Probability Analysis of the Relation of Salinity to Freshwater Discharge in the St. Sebastian River, Florida

By Shaun M. Wicklein and W. Scott Gain

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U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information write to:

District Chief
U.S. Geological Survey, WRD
Suite 3015
227 North Bronough Street
Tallahassee, FL 32301

Copies of this report can be purchased from:

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CONTENTS

FIGURES

TABLES

CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATIONS AND ACRONYMS

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter
inch (in)	25.4	millimeter
mile (mi)	1.609	kilometer
	Area	
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
	Flow Rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C = (°F-32)/1.8.

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Acronyms and additional abbreviations used in report:

SJRWMD St. Johns River Water Management District
USGS U.S. Geological Survey
µS/cm microsiemens per centimeter at 25 degrees Celsius

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Abstract

The St. Sebastian River lies in the southern part of the Indian River basin on the east coast of Florida. Increases in freshwater discharge due to urbanization and changes in land use have reduced salinity in the St. Sebastian River and, consequently, salinity in the Indian River, affecting the commercial fishing industry. Wind, water temperature, tidal flux, freshwater discharge, and downstream salinity all affect salinity in the St. Sebastian River estuary, but freshwater discharge is the only one of these hydrologic factors which might be affected by water-management practices.

A probability analysis of salinity conditions in the St. Sebastian River estuary, taking into account the effects of freshwater discharge over a period from May 1992 to March 1996, was used to determine the likelihood (probability) that salinities, as represented by daily mean specific-conductance values, will fall below a given threshold. The effects of freshwater discharge on salinities were evaluated with a simple volumetric model fitted to time series of measured specific conductance, by using nonlinear optimization techniques. Specific-conductance values for two depths at monitored sites represent stratified flow which results from differences in salt concentration between freshwater and saltwater. Layering of freshwater and saltwater is assumed, and the model is applied independently to each layer with the assumption that the water within the layer is well mixed. The model of specific conductance as a function of discharge (a salinity response model) was combined with a model of residual variation to produce a total probability model. Flow distributions and model residuals were integrated to produce a salinity distribution and determine differences in salinity probabilities as a result of changes in water-management practices.

Two possible management alternatives were analyzed: stormwater detention (reducing the peak rate of discharge but not reducing the overall flow volume) and stormwater retention (reducing peak discharges without later release). Detention of freshwater discharges increased the probability of specific-conductance values falling below a given limit (20,000 microsiemens per centimeter) for all sites but one. The retention of freshwater input to the system decreased the likelihood of falling below a selected limit of specific conductance at all sites. For limits of specific conductance (1,000 microsiemens per centimeter or 20,000 microsiemens per centimeter, depending on the site), the predicted days of occurrence below a limit decreased ranging from 17 to 68 percent of the predicted days of occurrence for unregulated flow.

The primary finding to be drawn from the discharge-salinity analysis is that an empirical-response model alone does not provide adequate information to assess the response of the system to changes in flow regime. Whether a given level of discharge can produce a given response on a given day is not as important as the probability of that response on a given day and over a period of many days. A deterministic model of the St. Sebastian River estuary based only on discharge would predict that retention of discharge peaks should increase the average salinity conditions in the St. Sebastian River estuary. The probabilistic model produces a very different response indicating that salinity can decrease by a power of three as discharges increase, and that random factors can predominate and control salinity until discharges increase sufficiently to flush the entire system of saltwater.

INTRODUCTION

The St. Sebastian River lies in the southern part of the Indian River on the east coast of Florida (fig. 1) and contributes about 16 percent of the total annual freshwater inflow to the Indian River (Knowles, 1995). Changes in land use in the St. Sebastian River basin for agriculture and land development have increased freshwater discharges into the system (Brown and others, 1962; Crain and others, 1975). These increases in freshwater inflow during storm events tend to reduce salinities in the Indian River, affecting the commercial fishing industry and resulting in loss of revenue (Indian River Lagoon Estuary Program, 1993).

Salinity conditions in the St. Sebastian River are highly dependent on patterns of mixing and circulation and on the volumetric contributions of saltwater and freshwater. The dynamic nature of streamflow and wind conditions causes variations in the relative contributions of saltwater and freshwater to the estuary, resulting in wide-ranging variations in salinity. Windspeed and direction, water temperature, tidal discharge, freshwater discharge, and downstream salinity generally affect salinity in an estuary. Freshwater discharge is the only one of these hydrologic factors which might be affected by water- management practices.

The St. Sebastian River estuary was predominantly a saline environment prior to development in the drainage basin that increased freshwater discharges. Large tidal influxes of highly saline water from the Indian River are much greater in volume than the relatively small freshwater inflows to the estuary from surface- and ground-water discharges. Density driven vertical stratification promotes increased saline conditions at the bottom of the St. Sebastian River by confining much of the less dense freshwater to the upper layers. Freshwater is preferentially transported from the system in the upper layers without completely mixing with, and diluting, the saltier water in lower layers.

Freshwater conditions at the bottom of the St. Sebastian River occur only infrequently in the undisturbed system and are associated with large stormwater inflows sufficient in volume and intensity to flush the heavier saltwater out of the river and into the Indian River. These freshwater conditions are of short duration primarily because the denser saltwater of the Indian River flows back into the lower reaches of the river with receding streamflow. Sustained high freshwater flows decrease salinity of the Indian River near the mouth of the St. Sebastian River, because the saltwater in the Indian River is being diluted. These high freshwater flows tend to reduce the average salinity of the Sebastian River also; but, dilution effects near the mouth of the St. Sebastian River are not observed further into the Indian River.

Changes in land use and urban development within the St. Sebastian River basin have increased both the total and peak rate of freshwater inflow into the river. Increased volumes and rates of inflow, in turn, have altered the general patterns of circulation and mixing within the estuary and have increased the frequency of occurrence of freshwater conditions above predevelopment conditions. Changes in mixing and circulation within the river system also affect constituent concentrations in water moving through the estuary.

Because average salinity conditions and the frequency of occurrence of freshwater conditions can have a defining effect on biological communities in the river, it is important to determine what effects changes in the freshwater flow regime may have on the river system. Uncontrolled factors, such as wind and salinity conditions in the Indian River and turbulent mixing in the St. Sebastian River, produce random variations in the observed response of salinity to freshwater discharge which cannot be predicted by strictly deterministic models, but which must be accounted for in any analysis of the effects of planned or unplanned changes in the river basin.

A conductance-monitoring network was established in May 1992 to provide data for calibration and verification of a two-dimensional deterministic hydrodynamic model of the St. Sebastian River. However, because of limitations of the deterministic model to simulate constituent diffusion due to vertical stratification of specific conductance, a statistical model was developed to predict specific conductance, and thus, salinity, from discharge. Salinity probability modeling is a tool used to predict salinity in an estuary that results from a range of hydrologic conditions. In order to develop a salinity probability model, the U.S. Geological Survey (USGS), in cooperation with the St. Johns River Water Management District (SJRWMD), conducted a study of data collected over a 4-year period to determine the relation of freshwater inflows on salinity within the St. Sebastian River estuary.

Purpose and Scope

This report describes a probability analysis of salinity conditions in the St. Sebastian River estuary, taking into account the effects of freshwater discharge

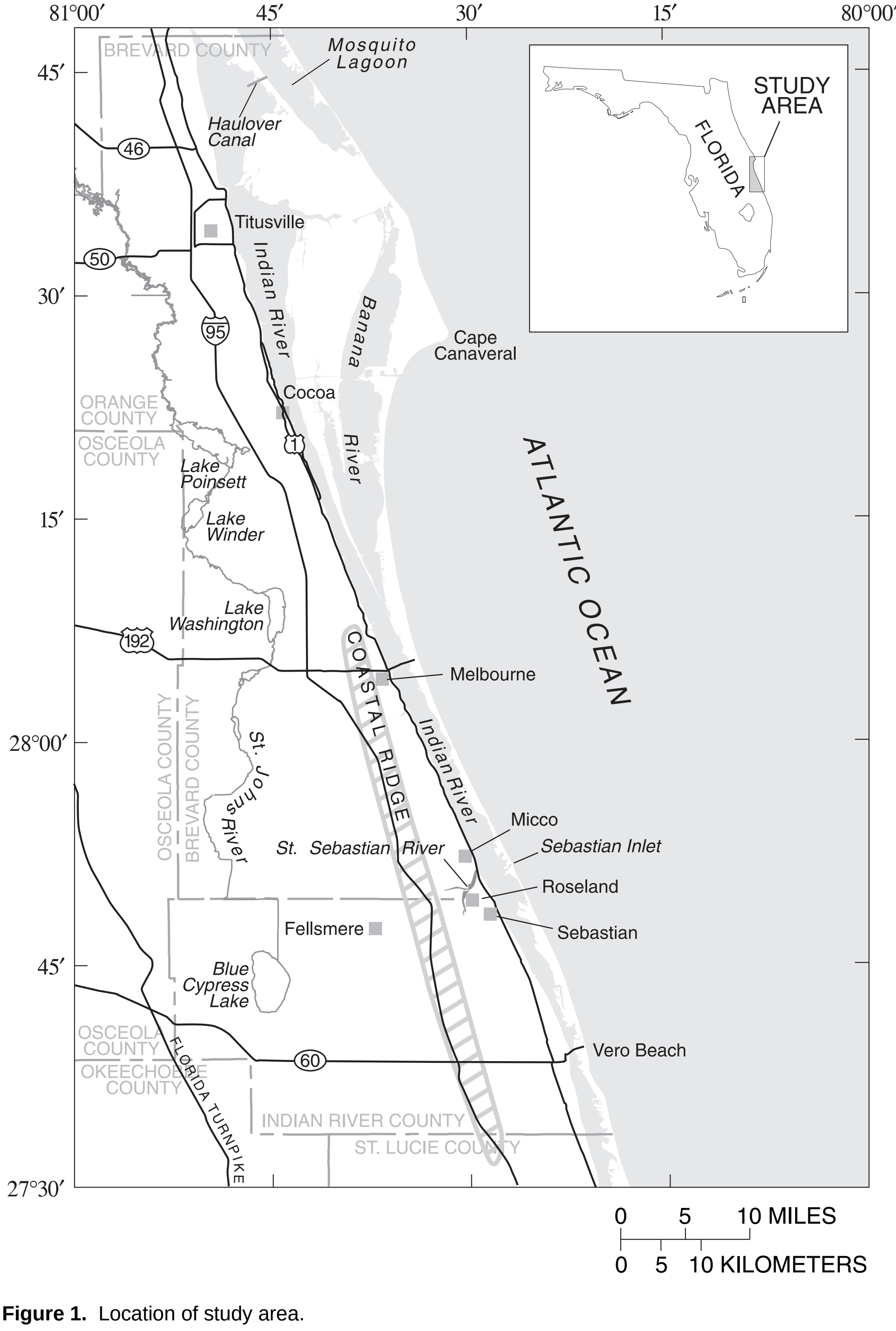


Figure 1. Location of study area.

over a period from May 1992 to March 1996. A probability analysis is used to determine the probability that salinities, as represented by daily mean specific-conductance values, will fall below a given threshold. The effects of freshwater discharge on salinities are evaluated with a simple volumetric model fitted to time series of measured specific-conductance values, by using nonlinear optimization techniques. The model of specific conductance as a function of discharge is combined with a model of residual variation to produce a total probability model. Flow distributions and model residuals are integrated to produce a salinity distribution and determine differences in salinity probabilities as a result of changes in watershed-management practices. There are three goals in development of the salinity-response model: (1) describe as much of the variation in specific conductance as possible in terms of freshwater discharge, (2) define a basic form of the model that is descriptive of all sites with a minimum number of degrees of freedom, and (3) eliminate bias in the residuals. Two possible management alternatives are analyzed: stormwater detention (reducing the peak rate of discharge but not reducing the overall flow volume) and stormwater retention (reducing peak discharges without later release). Tidal and freshwater flow conditions and probabilities are presented and discussed, as are the range and natural variability of salinity conditions in the estuary.

Description of Study Area

The St. Sebastian River lies on the boundary of Indian River County and Brevard County (fig. 1). The small town of Micco lies to the north, and the towns of Roseland and Sebastian lie to the south. Historically, swampy conditions over much of the St. Sebastian River basin precluded extensive development. The addition of a series of drainage canals led to the development of much of the southern part of the basin near the towns of Roseland and Sebastian. East of the St. Sebastian River is the Indian River, which is bordered to the east by a barrier island. Nearly due east of the mouth of the St. Sebastian River, breaching the barrier island, is Sebastian Inlet, one of only four connections between the Atlantic Ocean and the Indian River.

The shape of the land surface in the study area has changed little since Pleistocene time. The major landforms of the area are of two general types—terraces and ridges (Brown and others, 1962; Crain and others, 1975). Terraces and associated scarps were formed by ancient seas that once covered all of peninsular Florida. Ridges represent ancient shoreline deposits such as offshore sandbars and relict beaches.

The barrier island forming the east boundary of the Indian River is the remnant of an ancient offshore sandbar and forms a nearly continuous barrier to saltwater inflow. The barrier island extends more than 100 mi from Haulover Canal in the north (connecting the Indian River and Mosquito Lagoon) to the St. Lucie Inlet in the south. The barrier island ranges in altitude from 0 to about 25 ft and is breached in only two places—Sebastian and Fort Pierce Inlets. The coastal ridge is the first ridge west and inland of the Indian River, and ranges in altitude from about 5 to 50 ft. The natural effect of the coastal ridge is to block freshwater inflows from the west to the St. Sebastian River estuary. The coastal ridge extends from and forms the watershed boundary between the St. Johns River and Indian River. The natural drainage basin of the Indian River consists of a narrow strip of land, only a few miles wide in some locations, and over 100 mi long.

In recent decades, freshwater input to the Indian River has been increased by the channeling of water through manmade canals across the coastal ridge from the upper St. Johns River basin. Changes in the natural geomorphology, and consequently, in drainage characteristics of the Indian River and upper St. Johns River have affected the hydrology of the area, including the St. Sebastian River.

The subtropical climate of the Indian River basin is characterized by wet and dry seasons with frequent, intense thunderstorm activity during the wet season. The intensity of this thunderstorm activity creates a seasonal variation of up to twice the rainfall accumulation from dry to wet seasons (Knowles, 1995). Mean annual rainfall in the vicinity of the St. Sebastian River basin averages about 48 inches per year. Because of the seasonal variations in rainfall, freshwater inflow into the Indian River also varies by as much as 50 percent from dry to wet seasons. Seasonal variations in rainfall have little effect on the percentage of flow contributed to the Indian River by the St. Sebastian River basin.

The St. Sebastian River receives freshwater inflows from three major tributaries. North and South Prongs of the St. Sebastian River provide natural drainage from the north and south parts of the basin, respectively, and Canal 54 conveys water from areas to the west, much of which lie within the St. Johns River basin. Two smaller canals on the west end of Canal 54 drain the Fellsmere area and an area on the west side of the coastal ridge (fig. 2).

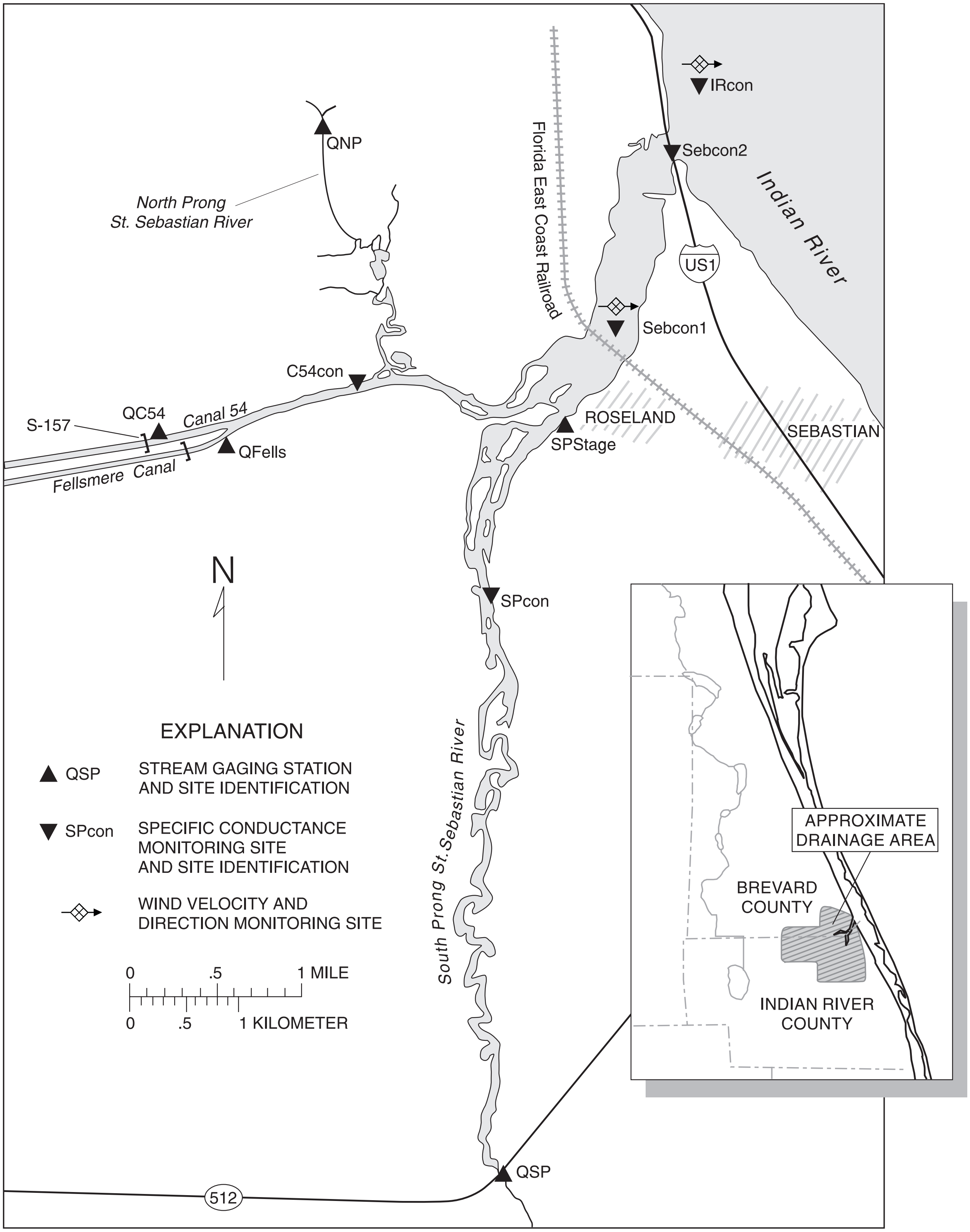


Figure 2. Data-collection sites, St. Sebastian River basin.

The North Prong St. Sebastian River is a small basin (approximately 28.5 mi^2) that is relatively undeveloped through the lower reaches and has been channeled in the upland reaches to provide drainage for citrus groves. The South Prong basin is larger than the North Prong basin and is approximately 63.7 mi^2. Urban land use in the upper basin is increasing as a result of expansion of the communities of Sebastian and Vero Lake Estates.

Canal 54 and Fellsmere Canal are manmade drainage systems that drain the inland areas of Brevard and Indian River Counties (Steward and VanArman, 1987). This inland area is referred to as the St. Johns Marsh, headwaters of the St. Johns River. Canal 54 drains about 100 to 150 mi^2 of the St. Johns Marsh, and the flow is controlled by Structure S-157. Fellsmere Canal is controlled by a weir structure and was dug to drain part of the St. Johns River Marsh for citrus cultivation.

The quality of water in the St. Sebastian River basin is determined by the mixing of waters from two principal sources: saltwater from the Atlantic Ocean propagated through the Indian River and upstream into the St. Sebastian River, and stormwater runoff input from natural and developed parts of the basin. Tidal fluctuations can generate substantial inflow of saltwater to the river. Tides along the east coast of Florida are primarily semidiurnal. Tidal variations throughout much of the St. Sebastian River typically produce changes in water-surface elevations of 0.5 ft. The rising and falling of tides in the St. Sebastian River results in transient storage changes of as much as 30 percent of the river’s volume. Tidal fluctuations are observed within the estuary as far upstream as structure S-157 on Canal 54 and State Road 512 on the South Prong of St. Sebastian River (fig. 2).

APPROACH

The data-collection network consists of ten sites: four stage and discharge sites, located at the major freshwater inputs into the St. Sebastian River; one stage-only site, located near the confluence of the North and South Prongs of the St. Sebastian River; and five conductance-monitoring sites. The conductance-monitoring sites were located at two upstream locations, located on the South Prong and Canal 54, and three downstream locations, one near the confluence of the North and South Prongs, another downstream at the crossing of U.S. 1, and the third in the Indian River just outside the mouth of the St. Sebastian River (fig. 2).

Data-collection sites were selected to provide representative information on main inflows and controlling hydrologic features within the study area. Types of data collected at each site were selected based on features of the site location and need for information at the location. Conductance data were collected to represent the inputs and outputs of the estuary and describe vertical stratification within the water column. Stage was measured at several locations throughout the study area, and discharge was measured at points of freshwater input to the system. Meteorological data were collected to represent weather conditions in and near the estuary. Information on data-collection sites, along with type of data collected, is presented in table 1.

Stage was measured at nine locations in the study area, five that are within the estuary: South Prong St. Sebastian River near Roseland (SPcon), South Prong St. Sebastian River at Roseland (SPStage), Canal 54 near North Prong St. Sebastian River (C54con), St. Sebastian River near Railroad Bridge (Sebcon1), and St. Sebastian River at U.S. 1 at Sebastian (Sebcon2) (fig. 2). The site SPStage was selected to represent stage for the entire estuary.

Discharge was determined at South Prong St. Sebastian River at Highway 512 near Sebastian (QSP), Fellsmere Canal near Micco (QFells), Canal 54 at S-157 near Micco (QC54), and North Prong St. Sebastian River near Micco (QNP). Continuous measurement of stage and measurement of discharge (six times per year) were performed at three of the sites: South Prong, North Prong, and Fellsmere Canal. Stage and discharge data for the Canal 54 were measured by the SJRWMD. All other stage and discharge data were collected by the USGS using standard methods described in Rantz and others, 1982.

Windspeed and direction data were collected at two locations: Sebcon1, within the estuary, and IRcon, just outside of the mouth of the estuary. Mean windspeed and wind direction were recorded at 15-minute intervals at St. Sebastian River near Railroad Bridge and Indian River near Sebastian.

Specific conductance was monitored at five sites: C54con, SPcon, Sebcon1, Sebcon2, and IRcon. Conductance was measured at 15-minute intervals at selected depths (table 2), and the measurement was corrected using water temperature to obtain a measurement of specific conductance corrected to 25 °C (Miller and others, 1988).

Table 1. Data-collection sites, St. Sebastian River basin, Fla.

[mi^2, square miles; data type: d, discharge; e, stage; c, conductance; t, temperature; r, rainfall; ws, windspeed; wd, wind direction; I, indeterminate; U, unknown; SJRWMD, St. Johns River Water Management District. Sites shown in figure 2]

Site	Site name and identification number	Latitude	Longitude	Date established	Drainage area (mi^2)	Data type
QSP	South Prong St. Sebastian River at State Road 512 (02251000)	27° 46' 09"	80° 30' 22"	05-04-93	35.0	d, e
SPcon	South Prong St. Sebastian River near Roseland (02251200)	27° 49' 06"	80° 30' 31"	02-09-87	61.2	e, c, t
SPStage	South Prong St. Sebastian River at Roseland (02251210)	27° 49' 56"	80° 30' 01"	02-10-87	[1]63.7	e
QFells	Fellsmere Canal near Micco (02251767)	27° 49' 49"	80° 32' 04"	01-15-91	I	d, e
QC54	Canal 54 at S-157 near Micco (SJRWMD)	27° 49' 49"	80° 32' 25"	U	I	d, e, r
C54con	Canal 54 near North Prong Sebastian River (275007080311200)	27° 50' 07"	80° 31' 12"	04-15-92	I	e, c, t
QNP	North Prong St. Sebastian River near Micco (02251500)	27° 51' 21"	80° 31' 28"	01-22-87	28.5	d, e
Sebcon1	St. Sebastian River near Railroad Bridge (275017080295600)	27° 50' 17"	80° 29' 56"	05-01-92	I	e, c, t, r, ws, wd
Sebcon2	St. Sebastian River at U.S. 1 at Sebastian (275114080292800)	27° 51' 14"	80° 29' 28"	05-14-92	I	e, c, t
IRcon	Indian River near Sebastian (275128080291800)	27° 51' 28"	80° 29' 18"	07-01-92	I	c, t, r, ws, wd

[1] Approximate drainage area.

A regression equation was developed using the relation of specific conductance to salinity at 25 °C (Neumann and others, 1966):

$$S = 0.0015C^2 + 0.578C + 0.019\,, \qquad (1)$$

where S is salinity (dissolved solids), in parts per thousand; and

C is specific conductance at 25 °C, in millisiemens per centimeter.

Because of this relation between salinity and specific conductance, defined by equation 1, specific conductance is used as an indicator of salinity in this report.

Elevation of the channel bottom in the vicinity of the gages ranged from 3.0 to 4.5 ft below sea level (table 2). Conductance measurements made in the upper layer of the water column were made at an average of 1.5 ft below the surface. Measurements made in the lower layer of the water column were made at an average of 4.3 ft below the surface. Because of the locations of the gage installations, the conductance measurements for SPcon were made in the upper layer, whereas conductance measurements at C54con were made in the lower layer.

Table 2. Conductance probe measurement locations and mean stage for St. Sebastian River basin conductance-measurement sites, May 1, 1992, to March 18, 1996

[Gage datum is 10.0 feet below sea level; --, not available]

Site	Elevation in feet above gage datum			
	Mean stage	Top probe	Bottom probe	Stream-bed
SPcon[1]	10.7	10.0	--	6.0
C54con[1]	10.7	--	6.0	5.5
Sebcon1	10.7	9.5	7.4	7.0
Sebcon2	10.8	8.7	5.9	5.7
IRcon[2]	10.5	8.5	6.0	5.5

[1] Site has only one probe.
[2] Mean stage not based on entire period.

Daily mean values of stage and surface area of the estuary were used to compute storage volumes and tidal flux for the system. Discharge was computed for the major inputs into the estuary system, and vectors of wind velocity and direction were computed from meteorological data collected over the study period. Daily mean specific conductance was used to represent salinity conditions within the system. Probabilities were computed for the occurrence of specific values of discharge and specific conductance from the observed data. A statistical model of specific conductance as a function of discharge was developed for the period from May 1992 to March 1996, and a second statistical model of residuals as a function of discharge was developed and combined with the specific-conductance model to produce estimated duration curves. By using this approach, probabilities of a particular specific-conductance value exceeding or failing to exceed a limit were computed for two alternative management scenarios, one for retention and the other for detention of freshwater discharges.

FACTORS AFFECTING SALINITY CONDITIONS IN THE ST. SEBASTIAN RIVER

Salinity conditions in the St. Sebastian River are highly dependent on patterns of mixing and circulation, and the relative volumes of saltwater and freshwater in the estuary. Wind, tidal flux, freshwater discharge, and system flushing affect specific conductance within the St. Sebastian River. Movement of water into and out of the estuary affects specific conductance and can be described by flushing characteristics of the system. The dynamic nature of streamflow and wind conditions cause variations in the relative volumes of saltwater and freshwater in the estuary and produce wide-ranging variations in salinity.

Wind

The shape and location of the St. Sebastian River estuary play a role in wind effects on tidal action within the system. Wind and salinity conditions in the Indian River and turbulent mixing in the St. Sebastian River produce random variations in the observed response of salinity to discharge which cannot be predicted but which must be accounted for in any analysis of salinity conditions in the river.

Monthly mean, mean monthly for all years of record, and annual mean windspeed and vector direction were calculated for each site and are shown graphically in figure 3. Mean values were calculated for normal components of wind velocity and direction so that the average direction and speed indicated is the final disposition of a wind-carried particle tracked over a monthly or annual time period. The wind vector summary in figure 3 indicates that winds across the estuary blew from a net northeasterly direction for the study period; however, this may not be indicative of a prevailing northeast wind. Generally, winds change throughout the day as offshore winds increase in the afternoon and frontal systems move through the area. Winds outside of the St. Sebastian River basin in the Indian River originate from a predominantly northwesterly direction.

Wind affects tidal transport within the confines of a shallow estuary (Smith, 1990). Winds prevailing from the north and northeast build up water within the St. Sebastian River estuary system. When high tides and strong winds combine, a large volume of water is forced farther upstream into the system. This combination of tide and wind is more likely to occur during the fall and winter months, when monthly mean winds prevail from the north and northeast and tidal storage is greatest. Although long-term prevailing winds can build up water within the estuary, tidal changes and freshwater discharges are still the primary factors affecting salinity. Short-term variable winds are more common in the afternoon during summer months and can cause turbulence within the system; this turbulence causes random variation in salinity during times of high salinities and lower freshwater flows.

Tidal Flux

Tidal influxes of highly saline water from the Indian River to the St. Sebastian River are much greater in volume than the relatively small freshwater inflows from surface- and ground-water sources. Tidal flux within the system is propagated by change in stage within the estuary. A graph of daily mean stage at the SPStage site indicates seasonal and monthly variations in stage that occur in close association with the Atlantic Ocean tides (fig. 4). Highest tides during the year generally are in October and November and lowest tides typically are from February through April. The stage change due to tides ranges from 2 to 3 ft in a typical year, and averages 0.5 ft over a typical tidal cycle. Although peak freshwater discharges from the St. Sebastian River commonly are observed in October and November, tidal flux appears to be the more important factor affecting stage within the estuary.

Storage for the St. Sebastian River was calculated using a model grid and a volume for each cell of the grid. Mean water-surface elevation (stage) in feet above sea level and bathymetric data were used to determine the depth of each grid cell. The total mean storage upstream from each of the four St. Sebastian River conductance-monitoring sites was calculated by summing the cell volumes upstream of the respective sites. The volume upstream from Sebcon2 (fig. 2) represents the total storage volume for the entire St. Sebastian River estuary.

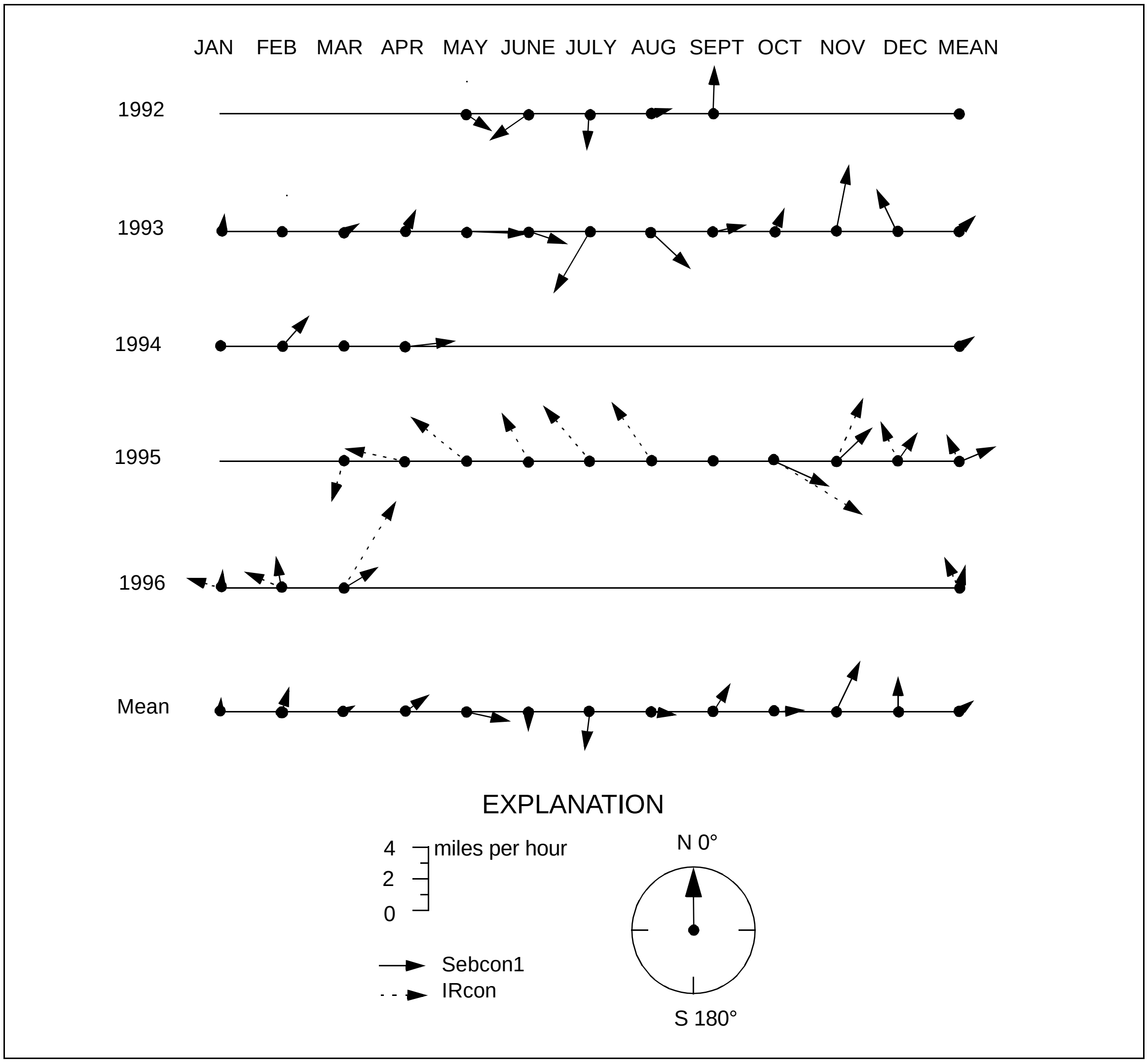


Figure 3. Wind vector summary for St. Sebastian River basin, May 1, 1992, to March 18, 1996. Arrowheads point towards direction from which wind originates.

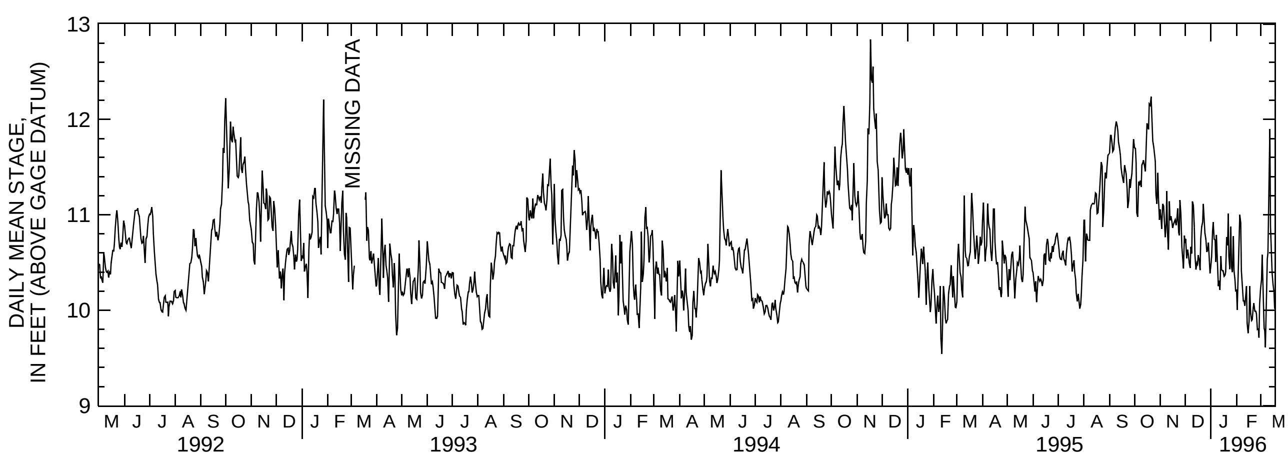


Figure 4. Daily mean stage at South Prong St. Sebastian River at Roseland, Fla. (SPStage).

The computed tidal flux represents a rate (positive or negative) of water flowing through a given cross section of the river and is considered the average flow rate of water as a result of stage change that passed through the cross section in one day. Tidal flux is computed as the average absolute value of tidal changes in storage calculated as the product of surface area and change in stage over tide cycles adjusted for the actual duration of inflow. Water-surface areas upstream from Sebcon2, Sebcon1, and C54con were estimated based on 7.5-minute USGS quadrangle maps. Water-surface area upstream of SPStage was estimated using change in stage and a regression equation that relates cross-sectional area to stage; this approach accounted for changes in surface area with changes in stage. Tidal flux, Q_T, in cubic feet per second, was calculated from change in stage and surface area by using the following equation:

$$Q_T = \frac{(\sum|\Delta H(SA)|)/2}{86,400}, \qquad (2)$$

where ΔH is 15-minute stage change, in feet; and
SA is surface area upstream from the site, in square feet.

Flow reversals and stratification of flow due to density gradients are common within the St. Sebastian River estuary, and tidal flux (fig. 5) does not exhibit the seasonal variations observed in daily mean stage. Over a full tidal cycle, the net tidal flux approaches zero because the volume of water that flows into the estuary is approximately equal to the volume that flows out.

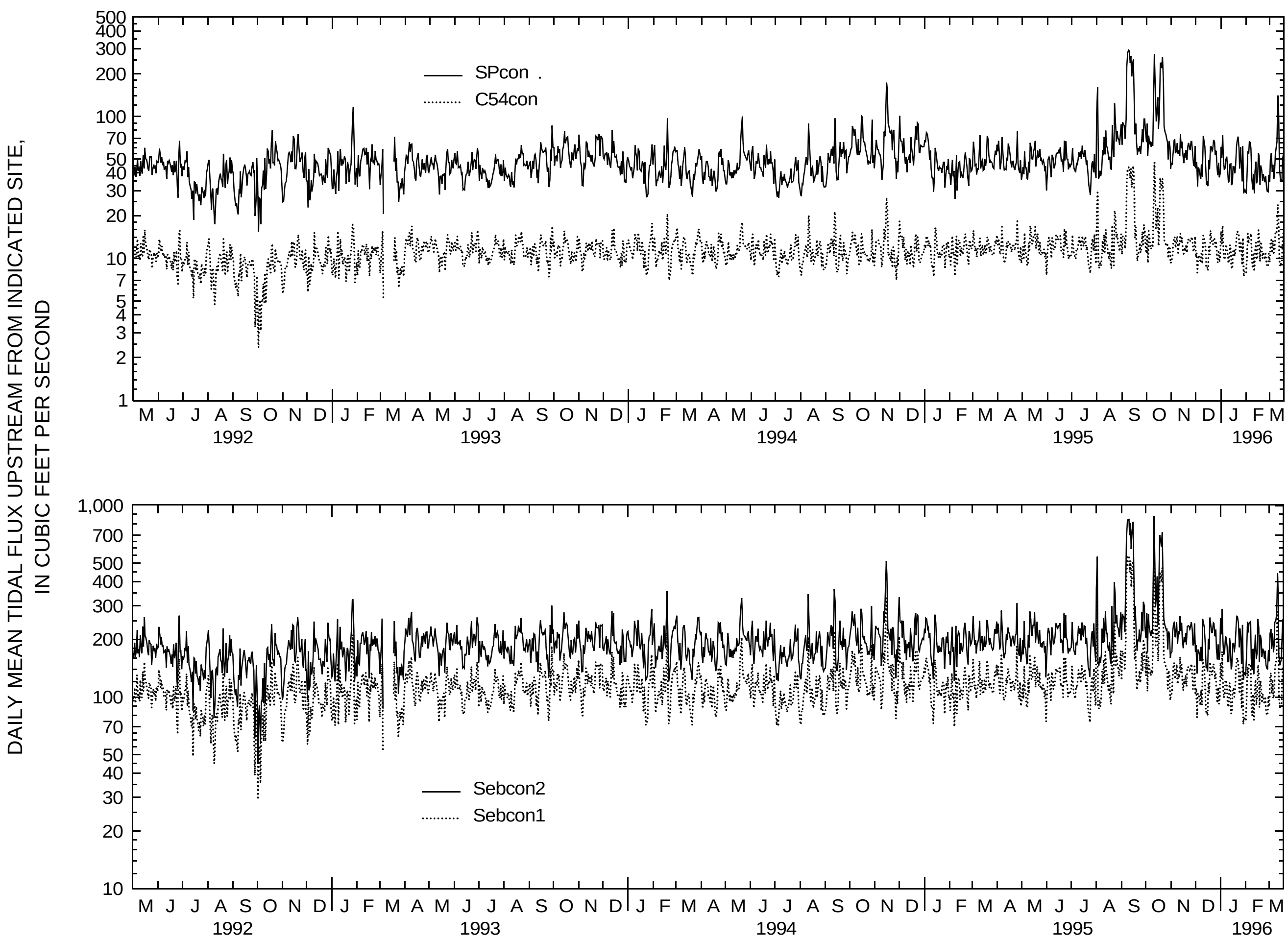


Figure 5. Daily mean tidal flux at St. Sebastian River basin.

Table 3. Tidal flux summary for St. Sebastian River basin, May 1, 1992, to March 18, 1996

[ft^2, square feet; ft^3/s, cubic feet per second]

Site	Upstream surface area (ft^2)	Maximum daily tidal flux[1] (ft^3/s)	Minimum daily tidal flux[2] (ft^3/s)	Mean tidal flux 1992-1996 (ft^3/s)
SPStage	[3]5,840,000	291	15.5	51.0
C54con	1,410,000	47.5	3.36	11.6
Sebcon1	14,100,000	551	29.2	118
Sebcon2	23,800,000	878	45.3	198

[1]October 11, 1995, at all sites except SPStage (September 9, 1995).
[2]October 2, 1992.
[3] Median upstream surface area.

Maximum, minimum, and mean tidal flux at selected sites (table 3) indicate the variability in tidal flux with location. Tidal flux at the mouth of the St. Sebastian River (represented by Sebcon2) ranged from 45.3 to 878 ft^3/s throughout the study period. Tidal flux decreased from downstream to upstream and the South Prong (SPStage) had a higher flux than Canal 54 (C54con). In November 1994, tropical storm Gordon produced the highest recorded stage during the study, but the increase in tidal flux resulting from the storm was relatively small. If freshwater inflow is assumed to be equal to zero, then the tidal flux, based on the annual mean value for the study, could flush the system in about 5.5 days. Based on tidal flux at the mouth of the estuary (Sebcon2), the system could be flushed in 1.3 days assuming the maximum value of tidal flux, and in 24.8 days assuming the minimum value of tidal flux. Saltwater in the upstream reaches of the river is flushed downstream more rapidly; the rate of flushing slows as the river becomes wider and deeper near the mouth.

Freshwater Discharge

Changes in land use and increased development within the St. Sebastian River basin tend to increase the total and peak rate of flow of freshwater into the river. Increased volumes and rates of inflow can, in turn, alter the general patterns of circulation and mixing within the estuary. Freshwater conditions at the bottom of the river occur only infrequently in the undisturbed system and are associated with large stormwater inflows sufficient in volume and rate to push the denser saltwater out of the St. Sebastian River and into the Indian River.

Time series of daily mean freshwater discharge data were compiled at the four major freshwater inputs (sites QSP, QFells, QC54, and QNP) into the St. Sebastian River estuary for the study period 1992-96 except for site QSP, which was installed in May 1993. Daily mean freshwater discharge data for missing periods were estimated using a multiple stepwise regression analysis on comparable discharge data at similar sites. Daily mean discharge record for South Prong St. Sebastian River was extrapolated to the beginning of the study period, and daily mean discharges for part of the fourth quarter of the 1995 water year for Fellsmere Canal were estimated. Runoff into the system from intermediate drainage between measured inputs and the mouth of the estuary is relatively insignificant. Thus, freshwater discharges at downstream sites are considered equivalent to the summation of freshwater discharges from upstream sites. Discharges for the major freshwater inputs (fig. 6) were combined to obtain total freshwater discharge for the entire system.

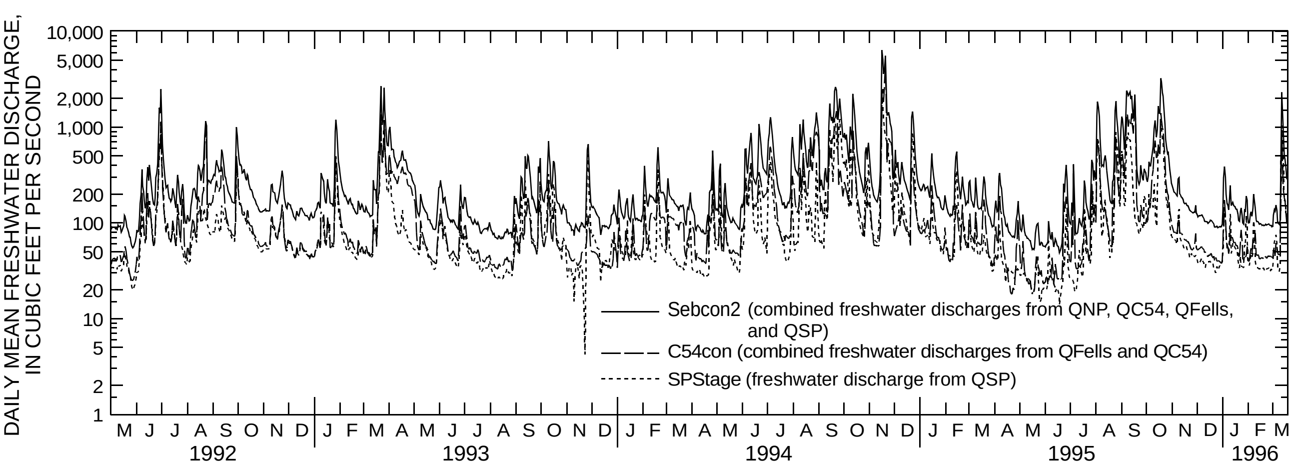


Figure 6. Daily mean freshwater discharges at South Prong St. Sebastian River at Roseland (SPStage), Canal 54 near North Prong St. Sebastian River (C54con), and St. Sebastian River at U.S. 1 at Sebastian (Sebcon2).

Table 4. Daily mean freshwater discharge summary for St. Sebastian River basin

[All discharge values are in cubic feet per second]

Site	Maximum daily discharge	Date	Minimum daily discharge	Date	Annual mean discharge 1992	1993	1994	1995	[1]1996	Mean discharge	Years
QSP	2,300	11-16-94	4.2	11-23-93	[1]89.5	88.0	177	114	87.7	117	1992-1996
QFells	1,780	11-16-94	18	04-21-95	67.1	75.2	118	94.3	59.5	91.9	1992-1996
QC54	3,990	11-20-94	0	multiple days	24.1	30.3	110	64.1	20.0	42.2	1971-1996
QNP	1,740	11-16-94	6.3	06-20-89	39.3	39.9	89.5	70.9	45.9	44.1	1987-1996
Total										**295.2**	

[1]Based on partial year.

Combined daily mean freshwater discharges ranged from 50 to 6,400 ft^3/s (during tropical storm Gordon, November 1994). The annual mean freshwater discharge of the system was 295 ft^3/s (table 4). A freshwater flux equivalent to the annual mean discharge would flush the system in 3.8 days. At minimum discharge, the freshwater flux would flush the system in 22.4 days. Tropical storm Gordon produced the maximum freshwater flow during the study; the freshwater flux for this storm would flush the system in less than 5 hours, or 0.2 day.

System Flushing

Salinity conditions in the St. Sebastian River are dependent on patterns of mixing and circulation of freshwater and saltwater. System flushing is based on inflow rates; flushing rates are determined by combining freshwater and saltwater inflows. Flushing periods presented in this report represent a minimum time in which the system contents will be replaced by new incoming water.

The time required for one system-volume of water in an estuary to be replaced may be expressed in terms of a tidal flushing period. Computation of a flushing period based on inflow rates assumes that freshwater and tidal inflows do not mix within the system, and that the first water into the system is the first water to leave the system. Due to stratification of flow observed in the estuary, these conditions typically do not exist. Calculations of flushing period, therefore, represent a minimum amount of time in which the system volume is replaced by either tidal flux, from incoming saltwater, or freshwater discharge from upstream sources. This minimum flushing period is calculated as the ratio of system-volume to daily flux for various values of tidal flux and freshwater inflow.

Flushing rates based on the combination of tide and freshwater discharge can be used to evaluate flushing characteristics of the system. The minimum time required for complete flushing of the entire system, based on minimum tidal flux and freshwater discharge, is 8.5 days. Combining tidal flux and freshwater discharge decreases the minimum time required to purge the system to one-third of the time required for tidal flux or freshwater discharge alone. Combined maximum tidal flux and freshwater discharge decreases the minimum flushing rate by less than 1 hour, to about 4 hours, compared to the flushing rate for maximum freshwater discharge alone. The combined mean freshwater and tidal fluxes flush the system in about 2.5 days on average. Based on the vertical stratification observed in this system, freshwater discharge typically is confined to the upper layer of flow. Therefore, the flushing times for upper and lower layers probably are significantly different. It is estimated that, during average conditions, the flushing period for the upper freshwater layer would be considerably less than 2.5 days, whereas the flushing time for the lower layer (due to tidal flux) would be about 3 to 4 days.

Flushing rates for system volumes can be combined with freshwater discharge probabilities to obtain a likelihood of flushing the system at a given flux (fig. 7). Ignoring mixing and stratified flow, freshwater discharges are sufficient to flush the South Prong upstream from its confluence with the St. Sebastian River (SPStage) and to flush the St. Sebastian River upstream from its confluence with the Indian River (Sebcon2) in a single day up to 9 percent of the time. Freshwater discharges are sufficient to flush Canal 54 upstream from site C54con in a single day up to 19 percent of the time.

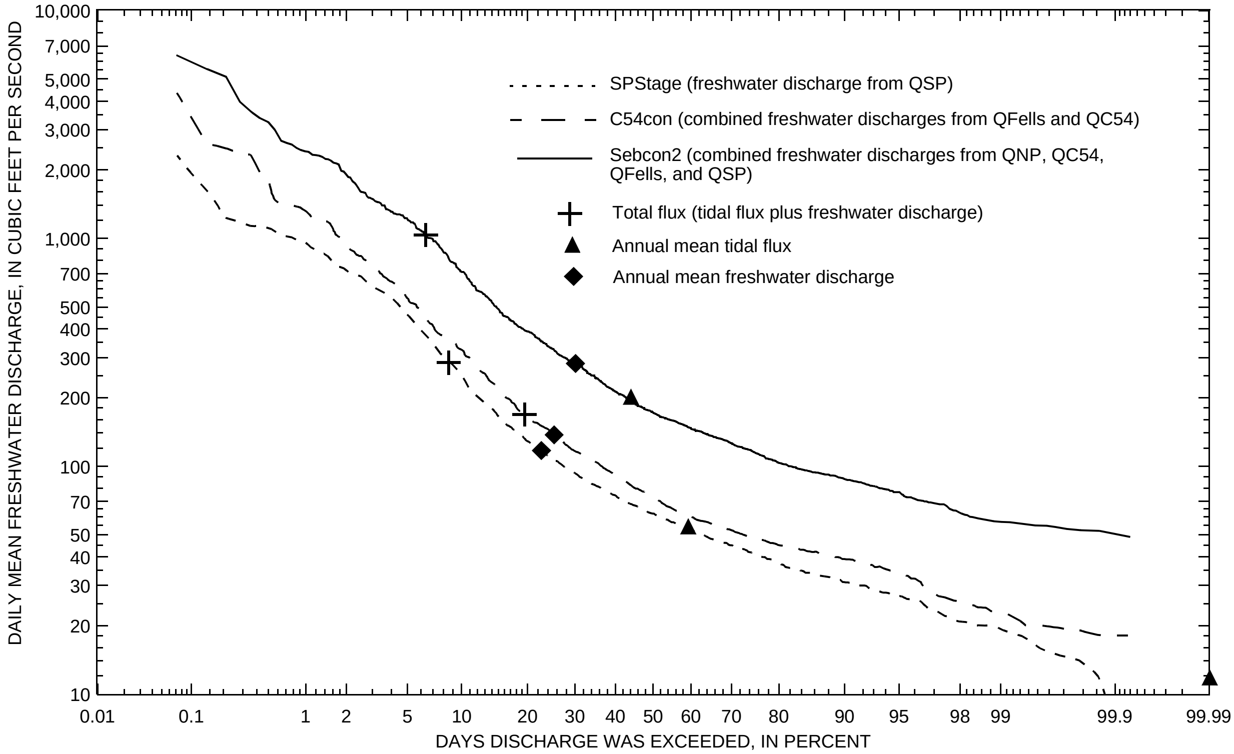


Figure 7. Discharge duration curves for South Prong St. Sebastian River at Roseland (SPStage), Canal 54 near North Prong St. Sebastian River (C54con), and St. Sebastian River at U.S. 1 at Sebastian (Sebcon2).

Annual mean tidal flux and annual mean freshwater discharge can be plotted on the same graph with freshwater discharge duration curves to obtain an estimate of the probability that freshwater discharges will exceed the annual means of tidal flux and freshwater discharge. Daily mean freshwater discharges will exceed the combined annual mean freshwater discharge, 295 ft^3/s (represented by the discharge-duration curve for site Sebcon2), 28 percent of the time and daily mean freshwater discharge will exceed the annual mean tidal flux, 198 ft^3/s, 45 percent of the time at Sebcon2.

SPECIFIC-CONDUCTANCE CHARACTERISTICS

Daily mean specific-conductance values for the upper and lower layers were calculated for each of the five conductance data-collection sites. Mean and standard deviation of differences between the upper layer and lower layer specific-conductance values were computed for each site by using instantaneous and daily mean values. The statistics were computed for the entire study period and for data divided into seasons (wet and dry); the resulting statistics are discussed later in this report.

Conductance data exhibit long-term serial correlation attributed to the gradual mixing of water upstream from day to day. Instantaneous and daily mean values of specific conductance were used as a comparison of the range of daily values. Standard deviations of daily mean specific conductance are smaller than the standard deviations of instantaneous specific-conductance values. Daily mean specific-conductance values were used for comparison and analysis in order to reduce the size of the data set, smooth the data set by averaging in outliers, reduce serial correlation, and maintain trends and characteristics of relatively short-term events. The use of daily mean specific-conductance values rather than instantaneous values did not cause any bias in the data analysis. The use of daily mean specific-conductance values may not reflect short-term extremes but better represents the general trend of the data.

In general, the daily range in instantaneous specific-conductance values is greater in the upper layer than in the lower layer at Sebcon2 (fig. 8). The daily range of instantaneous specific-conductance values tends to increase with increasing daily mean specific

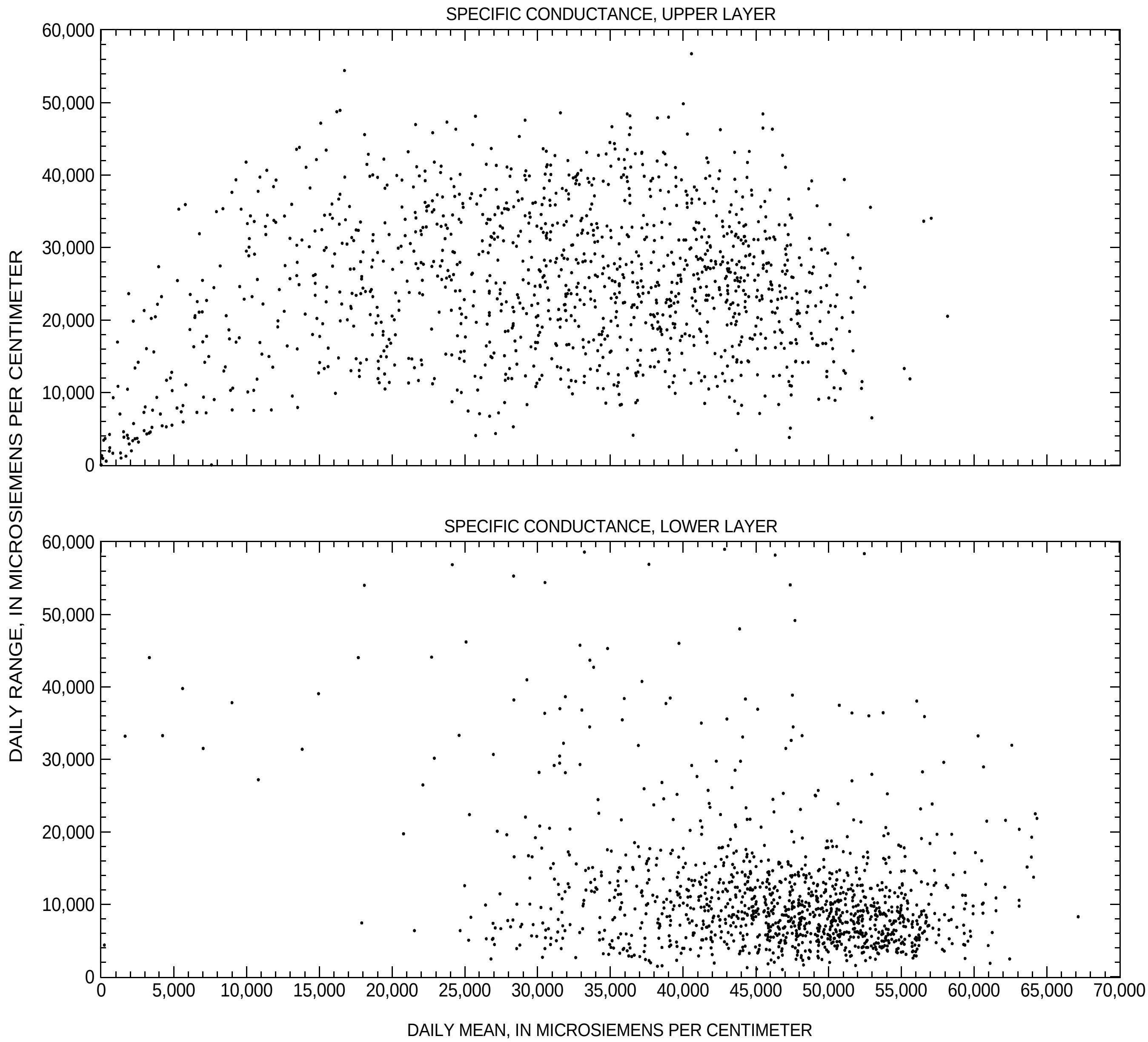


Figure 8. Daily range of specific-conductance values for St. Sebastian River at U.S. 1 at Sebastian (Sebcon2).

conductance to a maximum of about 50,000 µS/cm for daily mean specific conductances above about 15,000 µS/cm. Instantaneous specific conductance of the lower layer generally remains within a narrow range over the period of a day, typically ranging less than 20,000 µS/cm.

Time series of daily mean specific conductance data indicate some evidence of long-term seasonal trends associated with periods of sustained or diminished freshwater inflows; large changes in specific conductance were observed for a limited number of large storms. Though much of the long-term variation in specific conductance can be related to discharge, much of the short-term variation is not strongly related to discharge and appears to be influenced by other factors.

Daily mean specific-conductance values generally increased with distance downstream; values at C54con typically exceed values at SPcon (table 5). Specific-conductance values upstream from Sebcon1 ranged from near seawater values to freshwater values, less than 500 µS/cm, during the study. At the mouth of the estuary (site Sebcon2) specific-conductance values in the freshwater range were common in samples from the upper layer and values for upper and lower layers indicate greater stratification than at sites upstream from the mouth.

Table 5. Daily mean specific-conductance summary for St. Sebastian River basin, May 1, 1992, to March 18, 1996

[Specific-conductance values are in microsiemens per centimeter at 25 degrees Celsius; --, no data available]

Site	Maximum daily mean conductance	Date of sample	Minimum daily mean conductance	Date of sample	Annual mean conductance					Mean conductance 1992-1996
					1992	1993	1994	1995	1996	
C54con	55,600	05-14-93	270	10-19-95	26,400	28,800	17,500	24,500	27,100	24,000
SPcon	45,400	05-22-95	120	09-13-95	--	9,940	2,780	8,730	6,630	6,620
Sebcon1-upper[1]	53,800	09-04-93	120	10-19-95	27,800	20,100	15,200	15,500	20,200	22,000
Sebcon1-lower[2]	58,400	06-21-92	140	10-25-95	36,000	35,900	27,800	27,800	30,700	33,600
Sebcon2-upper[1]	58,100	06-21-95	350	10-19-95	31,500	33,300	26,600	32,400	35,300	31,400
Sebcon2-lower[2]	67,200	11-06-93	1,650	10-18-95	43,700	48,400	45,700	45,300	46,200	46,700
IRcon-upper[1]	62,800	10-09-92	7,670	10-17-95	39,000	43,900	43,800	43,100	28,300	42,500
IRcon-lower[2]	67,200	04-11-94	14,200	10-17-95	42,600	45,700	48,400	46,500	40,500	45,800

[1]Upper layer in the vertical water column.
[2] Lower layer in the vertical water column.

The range in observed specific-conductance values may be characterized by a family of duration curves. Daily mean specific-conductance duration curves indicate the number of days within a given period for which specific conductance is expected to be below a given value (Searcy, 1959; Riggs, 1968b). Duration curves presented in this report do not represent probabilities of specific-conductance values being less than a given specific conductance on any particular day; rather the curves represent the percent of time that the specific conductance can be expected to be less than a given value.

Duration curves for specific conductance at five conductance data-collection sites and for each layer are shown in figure 9. The change from lower conductance waters upstream to higher conductance waters downstream and comparison of upper layer to lower layer variations are apparent. The freshwater and saltwater layering in the system can be conceptualized as a wedge of less saline water on top of a wedge of saltwater. The similarities in shape and distribution of the specific-conductance duration curves from the upper layer specific-conductance values at the mouth of the estuary, Sebcon2-upper, and the lower layer specific-conductance values near the middle of the estuary, Sebcon1-lower, illustrate the wedges of freshwater and saltwater.

The differences in specific conductance from lower to upper layers indicate an increase in vertical stratification as the water in the estuary is channeled in and out of the constriction at the U.S. 1 bridge (Sebcon2) (fig. 2 and table 6). Stratification of flow in the St. Sebastian River has little effect on the daily mean specific-conductance values from lower to upper layers in the

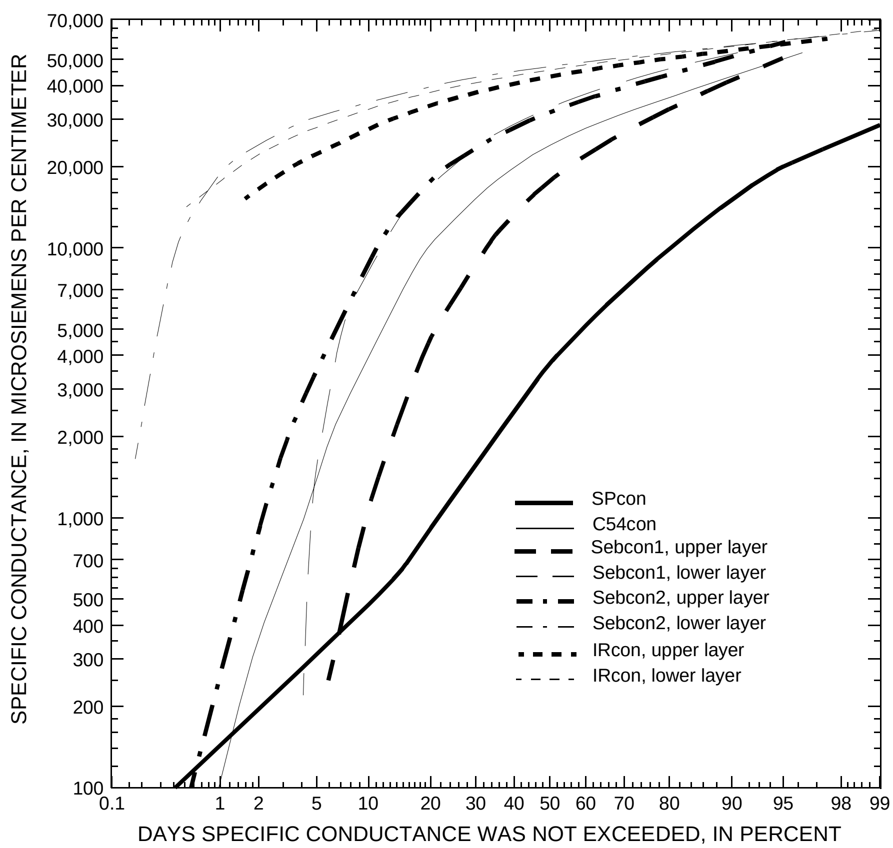


Figure 9. Specific-conductance duration curves for data-collection sites.

Table 6. Seasonal and period of record lower-layer to upper-layer differences for instantaneous and daily mean values of specific conductance, May 1, 1992, to March 18, 1996

[Specific-conductance values are in microsiemens per centimeter at 25 degrees Celsius; inst., instantaneous]

Site	Period of record		Wet season[1]		Dry season[2]	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Sebcon1 (inst.)	10.29	13.14	8.19	12.79	13.89	12.96
Sebcon1 (daily)	10.18	11.68	9.02	12.38	12.05	9.73
Sebcon2 (inst.)	15.30	13.32	16.81	14.05	14.11	12.59
Sebcon2 (daily)	15.41	10.33	16.96	11.13	14.19	9.49
IRcon (inst.)	3.39	7.07	3.38	7.44	3.39	6.60
IRcon (daily)	3.38	6.04	3.34	6.29	3.42	5.74

[1]June through October.

[2]November through May.

nearby Indian River, as indicated by the small vertical differences in means at IRcon. Overall, the difference in daily mean specific-conductance values from lower to upper layers increases with distance downstream within the St. Sebastian River and decreases in the Indian River, indicating greater layering in the St. Sebastian River than in the receiving water body, the Indian River.

Duration curves of specific conductance grouped by discharge ranges were computed for the conductance-monitoring sites (fig. 10). The curves indicate that, on average, low daily mean discharges produce substantially fewer days of low specific-conductance values at the monitoring sites. Departure of individual duration curves from the specific-conductance duration curve for all discharges for specific ranges of discharge

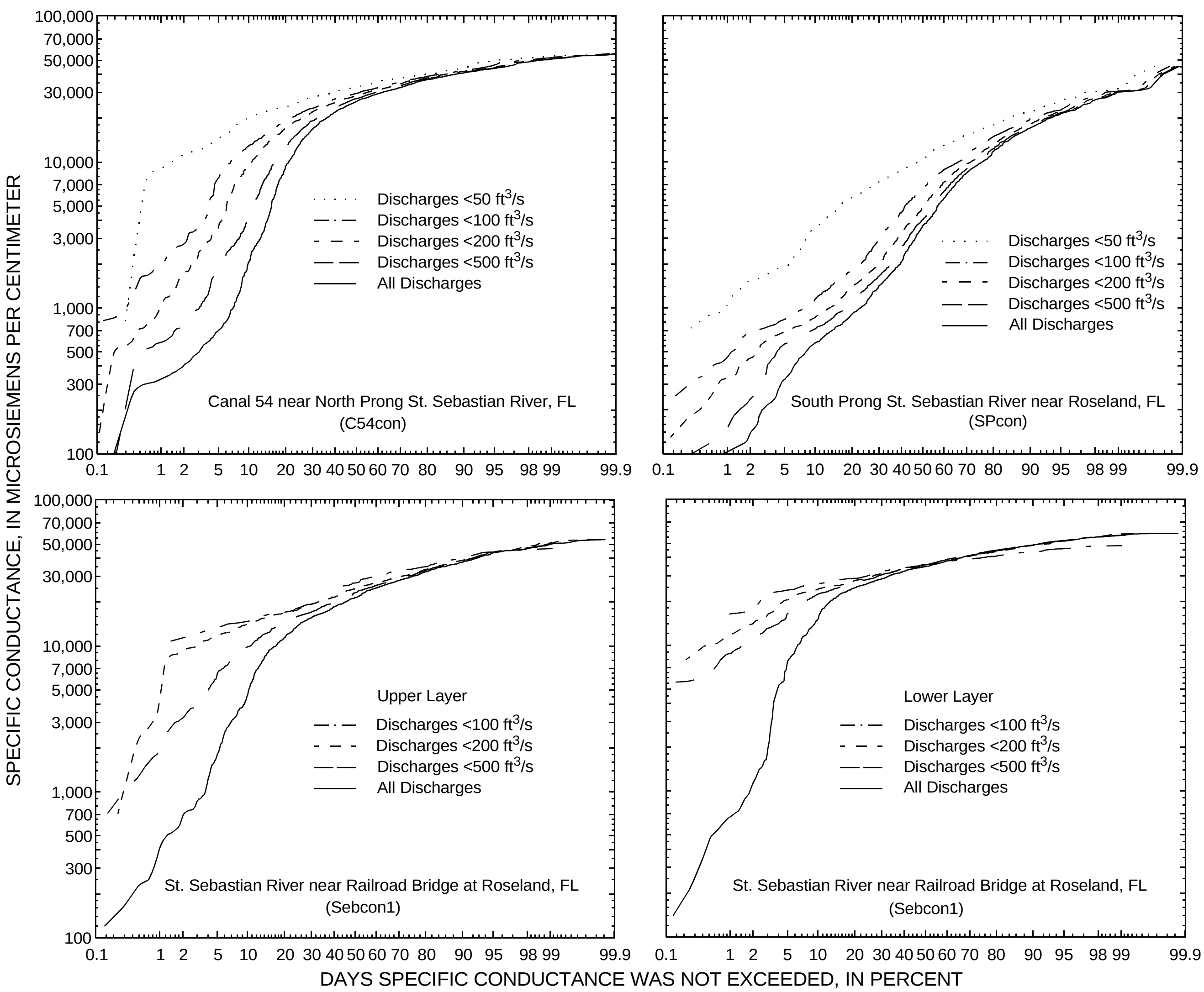


Figure 10. Specific-conductance duration curves for selected freshwater discharge ranges at conductance-monitoring sites.

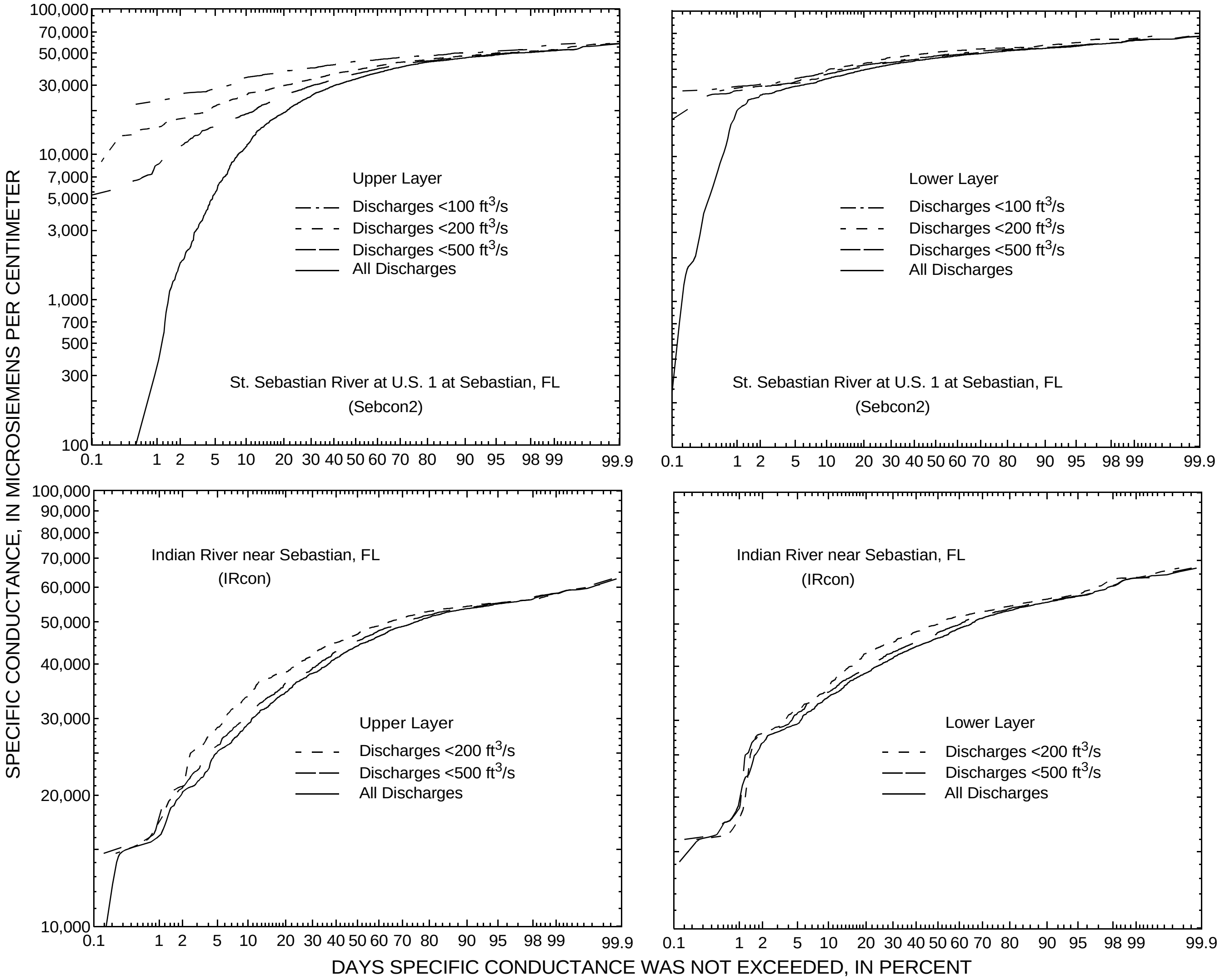


Figure 10. Specific-conductance duration curves for selected freshwater discharge ranges at conductance-monitoring sites--Continued.

is an indication that, in highly stratified waters, the effect of discharge magnitude on specific conductance (and thus, salinity) is relatively small up to a certain threshold discharge; beyond this threshold value, the volume of freshwater flow is sufficient to overcome the gradient between the freshwater/saltwater layers, thus shifting the duration curve.

The duration curves shown in figure 10 also indicate spatial variability in the specific-conductance duration curves with respect to discharge. Spacing of the duration curve family is a general indication of the effect freshwater discharges have on specific-conductance values at each site. Where freshwater is a small part of the total volume, specific-conductance values do not change significantly even with relatively large increases in freshwater discharge. Where freshwater is a large part of the total volume, small increases in freshwater inflow cause relatively large changes in specific conductance. These sites have a family of duration curves for selected discharge ranges that are well spaced and evenly separated at the lower ranges of specific conductance, indicating a more even distribution of specific conductances throughout the range of flows at the selected site (for example, sites C54con and SPcon). At these sites, small changes in freshwater discharge have a greater effect on specific conductance than at sites where freshwater discharge is a smaller percentage of the total flow (for example, downstream sites). As discharge gradients become more prevalent in the middle and near the mouth of the estuary, specific-conductance values are less readily affected by small changes in freshwater discharge and the gradient between freshwater and saltwater is overcome only by much larger inflows of freshwater (for example, Sebcon1 and Sebcon2-upper). Specific-conductance distributions for the lower layer at sites closer to the Indian River (for example, Sebcon2-lower and IRcon) are more highly affected by saltwater flux and less influenced by freshwater discharges.

THE PROBABILISTIC RELATION OF SALINITY TO FRESHWATER DISCHARGE

The relation of specific conductance to discharge was investigated in order to determine the effect of different flow regimes on salinity in the St. Sebastian River. Estimating the effect of changing flow regimes requires a predictive model that integrates both systematic and random components of salinity variation. Based on the specific-conductance-discharge relation, specific-conductance values were predicted for a series of discharges and the remaining variation in specific conductance was modeled as a random normal process. This approach required determination of a functional relation between discharge and specific conductance that minimized the standard deviation of residuals and resulted in a normal random independent distribution of residuals over a range of discharges. Then, the standard deviation of the residuals was modeled to represent the uncertainty in the estimated specific conductance for each successive discharge value in the time series. The probability of a particular salinity condition (as indicated by the salinity-specific-conductance relation) exceeding or failing to exceed a given limit could then be computed by summing the conditional probabilities that each predicted specific-conductance value in a time series was above or below that limit.

Modeling Specific Conductance as a Function of Discharge

The basic form of the model applied for this study has been used by Miller and McPherson (1991) and is derived from a simple solute-solvent dilution computation. The equation presented by Miller and McPherson was adapted to the St. Sebastian River estuary by assuming that a volume of water sampled at some fixed point can be represented by a volume of water composed of aliquots contributed from upstream and downstream. Specific-conductance data at each site for two depths indicates stratified flow of freshwater and saltwater. Because of this layering, the equation is applied independently to each layer with the assumption that the water within the layer is well mixed. Over a period of 1 day, specific-conductance values are averaged to produce a reasonable representation of the specific conductance of a volume of water that moved past the sampling point during the 24-hour period as water in the river moves upstream and downstream with the varying tide.

The model presented in this report assumes that the ratio of saltwater to freshwater mixing can be described as a function of freshwater discharge. The relation of specific conductance at a point of interest in the river to that of inflowing water is given by the equation

$$C_M = \frac{C_F V_F + C_S V_S}{V_F + V_S}, \tag{3}$$

where C_M is the specific conductance at a specific measurement site, in microsiemens per centimeter;
C_F is the specific conductance of the freshwater inflow, in microsiemens per centimeter;
C_S is the specific conductance of the saltwater inflow, in microsiemens per centimeter;
V_F is the volume of freshwater inflow, in cubic feet; and
V_S is the volume of the saltwater inflow, in cubic feet.

Over uniform time intervals, discharge rates can be substituted for volumes, and the equation can be written in the following form:

$$C_M = \frac{C_F Q_F + C_S Q_T}{Q_F + Q_T}, \tag{4}$$

where Q_F is the freshwater discharge at a specific measurement site, in cubic feet per second.

Empirical evaluation of freshwater discharge (Q_F) and tidal flux (Q_T) indicates that the ratio of tidal flux to freshwater discharge can be expressed as a function of freshwater discharge (fig. 11):

$$Q_T / Q_F = b_0 Q_F^{b_1}, \tag{5}$$

where b_0 is a discharge coefficient, and
b_1 is a power of discharge.

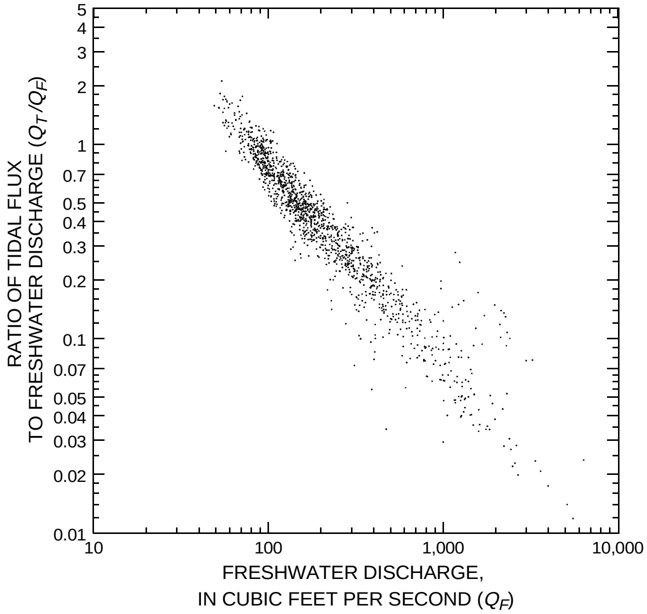


Figure 11. Freshwater discharge (Q_F) as a function of the ratio of tidal flux to freshwater discharge (Q_T/Q_F) at St. Sebastian River at U.S. 1 at Sebastian (Sebcon2).

Equation 4 may be expressed in terms of the ratio Q_T/Q_F by dividing the numerator and denominator by Q_F:

$$C_M = \frac{C_F Q_F / Q_F + C_S Q_T / Q_F}{Q_F / Q_F + Q_T / Q_F}. \qquad (6)$$

Substitution in equation 6 of the expression for the ratio Q_T/Q_F from equation 5 yields a statistical model of specific conductance as a function of discharge:

$$C_M = \frac{(C_F + b_0 Q_F^{b_1} C_S)}{(1 + b_0 Q_F^{b_1})} + \varepsilon, \qquad (7)$$

where ε is the random error and specific-conductance values of saltwater and freshwater are held constant.

The statistical model of specific conductance represents the effect of freshwater discharge displacing saltwater from the system. This effect generally is short-term and produces a highly random estimate of specific conductance for a given freshwater discharge.

In the statistical model of specific conductance (eq 7), serial correlation and dilution of the saltwater inflow from sustained freshwater flows were taken into account by applying a lagged smoothing technique to the estimated specific-conductance time series to reduce randomness in the specific-conductance estimate. The lagged smoothing technique is a weighting function that describes how specific-conductance estimates are affected by freshwater and saltwater mixing from previous days and is given as:

$$C_{SM_i} = \frac{(C_F + b_0 Q_F^{b_1} C_S)}{(1 + b_0 Q_F^{b_1})}(1 - b_2) + b_2 C_{SM_{i-1}} + \varepsilon, \qquad (8)$$

where C_{SM_i} is a specific-conductance value, in microsiemens per centimeter, accounting for serial correlation and mixing across days; and

b_2 is a weighting coefficient.

The lagged smoothing technique produces a less random estimate of specific conductance for a given freshwater discharge and accounts for long-term effects of sustained freshwater discharges.

Saltwater conductance values (C_S) were replaced by estimates for C_{SM_i} in the statistical model of specific conductance (eq 7) to provide an optimal mathematical expression that fit observed data. This optimal mathematical expression accounts for the relatively instantaneous response of specific conductance to freshwater discharge, serial correlation, and the dilution of saltwater inflow by sustained freshwater inflow. The statistical model of specific conductance as a function of discharge then becomes:

$$C_M = \frac{(C_F + b_3 Q_F^{b_1} C_{SM_i})}{(1 + b_3 Q_F^{b_1})} + \varepsilon, \qquad (9)$$

where b_3 is a discharge coefficient.

The salinity-response model (eq 9), based on daily mean discharge, was fit to observed daily mean specific-conductance data. This model includes two parts, each fit by least-squares nonlinear optimization. These two parts accounted for variation in specific conductance associated with two processes: long-term dilution as a result of sustained freshwater inflows (eq 8), and a short-term effect of freshwater discharge on saltwater inflow (eq 7).

The modeled fit was optimized using an iterative search routine available in the Quattro Pro version 5.0 spreadsheet software package. Nonlinear regression of measured and fitted specific-conductance values was performed by an iterative process of optimization. The summed squares of the residuals were minimized using quadratic, forward, conjugate, and automatic scaling processes in the optimizer routine. Various initial model parameters were used to start the optimization process to verify the final output of model variables and confirm that the minimization process was completed and repeatable.

The salinity-response model (eq 9) consists of six variables and an initial condition (table 7) used to start the model and activate the exponential smoothing part of the model. The initial condition for each site was set to represent specific-conductance values within the range of expected daily values of specific conductance for the given site. The specific conductance of freshwater (C_F) and saltwater (C_S) within the model was set at 250 and 50,000 µS/cm, respectively, and remain constant in the equation. These specific-conductance values represent average salinity conditions for freshwater inflow into the system and for tidally driven waters from the Indian River and were used as constants in the model for all sites and depths. Evaluation of the data indicated that the discharge power, b_1, could be set to the inverse cube of discharge at all sites, reducing the degrees of freedom without significantly affecting the fit of the salinity-response model. A damping coefficient (b_2), representing a percentage of the daily mean specific-conductance value from the previous day, that influences the current day was optimized for and found to be nearly constant for all sites (0.97 or 0.98) except South Prong St. Sebastian River (SPcon), which was more affected by freshwater inflow (damping coefficient of 0.87). Discharge coefficients (b_0 and b_3) were optimized for each site and generally decreased from upstream to downstream in proportion to system storage.

Table 7. Statistical parameters for the model of specific conductance as a function of discharge for St. Sebastian River basin, May 1, 1992, to March 18, 1996

[µS/cm, microsiemens per centimeter at 25 degrees Celsius. For this table, specific conductance of freshwater is 250 µS/cm or less and specific conductance of saltwater is 50,000 µS/cm or greater. Power of discharge (b_1) is -3 (see equation 9)]

Site	Discharge coefficients (b_0)	(b_3)	Weighting coefficient (b_2)	Initial condition µS/cm ($C_{SM_{i-1}}$)	Standard error µS/cm
C54con	0.011357	0.003666	0.98	27,000	11,900
SPcon	.040506	.004896	.87	5,000	4,300
Sebcon1-upper[1]	.006008	.001801	.97	10,000	12,400
Sebcon1-lower[2]	.003152	.001212	.98	30,000	11,900
Sebcon2-upper[1]	.003045	.001303	.98	15,000	10,300
Sebcon2-lower[2]	.000745	.000312	.98	30,000	7,290
IRcon-upper[1]	.001602	.000008	.98	20,000	8,100
IRcon-lower[2]	.001132	.000008	.98	35,000	8,000

[1]Upper layer in the vertical water column.
[2]Lower layer in the vertical water column.

There were three goals in development of the salinity-response model: (1) describe as much of the variation in specific conductance as possible in terms of freshwater discharge, (2) define a basic form of the model that is descriptive of all sites with a minimum number of degrees of freedom, and (3) eliminate bias in the residuals. The solute-solvent model applied by Miller and McPherson (1991) gave an “s” shaped form that appeared to match the overall pattern of the empirical relation of specific conductance to freshwater discharge observed in the data. The “s-curve” shape of equation 7 provided a reasonable relation of specific conductance to freshwater discharge and was consistent with the expected conditions given the relative influxes of freshwater and saltwater (fig. 12). Although the river was consistently stratified throughout most of the study (except during high-flow events) and, therefore, not well mixed vertically, conductance profiles measured during the study indicate water within the upper and lower layers is generally well mixed. However, movement of the halocline past the locations of the conductance-monitoring probes in the upper and lower layers added randomness to the data. This randomness was countered to some extent by the use of daily mean values of specific conductance.

Based on examination of the relation of specific conductance to discharge (fig. 12), two principal effects are indicated: a short-term effect from stratification, and a long-term effect from downstream saltwater dilution. The short-term effect is brought about by stormwater discharges which move the halocline to lower depths and farther downstream in the St. Sebastian River, producing a reduction in specific conductance at discharges above a given value. Although this discharge value differed from site to site, the underlying effect was similar for all sites -- a proportional decrease in specific conductance with an increase in discharge. Given the similarity in the rate of this response, a form of the statistical model (eq 7) based on a single set of calibration coefficients for freshwater and saltwater specific-conductance values was found to fit well for all sites. Discharge coefficients, which also were fit empirically, varied inversely with the cross-sectional area of the stream above the sampling point at each site (table 7). The largest discharge coefficient was observed at the upstream site on the South Prong St. Sebastian River, SPcon, where the cross-sectional area was the smallest; the smallest discharge coefficient was observed for the lower sampling point at the downstream site in the Indian River Lagoon, IRcon.

The mixing model (eq 7) alone accounts well for the short-term effects of discharge on specific conductance but does not account well for long-term dilution effects. When the mixing model is fit without accounting for long-term dilution, the resulting residuals are asym-

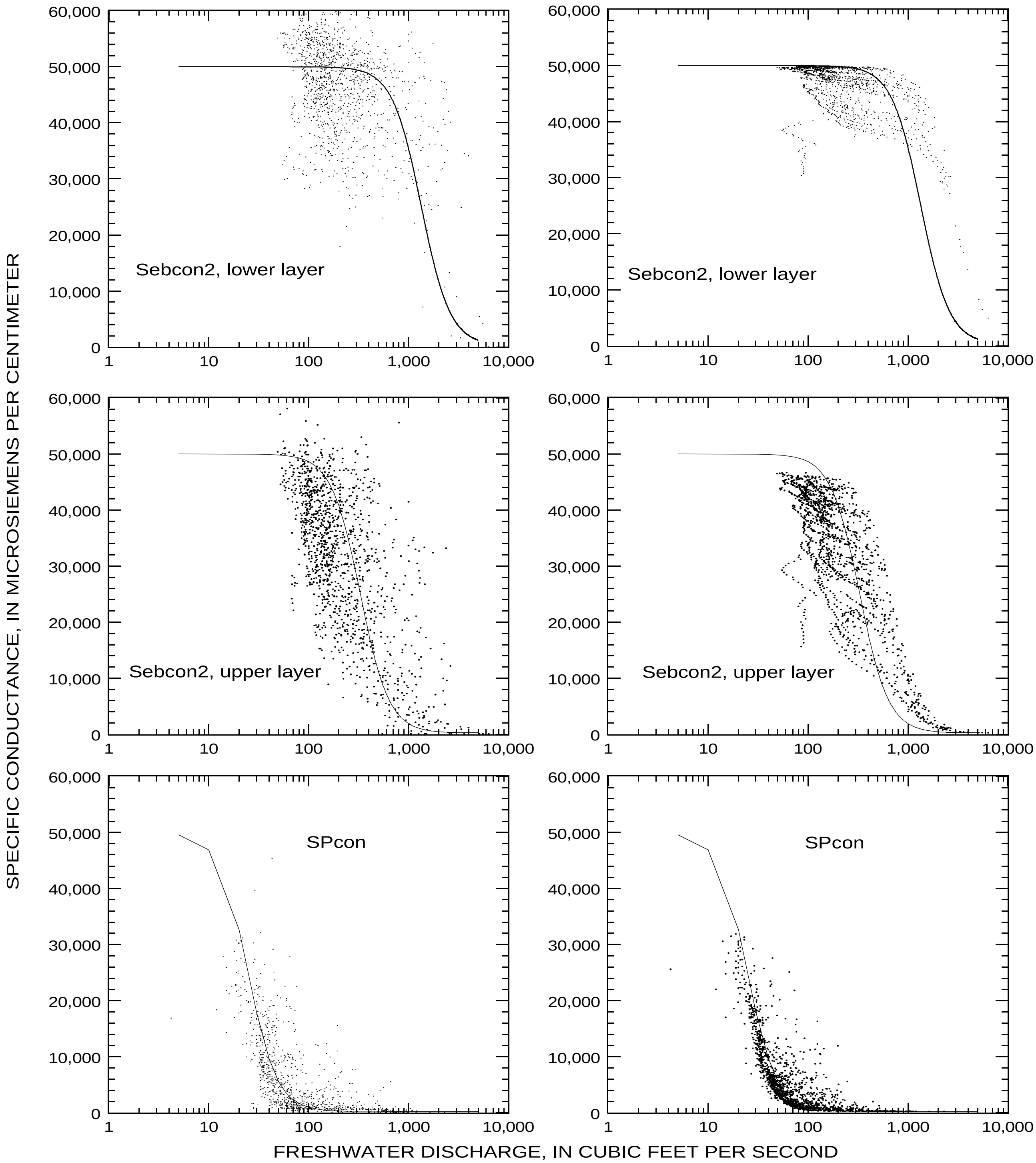


Figure 12. Specific conductance as a function of freshwater discharge at South Prong St. Sebastian River near Roseland (SPcon) and St. Sebastian River at U.S. 1 at Sebastian (Sebcon2). Left graphs show regression curve of specific conductance as a function of freshwater discharge (eq 7) using ordered freshwater discharges and observed specific conductance data. Right graphs show regression curve of specific conductance as a function of freshwater discharge (eq 7) using ordered freshwater discharges and specific conductance predicted using the salinity response model (eq 9).

metrical. The complete statistical model of specific conductance (eq 9) predicts specific-conductance values at high discharges well with very small residuals, but generally over predicts specific-conductance values at low discharges. This indicates that the system responds strongly to discharge at low specific conductances and to dilution at higher specific-conductance values. Simple exponential smoothing usually improved the model fit in the midrange of specific conductances, but was not sufficient to fit both the low and high specific conductances. The inclusion of a second long-term model (eq 8, a smoothed version of the original model, eq 7), in place of the saltwater specific conductance (C_S), resolved the asymmetry in residuals and allowed the model to be fit throughout the complete range of specific-conductance values. Although this model (eq 8) increased the degrees of freedom in the overall model (eq 9) and added a new layer of complexity, the probability analysis is predicated on a well-behaved set of residuals that can be estimated as a random process.

Variability in model residuals confirms the observation that the St. Sebastian River estuary is a system in which specific conductance responds strongly to increased freshwater discharge. Small increases in discharge above long-term or base-flow conditions can reduce specific conductance relatively quickly. Specific-conductance values respond more to higher discharges, as indicated by a reduction in the variability of model residuals at higher discharges (fig. 13). Model residuals

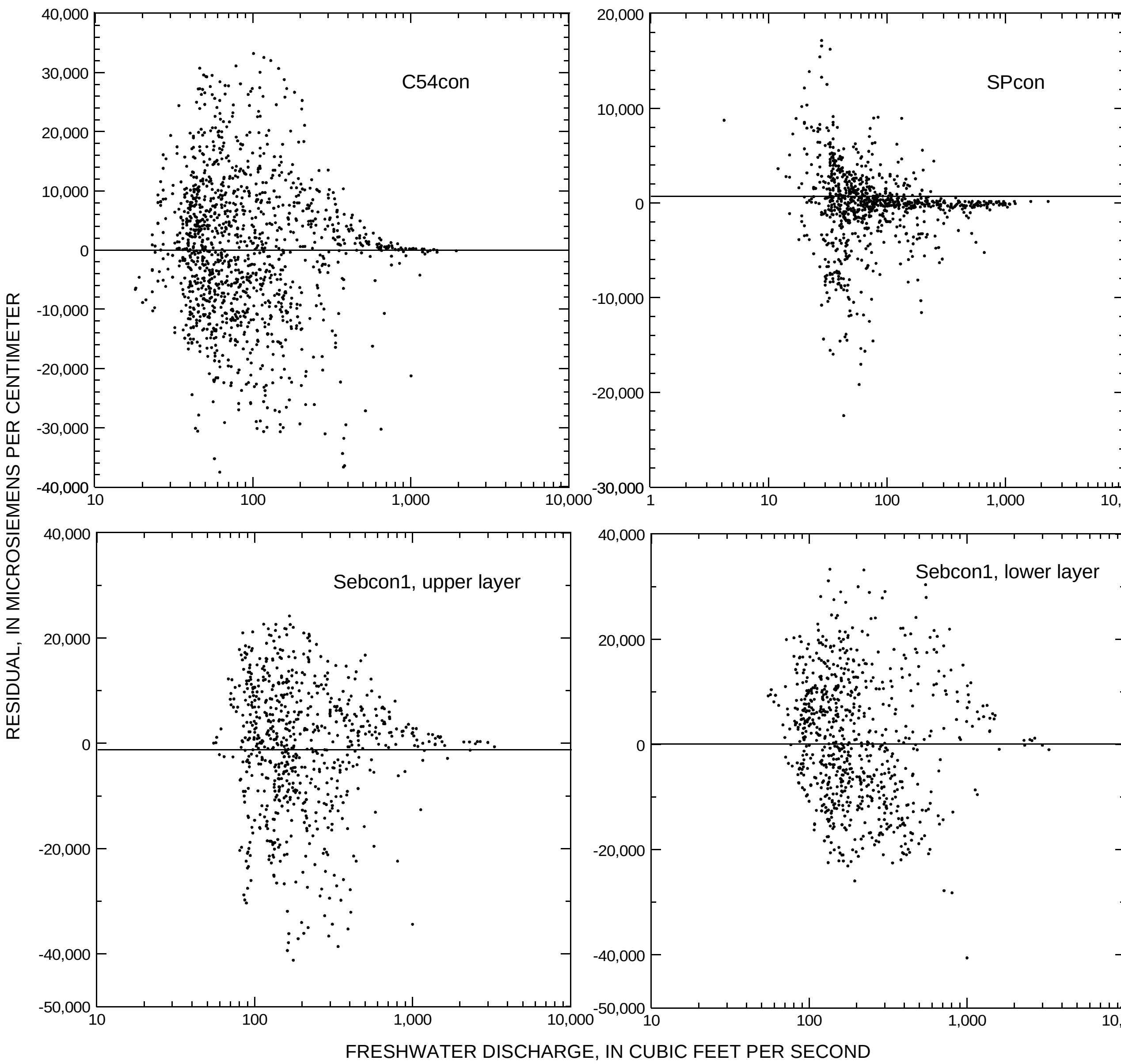


Figure 13. Relation of model residuals to freshwater discharge.

for upstream sites, where specific-conductance values are more strongly influenced by freshwater discharges (for example, SPcon), are increasingly heteroscedastic. Specific-conductance values at downstream sites, such as Sebcon2 and IRcon, are much less influenced by freshwater discharges and variance in model residuals becomes increasingly homoscedastic with distance downstream. Variation in the residuals at high specific-conductance values is related to other system properties that are not monitored and, therefore, cannot be accounted for in either the model or prospective management decisions. Neglecting minor deviations, the residuals describe a relatively random normal distribution throughout the range of discharges observed. Unexplained variation in the salinity-response model represents factors other than discharge that alter the probability function of specific conductance.

Time-series hydrographs of measured and simulated specific conductance show the fit of the salinity response model (fig. 14). Overall, the best model fit at all sites was for data representing periods of highest flows when discharge has the greatest effect on specific conductance. The standard error of the best-fit models for all sites ranged from 4,300 to 12,400 µS/cm.

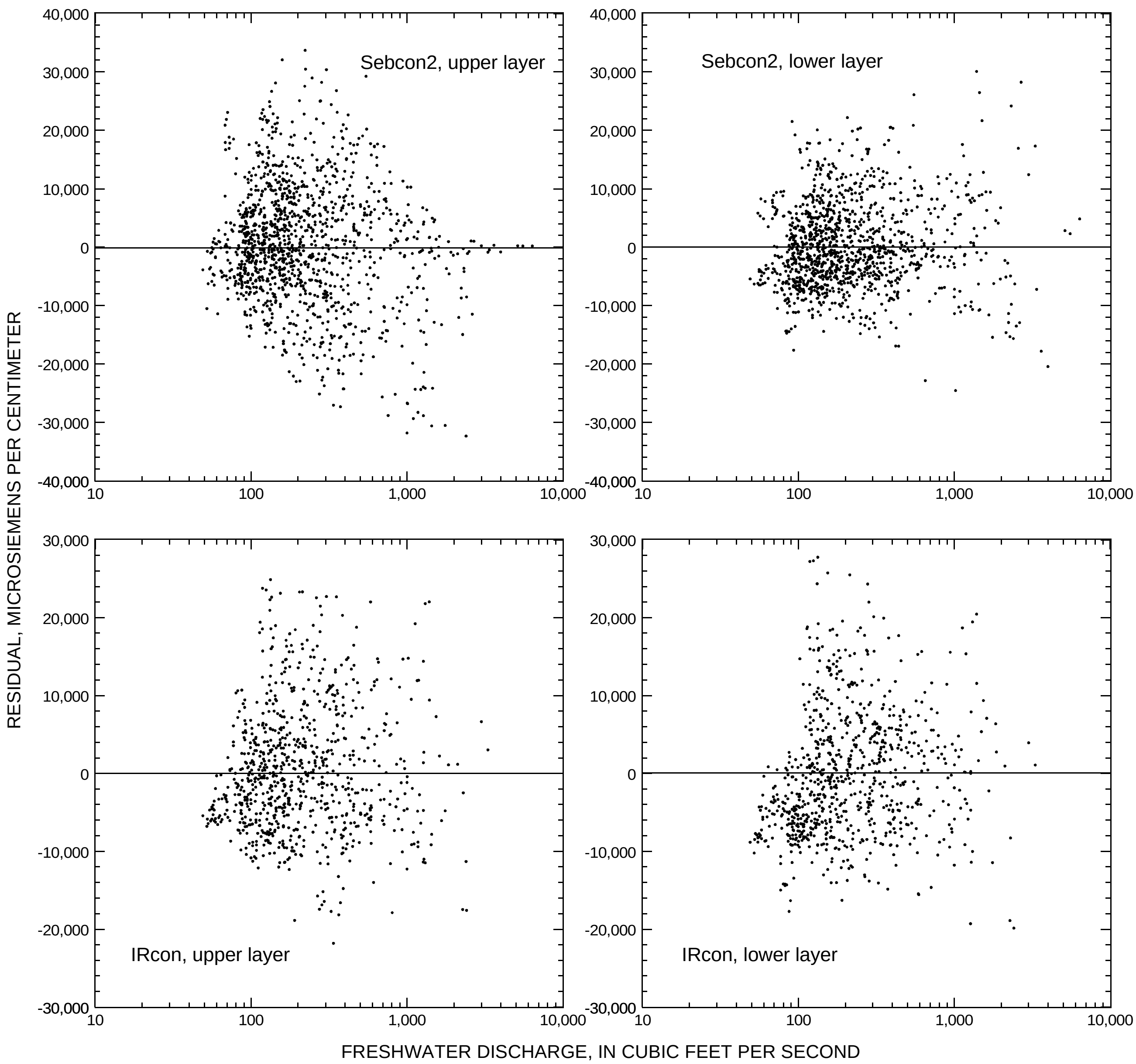


Figure 13. Relation of model residuals to freshwater discharge--Continued.

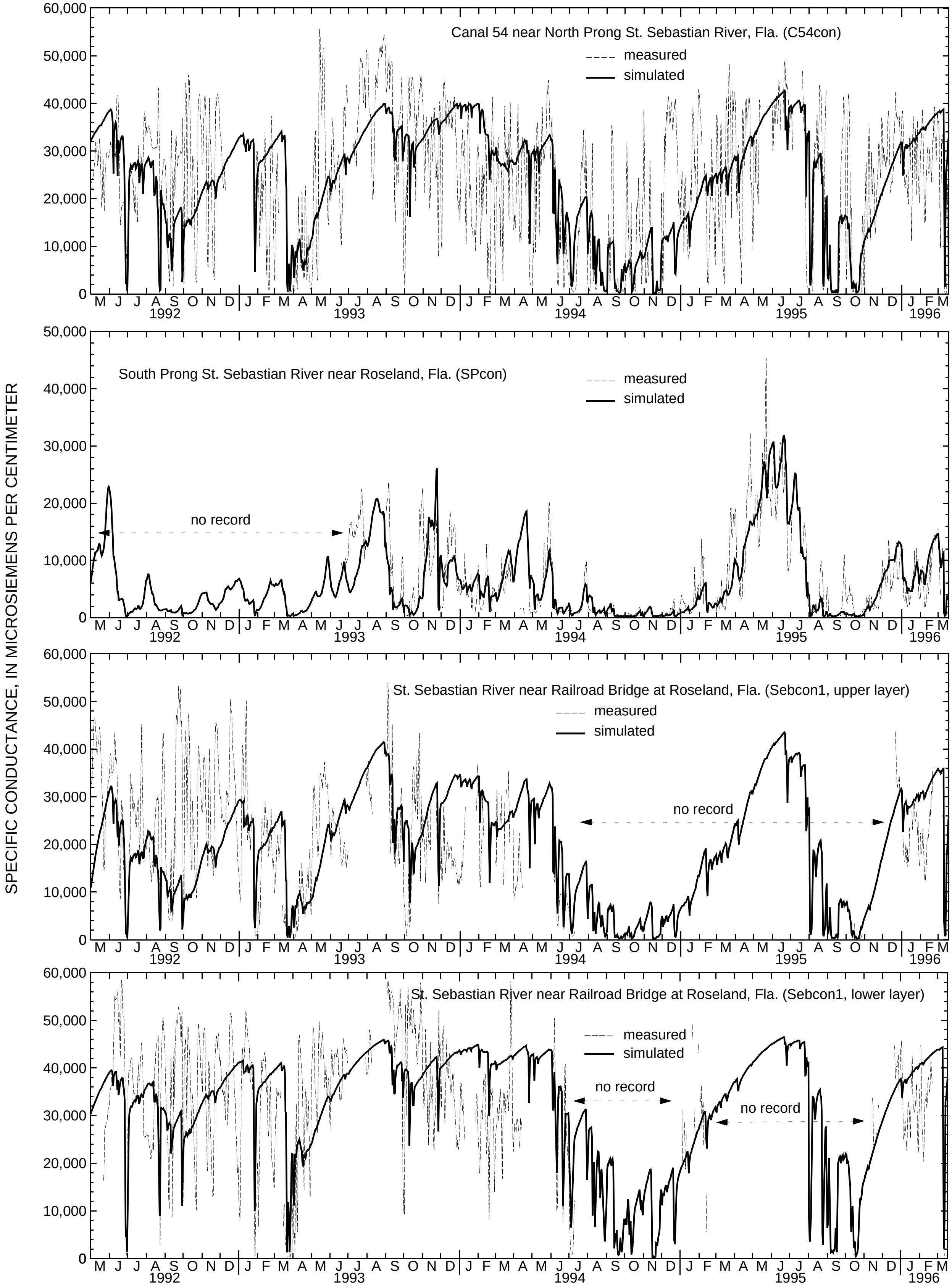


Figure 14. Measured and simulated daily specific-conductance values.

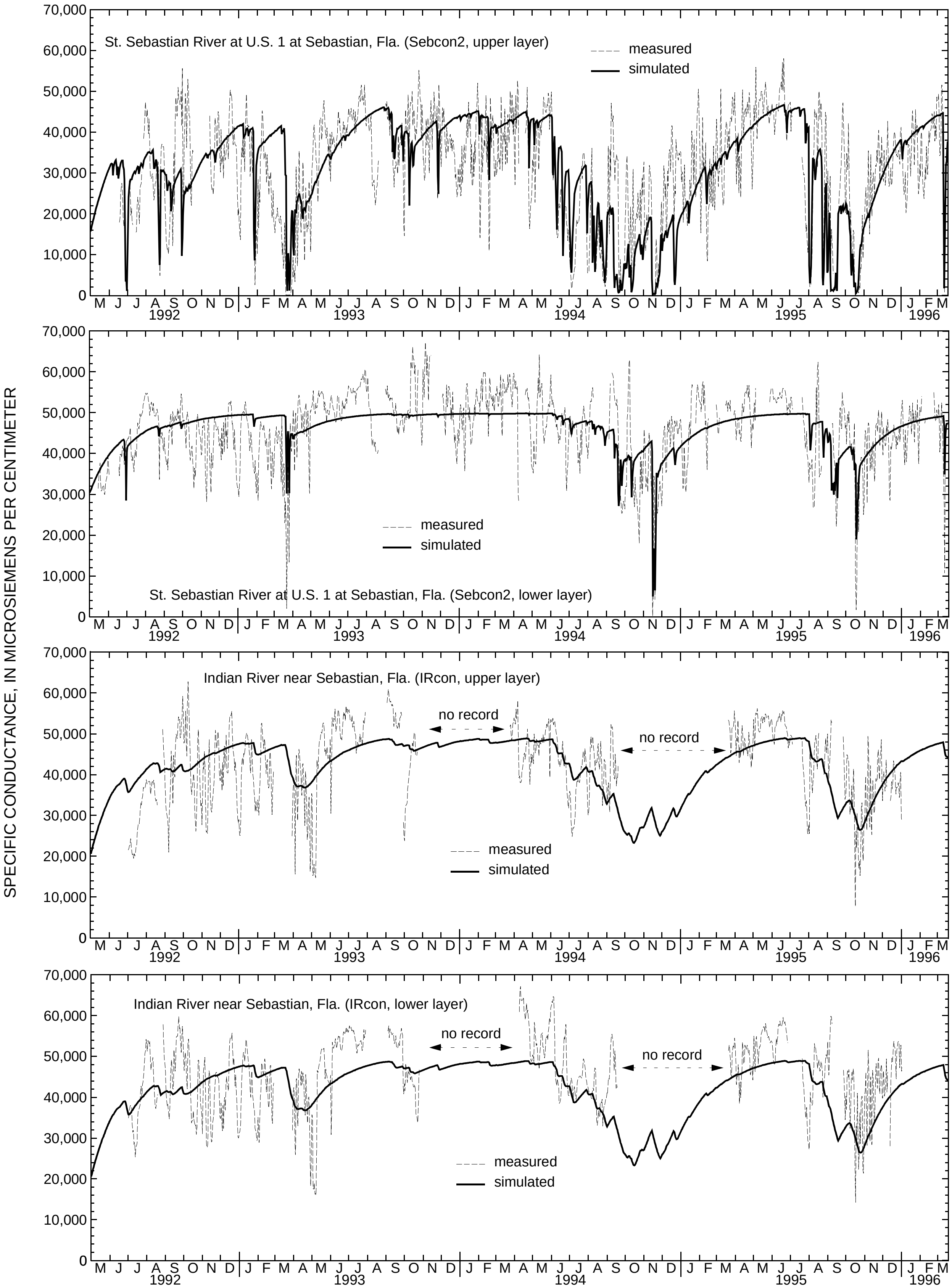
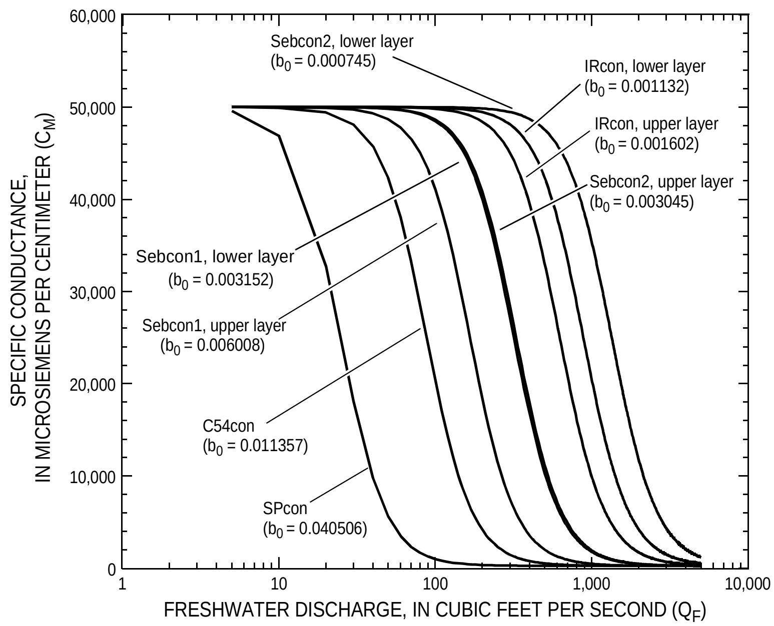


Figure 14. Measured and simulated daily specific-conductance values--Continued.

The limited ability of this model to predict specific conductance at low flows illustrates the limited extent to which controls on discharge (detention or retention of freshwater inflows) can be expected to alter salinity conditions in the river. Although discharge is a controlling factor in the occurrence of the very lowest salinity conditions in the river, observed specific-conductance values indicate many instances when salinities are at moderate levels when discharge clearly is not a controlling factor.

A plot of the fitted statistical models without lagged smoothing for all sites and layers is shown in figure 15. The order of the curves from left to right in the graph generally is from upstream to downstream and from upper to lower layers. Specific conductances for the South Prong site (SPcon), for example, tend to plot in the lower left area of the curve set and data for the Indian River (IRcon) tend to plot in the upper right area of the curve set. The effect of vertical stratification produces a similar movement from lower left to upper right, reflecting a greater volume of water upstream



Fitted statistical model without lagged smoothing given by equation 7:

$$C_M = \frac{(C_F + b_0 {Q_F}^{b_1} C_S)}{(1 + b_0 {Q_F}^{b_1})} + \varepsilon \quad ,$$

where C_F is specific conductance of freshwater (250 µS/cm),
C_M is specific conductance of saltwater (50,000 µS/cm),
b_0 is a coefficient of discharge,
b_1 is, -3, a power of discharge, and
ε is random error.

Figure 15. Fitted statistical model without lagged smoothing for specific conductance as a function of freshwater discharge at sites in the St. Sebastian River.

from and above the sampling point. The relative effect of moving from upstream to downstream in the river and from top to bottom in the vertical profile is best illustrated by the overlap in the models for the lower layer of the upstream St. Sebastian River site (Sebcon1, lower layer) and the upper layer of the downstream site (Sebcon2, upper layer).

During the process of optimization, the model parameters were not constrained to a given range of numerical values. The model calibration, however, was naturally constrained by the range of hydrologic conditions observed over the period of data collection. Discharge data during the study were reasonably representative of average conditions in the river basin based on comparisons to earlier discharge record (Knowles, 1995). The combined total flow of all freshwater inflows to the St. Sebastian River ranged from 50 to 6,400 ft^3/s and included several periods of sustained high and low flow. The distribution of flows between discharge events, which also can have a considerable effect on model response, was not compared to historical record but likely is representative of conditions in the basin. The application of the model to changes in freshwater inflow to the system is considered reasonable, because modeled estimates of effects of detention and retention were based on interpolations within the time and discharge domain of the original calibration data set.

Residual Uncertainty and Exceedance Probabilities

The residuals of the best-fit relation of the salinity-response model (eq 9) were modeled as a function of freshwater discharge to produce estimates of the uncertainty in daily mean specific-conductance values. These uncertainty estimates were combined with estimated specific-conductance values to produce an overall probability model. The standard deviation of residuals (Z) was modeled as the square root of the variance which is represented as a log relation of the squared residuals to discharge. The resulting equation is:

$$SEZ_q = \sqrt{b_4 Q^{b_5}}, \qquad (10)$$

where SEZ_q is the standard deviation of model residuals for a given discharge;

Q is the freshwater discharge, in cubic feet per second; and

b_4 and b_5 are fitting coefficients.

This form was used to predict the uncertainty in an estimated specific-conductance value for each successive discharge in a time series. Both fitting coefficients b_4 and b_5 were determined using nonlinear optimization for data at each site based on minimization of the difference between predicted and observed nonexceedance probabilities (X) by the objective function:

$$X = \sum_{j_1}^{j_n} \left[P[\hat{C} < C_{L_j}] - P[C < C_{L_j}] \right]^2, \qquad (11)$$

where $\hat{C}$ is the estimated specific conductance, in microsiemens per centimeter;

C_L is a given specific-conductance limit, in microsiemens per centimeter;

C is observed daily mean specific conductance, in microsiemens per centimeter; and

j is a discrete value of C_L.

The probability of the observed specific conductance not exceeding a defined limit was taken directly from empirical duration curves. Thirteen discrete values of C_L were evaluated, and C_L values ranged from 100 to 65,000 µS/cm and varied for individual sites.

The total probability (Kim, 1992, p. 16) of a particular specific-conductance value in the time series exceeding or failing to exceed a given limit was computed by summing the product of the probability of the conditioning event for all observed values of freshwater discharges and the conditional probability that each value in the complete time series might fall above or below that discrete specific conductance limit, given the uncertainty in residuals of the specific conductance model. The probability of daily specific-conductance values not exceeding a given limit was calculated assuming a Gaussian probability distribution of model residuals, and is represented as:

$$P[C < C_L] = \sum P[(C < C_L) | (Q = q)] \cdot P[Q = q], \qquad (12)$$

where $P[C < C_L]$ is the probability that specific conductance, C, is less than a given limit of specific conductance, C_L;

$P[(C < C_L)|(Q = q)]$ is the probability that specific conductance, C, is less than a given limit of specific conductance, C_L, given that $Q=q$;

q is a given value of freshwater discharge, in cubic feet per second; and

$P[Q = q]$ is the probability that $Q=q$.

In terms of a deterministic statistical model, the probability of a specific-conductance value being less than a given limit for a given discharge is expressed by:

$$P[(C < C_L)|(Q = q)] = P\left[\left(Z < C_L - \hat{C}\right)\middle|(Q = q)\right], \quad (13)$$

where Z is the residual from the specific-conductance model (eq 10).

If the residuals have a random normal distribution, the probability of nonexceedance for a given value of freshwater discharge is:

$$P[Z < (C_L - \hat{C})|(Q = q)] = N\left(\frac{C_L - \hat{C}}{\sigma_{Z_q}}\right), \quad (14)$$

where N is the Gaussian cumulative probability function, and

σ_{Z_q} is the standard deviation of Z at $Q=q$.

Accurate evaluations of equations 12, 13, and 14 are properly obtained by integration over the probability function of discharge (Q). Because that function of discharge is undetermined, the sample distribution of discharges observed over the study period was substituted for the unknown population distribution of discharges in the probability model evaluation. Total nonexceedance probabilities were calculated as the average of daily nonexceedance probabilities estimated for each day over the period of record based on estimates of specific conductance (C_M) from equation 9 and estimates of standard error of residuals (SEZ_q) from equation 10. The total nonexceedance probabilities calculated for each site and depth, assuming $P[Q = q] = 1/n$ for all observed values of freshwater discharge, are thus:

$$P[C < C_L] = \sum_{i=1}^{n} N\left[\frac{C_L - C_{M_i}}{(SEZ_q)_i}\right] \cdot \frac{1}{n}, \quad (15)$$

where i is a day, and

n is the number of days.

The model parameters were optimized to fit the predicted and observed specific-conductance duration curves for the subset of days having valid specific-conductance data during the study period. Then the fitted model was used to generate specific-conductance values during periods of missing data, and new duration curves were calculated.

Duration curves fitted by the probability model (eq 15) for estimated specific-conductance values and duration curves of observed specific conductance data are shown in figure 16. The values for parameters used in the computation of standard errors are given in table 8. Estimated duration curves generally fit empirical curves by a standard error factor of 1.28 which, when multiplied by or divided into a given duration estimate, gives a range of uncertainty. The standard error of the residuals model ranged from 4,400 µS/cm at SPcon to 12,000 µS/cm at Sebcon1, upper layer. The value of the fitting parameters in table 8 have little meaning other then to indicate the trend of the relation of residuals to discharge. The exponent of discharge (b_5) is positive for lower-layer sites at the lower end of the system and for IRcon, upper and lower layers, indicating an increase in residuals at higher discharges. Exponents were negative for upper-layer sites, indicating a downward trend in residuals with discharge. The relation of residuals to discharge for all sites shows a tendency to be at a minimum at the two extremes of specific conductance—the highest specific conductances, associated with the lowest discharges at downstream sites, and the lowest specific conductances, associated with the highest discharges at upstream sites. This pattern is to be expected from the plot of data in figure 12 and the relations shown in figure 15.

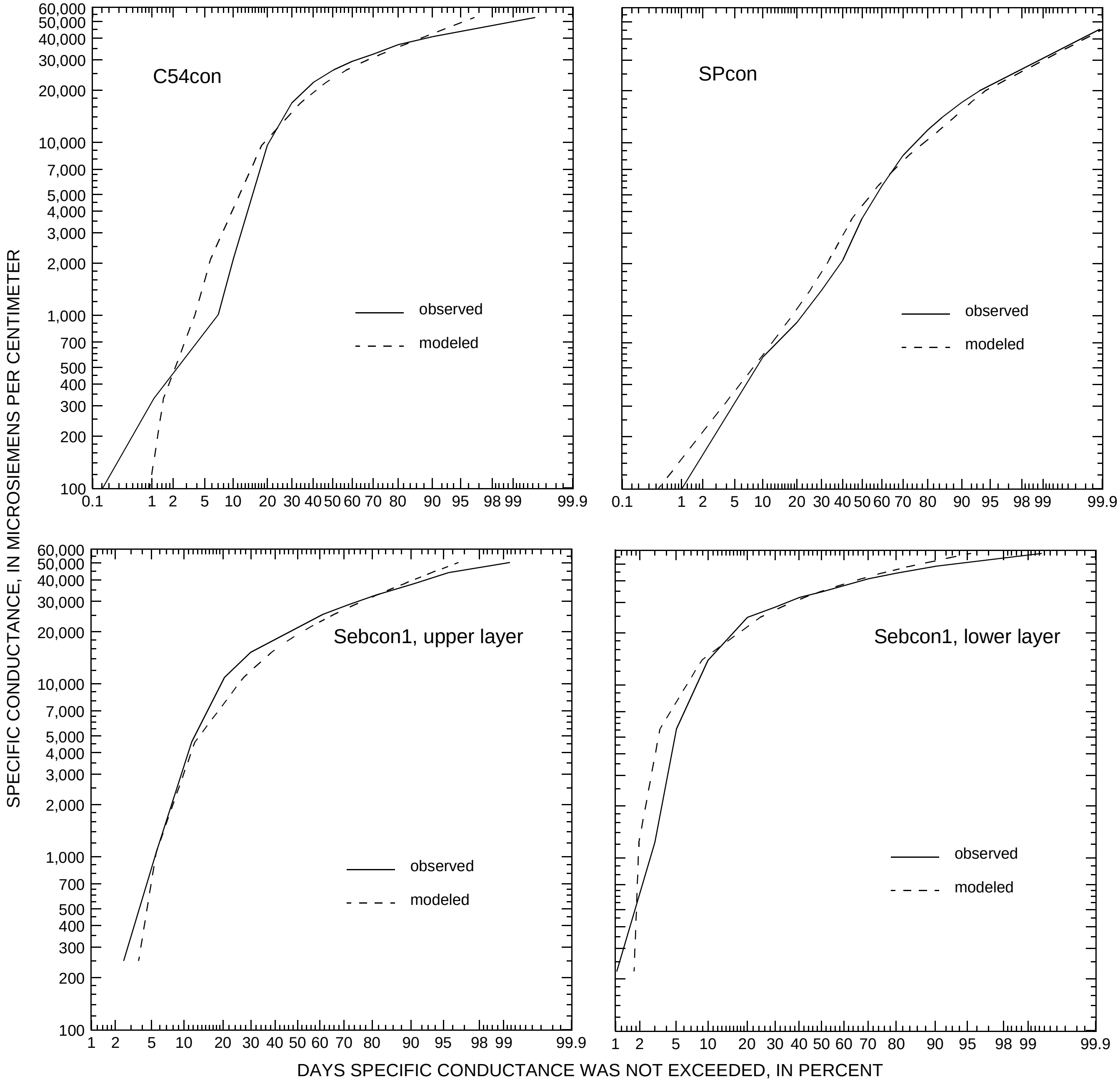


Figure 16. Specific-conductance duration curves for modeled and observed values.

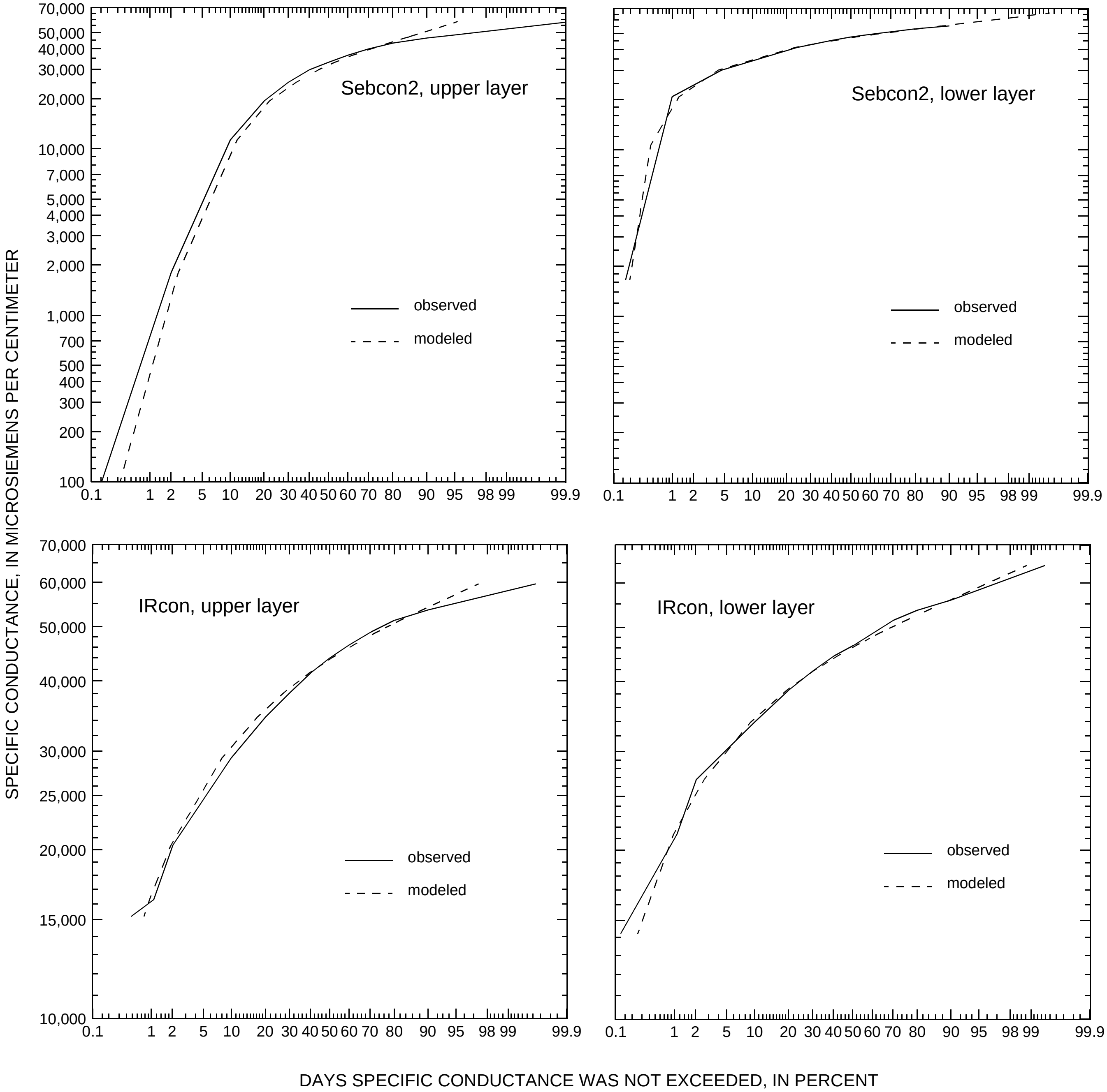


Figure 16. Specific conductance duration curves for modeled and observed values--Continued.

Table 8. Statistical parameters for the model of residuals as a function of discharge for St. Sebastian River basin, May 1, 1992, to March 18, 1996

[See equation 10]

Site	Multiplier b_4	Expondent b_5	Standard error[1]
C54con	3.162×10^{12}	-2.600	1.751
SPcon	3.200×10^{12}	-3.780	1.287
Sebcon1-upper[2]	2.358×10^{13}	-2.450	1.174
Sebcon1-lower[3]	2.060×10^{8}	-0.070	1.254
Sebcon2-upper[2]	2.258×10^{13}	-2.515	1.261
Sebcon2-lower[3]	1.862×10^{6}	0.599	1.147
IRcon-upper[2]	2.291×10^{6}	0.599	1.172
IRcon-lower[3]	2.239×10^{6}	0.599	1.244
Average			1.286

[1]Standard error of residual model fit. Each unit is a factor of the probability ratio of the observed to fitted probability curves. A factor of 1.00 indicates a perfect fit, a factor of 2.00 indicates half or twice the probability.

[2]Upper layer in the vertical water column.

[3]Lower layer in the vertical water column.

The relation of the absolute value of residuals and the models applied to compute daily standard errors are illustrated for three sites in figure 17. The difference in curves for the upper layer and lower layer sites at Sebcon2 illustrates the overall difference in residuals. Most of the curves produce relatively poor fits. However, the goal of curve fitting in this part of the model development was to account as well as possible for the extent and trends in errors, not to produce an exacting model of errors. The curves fit to most of the upper sites underestimate the variation in residuals in the mid-range of discharges. This was the result of fitting the model through optimization of duration curves rather than using a least-squares approach. The fit of duration curves tended to weight the fit of the model equally throughout the range of discharge and was insensitive to the density of data throughout that range. However, because the curves underestimate variability in the mid range of discharges, model-derived probabilities of nonexceedance in this range may be underestimated. This effect should not, however, bias the direction of the change predicted.

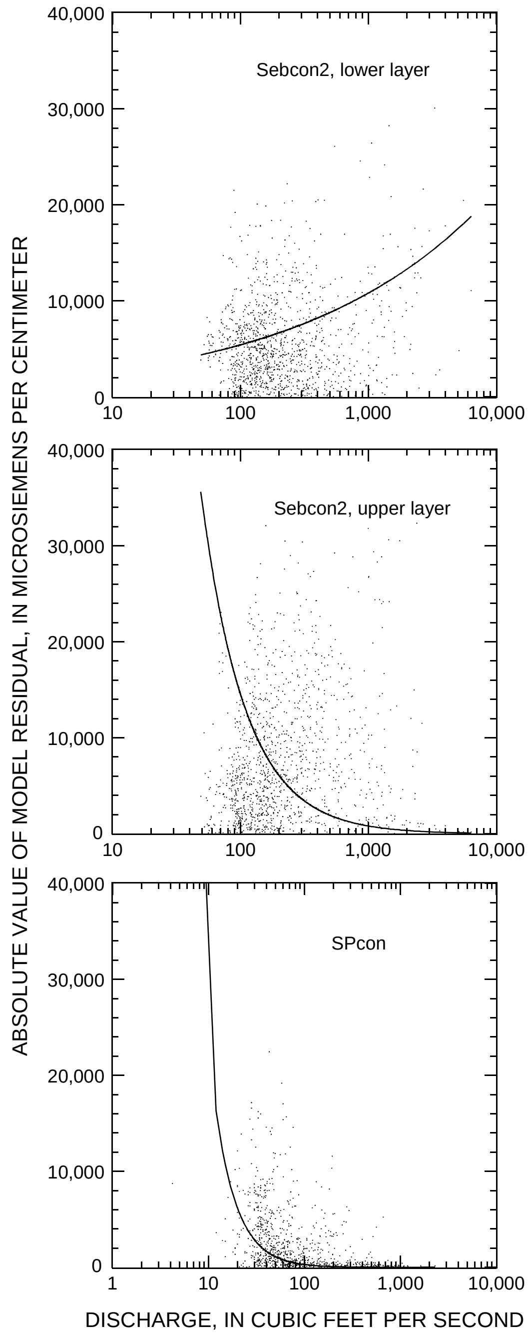


Figure 17. Absolute value of statistical model residuals as a function of discharge and residuals model regression curve.

The Response of Salinity Conditions to Changing Flow Regimes

Discharge management methods of detention and retention were investigated through use of the salinity response model (eq 9). Detention and retention affect timing and magnitude of discharge peaks, as well as days of occurrence above or below a given conductance limit.

Predicted duration curves for the modeled estuary under two flow regimes (detention and retention) were developed for each conductance data-collection site to show the potential change in the recurrence of predicted specific-conductance values for the period of data collection (fig. 18). These duration curves were

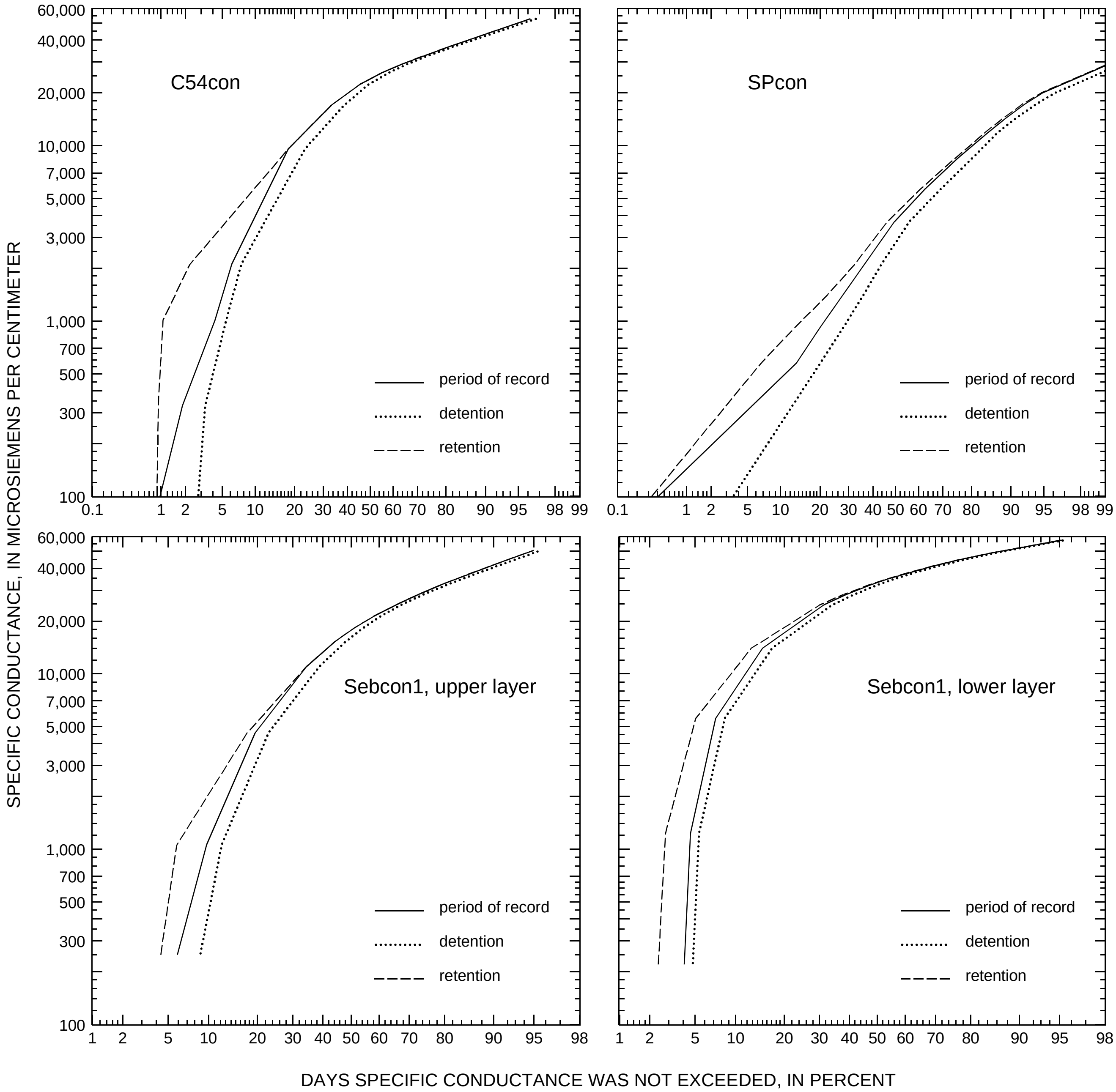


Figure 18. Specific-conductance duration curves comparing period of record to detention and retention for conductance data-collection sites.

computed from the probability model in the same way as previously described, except that the discharge time series were altered to reflect discharge management changes. In the case of detention, discharges for the period were smoothed over a 30-day period. The smoothing effectively produced the same volume of water for the period of record but spread the discharge peaks out over time. Stretching the discharges out over time increased the number of days flow was in the moderate- to low-flow discharge ranges. In the case of retention, peak discharges were reduced by subtracting all discharge above 800 ft^3/s to produce a 20 percent reduction in total flow. This simulated the effects of increased retention or diversion of freshwater out of the basin.

Modeled probabilities based on detention show that the probability of specific-conductance values falling below a given limit would increase for all sites except Sebcon2, lower layer, which shows a decrease in days of occurrence by a factor of 0.75 at a nonex-

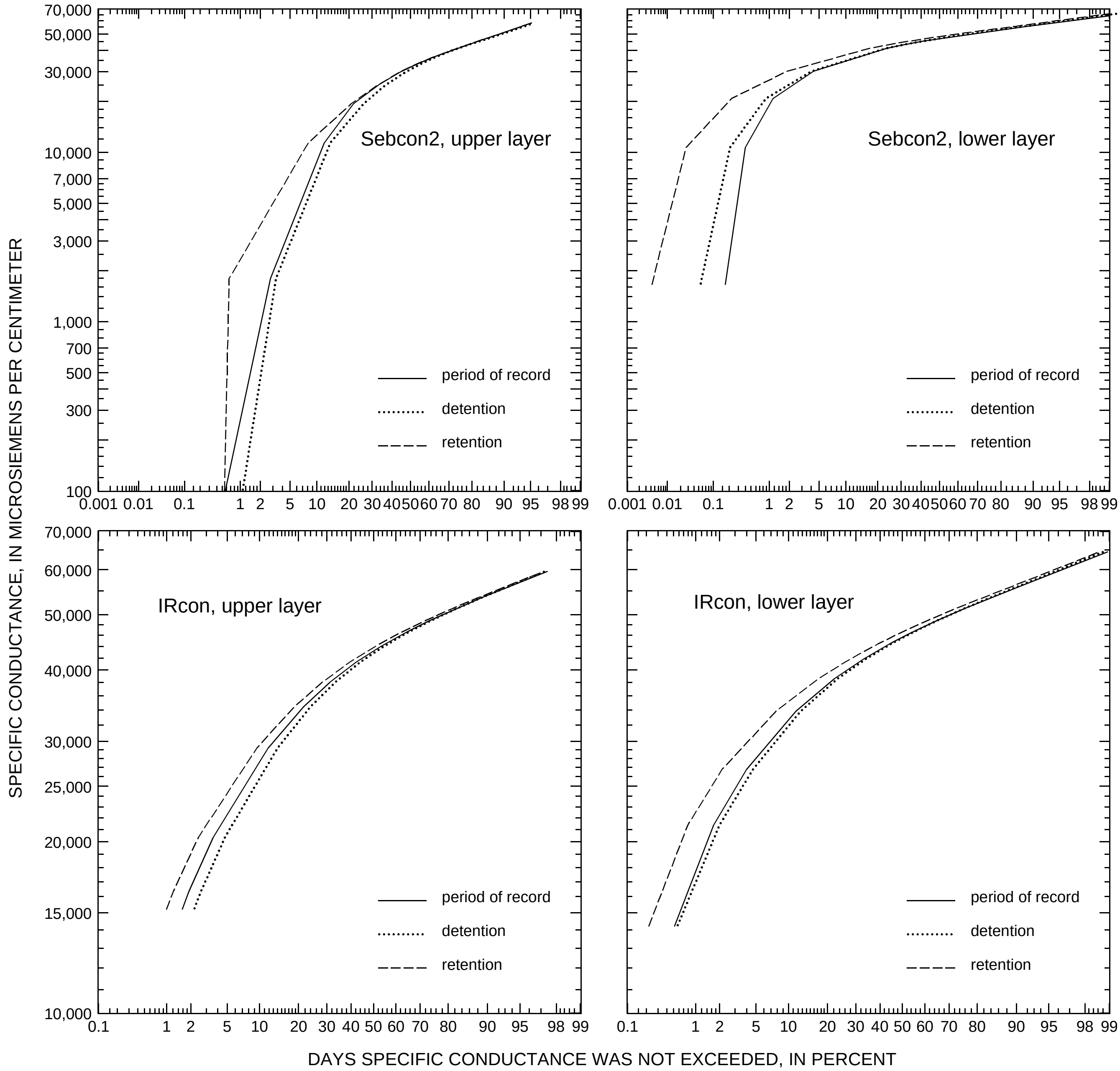


Figure 18. Specific-conductance duration curves comparing period of record to detention and retention for conductance data-collection sites--Continued.

ceedance limit of 20,000 µS/cm (table 9). Probability of nonexceedance increased by a factor of 1.17 at Sebcon1, lower layer, and IRcon, lower layer, and 1.38 at SPcon. Conductance limits for these sites were set at either 1,000 µS/cm or 20,000 µS/cm based on the ranges of daily values of specific conductance observed at the sites. The number of days of occurrence above a conductance of 20,000 µS/cm at SPcon and 40,000 µS/cm at C54con and Sebcon1 also were computed. As a result of using 30-day smoothed data, the number of days the specific conductance fell below the specified limit increased.

Detention of freshwater discharge changes the distribution of values in the specific conductance-discharge relation by decreasing the number of peak-flow days and increasing the number of low-flow days. Although detention reduces the likelihood of a low specific-conductance value on a given peak-flow day, it also increases the number of moderate-flow days by extending flow over a longer period of time. When random factors are taken into account, moderate-flow days may be only marginally less likely to produce a low specific-conductance value than high-flow days; for example, reduction of a single high-flow day may result in 10 or more moderate-flow days. Thus, detention may actually increase the total number of days of exposure to low salinity conditions.

Retention of freshwater discharge from the system, as applied here, simulated the elimination of peak discharge values above 800 ft^3/s, resulting in a 20 percent reduction in freshwater inflows. By changing the volume of water that passed through the system, the distribution of the specific conductance-discharge relation was altered and probability of specific-conductance values exceeding given limits changed. The elimination of freshwater input to the system decreased the likelihood of falling below a selected limit of specific conductance at all sites. For limits of specific conductance (1,000 µS/cm or 20,000 µS/cm, depending on the site), the predicted days of occurrence below a limit decreased, ranging from 17 percent (Sebcon2, lower layer) to 68 percent (SPcon and IRcon, upper layer) (table 9) of the predicted days of occurrence for unregulated flow.

Retention of volumes of freshwater from the system changes the specific conductance-discharge distribution by limiting the magnitude of peaks but not increasing the number of days of moderate flows. This dual effect of retention allows for fewer occurrences below a lower limit with no change in occurrences above a higher limit. Removal of freshwater inflow from peak flows decreases the number of high-flow discharge events, thereby decreasing the likelihood that specific conductances will fall below a limit. Retention of flow has less effect on low flows, because factors other than discharge control specific conductance variability so that the distribution of specific-conductance values is similar to natural conditions.

The primary finding to be drawn from this analysis is that understanding physical response of the system to a simple stimulus (such as discharge), as might be characterized by a deterministic model (or an empirical-response model alone), does not provide adequate information to assess either the character of the system or the response of the system to stress. The overall character of the system is fundamentally probabilistic in nature and should be characterized in such terms. Whether a given level of discharge can produce

Table 9. Predicted days of occurrence at a given threshold of specific conductance for the period of record, detention, and retention conditions, May 1, 1992, to March 18, 1996

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; d/yr, days per year]

Site	Conductivity limit (µS/cm)	Nonexceedence				
			Detention		Retention	
		Predicted occurrence (d/yr)	Predicted occurrence (d/yr)	Occurrence adjustment	Predicted occurrence (d/yr)	Occurrence adjustment
C54con	1,000	15	20	1.30	3.9	0.25
SPcon	1,000	78	108	1.38	53	.68
Sebcon1-upper[1]	1,000	34	44	1.27	21	.60
Sebcon1-lower[2]	1,000	16	19	1.17	9.9	.60
Sebcon2-upper[1]	1,000	6.2	7.4	1.18	2.2	.35
Sebcon2-lower[2]	20,000	3.8	2.9	0.75	0.7	.17
IRcon-upper[1]	20,000	12	16	1.34	8.4	.68
IRcon-lower[2]	20,000	4.9	5.8	1.17	2.2	.46

Site	Conductivity limit (µS/cm)	Exceedence				
			Detention		Retention	
		Predicted occurrence (d/yr)	Predicted occurrence (d/yr)	Occurrence adjustment	Predicted occurrence (d/yr)	Occurrence adjustment
C54con	40,000	50	46	0.92	50	1.00
SPcon	20,000	19	14	.74	19	1.00
Sebcon1-upper[1]	40,000	42	38	.90	42	1.00
Sebcon1-lower[2]	40,000	122	115	.95	122	1.00

[1]Upper layer in the vertical water column.

[2] Lower layer in the vertical water column.

a given response in the system is not as important as the probability of that response on a given day and over a period of many days. Although the many environmental conditions and forces acting upon the system, such as wind, tide, rain, and discharge patterns, can be monitored over time for calibration, they cannot be anticipated in a deterministic way for hypothetical simulations of effects. By treating these factors as random terms in the response of the system, a degree of specificity is lost, but a degree of reliability is gained.

A deterministic model of this system based only on discharge (as any hypothetical simulation must be, because other factors are uncontrolled and can only be assumed) would predict that a smoothing of discharges produced by increased retention (and a corresponding reduction in peaks) should increase average salinity conditions in the St. Sebastian River. This follows from the simple relation of specific conductance to discharge which indicates higher specific conductance values at lower peak discharges. The probabilistic model produces a very different response because it addresses the likelihood that other uncontrolled factors will combine to create low-salinity events. The “s-curve” shaped relation of the response model demonstrated that specific conductance, and thus, salinity, can decrease by a power of three as discharge increases. The analysis of residuals showed further that, once storm discharges exceed a low threshold, random factors can predominate and control specific-conductance values (and salinity) until discharges increase sufficiently to flush the entire system of saltwater.

SUMMARY AND CONCLUSIONS

The St. Sebastian River lies in the southern part of the Indian River basin on the east coast of Florida. Increases in freshwater discharge due to urbanization and changes in land use have reduced salinity (dissolved solids) in the St. Sebastian River and consequently, salinity in the Indian River, affecting the commercial fishing industry. Wind, water temperature, tidal flux, freshwater discharge, and downstream salinity all affect salinity in the St. Sebastian River estuary, but freshwater discharge is the only one of these hydrologic factors which might be affected by water-management practices.

A specific-conductance monitoring network was established in May 1992 to provide data for calibration and verification of a two-dimensional deterministic hydrodynamic model of the St. Sebastian River. However, because of limitations of the deterministic model to simulate constituent diffusion due to vertical stratification of specific conductance, a statistical model was developed to predict specific conductance, and thus, salinity, from discharge. A probability analysis of salinity conditions in the St. Sebastian River estuary, taking into account the effects of freshwater discharge, was used to determine the likelihood (probability) that salinities will fall below a given threshold. The relation of specific conductance to discharge and a probability analysis of salinity conditions were used to determine the effect of different flow regimes on salinity in the St. Sebastian River.

Long-term prevailing winds can build up water levels within the estuary, but tidal changes and freshwater discharges are the primary factors affecting salinity within the system. Tidal flux, propagated by tidal changes, ranged from 45.3 to 878 ft^3/s at the mouth of the St. Sebastian River during the study. Daily mean freshwater discharges at the mouth of the estuary ranged from 50 to 6,400 ft^3/s (during tropical storm Gordon, November 1994). The annual mean freshwater discharge of the system was 295 ft^3/s, and freshwater flux equivalent to the annual mean discharge would flush the system in 3.8 days. At minimum discharge, the freshwater flux would flush the system in 22.4 days and at maximum, the freshwater flux would flush the system in less than 5 hours, or 0.2 day. Based on the extreme vertical stratification observed in this system, it is estimated that, during average conditions, the flushing period for the upper freshwater layer would be considerably less than 2.5 days, whereas the flushing time for the lower layer (due to tidal flux) would be about 3 to 4 days.

Flushing rates for system volumes can be combined with freshwater discharge probabilities to obtain a likelihood of flushing the system at a given flux. Ignoring mixing and stratified flow, freshwater discharges are sufficient to flush the South Prong upstream from its confluence with the St. Sebastian River and to flush the St. Sebastian River upstream from its confluence with the Indian River in a single day up to 9 percent of the time. Freshwater discharges alone are sufficient to flush Canal 54 upstream from site C54con in 24 hours up to 19 percent of the time.

Specific-conductance values at monitored sites ranged from near seawater values to less than 500 μS/cm and exhibit long-term serial correlation attributed to the gradual mixing of water from day to day. Overall, the difference in daily mean specific-conductance values from lower to upper layers increases with distance downstream in the St. Sebastian River and decreases in the Indian River, indicating greater layering up to the mouth of the St. Sebastian River than in the receiving water body, the Indian River.

At sites where freshwater is a large part of the total volume, small increases in freshwater inflow cause relatively large changes in specific conductance. These sites have a family of duration curves for selected discharge ranges that are well spaced and evenly separated at the lower ranges of specific conductance, indicating a more even distribution of specific-conductance values throughout the range of flows at the selected site. At these sites, small changes in freshwater discharge have a greater effect on specific conductance than at sites where freshwater discharge is a smaller percentage of the total flow. As discharge gradients become more prevalent in the middle and near the mouth of the estuary, specific conductance values are less readily affected by small changes in freshwater discharge and the gradient between freshwater and saltwater is overcome only by much larger inflows of freshwater. Specific-conductance distributions for the lower layers at sites closer to the Indian River are more highly affected by saltwater flux and less influenced by freshwater discharges.

Estimating the effects of changing flows on salinity requires a predictive model that integrates both systematic and random components of salinity variation. The best salinity-response model fit at all sites was for data representing periods of highest flows, when discharge has the greatest effect on specific conductance. The standard error of the best-fit models for all sites ranged from 4,300 to 12,400 µS/cm.

The residuals from the best-fit relation of the salinity-response model were modeled as a function of freshwater discharge to produce estimates of the uncertainty in daily mean specific-conductance values. Duration curves based on simulated values generally fit empirical curves by a standard error factor of 1.28, and the standard error of the residuals model ranged from 4,400 µS/cm at SPcon to 12,000 µS/cm at Sebcon1-upper. The application of the model to changes in freshwater inflow to the system is considered reasonable, because modeled estimates of effects of detention and retention were based on interpolations within the time and discharge domain of the original calibration data set.

Discharge management methods of detention and retention were investigated through use of the salinity-response model. Detention of freshwater discharges increased the probability of specific conductance values falling below a given limit (20,000 µS/cm) for all sites but one. The retention of freshwater input to the system decreased the likelihood of falling below a selected limit of specific conductance at all sites. For limits of specific conductance (1,000 µS/cm or 20,000 µS/cm, depending on the site) the predicted days of occurrence below a limit decreased ranging from 17 percent (Sebcon2-lower) to 68 percent (SPcon and IRcon-upper) of the predicted days of occurrence for unregulated flow.

The primary finding to be drawn from the discharge-salinity analysis is that an empirical-response model alone does not provide adequate information to assess the response of the system to changes in flow regime. Whether a given level of discharge can produce a given response on a given day is not as important as the probability of that response on a given day and over a period of many days. A deterministic model of the St. Sebastian River estuary based only on discharge would predict that retention of discharge peaks should increase the average salinity conditions in the St. Sebastian River estuary. The probabilistic model produces a very different response indicating that salinity can decrease by a power of three as discharges increase, and that random factors can predominate and control salinity until discharges increase sufficiently to flush the entire system of saltwater.

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