending from January 1940 through December 2007.

The flow volumes in acre-feet and loads in tons are 1940-2007 or 1900-2007 totals. The reservoir storage volumes in acre-feet and loads in tons are totals at the beginning of January 1940 and end of December 2007. The concentrations are computed in WRAP-SALT by combining the total volumes and total loads.

Even though the WRAP-SIM DAT and OUT files contain 3,834 control points, the WRAP-SALT salinity tracking computations are performed for only 1,941 control points. The 1,941 control points are located upstream of control point BRGM73 but not upstream of LRCA58 and BRSE11. Control points LRCA58 and BRSE11 are upstream boundaries for which only the loads and concentrations of the regulated streamflows enter the salinity simulations.

Table 8.2 Total Volume and Load Summary in SMS File for Simulation 1 (Bwam8, 1940-2007)

	Volume	Load	Concentration
Naturalized flows	321151552.	127202104.	291.3
Regulated flows at boundary	97300496.	97986664.	740.7
Return flows	5898104.	5360824.	668.5
CI record constant inflows	2941136.	1461161.	365.4
Channel loss credits	12373307.	15560305.	924.9
Channel losses	1698884.	2737613.	1185.2
Regulated flows at outlet	351355488.	164130256.	343.6
Diversions	71257824.	57220640.	590.6
Other flows and loads	-7571298.	-3530724.	343.0
Net evaporation	23265614.	0.	0.0
Load losses from CP record CLI(cp)		26945616.	
	----------	----------	----------
Inflows - Outflows	-341917.	67657.	-145.5
	----------	----------	----------
Beginning reservoir storage	2803318.	3210527.	842.3
Ending reservoir storage	2789651.	3084914.	813.3
	----------	----------	----------
Change in storage	-13667.	-125614.	6759.8
	----------	----------	----------
Volume and load differences	-328250.	193271.	-433.0
Negative inflows to cpts	4066677.	25240842.	4564.9
Negative incremental nat flows	432835520.		
Naturalized flows at outlet	434901216.		

Number of control points in SIM DAT and OUT files: 3834
Number of control points included in SALT simulation: 1941

The *regulated flows at boundary* of 97,300,496 acre-feet and 97,9866,664 tons in Table 8.2 are the sum of the 1940-2007 total volumes and loads at control points BRSE11 and LRCA58 at the Seymour and Cameron gages. The last column of Table 8.2 consists of volume-weighted concentrations in mg/l computed by multiplying loads/volumes by the factor 735.48.

Incremental naturalized flows are computed by subtracting flows at an upstream control points from the flow at the next downstream control point. The incremental naturalized flows between these control points may be either positive or negative. The first line of Table 8.2 indicates that the incremental naturalized flows for the 816-months of the 1940-2007 hydrologic period-of-analysis sum to 321,151,552 acre-feet, which includes negative incremental monthly flow volumes totaling 432,835,520 acre-feet and positive incremental flow volumes totaling 753,987,072 acre-feet.

All of the volume and load budget components in Table 8.2 are defined in the WRAP Salinity Manual (Wurbs 2009). The volume and load balance differences in Table 8.2 of -328,250 acre-feet and 193,271 tons are the additional amounts required for perfectly precise volume and load balances. These are the amounts by which the budgets do not balance and ideally should be zero. The volume difference of -328,250 is 0.078 percent of the sum of the net naturalized flows inflow of 321,151,552 acre-feet plus regulated flow inflows of 97,300,496 acre-feet. The load difference of 193,326 tons is 0.086 percent of the sum of the net naturalized flow inflow load of 127,202,104 tons plus regulated flow inflow load of 97,986,664 tons. These differences are minimal considering the complexities of performing volume and load accounting for a complex river basin modeled with 1,941 control points.

The volume-weighted concentration of the regulated flows at the basin outlet is 343.6 mg/l. The 1964-1986 mean concentrations of the flows measured by the USGS at the Richmond gage is 339 mg/l. The simulated concentrations are expected to be somewhat higher than the 1940-1986 measurements due to increased water supply diversions from the low-salinity tributaries and increased reservoir surface evaporation with the construction of more reservoirs during or after the 1964-1986 period of the USGS data collection program.

Table 8.3 provides the summary of the control points. The 1940-2007 means of volumes (acre-feet), TDS loads (tons), and TDS concentrations are tabulated for inflows, outflows, and reservoir storage at each of the control points. Since control points BRSE11 and LRCA58 are upstream boundaries, only outflows are included in the simulation and the summary table. The mean concentration of flows leaving the Cameron gage (LRCA58), Seymour gage (BRSE11), Richmond gage (BRRI70), and basin outlet (BRGM73) are 256 mg/l, 3,267 mg/l, 353 mg/l, and 344 mg/l.

Table 8.4 and Table 8.5 are frequency tables for concentrations of streamflows below each of the selected control points and concentrations of reservoir storage at selected control points. At the Richmond gage (BRRI70), the 50 % exceedance frequency (median) TDS concentration is 349 mg/l for the conditions and premises represented by the model. The concentration at the Cameron gage (LRCA58) is 256 mg/l for all frequencies in the flow frequency table because a constant 256 mg/l was specified in the input SIN file.

Table 8.3 Control Point Summary (Bwam8, 1940-2007)

Control Point	Mean Monthly Volume (ac-ft)			Mean Monthly Load (tons)			Mean Concentration (mg/l)		
	Inflow	Outflow	Storage	Inflow	Outflow	Storage	Inflow	Outflow	Storage
LRCA58	0	100,048	0	0	34,824	0	0.0	256.0	0.0
BRSE11	0	19,193	0	0	85,258	0	0.0	3,266.8	0.0
421331	7,271	3,869	251,401	6,641	6,366	438,680	671.7	1,210.0	1,283.2
BRSB23	45,617	45,617	0	119,898	119,899	0	1,932.9	1,932.9	0.0
515531	56,368	51,985	544,292	130,472	131,046	1,275,992	1,702.2	1,853.8	1,724.0
515631	70,650	69,015	127,349	106,851	108,361	226,961	1,112.2	1,154.6	1,310.6
515731	94,957	90,530	545,895	108,501	109,235	699,968	840.3	887.4	943.0
515831	6,999	6,403	39,081	2,016	2,004	13,309	211.8	230.1	250.4
509431	32,532	30,573	197,111	9,624	9,473	70,991	217.6	227.9	264.9
BRBR59	304,019	304,019	0	173,757	173,757	0	420.3	420.3	0.0
516431	20,026	18,895	130,109	5,681	5,685	41,148	208.6	221.3	232.6
516531	19,940	18,115	187,562	5,637	5,638	61,168	207.9	228.9	239.8
BRHE68	413,723	413,723	0	205,875	205,875	0	365.9	365.9	0.0
BRRI70	452,223	452,223	0	216,953	216,954	0	352.8	352.8	0.0
BRGM73	430,583	430,583	0	201,140	201,140	0	343.5	343.5	0.0

Table 8.4 Concentration Frequency for Downstream Streamflows (Bwam8, 1940-2007)

Control Point	N	Mean	Standard Deviation	Percentage of Months with Concentration Equaling or Exceeding Values											
				100%	99%	98%	95%	90%	75%	60%	50%	40%	25%	10%	Max
LRCA58	816	256	0	256.0	256.0	256.0	256.0	256	256	256	256	256	256	256	256
BRSE11	816	6,331	3,456	0.0	0.0	1,128.2	1,553.5	2,093	3,566	5,052	5,932	7,152	8,778	11,059	26,422
421331	816	1,369	508	600.0	626.4	661.2	710.2	799	1,014	1,129	1,228	1,346	1,768	2,113	3,290
BRSB23	816	4,117	3,425	0.0	477.2	751.9	1,039.6	1,372	2,112	3,019	3,574	4,109	5,211	7,384	56,526
515531	816	1,729	447	0.0	457.2	721.5	946.8	1,126	1,497	1,678	1,783	1,866	1,998	2,276	2,867
515631	816	1,307	738	0.0	0.0	0.0	152.6	538	885	1,137	1,236	1,351	1,592	2,103	5,000
515731	816	935	380	0.0	0.0	0.0	453.8	577	709	808	897	948	1129	1463	2,192
515831	816	254	106	0.0	9.1	14.1	1,14.4	147	192	215	233	257	322	408	580
509431	816	260	96	0.0	0.0	0.0	1,26.1	177	220	245	259	271	296	356	1,280
BRBR59	816	517	400	0.0	26.8	59.4	92.8	128	204	316	421	515	724	1117	2,541
516431	816	245	71	0.0	91.7	1,44.6	163.1	181	206	221	231	244	271	327	860
516531	816	246	57	74.2	105.4	1,43.2	172.2	184	209	227	237	249	277	327	446
BRHE68	816	457	350	0.0	48.5	73.7	1,10.1	140	206	296	364	443	594	924	3,236
BRRI70	816	436	344	0.0	38.4	69.3	1,13.9	144	209	286	349	416	544	861	3,733
BRGM73	816	825	6,923	0.0	30.1	77.2	1,24.3	154	222	294	341	398	526	838	148,400

Table 8.5 Concentration Frequency for Reservoir Storage

Control Point	N	Mean	Standard Deviation	Percentage of Months with Concentration Equaling or Exceeding Values											
				100%	99%	98%	95%	90%	75%	60%	50%	40%	25%	10%	Max
421331	816	1,370	508	600.0	626.4	661.2	710.2	803	1,018	1,131	1,231	1,348	1,768	2,113	3,290
515531	816	1,728	448	0.0	457.2	721.5	946.8	1,126	1,494	1,678	1,783	1,866	1,998	2,276	2,867
515631	816	1,317	749	0.0	0.0	0.0	152.6	551	885	1,141	1,237	1,359	1,615	2,123	5,365
515731	816	948	372	0.0	0.0	105.2	516.2	587	713	817	904	955	1,135	1,473	2,287
515831	816	254	106	0.0	9.1	14.1	114.4	147	192	215	233	257	324	409	580
509431	816	267	90	0.0	62.0	101.7	151.6	189	224	248	261	272	299	358	1,280
516531	816	246	57	74.2	105.4	143.2	172.2	184	209	227	237	249	277	327	446
516431	816	244	72	0.0	83.5	124.5	161.0	180	206	221	231	244	271	326	878

8.2.2 Bwam8 Simulation for 1900-2007 Hydrologic Period-of-Analysis

The Bwam8 simulation was repeated for a hydrologic period-of-analysis of 1900-2007 with all other input data remaining the same. Sequences of 1900-1939 monthly naturalized flows and net evaporation less precipitation rates were activated in the FLO and EVA files of the SIM input dataset.

The results with the two alternative simulation periods are similar. A WRAP simulation develops frequency and reliability statistics based on simulating a specified scenario of water resources development, management, and use during historical hydrologic sequences representing natural river basin hydrology. A 1,296 month (1900-2007) simulation would normally provide a better estimate of these statistics than a 816 month (1940-2007) simulation. However, grater uncertainties are inherent in the naturalized flows prior to 1940 due to fewer stream gaging stations. The salinity data are based on October 1964 through September 1986 measurements extended computationally to cover the entire 1900-2007 simulation period as outlined in Chapter VII. The 1940-1997 alternative may be best for the salinity simulation studies.

The volume and load budget from the SMS file is reproduced below as Table 8.6. Likewise the results of simulation 1, Table 8.7 represents control point summary. Also, concentration frequencies of each control point and reservoir are tabulated in Table 8.8 and Table 8.9.

Table 8.6 Total Volume and Load Summary in SMS File for Simulation 2
(Bwam8, 1900-2007)

	Volume	Load	Concentration
Naturalized flows	285978112.	118702120.	305.3
Regulated flows at boundary	92405288.	102139544.	813.0
Return flows	5807254.	5381234.	681.5
CI record constant inflows	2941136.	1462790.	365.8
Channel loss credits	12774677.	16028811.	922.8
Channel losses	1699773.	2859973.	1237.5
Regulated flows at outlet	310745280.	153290912.	362.8
Diversions	70703080.	59816424.	622.2
Other flows and loads	-7909404.	-3033864.	282.1
Net evaporation	25339908.	0.	0.0
Load losses from CP record CLI(cp)		29383456.	
	----------	----------	----------
Inflows - Outflows	-672170.	1397596.	-1529.2
	----------	----------	----------
Beginning reservoir storage	2803318.	3210527.	842.3
Ending reservoir storage	2455284.	4340482.	1300.2
	----------	----------	----------
Change in storage	-348033.	1129955.	-2387.9
	----------	----------	----------
Volume and load differences	-324136.	267641.	-607.3
Negative inflows to cpts	4617908.	21897184.	3487.5
Negative incremental nat flows	565452160.		
Naturalized flows at outlet	394708928.		

Number of control points in SIM DAT and OUT files: 3834
Number of control points included in SALT simulation: 1941

Table 8.7 Control Point Summary (Bwam8, 1900-2007)

Control Point	Mean Monthly Volume (ac-ft)			Mean Monthly Load (tons)			Mean Concentration (mg/l)		
	Inflow	Outflow	Storage	Inflow	Outflow	Storage	Inflow	Outflow	Storage
LRCA58	0	90,260	0	0	31,417	0	0.0	256.0	0.0
BRSE11	0	22,982	0	0	93,754	0	0.0	3,000.0	0.0
421331	7,494	3,756	26,7457	7,372	7,092	511,710	723.4	1,388.4	1,407.0
BRSB23	54,012	54,012	0	132,587	132,596	0	1,805.2	1,805.4	0.0
515531	64,566	59,927	54,4854	142,330	142,295	1,177,749	1,621.1	1,746.2	1,589.6
515631	76,580	74,814	12,7425	116,702	117,706	221,019	1,120.7	1,157.0	1,275.6
515731	104,882	99,905	54,5269	117,603	117,635	671,892	824.6	865.9	906.2
515831	6,169	5,531	3,9128	1,847	1,839	15,073	220.1	244.5	283.3
509431	27,690	25,610	196,267	8,522	8,515	75,305	226.3	244.5	282.2
BRBR59	275,710	275,710	0	169,688	169,689	0	452.6	452.6	0.0
516431	19,106	17,987	129,072	5,601	5,624	41,817	215.6	229.9	238.3
516531	18,373	16,526	186,393	5,405	5,385	63,291	216.3	239.6	249.7
BRHE68	374,288	374,288	0	200,226	200,226	0	393.4	393.4	0.0
BRRI70	406,593	406,593	0	209,478	209,479	0	378.9	378.9	0.0
BRGM73	380,815	380,815	0	187,857	187,857	0	362.8	362.8	0.0

Table 8.8 Concentration Frequency for Downstream Streamflows (Bwam8, 1900-2007)

Control Point	N	Mean	Standard Deviation	Percentage of Months with Concentration Equaling or Exceeding Values											
				100%	99%	98%	95%	90%	75%	60%	50%	40%	25%	10%	Max
LRCA58	816	256	0	256.0	256.0	256.0	256.0	256	256	256	256	256	256	256	256
BRSE11	816	6,109	3,592	0.0	0.0	0.0	978.6	1,583	3,152	4,891	5,729	6,957	8,629	11,224	15,380
421331	816	1,469	453	607.3	770.7	804.7	861.1	943	1,153	1,298	1,436	1,536	1,670	2,100	3,432
BRSB23	816	4,666	16,796	0.0	0.0	0.0	738.1	1,143	1,964	2,770	3,399	3,895	4,905	6,647	458,354
515531	816	1,593	416	0.0	595.3	805.7	955.9	1,106	1,338	1,467	1,571	1,695	1,879	2,063	2,870
515631	816	1,269	753	0.0	0.0	0.0	148.8	429	857	1,075	1,161	1,257	1,585	2,112	5,000
515731	816	903	374	0.0	0.0	0.0	334.4	535	660	774	861	941	1,093	1,373	2,278
515831	816	287	95	0.0	16.6	113.3	152.8	182	227	257	272	299	345	418	580
509431	816	280	108	0.0	0.0	4.4	134.8	193	235	257	268	280	305	393	759
BRBR59	816	568	501	0.0	16.5	36.1	81.0	127	216	335	445	560	764	1200	5,658
516431	816	248	65	0.0	119.6	152.5	166.3	182	212	230	240	251	281	321	868
516531	816	254	55	74.2	108.0	146.3	174.8	193	222	236	249	262	286	330	446
BRHE68	816	508	460	0.0	25.2	64.3	109.3	141	219	305	389	474	624	1,037	4,904
BRRI70	816	497	508	0.0	36.6	64.4	114.1	142	220	297	370	443	583	988	7,774
BRGM73	816	697	4,610	0.0	28.3	69.4	122.1	151	232	300	352	420	556	970	120,257

Table 8.9 Concentration Frequency for Reservoir Storage (Bwam8, 1900-2007)

Control Point	N	Mean	Standard Deviation	Percentage of Months with Concentration Equaling or Exceeding Values 100%	99%	98%	95%	90%	75%	60%	50%	40%	25%	10%	Max
421331	816	1,470	452	607.3	770.7	810.7	861.3	944	1,155	1,299	1,437	1,536	1,670	2,100	3,432
515531	816	1,594	416	0.0	595.3	805.7	955.9	1,106	1,338	1,467	1,571	1,695	1,879	2,065	2,870
515631	816	1,286	805	0.0	0.0	0.0	148.8	429	858	1,076	1,162	1,259	1,611	2,137	8,190
515731	816	912	369	0.0	0.0	157.2	382.7	556	665	781	864	944	1,100	1,391	2,546
515831	816	287	95	0.0	16.6	113.3	152.8	182	227	257	272	300	345	418	580
509431	816	286	102	0.0	65.0	110.0	166.4	201	238	258	270	281	306	393	759
516531	816	254	55	74.2	108.0	146.3	174.8	193	222	236	249	262	286	330	446
516431	816	247	66	0.0	95.1	148.2	164.2	180	212	230	239	250	281	320	887

8.3 Salinity Simulations with BRAC8 Dataset (Simulation 3)

8.3.1 Brazos River Authority Condensed Datasets (BRAC3 and BRAC8)

As mentioned in Chapter VII, Wurbs and Kim (Wurbs and Kim 2008) explain the concept of a condensed WRAP input dataset and document the development of the Brazos River Authority Condensed datasets (BRAC3 and BRAC8) by condensing the TCEQ WAM System Brazos datasets for the authorized use (Bwam3) and current use (Bwam8) scenarios. The objective of the condensed dataset methodology is to develop and apply a much simpler dataset for purposes of decision support studies for a particular reservoir/river water management system. The condensed model allows alternative operating plans for the primary water management system to be simulated based on the premise of assuring protection of all other water rights. Selected water rights, control points, and reservoirs are removed with their effects retained in the adjusted stream inflow input data for the condensed dataset.

Figure 8.1 is a schematic of the spatial configuration of the system as defined by the 48 control points. The 48 control points included in the BRAC8 dataset are listed in Table 8.10, Table 8.11, and Table 8.12. The 22 control points in Table 8.10 are locations of stream gaging stations. The 11 control points in Table 8.11 represent stream confluences and the basin outlet. The 15 control points in Table 8.12 are locations of reservoirs including the proposed Allens Creek Reservoir project which is not included in the BRAC8 dataset though in the authorized use BRAC3 dataset.

Table 8.10 BRAC8 Control Points at USGS Gaging Stations

WAM CP ID	River	Nearest City	USGS Gage No.	**Watershed** Area (square miles)
DMAS09	Double Mountain Fork	Aspermont	08080500	265
BRSE11	Brazos River	Seymour	08082500	5,996
BRSB23	Brazos River	South Bend	08088000	13,171
BRPP27	Brazos River	Palo Pinto	08089000	14,309
BRDE29	Brazos River	Dennis	08090800	15,733
BRGR30	Brazos River	Glen Rose	08091000	16,320
BRAQ33	Brazos River	Aquilla	08093100	17,746
BRWA41	Brazos River	Waco	08096500	20,065
BRHB42	Brazos River	Highbank	08098290	20,900
LEHM46	Leon River	Hamilton	08100000	1,928
LEGT47	Leon River	Gatesville	08100500	2,379
LEBE49	Leon River	Belton	08102500	3,579
LABE52	Lampasas River	Belton	08104100	1,321
LRLR53	Little River	Little River	08104500	5,266
GALA57	San Gabriel River	Laneport	08105700	737
LRCA58	Little River	Cameron	08106500	7,100
BRBR59	Brazos River	Bryan	08109000	30,016
NAEA66	Navasota River	Easterly	08110500	936
NABR67	Navasota River	Bryan	08111000	1,427
BRHE68	Brazos River	Hempstead	08111500	34,374
BRRI70	Brazos River	Richmond	08114000	35,454
BRRO72	Brazos River	Rosharon	08116650	35,775

Table 8.11 BRAC8 Control Points for Stream Confluences and the Basin Outlet

Control Point	Location
CON036	Confluence of Hubbard Creek and Brazos River
CON063	Confluence of Squaw Creek and Brazos River
CON070	Confluence of Aquilla Creek and Brazos River
433901	Confluence of Bosque and Brazos River
CON096	Confluence of Lampasas and Little River
CON108	Confluence of Little River and San Gabriel
CON111	Confluence of Little River and Brazos River
CON130	Confluence of Yegua Creek and Brazos River
CON147	Confluence of Navasota River and Brazos River
CON234	Confluence of Allens Creek and Brazos River
BRGM73	Brazos River Outlet at the Gulf of Mexico

Table 8.12 BRAC Control Points for Reservoirs

Control Point	Reservoir	Reservoir Identifier	Storage (acre-feet)	Diversion (ac-ft/yr)
		Brazos River Authority and Corps of Engineers		
515531	Possum Kingdom	POSDOM	552,013	59,482
515631	Granbury	GRNBRY	132,821	36,025
515731	Whitney	WHIT	561,074	18,336
515831	Aquilla	AQUILA	41,700	2,394
509431	Waco	WACO	206,562	38,348
515931	Proctor	PRCTOR	54,702	14,068
516031	Belton	BELTON	432,978	107,738
516131	Stillhouse Hollow	STLHSE	224,279	67,768
516231	Georgetown	GRGTWN	36,980	11,943
516331	Granger	GRNGER	50,540	2,569
516531	Limestone	LMSTNE	208,017	39,337
516431	Somerville	SMRVLE	154,254	48,000
	Total		2,655,920	446,008
292531	Allens Creek	Site of proposed reservoir.		
		West Central Texas Municipal Water District		
421331	Hubbard Creek	HUBBRD	317,750	9,924
		Comanche Peak Nuclear Power Plant		
409732	Squaw Creek	SQWCRK	151,015	17,536

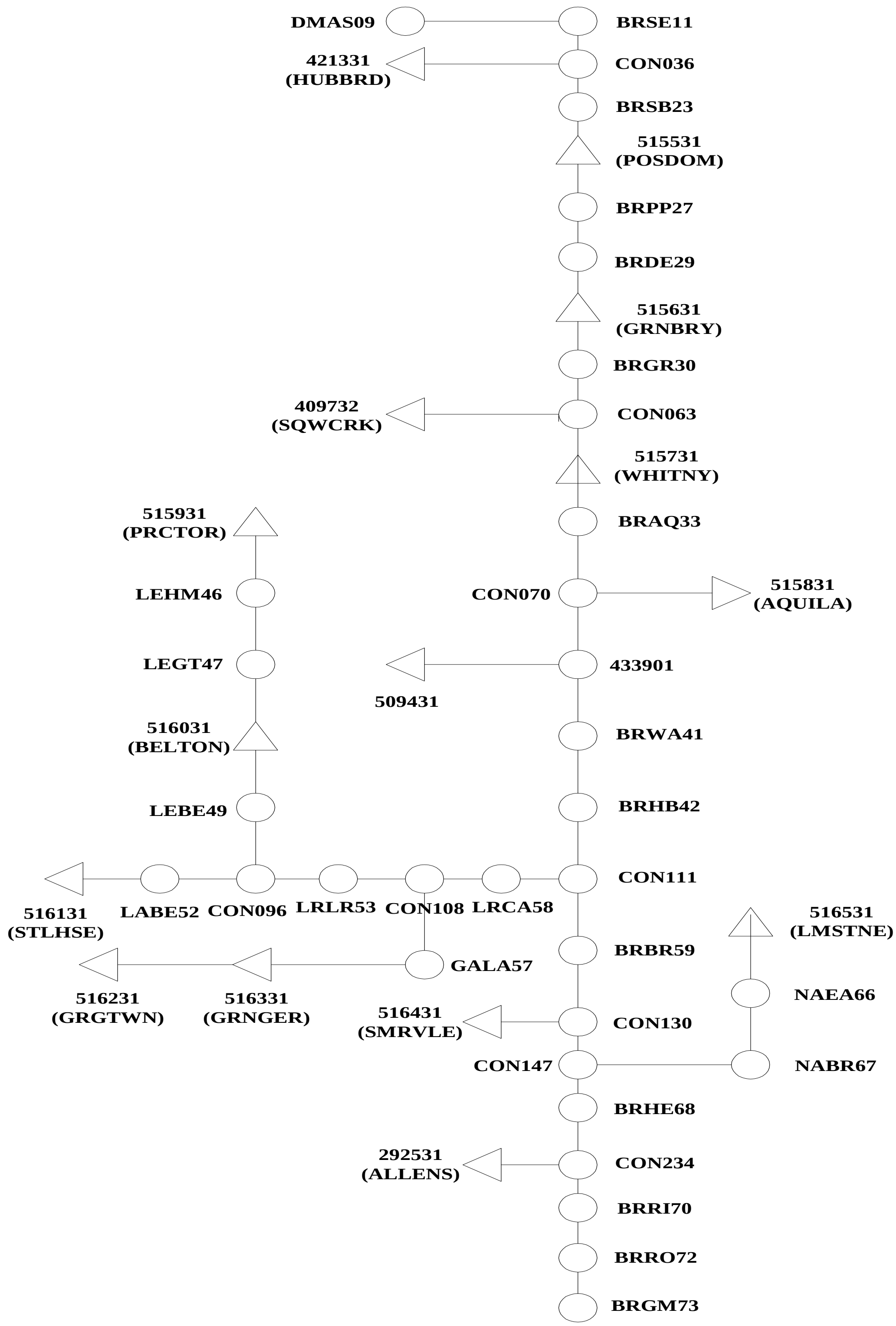

Figure 8.1 BRAC8 Control Point Schematic (Wurbs and Kim 2008)

The 14 reservoirs included in the BRAC8 input DAT file and the water supply diversions from the reservoirs are tabulated in Table 8.12. These lakeside diversions from the 14 reservoirs are the only diversion included in the BRAC8 DAT file. The total storage capacity of 3,123,685 acre-feet in these 14 reservoirs account for 77.7 percent of the 4,023,350 acre-feet of storage capacity in the 711 reservoirs in the Bwam8 DAT file. The 2,655,920 acre-feet of storage capacity in the 12 Brazos River Authority reservoirs represent 66.0 percent of the total Bwam8 storage capacity. The total annual diversion demand of 446,008 acre-feet/year is 29.8 percent of the total diversion demand in the Bwam8 dataset.

8.3.2 Results of BRAC8 Simulation

Conceptually, most of the BRAC8 and Bwam8 results should be the same. However, naturalized streamflows are conceptually different. The Bwam8 *"naturalized flows"* represent natural flows without the effects of human water resources development. The BRAC8 *"naturalized flows"* are the streamflows adjusted for the effects of all of the Bwam8 water management and use activities except those included in BRAC8 DAT file. The simulation results from the two simulations match very closely as they conceptually should, though not absolutely perfectly. A perfect match would be essentially impossible. The BRAC8 simulation results appear to be a reasonably good match to the Bwam8 results.

Table 8.13 represents the total load and volume summary form the BRAC8 simulation. Table 8.13 is comparable to the Bwam8 summary table of Table 8.2. The control points summary is tabulated in Table 8.14. Likewise the results of Bwam8, frequency tables of flow concentration and storage concentration are provided in the tables on pages 231 and 232.

Table 8.13 Total Volume and Load Summary in SMS File for Simulation 3 (BRAC8, 1940-2007)

		Volume	Load
Concentration			
Naturalized flows	285978112.	118702120.	305.3
Regulated flows at boundary	92405288.	102139544.	813.0
Return flows	5807254.	5381234.	681.5
CI record constant inflows	2941136.	1462790.	365.8
Channel loss credits	12774677.	16028811.	922.8
Channel losses	1699773.	2859973.	1237.5
Regulated flows at outlet	310745280.	153290912.	362.8
Diversions	70703080.	59816424.	622.2
Other flows and loads	-7909404.	-3033864.	282.1
Net evaporation	25339908.	0.	0.0
Load losses from CP record CLI(cp)		29383456.	
Inflows - Outflows	-672170.	1397596.	-1529.2
Beginning reservoir storage	2803318.	3210527.	842.3
Ending reservoir storage	2455284.	4340482.	1300.2
Change in storage	-348033.	1129955.	-2387.9
Volume and load differences	-324136.	267641.	-607.3
Negative inflows to cpts	4617908.	21897184.	3487.5
Negative incremental nat flows	565452160.		
Naturalized flows at outlet	394708928.		

Number of control points in SIM DAT and OUT files: 3834
Number of control points included in SALT simulation: 1941

Table 8.14, the mean TDS inflow loads at the upper boundaries in the mode are 34,948 tons/month at control point LRAC58 (Cameron gage on the Little River) and 85,258 tons/month at control point BRSE11 (Seymour gage on the Brazos River), which expressed as a total load over 68 years is the 98,088,264 tons shown in Table 8.13. The mean TDS outflow load at control point BRGM73 (outlet at Gulf) is 213,305 tons/month (Table 8.14) which is equivalent to a total load over 816 months of 174,007,296 tons (Table 8.13). The mean TDS concentration of outflows at control point BRGM73 (basin outlet) is 364 mg/l as shown in both Table 8.13 and Table 8.14.

Table 8.15 provides a comparison of the BRAC8 summary in Table 8.14 with Bwam8 summary from Table 8.3. In Table 8.15, each of the BRAC8 quantities in Table 8.14 is expressed as a percentage of the corresponding Bwam8 quantity in the summary table of Table 8.3. For example, the outflow concentration at BRHE68 of 375.1 mg/l shown in Table 8.14 is 102.51 percent of the corresponding concentration of 365.9 mg/l form Table 8.3. Table 8.15 shows that the BRAC8 model reproduce the Bwam8 simulation results closely though not perfectly.

Table 8.14 Control Point Summary for Simulation 3 (BRAC8, 1940-2007)

Control Point	Mean Monthly Volume (ac-ft)			Mean Monthly Load (tons)			Mean Concentration (mg/l)		
	Inflow	Outflow	Storage	Inflow	Outflow	Storage	Inflow	Outflow	Storage
LRCA58	0	100,405	0	0	34,948	0	0.0	256.0	0.0
BRSE11	0	19,164	0	0	85,258	0	0.0	3,271.7	0.0
421331	7,279	3,877	25,1374	6,554	6,289	432,635	662.2	1,192.9	1,265.7
BRSB23	45,029	45,029	0	112,095	112,095	0	1,830.7	1,830.7	0.0
515531	55,721	51,338	544,291	122,277	122,761	1,201,669	1,613.8	1,758.5	1,623.6
515631	70,532	68,894	127,657	106,634	107,764	250,905	1,111.8	1,150.3	1,445.4
515731	96,074	91,646	545,949	112,859	113,475	714,129	863.9	910.6	961.9
515831	7,003	6,406	39,117	2,016	2,005	13,288	211.7	230.2	249.8
509431	34,059	32,100	197,163	10,013	9,927	67,602	216.2	227.4	252.1
BRBR59	304,376	304,376	0	179,291	179,291	0	433.2	433.2	0.0
516431	20,028	18,896	130,110	5,492	5,496	39,749	201.7	213.9	224.7
516531	19,940	18,115	187,558	5,586	5,585	59,330	206.0	226.7	232.6
BRHE68	414,067	414,067	0	211,178	211,178	0	375.1	375.1	0.0
BRRI70	452,558	452,558	0	223,052	223,052	0	362.5	362.5	0.0
BRGM73	430,889	430,889	0	213,204	213,305	0	363.9	364.0	0.0

Table 8.15 Comparison of Control Point Summaries of Simulation 1 and 3 (Table 8.3 and Table 8.14)

	Volume (%)			Load (%)			Concentration (%)		
CP	Inflow	Outflow	Storage	Inflow	Outflow	Storage	Inflow	Outflow	Storage
LRCA58	–	100.36	–	–	100.36	–	–	100.00	–
BRSE11	–	99.85	–	–	100.00	–	–	100.15	–
421331	100.11	100.21	99.99	98.69	98.79	98.62	98.59	98.59	98.64
BRSB23	98.71	98.71	–	93.49	93.49	–	94.71	94.71	–
515531	98.85	98.76	100.00	93.72	93.68	94.18	94.81	94.86	94.18
515631	99.83	99.82	100.24	99.80	99.45	110.55	99.96	99.63	110.29
515731	101.18	101.23	100.01	104.02	103.88	102.02	102.81	102.61	102.00
515831	100.06	100.05	100.09	100.00	100.05	99.84	99.95	100.04	99.76
509431	104.69	104.99	100.03	104.04	104.79	95.23	99.36	99.78	95.17
BRBR59	100.12	100.12	–	103.18	103.18	–	103.07	103.07	–
516431	100.01	100.01	100.00	96.67	96.68	96.60	96.69	96.66	96.60
516531	100.00	100.00	100.00	99.10	99.06	97.00	99.09	99.04	97.00
BRHE68	100.08	100.08	–	102.58	102.58	–	102.51	102.51	–
BRRI70	100.07	100.07	–	102.81	102.81	–	102.75	102.75	–
BRGM73	100.07	100.07	–	106.00	106.05	–	105.94	105.97	–

Control point BRGM73 represents the outlet of the Brazos River at the Gulf of Mexico. In reality, the flow of the Brazos River mixes with sea water near the outlet. The concentration in the lower reach of the river is affected by salt water intrusion from the Gulf of Mexico which in not modeled by WRAP-SALT. There is also another unrelated modeling issue at control point BRGM73 in the BRAC8 model. The computed concentrations at control point BRGM73 are unrealistically high in some months and the 1940-2007 mean concentration is a little to high. Due to significant diversions from the lower Brazos River in the original Bwam8 model at control points just upstream of BRGM8, the flows in the BRAC8 FLO file at control point BRGM8 are less than flow upstream but salt loads are higher. This effect captured imperfectly in the BRAC8 model.

BRGM73 is included in the BRAC8 dataset for completeness but does not affect the simulation results at the other control points or the usefulness of the model.

The mean flow concentrations at five gaging stations from the 1964-1986 U.S. Geological Survey (USGS) water quality sampling program, shown in Table 3.4 and the Bwam8 and BRAC8 simulations are compared below in Table 8.16. The concentrations from the Bwam8 and BRAC8 simulations ideally should be the same. Both the Bwam8 and BRAC8 models combine a representation of current (1990's) water management/use with 1940-2007 hydrology. The measured concentrations represent actual water management/use during 1964-1986 and actual 1964-1986 hydrology.

Table 8.16 Comparison of Mean Streamflow Concentrations

Stream Gaging Station	CP	USGS Table 1.2	Bwam8 Table 8.8	BRAC8 Table 8.15
		(mg/l)	(mg/l)	(mg/l)
Cameron gage on Little River	LRCA58	256	256	256
Seymour gage on Brazos River	BRSE11	3,590	3,267	3,272
Graford gage below PK Dam	515531	1,531	1,854	1,759
Whitney gage below Whitney Dam	515731	928	1,155	1,150
Richmond gage on Brazos River	BRRI70	339	352.8	362.5

Whereas the concentrations in Table 8.13 and Table 8.14 are volume-weighted concentrations computed based on combining total volumes and total loads, the means in the frequency tables are of Table 8.17 are arithmetic averages of 816 volume-weighted monthly concentrations. The volume-weighted mean storage concentration of Possum Kingdom Reservoir located at control point 515531 is 1,624 mg/l and the arithmetic average for the 816 months of the simulation is 1,628 mg/l. The median (50 %

exceedance frequency) concentration of Possum Kingdom Reservoir is 1,676 mg/l. The TDS concentration equals or exceeds 1,901 mg/l during 25 percent of the time and 2,132 mg/l for 10 percent of the time. There is an estimated 90 % probability that the volume-weighted TDS concentration of the water stored in Possum Kingdom Reservoir will equal or exceed 1,067 mg/l at any randomly selected point in time.

Table 8.17 Concentration Frequency For Downstream Streamflows (BRAC8, 1940-2007)

Control Point	N	Mean	Standard Deviation	Percentage of Months with Concentration Equaling or Exceeding Values											
				100%	99%	98%	95%	90%	75%	60%	50%	40%	25%	10%	Max
BRSE11	816	6,362	3,531	0.0	0.0	1,127.6	1,545.2	2,111	3,566	5,052	5,932	7,152	8,787	11,123	26,420
421331	816	1,350	496	584.6	622.1	653.9	696.7	793	1,002	1,114	1,208	1,331	1,753	2,072	3,205
BRSB23	816	3,530	2,553	435.7	728.1	893.8	1,122.8	1,382	1,888	2,475	3,016	3,467	4,446	6,144	31,251
515531	816	1,628	415	311.5	581.8	692.5	912.7	1,067	1,354	1,568	1,676	1,758	1,901	2,132	2,688
515631	816	1,335	824	0.0	0.0	0.0	220.7	580	878	1,108	1,222	1,358	1,583	2,113	5,000
515731	816	960	411	0.0	0.0	250.2	536.0	603	686	820	878	937	1,150	1,431	2,706
515831	816	253	105	0.0	8.4	14.5	113.9	146	192	214	232	257	321	406	578
509431	816	254	80	0.0	100.6	125.2	161.9	183	212	231	246	261	285	338	1,189
LRCA58	816	256	0	256.0	256.0	256.0	256.0	256	256	256	256	256	256	256	256
BRBR59	816	503	309	25.8	171.9	196.4	228.1	252	307	364	403	454	588	902	2,408
516431	816	236	69	0.0	87.7	135.8	159.4	174	198	214	224	235	260	314	821
516531	816	238	53	60.8	89.0	160.5	171.5	182	204	217	227	244	265	312	415
BRHE68	816	444	275	23.6	157.7	176.7	203.7	226	271	321	363	410	518	783	2,632
BRRI70	816	432	283	28.8	141.2	162.2	194.9	220	262	310	350	398	497	754	3,100
BRGM73	816	31,301	427,943	0.0	0.0	0.0	145.7	193	249	305	350	420	642	1,788	10,122,996

The outflow at control point BRHE68 at the Hempstead gage consists of the regulated flow in the Brazos River just downstream of this site. The flow frequency table of Table 8.17 indicates that the estimated probability that the TDS concentration will equal or exceed 518 mg/l at any randomly selected time at this location is 25 percent.

The mean monthly flow equaled or exceeded 271 mg/l during 75 percent of the 816 months of the simulation.

Table 8.18 Concentration Frequency for Reservoir Storage (BRAC8, 1040-2007)

Control Point	N	Mean	Standard Deviation	100%	99%	98%	95%	90%	75%	60%	50%	40%	25%	10%	Max
				Percentage of Months with Concentration Equaling or Exceeding Values											
421331	816	1,350	495	584.6	622.1	653.9	696.7	793	1,008	1,114	1,208	1,332	1,753	2,072	3,205
515531	816	1,628	415	311.5	581.8	692.5	912.7	1,067	1,354	1,566	1,676	1,758	1,901	2,132	2,688
515631	816	1,459	1,559	0.0	0.0	0.0	220.7	583	878	1,112	1,230	1,363	1,591	2,154	15,147
515731	816	968	407	0.0	129.1	329.6	554.0	609	691	825	879	938	1,154	1,436	2,706
515831	816	254	105	0.0	8.4	14.5	113.9	146	192	214	232	257	322	406	578
509431	816	255	80	0.0	100.6	125.2	161.9	183	212	231	246	261	285	340	1189
516531	816	238	53	60.8	89.0	160.5	171.5	182	204	217	227	244	265	312	415
516431	816	235	70	0.0	83.7	116.4	158.2	173	198	214	224	235	259	314	838

All of the water supply diversion targets included in the DAT file of the BRAC8 input dataset are included in Table 8.12. The reliability table reproduced from the TABLE TOU file as Table 8.19 includes only the diversions at those control points included in the salinity simulation, which are those control points that are not upstream of the specified upper boundaries at LRCA58 and BRSE11. Thus, diversion at Lakes Proctor, Belton, Stillhouse Hollow, Georgetown, and Granger included in Table 8.12 are not included in Table 8.19.

A constrain limit of 1,000 mg/l was used to consider salinity impacts on diversion reliability. Volume and period reliabilities are computed based on supplying diversion target only if the TDS concentration at the diversion location in a given month is at or below the limit of 1,000 mg/l. The reliability table can be constructed for any specified maximum concentration limit. The reliability table provides three sets of period and volume reliabilities. The first set is based on declaring a diversion shortage in a particular month is either supply is insufficient in either quantity or quality. The second set considers only quantity and results in identically the same reliabilities computed for a WRAP-SIM simulation with WRAP-SALT. The third set of reliabilities considers only water quality, declaring shortages only if the concentration exceeds the specified limit.

Table 8.19 Diversion Reliability With and Without Salinity Constraint of 1,000mg/l (BRAC8, 1940-2007)

Control Point	Target Diversion (ac-ft/yr)	Both Quantity & Quality Reliability			Quantity Only Reliability			Quality Only Reliability			Number Months Concentration	
		Shortage (ac-ft/yr)	Volume (%)	Period (%)	Shortage (ac-ft/yr)	Volume (%)	Period (%)	Shortage (ac-ft/yr)	Volume (%)	Period (%)	Zero	Exceeds Limit
421331	9,923.5	7,450.87	24.92	24.75	0.0	100.00	100.00	7,450.87	24.92	24.75	0	614
515531	59,482.1	55,145.52	7.29	7.23	0.0	100.00	100.00	55,145.52	7.29	7.23	0	757
515631	36,025.4	24,940.79	30.77	31.37	0.0	100.00	100.00	24,940.79	30.77	31.37	25	560
515731	18,336.0	6,371.19	65.25	64.22	0.0	100.00	100.00	6,371.19	65.25	64.22	8	292
515831	2,394.3	0.00	100.00	100.00	0.0	100.00	100.00	0.00	100.00	100.00	2	0
509431	38,348.0	119.75	99.69	99.75	0.0	100.00	100.00	119.75	99.69	99.75	2	2
516431	48,000.1	81.57	99.83	99.51	81.57	99.83	99.51	0.00	100.00	100.00	1	0
516531	39,337.1	0.00	100.00	100.00	0.0	99.83	100.00	0.00	100.00	100.00	0	0
Total	251,846.3	94,109.70	62.63		81.57	99.97		94,028.12	62.66			

The annual diversion target of 36,025 acre-feet/year at Granbury Reservoir (515631) is distributed over the 12 months of the year in WRAP-SIM based on as set or 12 factors. Without the salinity constraint, the period and volume reliability are 100 %. However, the TDS concentration in Granbury Reservoir is 1,000 mg/l or less during only 31.37 percent of the 816 months. The volume reliability is 30.77 %.

8.4 Salinity Simulations with BRAC2008 Dataset (Simulation 4)

8.4.1 BRAC2008 Dataset

The BRAC8 input file with filename extension DAT was the only WRAP-SIM input file modified to create the BRAC2008 model. The BRAC8 file with filename extension FLO, EVA, and RUF were adopted for the BRAC2008 dataset without change. The WRAP-SALT input SIN file was adopted with the only change being a tightening on the limits placed on reservoir storage and outflow concentrations.

Water use in the BRAC8 input DAT file was modified as follows. The annual diversion amounts for the Brazos River Authority water right (WR record) were replaced with the quantities tabulated in Table 8.20. The diversion targets were placed at the control points shown in the table. Diversions located at a particular reservoir are treated as a lakeside diversion supplied by that reservoir. Diversions at non-reservoir control points are supplied by available streamflow supplemented as necessary by releases from reservoir located upstream.

Lake Waco is managed differently than the other BRA reservoirs. The Brazos River Authority holds a water supply storage contract with the U.S. Army Corps of Engineering for conservation pool in the federal Lake Waco, but the City of Waco holds the water right permit. The Lake Waco water supply storage is committed totally to supplying the City of Waco. Water use from Lake Waco is not included in the diversion listed in the Table 8.20. The Bwam8 and BRAC8 diversions at Lake Waco as well as water use from the non-BRA Hubbard Creek and Squaw Creek Reservoirs remain in the BRAC2008 DAT file without modification.

Proctor Reservoir is committed to lakeside diversions and downstream diversions above the Lake Belton which can not be supplied to by any other reservoir. The other ten BRA reservoirs are operated as a multiple-reservoir system to supply diversion demands at downstream control points.

Table 8.20 Water Supply Diversions by BRA Customers During 2008

Water Supply Diversion Location	Control Point	2008 Annual Diversion (acre-feet/year)				
		Industrial	Irrigation	Mining	Municipal	Total
Lake Possum Kingdom	515531	1,016	321	1,229	1,401	3,968
Brazos River at Palo Pinto gage	BRPP27	0	0	277	0	277
Brazos River at Dennis gage	BRDE29	0	112	2,045	0	2,157
Lake Granbury	515631	51,196	3,091	1,077	6,912	62,276
Brazos River at Glen Rose gage	BRGR30	0	103	1,001	0	1,103
Lake Whitney	515731	1,046	786	30	13	1,875
Lake Aquilla	515831	0	0	0	5,716	5,716
Brazos River at Waco gage	BRWA41	0	333	0	325	658
Brazos River at Highbank gage	BRHB42	0	1,977	0	0	1,977
Lake Proctor	515931	0	4,438	0	2,695	7,134
Leon River at Belton	LEBE49	0	204	0	6,268	6,472
Lake Belton	516031	0	0	0	43,212	43,212
Lake Stillhouse Hollow	516131	0	56	0	26,774	26,830
Lake Georgetown	516231	0	0	0	13,440	13,440
Lake Granger	516331	0	1	0	2,803	2,804
Little River at Little River gage	LRLR53	0	93	0	0	93
Confluence of San Gabriel & Little R.	CON108	2,606	0	8	0	2,614
Confluence of Little and Brazos Rivers	CON111	0	120	13	0	133
Lake Somerville	516431	0	0	0	3,499	3,499
Lake Limestone	516531	32,391	0	5	181	32,577
Navasota River at Easterly gage	NAEA66	3,665	0	0	0	3,665
Brazos River at Hempstead gage	BRHE68	35,938	30	0	0	35,968
Brazos River at Rosharon gage	BRRO72	0	232	0	0	232
Totals		127,858	11,897	5,685	113,239	258,680

Waco and Whitney Reservoirs are modeled as multiple owner reservoirs in the Bwam8 and BRAC8 DAT files but are simplified in the BRAC2008 DAT files by removing the multiple-component differentiation. The dual simulation feature connected to Waco and Whitney Reservoirs in the Bwam8 and BRAC8 DAT files is also deactivated.

The WRAP-SALT salinity input SIN file was adopted for the BRAC2008 model with the only modification being the minimum reservoir storage and maximum outflow concentrations entered on the CC limits were revised. The minimum storage concentration limit was set at 300 mg/l for Lakes Possum Kingdom, Granbury, and Whitney. The outflow concentration limit was set at 4,000 mg/l, 3,000 mg/l, and 2,000 mg/l for Lakes Possum Kingdom, Granbury, and Whitney, respectively.

8.4.2 Results of BRAC2008 Simulation

The volume and volume balance summary from the WRAP-SALT SMS file is shown in Table 8.21, Table 8.22, Table 8.23, Table 8.24 and Table 8.25 were created with TABLES from WRAP-SALT simulation results.

Table 8.21 Total Volume and Load Summary from SMS File for Simulation 4 (BRAC2008. 1940-2007)

Naturalized flows	278926528.	108170504.	285.2
Regulated flows at boundary	101629552.	99505560.	720.1
Return flows	1843957.	2691733.	1073.6
CI record constant inflows	0.	0.	0.0
Channel loss credits	5256028.	5420298.	758.5
Channel losses	245065.	255773.	767.6
Regulated flows at outlet	359092288.	175248864.	358.9
Diversions	14821904.	14983512.	743.5
Other flows and loads	-536204.	-789991.	1083.6
Net evaporation	14032627.	0.	0.0
Load losses from CP record CLI(cp)		26077196.	
	----------	----------	----------
Inflows - Outflows	387.	12741.	24241.8
	----------	----------	----------
Beginning reservoir storage	1872393.	2435549.	956.7
Ending reservoir storage	1872393.	2049735.	805.1
	----------	----------	----------
Change in storage	0.	-385814.	0.0
	----------	----------	----------
Volume and load differences	387.	398555.	758327.2
Negative inflows to cpts	5946.	303488.	37538.1
Negative incremental nat flows	50916092.		
Naturalized flows at outlet	390631424.		
Number of control points in SIM DAT and OUT files:		48	
Number of control points included in SALT simulation:		34	

The volume and load balance differences in Table 8.21 of 387 acre-feet and 398,555 tons are the additional amounts required for perfectly precise volume and load balances. There are the amounts by which the budgets do no balance and ideally should be zero. The volume difference of 387 acre-feet is small enough to be viewed as essentially zero. The load difference of 398,555 tons is 0.19 percent of the sum of the net naturalized flow inflow load of 108,170,504 tons plus regulated flow inflow load of 99,505,560 tons. Thus, the load difference is also reasonably minimal.

Table 8.22 Control Point Summary for Simulation 4 (BRAC2008, 1940-2007)

Control Point	Mean Monthly Volume (ac-ft)			Mean Monthly Load (tons)			Mean Concentration (mg/l)		
	Inflow	Outflow	Storage	Inflow	Outflow	Storage	Inflow	Outflow	Storage
LRCA58	0	105,396	0	0	36,685	0	0.0	256.0	0.0
BRSE11	0	19,151	0	0	85,258	0	0.0	3,274.0	0.0
421331	7,279	3,877	251,384	6,554	6,289	432,665	662.2	1,192.9	1,265.7
BRSB23	45,127	45,127	0	112,358	112,358	0	1,831.0	1,831.0	0.0
515531	55,818	51,415	546,844	122,539	123,022	1,207,620	1,614.4	1,759.6	1,624.0
515631	72,871	71,268	125,168	109,594	109,981	220,302	1,106.0	1,134.9	1,294.3
515731	97,165	94,282	305,855	113,072	113,220	407,180	855.8	883.1	979.0
515831	6,988	6,407	37,894	2,009	1,999	12,736	211.4	229.4	247.2
509431	33,829	32,785	59,093	9,907	9,914	20,368	215.4	222.4	253.5
BRBR59	312,446	312,446	0	181,375	181,375	0	426.9	426.9	0.0
516431	20,028	18,756	149,477	5,492	5,496	47,569	201.7	215.5	234.0
516531	19,940	18,104	189,172	5,586	5,585	59,910	206.0	226.9	232.9
BRHE68	423,567	423,567	0	213,243	213,243	0	370.2	370.2	0.0
BRRI70	462,008	462,008	0	225,097	225,097	0	358.3	358.3	0.0
BRGM73	440,070	440,070	0	215,082	215,163	0	359.4	359.6	0.0

No inflows are indicated for control point BRSE11 at the Seymour gage on the Brazos and LRCA58 at the Cameron gage on the Little River since these are upstream computational boundaries in the salinity tracking simulation model. The mean outflow concentration at BRSE11, LRCA58, and BRRI70 are 3,274 mg/l, 256 mg/l, and 358 mg/l, respectively. The 1940-2007 volume weighted storage concentration at Lakes Possum Kingdom, Granbury, and Whitney located at control points 515531, 515631, and 515731 are 1,624 mg/l, 1,294 mg/l, and 979 mg/l. The mean outflow concentrations at these reservoirs are 1,760 mg/l, 1,135 mg/l, and 883 mg/l.

Table 8.23 Concentration Frequency for Downstream Streamflows
(BRAC2008, 1940-2007)

Control Point	N	Mean	Standard Deviation	Percentage of Months with Concentration Equaling or Exceeding Values											
				100%	99%	98%	95%	90%	75%	60%	50%	40%	25%	10%	Max
LRCA58	816	256	0	256.0	256.0	256.0	256.0	256	256	256	256	256	256	256	256
BRSE11	816	6,363	3,529	0.0	0.0	1127.6	1,545.2	2,117	3,566	5,052	5,932	7,152	8,778	11,123	26,420
421331	816	1,350	496	584.6	622.1	653.9	696.7	793	1,002	1,114	1,208	1,331	1,753	2,073	3,205
BRSB23	816	3,530	2,553	435.7	728.1	893.6	1,128.8	1,382	1,888	2,475	3,016	3,467	4,445	6,144	31,252
515531	816	1,628	415	311.6	582.1	692.7	912.7	1,067	1,353	1,564	1,675	1,756	1,897	2,133	2,685
515631	816	1,275	579	0.0	0.0	70.3	357.1	627	912	1,128	1,230	1,358	1,528	1,992	3,000
515731	816	959	369	0.0	279.0	301.9	453.7	574	715	806	885	987	1,171	1,457	2,000
515831	816	253	105	0.0	8.4	13.8	113.9	146	192	214	232	256	322	406	587
509431	816	256	109	0.0	0.0	0.5	100.9	138	193	224	244	267	313	384	681
BRBR59	816	514	309	107.7	197.7	213.2	237.6	263	312	374	414	473	607	905	2,790
516431	816	236	62	43.2	87.6	138.6	159.6	173	198	214	225	239	260	319	450
516531	816	238	53	60.4	88.6	160.7	171.8	182	204	217	227	244	265	312	410
BRHE68	816	448	266	83.6	161.7	186.8	209.8	231	276	324	369	420	528	790	2,346
BRRI70	816	435	272	81.8	149.7	173.1	201.8	224	269	314	354	401	507	763	2,693
BRGM73	816	654,250	4,948,911	0.0	0.0	0.0	153.4	200	254	306	360	431	666	1815	72,352,808

Table 8.24 Concentration Frequency for Reservoir Storage for Simulation 4
(BRAC2008, 1940-2007)

Control Point	N	Mean	Standard Deviation	Percentage of Months with Concentration Equaling or Exceeding Values											
				100%	99%	98%	95%	90%	75%	60%	50%	40%	25%	10%	Max
421331	816	1350	495	584.6	622.1	653.9	696.7	793	1,008	1,114	1,208	1,332	1,753	2,073	3,205
515531	816	1627	416	311.6	582.1	692.7	912.7	1,067	1,353	1,563	1,675	1,756	1,897	2,133	2,685
515631	816	1305	640	0.0	116.9	191.8	380.0	631	915	1,135	1,239	1,365	1,541	1,994	5,322
515731	816	983	433	178.1	285.9	306.9	466.3	580	717	811	890	990	1,177	1,468	3,453
515831	816	253	106	0.0	8.4	13.8	113.9	146	192	214	232	257	323	407	587
509431	816	258	117	0.0	0.0	0.5	100.9	139	193	225	245	268	314	391	1178
516531	816	238	53	60.4	88.6	160.7	171.8	182	204	217	227	244	265	312	410
516431	816	235	70	0.0	83.7	116.4	158.2	173	198	214	224	235	259	314	838

Table 8.25 Reliabilities With and Without Salinity Constraints for Simulation 4 (BRAC2008, 1940-2007)

Control Point	Target Diversion (ac-ft/yr)	Both Quantity & Quality Reliability			Quantity Only Reliability			Quality Only Reliability			Number Months Concentration	
		Shortage (ac-ft/yr)	Volume (%)	Period (%)	Shortage (ac-ft/yr)	Volume (%)	Period (%)	Shortage (ac-ft/yr)	Volume (%)	Period (%)	Zero	Exceeds Limit
421331	9,923.5	7,450.87	24.92	24.75	0.00	100.00	100.00	7,450.87	24.92	24.75	0	614
515531	3,967.0	3,678.94	7.26	7.23	0.00	100.00	100.00	3,678.94	7.26	7.23	0	757
BRPP27	277.0	249.15	10.07	10.05	0.00	100.00	100.00	249.15	10.07	10.05	2	734
BRDE29	2,157.0	1,444.63	33.03	33.21	0.00	100.00	100.00	1,444.63	33.03	33.21	10	545
515631	62,275.9	43,694.09	29.84	30.39	0.00	100.00	100.00	43,694.09	29.84	30.39	14	568
BRGR30	1,104.0	662.46	39.99	40.44	0.00	100.00	100.00	662.46	39.99	40.44	26	486
409732	17,536.1	4,302.58	75.46	69.85	3918.74	77.65	71.32	927.39	94.71	94.73	103	43
515731	18,75.0	662.74	64.65	61.76	0.00	100.00	100.00	662.74	64.65	61.76	1	312
515831	57,16.0	0.00	100.00	100.00	0.00	100.00	100.00	0.00	100.00	100.00	2	0
509431	38,348.0	0.00	100.00	100.00	0.00	100.00	100.00	0.00	100.00	100.00	17	0
BRWA41	658.0	168.55	74.38	76.10	0.00	100.00	100.00	168.55	74.38	76.10	3	195
BRHB42	19,77.0	436.71	77.91	82.35	0.00	100.00	100.00	436.71	77.91	82.35	0	144
CON111	133.0	14.63	89.00	92.16	0.00	100.00	100.00	14.63	89.00	92.16	0	64
516431	3,499.0	0.00	100.00	100.00	0.00	100.00	100.00	0.00	100.00	100.00	0	0
516531	32,572.0	0.00	100.00	100.00	0.00	100.00	100.00	0.00	100.00	100.00	0	0
NAEA66	3,665.0	2.21	99.94	99.88	0.00	100.00	100.00	2.21	99.94	99.88	0	1
BRHE68	35,968.0	1,742.40	95.16	95.34	0.00	100.00	100.00	1,742.40	95.16	95.34	0	38
BRRO72	232.0	29.50	87.29	92.03	0.00	100.00	100.00	29.50	87.29	92.03	1	65
Total	221,883.5	64,539.45	70.91		3,918.74	98.23		61,164.27	72.43			

Diversion targets totaling 221,883.5 acre-feet/year are assigned to 18control points as indicated in Table 8.25. The 14 control points located upstream of BRSE11 and LRCA58 are not included in the WRAP-SALT salinity tracking computations and thus are not included in Table 8.25.Several of the BRA diversion listed in Table 8.20 are located in the Little River Basin above control point LRCA58 and thus not included in the WRAP-SALT simulation.

The reliability table of Table 8.25 reflects a specified maximum concentration limit of 1,000 mg/l. Volume and period reliabilities are computed based on supplying diversion targets only if the TDS concentration at the diversion location in a given month is at or below the limit of 1,000 mg/l. Thus, the period reliabilities of Table 8.25 are a count of the percentage of the 816 months of the simulation for which the TDS concentrations at the locations of the diversion targets did not exceed 1,000 mg/l.

The annual diversion target of 35,968 acre-feet/year at control point BRHE68 is distributed over the 12 months of the year in WRAP-SIM based on a set or 12 factors. The monthly diversions are supplied by streamflow at control point BRHE68 which is partially controlled by release from ten BRA reservoirs located upstream. Without the salinity constraint, the period and volume reliability for the 35,968 acre-feet/year demand are 100.0%. However, the TDS concentration at control point BRHE68 is 1,000 mg/l or less during only 95.34 percent of the 816 months, resulting in a period reliability of 95.34 percent shown in Table 8.25.

8.5 Multiple-Reservoir System Operation (Simulations 5 through 9)

Much of the salt in the Brazos River is from relatively small sub-watershed salt source areas located above the Seymour gage. The salt concentration of the Brazos River decreases in a downstream direction with low-salinity tributary inflows from Aquilla Creek, Bosque River, Little River, Navasota River, Yequa Creek, and other tributaries. The Little River Sub-Basin is the largest of the low-salinity tributary water sources. The dramatic differences in salt concentrations in the three main-stem upper Brazos River reservoirs versus the reservoirs located on tributary stream suggest the possibility of multiple-reservoir operating plans designed to lower salt concentrations in the lower Brazos River. Multiple-reservoir system operating plans may alter the blending of water from the high salinity upper Brazos River and low-salinity tributaries. The WRAP modeling system is applied to explore the potential impacts of multiple-reservoir system operations on salinity concentrations.

8.5.1 Multiple-Reservoir System Operations

The 12 reservoirs owned and operated by U.S. Army Corps of Engineering and Brazos River Authority are listed in Table 8.26. The locations of the reservoirs are shown in Figure 3.2. Possum Kingdom, Granbury, and Limestone Reservoirs are owned and operated by the BRA. The other nine reservoirs are owned and operated by the Fort Worth District of the Corps of Engineers. The BRA has contracted for most of the water supply storage capacity of the nine federal reservoirs. The Corps of Engineers is responsible for flood control operations.

The conservation storage capacity of each of the reservoirs is shown in the last column of Table 8.26. The nine federal reservoirs also contain large flood control storage pools which are not included in the storage capacity shown in the table. Flood control operations are not included in the monthly computational time step WRAP-SIM/SALT model. The model is based on the premise that flood waters are stored and released within the same month.

Hydroelectric power plants are located at Possum Kingdom and Whitney Reservoirs. However, there are no priority water rights for generating hydroelectric energy. Energy is generated by passing spills and water released for downstream water supply diversions through the turbines. Hydropower operations are not included in the model.

Table 8.26 Reservoirs Operated by the Corps of Engineers and Brazos River Authority

Reservoir	Reservoir Identifier in Model	River	Control Point Identifier	Storage Capacity (acre-feet)
Possum Kingdom	POSDOM	Brazos River	515531	552,013
Granbury	GRNBRY	Brazos River	515631	132,821
Whitney	WHIT	Brazos River	515731	561,074
Aquilla	AQUILA	Aquilla Creek	515831	41,700
Belton	BELTON	Leon River	516031	432,978
Stillhouse Hollow	STLHSE	Lampases River	516131	224,279
Georgetown	GRGTWN	San Gabriel River	516231	36,980
Granger	GRNGER	San Gabriel River	516331	50,540
Limestone	LMSTNE	Navasota River	516531	208,017
Somerville	SMRVLE	Yequa Creek	516431	154,254
Proctor	PRCTOR	Leon River	515931	54,702
Waco	LKWACO	Bosque River	509431	206,562

The BRA holds water right permits for the 11 other reservoirs listed in Table 8.20. Lake Proctor is committed both in reality and in the model to supplying lakeside diversions and diversions from the Leon River above Lake Belton. The other ten reservoirs are operated as a multiple-reservoir system supplying diversions at downstream sites as well as lakeside diversions.

The BRA water supply diversions incorporated in the BRAC2008 model are listed in Table 8.20. The diversions are placed in the model at the control points listed in Table 8.20 and supplied by streamflows at the diversion site supplemented by releases from reservoirs located upstream as required. Those diversions from the Brazos River that can be supplied by releases from two or more upstream reservoirs are listed in Table 8.27. Other diversions from the Little River are also supplied from multiple upstream reservoirs. However, the modifications to reservoir operations in the alternative BRAC2008 simulations discussed here deal with the water supply diversions from the Brazos River listed in Table 8.27.

Table 8.27 Multiple-Reservoir System Diversions

Diversion Location	Control Point	Annual Diversion
		(ac-ft/yr)
Brazos River at Waco gage	BRWA41	658
Brazos River at Highbank gage	BRHB42	1,977
Confluence of Little and Brazos Rivers	CON111	133
Brazos River at Hempstead gage	BRHE68	35,968
Brazos River at Rosharon gage	BRRO72	232

In simulation 4 presented in the preceding section, multiple-reservoir system release decisions are based on balancing storage. In a given month, for a particular diversion requirement associated with releases from multiple upstream reservoirs, available unregulated streamflow at the diversion site is appropriated first. Reservoir releases are then made as needed. The storage contents expressed as a percentage of storage capacity of each of the multiple reservoirs are compared within WRAP-SIM. The diversion is supplied that month from the reservoir with the lowest storage contents expressed as a percentage of storage capacity.

Multiple-reservoir system operations in simulation 7 as well as simulation 4 are based on balancing storage. Multiple-reservoir operations in simulations 5, 6, 8, and 9 continue to be based on balancing storage depletions, with the following key exceptions. In simulation 5 and 6, the diversions listed in Table 8.27 are supplied from Possum Kingdom, Granbury, and Whitney Reservoirs. In simulation 8 and 9, the diversions requirements listed in Table 8.27 are met from the tributary reservoirs. These simulations represent the extremes of supplying diversions totally from the high-salinity upper Brazos River reservoirs versus the low-salinity tributary reservoirs.

During low-flow conditions, the choice of which reservoirs from which to make releases for diversion demands from the lower Brazos River will obviously impact salt concentrations of river flows as well as the diverted water. However, modifications in multiple-reservoir system operations were found to have little impact on the concentration statistics derived from the simulation model due the relatively small magnitude of the lower Brazos River diversion listed in Table 8.27. These diversions are supplied largely by unregulated streamflow supplemented by reservoir releases when needed. The reservoir releases were found to not greatly impact the simulated concentrations. Therefore, a large hypothetical diversion at control point BRRI70 (Richmond gage) was added to explore the effects on salinity of reservoir operations for an increased water supply demand.

Simulations 7, 8, and 9 include an additional municipal water supply diversion demand of 260,000 acre-feet/year at control point BRRI70 (Richmond gage). This hypothetic diversion was added simply to investigate the impacts on salinity of increasing the diversion. Without consideration of salinity constraints, the 260,000 acre-feet/year has volume and period reliabilities of 100 percent in all of the alternative simulations. For purpose of comparing relative magnitudes of water supply diversion, the total annual diversions associated with BRA water rights in each of the datasets are listed below:

Bwam3 and BRAC3 authorized use: 853,428 acre-feet/year

Bwam8 and BRAC8 current use: 446,008 acre-feet/year (Table 8.12)

BRAC2008 actual use during 2008: 258,680 acre-feet/year (Table 8.20)

Table 8.28 provides the descriptions of each simulation based on alternative multiple-reservoir system operations. All six simulations are based on the same WRAP-SALT input SIN file without any revisions. The only input file that changes is the WRAP-SIM DAT file. The only changes are:

- the specification of which reservoirs are operated to supply the diversion demands listed in Table 8.27
- the addition of a 260,000 acre-feet/year at control point BRRI70 in the DAT file for simulations 7, 8, and 9.

Table 8.28 Alternative Simulations for Multiple-Reservoir System Operations

Simulation	Multiple-Reservoir System Operation	
	Maximizing Releases	Minimizing Releases
5	Possum Kingdom, Granbury, Whitney Reservoirs	Tributary Reservoirs
6	Tributary Reservoirs	Possum Kingdom, Granbury, Whitney Reservoirs
7	Simulation 4 + diversion of 260,000 acre-feet/year at BRRI70	
8	Simulation 5 + diversion of 260,000 acre-feet/year at BRRI70	
9	Simulation 6 + diversion of 260,000 acre-feet/year at BRRI70	

8.5.2 Results of Simulations

Results for the six simulations are compared in Table 8.29 and Table 8.30. Volume-weighted mean concentrations, arithmetic average of the 816 concentrations, and concentrations that are equaled or exceeded during 90%, 75%, 50%, 25%, and 10% of the 816 months of the 1940-2007 hydrologic period-of-analysis are compared in Table 8.29 for storage concentrations in Lake Whitney and concentrations of streamflows at the Bryan, Hempstead, and Richmond gage.

The reliabilities for BRA diversions shown in Table 8.30 are for a maximum TDS concentration limit of 1,000 mg/l. the reliabilities for the diversions at control points BRHE58 and BRRI70 and most of the other diversions are 100% if salinity is not considered. Period and volume reliabilities for the 35,968 acre-feet/year diversion at control point BRHE58 (Hempstead gage) and the 260,000 acre-feet/year hypothetical added diversion at control point BRRI70 (Richmond gage) are presented in Table 8.30 for the six alternative simulations. Volume reliabilities for the aggregated totals of all the BRA diversions plus the 260,000 acre-feet/year hypothetical are also included in Table 8.30.

Simulations 4, 5, and 6 show little variation in concentrations with variations in multiple-reservoir system operating strategies. Simulations 5 and 6 represent opposite extremes of releasing only from the 7 tributary reservoirs versus releasing only form the 3 main-stem Brazos River reservoirs to supply the diversions listed in Table 8.27. The differences in the simulation results are minimal. The flows in the lower Brazos River are relatively large compared to the diversions of Table 8.27 most of the time. Reservoir releases for water supply diversions represent a relatively small portion of the river flow and load most of the time. However, the choice of reservoir from which to release may significantly affect downstream concentrations during low flow conditions.

Table 8.29 Concentration Statistics for Alternative Simulations

Simulation	4	5	6	7	8	9
Reservoirs	balanced	Brazos	Tributary	balanced	Brazos	tributary
Added Diversion	no	no	No	yes	yes	yes
	Storage Concentration (mg/l) of Whitney Reservoir (515731)					
Weighted Mean	979.0	979.7	980.9	1,021.4	961.3	991.3
Arithmetic Mean	983	984	985	1,042	973	996
90%	580	580	574	569	559	573
75%	717	720	722	717	727	719
50%	890	889	892	909	932	888
25%	1,177	1,178	1,175	1,170	1,172	1,183
10%	1,468	1,467	1,454	1,494	1,468	1,456
	Concentration (mg/l) at Bryan Gage (BRBR59)					
Weighted Mean	426.9	426.7	429.4	425.5	415.0	426.0
Arithmetic Mean	514	515	544	521	535	486
90%	263	262	262	258	258	262
75%	312	312	313	309	309	309
50%	414	415	410	413	436	397
25%	607	608	609	626	678	566
10%	905	903	897	929	1,003	833
	Concentration (mg/l) at Hempstead Gage (BRHE68)					
Weighted Mean	370.2	370.1	372.2	367.6	359.6	368.0
Arithmetic Mean	448	448	463	455	465	420
90%	231	231	230	228	229	230
75%	276	276	277	273	272	273
50%	369	370	369	372	384	351
25%	528	527	522	539	569	480
10%	790	787	786	810	847	671
	Concentration (mg/l) at Richmond Gage (BRRI70)					
Weighted Mean	358.3	358.1	360.1	356.0	348.6	356.4
Arithmetic Mean	435	435	447	440	448	410
90%	224	223	223	222	223	222
75%	269	269	268	265	264	264
50%	354	355	355	355	368	344
25%	507	507	506	518	547	467
10%	763	762	761	777	796	652

Table 8.30 Diversion Reliabilities for Limit of 1,000 mg/l

Simulation		4	5	6	7	8	9
Reservoirs		balanced	Brazos	tributary	balanced	Brazos	tributary
Added Diversion		no	no	no	yes	yes	yes
CP	Diversion (ac-ft/year)						
				Period Reliability (%)			
BRHE68	35,968	95.34	95.34	95.47	94.73	95.10	97.43
BRRI70	260,000	–	–	–	95.47	95.71	97.43
				Volume Reliability (%)			
BRHE58	35,968	95.16	95.16	95.34	94.61	95.01	97.25
BRRI70	260,000	–	–	–	94.86	94.94	97.13
Total	221,884	72.43	72.43	72.32	–	–	–
Total	481,883	–	–	–	84.25	84.49	85.86

The hypothetical 260,000 acre-feet/year diversion at the Richmond gage was added to test the impact of increasing water supply demands. With the increased diversion, concentrations in the lower Brazos River are significantly more sensitive to reservoir release choices. The differences in lower Brazos River concentrations between simulations 7, 8, and 9 are greatest for high concentrations which tend to be associated with low flows.

8.6 Natural Salt Pollution Control Impoundments (Simulation 10)

8.6.1 Salt Control Impoundments

During the 1960's-1970's, the Fort Worth District of the U.S. Army Corps of Engineers, in collaboration with other federal and non-federal agencies, investigated a variety of measures for dealing with natural salt pollution in the Brazos River Basin (USACE 1973 and 1983). These studies resulted in a proposal to construct a system of three brine impoundments which would be located at the sites shown in Figure 8.2. Wurbs et al (Wurbs et al. 1993) further investigated the effects of the implements on downstream salinity concentrations. The proposed salt control plan has not been implemented due to economic, financial, institutional, and environmental constraints. Simulation 10 consists of altering the BRAC2008 dataset to approximate the effects of a hypothetical implementation of this previously proposed salt impoundment plan.

The USACE (USACE 1973 and 1983) investigation included formulation and evaluation of an array of strategies for dealing with the salt problem. The final recommended plan consists of three impoundments: Croton Lake on Croton Creek, Dove Lake on slat Croton Creek, and Kiowa Peak Lake on North Croton Creek.

The proposed salt control dams would impound the runoff from their upstream watersheds. A connecting pipeline would be provided for transferring excess water from Croton and Dove Lakes to Kiowa Peak Lake. The impounded water will be partially lost over time due to evaporation, with the remaining brine being permanently stored in Kiowa Peak Lake. The dams would consist of earth-fill embankments with outlet structures for emergencies only. No outflows are planned during the project life (Wurbs et al. 1993).

Simulation 10 consists of modifying the BRAC2008 model to approximate the effects of implementing the proposed salt impoundments. The impoundments are modeled based on the premise that all flows and loads at gaging stations 3, 4, and 6 in

Figure 8.2 and Figure 3.2 are prevented from flowing into the Brazos River. The flows and loads at control point BRSE11 at the Seymour gage are reduced to represent removal of all flows and loads at stations 3, 4, and 6.

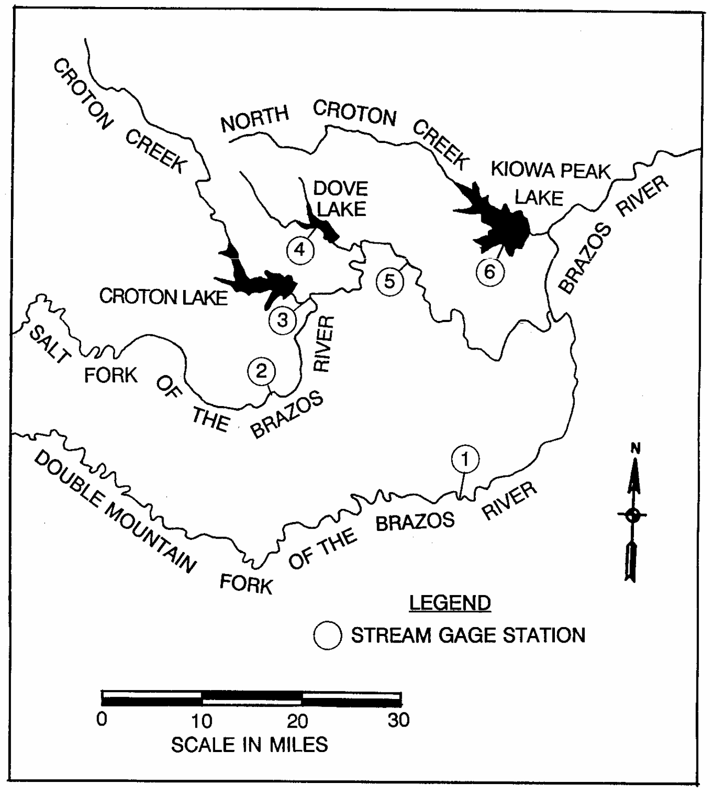

Figure 8.2 Gaging Stations and Proposed Impoundments in Upper Brazos River Basin

The compilation and analysis of the USGS/USACE salinity data reported by Wurbs et al (Wurbs et al. 1993) includes an investigation of the potential impacts of the salt control dams on salinity at downstream locations on the Brazos River. The data in Table 8.32 is reproduced from that study. The gage on Salt Croton Creek near

Aspermont (Figure 3.2 map number 4) has a period-of-record of 1969-1977. Other period-of-record are as follows.

Table 8.31 Period-of-Record of Selected Gaging Station for Simulation 10

Map Number	Gaging Station	Period-of-Record
3	Croton Creek at Jayton	1964-1986
4	Salt Croton Creek at Aspermont	1966-1977
6	North Croton Creek at Knox City	1966-1986
7	Brazos River at Seymour	1964-1986

Regression analyses were applied to the flows and load to develop complete water year 1964-1986 sequences at all stations. Table 8.32 includes means for water years 1966-1977 which contain only observed data and water years 1964-1986 which contains both observed and regressed data.

Table 8.32 Flows and Loads in the Upper Basin

USGS Gaging Station	Map Number	Mean Flow (cfs)	Mean Load (tons/day)	Mean Conc (mg/l)	Mean Flow (%)	Mean Load (%)
			October 1968 through September 1977			
Salt Fork of Brazos at Peacock	2	41	594	5,380	16.3	22.1
Croton Creek at Jayton	3	12	200	6,030	4.8	7.4
Salt Croton Creek at Aspermont	4	4	673	56,920	1.6	25.0
Salt Fork of Brazos at Aspermont	5	63	1,548	9,090	25.1	57.5
North Croton Creek at Knox City	6	11	163	5,400	4.4	6.2
Brazos River at Seymour	7	251	2,693	3,980	100.0	100.0
			October 1963 through September 1986			
Salt Fork of Brazos at Peacock	2	40	684	5,780	14.9	26.3
Croton Creek at Jayton	3	13	225	6,540	4.8	8.7
Salt Croton Creek at Aspermont	4	5	676	54,560	1.9	26.0
Salt Fork of Brazos at Aspermont	5	62	1,660	10,000	23.0	63.8
North Croton Creek at Knox City	6	17	211	4,720	6.3	8.1
Brazos River at Seymour	7	269	2,601	3,590	100.0	100.0

The mean flows and loads are expressed in the last two columns of Table 8.32 as a percentage of the means at the Seymour gage on the Brazos River. The percentages shown in Table 8.33 were adopted for the simulation study. The 1940-2007 monthly naturalized flow volumes in the WRAP-SIM BRAC2008 model at control point BRSE11 are reduced 12.7 percent. A water right is inserted in the DAT file with a diversion at control point BRSE11 computed as 12.7 percent of the flow at BRSE11. The 1940-2007 monthly salt loads in the WRAP-SALT BRAC2008 model at control point BRSE11 are reduced 41.9 percent using a multiplier factor of 0.582 entered on the *CP* record for BRSE11 in the SIN file.

Table 8.33 Flows and Loads at Impoundment Sites
as Percentage of Flows and Loads at the Seymour Gage

	Flow (%)	Load (%)
3 Croton Creek at Jayton	4.8%	8.7%
4 Salt Croton Creek at Aspermont	1.6%	25.0%
6 North Croton Creek at Knox City	6.3%	8.1%
Total	12.7%	41.8%

Much of the salt impounded by the salt control dams may be naturally loss anyway in its flow through the river system due to bank seepage and other losses. Channel losses are a key complexity addressed only approximately in modeling the salt control impoundments. In general, channel loss factors in the SIM input file and computations related to channel losses in both WRAP-SIM and WRAP-SALT are approximate involving significant uncertainties. These modeling uncertainties are magnified when adding the salt control impoundments to the model.

Losses of flow and load between the salt control dams and the Seymour gage (BRSE11) are not considered in the modeling strategy adopted. Also, as explained below, the salt load and concentration reductions due to the salt impoundments in the model at all locations on the Brazos River from the Seymour gage downstream to the Gulf of Mexico may be high due to only partially adjusting for the impacts of channel losses all along the river. Natural losses of load in the river may be greater than reflected in the model. This would mean that the salt control impoundments are less effective in reducing downstream concentrations then indicated by the model.

Control points CON036 and BRSE23 (South Bend gage) are located between control point BRSE11 (Seymour gage) and control point 515531 (Possum Kingdom Reservoir). Channel loss factors of 0.4146, 0.0100, and 0.179 are entered for control points BRSE11, CON036, and BRSB23. Channel loss factors for the other reaches of the Brazos River further downstream are relatively small.

Channel loss computations are included in the WRAP-SIM simulation. Channel losses are considered by SIM in the downstream propagation of the diversion at BRSE11 representing the 12.7% reduction of the flows at BRSE11.

Salinity load losses are addressed by two different features of WRAP-SALT as explained below. The first modeling feature connects load losses to WRAP-SIM channel losses and channel loss credits. The second feature for dealing with losses of salt load is an option that involves additional load losses that are not associated with volume losses.

WRAP-SALT assigns a concentration to channel losses and channel loss credits during each month of the salinity tracking simulation based on combining the channel loss/credit volumes from the SIM simulation results with concentrations approximated as the concentration of the regulated flows at upstream control points. Since the flow reduction is much less than the 41.8% load reduction at control point BRSE11, the effects of channel losses on the downstream propagation of the salt load reduction will probably be significantly underestimated by this modeling feature. On the other hand, flow volume losses conceivably could actually be greater than salt losses due to evaporation. In reality, salt losses may not necessarily be linearly proportional to volume losses as assumed in the model.

Another pertinent optional feature is activated in the Brazos SIN file. Loads entering Possum Kingdom, Granbury, and Whitney Reservoirs are reduced by 17.42%, 6.587%, and 3.00%, respectively, as described in Chapter VII. This feature also reduces the effects of the salt control impoundments in the downstream propagation of the load reductions.

8.6.2 Results of Simulation 10

The results of simulations 4 and 10 are compared in Table 8.34 and Table 8.35. Simulation 4 is based on the original BRAC2008 dataset. Simulation 10 uses the same BRAC2008 dataset with the only change being addition of the salt control impoundments. The reduction in the 1940-2007 means of simulated flow volumes and loads at five locations on the Brazos River due to the salt control impoundments are shown in Table 8.34 by comparing results from simulations 4 and 10. Figure 8.3 and Figure 8.4 represent the comparison of the results of the TDS concentration for each control point and three reservoirs from simulation 4 and 10. The reduction in TDS load at the Seymour gage due to the salt control impoundments is 35,638 tons/month, which is 41.80 percent of the load of 85,258 tons/month without the salt control impoundments. The reduction in TDS load at the Richmond gage due to the salt control impoundments is 23,346 tons/month. The load reduction at the Richmond gage is significantly less than the load reduction at the Seymour gage due to channel losses and additional losses of load in the three reservoirs.

Table 8.34 Mean Flow Volume and Load Without and With the Salt Dams (Simulation 4 and 10)

Gaging Station	Control Point	Mean Flow (acre-feet/month)				Mean Load (tons/month)			
		Sim 4	Sim 10	Loss	Loss	Sim 4	Sim 10	Loss	Loss
Seymour	BRSE11	19,151	17,386	1,765	9.22%	85,258	49,620	35,638	41.80%
South bend	BRSB23	45,127	44,171	956	2.12%	112,358	78,978	33,380	29.71%
Bryan	BRBR59	312,446	311,539	907	0.29%	181,375	158,077	23,298	12.85%
Hempstead	BRHE68	423,567	422,682	885	0.21%	213,243	189,973	23,270	10.91%
Richmond	BRRI70	462,008	461,144	864	0.19%	225,097	201,751	23,346	10.37%

Statistics for the concentration of the water stored in Lakes Possum Kingdom, Granbury, and Whitney are tabulated in Table 8.35. The volume-weighted mean concentration, arithmetic average the 816 concentrations, and concentrations that are equaled or exceeded during 90%, 75%, 50%, 25%, and 10% of the 816 months of the 1940-2007 hydrologic period-of-analysis are compared for simulation 10 versus 4.

Table 8.35 Comparison of Reservoir Storage Concentrations

Simulation	4	10
Mean Storage Concentrations (mg/l)		
Possum Kingdom Reservoir (515531)		
Weighted Mean	1,624.0	1,193
Arithmetic Mean	1,627	1,195
90%	1,067	813
75%	1,353	1,022
50%	1,675	1,210
25%	1,897	1,380
10%	2,133	1,540
Granbury Reservoir		
Weighted Mean	1,294.3	970.9
Arithmetic Mean	1,305	981
90%	631	516
75%	915	722
50%	1,239	938
25%	1,541	1,183
10%	1,994	1,468
Whitney Reservoir (515731)		
Weighted Mean	979.0	775.9
Arithmetic Mean	983	779
90%	580	458
75%	717	583
50%	890	715
25%	1,177	929
10%	1,468	1,106

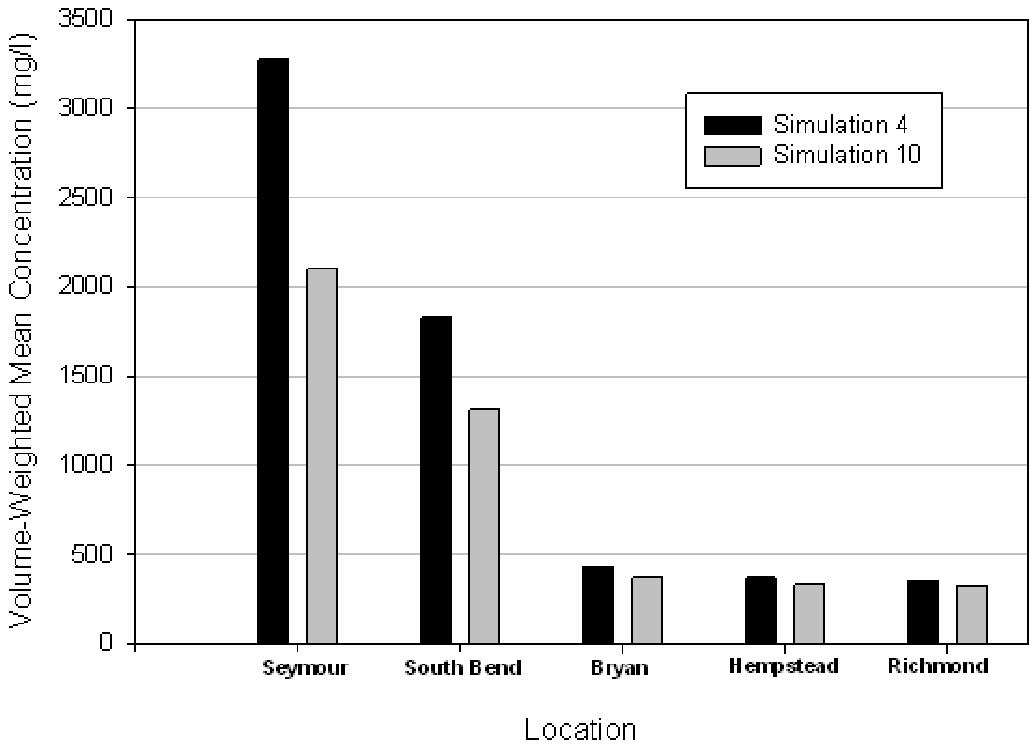

Figure 8.3 Comparison of the Results of Each Control Point from Simulation 4 and 10

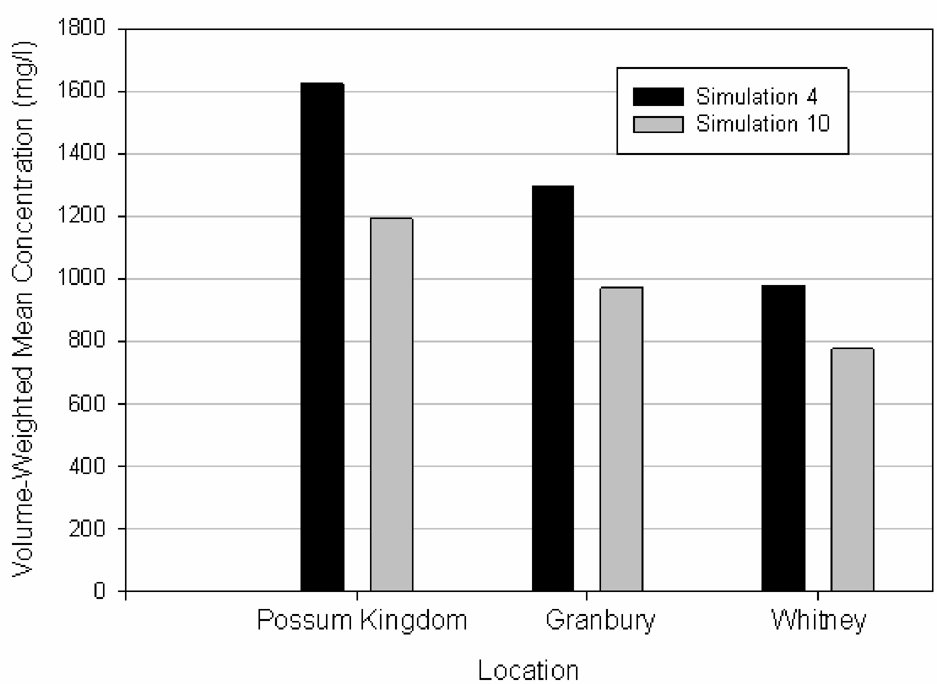

Figure 8.4 Comparison of the Results of Each Control Point from Simulation 4 and 10

A comparison of the results of simulations 4 and 10 indicate that the previously proposed salt control impoundments potentially could significantly reduce the salinity loads and concentrations in the three reservoirs and at all locations on the Brazos River from the impoundments downstream to the Gulf of Mexico. The results necessarily reflect all of the approximations and uncertainties inherent in the model including the previously discussed issue of inaccuracies in modeling natural losses of volume and load in river channels and reservoirs.

CHAPTER IX

SUMMARY AND CONCLUSIONS

This final chapter outlines the overall research investigation and summarizes each component. Conclusions and key observations are integrated in the summary discussions of each component of the research. The flow and storage volume budget and TDS load budget studies and related analyses presented in Chapters III, IV, and V represent a complete research investigation even without the WRAP simulation studies presented in Chapters VI, VII, and VIII. The primary motivation for the volume and load budget studies was the development of a database to support the Water Rights Analysis Package (WRAP) simulation studies. However, the analyses of observed and synthesized data reported in Chapters III, IV, and V also provide insight into the characteristics of flow and storage volumes and salinity loads and concentrations in the river/reservoir system independently of the WRAP modeling studies.

The simulation studies presented in Chapters VI, VII, and VIII consisted of testing, improving, and applying the salinity simulation capabilities of the WRAP modeling system using the Brazos River Basin dataset from the TCEQWAM System and variations thereof combined with the USGS salinity data. Methodologies for developing WRAP-SALT salinity input datasets were developed and applied. Alternative simulations for the Brazos River Basin were performed to analyze the effects of salt concentration constraints on the reliabilities of reservoir system operation and the effects of the reservoir operating systems on the salinity of the river system.

9.1 Natural Salt Pollution in the Brazos River Basin

Natural salt pollution originating from geologic formations in the Permian Basin geologic region in the High Plains of Texas, Oklahoma, New Mexico, and Kansas severely constrains the water supply capabilities of the Brazos River and other neighboring rivers. Salt springs and seeps and salt flats in the upper watersheds of the Brazos, Colorado, Pecos, Red, Canadian, and Arkansas Rivers contribute large salt loads to these rivers. The salinity limits the municipal, industrial, and agricultural use of water supplied by a number of large reservoirs located on these rivers.

Much of the salinity of the Brazos River originates from salt seeps and springs in sub-watersheds of the Salt Fork and Double Mountain Fork of the Brazos River some distance upstream of the USGS gage on the Brazos River near Seymour. Salt concentrations are extremely high on several of the small stream originating in these primary salt source sub-watersheds such as Croton Creek, Salt Croton Creek, North Croton Creek, and others. Salinity concentrations of the Brazos River decrease in a downstream direction with inflows from low-salinity tributaries such as Aquilla Creek, Bosque River, Little River, Navasota River, Yequa Creek, and other streams.

The Fort Worth District of the U.S. Army Corps of Engineers in collaboration with other agencies conducted extensive Brazos River Basin natural salt pollution control studies during the 1960's-1980's. The USGS conducted an extensive water quality data collection program from October 1963 through September 1986 in support of the USACE salt control studies. This research was performed based on these 1964-1986 data along with other additional data from the USGS and elsewhere. The USGS collected salinity data before 1964-1986 and has continued since then but not nearly as extensively as during the USACE-sponsored sampling program.

Mean flows and TDS loads and concentrations during water years 1964-1986 at eight gaging stations are shown in Table 4.8 expressed as a percentage of the amounts at the Whitney gage located downstream of Whitney Dam. Locations of the gages are shown in Figure 3.2. The Seymour gage on the Brazos River is located 405 miles upstream of the Whitney. The mean flow at the Seymour gage is 21.9 percent of the mean flow at the Whitney gage. However, the mean TDS load at the Seymour gage is 84.6 percent of the mean TDS load at the Whitney gage. The mean TDS concentration of the flow at the Seymour gage is 387 percent of the mean TDS concentration at the Whitney gage. Likewise, the mean flow at the Richmond gage 350 river miles below the Whitney gage is 558% of the mean flow at the Whitney gage. The mean TDS load and concentration at the Richmond gage are 204% and 37%, respectively, of the load and concentration at the Whitney gage.

Monthly volumes of river flows during the period October 1963 through September 1986 at six gaging stations are plotted in Figures 4.2 through 4.7. The corresponding TDS loads are plotted in Figures 4.8 through 4.13. The mean monthly TDS concentrations are shown in Figures 4.14–4.19. The monthly flows, loads, and concentrations fluctuate greatly during the 23-year period-of-analysis. The monthly flow volumes show tremendous variability including the extremes of floods and droughts. TDS loads fluctuate along with the flow volumes. The TDS concentrations also exhibit dramatic variability. The fluctuations in concentrations are dampened somewhat by reservoir storage at the gages located below the dams.

Though less variable than stream flow concentrations, storage concentrations also fluctuate over time and can vary greatly over short time periods of a few days or weeks. Salt concentrations can vary greatly with the timing and location of rainfall events causing floods as well as responding to longer periods of low-flows and prolonged droughts.

The example of major flooding causing a rapid decrease in salinity concentrations that is probably most noticeable in the plots occurred during the first week of August 1978 as a result of Tropical Storm Amelia. Much of the lower-salinity Hubbard Creek watershed located above Lake Possum Kingdom received 15 to 30 inches of rainfall during July 31 to August 5, 1978 while the primary salt source areas in the Salt Fork and Double Maintain Fork watersheds received relatively little rain. The mean monthly TDS concentration of the August 1978 flows at the South Bend gage just above Possum Kingdom Lake was 420 mg/l, compared to the 1964-1986 mean of 1,700 mg/l. The flood greatly lowered TDS concentrations through the river/reservoir system downstream of the South Bend gage as is evident from Figure 4.15. The USGS reported a significant impact of the flood on water quality in streams throughout central Texas.

9.2 Volume and Load Budget Studies

Water and salinity budget studies were performed for each of five sub-reaches of a 405 mile long reach of the Brazos River between the USGS stream gaging stations near Seymour and Whitney based primarily upon water year 1964-1986 USGS monthly flow volumes and TDS loads supplemented as needed by other observed or synthesized (computed) water quantity and quality data. The budgets consist of Microsoft Excel spreadsheets of 1963-1986 sequences of 276 monthly inflow, outflow, and storage volumes and the corresponding inflow, outflow, and storage TDS loads for each of the 5 reaches. The inflows and outflows are subdivided into components. Component inflow and outflow quantities and storage changes sum to zero as appropriate to balance the budgets. Some components such as monthly stream flow volumes and loads and end-of-month reservoir storage volumes are observed data, with only gaps in the records synthesized (computed) as part of the study. Other components such as end-of-month reservoir storage loads were computed in conjunction with the study since observed data are not available. Concentrations were computed by combining volumes and loads.

9.2.1 Components of the Volume and Load Budgets

The 1964-1986 mean flow and storage volumes and total dissolved solids (TDS) loads for the components of the volume and load budgets for the five river reaches are tabulated in Tables 4.4 and 4.5. The budgets include flow and load components defined as the quantities required to balancing the budgets. Thus, the component amounts sum to zero, balancing each budget. The concentrations determined by dividing the mean loads by the corresponding mean flow volumes are shown in Table 4.6. Reservoir storage volumes, loads, and volume-weighted mean concentrations are summarized in Table 4.7.

Most of the inflow and outflow for each reach is reflected in the river flows at the upstream and downstream gages defining the upper and lower ends of the reach. The 1964-1986 mean flow at the Glen Rose gage upstream of Lake Whitney and the Whitney gage downstream of Lake Whitney are 61,670 acre-feet/month and 74,193 acre-feet/month (Table 4.4). The mean TDS loads at the upstream and downstream ends of the Glen Rose to Whitney reach are 90,017 and 93,538 tons/month (Table 4.5). The corresponding concentrations are 1,073 mg/l and 927 mg/l (Table 4.6).

The naturalized flows from the TCEQ WAM System dataset are shown as the last two lines of Table 4.4 though not a part of the actual volume budget. Naturalized flows were developed for the WAM System by adjusting gaged flows to remove the effects of water resources development and use. Naturalized flows represent natural river basin conditions without reservoirs and human water use. A comparison of the actual river flows in the first two lines of Table 4.4 with the naturalized flows in the last two lines provides a measure of the reduction in flows due to reservoir storage and water supply diversions in the river system upstream of the gages.

The net reservoir water surface evaporation less precipitation for Lake Whitney is 3,603 acre-feet/month (Table 4.4). The volume in storage in Lake Whitney at the beginning of October 1963 was 332,300 ac-ft and at the end of September 1986 was

632,500 ac-ft (Table 4.7) resulting in a net increase in storage of 1,088 ac-ft/month (Table 4.4) when averaged over 276 months. The 1964-1986 mean storage volume of Lake Whitney of 475,928 acre-feet (Table 4.7) is equivalent to 6.4 months of outflow at the downstream mean flow rate of 74,193 acre-feet/month (Table 4.4). The Lake Whitney conservation pool storage capacity of 627,100 ac-ft (Table 3.2) is equivalent to 8.5 months of outflow at the rate of 74,193 acre-feet/month. The 570,240 acre-feet capacity of Possum Kingdom Lake is equivalent to 13.3 months of outflow at the mean rate of 42,998 acre-feet/month. The storage capacity of Granbury Lake is 2.5 months of its mean outflow.

Recorded water supply diversion data available for Lake Granbury indicate that diversions averaged 923 acre-feet/month over the 1964-1986 period-of-analysis. Concentrations of the water diverted each month were assumed equal to the storage concentration at the beginning of the month in the load budget calculations.

The other inflow volume (F_{OI}) and other outflow volume (F_{OO}) are monthly amounts required to balance the volume budget each month. The other flow volume differences are the summation of all other components of the volume budget and are positive in some months and negative in other months. This volume difference was assigned to the variable F_{OI} if positive in a particular month and F_{OO} if negative. Of course, the volume difference required to balance the volume budget in a particular month is probably the net of both other inflows and outflows. Thus, the procedure adopted here of assigning the monthly volume differences as being either totally inflow (F_{OI}) or totally outflow (F_{OO}) is an approximation. The other inflows (F_{OI}) may include rainfall runoff from the incremental watersheds, stream underflow not measured by the upstream gage, water supply diversions, and water supply return flows. The other outflows (F_{OO}) may be stream underflow not measured by the downstream gage, seepage from the river and reservoir into the ground, evapotranspiration not accounted for by the reservoir surface evaporation term, and water supply diversions. The other flows (F_{OI} and F_{OO}) terms may also reflect timing effects of flows passing through the reach and inaccuracies in the other components of the water budget.

The 1964-1986 means of the other inflow volume (F_{OI}) and other outflow volume (F_{OO}) for the Glen Rose to Whitney reach are 19,447 and 2,233 acre-feet/month, respectively (Table 4.4). The other inflow volume (F_{OI}) should consist largely of rainfall runoff from the local incremental watersheds draining to the reaches between their upstream and downstream gages. The mean other inflow volume (F_{OI}) of 19,447 acre-feet/month is equivalent to a depth of 3.2 inches (Table 4.9) for the 1,371 square mile incremental watershed, which is a reasonable rainfall runoff depth for this region. The other outflow volumes (F_{OO}) reflecting diversions and losses are a relatively small component of the volume budget.

For the three reaches containing Possum Kingdom, Granbury, and Whitney Reservoirs, the other inflow load (L_{OI}) was estimated by applying a concentration of 270 mg/l to the other inflow volume (F_{OI}). This concentration is representative of other similar watersheds in the vicinity for which salinity measurements are available. The other outflow load (L_{OO}) was estimated by applying the monthly concentration at the downstream gage each month. The 1964-1986 means of the other inflow load (L_{OI}) and other outflow load (L_{OO}) for the Glen Rose to Whitney reach are 7,139 and 3,103 tons/month (Table 4.5).

The other load (L_X) term is the additional load difference required to balance the load budget for the South Bend to Graford (Lake Possum Kingdom) and Glen Rose to Whitney (Lake Whitney) reaches. The 1964-1986 mean load difference was calculated by summing the 1964-1986 means of the other components and then distributing to the 276 individual months. Several alternative methods for allocating L_X to each month were investigated as discussed in Appendix B. The load balances are achieved automatically in the computational algorithms for the other two reaches. The other loads (L_X) required to balancing the load budgets for the South Bend to Graford and Glen Rose to Whitney reaches are additional outflows of 12,787 and inflows of 1,298 tons/month, respectively (Table 4.5). Ideally L_X should be zero. The L_X term represents inaccuracies in the other terms or additional loads not reflected in the other terms. There are no outflow volumes in the volume budget corresponding to the L_X load losses.

The salinity budget for Lake Whitney was further adjusted to match the volume-weighted storage concentration determined by the USGS based on lake water quality surveys performed at 30 points in time between September 1970 and May 1980. The adjustments involved changing the timing of load inflows and outflows as necessary to match the observed storage concentrations.

9.2.2 Reservoir Storage Volumes, Loads, and Concentrations

Observed storage volumes for Lakes Possum Kingdom, Granbury, and Whitney are plotted in Figures 4.20−4.22. The corresponding computed TDS loads in storage are plotted in Figures 4.23−4.25. Storage concentrations are plotted in Figures 4.26−4.28. Means are tabulated in Tables 4.7. The computed reservoir storage concentrations are volume-weighted mean end-of-month concentrations. Impoundment of water Lakes Possum Kingdom, Granbury, and Whitney began in 1941, 1970, and 1951, respectively. A sediment survey in 1974 indicated that the storage capacity of Possum Kingdom Lake had decreased significantly since initial impoundment in 1941. The storage volumes for October 1963 through September 1973 at Possum Kingdom Lake plotted in Figure 4.20 were adjusted in the volume budget calculations to partially correct the USGS data for sediment accumulation not otherwise reflected in the published data.

End-of-month storage loads and volume-weighted storage concentrations were computed for the three reservoirs. The computations for Lake Granbury are very different than for Lake Possum Kingdom and Lake Whitney due primarily to differences in data availability but also due to the smaller size and later construction of Lake Granbury.

Storage loads in Lakes Possum Kingdom and Whitney were computed for the end of each of the 276 months based on summing inflow and outflow loads for each month starting with the specified load shown in Table 4.7 in storage at the beginning of October 1963. The unknown concentrations of water stored in Lakes Possum Kingdom and Whitney at the beginning and the end of the October 1963 to September 1986 period-of-analysis were set based on the corresponding observed outflow concentrations. This is the storage concentration at the beginning of October 1963 and the end of September 1986. The October 1963 beginning concentration in Possum Kingdom Reservoir was set equal to the mean outflow concentration during the first 21 months beginning in October 1963. The first 21 months represent the retention period during which the outflows sum to approximately the storage volume at the beginning of October 1963. Likewise, the October 1963 beginning concentration in Whitney Reservoir was set equal to the mean outflow concentration during the first 11 months beginning in October 1963. The September 1986 storage concentrations of both reservoirs were set equal to the September 1986 outflow concentrations.

Volume-weighted mean dissolved solids concentrations of storage in Lake Whitney and Lake Granbury are available from USGS reports as follows. Water quality surveys of Lake Whitney were performed on 30 dates between 1970 and 1980. Measurements were made in Lake Granbury on 28 dates between 1970 and 1979. The 28 Lake Granbury measurement-based storage concentrations are plotted in Figure 4.30 along with the storage concentrations computed in the salinity budget analysis. The 30 measurement-based Whitney storage concentrations are plotted in Figure 4.29 along with the initial storage concentrations computed in the salinity budget analysis without the calibration adjustments.

9.3 Simulation Studies with the WRAP Modeling System

Chapters VI, VII, and VIII deal with the salinity simulation features of the Water Rights Analysis Package (WRAP) modeling system. Chapter VI presents an investigation of methods for routing salinity through reservoirs using a dataset derived from the volume and load analyses of Chapters III, IV, and V. Chapter VII documents the development of a salinity inflow dataset for the WRAP-SALT input file for the entire Brazos River Basin. Chapter VIII presents a WRAP-SIM and SALT simulation study assessing the interactions between water management and salinity.

9.3.1 Salinity Routing Parameter Calibration Studies

A WRAP-SIM and SALT input dataset was created based on the water and salinity budget data designed for the sole purpose of testing the salinity routing methods and calibrating the salinity routing parameters.

The dataset of Chapter VI for investigating computational methods and input parameters for routing salinity through reservoirs incorporates the volume and salinity budget results for six reaches of the Brazos River between the Seymour and Whitney gaging stations. These reaches contain Lakes Possum Kingdom, Granbury, and Whitney. The volume budget data are converted into a WRAP-SIM simulation results output file and WRAP-SALT salinity input file. The program SIM output file read by program SALT precisely reproduces the volume budget. All TDS load and flow volume inflows and outflows other than the flows in the river below the dams are aggregated together in the SIM output and salinity input files read by SALT. Thus, SALT computes volume-weighted storage loads and concentrations and the loads and concentrations of the river flows below the dams with all other variables fixed to perfectly match the results of the volume and load budget study. Computed storage and outflow concentrations from the WRAP-SALT simulation results can be compared with the measurement-based data from the salinity budget study.

The results of extensive calibration studies are presented in Chapter VI. The regression analyses and plots of Chapter V serve to explore the relationships between reservoir outflow and storage concentration for alternative lags. The analysis of the data in Chapter V is designed to complement the analyses of Chapter VI. Chapter V focuses on the lag time dimension of salinity routing.

The WRAP-SALT reservoir salinity routing procedure is based on Equations 6.1, 6.2, and 6.3 in Chapter VI and associated input parameters. There are two different aspects of salinity routing with one aspect represented by the lag options and the other represented by the factors F_1 and F_2 in Equation 6.2. The lag parameter and lag options control the timing (lag time) features of the WRAP-SALT algorithms for routing salinity through reservoirs. The parameters F_1 and F_2 address differences between the long-term levels of volume-weighted outflow concentrations versus volume-weighted storage concentrations reflecting losses or gains of salinity load in the reservoir.

The concept of lag time addresses the issue of the time required for entering salt loads to be transported through a large reservoir. Lag options have been extensively investigated in this study based on the initial premise that lag time is an important key consideration in salinity routing. However, this was found to not be the case for the two reservoirs analyzed. Lag times of zero or one month were found to be optimal for Possum Kingdom and Whitney Reservoirs. These reservoirs can probably be best simulated without activation of the lag options (zero lag). If the lag option is activated, the optimal lag is one month. A reasonable approach is to adopt the beginning-of-month option combined with zero lag.

Loss of salinity load in the reservoirs is another consideration. Load losses can be modeled in WRAP-SALT either by using the parameters F_1 and F_2 in the routing equation or alternatively by expressing losses as a specified fraction of inflow or storage loads. The approach of modeling load losses as a fraction of inflow loads was adopted in the simulation studies presented in Chapter VIII.

9.3.2 Salinity Inflows to the River System

Chapter VII documents the development of a salinity inflow dataset for the Brazos River Basin for incorporation into the WRAP-SALT input SIN file used in the simulation studies presented in Chapter VIII. The reservoir salinity routing specifications from Chapter VI discussed above are also included in SALT input file. However, most of the data in the SIN file is composed of loads or concentrations defining salt loads entering the river system. Formulation and application of methodologies for developing these salt inflow sequences are covered in Chapter VII.

The Water Rights Analysis Package (WRAP) computer program SALT reads a salinity input file with the filename extension SIN. The majority of the data contained in the SIN file consists of concentrations and/or loads that define the salinity inflows to the river/reservoir system. Time series sequences of loads or concentrations may be entered in the SIN file for each of the months of the simulation. Alternatively, constant mean concentrations may be input and repeated within the WRAP-SALT simulation for all months. The WRAP-SALT load or concentration input data are entered in the SIN file for specific control points representing locations in the river system. The load or concentration data entered for a particular control point may be repeated automatically within WRAP-SALT for any number of other control points.

A single SIN file was developed which is designed for use with the Brazos River Basin datasets from the Texas Commission on Environmental Quality (TCEQ) Water Availability Modeling (WAM) System or the Brazos River Authority Condensed (BRAC) datasets. Observed October 1963 through September 1986 total dissolved solids (TDS) loads and concentrations are extended based on TCEQ WAM System naturalized flows using the methodology outlined in Chapter VII to cover the period from January 1900 through December 2007.

The WRAP-SALT input data representing TDS loads entering the Brazos River and its tributaries represents actual 1964-1986 conditions with adjustments removing the effects of Lakes Possum Kingdom, Granbury, and Whitney. The volume and TDS load data used in developing the salinity dataset have been adjusted to remove the timing effects of storage in Lakes Possum Kingdom, Granbury, and Whitney. The volume budget also allows consideration of net reservoir evaporation less precipitation by which the three reservoirs affect volumes and concentrations but not loads. Loads and volumes of water supply diversions from Lake Granbury are also separated out. TCEQ WAM System naturalized flows reflect natural hydrology. The Brazos River Authority Condensed (BRAC8) dataset described in Chapter VIII includes stream flow inflows reflecting all water management and use in the Brazos River Basin except that associated with the BRA System.

The WRAP-SALT salinity input dataset maintains the load budget established in the load budget study for water years 1964-1986. The means for the 276-month 1964-1986 period will match between the WRAP-SALT input dataset and the load budget dataset. The loads entering the river system during the months of the 1900-1963 and 1987-2007 portions of the WRAP hydrologic simulation period-of-analysis are synthesized as a function of stream flow volumes and thus should not and do not exactly match the 1964-1986 mean loads.

A linear interpolation methodology for extending salinity data sequences was formulated and implemented in the new computer program SALIN. The 1964-1986 salinity data was extended to cover the entire 1900-2007 hydrologic period-of-analyses based on 1900-2007 sequences of monthly naturalized stream flow volumes from the TCEQ WAM System. Regression analysis was also explored. However, maintaining variability in the concentrations is important. The variability of the concentrations is lost with regression analysis. The linear interpolation method was found to work well in maintaining variability and the other characteristics of the loads and concentrations.

The WRAP-SALT simulation model performs salt load accounting computations that track the entering loads through the river/reservoir over time. Loads leave the river/reservoir system with the WRAP-SIM simulated diversions, channel losses, and regulated flows at the outlet. WRAP-SALT also has a feature for modeling additional otherwise unaccounted losses of load. For the Brazos River Basin, such additional losses are assigned to the control points of Possum Kingdom, Granbury, and Whitney Reservoirs. The losses each month are computed within WRAP-SALT as a specified fraction of the loads entering the reservoir. The input parameters in the WRAP-SALT salinity SIN input file are the percentages 17.42%, 6.59%, and 3.00% for Lakes Possum Kingdom, Granbury, and Whitney, respectively. WRAP-SALT computes losses by multiplying these percentages by the regulated inflow loads to the reservoir each month.

9.3.3 Simulation of the Brazos River/Reservoir System

Chapter VIII documents a salinity simulation study of the Brazos River Basin using the WRAP modeling system, variations of the TCEQ WAM System dataset for the Brazos River Basin, and the salinity dataset developed in this study. The simulation model provides capabilities for computing frequency statistics of salinity concentrations and water supply reliability indices for alternative scenarios of water management and use. The results of the following ten alternative simulations are presented in Chapter VIII.

Simulations 1 and 2 demonstrate that WRAP-SALT can be effectively applied with a complex TCEQ WAM System dataset for a large river basin. Simulations with 1900-2007 and 1940-2007 hydrologic periods-of-analysis yield similar results. Results for both simulations appear to be reasonable. The 1940-2007 simulation was adopted for the remaining simulations since the naturalized flows for 1900-1939 are based on fewer stream gaging stations than the later flows.

Simulation 3 confirms that the model works fine with a condensed dataset. The results for simulations 2 and 3 with the Bwam8 and BRAC8 dataset match closely.

Simulation 4 with the BRAC2008 dataset is designed to combine actual current water resources development, management, and use with historical 1940-2007 natural river basin hydrology. The discharge-weighted 1940-2007 mean regulated flow concentration at the Richmond gage on the lower Brazos River is 358 mg/l in the BRAC2008 simulation 4 as compared to a 1964-1986 mean of 339 mg/l for observed concentrations. The current conditions simulated concentrations are expected to be somewhat greater than the 1964-1986 observed concentrations due to increased water supply diversions from the low-salinity tributaries and increased reservoir surface evaporation with the construction of additional reservoirs during and after the 1964-1986 period of the USGS water quality sampling program. The 1940-2007 hydrologic period-of-analysis also includes the 1950-1957 drought. Simulation results show a significant increase in concentrations during the 1950-1957 drought and other extended periods of low flows.

Simulations 5, 6, 7, 8, and 9 were performed to explore the effects on salinity concentrations of multiple-reservoir system operations. The concentrations of water supply diversions and stream flows along the lower Brazos River should be dependent on whether reservoir releases for the downstream diversions are from the reservoirs on the low-salinity tributaries or Lakes Possum Kingdom, Granbury, and Whitney on the upper Brazos River. The BRAC2008 simulations indicated little difference in lower Brazos River salinity concentration statistics with different multiple-reservoir system operating strategies. Reservoir releases for lower basin water supply diversions are a relatively small portion of the flow of the lower Brazos River most of the time. The sensitivity of lower Brazos River concentrations to different multiple-reservoir system operating strategies was demonstrated in increase with a large increase in diversions from the lower Brazos.

The Corps of Engineers during the 1970's−1980's performed investigations of alternative measures for controlling natural salt pollution in the Brazos River Basin. Primary salt source areas were identified. The studies resulted in a recommendation to construct a system of three dams on small tributaries of the Salt Fork and Double Mountain Forks of the Brazos River to impound runoff from key salt source watersheds. The salt control plan was never implemented due to economic, financial, and other constraints.

Simulation 10 consists of adding the three salt control impoundments to the BRAC2008 model. The simulation is based on the premise that all flows and loads at gaging stations near the sites of the salt dams are permanently prevented from entering the Brazos River. Simulation results indicate that reductions in salt concentration could potentially be significant. Of course, simulation results always reflect the premises and approximations incorporated in the model. The question of natural loss of portions of the salt load even without the salt dams is pertinent. Model estimates of losses of salt load along the length of the river and in the reservoirs are uncertain. Without the system of three salt control impoundments, the estimated median storage concentration of Possum Kingdom Lake is 1,675 mg/l compared with an estimated 1,210 mg/l with the proposed salt control project. The median concentration of the flow at the Richmond gage is estimated to be 354 mg/l and 325 mg/l without and with construction of the proposed project.

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APPENDIX A

COMPARISON OF ALTERNATIVE METHODS FOR SYNTHESIZING SOUTH BEND LOADS

Various computational approaches and variations thereof were investigated during the development of the volume and load budgets for the fiver river reaches. The results presented in the preceding Chapter IV are based upon those premises and methods that were adopted as being most realistic.

The USGS salinity data includes loads for November 1978 through September 1981 at the South Bend gage. The method adopted to synthesized South Bend for the remainder of October 1963 through September 1986 period-of-analysis is presented in Chapter IV. Two other alternative methods are presented as follows for comparison.

1. Alternative Method 1

The loads for the missing portions of the 1964-1986 period-of-analysis were computed for the load budget by regression analyses as a function of South Bend flows and loads at the Seymour and Eliasville gages (Figure 3.2 map number 7 and 11). The 1964-1986 flow record at South Bend is complete. The 1964-1986 load record at Seymour is complete. Loads are available at Eliasville for September 1963 through September 1983.

Missing loads in the Eliasville load (L_{11}) record were synthesized by regression with flows at Eliasville. The South Bend loads (L_{12}) for September 1963 through November 1978 are computed as a function of South Bend flows (F_{12}) and the summation of Seymour loads (L_7) and Eliasville loads (L_{11}), as follows. The correlation coefficient (R) is 0.968. The subscripts represent the map numbers in Figure 3.2.

$$L_{12} = 15.10\, F_{12}^{0.5022}\, (L_{11} + L_7)^{0.3094}$$

2. Alternative Method 2

The second alternative method uses regression analyses as a function of incremental flow ($F_{incremental}$) and incremental loads ($L_{incremental}$). Incremental flows were determined for each month of the entire 1964-1986 period-of-analysis. Incremental loads were determined for each month of the period November 1977 through September 1981 for which loads are available for the South Bend as well as for the Seymour and Eliasville gages. Incremental flows and incremental loads were computed as follows. The correlation coefficients (R) are 0.86 and 0.83.

$$F_{incremental} = F_{South\ Bend} - F_{Eliasville} - F_{Seymour}$$

$$L_{incremental} = L_{South\ Bend} - L_{Eliasville} - L_{Seymour}$$

$$\text{If } F_{incremental} > 0 \qquad L_{incremental} = L_{OI} = 2.899\, F_{OI} + 151.79$$

$$\text{If } F_{incremental} < 0 \qquad L_{incremental} = L_{OO} = 8.791\, F_{OO}^{0.8478} + 151.79$$

The results of TDS load and TDS concentration from the adopted method described in Chapter IV and each of the two alternative methods are presented below in Table A.1. The October 1963 through September 1986 monthly TDS loads, and TDS concentrations of each alternative method are plotted in Figure A.1 through Figure A.4.

Table A.1 Comparison of Means for Upstream Reach

Gaging Station	Flow (ac-ft/month)	Load (tons/month)	Concentration (mg/l)
October 1963 − September 1986 (276 months)			
Seymour	16,215	79,127	3,589
Eliasville	17,720	18,918	785
South Bend (Adopted Method)		105,068	1,996
South Bend (Alternative Method 1)	38,712	89,395	1,698
South Bend (Alternative Method 2)		104,937	1,994
October 1963 − October 1977 (168 months)			
Seymour	15,508	86,325	4,094
Eliasville	13,747	17,233	922
South Bend (Adopted Method)		112,646	2,363
South Bend (Alternative Method 1)	35,055	89,182	1,871
South Bend (Alternative Method 2)		112,507	2,361
November 1977 − September 1981 (47 months)			
Seymour	12,117	51,351	3,117
Eliasville	22,869	17,194	553
South Bend	37,654	72,023	1,407
October 1981 − September 1986 (61 months)			
Seymour	21,416	80,611	2,768
Eliasville	24,877	25,014	740
South Bend (Adopted Method)		109.608	1,617
South Bend (Alternative Method 1)	49,843	103,690	1,530
South Bend (Alternative Method 2)		109,400	1,614

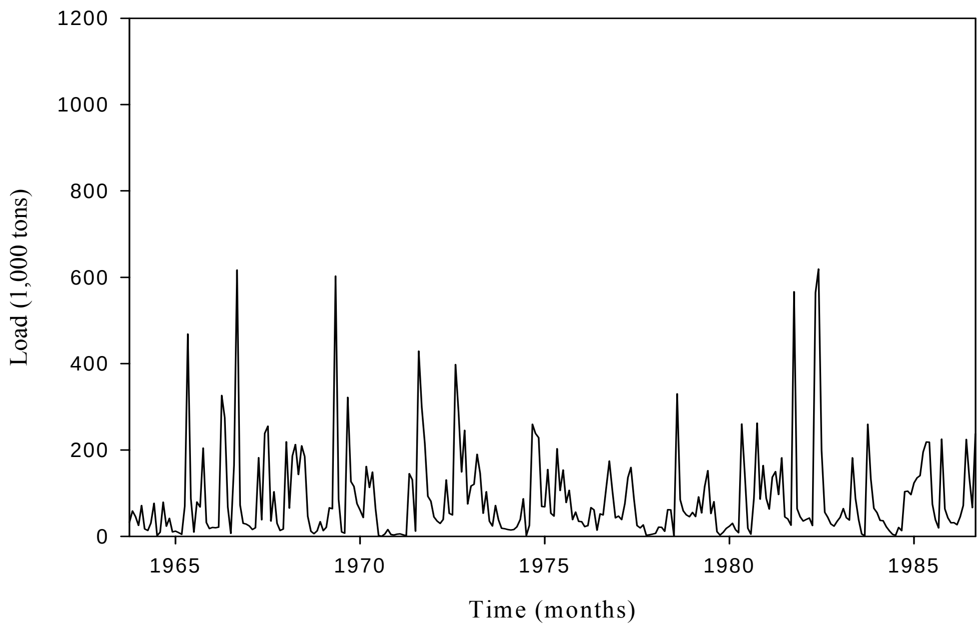


Figure A.1 Monthly TDS Loads at South Bend (Alternative Method 1)

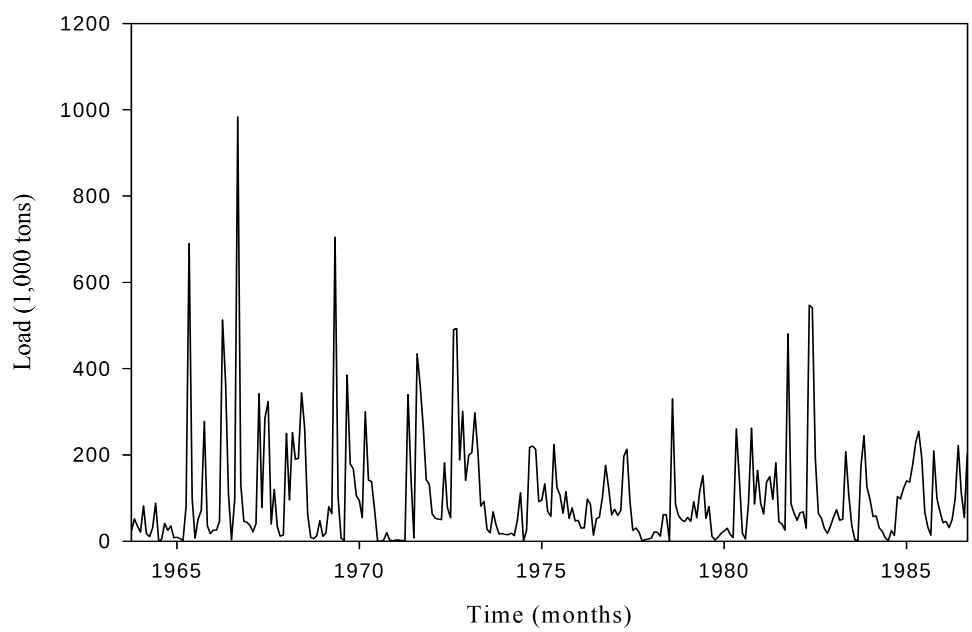


Figure A.2 Monthly TDS Loads at South Bend (Alternative Method 2)

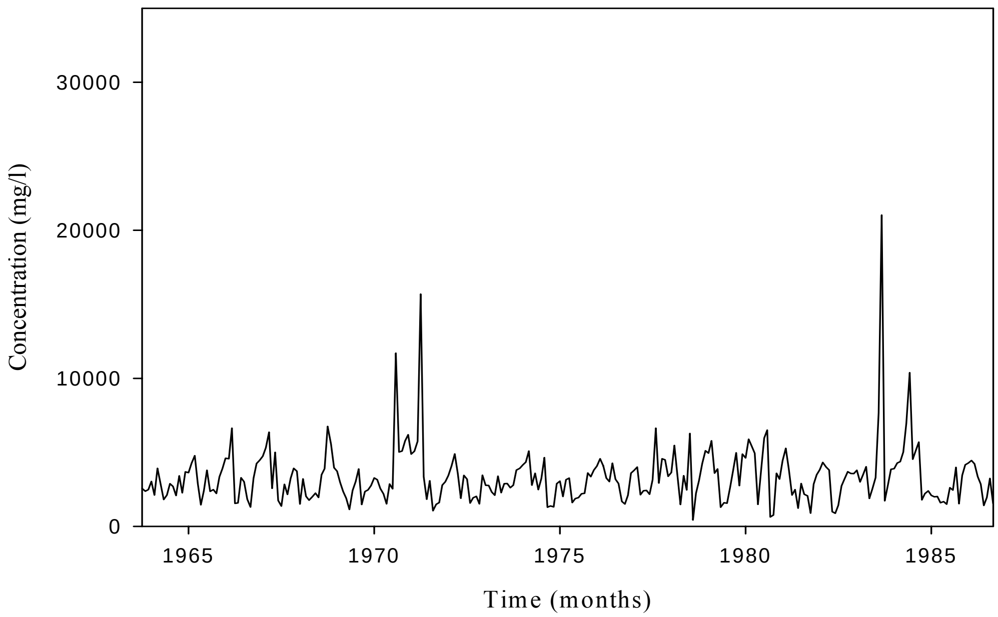


Figure A.3 TDS Load Concentrations at South Bend (Alternative Method 1)

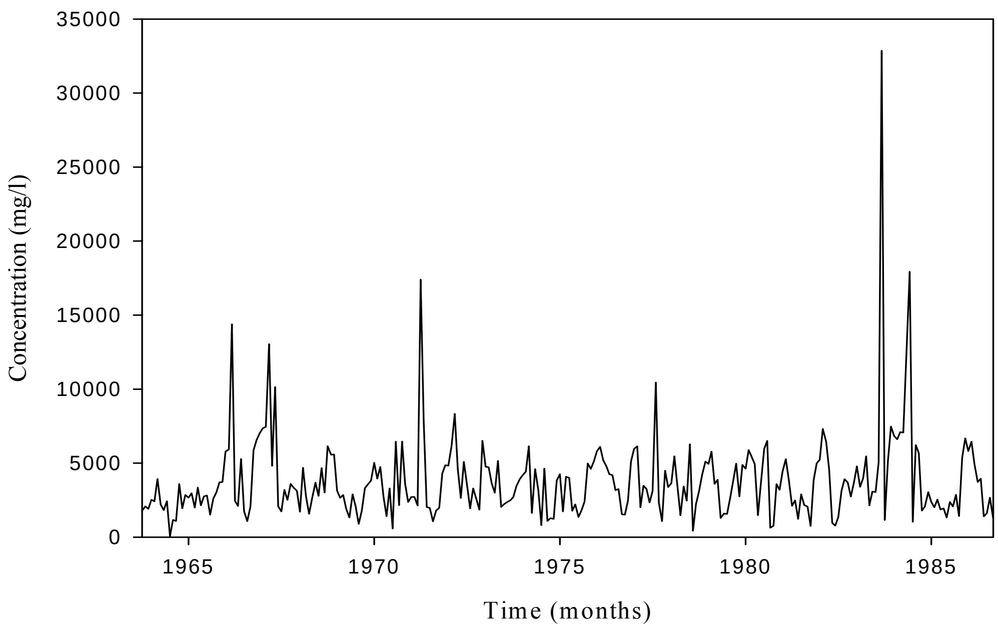


Figure A.4 TDS Load Concentrations at South Bend (Alternative Method 2)

APPENDIX B

ALTERNATIVE METHODS FOR DISTRIBUTING EXCESS LOAD FOR LAKE POSSUM KINGDOM AND WHITNEY

1. Alternative Methods for Distributing Excess Load for South Bend to Graford Reach

The other load L_X defined and computed in Chapter III is the load required to balance the long-term 1964-1986 load budget. Other loads (L_X) represent inaccuracies in the other budget terms. The other load term between South Bend gage and Graford gage is relatively large. Possum Kingdom reservoir storage loads results vary significantly depending of how the total 1964-1986 L_X is distributed to each individual month. Seven alternative methods for allocating are presented and compared as follows. Alternative method 5 was adopted.

Alternative method 1 is based on net inflow loads defined by the following equation.

$$\text{Net inflow load} = \text{Inflow load} - \text{Outflow load}$$

A positive net inflow load means storage load increase and a negative net inflow load represents storage load decreases. The other load L_X were distributed by the proportions to net inflow load during months with positive net inflow load and the proportions for each month were developed based on the following procedure.

$$\text{Proportions} = \frac{\text{Net inflow load at each month}}{\sum \text{Positive net inflow loads}}$$

$$L_X = \text{Proportions} \times \text{Positive Net Inflow Load at each month}$$

$$\text{If (Net inflow load)} = 0, \qquad L_X = 0.0$$

Unlike alternative method 1 which allocates L_X to each of 276 months of the October 1963 through September 1986 period-of-analysis, alternative method 2 through 7 distribute L_X during specific periods selected by turning points and peak points. These turning points and peak points were selected from the results of alternative method 1. Turning points represent the occurrence of significant changes during these period-of-analysis. Peak points were selected as the month with a maximum load value or maximum concentration. After determining the periods, L_X were allocated uniformly during selected periods. Method 5 considered the retention time. Retention time is a representation of the time required for a monthly volume of water and its salt load to flow through a reservoir. Possum Kingdom Reservoir retention time for the beginning storage volume of October 1963 was computed as 21 months. Table B.1 shows the volume-weighted storage load and concentration resulting from the alternative methods. Alternative method 5 was adopted as the method for developing load budget between South Bend Gage and Graford Gage after comparing and analyzing with the results of other alternative methods. Figure B.1 shows the different periods of alternative methods. The October 1963 through September 1986 monthly storage TDS loads at the Possum Kingdom Reservoir, the comparison of Possum Kingdom storage and outflow TDS concentration were plotted in Figure B.2 through Figure B.15.

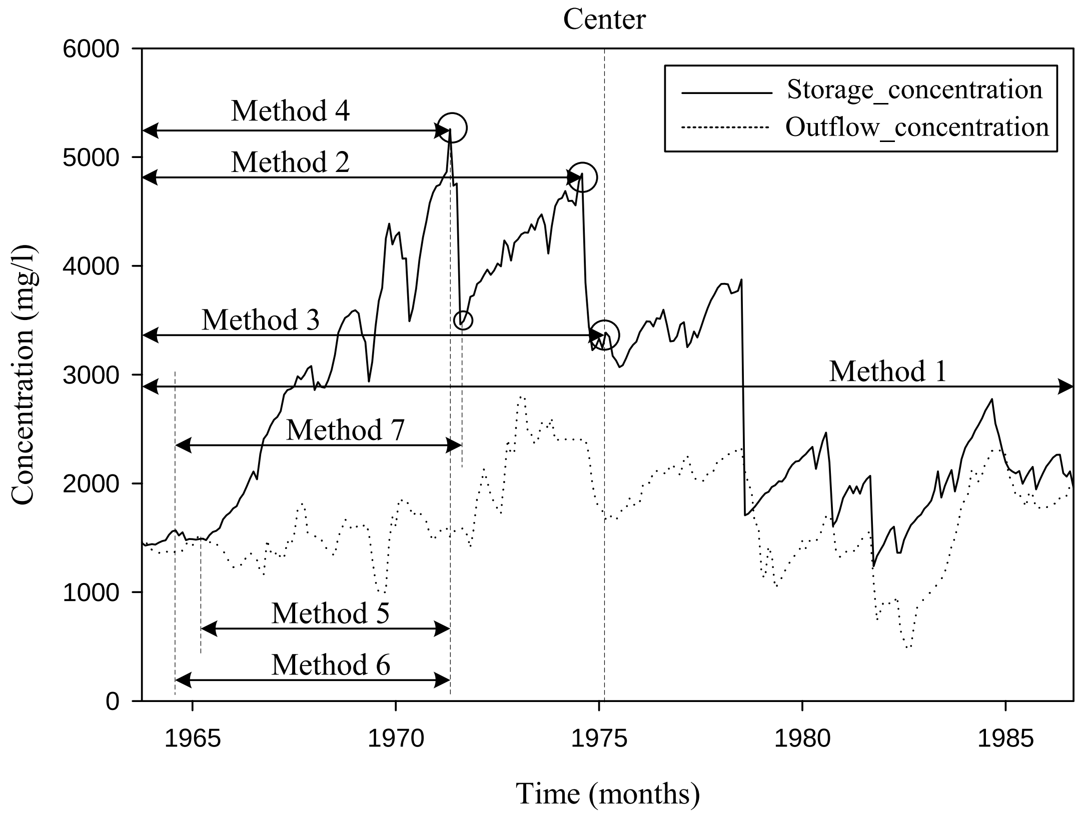


Figure B.1 The Periods for Distributing L_X Depended Upon the Alternative Methods

Table B.1 Comparison of Storage TDS Loads and TDS Concentrations

	276-month mean storage TDS load (tons)	276-month mean storage TDS concentration (mg/l)
Alternative Method 1	1,973,839	2,808
Alternative Method 2	1,264,164	1,798
Alternative Method 3	1,302,527	1,853
Alternative Method 4	1,008,415	1,435
Alternative Method 5	1,142,683	1,626
Alternative Method 6	1,078,746	1,535
Alternative Method 7	1,097,927	1,562

Figure B.2 Storage Loads in Possum Kingdom Reservoir (Method 1)

Figure B.3 Storage Loads in Possum Kingdom Reservoir (Method 2)

Figure B.4 Storage Loads in Possum Kingdom Reservoir (Method 3)

Figure B.5 Storage Loads in Possum Kingdom Reservoir (Method 4)

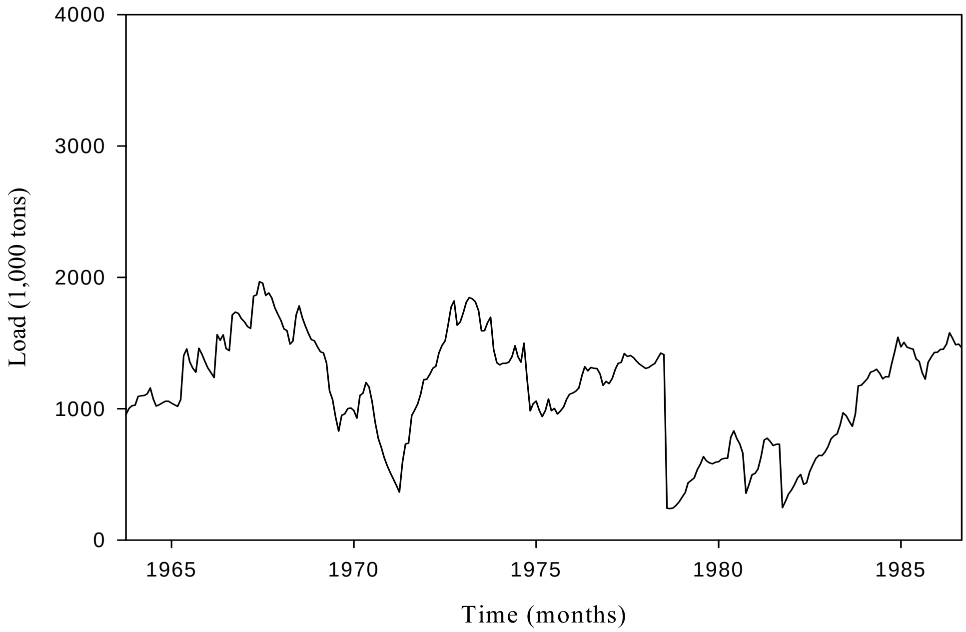


Figure B.6 Storage Loads in Possum Kingdom Reservoir (Method 5)

Figure B.7 Storage Loads in Possum Kingdom Reservoir (Method 6)

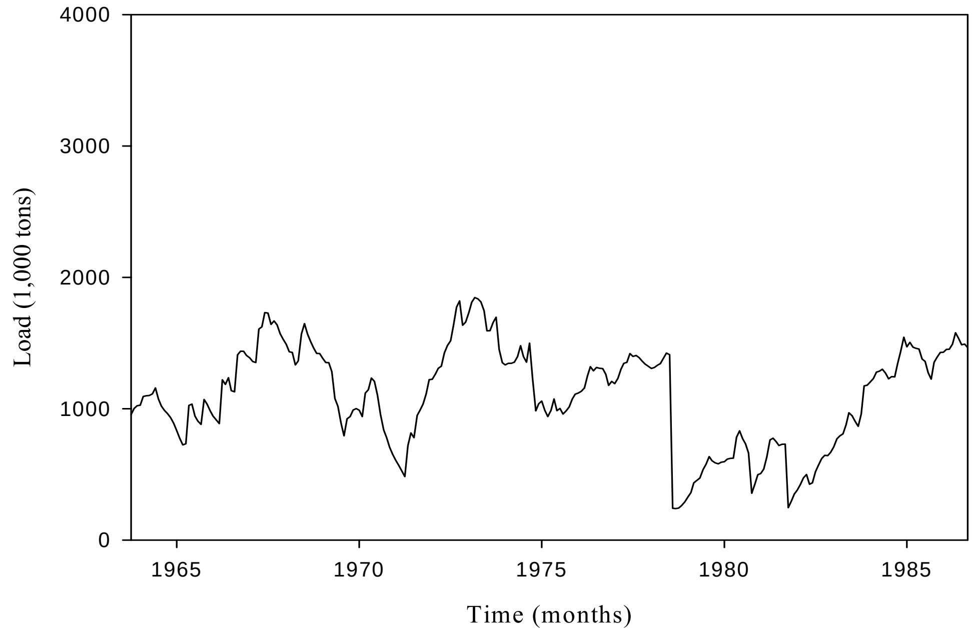


Figure B.8 Storage Loads in Possum Kingdom Reservoir (Method 7)

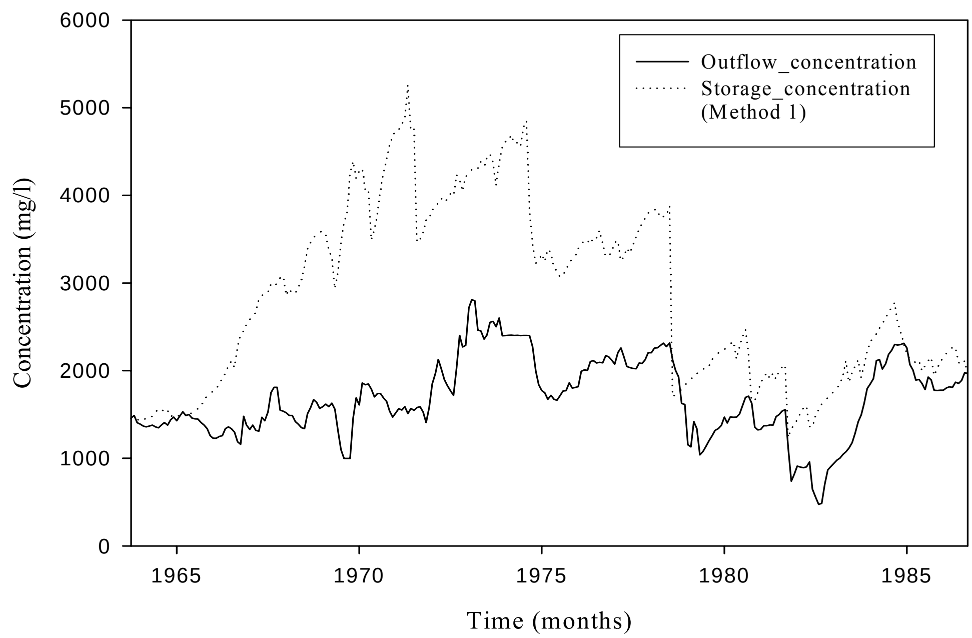


Figure B.9 Comparison of Possum Kingdom Storage and Outflow Concentrations (Method 1)

Figure B.10 Comparison of Possum Kingdom Storage and Outflow Concentrations (Method 2)

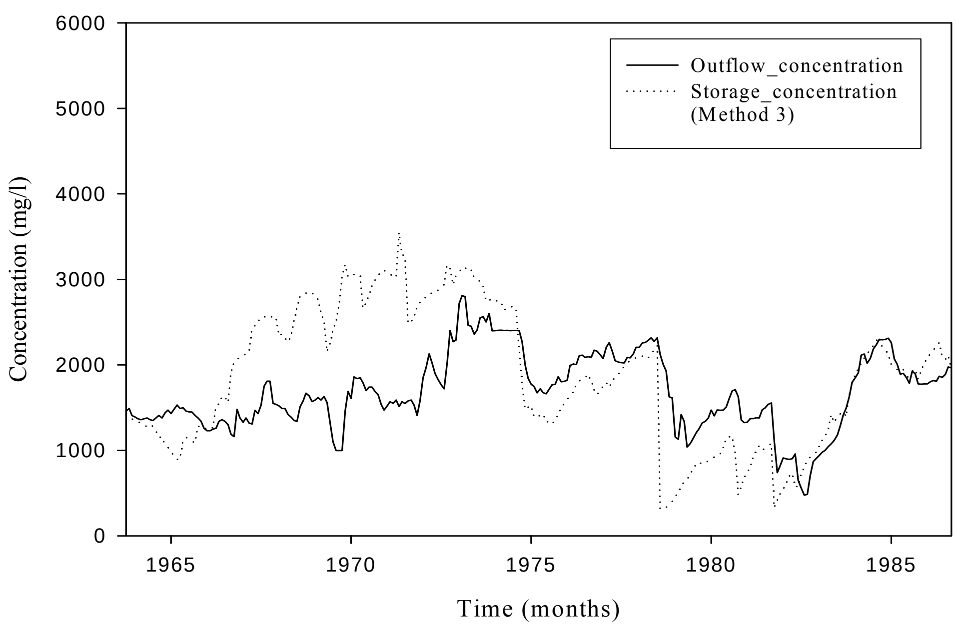


Figure B.11 Comparison of Possum Kingdom Storage and Outflow Concentrations (Method 3)

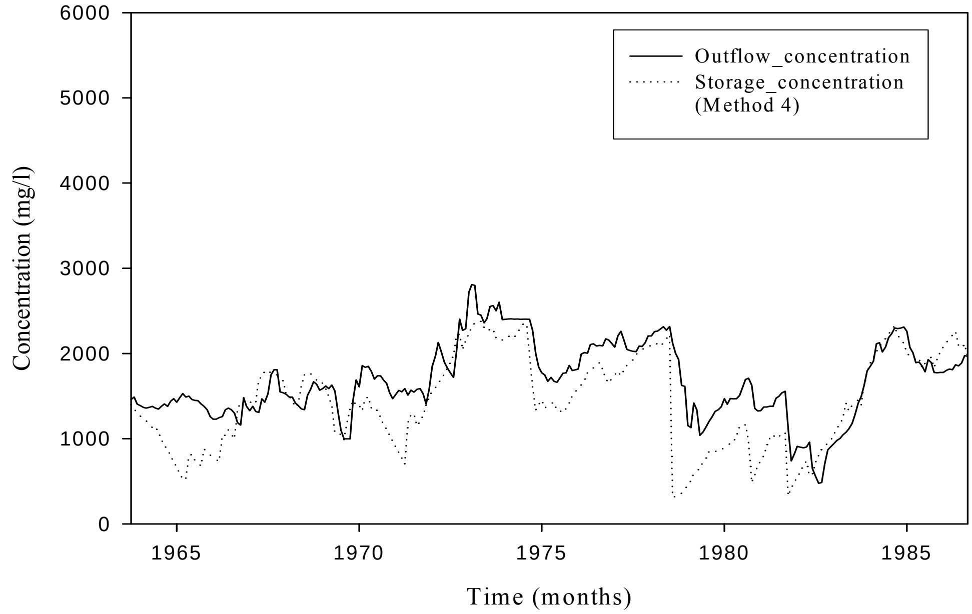


Figure B.12 Comparison of Possum Kingdom Storage and Outflow Concentrations (Method 4)

Figure B.13 Comparison of Possum Kingdom Storage and Outflow Concentrations (Method 5)

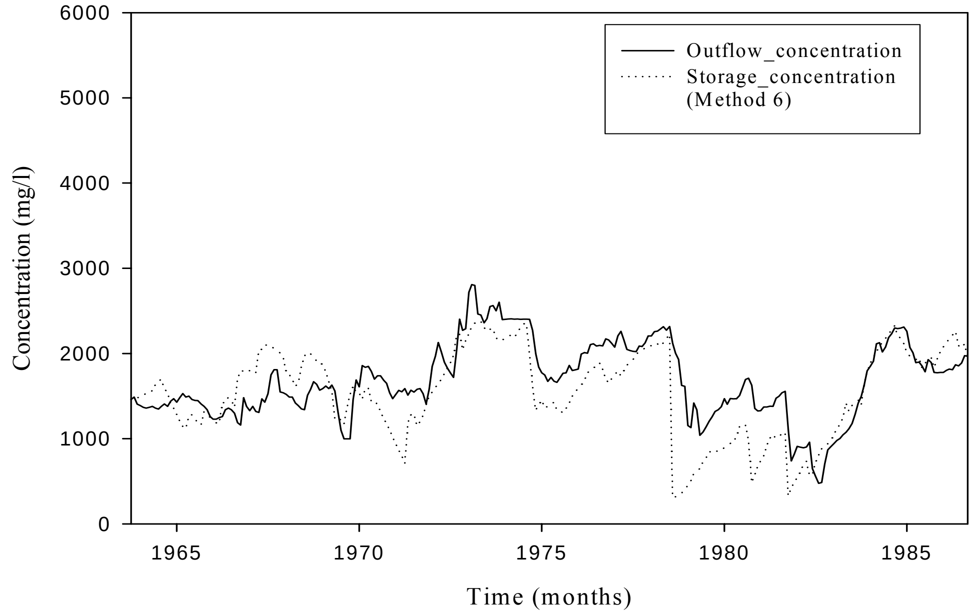


Figure B.14 Comparison of Possum Kingdom Storage and Outflow Concentrations (Method 6)

Figure B.15 Comparison of Possum Kingdom Storage and Outflow Concentrations (Method 7)

2. Alternative Methods for Distributing Excess Load for Glen Rose to Whitney Reach

The other loads L_X between Glen Rose and Whitney reach are 358,354 tons for the period from October 1963 through September 1986. Like the computation of Possum Kingdom Reservoir storage concentrations, the results of Whitney Reservoir storage concentrations also vary significantly depending on how L_X is distributed to each month.

Two alternative methods were examined and compared to compute Whitney Reservoir storage concentrations. Alternative method 1 for distributing L_X to each month is the same as the alternative method 1 for computing Possum Kingdom Reservoir storage concentrations. Alternative method 2 distributes L_X during selected periods. Figure B.16 represents the periods for allocating L_X to each month. Alternative method was adopted as the method for developing load budget between Glen Rose and Whitney reach. The 1964-1986 storage load, volume-weighted storage concentrations, and the period for each method are presented in Table B.2. Figure B.17 through B.20 represent storage loads of each method and the comparisons of Whitney storage and outflow concentrations from each method.

Table B.2 Period, Storage, TDS load and TDS concentration of each method

	276-month mean storage TDS load (tons)	276-month mean storage TDS concentration (mg/l)	Period
Alternative Method 1	836,316	1,292	Oct 1963 – Sep1986
Alternative Method 2	717,722	1,109	May 1979 – Sep1986

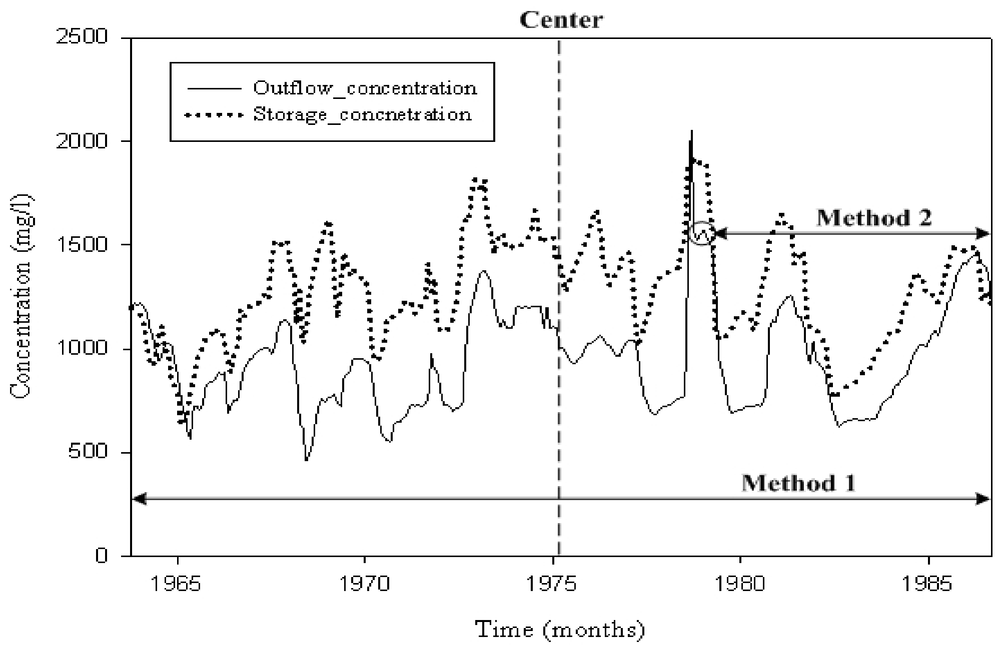


Figure B.16 Periods for Distributing L_X Depended Upon the Alternative Methods

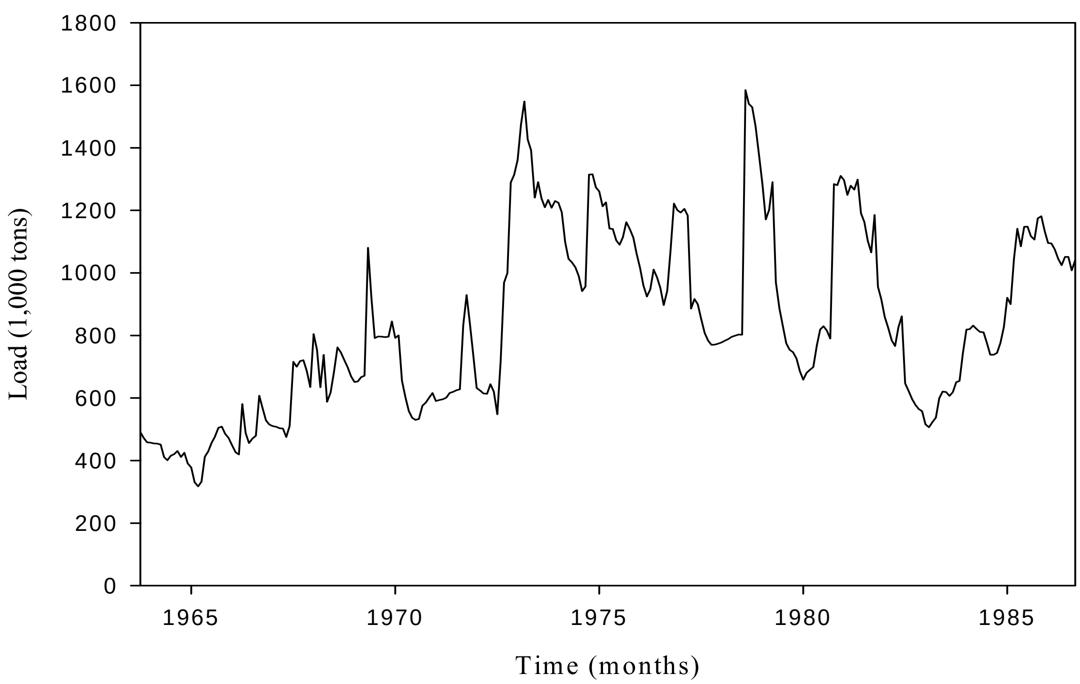


Figure B.17 Storage Loads in Whitney Reservoir (Method 1)

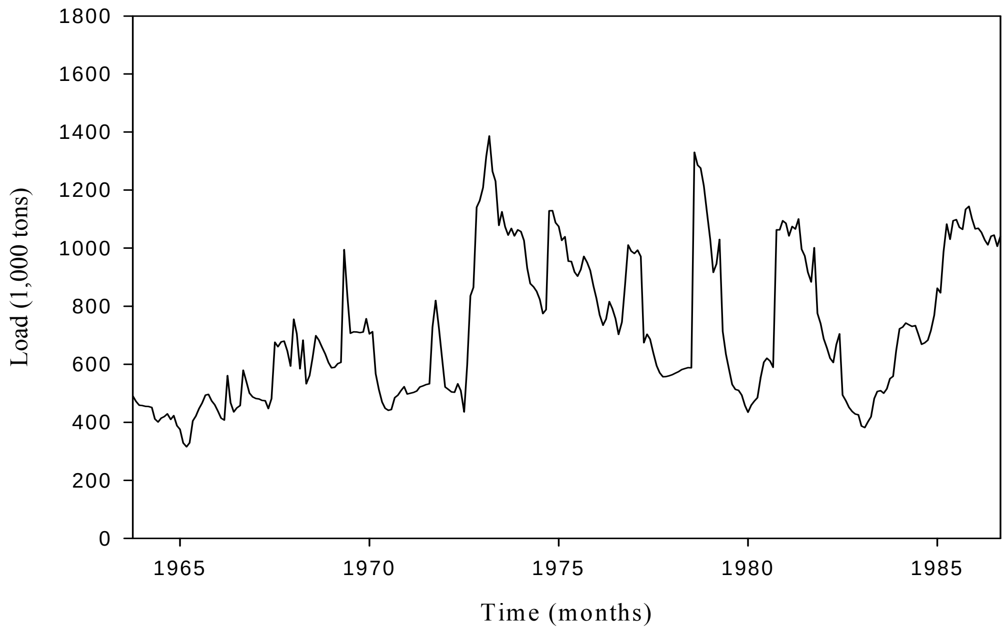


Figure B.18 Storage Loads in Whitney Reservoir (Method 2)

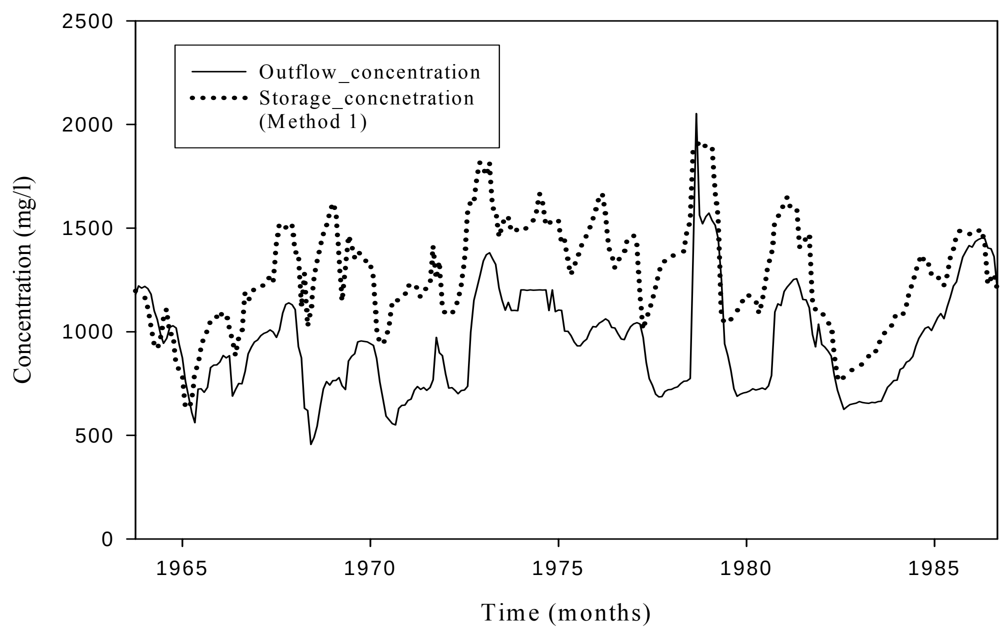


Figure B.19 Comparison of Whitney Storage and Outflow Concentrations (Method 1)

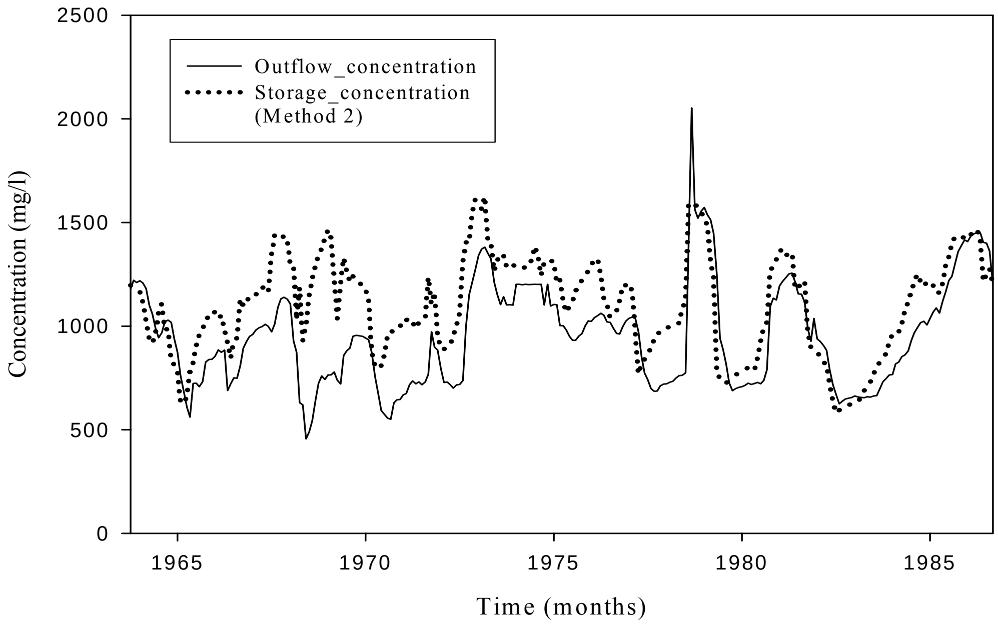
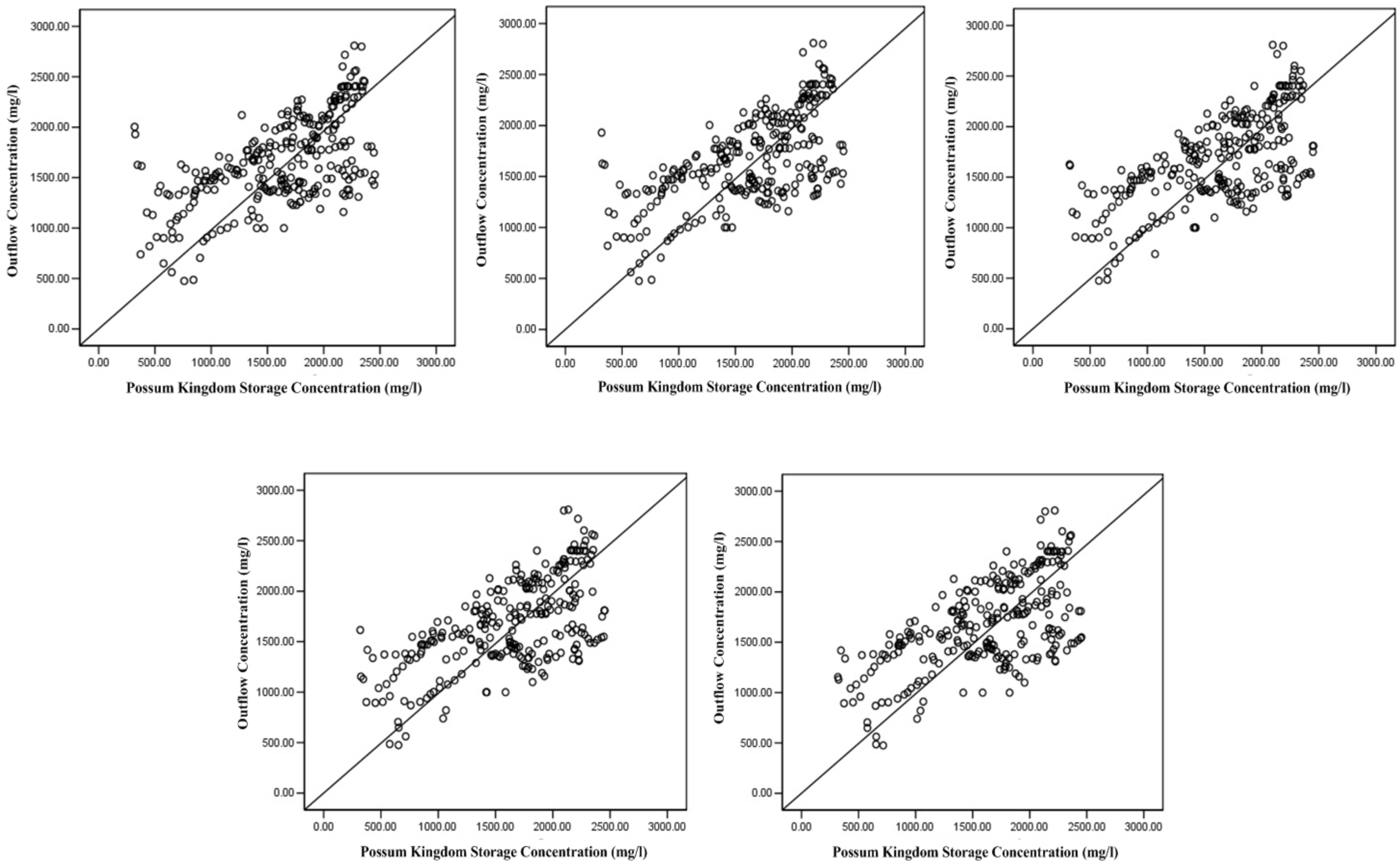


Figure B.20 Comparison of Whitney Storage and Outflow Concentrations (Method 2)

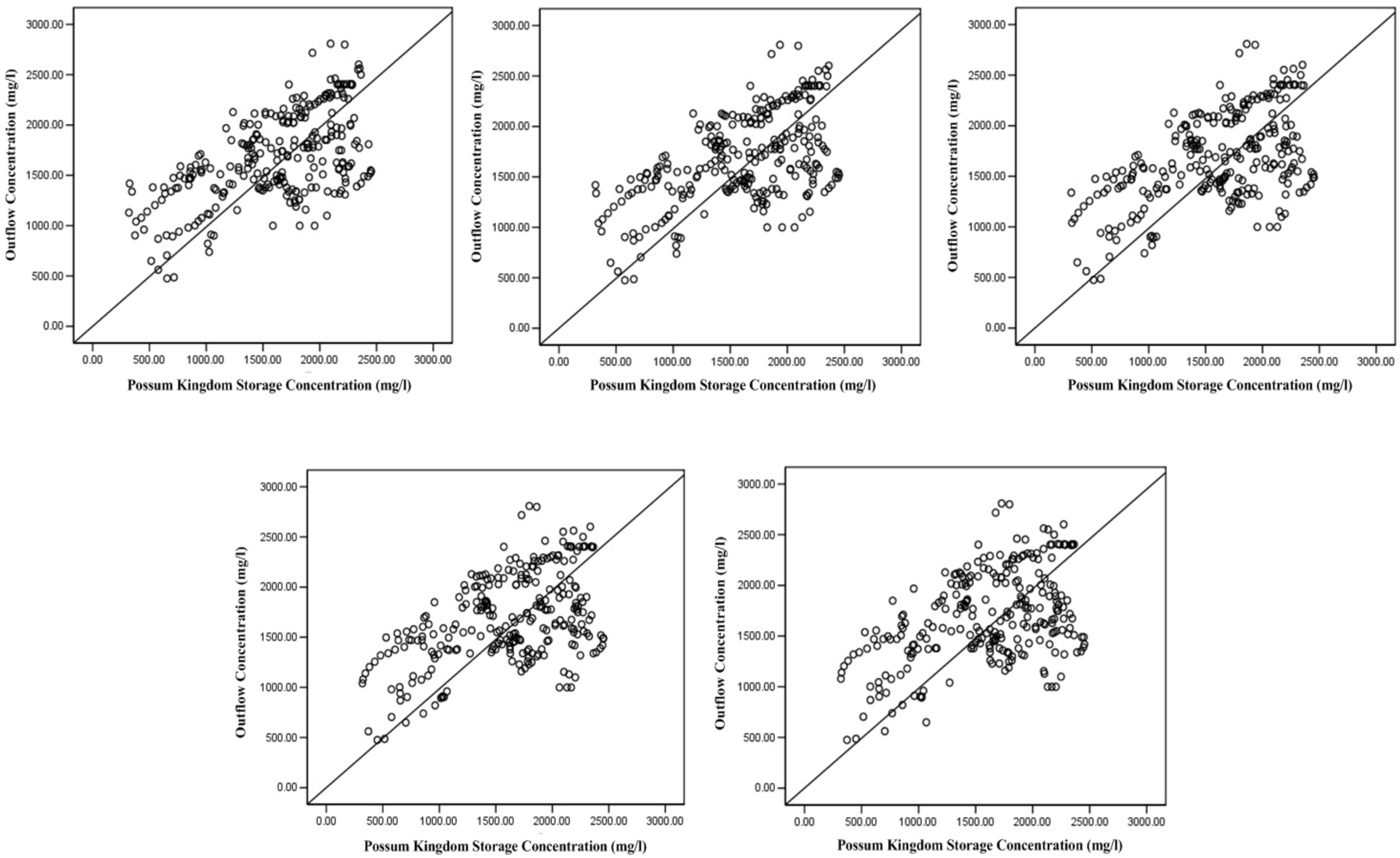
APPENDIX C

PLOTS OF REGRESSION ANALYSES RESULTS IN CHAPTER V

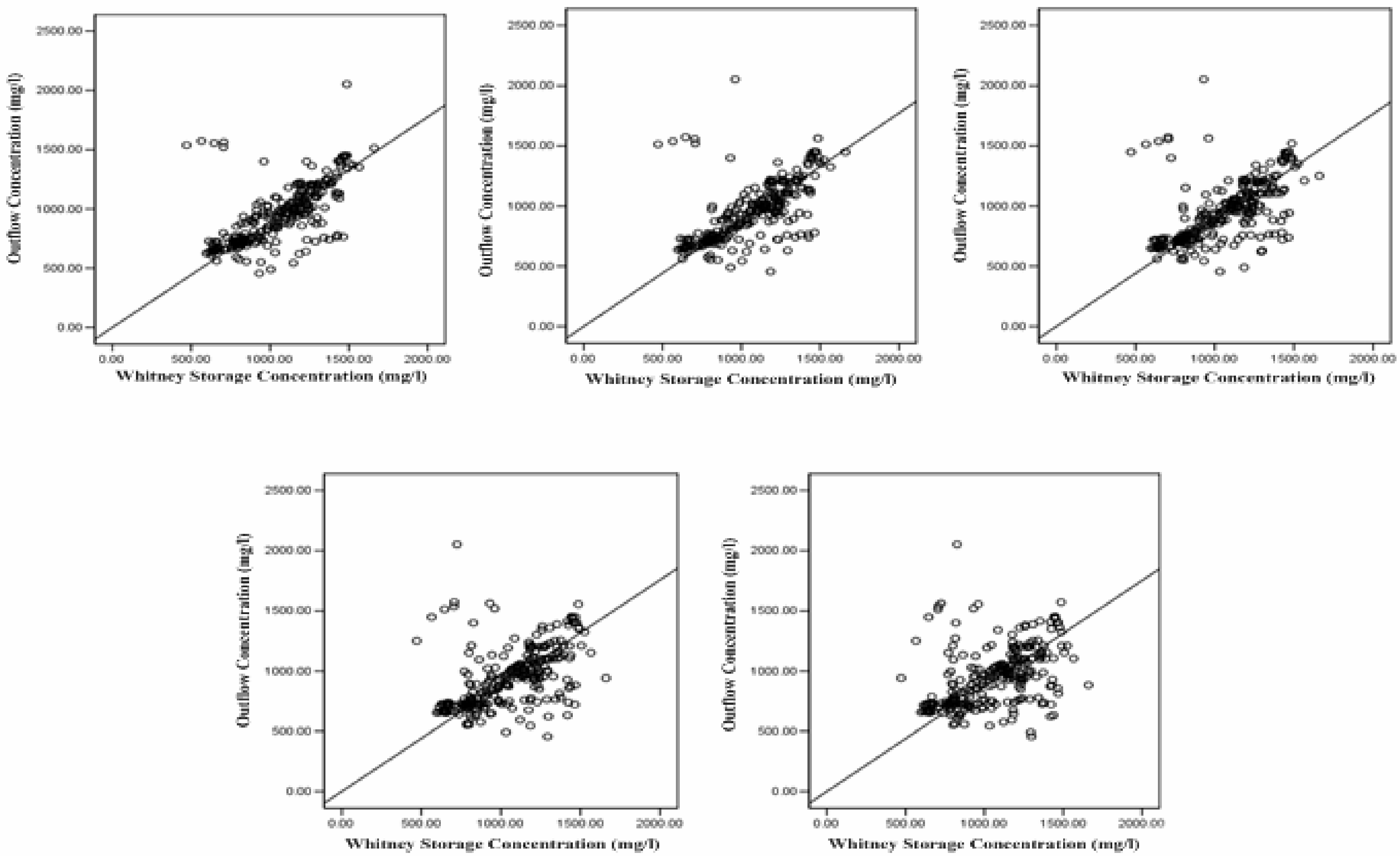
Possum Kingdom Storage versus Outflow Concentration (Lag time = 0 to 4 months)



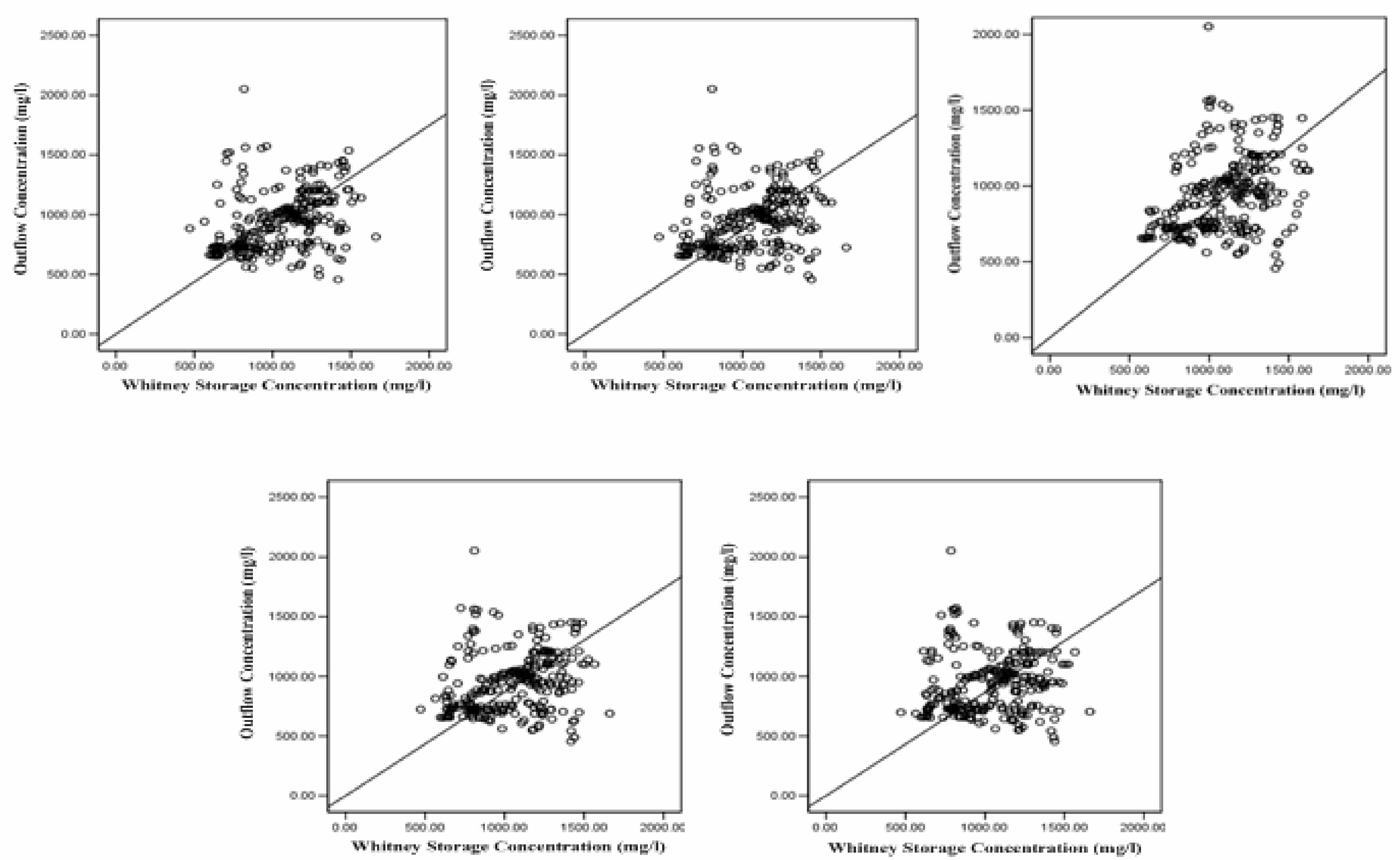
Possum Kingdom Storage versus Outflow Concentration (Lag time = 5 to 9 months)



Whitney Storage versus Outflow Concentration (Lag time = 0 to 4 months)



Whitney Storage versus Outflow Concentration (Lag time = 5 to 9 months)



APPENDIX D

PLOTS OF THE OBSERVED AND SIMULATED RESERVOIR STORAGE AND OUTFLOW CONCENTRATIONS

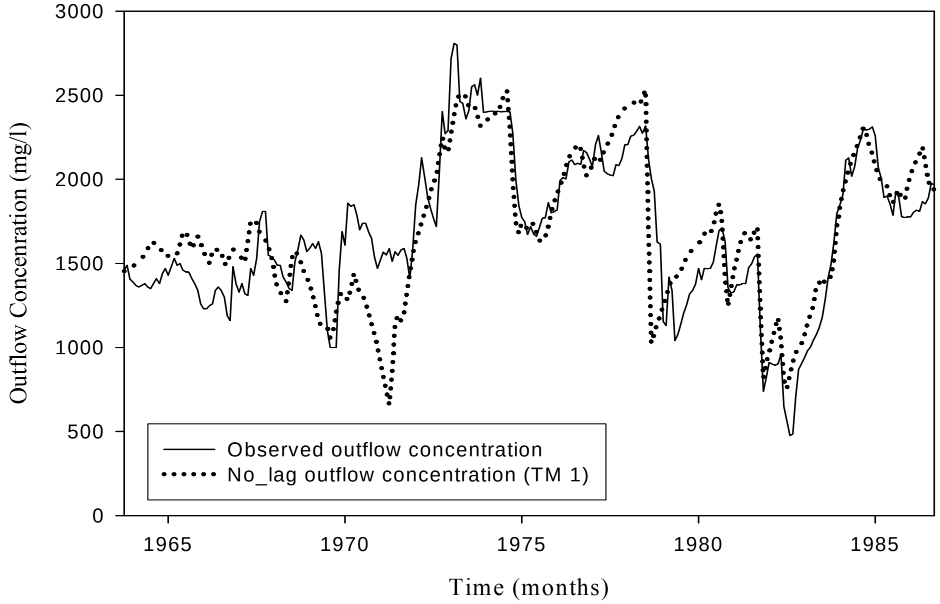


Figure D.1 Comparison of Observed and Simulated Flow Concentrations at Graford Gage (No Lag, TM Option 1)

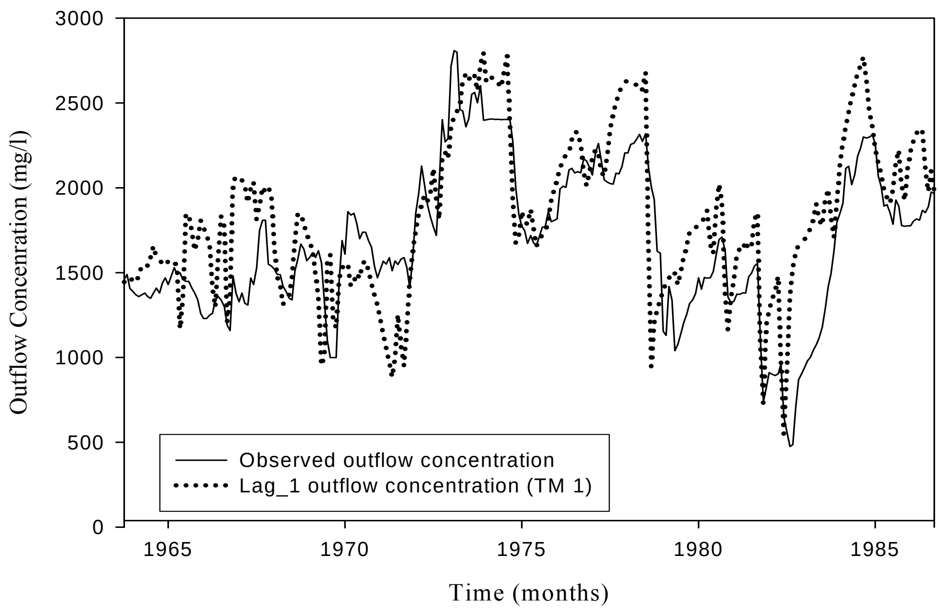


Figure D.2 Comparison of Observed and Simulated Flow Concentrations at Graford Gage (Lag 1 month, TM Option 1)

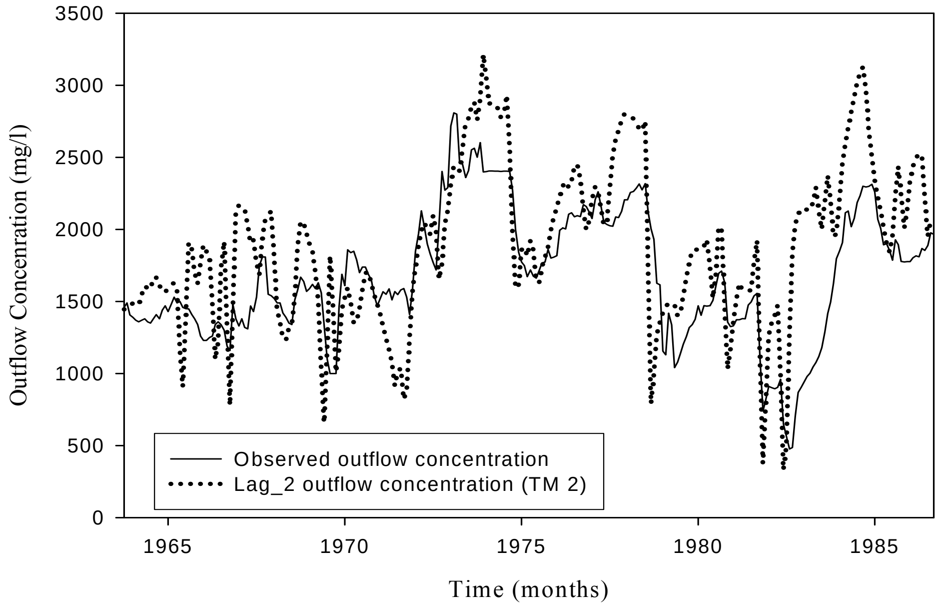


Figure D.3 Comparison of Observed and Simulated Outflow Concentrations at Graford Gage (Lag 2 months, TM Option 1)

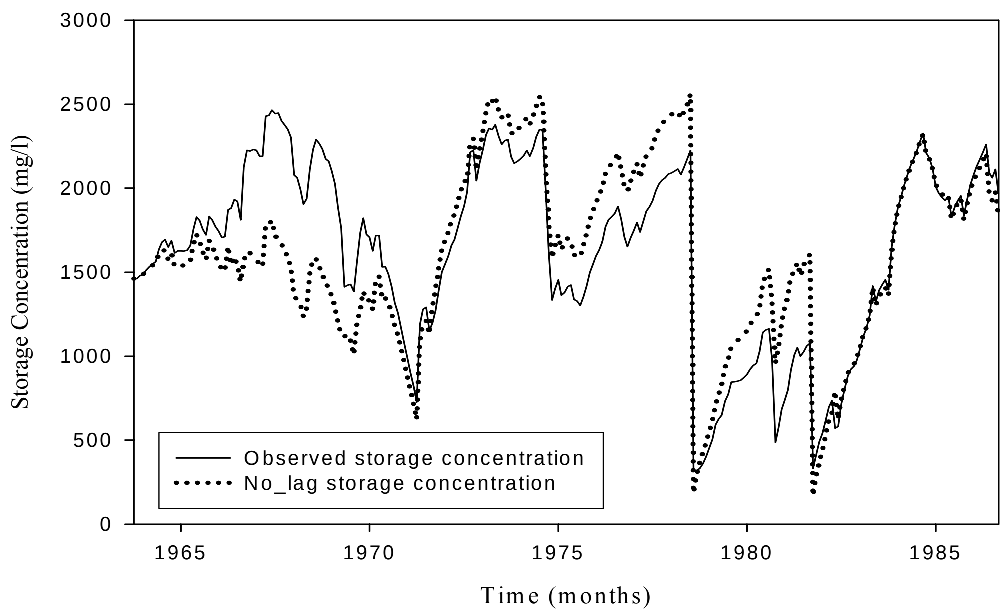


Figure D.4 Comparison of Observed and Simulated Storage Concentrations at Possum Kingdom Reservoir (No Lag, TM Option 1)

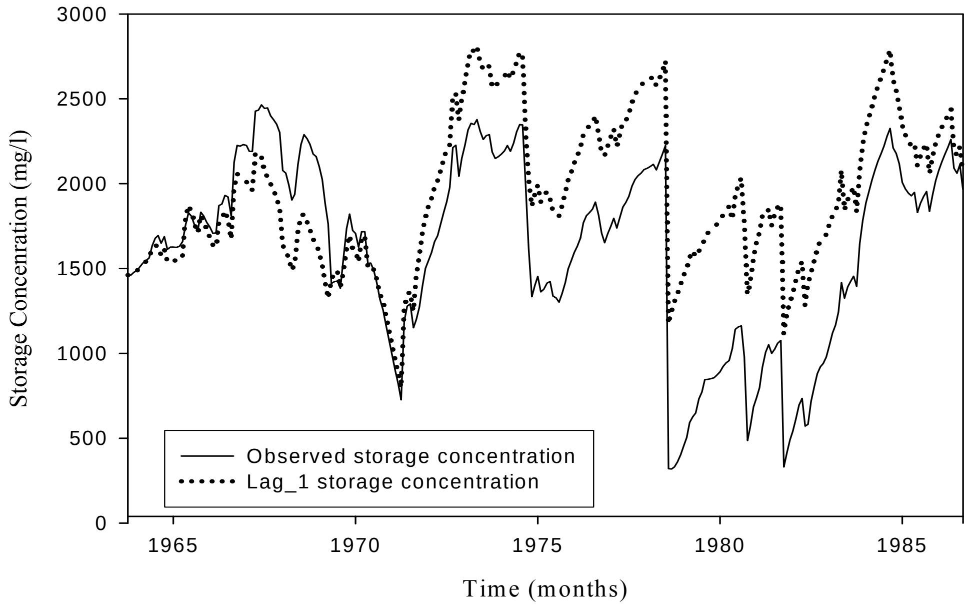


Figure D.5 Comparison of Observed and Simulated Storage Concentrations at Possum Kingdom Reservoir (Lag 1 month, TM Option 1)

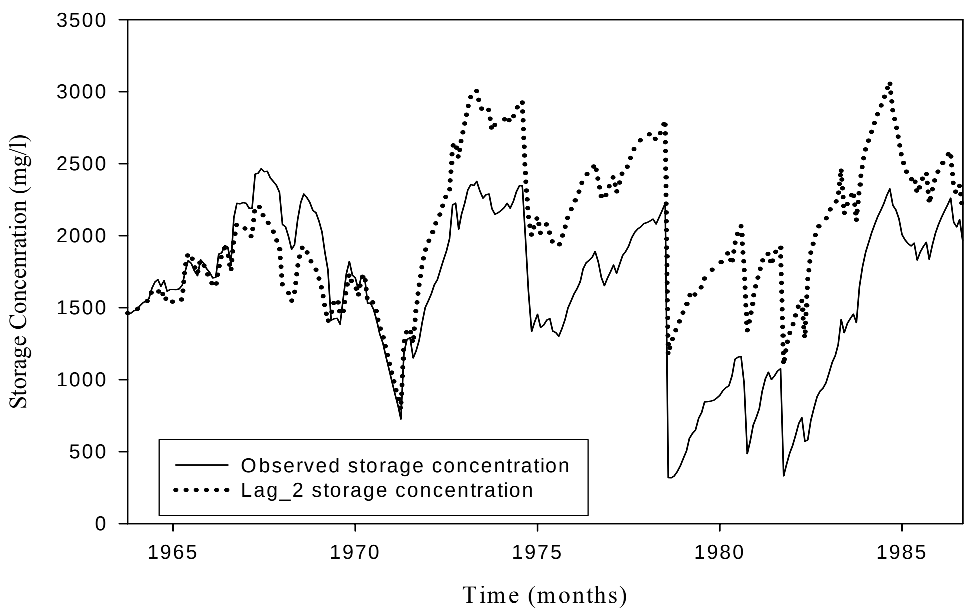


Figure D.6 Comparison of Observed and Simulated Storage Concentrations at Possum Kingdom Reservoir (Lag 2 months, TM Option 1)

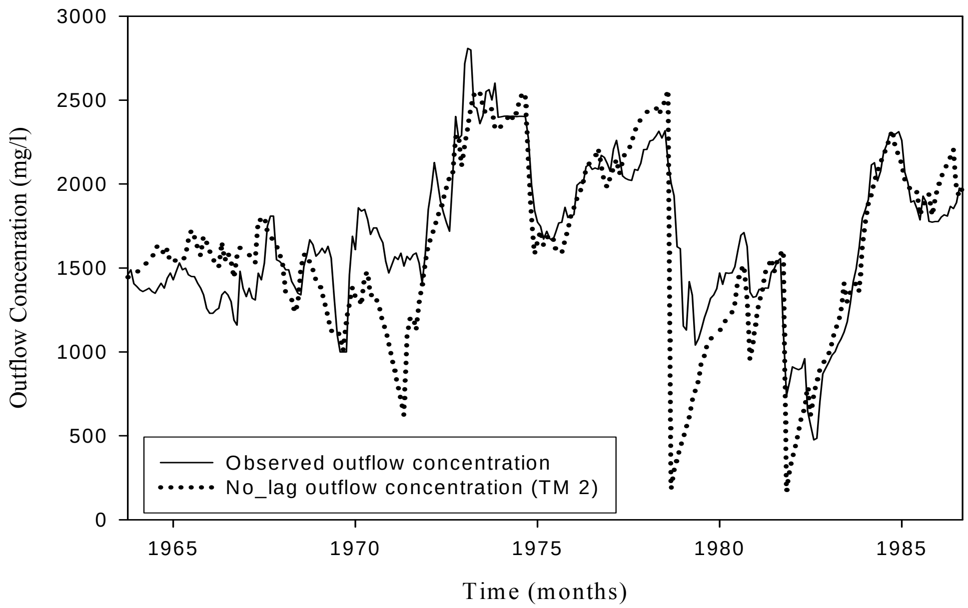


Figure D.7 Comparison of Observed and Simulated Flow Concentration at Graford Gage (No Lag, TM Option 2)

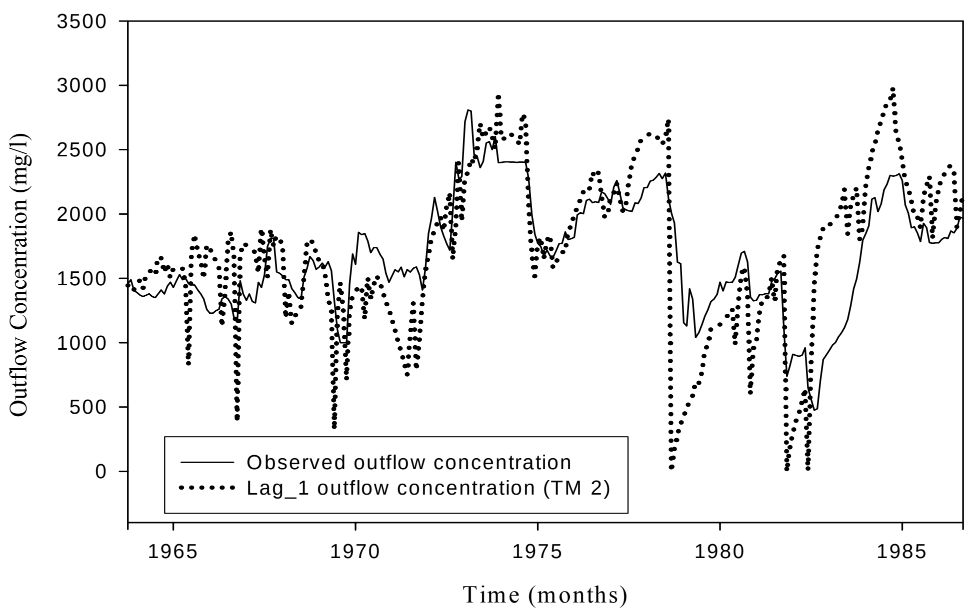


Figure D.8 Comparison of Observed and Simulated Flow Concentration at Graford Gage (Lag 1 month, TM Option 2)

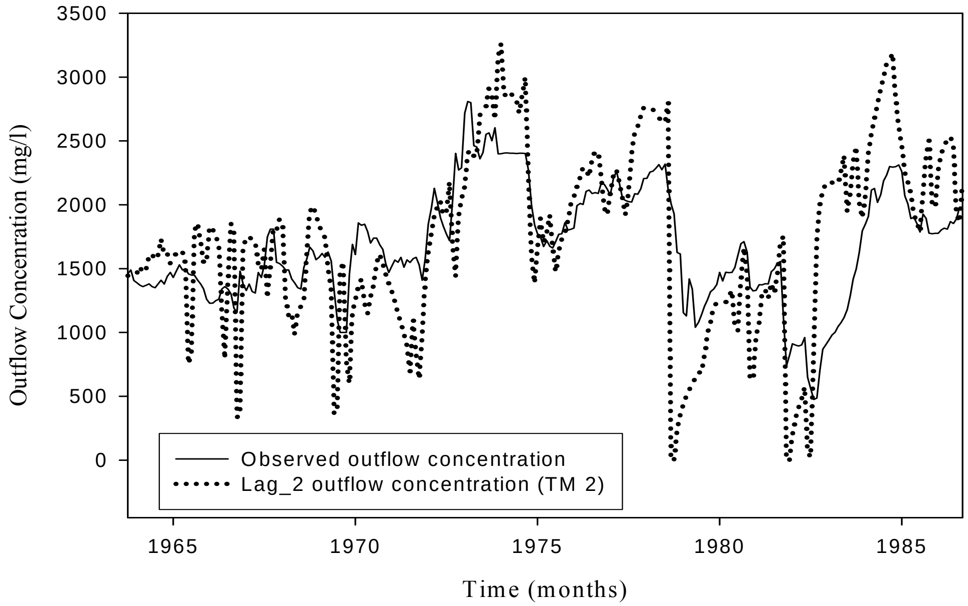


Figure D.9 Comparison of Observed and Simulated Flow Concentration at Graford gage (Lag 2 months, TM Option 2)

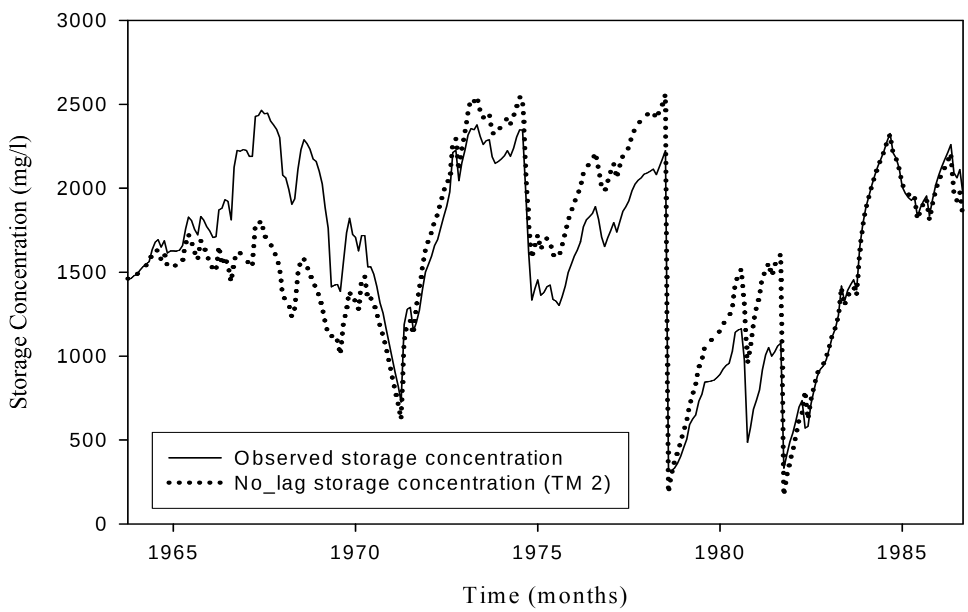


Figure D.10 Comparison of Observed and Simulated Storage Concentrations at Possum Kingdom Reservoir (No Lag, TM Option 2)

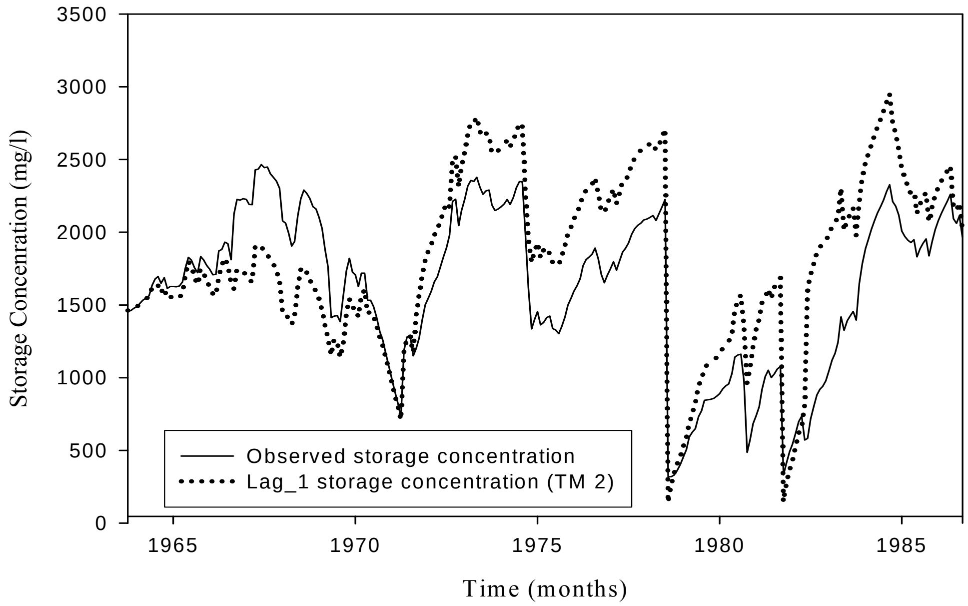


Figure D.11 Comparison of Observed and Simulated Storage Concentrations at Possum Kingdom Reservoir (Lag 1 month, TM Option 2)

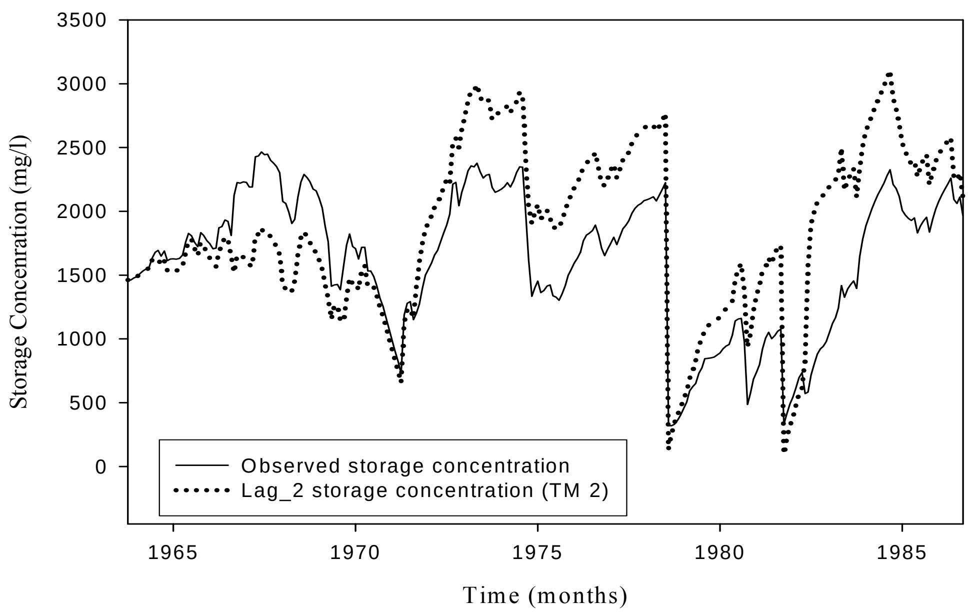


Figure D.12 Comparison of Observed and Simulated Storage Concentrations at Possum Kingdom Reservoir (Lag 2 months, TM Option 2)

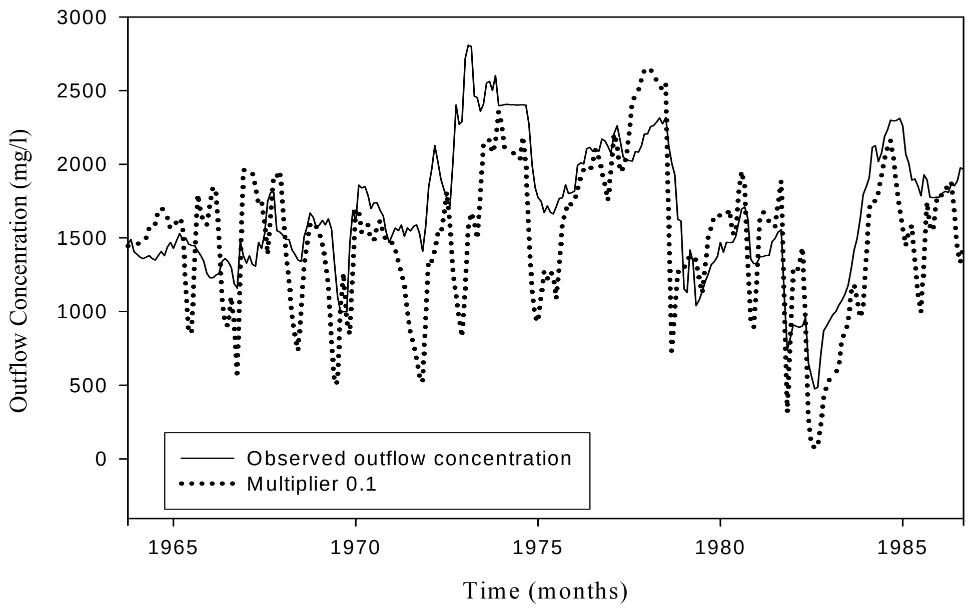


Figure D.13 Comparison of Observed and Simulated Concentration at Graford Gage (Multiplier 0.1, TM Option 1)

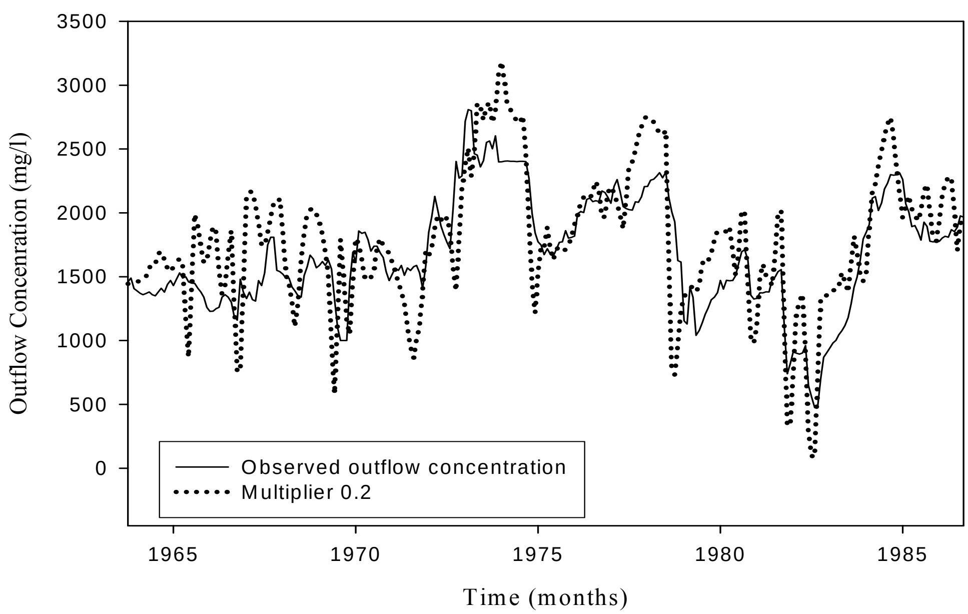


Figure D.14 Comparison of Observed and Simulated Concentration at Graford Gage (Multiplier 0.2, TM Option 1)

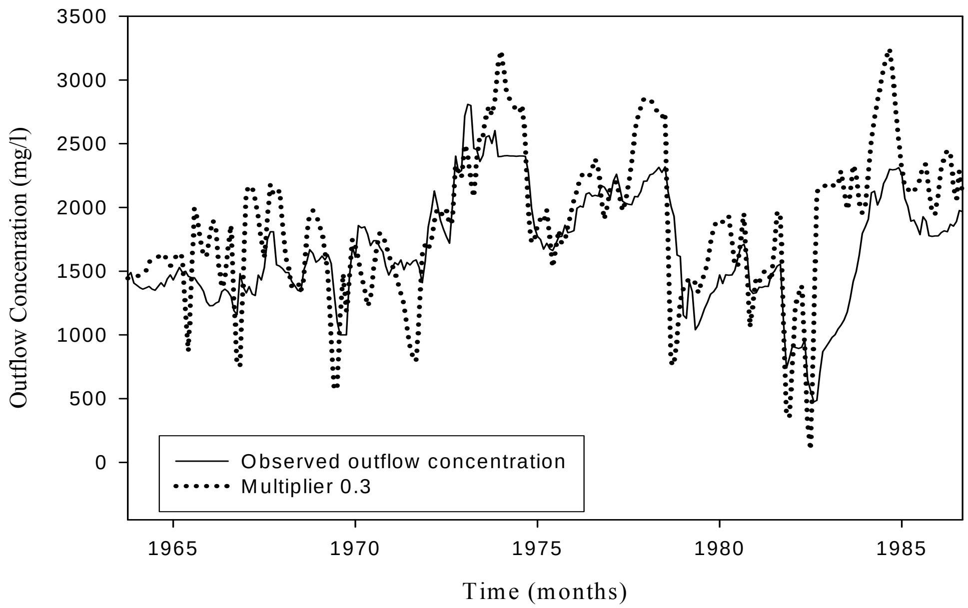


Figure D.15 Comparison of Observed and Simulated Concentration at Graford Gage (Multiplier 0.3, TM Option 1)

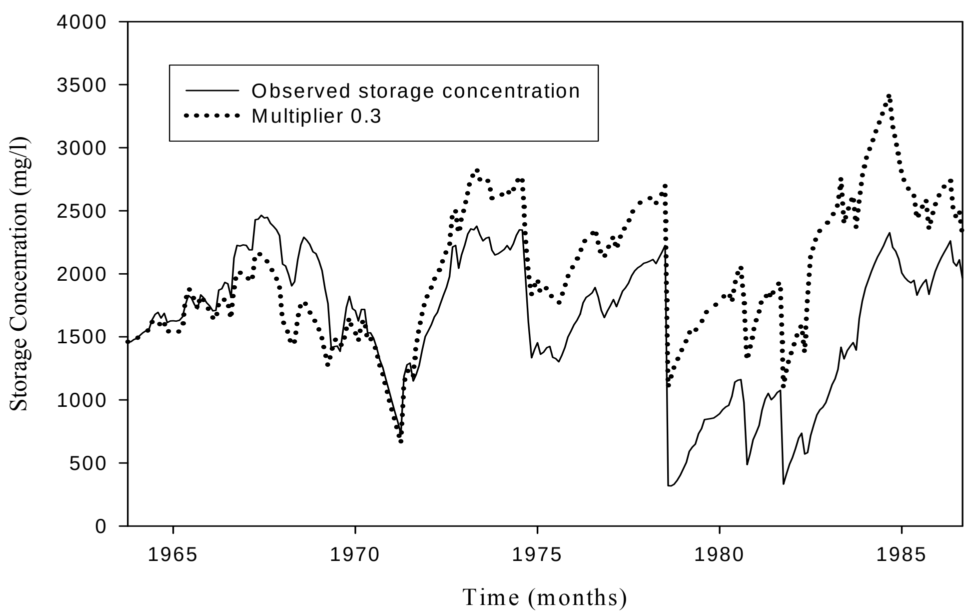


Figure D.16 Comparison of Observed and Simulated Storage Concentration at Possum Kingdom Reservoir (Multiplier 0.3, TM Option 1)

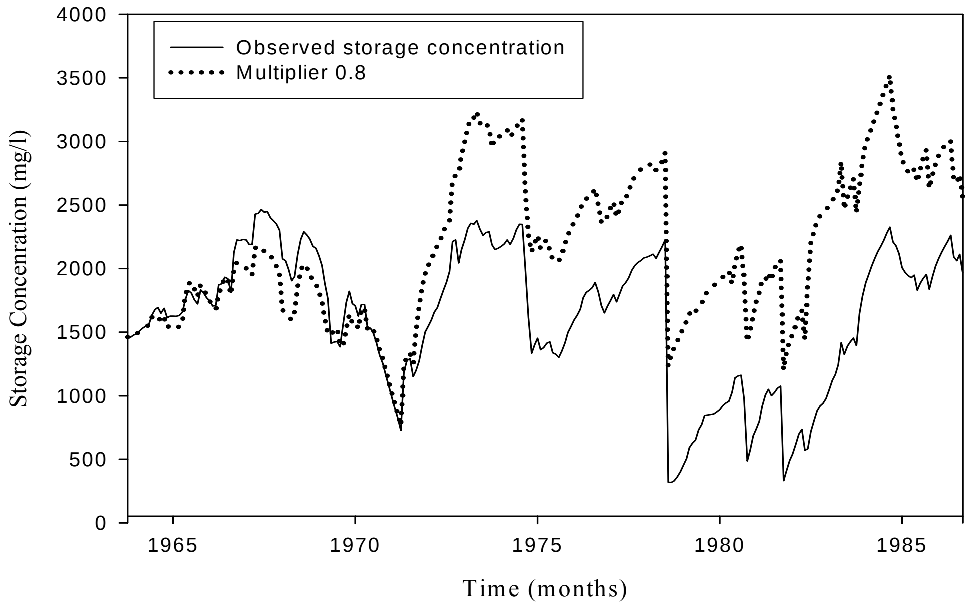


Figure D.17 Comparison of Observed and Simulated Storage Concentration at Possum Kingdom Reservoir (Multiplier 0.8, TM Option 1)

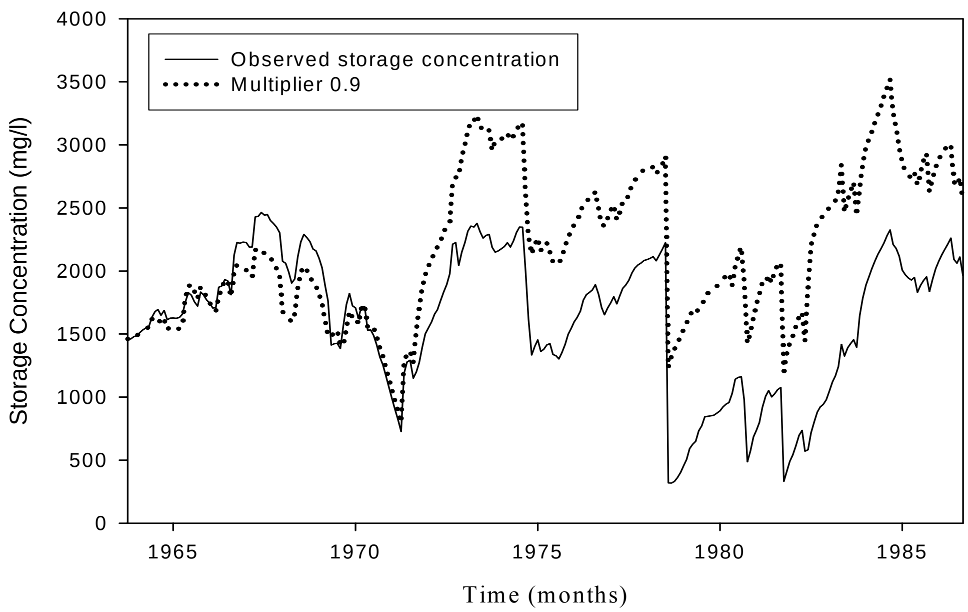


Figure D.18 Comparison of Observed and Simulated Storage Concentration at Possum Kingdom Reservoir (Multiplier 0.9, TM Option 1)

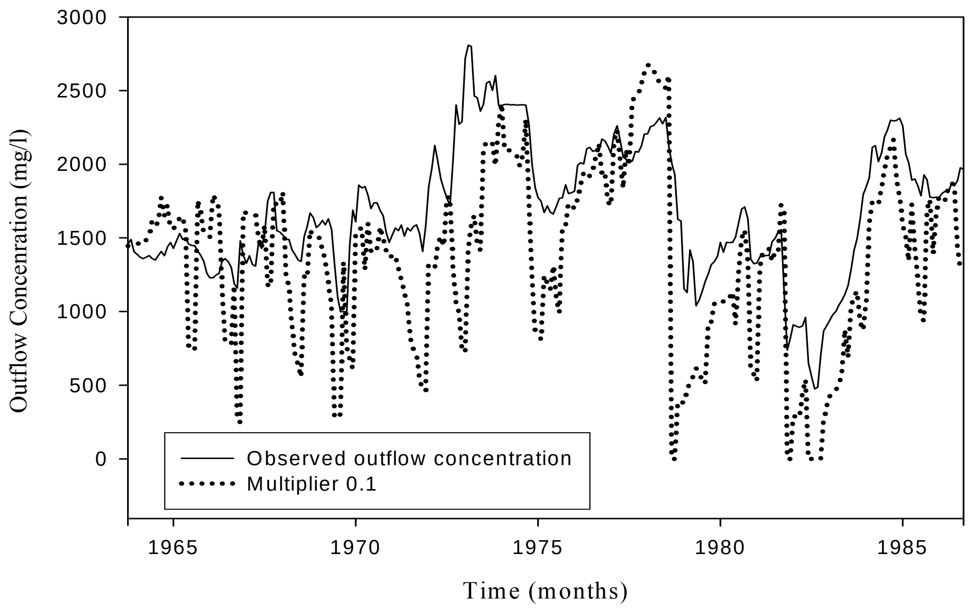


Figure D.19 Comparison of Observed and Simulated Concentration at Graford Gage (Multiplier 0.1, TM Option 2)

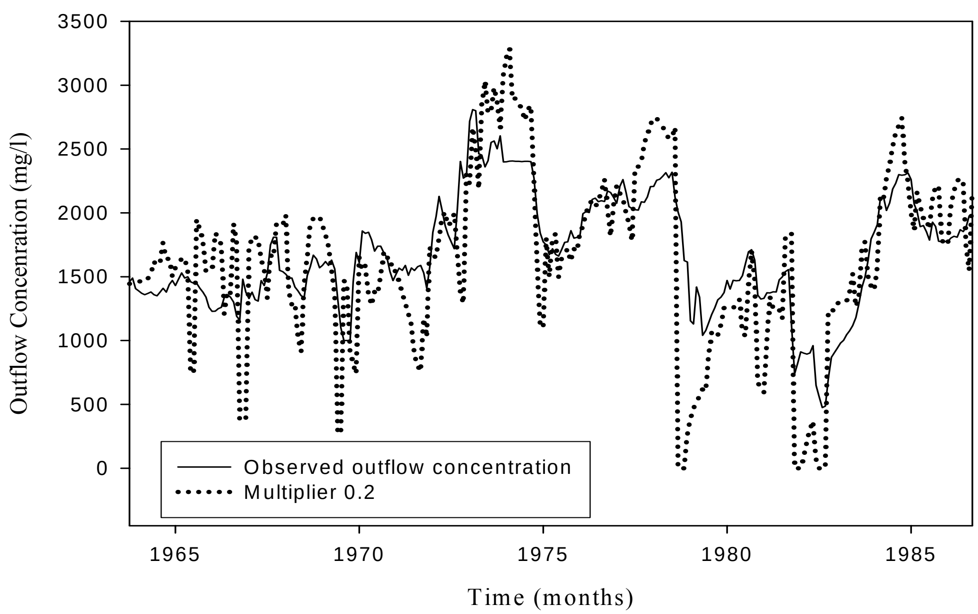


Figure D.20 Comparison of Observed and Simulated Concentration at Graford Gage (Multiplier 0.2, TM Option 2)

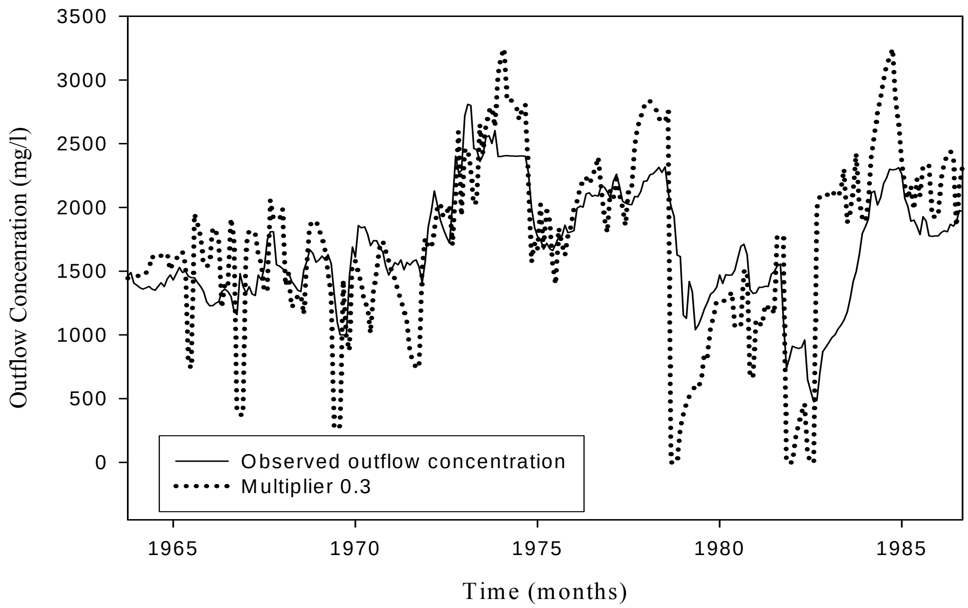


Figure D.21 Comparison of Observed and Simulated Concentration at Graford Gage (Multiplier 0.3, TM Option 2)

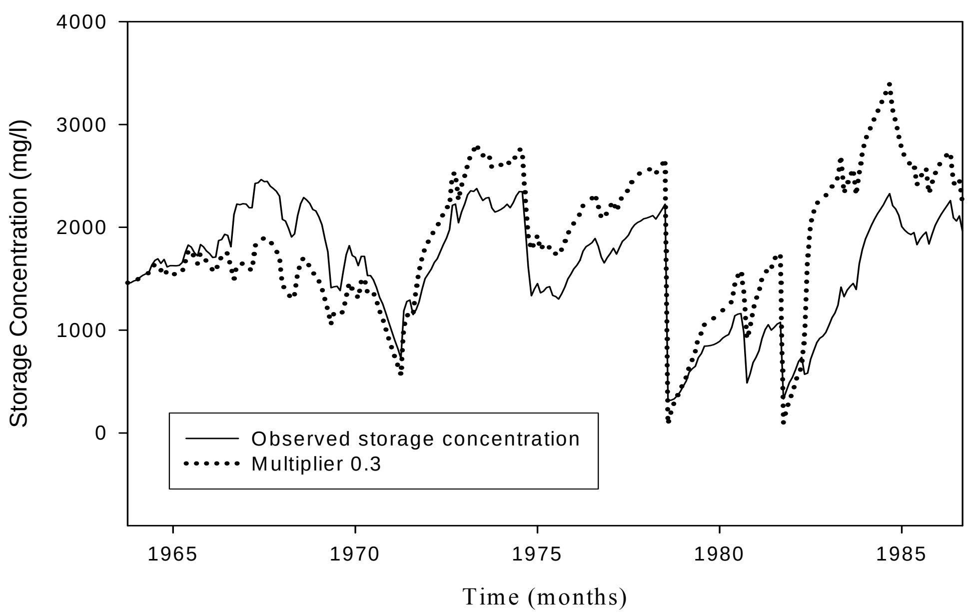


Figure D.22 Comparison of Observed and Simulated Storage Concentration at Possum Kingdom Reservoir (Multiplier 0.3, TM Option 2)

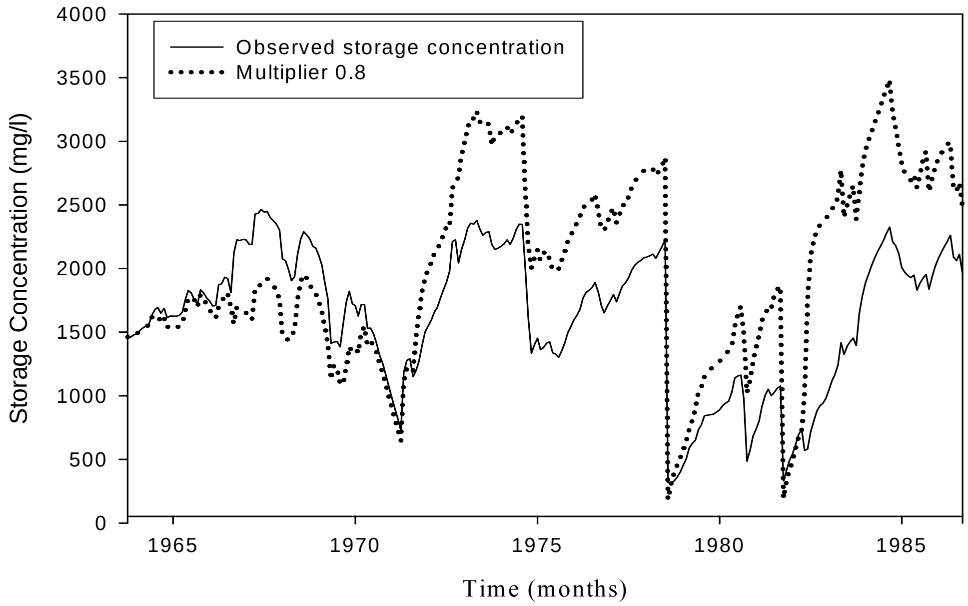


Figure D.23 Comparison of Observed and Simulated Storage Concentration at Possum Kingdom Reservoir (Multiplier 0.8, TM Option 2)

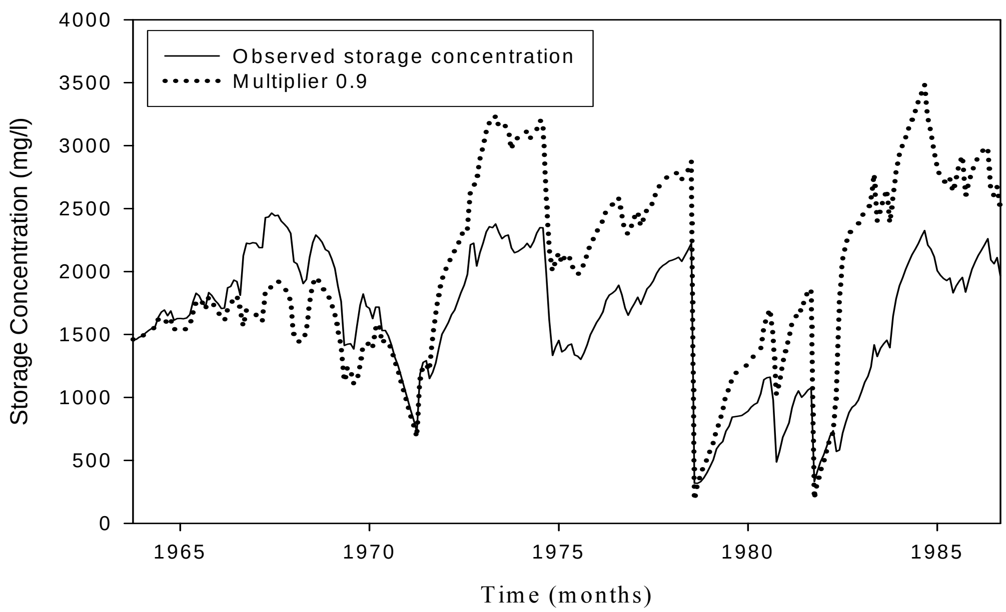


Figure D.24 Comparison of Observed and Simulated Storage Concentration at Possum Kingdom Reservoir (Multiplier 0.9, TM Option 2)

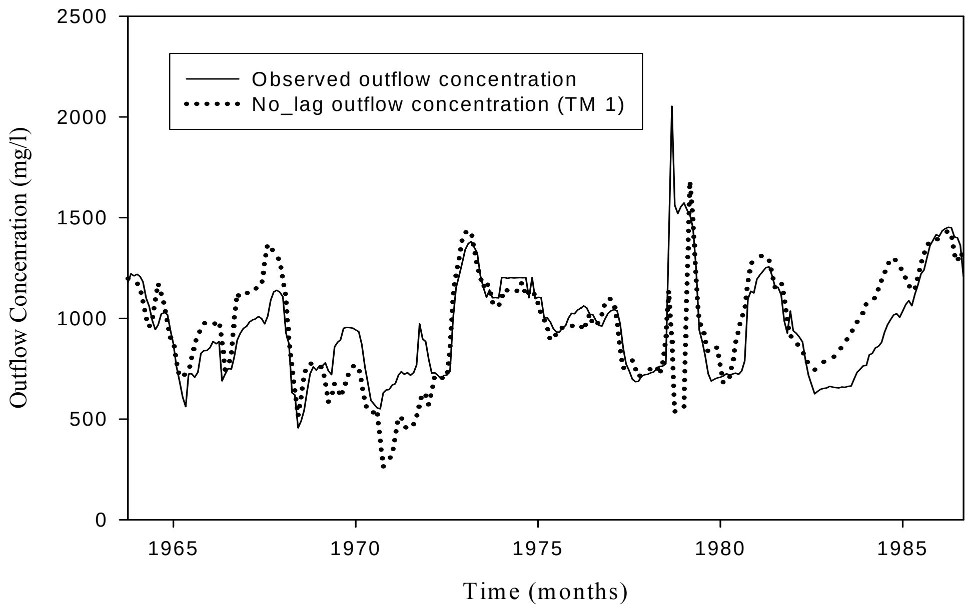


Figure D.25 Comparison of Observed and Simulated Flow Concentrations at Whitney gage (No lag, TM option 1)

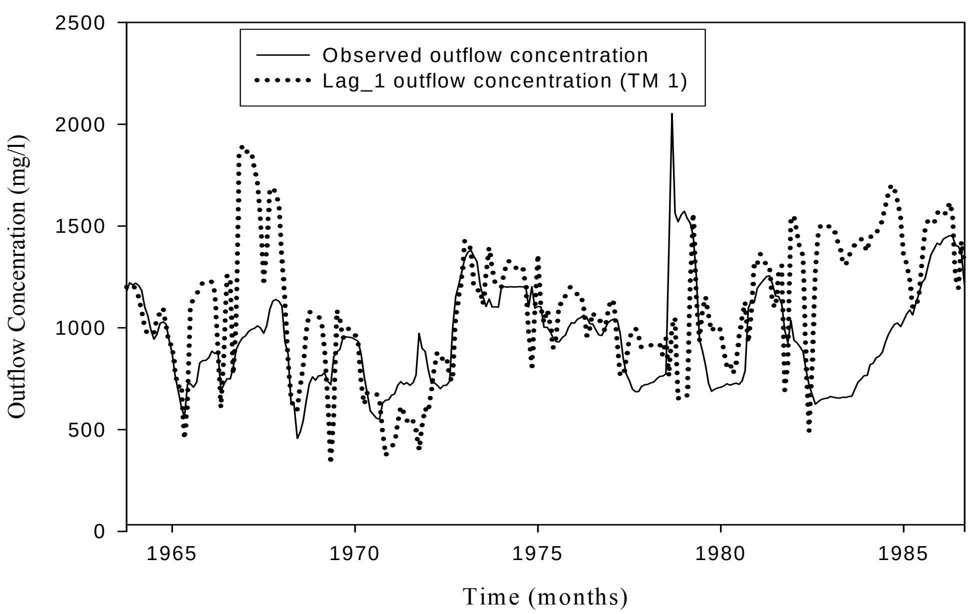


Figure D.26 Comparison of Observed and Simulated Flow Concentrations at Whitney gage (Lag 1 month, TM option 1)

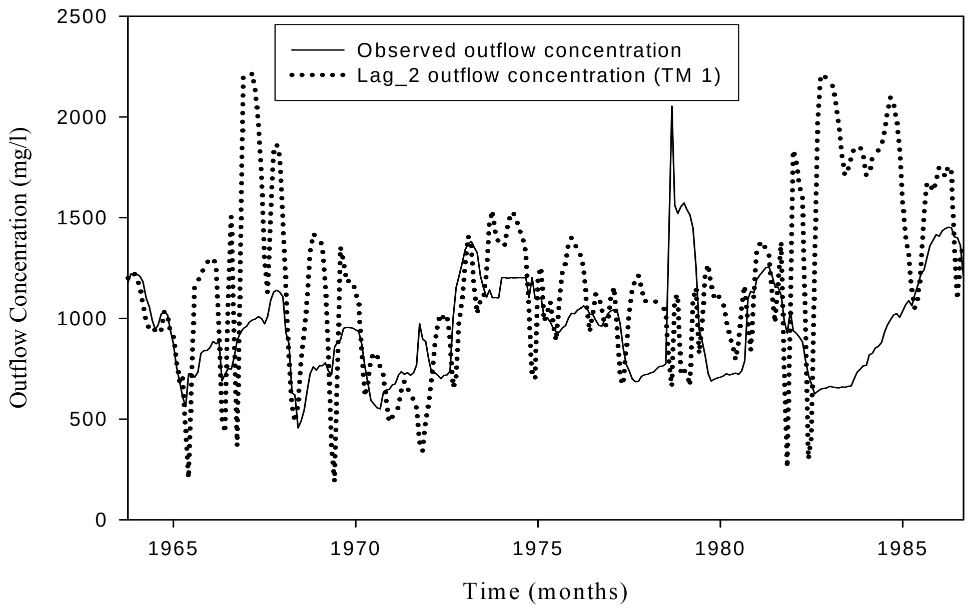


Figure D.27 Comparison of Observed and Simulated Flow Concentrations at Whitney gage (Lag 2 months, TM option 1)

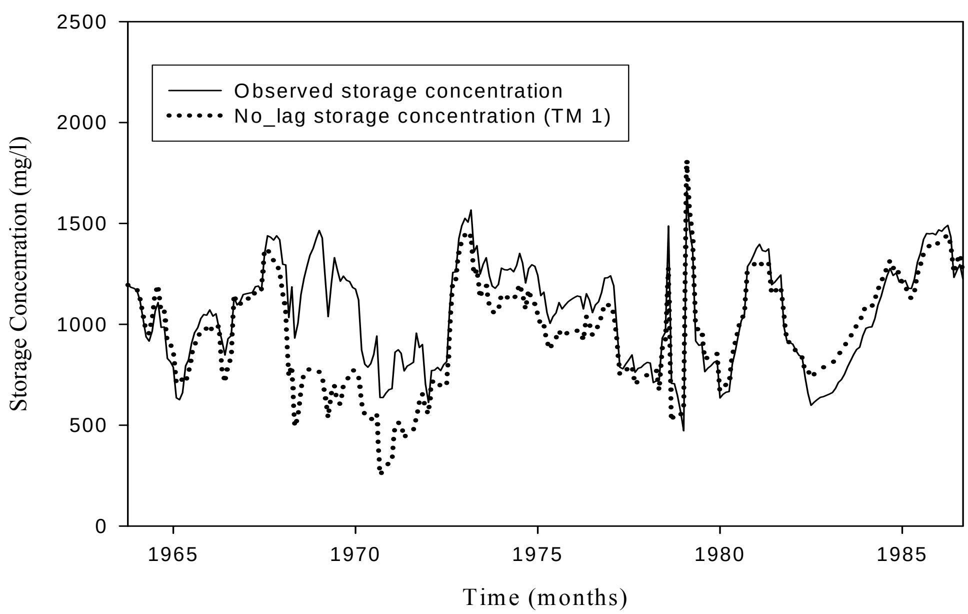


Figure D.28 Comparison of Observed and Simulated Storage Concentrations at Whitney Reservoir (No lag, TM option 1)

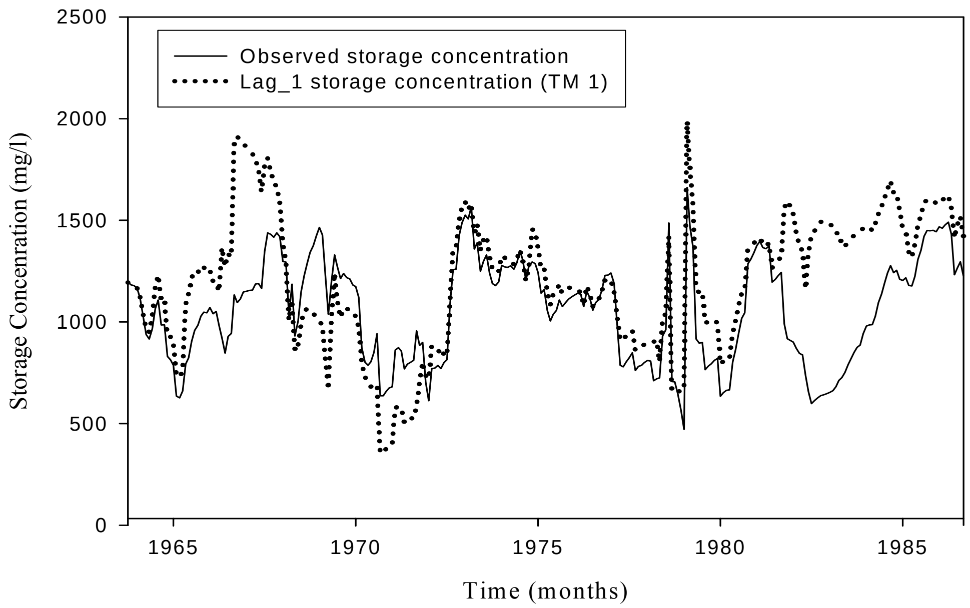


Figure D.29 Comparison of Observed and Simulated Storage Concentrations at Whitney Reservoir (Lag 1 month, TM option 1)

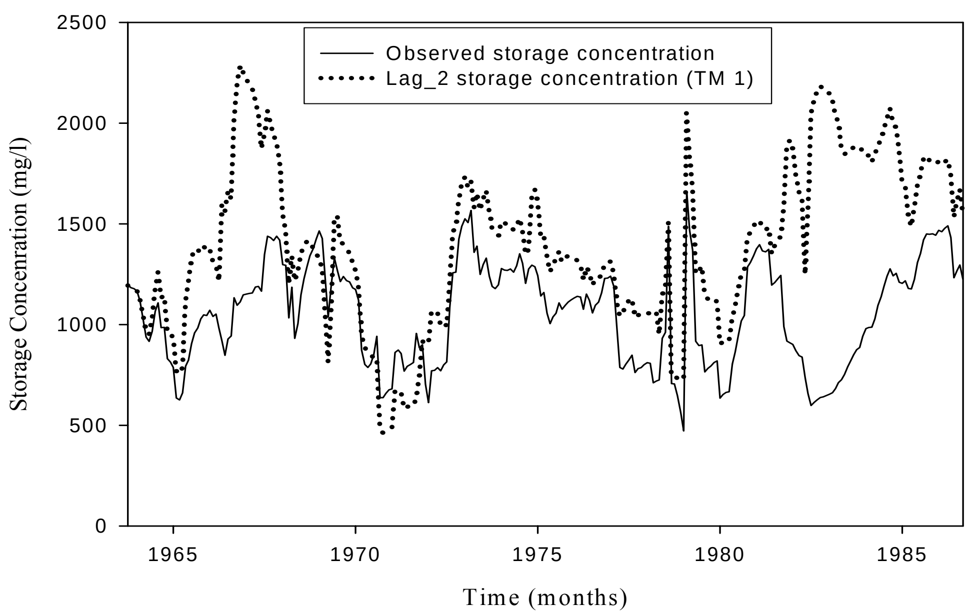


Figure D.30 Comparison of Observed and Simulated Storage Concentrations at Whitney Reservoir (Lag 2 months, TM option 1)

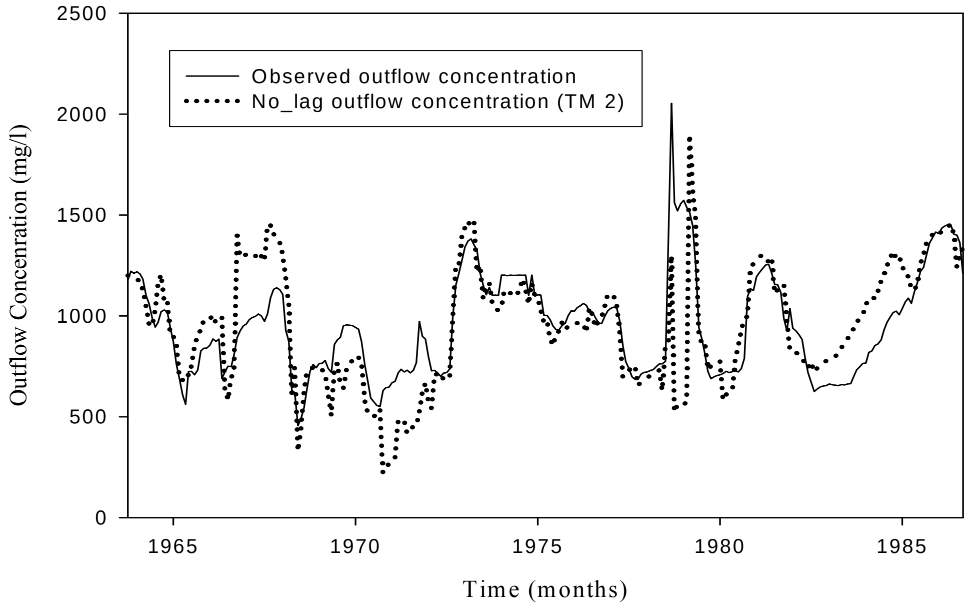


Figure D.31 Comparison of Observed and Simulated Flow Concentrations at Whitney gage (No lag, TM option 2)

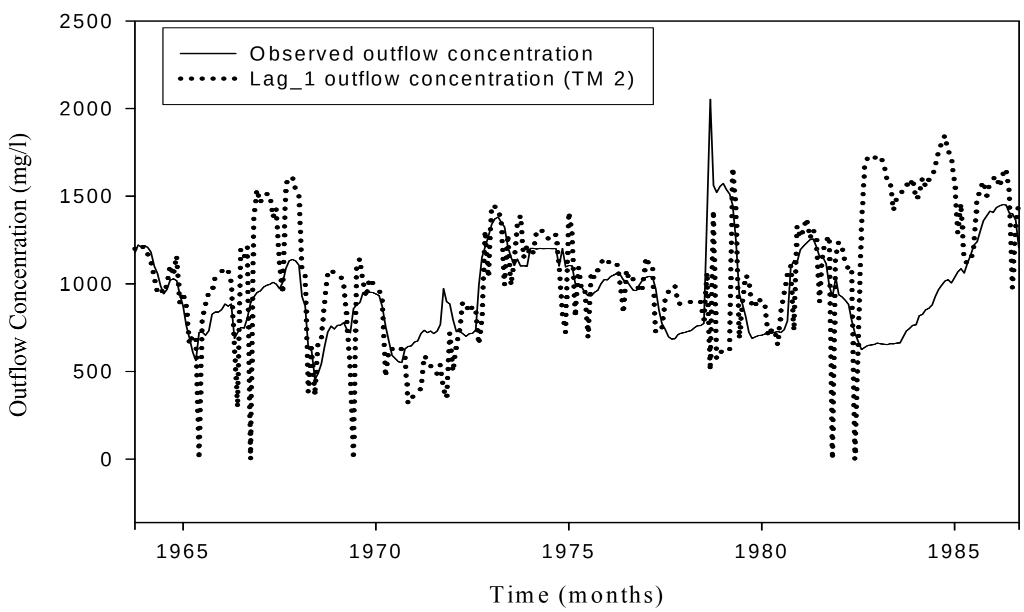


Figure D.32 Comparison of Observed and Simulated Flow Concentrations at Whitney gage (Lag 1 month, TM option 2)

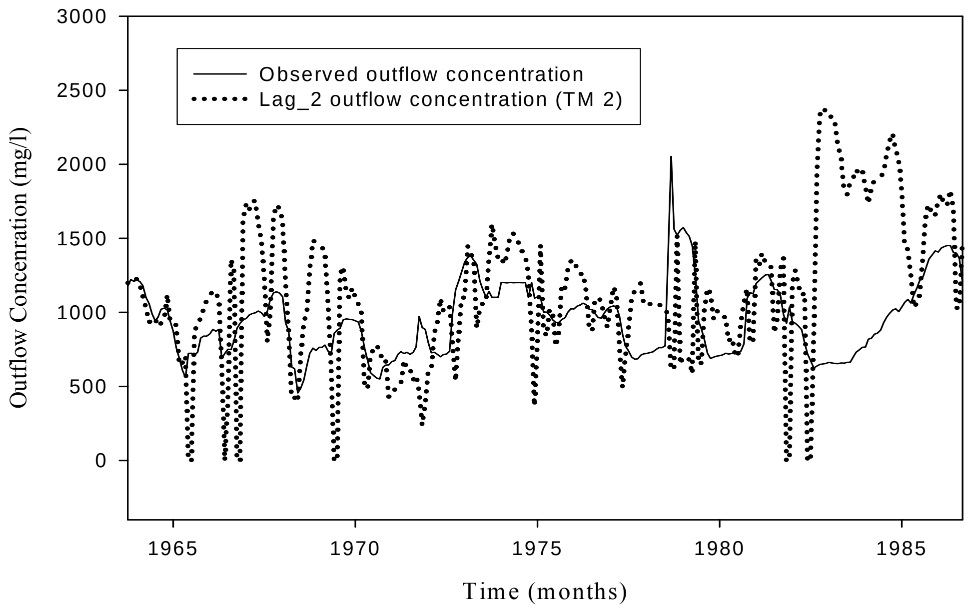


Figure D.33 Comparison of Observed and Simulated Flow Concentrations at Whitney gage (Lag 2 months, TM option 2)

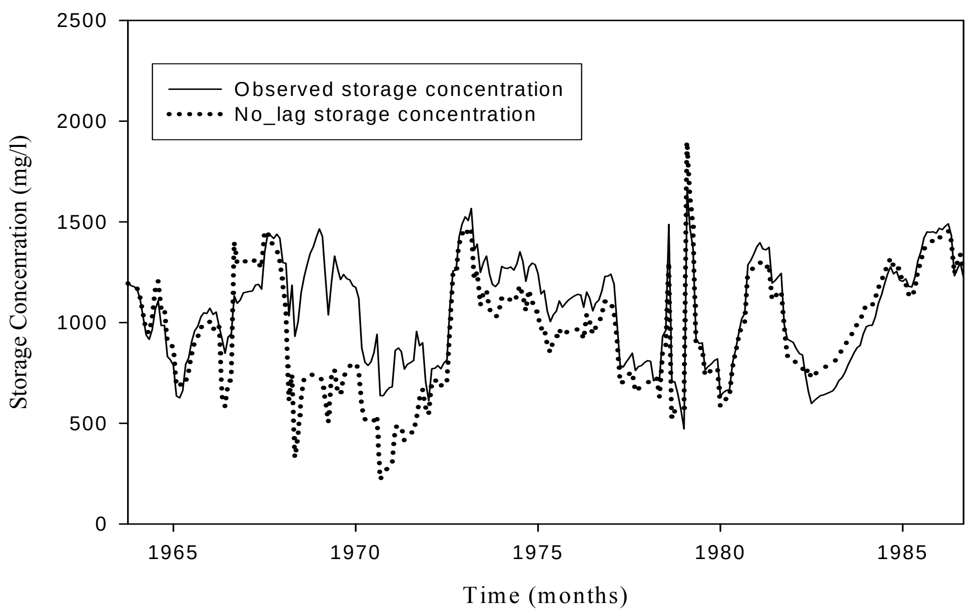


Figure D.34 Comparison of Observed and Simulated Storage Concentrations at Whitney Reservoir (No Lag, TM option 2)

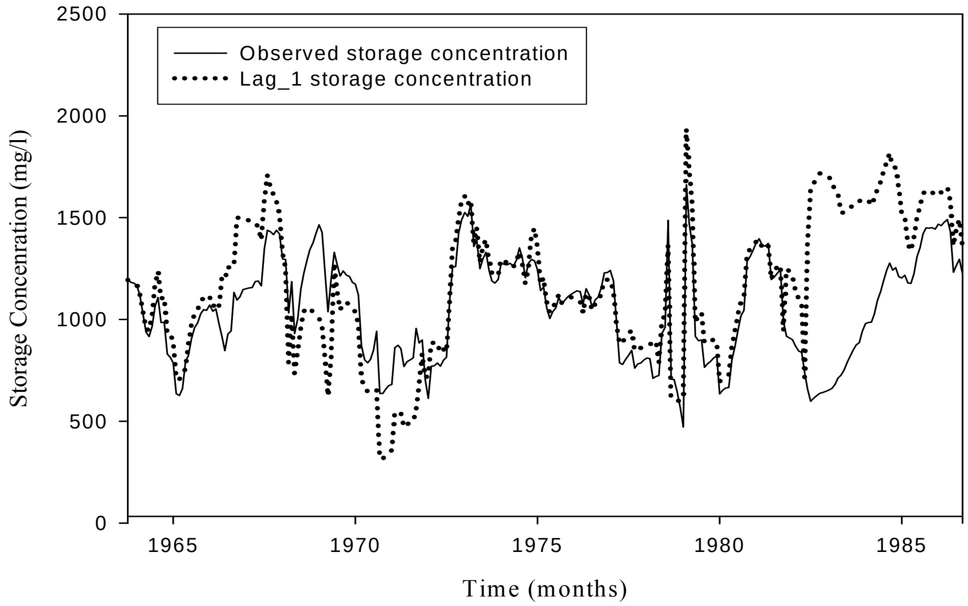


Figure D.35 Comparison of Observed and Simulated Storage Concentrations at Whitney Reservoir (Lag 1 month, TM option 2)

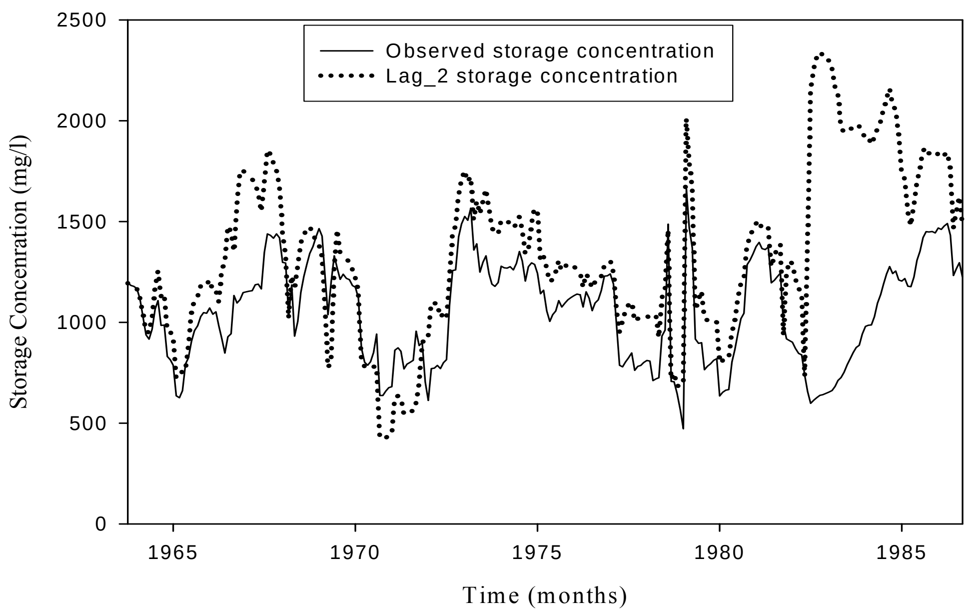


Figure D.36 Comparison of Observed and Simulated Storage Concentrations at Whitney Reservoir (Lag 2 months, TM option 2)

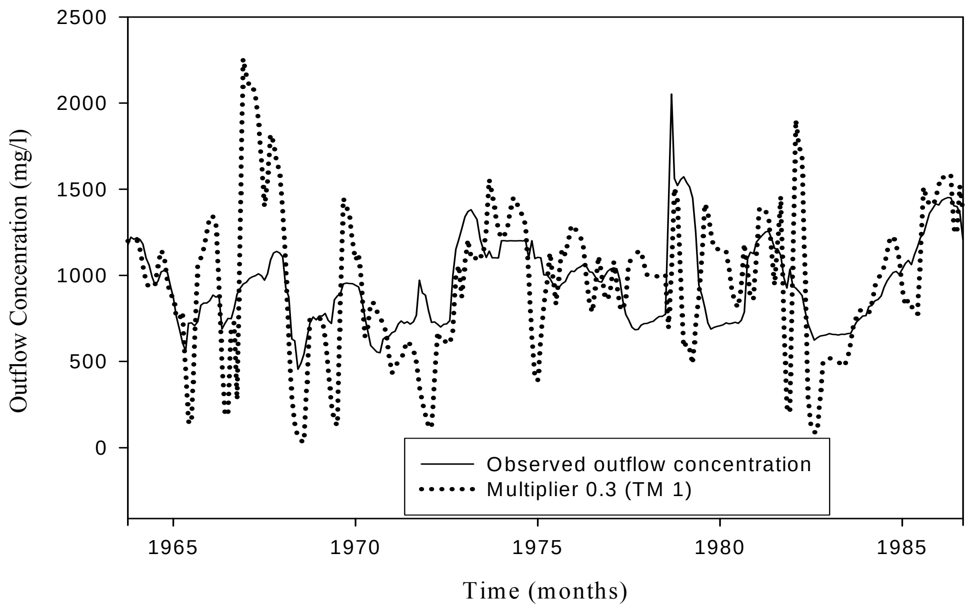


Figure D.37 Comparison of Observed and Simulated Flow Concentration at Whitney Gage (Multiplier 0.3, TM option 1)

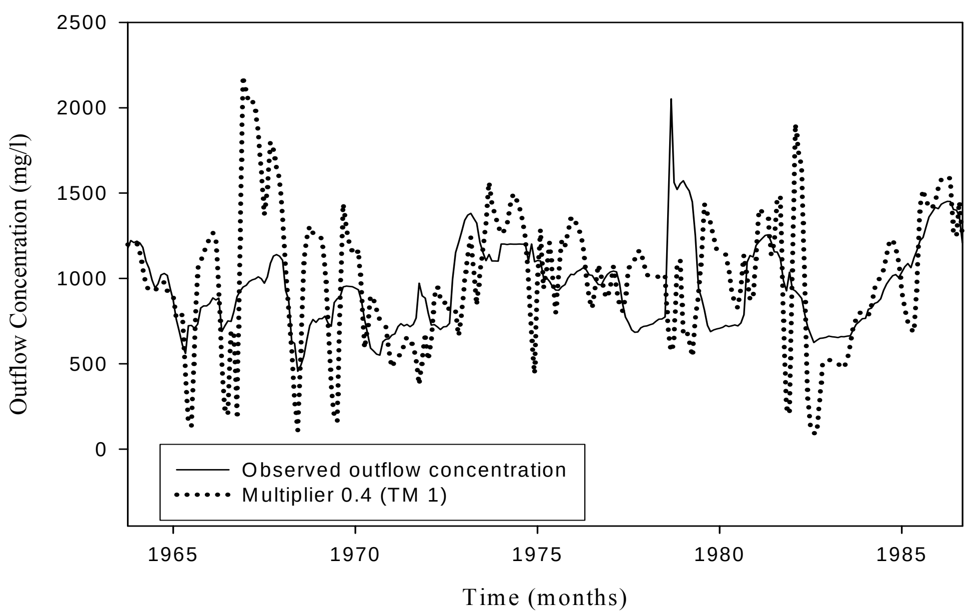


Figure D.38 Comparison of Observed and Simulated Flow Concentration at Whitney Gage (Multiplier 0.4, TM Option 1)

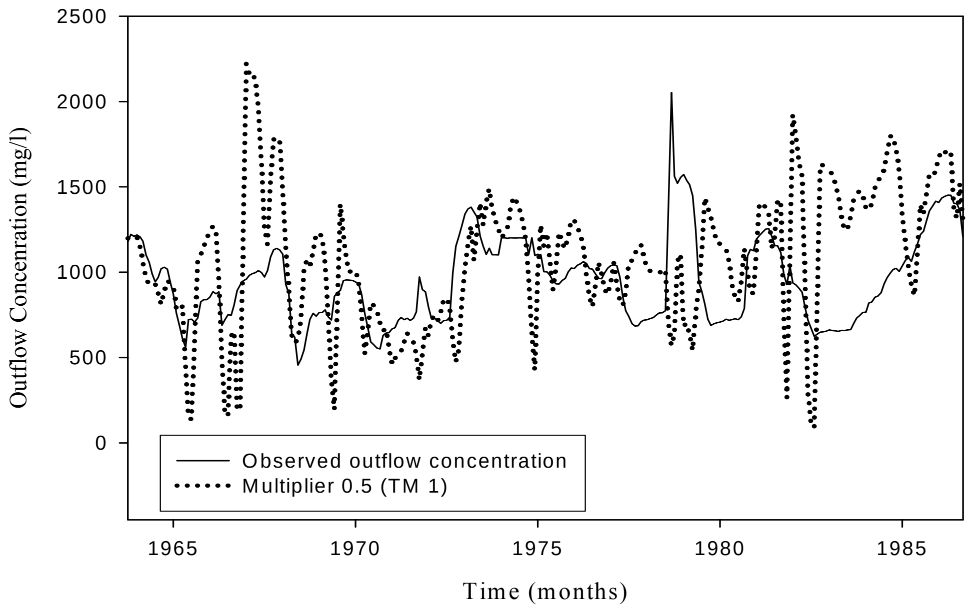


Figure D.39 Comparison of Observed and Simulated Flow Concentration at Whitney Gage (Multiplier 0.5, TM Option 1)

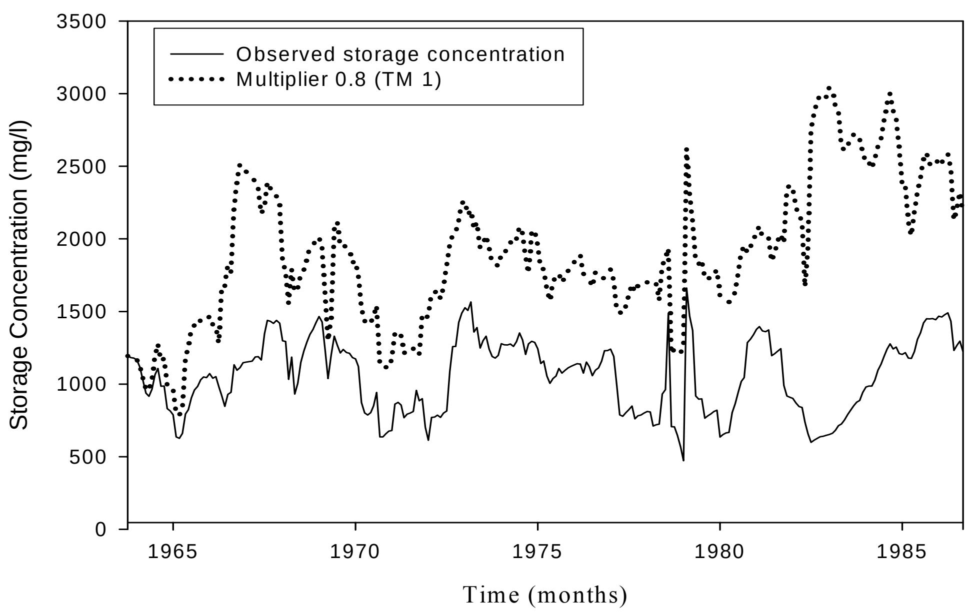


Figure D.40 Comparison of Observed and Simulated Storage Concentration at Whitney Reservoir (Multiplier 0.8, TM Option 1)

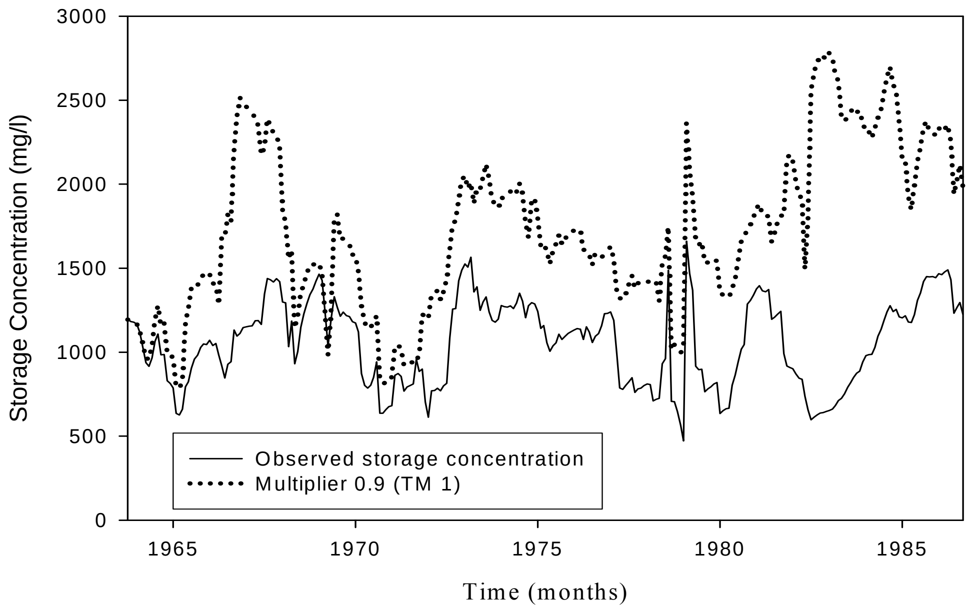


Figure D.41 Comparison of Observed and Simulated Storage Concentration at Whitney Reservoir (Multiplier 0.9, TM Option 1)

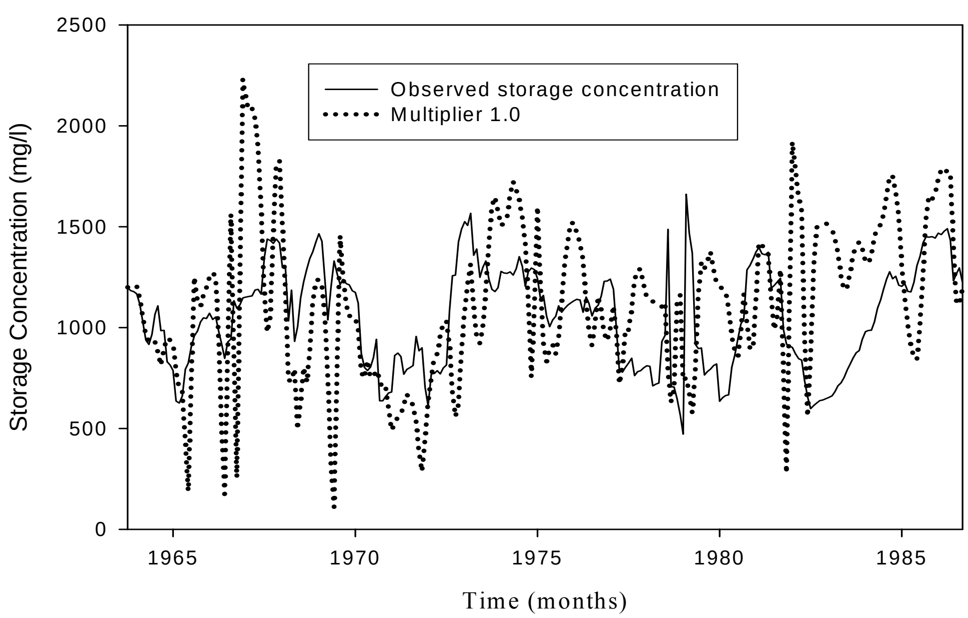


Figure D.42 Comparison of Observed and Simulated Storage Concentration at Whitney Reservoir (Multiplier 1.0, TM Option 1)

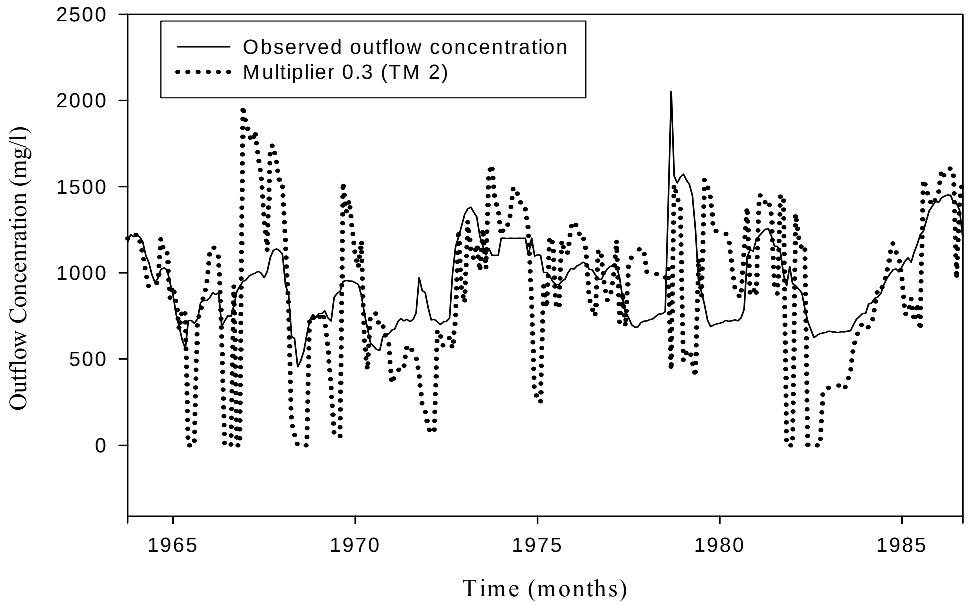


Figure D.43 Comparison of Observed and Simulated Flow Concentration at Whitney Gage (Multiplier 0.3, TM Option 2)

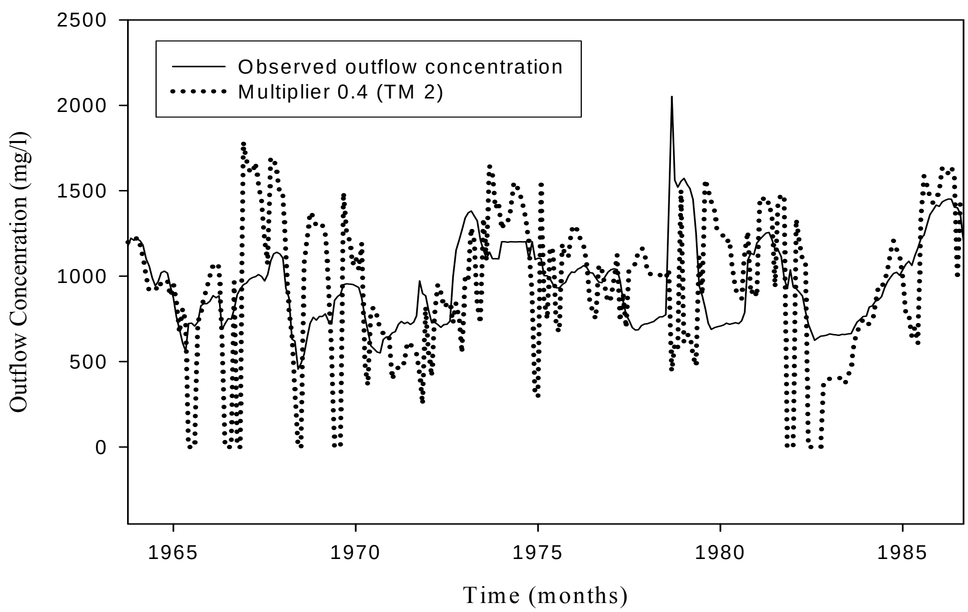


Figure D.44 Comparison of Observed and Simulated Flow Concentration at Whitney Gage (Multiplier 0.4, TM Option 2)

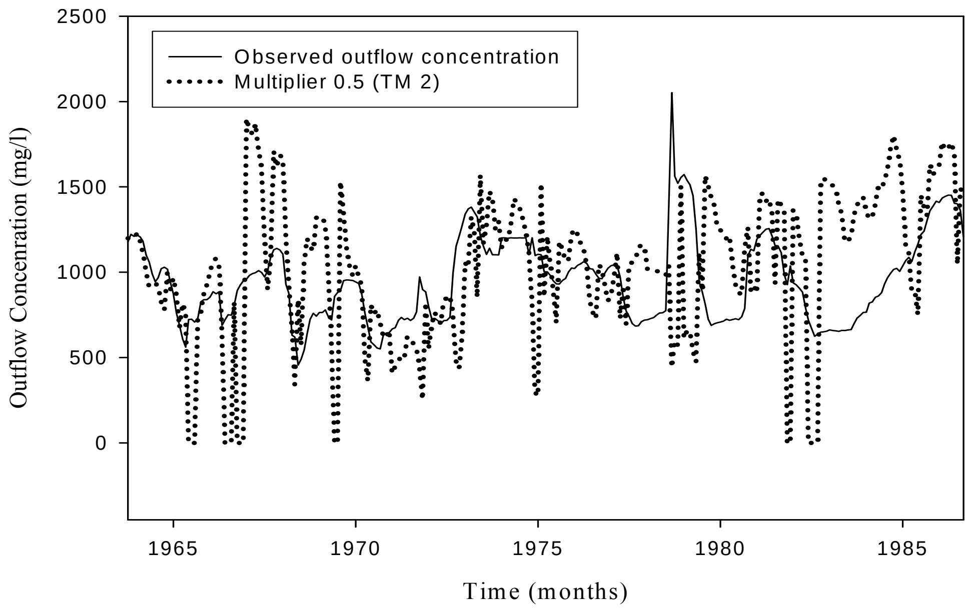


Figure D.45 Comparison of Observed and Simulated Flow Concentration at Whitney Gage (Multiplier 0.5, TM Option 2)

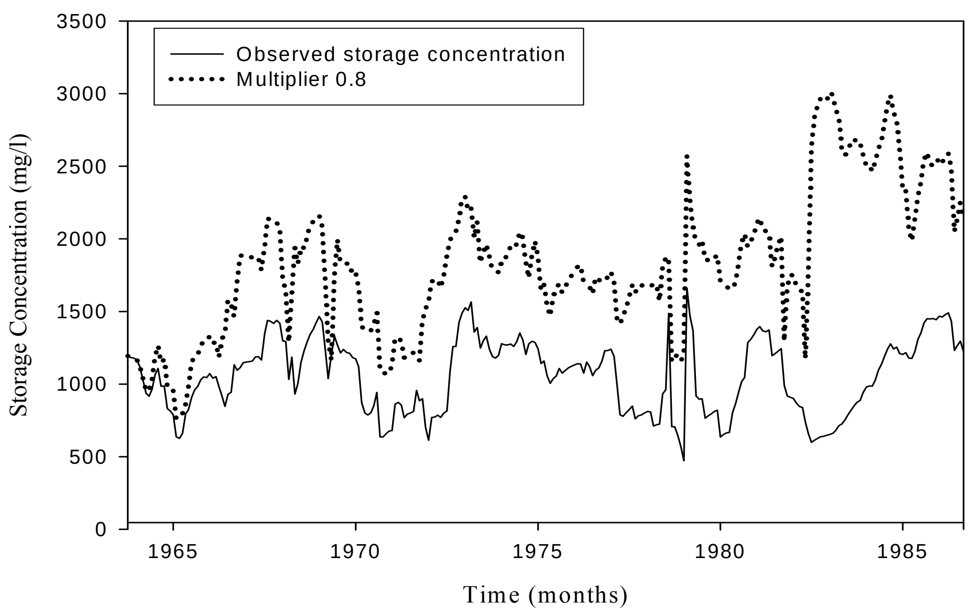


Figure D.46 Comparison of Observed and Simulated Storage Concentration at Whitney Reservoir (Multiplier 0.8, TM Option 2)

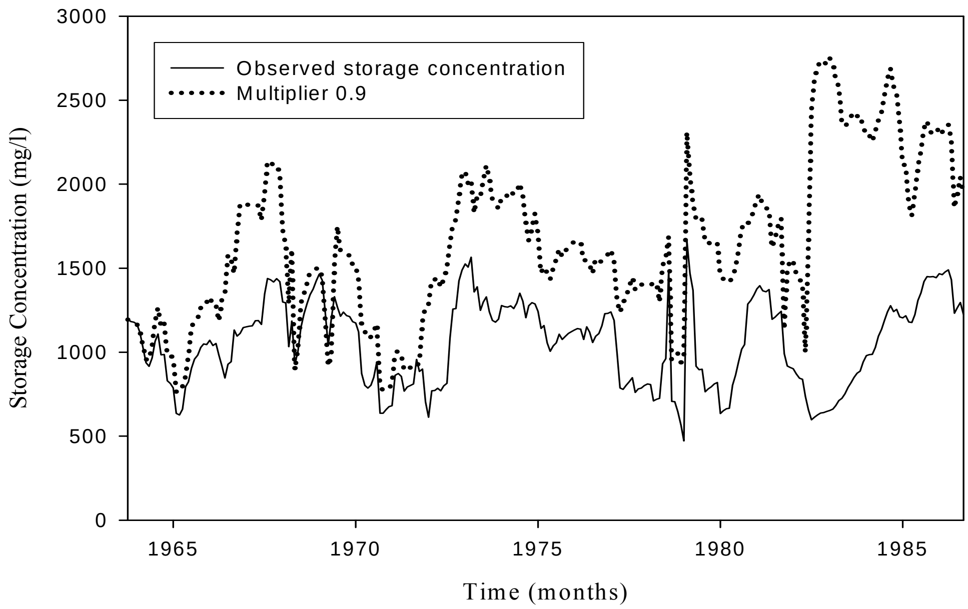


Figure D.47 Comparison of Observed and Simulated Storage Concentration at Whitney Reservoir (Multiplier 0.9, TM Option 2)

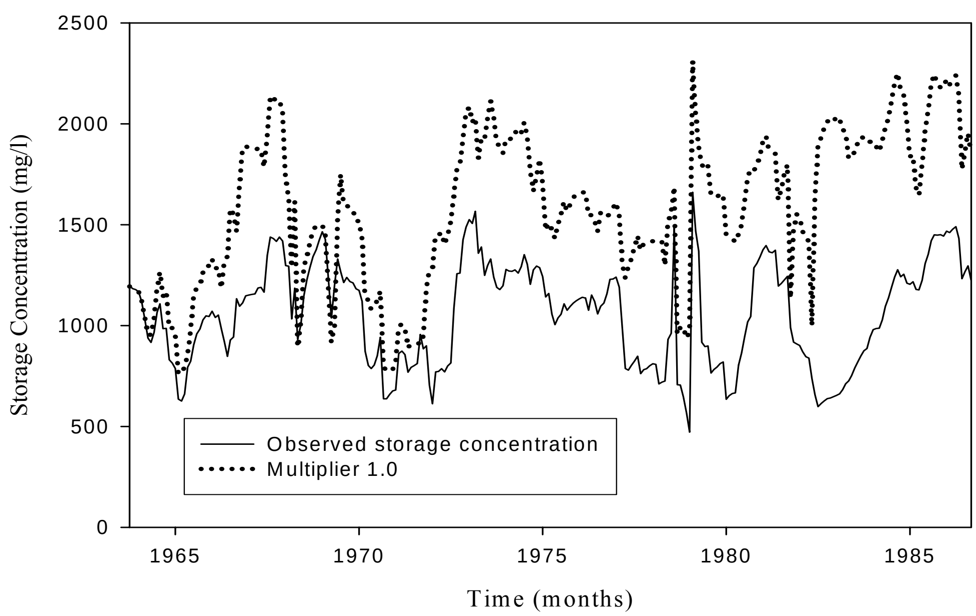


Figure D.48 Comparison of Observed and Simulated Storage Concentration at Whitney Reservoir (Multiplier 1.0, TM Option 2)

VITA

Chi Hun Lee was born in Jeju, Korea. He is the son of Mr. Jejoong Lee and Mrs. Dukja Ko. He received his B.S. and M.S. degree in civil engineering from Hongik University in 2001 and 2003. After receiving his M.S. degree, he entered the Research Center for Disaster Prevention & Safety Management in Hongik University and worked for one year as a researcher in the field of hydraulics and hydrology. Also, he worked for one year as a lecturer at Seoil University, Korea. Since joining the water resources engineering program in the Civil Engineering Department at Texas A&M University for his doctoral degree, his research has been focused on the salinity impacts on water resources management. He graduated with his Ph.D. in May 2010. Dr. Lee can be contacted at:

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