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MIDDLE ST. JOHNS RIVER MINIMUM FLOWS AND LEVELS HYDROLOGIC METHODS REPORT

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by

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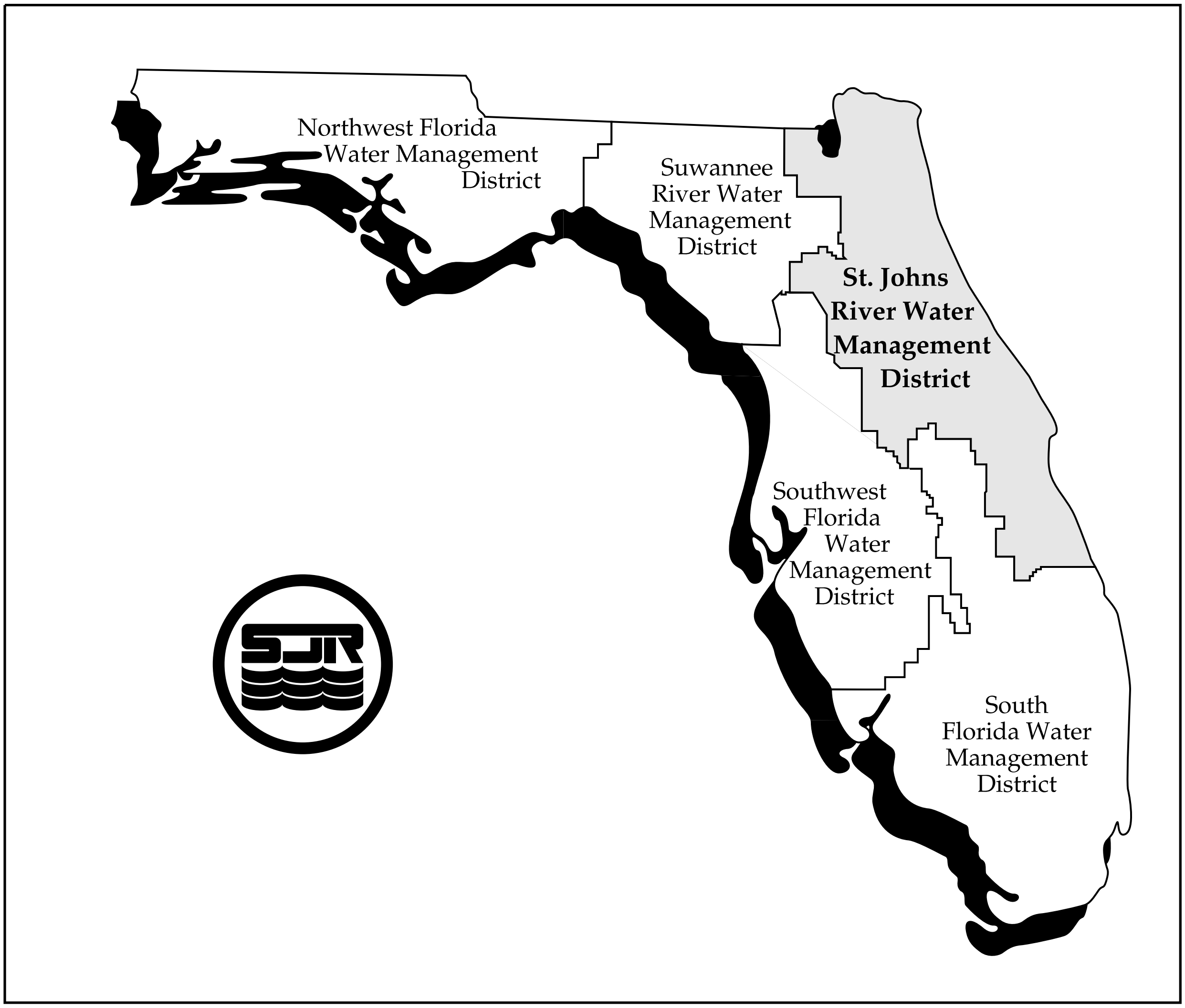

The St. Johns River Water Management District (SJRWMD) was created by the Florida Legislature in 1972 to be one of five water management districts in Florida. It includes all or part of 18 counties in northeast Florida. The mission of SJRWMD is to ensure the sustainable use and protection of water resources for the benefit of the people of the District and the state of Florida. SJRWMD accomplishes its mission through regulation; applied research; assistance to federal, state, and local governments; operation and maintenance of water control works; and land acquisition and management.

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EXECUTIVE SUMMARY

The middle St. Johns River (MSJR) is being considered as a possible alternative water supply source to help meet the projected future increased demand for water in the St. Johns River Water Management District (SJRWMD) (Figure ES1). Although other factors may ultimately be more limiting, minimum flows and levels (MFLs) will provide the initial limits to surface water withdrawals from the MSJR.

The basic task in analyzing changes to a hydrologic system is to quantify those changes and assess their acceptability. Often, simple operations are performed on gage records to assess the effects of alterations on a hydrologic system. For example, the amount of surface water withdrawal might be subtracted from daily flows gaged at a site. Frequency analysis on the resulting time series could then be used to assess changes to the system. However, a riverine system as complex as the MSJR requires the use of hydrologic modeling and the concomitant analyses. This is especially true when analyzing hydrologic changes in the context of MFLs. Modeling results will provide the framework needed to analyze and implement MFLs on the MSJR. By analyzing the output from hydrologic models, reasonable management decisions can be made regarding surface water withdrawals from the MSJR.

Three preliminary MFLs have been adopted for the St. Johns River (SJR) at State Road (SR) 44 near DeLand: a Minimum Frequent High flow and level, a Minimum Average flow and level, and a Minimum Frequent Low flow and level. These MFLs are composites of MFLs set at four locations between Lake Monroe and Lake Woodruff. In conjunction with setting MFLs for the MSJR, SJRWMD developed a hydrologic model of the MSJR—the MSJR SSARR model. This model simulates the flow rate of water at different points in the MSJR using historical rainfall, evaporation, and groundwater levels. At the same time, this model simulates stages at selected locations within the model domain. In order to determine stages between locations provided in the hydrologic model, SJRWMD also developed a one-dimensional water surface profile model for the MSJR—the MSJR HEC-RAS model. These two models enable SJRWMD to determine the limits of surface water withdrawals from the Middle St. Johns River Basin in the context of MFLs.

The model domain covers the MSJR from Lake Harney to Lake George (Figure ES1). The critical calibration parameters for the hydrologic model within this domain were stages and flows of the SJR at SR 44 near DeLand and stages of

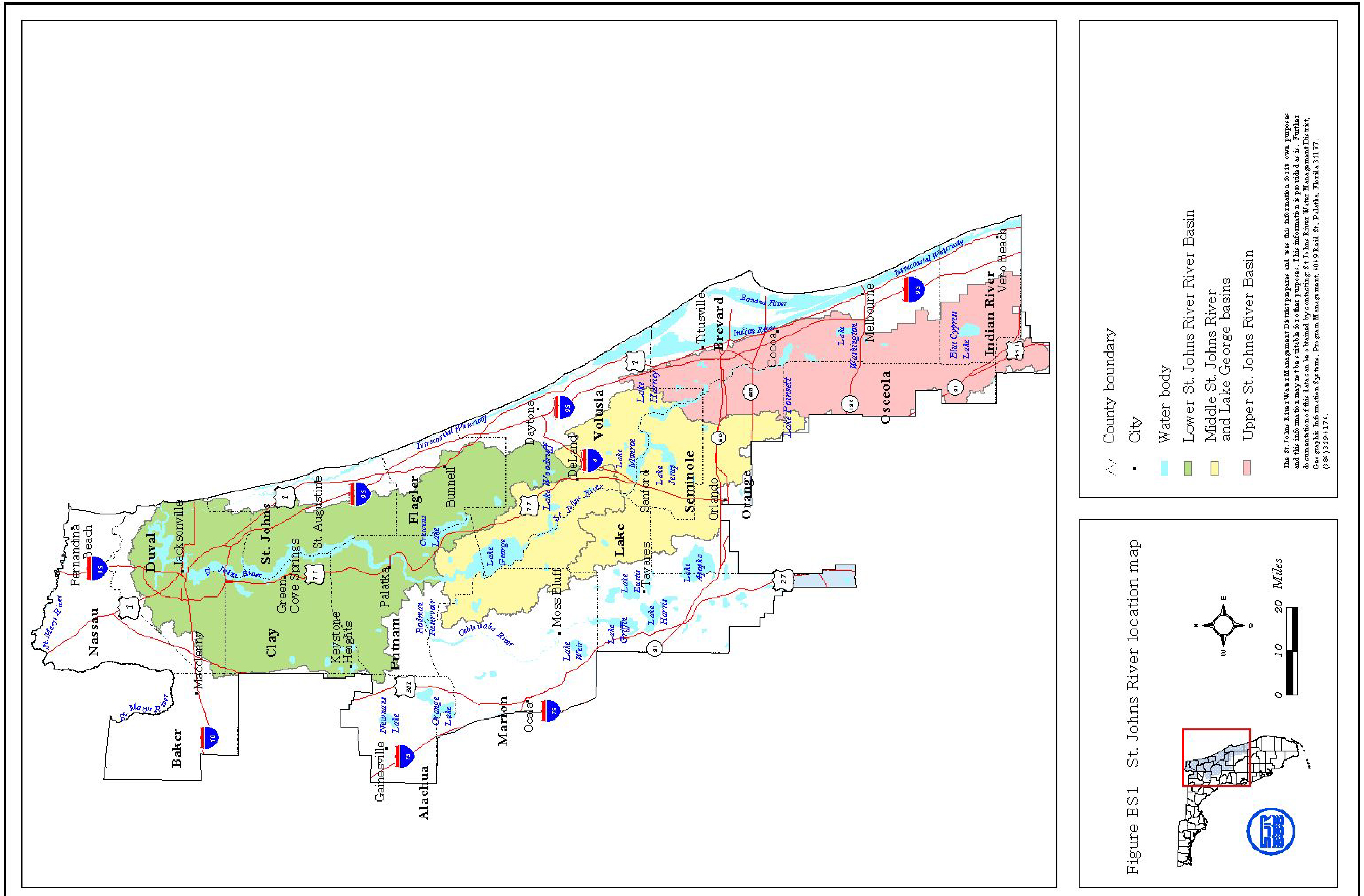

Figure ES1 St. Johns River location map

the SJR near Sanford (Lake Monroe). For the water surface profile model, the calibration parameters were stages at SJR gages located above Lake Harney, on Lake Monroe, at SR 44 near DeLand, and at SR 40 near Astor.

The purpose of this report is to describe and document the development of the models used in assessing MFLs for the MSJR. Also included in this report are five examples of hypothetical MSJR surface water withdrawal alternatives as they relate to MFLs.

Modeling results indicate that all three adopted MFLs are being met on the MSJR under existing conditions. Depending on withdrawal criteria, the models indicate that between 143 and 175 million gallons per day of water are available from the river before the MFLs cease to be met.

It should be emphasized that the withdrawal scenarios included in this report are examples of application of the calibrated models and are not meant to provide a comprehensive analysis of the potential water supply yield of the SJR near DeLand. Additional analyses will be performed as part of a comprehensive investigation of the potential water supply yield of the MSJR, given the proposed MFLs.

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INTRODUCTION

The middle St. Johns River (MSJR) (Figure 1) is being considered as a possible alternative water supply source to help meet the projected future increased demand for water in the St. Johns River Water Management District (SJRWMD) (Vergara 2000). Although other factors may ultimately be more limiting, minimum flows and levels (MFLs) will provide the initial limits to surface water withdrawals from the MSJR. For the purposes of the surface water modeling effort described in this document, the Lake George Basin is included as part of the Middle St. Johns River Basin (MSJRB).

The basic task in analyzing changes to a hydrologic system is to quantify those changes and assess their acceptability. Often, simple operations are performed on gaging records to assess the effects of alterations on a hydrologic system. For example, the amount of surface water withdrawal might be subtracted from daily flows gaged at a site. Frequency analysis on the resulting time series (Appendix A) could be compared to the frequency analysis of the original flows to assess changes to the system. However, analysis of possible changes to a riverine system as complex as the MSJR requires the use of hydrologic modeling and the concomitant analyses. This is especially true when analyzing hydrologic changes in the context of MFLs. Modeling results will provide the framework needed to implement MFLs on the MSJR. By analyzing the output from hydrologic models, reasonable management decisions can be made regarding surface water withdrawals from the MSJR.

PURPOSE AND SCOPE

Three MFLs have been adopted for the St. Johns River (SJR) at State Road (SR) 44 near DeLand (Mace 2003): a Minimum Frequent High flow and level, a Minimum Average flow and level, and a Minimum Frequent Low flow and level. These MFLs are composites of MFLs set at four locations between Lake Monroe and Lake Woodruff. In conjunction with setting MFLs for the MSJR, SJRWMD developed a hydrologic model of the MSJR that simulates the amount of water at different points in the MSJR using historical rainfall, evaporation, and groundwater levels. The hydrologic model also simulates stages at selected locations within the model domain. In order to determine stages between locations provided for in the hydrologic model, SJRWMD has also developed a one-dimensional water surface profile model for the MSJR. These two models enable SJRWMD to determine the quantities of water that can be withdrawn from the MSJRB without causing flows and levels to fall below adopted MFLs.

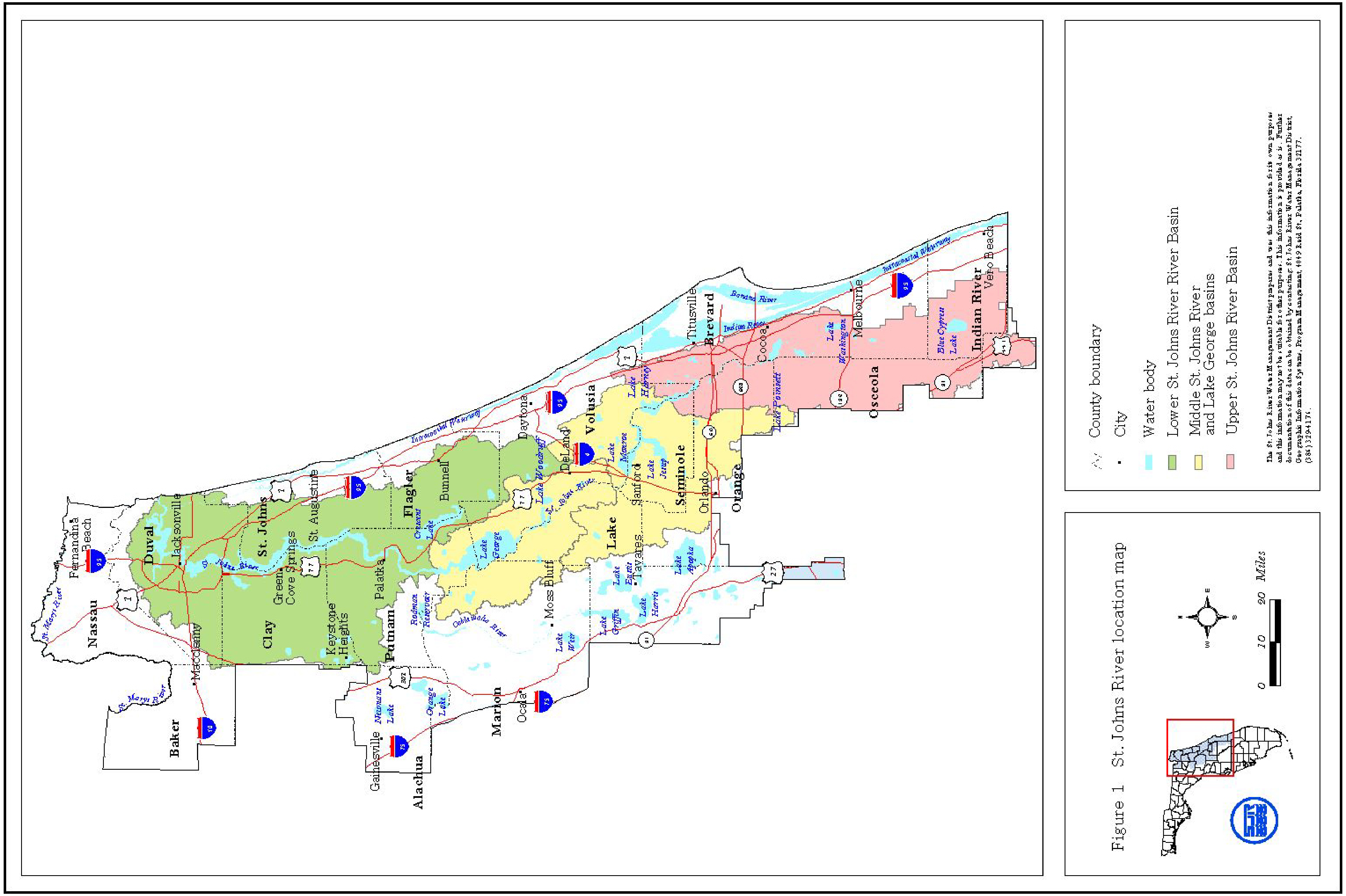


Figure 1 St. Johns River location map

The purpose of this report is to describe and document the following:

- Model selection
- Model calibration criteria
- Model development and calibration
- Model application assumptions
- Model performance assessment
- Statistical analysis used in implementing the MSJR MFLs
- Hypothetical MSJR surface water withdrawal alternatives relating to MFLs

The model domain covers the MSJR from Lake Harney to Lake George (Figure 1). The critical calibration parameters for the hydrologic model within this domain were stages and flows of the SJR at SR 44 near DeLand and stages of the SJR near Sanford (Lake Monroe). For the water surface profile model, the calibration parameters were stages at SJR gages located above Lake Harney, on Lake Monroe, at SR 44 near DeLand, and at SR 40 near Astor.

HYDROLOGIC MODEL OF THE MIDDLE ST. JOHNS RIVER

Hydrologic modeling and analysis provide the framework needed to implement MFLs on the MSJR. By analyzing modeling results, reasonable management decisions can be made regarding surface water withdrawals from the MSJR. This chapter of the MSJR hydrologic methods report discusses the following:

- Model selection
- Model calibration criteria
- Selected model (SSARR)
- Principal modeling assumptions
- Parallel versions of the MSJR SSARR model
- Calibration of the MSJR SSARR model
- Appropriateness of modeling assumptions

MODEL SELECTION

Before selecting a model to assess hydrologic changes in the context of MFLs, it must be established that the system in question and its relationship to MFLs cannot be represented adequately without a model. Often, simple operations are performed on gaging records to assess the effects of alterations on a hydrologic system. For example, the amount of surface water withdrawal might be subtracted from daily flows gaged at a site. Frequency analysis on the resulting time series (see Appendix A) could be compared to a frequency analysis of the original flows to assess a system with respect to MFLs. CH2M HILL (1997) essentially shifted flow duration curves (see Appendix A) to obtain preliminary analyses of the effects of withdrawals on the MSJR system. While these methods might be adequate in a preliminary analysis of withdrawals, they are inadequate for examining the effects of hydrologic changes, especially in the context of MFLs, for a system as complex as the MSJRB. For example, the effects of a surface water withdrawal from the MSJR will depend on whether stages are high or low and will propagate both upstream and downstream. Computer models are appropriate tools for analyzing the effects of these types of changes.

When selecting a model or combination of models to provide useful simulations of a hydrologic system, two principal factors should be considered. The first factor to consider is the model's ultimate purpose. If, for example, the model was designed to analyze an urban flooding problem, then the model would require sufficient detail and sufficiently small time steps to adequately simulate flooding effects in an urban setting. In the context of the MSJR MFLs, a long-term (covering 30 years or more) simulation of stages and flows is important. In addition, the model should be capable of simulating changes to the hydrologic system to ensure that the impact of proposed withdrawals from the system can be adequately addressed.

The second factor that should be considered in selecting a model or combination of models is the hydrologic and physical data available to develop and calibrate the models. For instance, unless a dense network of hourly rainfall is available, the use of a highly detailed model capable of simulating a complex urban flood is inappropriate. In the case of the MSJR, a daily-time-step model is adequate and daily-value data are available to run the model.

The Streamflow Synthesis and Reservoir Regulation (SSARR) mathematical model, a rainfall-runoff-routing model developed by the Portland District of the U.S. Army Corps of Engineers (USACE 1986; Ponce 1989), was selected for the MSJR MFLs modeling effort. SSARR is a standard hydrologic model that has been used in many parts of the world for many different applications. SSARR is a continuous simulation model, so in this sense it is well suited to the SJRWMD approach to MFLs. This model is well suited to a situation where relatively few long-term, daily rainfall stations are available, necessitating the use of relatively large drainage basins on the order of 100 square miles apiece.

SSARR is also appropriate for use in the MSJR because of its backwater mode. SSARR is able to perform routing in situations such as the MSJR where stages and flows are affected by backwater effects from a downstream time-variant source (Ponce 1989, p. 429). This feature allows modeling of the system without developing an unsteady-flow water surface model such as UNET (Barkau 1991). These unsteady-flow models have been developed to simulate short-term events and are not well suited to modeling long-term, continuous simulations covering 30 or more years.

SJRWMD has used SSARR as the basis in the development of the MSJR SSARR model, which is described in this document.

MODEL CALIBRATION CRITERIA

Calibration of a hydrologic model is a standard procedure in which model output is compared to measured field data. The MSJR SSARR model will be used to determine the effects of consumptive use withdrawals on the MSJR system. Therefore, the model's ability to simulate stream flow will be tested by calibration against flow measurements from the field. The effects of water withdrawals from the MSJR system will be translated to vegetation and soil changes through simulation of water surface levels. Therefore, the MSJR SSARR model will additionally be calibrated against measured stages at selected locations within the system.

Calibration criteria, used to judge the adequacy of a model, are determined before model calibration. In the case of the MSJR SSARR model, the calibration criteria concentrate on simulation of stages. The goal is to maximize the number of simulated values within ±0.5 foot (ft) of the corresponding measured data.

Although it is important to simulate specific events as closely as possible, in an MFLs context, it is more important to statistically replicate the hydrologic characteristics of a system. This is especially important to consider in view of the sparse rainfall record available.

Because magnitudes vary so much from gage to gage, flow simulation is not assessed against a specific benchmark. Instead, based on trends and magnitudes, a judgment is made as to the adequacy of the simulations.

SELECTED MODEL (SSARR)

The SSARR model is composed of watershed and river system submodels. The watershed submodel simulates rainfall-runoff and accounts for interception, evapotranspiration, baseflow infiltration, and routing of runoff into the stream network. This submodel also accounts for groundwater flow through the local water table aquifer, but not for flow through the regional surficial aquifer, intermediate aquifer, or Floridan aquifer systems.

The basic routing method used by SSARR to model a watershed is a cascade-of-reservoirs technique (USACE 1986; Ponce 1989). A watershed is represented as a series of lakes, which conceptually simulates the natural delay of runoff.

The river system submodel routes streamflows from upstream to downstream points through lake storage. The river system submodel also uses the cascade-of-reservoirs technique to simulate channel routing. Lake routing is accomplished by an iterative solution of an equation involving inflow, outflow, and storage. The model accounts for evaporation losses and rainfall gains for each lake.

The SSARR user manual (USACE 1986) contains a complete description of the model. Ponce (1989) also provides a description of SSARR.

Input data needed to operate SSARR include the following:

- Job control parameters
- Constant characteristics and relationships
- Initial conditions data
- Time-series data

Job Control Parameters

Job control parameters used by SSARR include the simulation period, data time intervals (i.e., daily, hourly, etc.), and output options (e.g., the stations for which output is required). The simulation period used in the MSJR SSARR model was 1 year and the time step was 1 day. Long-term simulations were composed of a series of 1-year segments.

Constant Characteristics and Relationships

The constant characteristics and relationships of a watershed are features such as drainage area, characteristics affecting runoff, hydrograph shape parameters, stage / storage relationships, stage / flow relationships, drainage system configuration, and so on.

The constant characteristics and relationships discussed in detail here are the soil moisture-runoff relationships, drainage areas, drainage system configuration, stage / storage relationships, and stage / flow relationships.

Soil Moisture-Runoff Relationships. The Soil Moisture Index (SMI), measured in inches, is an indicator of relative soil wetness and, consequently, of watershed runoff potential (Figure 2). Rainfall input is divided by SSARR into surface runoff and soil moisture increases. The percentage of rainfall available for runoff (runoff percentage, or ROP) is based on an empirically derived relationship between soil moisture and ROP. This relationship determines the runoff percentage; rainfall that is not converted by the model into runoff is added to the SMI.

Soil moisture (as represented by the SMI) in SSARR is depleted only by evapotranspiration (ET). ET losses include transpiration by vegetation, interception losses, and direct evaporation of groundwater. The maximum of the sum of these losses is referred to as potential ET (Ponce 1989). Because these data are difficult to collect, the potential ET can be approximated as a percentage of

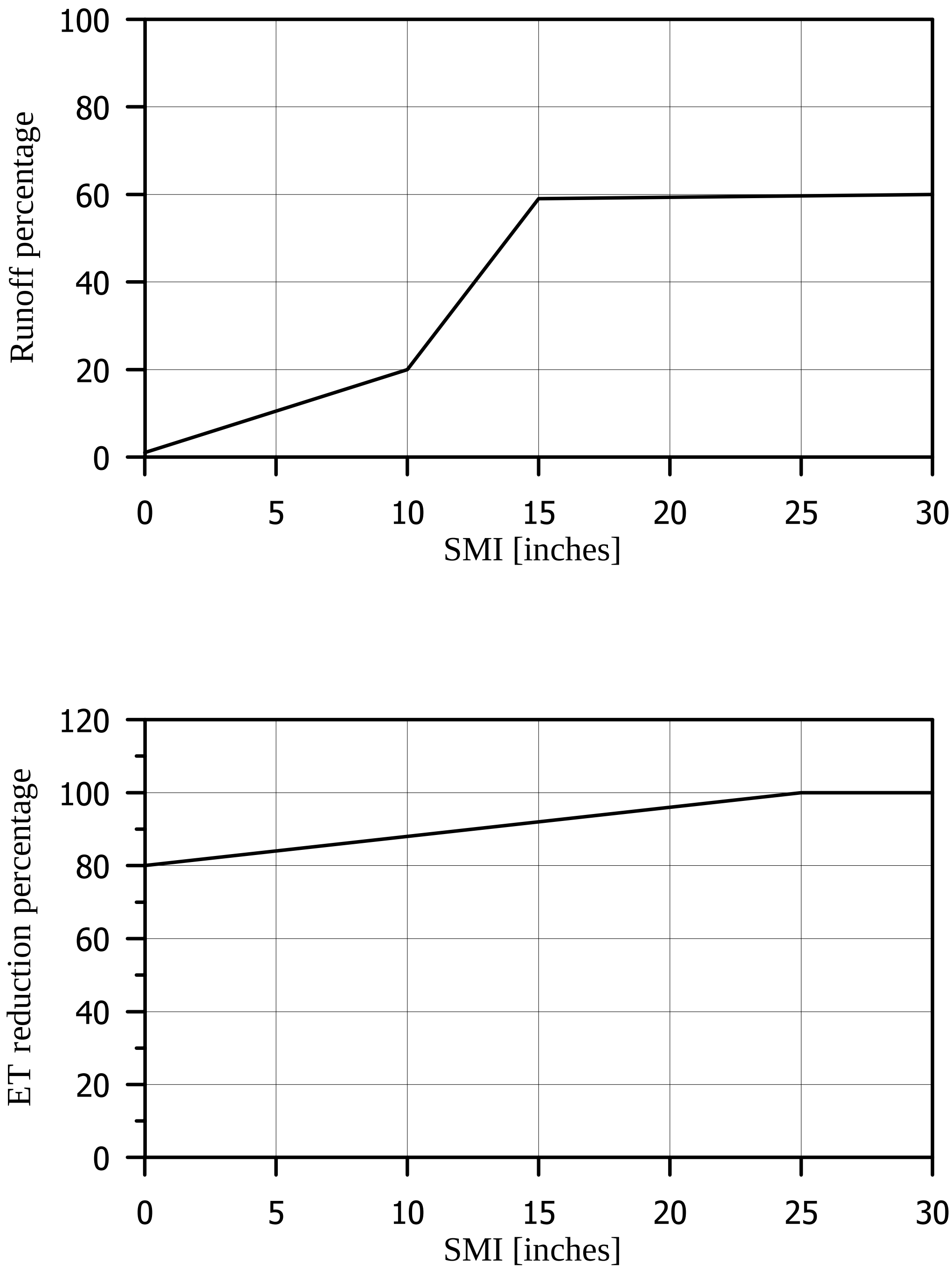


Figure 2. Typical soil moisture relationships for the MSJR SSARR hydrologic model: Runoff percentage versus SMI (soil moisture index) and evapotranspiration reduction percentage versus SMI

pan evaporation (Ponce 1989; Linsley et al. 1982); the final percentage is determined during model calibration. The monthly pan evaporation data at a NOAA (National Oceanic and Atmospheric Administration) weather station is used to obtain daily potential ET.

The actual amount of ET, referred to as effective ET, varies with changing soil moisture conditions. The soil moisture lost through ET decreases as the soil dries out. Thus, the potential ET is multiplied by a factor, based on the SMI, to obtain the effective ET (Figure 2). The final form of the relationship between the SMI and the effective ET is determined during model calibration. SSARR determines the effective ET and reduces the SMI by the effective ET before calculating runoff.

Drainage Areas. Drainage areas for the MSJR SSARR model were obtained from data published by SJRWMD (Adamus et al. 1997) (Figure 3). Basins appearing in Figure 3 are referred to as Planning Unit basins. The actual MSJR SSARR model drainage areas (Table 1) do not necessarily correspond to the Planning Unit basins because they are determined by factors such as gage location and rain gage coverage area. The drainage areas of the MSJR SSARR model are smaller than those listed in Adamus et al. (1997) because areas not contributing runoff, as determined by inspection of topographic maps, were subtracted prior to inclusion in the model. Adamus et al. (1997) divided the MSJR model domain into three basins: the Upper St. Johns River (USJR) Basin (Basin 6, Figure 3), the MSJRB (Basin 4, Figure 3), and the Lake George Basin (Basin 5, Figure 3). For the present study, the Lake George Basin will be considered part of the MSJRB.

Drainage System Configuration. A schematic of the MSJR SSARR model is a useful way to present the configuration of the various components of the hydrologic system (Figure 4). The schematic shows the location of different model elements such as drainage basins, lakes, channel routing relationships, and springs. The MSJR is modeled as a series of lakes running from Lake Poinsett to Lake George.

Stage/Storage Relationships. The relationship of storage capacity to elevation for each lake is based on areas derived from topographic contours on U.S. Geological Survey (USGS) quadrangle maps and, where available, lake depths from USGS quadrangle maps. Where lake depths were not available, areas were extrapolated from those obtained from the topographic maps. The storage capacity curve for each lake is incorporated in the model as a two-variable table relating stage and storage capacity.

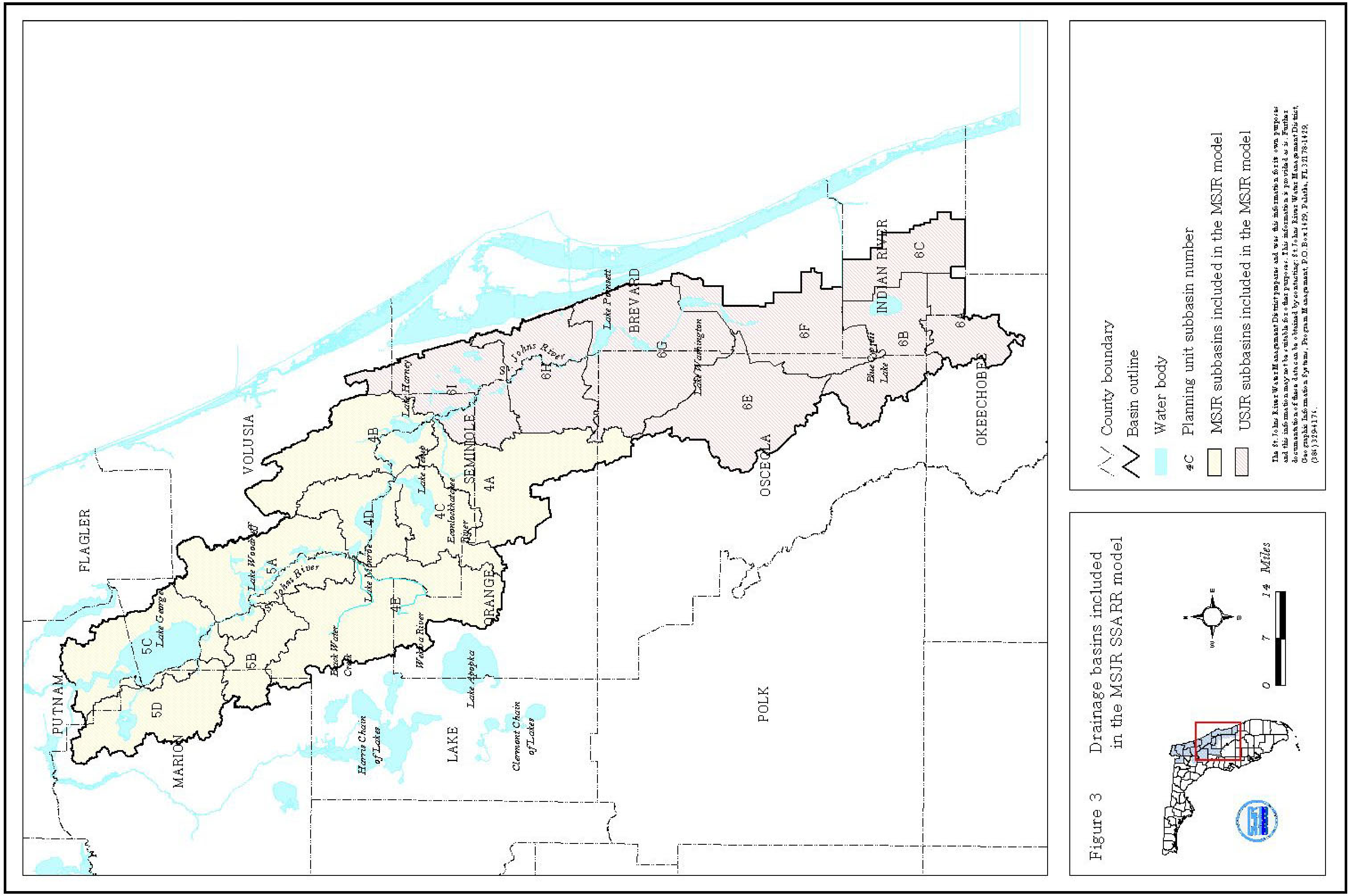


Figure 3 Drainage basins included in the MSJR SSARR model

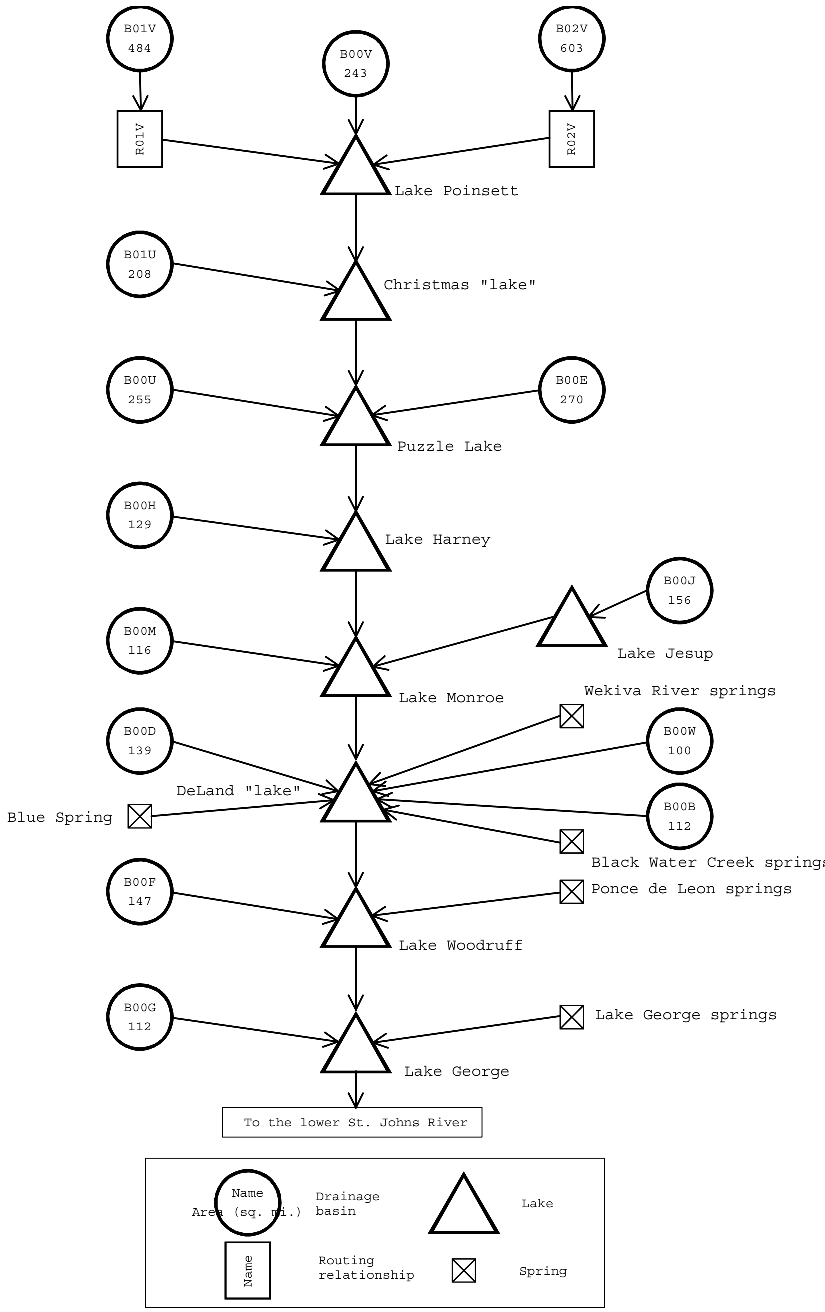


Figure 4. Schematic of the MSJR SSARR model

Table 1. Drainage areas in the MSJR SSARR model

SSARR Basin Name	Drainage Area (square miles)	Description	NOAA Rainfall Stations Used in Basin[1]
B01V	484	USJR, Blue Cypress Lake and south	Vero Beach 4W
B02V	603	USJR between Blue Cypress Lake and Lake Washington	Melbourne WSO
B00V	243	USJR around Lake Poinsett	Melbourne WSO
B01U	208	USJR between Lake Poinsett and the SJR near Christmas gage	Titusville (50%) Bithlo (50%)
B00U	255	USJR between the SJR near Christmas gage and Lake Harney	Titusville (60%) Bithlo (40%)
B00E	270	Econlockhatchee River	Bithlo
B00H	129	MSJR around Lake Harney	Titusville (50%) Sanford EXP STN (50%)
B00J	156	Basin around Lake Jesup	Sanford EXP STN
B00M	116	MSJR around Lake Monroe	Sanford EXP STN
B00W	100	Wekiva River	Sanford EXP STN
B00B	112	Black Water Creek	DeLand 1SSE
B00D	139	MSJR between Lake Monroe and DeLand	DeLand 1SSE
B00F	147	MSJR around Lake Woodruff	DeLand 1SSE
B00G	112	MSJR around Lake George	Crescent City

Note: EXP STN = experimental station
MSJR = Middle St. Johns River
NOAA = National Oceanic and Atmospheric Administration
SJR = St. Johns River
USJR = Upper St. Johns River

[1]See Table 2 and Figure 8

Stage/Flow Relationships. The relationship between lake stage and lake flow is referred to as a rating relationship. The MSJR SSARR model contains two types of rating relationships.

The first type of rating relationship is one in which flow depends only on the stage of the lake itself; that is, there is a one-to-one relationship between stage and flow and is referred to as a rating curve. For example, the rating curve for the SJR near Christmas (Figure 5) can be approximated by a simple function: a given stage is associated with a single flow. This particular rating curve was developed using stage and flow gaged during 1998 at the USGS gage.

The second type of rating relationship is one in which flow depends on the stage of the river as well as the slope of the water surface (difference in stage between a lake and the downstream water body). For example, the rating relationship for

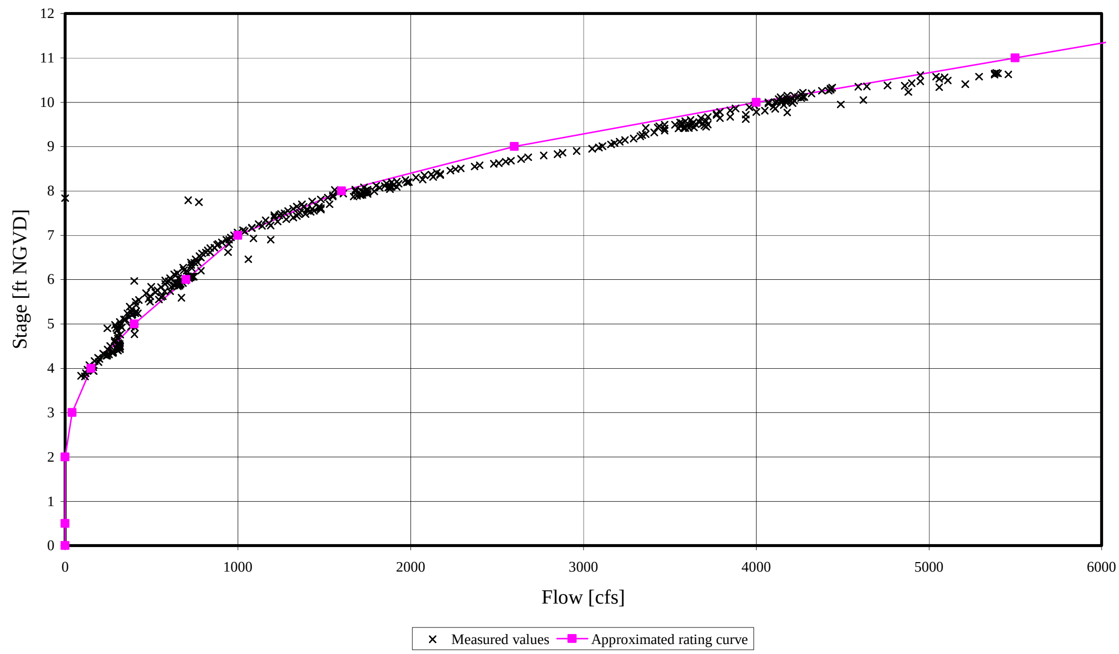


Figure 5. Rating curve (stage versus flow) for the SJR near Christmas USGS gage (1998)

flow from Lake Monroe cannot be approximated by a simple function relating stage and flow (Figure 6). Lake Monroe outflow depends on the Lake Monroe stage as well as the downstream stage. If flow is plotted against stage differences between Lake Monroe and the MSJR near DeLand, there is more of a one-to-one relationship between flow and stage (Figure 7). The Lake Monroe rating relationship, based on 1997 data collected at the Lake Monroe and DeLand gages, was used as a basis for determining rating relationships for other lakes within the MSJR SSARR model. The final form of each of this type of rating relationship was determined during model calibration.

Land Use and Soils. Beyond estimating the amount of impervious area, land use and soils are often not used in the development of SSARR models and, therefore, are not detailed here.

Initial Conditions Data

Initial conditions specify the values of watershed variables on the starting day of a 1-year simulation. These variables include the current value of the SMI; the

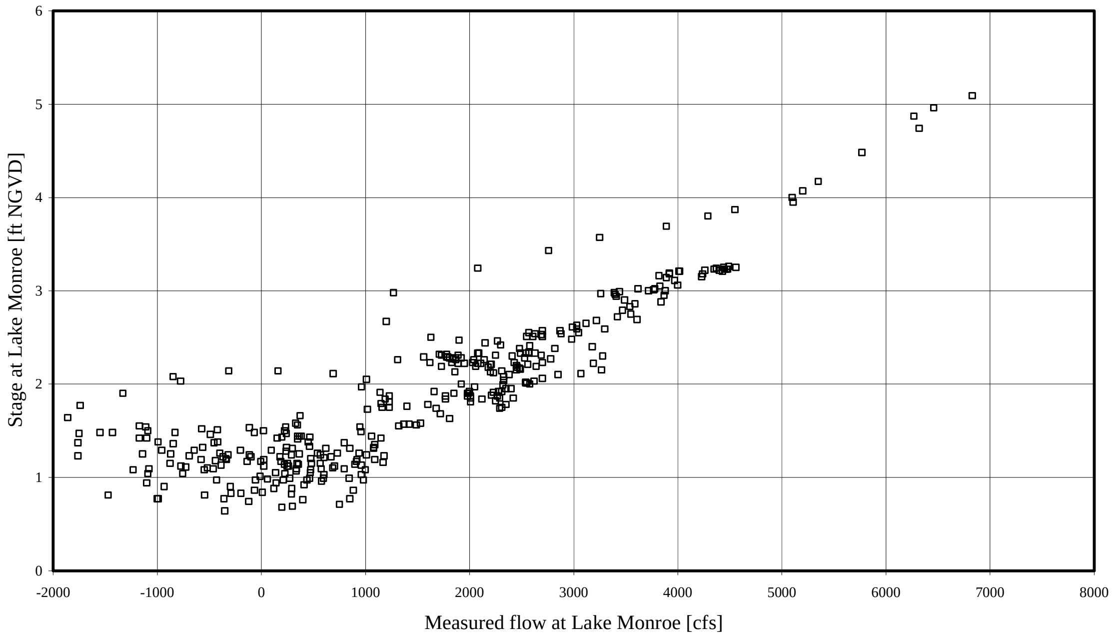


Figure 6. Rating curve (stage versus flow) at the SJR near Sanford (Lake Monroe) gage (1997)

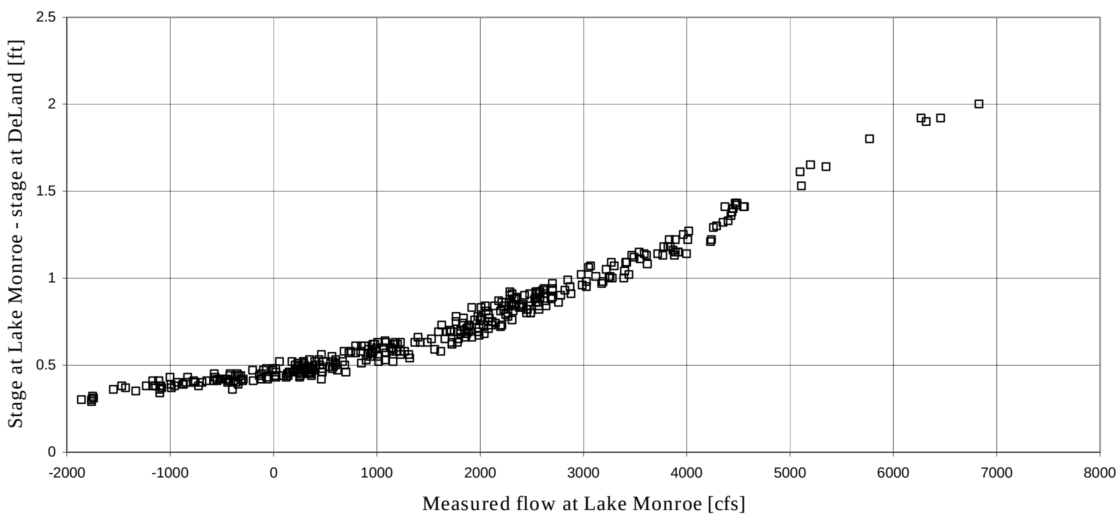


Figure 7. Plot of stage difference between the SJR near Sanford (Lake Monroe) gage and the SJR at SR 44 near DeLand gage versus flow at the SJR near Sanford (Lake Monroe) gage (1997)

initial runoff from each drainage basin; and the initial storage, elevation, and outflow for each lake. Model simulations were divided into periods of 1 year. Long-term simulations were composed of a series of 1-year segments. The model automatically uses conditions calculated at the end of 1 year of simulation to start the following year's simulation.

Time-Series Data

SSARR uses a number of different types of time-series data as input. Rainfall, evaporation, stage data, potentiometric surface levels of the Floridan aquifer system, and flow data are used for the MSJR SSARR model. In addition, the MSJR SSARR model includes simulated spring flows.

Rainfall. The MSJR SSARR model uses daily rainfall totals. Rainfall data gathered at NOAA weather stations were used for model calibration and long-term simulations (see Table 2, Figure 8).

Table 2. Rainfall stations located within the MSJR SSARR model domain

Principal NOAA Station (period of record)	County	NOAA Number	Supplementary Station (data period)	Supplementary Station Number	Composite Period of Record
Bithlo (1954–88)	Orange	0758	Christmas (1946–53) Story Ranch (1989–98)	NOAA 1565 SJRWMD 0277	1946–98
Crescent City (1897–1998)	Putnam	1978	—	—	1887–1998
DeLand 1SSE (1909–98)	Volusia	2229	—	—	1909–98
Melbourne WSO (1938–98)	Brevard	5612	—	—	1938–98
Orlando WSO McCoy (1974–98)	Orange	6628	Orlando WB AP (1892–1973)	NOAA 6638	1892–1998
Sanford EXP STN (1956–98)	Seminole	7982	Sanford (1913–55)	NOAA 7977	1913–98
Titusville (1901–98)	Brevard	8942	—	—	1901–98
Vero Beach 4W (1965–98)	Indian River	9219	Vero Beach FAA AP (1943–64)	NOAA 9214	1943–98

Note: MSJR = Middle St. Johns River
NOAA = National Oceanic and Atmospheric Administration
SJRWMD = St. Johns River Water Management District

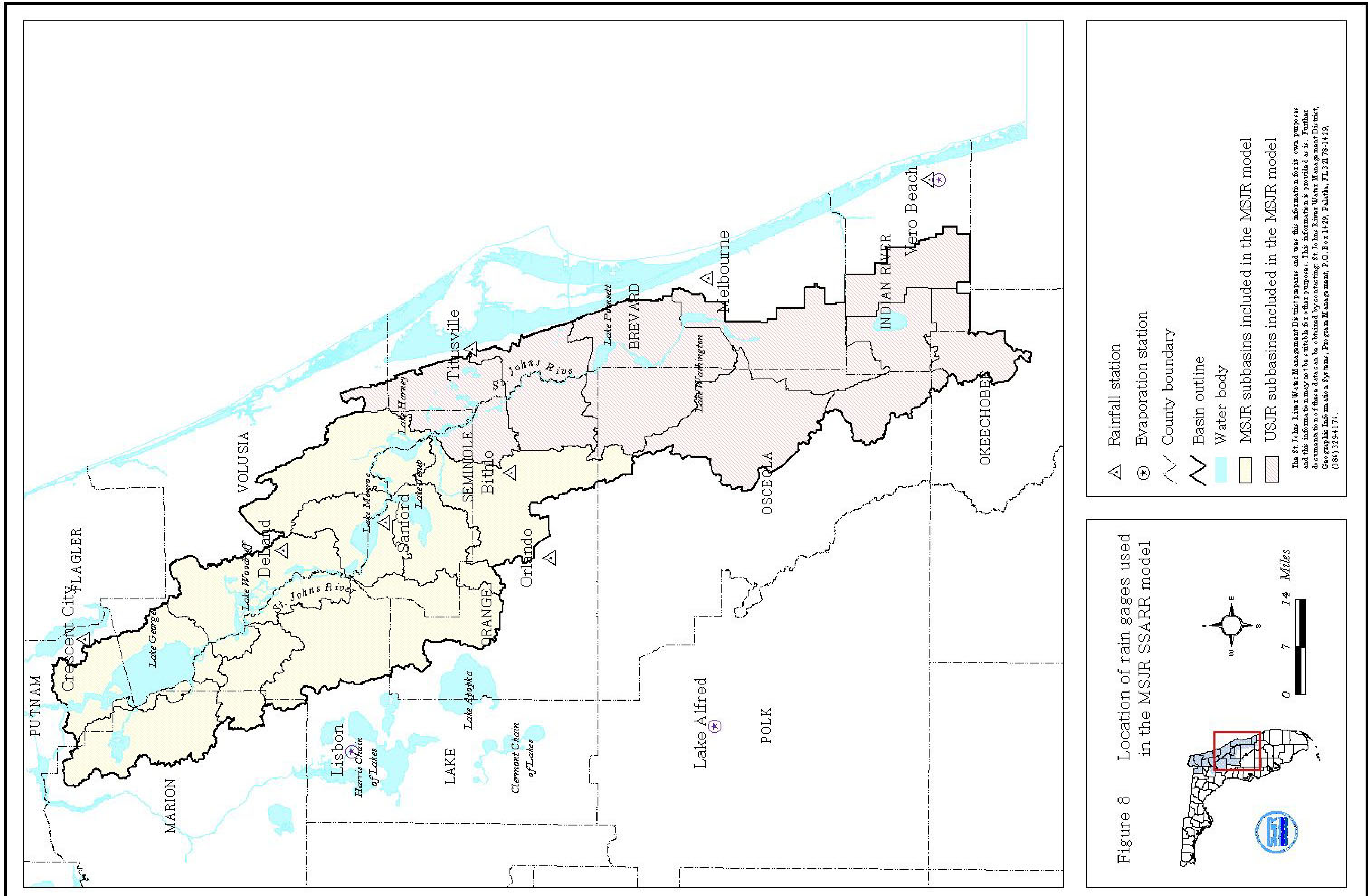


Figure 8 Location of rain gages used in the MSJR SSARR model

Lake and river stages. Calibration of a hydrologic model is accomplished by comparing measured daily stage values to those generated by the model. Daily data from seven stage gages (Table 3, Figure 9) were used in the development of the MSJR SSARR model.

Floridan aquifer potentiometric surface levels. Potentiometric surface data from two Floridan aquifer wells (Table 3, Figure 9) were used in the simulation of spring flows along the MSJR. Levels at these two wells are recorded approximately once a month; daily values were interpolated from the records.

Flow data. Calibration of a hydrologic model is accomplished by comparing measured daily flow values to those generated by the model. Daily data from nine flow gaging stations (Table 3, Figure 9) were used in the development of the MSJR SSARR model.

Pan evaporation. Pan evaporation data are important to the MSJR SSARR model in two ways: (1) the calculation of direct lake evaporation and (2) the estimation of ET.

The pan evaporation concept provides a standard method of measuring evaporation (Linsley et al. 1982). Monthly pan evaporation data are published at four NOAA stations in SJRWMD: Gainesville, Lake Alfred, Lisbon, and Vero Beach (Figure 8). Average annual pan evaporation varies from 73.11 inches at Lake Alfred to 59.08 inches at Lisbon (Table 4). The maximum annual pan evaporation varies from 86.25 inches at Lake Alfred to 67.57 inches at Lisbon. Minimum annual pan evaporation varies from 53.68 inches at Gainesville to 66.76 inches at Lake Alfred.

Direct lake evaporation can be estimated using pan evaporation data multiplied by a coefficient (Ponce 1989; Linsley et al. 1982; USGS 1954). Although coefficients vary, 0.81 is often used in the vicinity of SJRWMD, based on a study at Lake Okeechobee (USGS 1954). Estimates of average annual lake evaporation using this coefficient vary from 59.22 inches at Lake Alfred to 47.85 inches at Lisbon (Table 5). Values published by the National Weather Service (NWS) (Linsley et al. 1982, p. 173) indicate that average annual evaporation for shallow lakes in SJRWMD should vary from 45 to 48 inches per year. Therefore, Lisbon pan evaporation data were used to calculate direct lake evaporation for the MSJR SSARR model.

Table 3. Stage and flow gaging stations located within the MSJR SSARR model domain

Station	USGS Number	Period of Record	Record Accuracy[1,2]
Stage Stations			
Lake George near Salt Springs	02236210	1936–50, 1972–98	NA
Lake Jesup near Sanford	02234434	1942–98	NA
Flow Stations			
Lake Jesup outlet near Sanford	02234435	1993–98	Poor
SJR at Astor	02236125	1994–98	Fair, except for periods of estimated daily flow, which are poor
Econlockhatchee River near Chuluota	02233500	1935–98	Fair, except for periods of estimated daily flow, which are poor
Wekiva River near Sanford	02235000	1935–98	Fair
Stage and Flow Stations			
SJR above Lake Harney, near Geneva	02234000	1981–98 flow 1941–98 stage	Fair, except for periods of estimated daily flow and those below 200 cfs, which are poor
SJR near Christmas	02232500	1933–98	Fair, except for periods of estimated daily flow, which are poor
SJR near Cocoa (Lake Poinsett)	02232400	1953–98 flow 1941–98 stage	Fair, except for periods of estimated daily flow, which are poor
SJR near DeLand (at SR 44)	02236000	1933–98 flow 1945–98 stage	Fair; much of the record is poor, below 2,000 cfs
SJR near Sanford (Lake Monroe)	02234500	1987–89, 1995–98 flow 1920–98 stage	Fair, except for periods of estimated daily flow, which are poor
Floridan Aquifer Wells			
Seminole 257 well near Sanford, S-257	284750081132301	1952–98	NA
J.C. Mew well replacement at Seville, V-0510 (also known as V-095)	291748081290301	1936–98	NA

Note: cfs = cubic feet per second
MSJR = Middle St. Johns River
NA = not applicable
SJR = St. Johns River
SR = state road
USGS = U.S. Geological Survey

[1]Source: USGS 1997. Note: "The accuracy of streamflow records depends primarily on: (1) The stability of the stage-discharge [flow] relation or, if the control is unstable, the frequency of discharge [flow] measurements; and (2) the accuracy of measurements of stage, measurements of discharge [flow], and interpretation of records" (p. 19). The accuracy grades are described as follows:

"Excellent" means that about 95% of the daily discharges [flows] are within 5% of their true values.
"Good" means that about 95% of the daily discharges [flows] are within 10% of their true values.
"Fair" means that about 95% of the daily discharges [flows] are within 15% of their true values.
"Poor" means records do not meet the criteria mentioned above.

[2]Record accuracy is assessed yearly, so it varies at any given gage. What appears here is a general characterization of record accuracy.

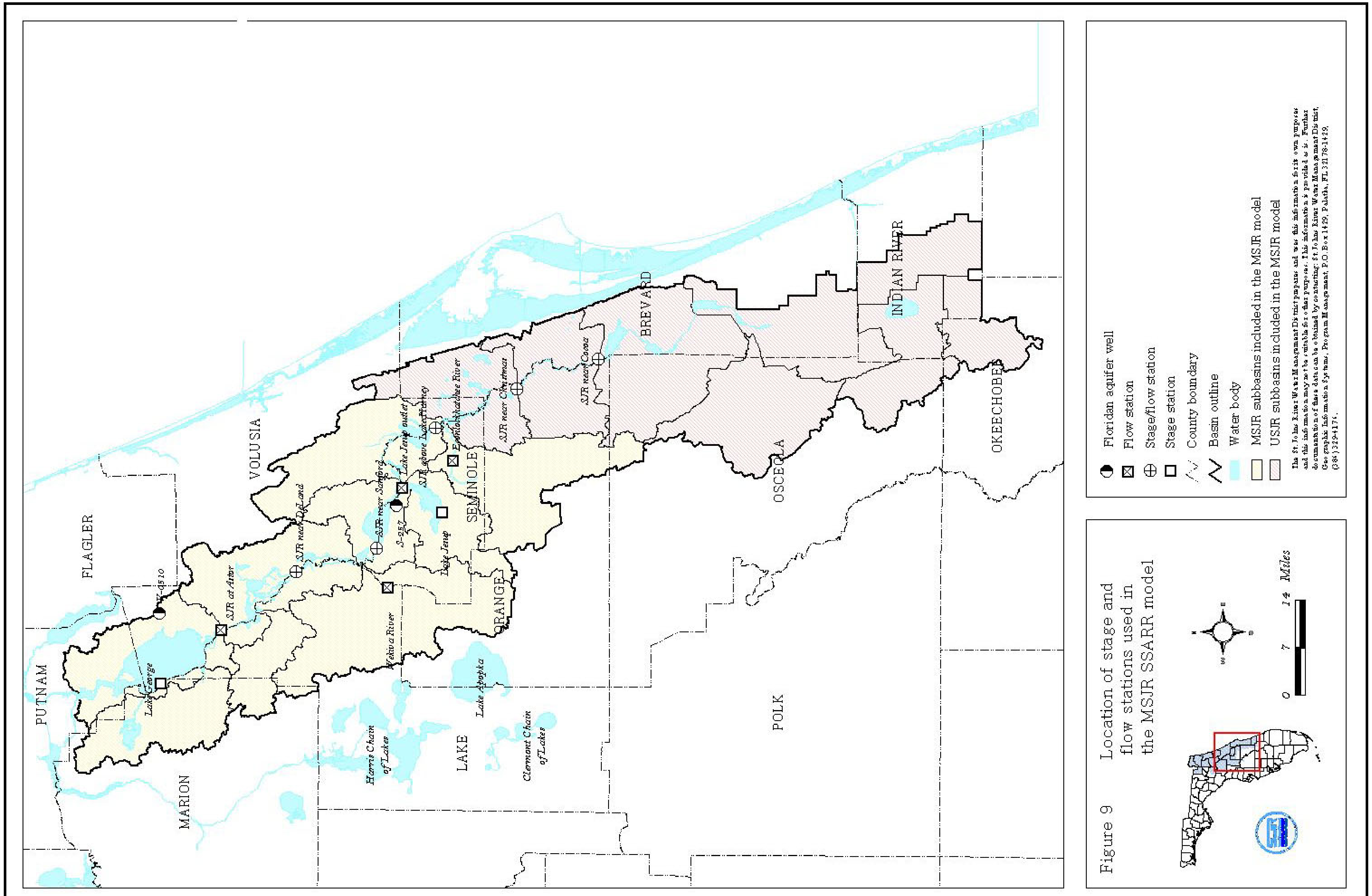


Figure 9 Location of stage and flow stations used in the MSJR SSARR model

Table 4. Summary of pan evaporation data from NOAA stations located in SJRWMD

Location	Period of Record	Maximum Annual Pan Evaporation (inches)	Minimum Annual Pan Evaporation (inches)	Average Annual Pan Evaporation (inches)
Gainesville	1954–98	73.63	53.68	63.88
Lake Alfred	1965–98	86.25	66.76	73.11
Lisbon	1960–98	67.57	54.37	59.08
Vero Beach	1952–98	79.41	55.35	67.67

Note: NOAA = National Oceanic and Atmospheric Administration
SJRWMD = St. Johns River Water Management District

Table 5. Estimated lake evaporation for NOAA stations in the SJRWMD area

Location	Average Annual Pan Evaporation (inches)	Estimated Annual Lake Evaporation (inches)[1]
Gainesville	63.88	51.74
Lake Alfred	73.11	59.22
Lisbon	59.08	47.85
Vero Beach	67.67	54.81

Note: NOAA = National Oceanic and Atmospheric Administration
SJRWMD = St. Johns River Water Management District

[1]Calculated by multiplying the average annual pan evaporation amounts from Table 4 x 0.81

Lake evaporation coefficients vary from month to month (USGS 1954). Monthly coefficients for the MSJR SSARR model were obtained from a study of evaporation on Lake Okeechobee, Florida (USGS 1954). Using average monthly pan evaporation at Lisbon and the corresponding monthly coefficients yields an average annual evaporation of 48.18 inches (Table 6). Again, this rate is very close to the range published by NWS (Linsley et al. 1982, p. 173) for average annual evaporation from shallow lakes in the vicinity of SJRWMD. Monthly pan evaporation was divided by the number of days in a month to obtain a daily pan evaporation value. For model simulation of hydrologic conditions between 1960 and 1998 (Table 4), published monthly pan evaporation was used. For simulation years prior to 1960, average monthly pan evaporation was used.

Table 6. Summary of average monthly lake evaporation applied in the MSJR SSARR model

Month	Monthly Pan-to-Lake Coefficients[1]	Average Monthly Pan Evaporation[2] (inches)	Estimated Lake Evaporation (inches)
January	0.77	2.37	1.82
February	0.69	2.94	2.03
March	0.73	4.92	3.59
April	0.84	6.52	5.48
May	0.82	7.39	6.06
June	0.85	6.91	5.88
July	0.91	6.89	6.27
August	0.91	6.33	5.76
September	0.85	5.24	4.45
October	0.76	4.05	3.08
November	0.71	2.72	1.93
December	0.83	2.19	1.82
Total	—	58.49	48.18

Note: MSJR = Middle St. Johns River

[1]USGS 1954, p. 128
[2]Lisbon NOAA station

Potential ET from a watershed can be estimated using a set percentage of daily pan evaporation (Ponce 1989; Linsley et al. 1982). For the MSJR SSARR model, this percentage varied from 105 to 115%. Because pan evaporation measured at the Lisbon NOAA station was used to calculate lake evaporation, as described above, it was also used to determine evapotranspiration for the MSJR SSARR model (see p. 8 for an explanation of how SSARR uses pan evaporation data for estimating ET).

Spring flow in the MSJR. Springs contribute a substantial portion of the flow in some parts of the MSJR, especially in times of low flow. Thus, it was necessary to include springflow simulation in the MSJR SSARR model (Figures 4 and 10, Table 7). Groundwater flow models are often used for springflow simulations. However, groundwater models are generally so complex that simulation of daily values is not practical. Therefore, a simpler method of estimating spring flows was developed, as follows.

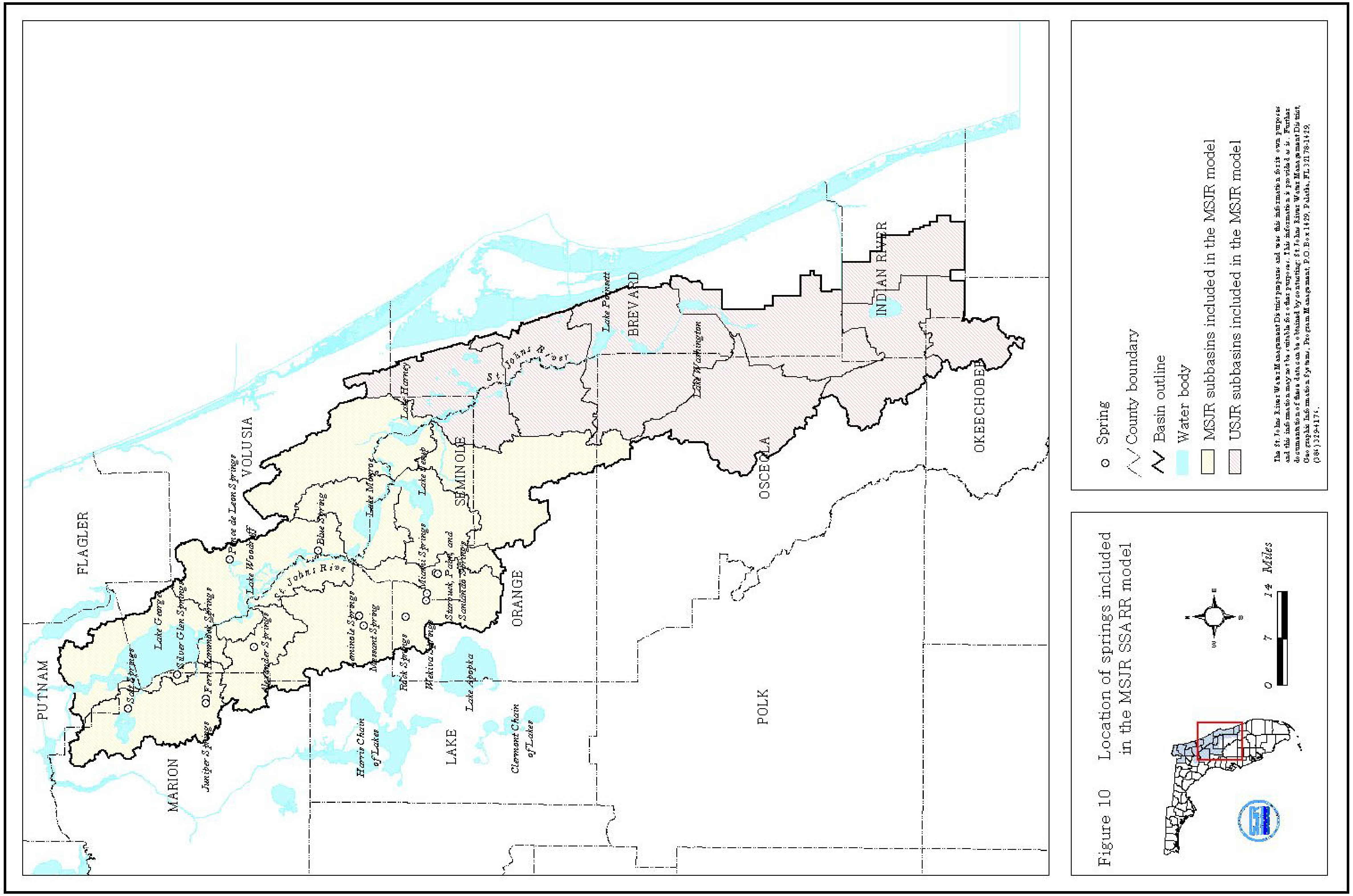


Figure 10 Location of springs included in the MSJR SSARR model

Table 7. Springs included in the MSJR SSARR model domain

Spring	Number of Measurements	Number of Years	Period of Record[1]	Mean Flow[2] (cfs)
Alexander[3]	95	24	1931–93	110
Blue	516	62	1932–93	158
Fern Hammock[3]	48	28	1935–2000	13
Juniper[3]	51	28	1935–2000	10
Messant[4]	14	14	1946–92	16
Miami[5]	52	24	1945–93	4.7
Palm[5]	74	25	1941–92	7.6
Ponce de Leon	202	35	1929–93	28
Rock[5]	169	41	1931–93	61
Salt[3]	55	32	1929–2000	81
Sanlando[5]	76	27	1941–92	20
Seminole[4]	26	17	1931–93	33
Silver Glen[3]	47	28	1931–2000	107
Starbuck[5]	72	23	1944–92	14
Wekiva[5]	164	36	1932–93	70

Note: MSJR = Middle St. Johns River

[1]Data collected by the U.S. Geological Survey since 1929 and the St. Johns River Water Management District since 1983; frequency of measurement varies widely
[2]Average of annual mean spring flows
[3]Modeled as part of a total of Lake George springs
[4]Modeled as part of a total of Black Water Creek springs
[5]Modeled as part of a total of Wekiva River springs

Source: Rao and Clapp 1996

The difference in elevation between a spring pool and the potentiometric surface of the Floridan aquifer in the vicinity of the spring determines the amount of flow emanating from that spring. The basic principle for describing the flow of groundwater dates from the middle of the nineteenth century and the work of Henri Darcy with flows through filter sand (Terzaghi and Peck 1967). The discussion that follows will assume an idealization of a spring along the lines of Darcy's experiments. Darcy's law can be expressed as

$$Q = K\frac{(E_w - E_p)}{L}A \qquad \textbf{(1)}$$

where

Q = spring flow
K = coefficient of permeability or hydraulic conductivity
E_w = elevation of the potentiometric surface of the Floridan aquifer in the vicinity of well w
E_p = elevation of the spring pool
L = length of the material through which water percolates from aquifer to spring pool
A = cross-sectional area of material through which water percolates from aquifer to spring pool

If L and A are assumed to be constant, then Equation 1 can be written

$$Q = \hat{K}E_w - \hat{K}E_p \quad \textbf{(2)}$$

where

$\hat{K}$ = a constant that is a function of the local geology

If E_p is assumed to be a constant, then Equation 2 can be written as

$$Q = \hat{K}E_w + \hat{E} \quad \textbf{(3)}$$

which is in the mathematical form of a straight line with a slope of $\hat{K}$ and an intercept of $\hat{E}$.

There are alternatives to a linear relationship for estimating flow through a porous media (Li et al. 1998). One alternative is the quadratic relationship suggested by Forchheimer (Li et al. 1998), which can be written

$$rQ + sQ^2 = (E_w - E_p) \quad \textbf{(4)}$$

where r and s are constants that depend on the characteristics of the porous media. Prony (Li et al. 1998) has suggested a power relationship that can be written

$$Q = c_0(E_w - E_p)^{c_1} \quad \textbf{(5)}$$

where c_0 and c_1 are constants depending on the flow conditions, the characteristics of the porous media, and the fluid.

For the MSJR SSARR model, most of the springs were modeled with the power relationship (Table 8). A linear relationship was used for the Wekiva River springs and the Black Water Creek springs.

Table 8. Modeling parameters for springs included in the MSJR SSARR model

Power Relationship Springs		
Spring Name	c_0	c_1
Blue	8.5×10^{-7}	6
Ponce de Leon	8.8×10^{-5}	4
Silver Glen*	6.3×10^{-7}	6
Juniper and Fern Hammock*	1.4×10^{-7}	6
Alexander*	6.9×10^{-7}	6
Salt*	4.7×10^{-7}	6
Linear Relationship Springs		
Spring Name	$\hat{K}$	$\hat{E}$
Wekiva River springs	6.70	34.5
Black Water Creek springs	3.17	–12.5

Note: MSJR = Middle St. Johns River

*Modeled as Lake George springs

The power relationship was used to provide at least some physical basis for the simulations. For example, the pool level at Ponce de Leon Springs (Figures 4 and 10) is approximately 5 ft NGVD (National Geodetic Vertical Datum). Assuming that a potentiometric surface at the same level would generate zero flow (Figure 11), a power relationship was necessary to tie in with the flow measurements. A function representing the relationship between daily spring flow and daily potentiometric surface level at V-0510 (Figure 9, Table 3), depicted in Figure 11, is included in the MSJR SSARR model. For example, a potentiometric surface level of 26 ft NGVD at well V-0510 would translate to a spring flow at Ponce de Leon Springs of approximately 40 cubic feet per second (cfs). Functions representing the other springs along the MSJR (Figure 10) were similarly included in the MSJR model (Figure 4).

single units (Table 7, Figures 4 and 10). Springs around Lake George (Alexander, Fern Hammock, Juniper, and Silver Glen) were each fitted to a power relationship before being summed together to form a single rating curve in the SSARR model. There have been very few flow measurements taken at springs in the Black Water Creek basin. Messant and Seminole springs (Figure 10, Table 7) were better represented by a simpler Darcy relationship (Figure 12). Springs in the Wekiva River basin (Wekiva, Rock, Miami, Sanlando, Palm, and Starbuck)

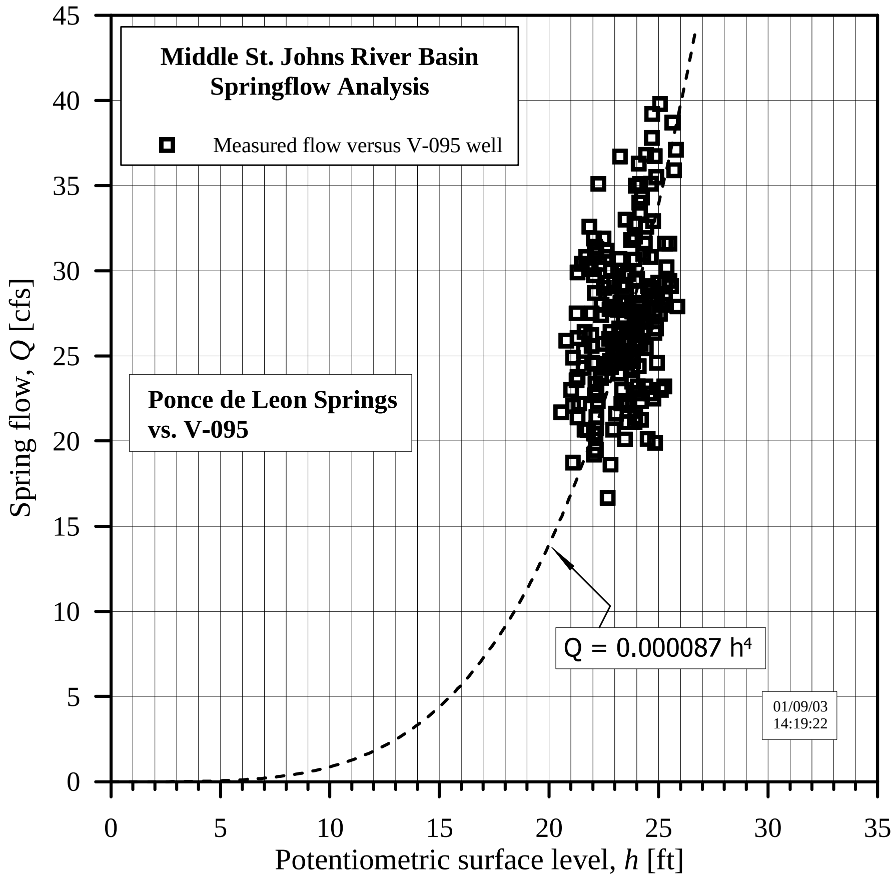


Figure 11. Power relationship between potentiometric level at well V-095 (also known as V-0510) and Ponce de Leon Springs flow

To simplify the MSJR SSARR model, three groups of springs were modeled as were represented by the Darcy relationship because they have significantly different pool levels.

PRINCIPAL MODELING ASSUMPTIONS

No model can include all factors that affect the hydrologic cycle. Therefore, any modeling study must include simplifying assumptions. In analyzing the final product of the model, a judgment is made as to the appropriateness of the assumptions. The principal assumptions made in developing the MSJR SSARR model follow:

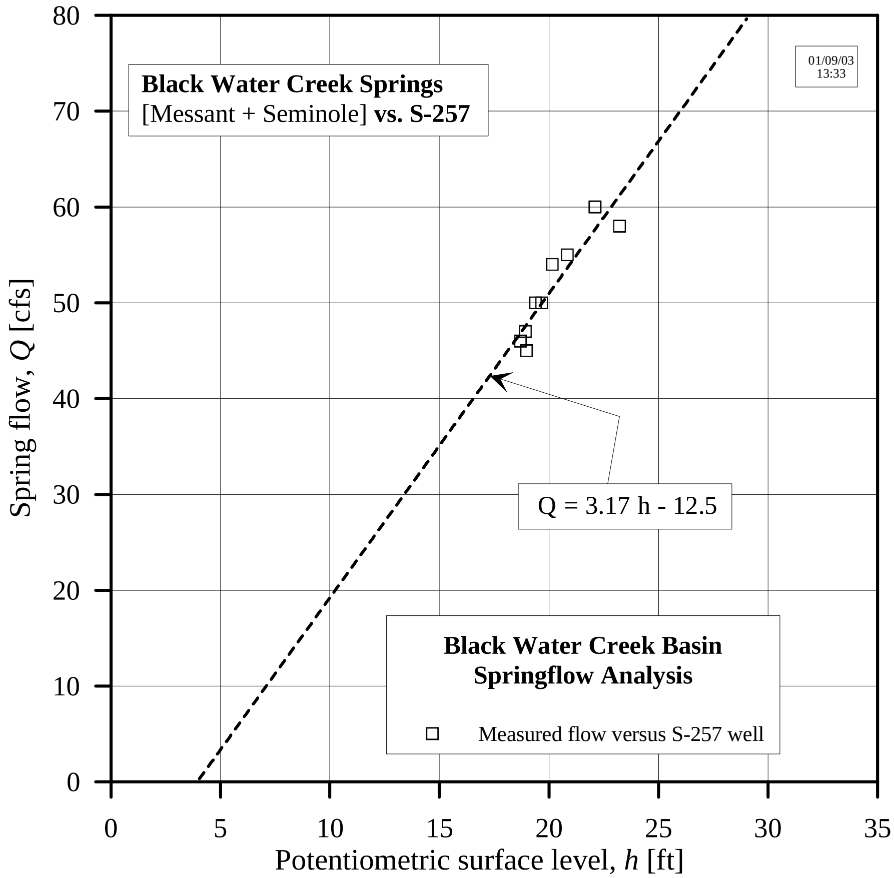


Figure 12. Darcy relationship between potentiometric level at well S-257 and total spring flow for Black Water Creek springs

- SSARR accounts for local water table flow in the form of interflow and baseflow (Ponce 1989) from basins along the river but not from those removed from it. The assumption is made that any flow from outside the immediate basin is small compared to the overall water budget.

- Flow contributions from unnamed, minor springs and Floridan aquifer artesian seeps along the river are small when compared to the overall water budget.

- Rating curves do not change on a seasonal basis.

- The drainage areas in the MSJR system are large enough that local changes in land use occurring in the past (notably, increased urbanization) caused relatively minor effects on runoff and infiltration. Accordingly, gaging records are considered homogeneous.

- From Lake Poinsett to Lake George, the MSJR can be modeled as a series of lakes for purposes of routing (see Figure 4). This assumption disregards routing in river segments between lakes and also replaces segments of river near DeLand and near Christmas with lakes. Breaking down the river as a series of lakes allowed for the use of the backwater mode in SSARR (see p. 6).

- Quite often, negative flows in the lower reaches of the MSJR are caused by phenomena such as wind and tides that cannot be accounted for in SSARR. Therefore, the assumption is made that these negative flows are local and temporary in nature and will average out over the medium term. Because MFLs typically deal with flows and / or stages over periods of one or more months, this assumption should be realistic. Negative flows caused by normal hydraulic head differences (e.g., flows into Lake Jesup from Lake Monroe, when the former is lower than the latter) can be modeled by SSARR.

PARALLEL VERSIONS OF THE MSJR SSARR MODEL

One valuable asset in the hydrologic modeling of the MSJR is the availability of a number of long-term daily flow gaging records (Table 3, Figure 9). Based on this availability, two parallel versions of the MSJR SSARR model were developed. The first model contains the basin configuration as shown in Figures 3 and 4. This model will hereafter be referred to as the “complete model.”

The second model takes advantage of the gaging records and includes them as inputs. While realizing that gaging records contain errors (see Table 3 for an explanation of these errors), including these records as model inputs will remove some of the model uncertainty and result in an improved simulation. The gaging records used as model inputs were the SJR near Christmas, the Econlockhatchee River near Chuluota, and the Wekiva River near Sanford (Figures 4 and 9, Table 3). This model will hereafter be referred to as the “gage model.” The two models are identical except that the gaging records replace simulations of these river basins in the complete model.

The model domain of interest for the present study is between Lake Harney and Lake George. Barring significant changes in the basin over the years, the records could be used as model inputs, thus avoiding development of the more complete model. The more complete model was set up for the following reasons:

- Calibrating to upstream gages such as the Econlockhatchee River provided insights into hydrologic parameters in other, ungaged areas of the model.

- The complete model will be used to simulate the effects on the MSJR of potential future hydrologic changes occurring upstream of Christmas.

- Comparison of results from both models, particularly cumulative flow volumes, should give some indication of significant hydrologic changes, if any, occurring over the years.

Results from both versions of the model will be analyzed, with an emphasis—because of the decreased model uncertainties mentioned previously—on results from the gage model. The gage model will be used to analyze withdrawals in the context of MFLs.

CALIBRATION OF THE MSJR SSARR MODEL

The MSJR SSARR model was calibrated by comparing measured lake stages and flow amounts with simulated values. The calibration involved a series of trial and error runs to obtain the closest simulation to measured values, by adjusting some model parameters while leaving other parameters constant. The following model characteristics and relationships were adjusted:

- Soil moisture-runoff relationships (Figure 2)
- Parameters affecting the shape of hydrographs
- Parameters affecting division of runoff into base, subsurface, and surface flows
- The ratio of potential ET to pan evaporation
- Stage/flow relationships dependent on downstream stages

The following model characteristics and relationships were held constant:

- Drainage areas
- Stage/storage relationships
- The ratio of lake evaporation to pan evaporation (see p. 18)
- Stage/flow relationships not dependent on downstream stages

There are a number of ways to compare model simulations with measured values. The most obvious comparison of simulated to measured stage or flow values is by visual examination. This involves plotting stage or flow hydrographs and visually assessing the ability of the model to simulate short-term hydrologic event characteristics, such as maximum stage, maximum flow, shape of hydrograph, and so on. Scatter plots comparing individual simulated values with the corresponding measured values can also be used in model assessment.

As discussed previously, the sparseness of rainfall gages in the MSJR will likely cause sizeable short-term differences between simulated and corresponding measured stage or flow values. As a result, scatter plots of monthly average stage and monthly average flow were utilized to provide a more meaningful comparison for judging the MSJR SSARR model. Comparisons of stage duration and annual flow volumes were also used.

Initially, the MSJR SSARR model was calibrated with data from 1990–98. However, the subsequent simulation for the entire period of record (1952–98), significantly and systematically underestimated the flow volumes at all the principal gaging points along the MSJR (Figure 9). As a result, the entire period of record was used to calibrate the model based on the following considerations.

- The long period of record for various rain, stage, and flow gaging stations in the MSJR is a valuable asset that should be fully utilized in the hydrologic simulation.

- Even though the rain gage data used in the MSJR SSARR model have long periods of record, gage locations are relatively sparse. As discussed previously, this sparseness can translate into relatively large departures from measured values and probably caused the underestimation of flow volume as described previously. As a result, the model would have been calibrated differently depending on which years of record were used. However, a long period of record should represent a large variety of hydrologic conditions. Periods of overestimation of rainfall and runoff should be balanced out with periods of underestimation providing for a representative long-term simulation. As mentioned previously, in the context of MFLs, the goal of a model is to provide a simulation that is statistically similar to the historical data.

Because the entire period of record was used in model calibration, verification per se was not performed. As a result, model performance was judged on the basis of calibration results alone by using a number of comparisons between modeled and measured values. These comparisons were as follows:

- Monthly average stages
- Monthly average flows
- Cumulative sums of annual flow volumes
- Stage duration curves
- Monthly stage duration curves
- Day-to-day simulations
- Maximum stages continuously exceeded
- Minimum average stages
- Minimum stages continuously not exceeded

For the first four comparisons, the analysis description that follows includes both the complete and the gage versions of the MSJR SSARR model. These four measures should be sufficient to evaluate the performance of the complete model in the event it is needed to assess the effects on the MSJR of hydrologic changes occurring upstream of Christmas or in the Wekiva River or Econlockhatchee River basins. For the remainder of the comparisons, the analysis will involve only the gage model in order to simplify the report. In addition to the listed comparisons, analyses pertaining to simulation of spring flows and average annual runoff are included.

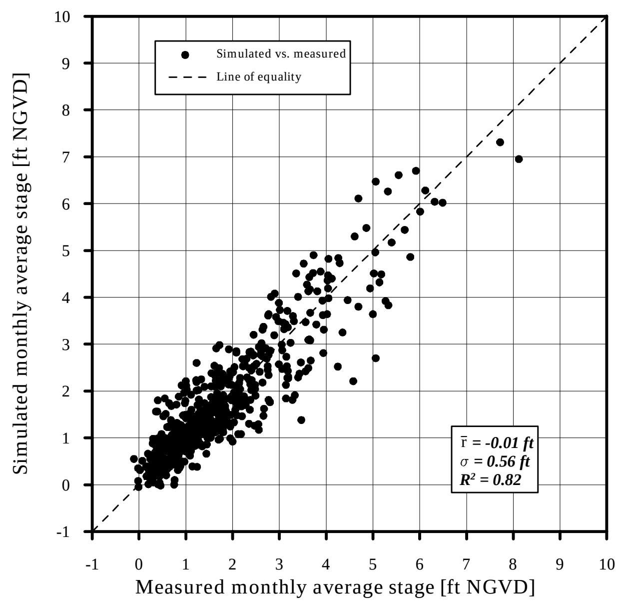
Monthly average stages. A scatter plot of simulated values against measured values is a commonly used measure of model performance. A perfect match between simulated and measured values would result in a straight line with no variance. Conversely, a completely random scattering of points would indicate little or no correlation between simulated and measured values. Therefore, the closer the scatter plot of simulated vs. measured values approximates a straight line, the better the agreement between modeled and measured values and, presumably, the better the hydrologic model simulates the system in question. While a comparison of daily values can be performed, for a long-term simulation, the large amount of data becomes cumbersome. In such cases, the comparison of average monthly stages should provide a meaningful measure of model performance while reducing the amount of data presented.

A residual is the difference between a simulated value and the corresponding measured value. Ideally, the mean of residuals ($\bar{r}$) should be near zero, with relatively small standard deviation (σ). Furthermore, residuals should be more or less equally balanced between positive and negative values. A measure of the scatter of residuals around the mean is provided by the standard deviation. Assuming that residuals are normally distributed, then approximately 70% of the values would be expected to be within ±1 standard deviation of the mean (Sokal and Rohlf 1969). In keeping with the calibration criterion of maximizing the number of simulated stage values within ±0.5 ft of the measured values, the size of the standard deviation provides a measure of whether most residual values are within this range. For the remainder of the discussion about residuals, it is assumed that approximately 70% of residuals are expected to lie between ±1 standard deviation of the mean residual. If the residuals are sorted by size, a cumulative probability function can be developed.

The coefficient of determination, R^2, is a standard measure of how well data are explained by a best-fit line (Sokal and Rohlf 1969). The coefficient of determination is used as a measure of the proportion of the total variation that has been explained by the best-fit line and varies between 0 (none of the variation in a measured variable is explained by the model) to 1 (all of the variation in a measured variable is explained by the model).

The scatter plot of mean monthly stages for the SJR near Sanford (Lake Monroe) (Figure 13) for the complete model shows an obvious correlation between measured and simulated values. The mean residual for the complete model is −0.01 ft (Table 9), with a standard deviation of ±0.56 ft. As indicated on Figure 13b, 50% of the residuals are negative and 50% are positive. Using the assumption discussed in the previous paragraph, approximately 70% of the residuals lie between +0.55 and −0.57 ft (the mean residual ±1 standard deviation). R^2 is equal to 0.82. With the use of measured inflows (Figure 14, Table 9), the mean residual is 0.03 ft and the standard deviation falls to ±0.48 ft. About 48% of the values are negative and 52% are positive. Approximately 70% of the residuals lie between +0.51 and −0.45 ft. R^2 increases to 0.89. Monthly residual analyses of these data are included in this report as an appendix (Table 9, Figures B5–B8). Although for some months 70% of the values do not lie within the ±0.5 ft calibration criterion, the emphasis within the context of MFLs is maintaining a statistically similar hydrology to historical data, so more consideration should be given to integrated calibration measures such as duration and frequency analyses.

The scatter plot of mean monthly stages for the SJR at SR 44 near DeLand (Figure 15) for the complete model shows an obvious correlation between simulated and measured values. The mean residual is 0.03 ft (Table 9), with a standard deviation of ±0.43 ft. About 45% of the residuals are negative and 55% are positive. Approximately 70% of the residuals lie between +0.46 and −0.40 ft.



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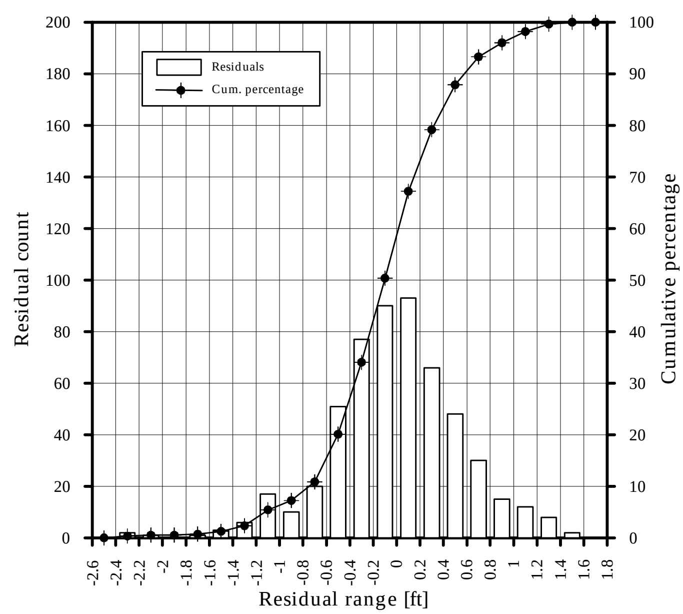

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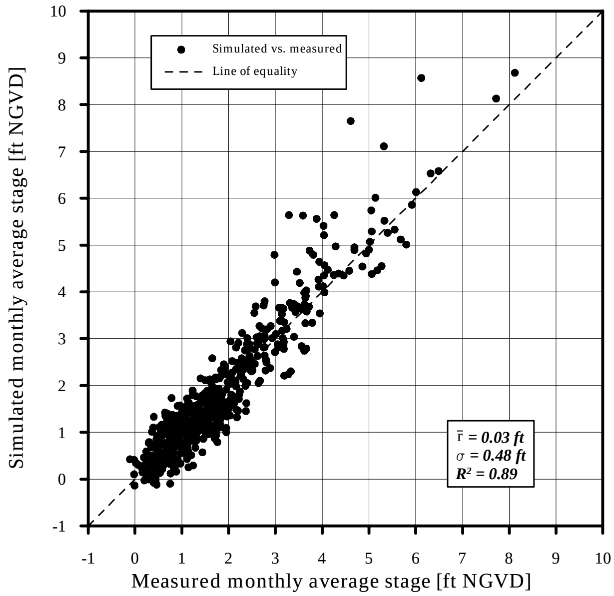
Figure 13. Residual analysis of monthly average stages for the SJR near Sanford (Lake Monroe); results correspond to the complete mode



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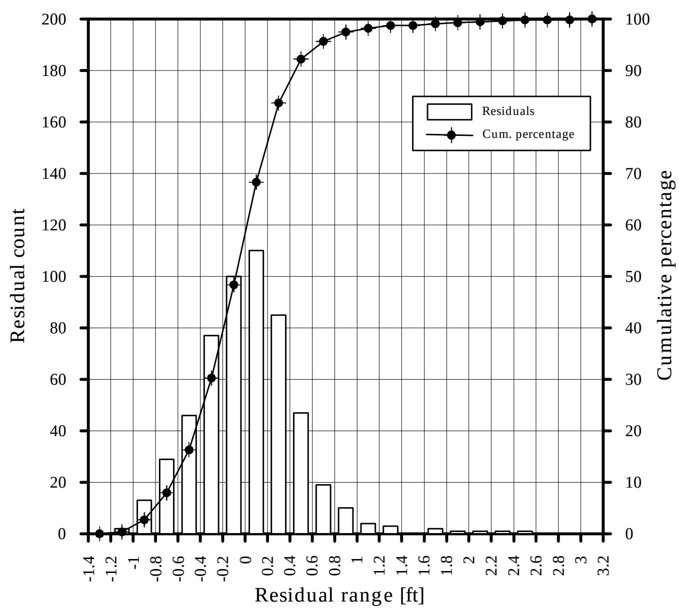


[b]

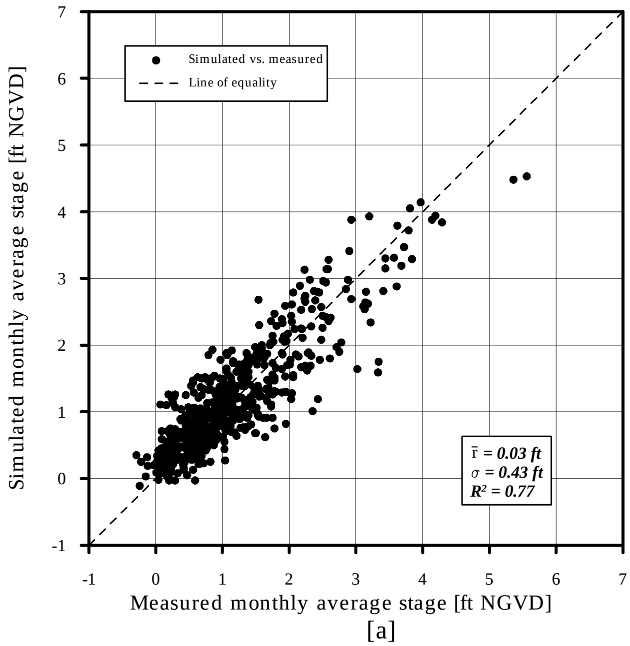
Figure 14. Residual analysis of monthly average stages for the SJR near Sanford (Lake Monroe); results correspond to the gage model

Table 9. Residual analysis statistics for the MSJR SSARR model

Simulation (1953–98)	SJR at SR 44 Near DeLand: Stage				SJR Near Sanford (Lake Monroe): Stage				SJR at SR 44 Near DeLand: Flow		
	Mean Residual, $\bar{r}$ (feet)	Standard Deviation, σ (feet)	$[\bar{r} \pm \sigma]$ (feet, feet)	R^2	Mean Residual, $\bar{r}$ (feet)	Standard Deviation, σ (feet)	$[\bar{r} \pm \sigma]$ (feet, feet)	R^2	Mean Residual, $\bar{r}$ (cfs)	Standard Deviation, σ (cfs)	R^2
Complete model	0.03	±0.43	+0.46, –0.40	0.77	–0.01	±0.56	+0.55, –0.57	0.82	–2	±1,114	0.75
Gage model	0.05	±0.38	+0.43, –0.33	0.83	0.03	±0.48	+0.51, –0.45	0.89	31	±698	0.90
January	0.09	±0.40	+0.49, –0.31	0.76	0.02	±0.53	+0.55, –0.51	0.82	–155	±525	0.92
February	0.14	±0.31	+0.45, –0.17	0.78	0.03	±0.34	+0.37, –0.31	0.88	–123	±451	0.92
March	0.15	±0.31	+0.46, –0.16	0.84	0.05	±0.35	+0.40, –0.30	0.91	–155	±610	0.92
April	0.16	±0.27	+0.43, –0.11	0.90	0.09	±0.32	+0.41, –0.23	0.94	–207	±518	0.95
May	0.04	±0.35	+0.30, –0.31	0.69	0.00	±0.39	+0.39, –0.39	0.84	52	±467	0.85
June	–0.08	±0.31	+0.23, –0.39	0.63	–0.14	±0.39	+0.25, –0.53	0.70	30	±602	0.76
July	0.20	±0.25	+0.45, –0.05	0.89	0.12	±0.31	+0.43, –0.19	0.92	–142	±609	0.94
August	0.27	±0.35	+0.62, –0.08	0.83	0.28	±0.46	+0.74, –0.18	0.89	315	±776	0.87
September	–0.05	±0.34	+0.29, –0.39	0.87	0.04	±0.49	+0.53, –0.45	0.90	417	±848	0.90
October	–0.32	±0.37	+0.05, –0.69	0.90	–0.15	±0.55	+0.40, –0.70	0.93	283	±1,110	0.90
November	–0.16	±0.42	+0.26, –0.58	0.86	–0.06	±0.68	+0.62, –0.74	0.90	36	±586	0.94
December	0.08	±0.47	+0.55, –0.39	0.79	0.08	±0.67	+0.75, –0.59	0.85	26	±719	0.89

Note: cfs = cubic feet per second
MSJR = Middle St. Johns River
SJR = St. Johns River
SR = state road

Complete model and gage model simulation results are for all months; January through December simulation results are for gage model



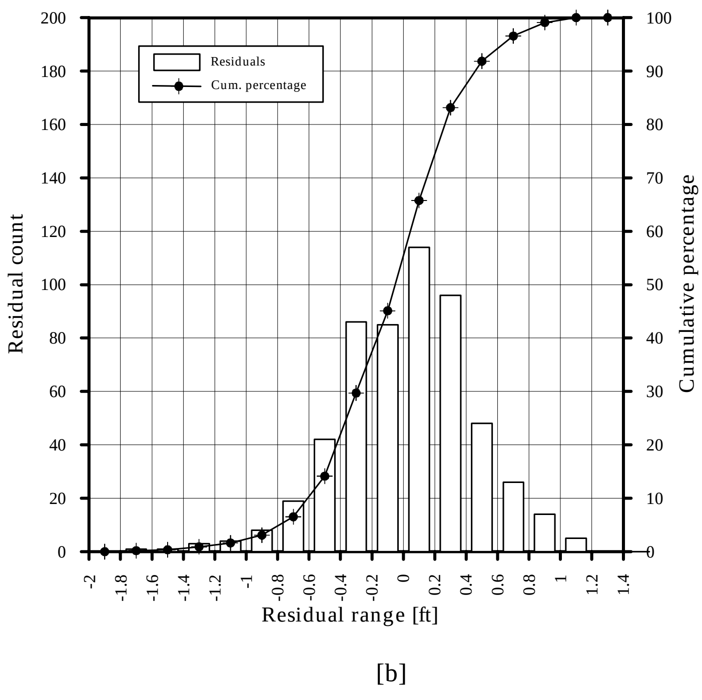


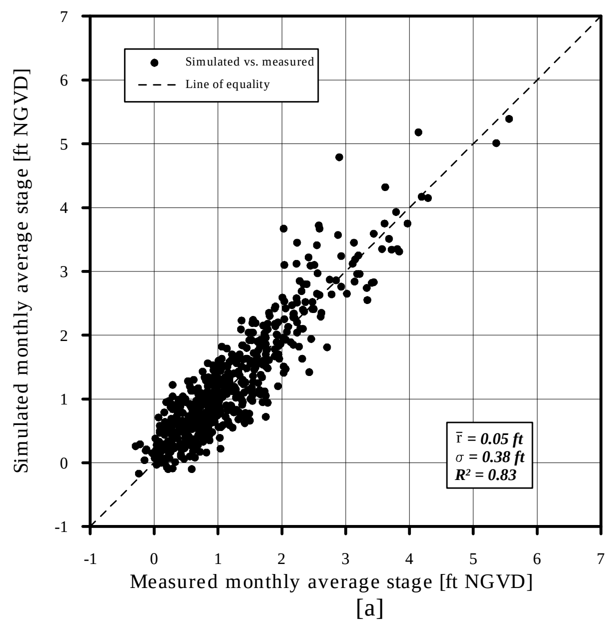
Figure 15. Residual analysis of monthly average stages for the SJR at SR 44 near DeLand; results correspond to the complete model

R^2 is equal to 0.77. With the use of measured inflows (Figure 16, Table 9), the mean residual is 0.05 ft and the standard deviation falls to ±0.38 ft. About 45% of the values are negative and 55% are positive. Approximately 70% of the residuals lie between +0.43 and −0.33 ft. R^2 increases to 0.83. Monthly residual analyses of the data are included in this report as an appendix (Table 9, Figures B1–B4). Although for some months 70% of the values do not lie within the ±0.5 ft calibration criterion, it should be remembered that the emphasis in the context of MFLs is maintaining a statistically similar hydrology to historical data, so more emphasis should be put on integrated calibration measures such as duration and frequency analyses.

Monthly average flows. The scatter plot of mean monthly flows for the SJR at SR 44 near DeLand (Figure 17) for the complete model shows an obvious correlation between measured and modeled values. The mean residual is −2 cfs (Table 9), with a standard deviation of ±1,114 cfs. About 48% of the residuals are negative and 52% are positive. R^2 is equal to 0.75. With the use of measured inflows (Figure 18, Table 9), the mean residual is 31 cfs; as expected, the standard deviation falls considerably, to ±698 cfs. About 48% of the values are negative and 52% are positive. R^2 increases to 0.90. Monthly residual analyses of the data are included in this report as an appendix (Table 9, Figures B9–B12).

Cumulative sums of annual flow volumes. Comparison of cumulative sums of simulated and measured annual flow volumes provides an indication of the model's ability to accurately simulate the amount of water flowing through a hydrologic system. Although simulations of short durations (1 or 2 years) may deviate from measured values, significant problems with the hydrologic simulation will appear as systematic or increasing departures from measured data. Significant departures from measured values might indicate an inability of the model to properly simulate water quantities. A sustained or systematic departure, especially midway through a series of years, might also be an indication of significant hydrologic changes in the basin.

For the complete model, simulations of annual flow volumes for the SJR near Cocoa, the SJR near Christmas, and the SJR near DeLand have similar patterns when compared to measured values (Figure 19). Between 1952 and 1961, the model has a tendency to underestimate flow volumes. However, between 1994 and 1998, the model tends to overestimate flow volumes. In general, the sums for simulated values are parallel to those of measured values. The total flow volumes for the period of simulation are similar to the measured values at all four gages.



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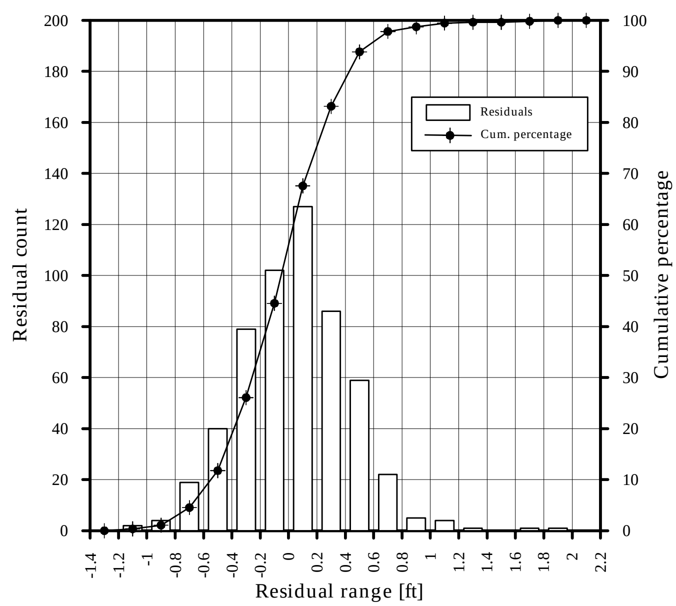

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Figure 16. Residual analysis of monthly average stages for the SJR at SR 44 near DeLand; results correspond to the gage model

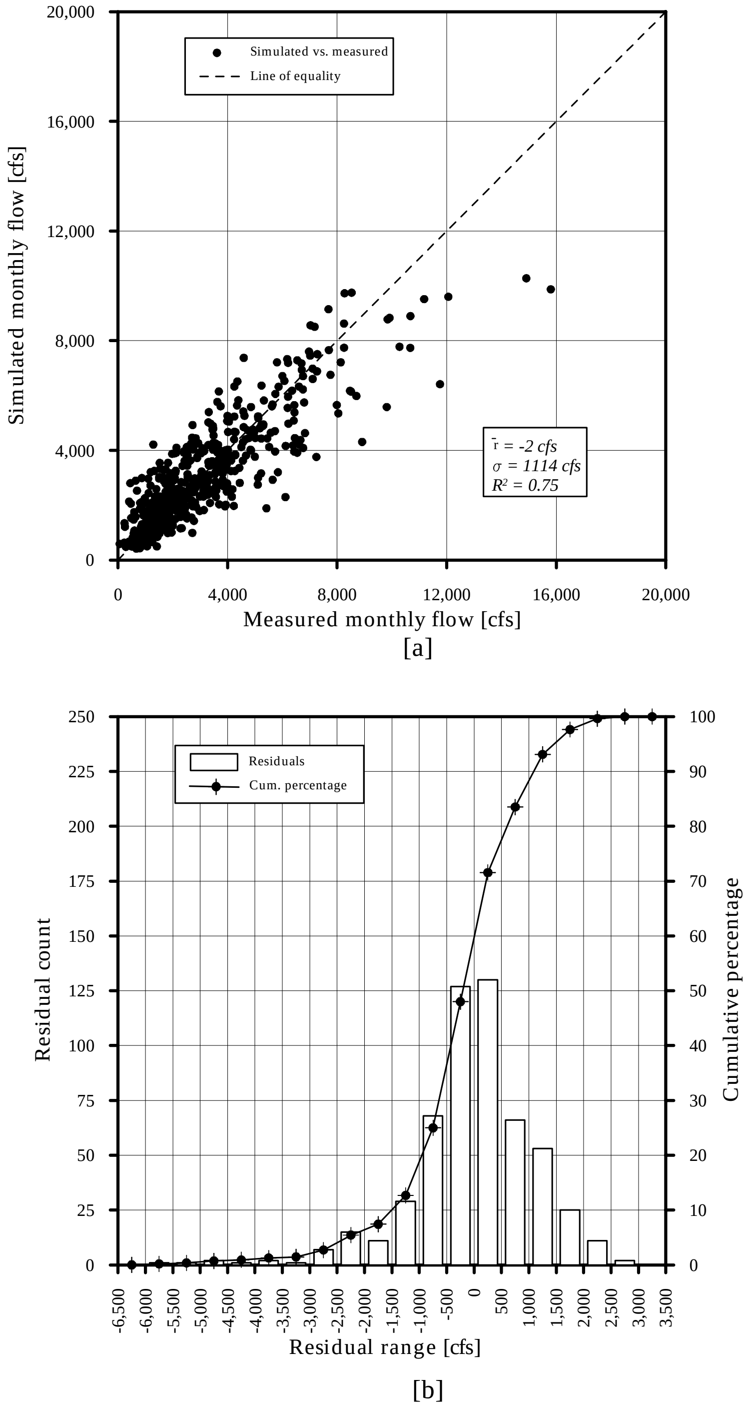
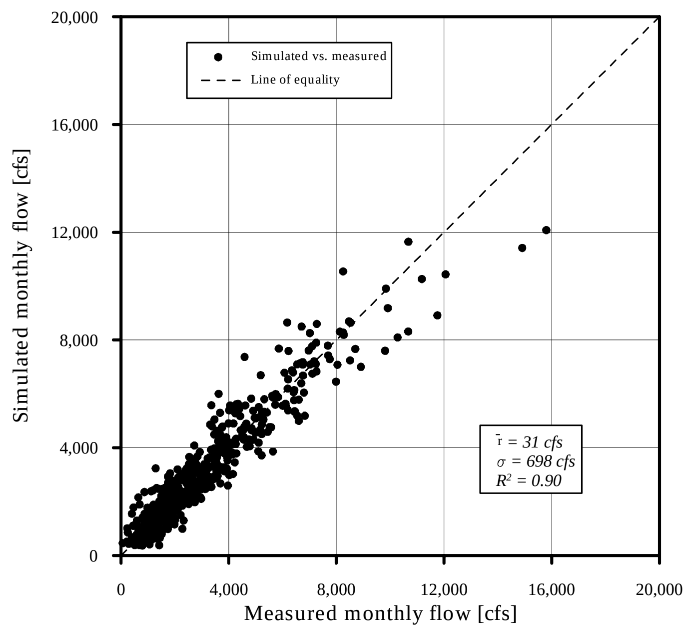


Figure 17. Residual analysis of monthly average flows for the SJR at SR 44 near DeLand; results correspond to the complete model



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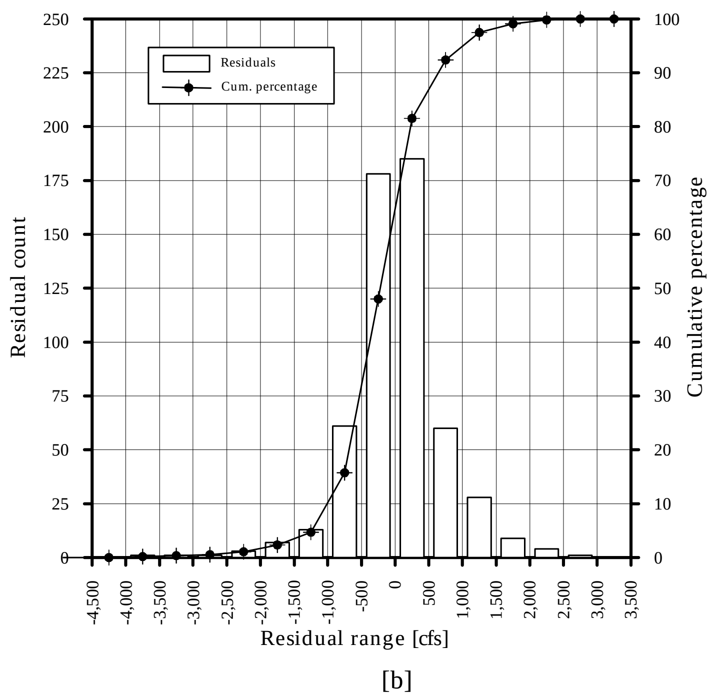

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Figure 18. Residual analysis of monthly average flows for the SJR at SR 44 near DeLand; results correspond to the gage model

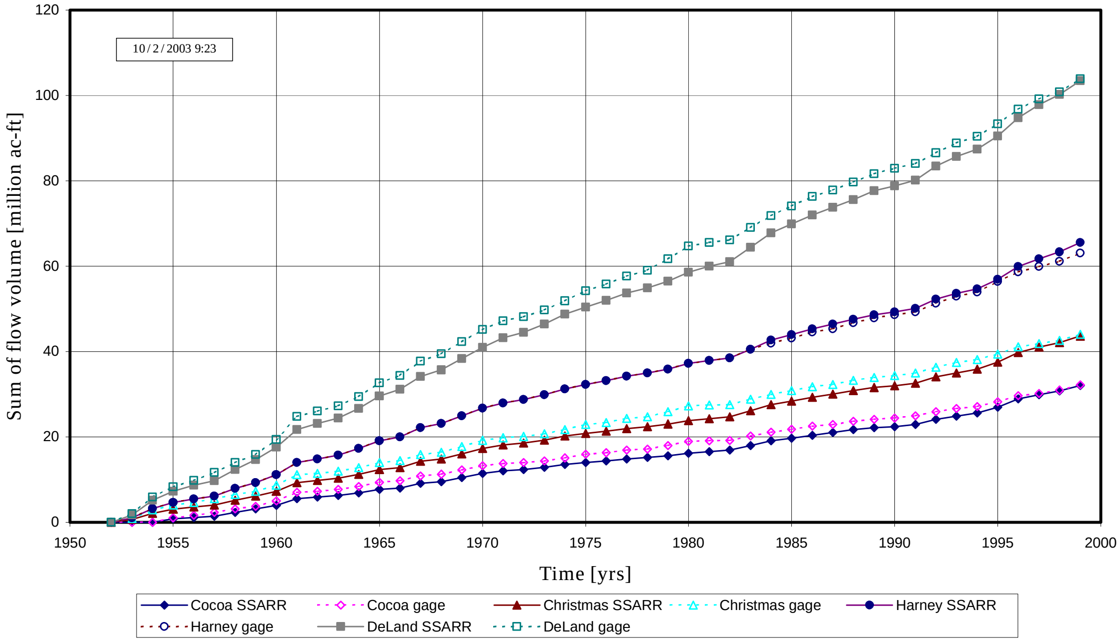
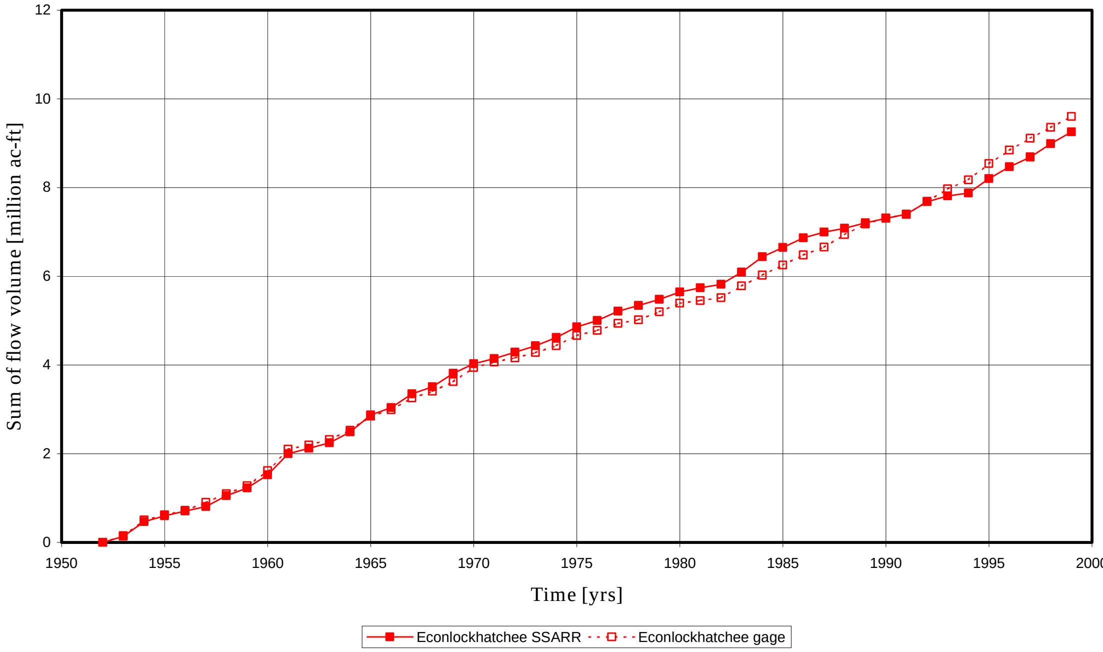


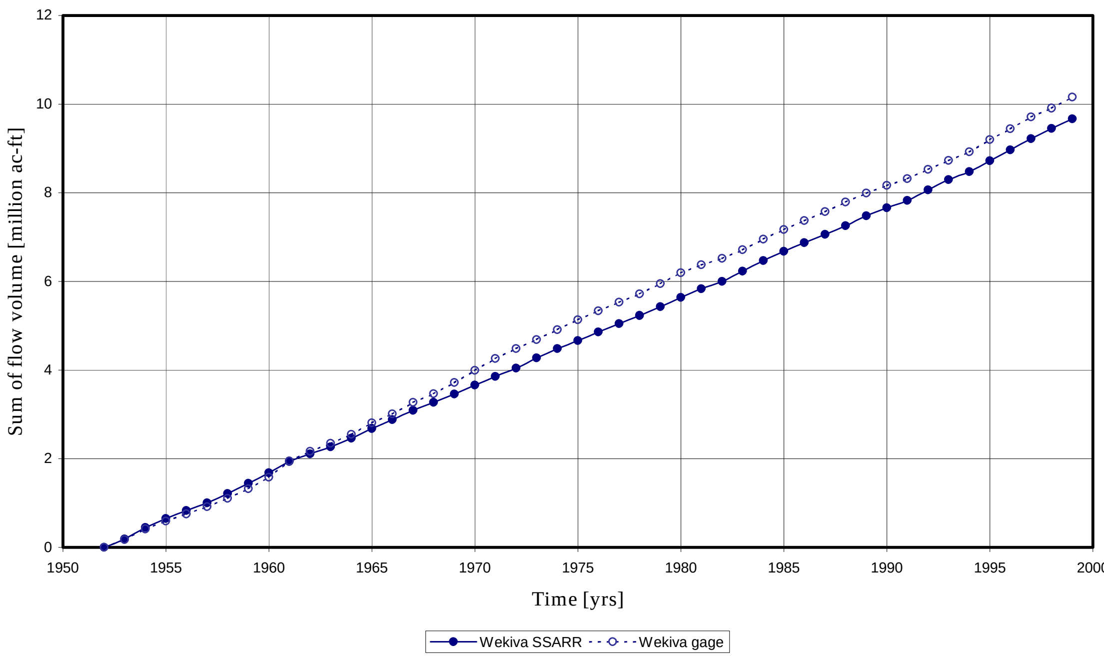
Figure 19. Measured and simulated cumulative flow volumes: the SJR near DeLand, the SJR at Lake Harney (covering only 1982–98), the SJR at Christmas, and the SJR at Lake Poinsett (covering only 1954–98)

Comparison of the measured and simulated cumulative sums for the Econlockhatchee River does not indicate any obvious departures over the years of simulation (Figure 20a). The simulated total flow volume for the 46 years is quite similar to the measured.

Comparison of the measured and simulated cumulative sums for the Wekiva River does show some departure between about 1962 to 1972. Other than those years, however, the two curves are essentially parallel. The simulated total flow volume for the 46 years is smaller than the measured total, but quite similar (Figure 20b). Some of the shortfall is accounted for by unnamed springs in the Wekiva River basin that are not included in the model.



(a)



(b)

Figure 20. Measured and simulated cumulative flow volumes: the Econlockhatchee River (a) and the Wekiva River (b)

Residual analyses and scatter plots comparing simulated and measured flow volumes from individual years of simulation appear in Appendix C. The R^2 for annual simulated flow volumes for the St. Johns River at SR 44 near DeLand was 0.72 (Figure C1). For about 49% of the years included in the model, the simulated flow volumes were lower than the corresponding measured flow volumes and for 51% of the years, the simulated flow volumes were higher than the corresponding measured values. The coefficients of determination for the SJR near Christmas (Figure C2), the SJR near Cocoa (Figure C3), and the Econlockhatchee River near Chuluota (Figure C4) are all between 0.62 and 0.67. The low R^2 of 0.36 for simulation of the Wekiva River (Figure C5) is misleading because the coefficient calculation is limited by the minimum values involved. If the regression line is forced through the origin, the R^2 increases to 0.98.

When historical gage records are included in the gage model, the fit of the simulated cumulative sum of flow volumes is closer to that of measured values (Figure 21) for the SJR at SR 44 near DeLand than for the complete model (Figure 19). Although approximately 60% of the total flow is accounted for by the three gaging stations, this improvement in fit tends to increase confidence in the 40% of the total still simulated by the model. Comparison of the cumulative sums for the complete model (Figure 19) and the gage model (Figure 21) also indicates that much of the uncertainty in the complete model seems to lie upstream of Christmas.

As expected, the fit of simulated annual flow volumes to measured flow volumes is improved significantly by inclusion of the measured inflows (Figure C6). The coefficient of determination increases from 0.72 to 0.92.

Stage duration curves. Measured and simulated stage duration curves were developed at five locations within the MSJR SSARR model domain. Emphasis should be placed on the gages at Lake Monroe, near DeLand, and at Lake George because they bracket the segment of the MSJR where MFLs have been adopted. Except for some of the extreme percent chances of exceedence (i.e., 0% and 100%), simulations are within the ±0.5 ft calibration criterion at all percentiles at the five different locations for the complete model (Table 10, Figures 22 and 23). In the context of MFLs, the extreme percent chance exceedences are relatively unimportant, so differences outside the calibration criterion are probably inconsequential. For the gage model, all percent exceedences at all five locations are within the ±0.5 ft calibration criterion except for the extreme highs (Table 10, Figures 24 and 25).

Table 10. Differences in measured and simulated stage duration curves for the MSJR SSARR model (values in feet)

Percent Chance of Exceedence	SJR Above Lake Harney	Lake Jesup, Near Sanford	SJR Near Sanford (Lake Monroe)	SJR at SR 44 Near DeLand	Lake George
Complete Model					
100	0.2	0.2	0.2	0.6	0.2
95	0.1	0.0	0.1	0.1	0.0
90	0.1	0.0	0.1	0.1	0.0
80	0.2	0.1	0.1	0.1	0.0
70	0.2	0.1	0.1	0.1	–0.1
60	0.1	0.1	0.0	0.1	–0.1
50	0.1	0.0	0.0	0.0	–0.1
40	0.1	0.0	0.0	0.0	–0.1
30	–0.1	0.0	–0.1	0.0	–0.1
20	–0.2	0.0	–0.1	–0.1	–0.1
10	–0.3	0.0	–0.1	0.0	0.0
5	0.0	0.1	0.0	–0.1	0.0
0	0.0	–0.6	–1.0	–1.0	0.2
Gage Model					
100	0.0	0.2	0.2	0.4	0.2
95	0.0	–0.1	0.0	0.1	0.0
90	0.0	–0.1	0.0	0.1	0.0
80	0.0	0.0	0.0	0.1	–0.1
70	0.0	0.0	0.0	0.0	–0.1
60	–0.1	0.0	0.0	0.0	–0.1
50	0.0	–0.1	–0.1	0.0	–0.1
40	0.0	0.0	–0.1	0.0	–0.1
30	–0.1	0.1	–0.1	0.0	–0.1
20	0.1	0.2	0.1	0.0	0.0
10	0.3	0.3	0.2	0.1	0.1
5	0.5	0.4	0.3	0.1	0.1
0	2.2	0.4	0.6	–0.2	0.6

Note: MSJR = Middle St. Johns River
SJR = St. Johns River
SR = state road

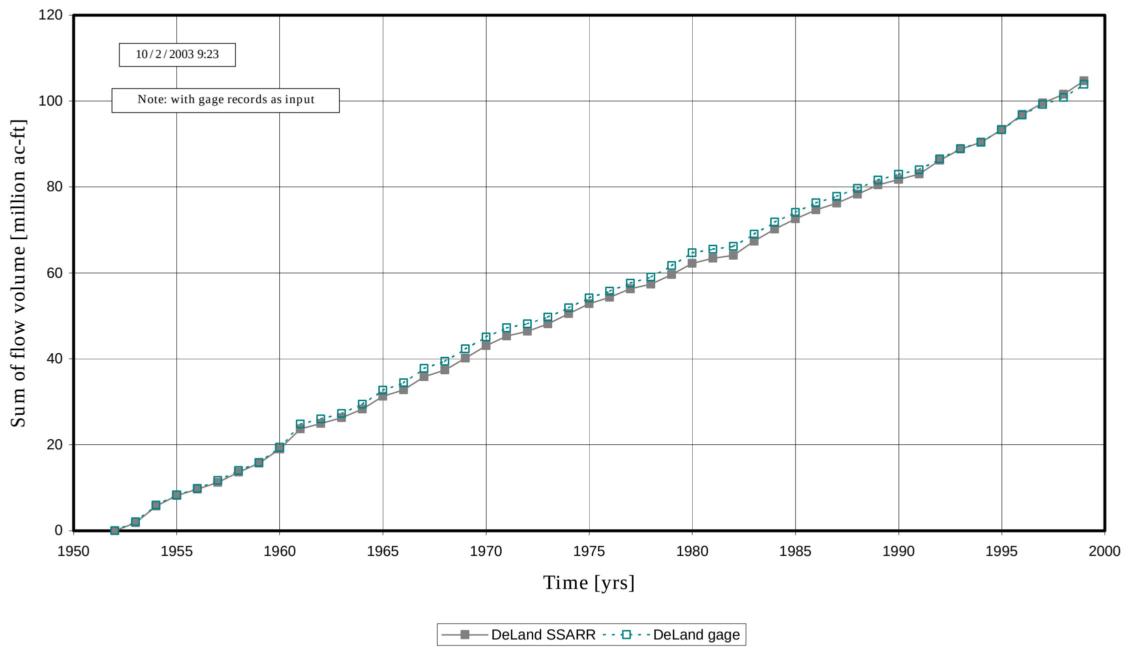


Figure 21. Measured and simulated cumulative flow volumes: the SJR at SR 44 near DeLand. The model includes measured input for the SJR at Christmas, the Econlockhatchee River, and the Wekiva River

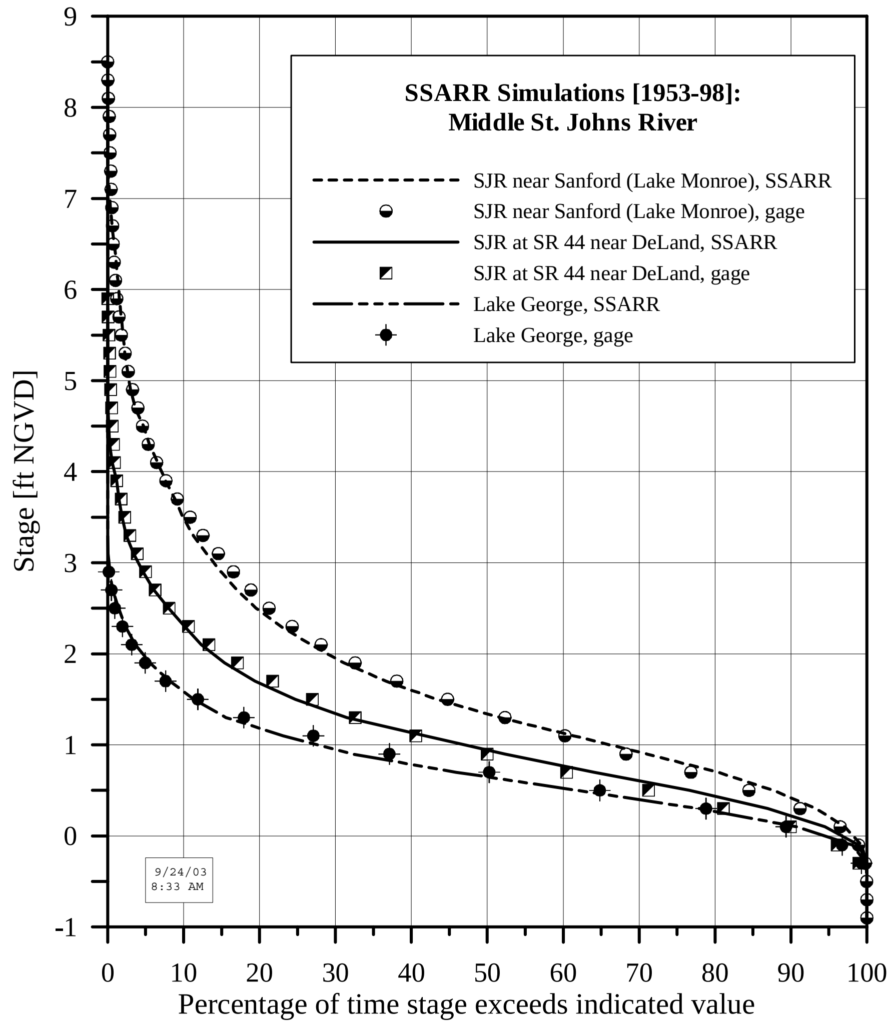


Figure 22. Measured and simulated stage duration curves: Lake George, the SJR at SR 44 near DeLand, and the SJR near Sanford (Lake Monroe); results correspond to the complete model (see p. 29)

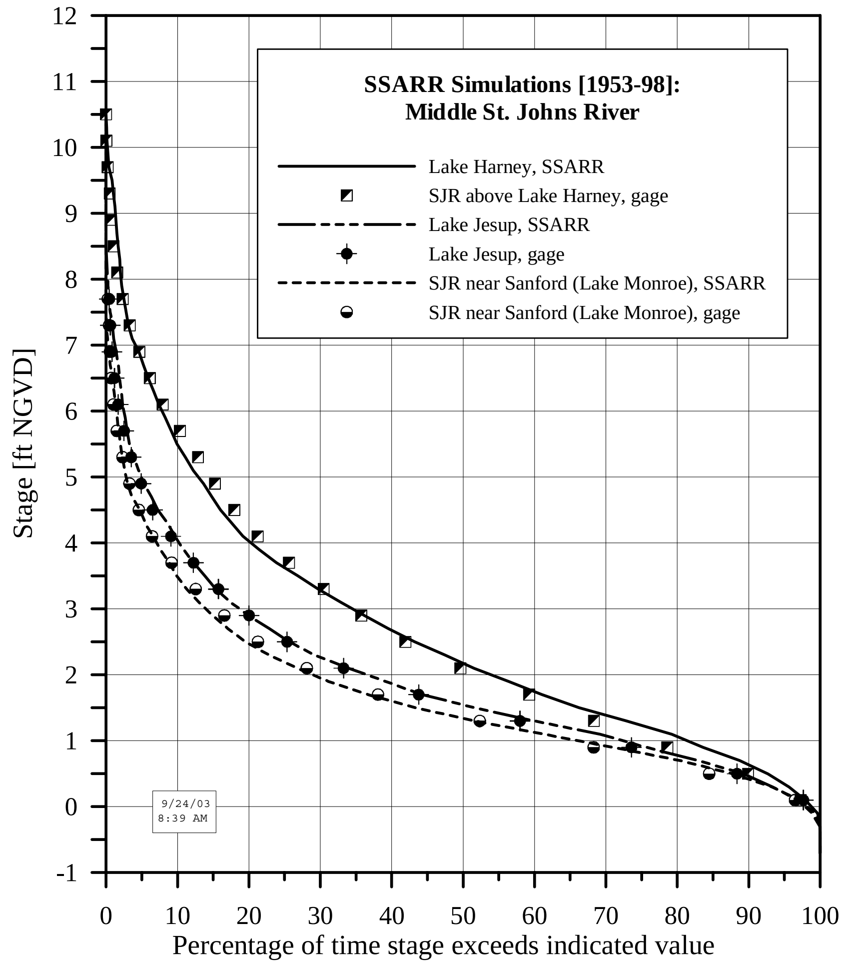


Figure 23. Measured and simulated stage duration curves: the SJR near Sanford (Lake Monroe), Lake Jesup, and Lake Harney; results correspond to the complete model (see p. 29)

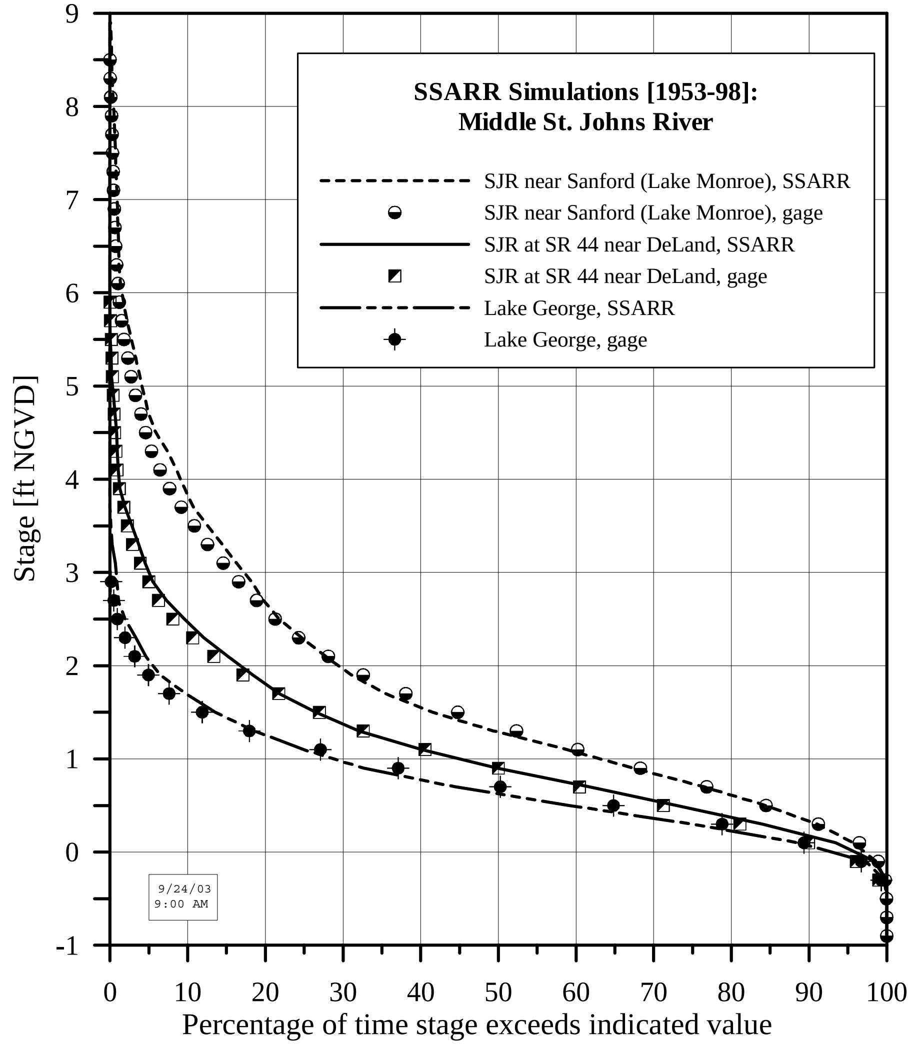


Figure 24. Measured and simulated stage duration curves: Lake George, the SJR at SR 44 near DeLand, and the SJR near Sanford (Lake Monroe); results correspond to the gage model (see p. 29)

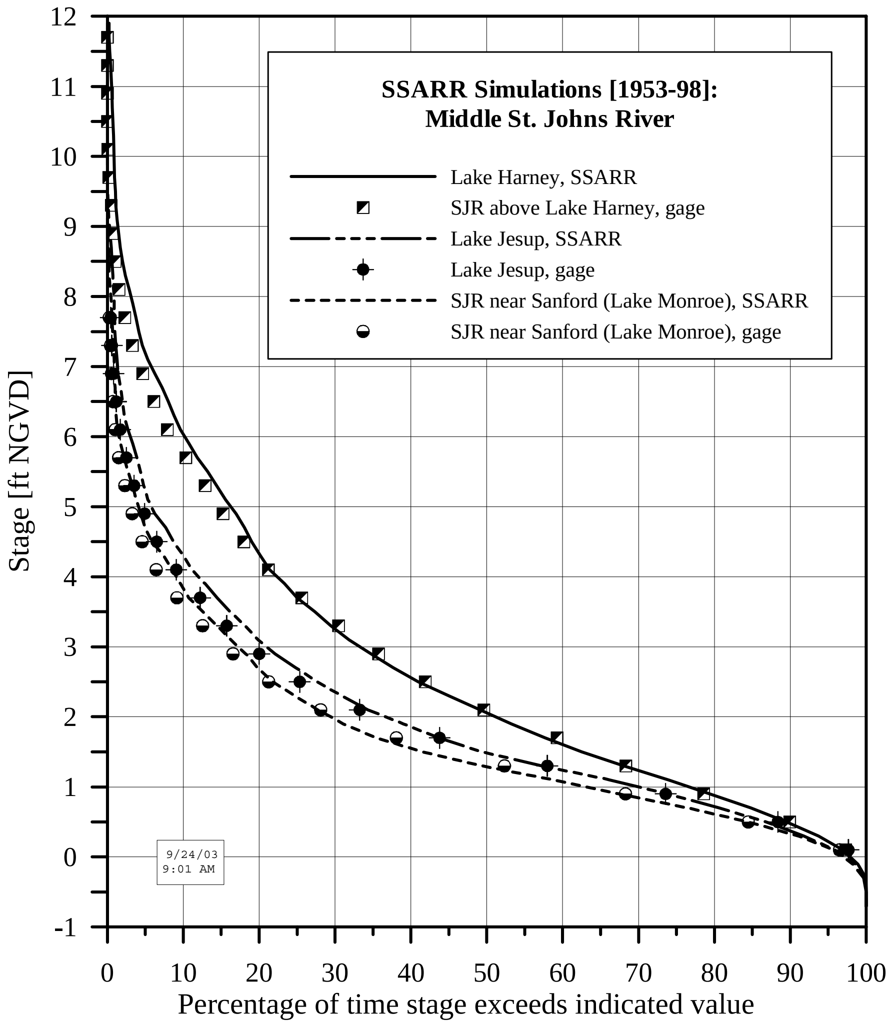


Figure 25. Measured and simulated stage duration curves: the SJR near Sanford (Lake Monroe), Lake Jesup, and Lake Harney; results correspond to the gage model (see p. 29)

Monthly stage duration curves. Measured and simulated monthly stage duration curves were developed for the Lake Monroe and DeLand gages. With the exception of August and December at a 10% chance of exceedence for the SJR near Sanford (Lake Monroe), the values between 90% and 10% are all within the ±0.5 ft calibration criterion (Table 11, Figures 26 and 27). The simulated 100% chance exceedence is generally high at the SJR at SR 44 near DeLand. This might be due to local, short-term effects, such as tides and winds that cannot be accounted for in SSARR. Differences for the 0% chance exceedence are generally not within the calibration criterion. However, in the context of MFLs, the extreme highs are relatively unimportant, so this should be inconsequential.

Day-to-day simulations. As discussed previously, some simplifying hydraulic assumptions were made in order to model the MSJR with SSARR. Comparison of stage and flow hydrographs at Lake Monroe and DeLand (Figures 28 and 29) indicate that the model adequately simulates the day-to-day routing for the MSJR system. However, these figures demonstrate the inability of the model to simulate some of the flow reversals caused by winds and tides (e.g., in mid-May and mid-June). At the same time, the figures demonstrate that the events are short-term in nature and, therefore, inconsequential from an MFLs perspective.

Maximum stages continuously exceeded. In the context of MFLs, maximum stages continuously exceeded for 30 days (see Appendix A for some explanation of frequency analysis) are used in the establishment of the Minimum Frequent High level. Therefore, comparison of measured and simulated stages continuously exceeded for 30 days should indicate the model's ability to assess the MSJR at this particular level. For the SJR at SR 44 near DeLand, simulated stages are within ±0.1 ft of measured counterparts, well within the calibration criterion of ±0.5 ft (Table 12, Figure 30). For the SJR near Sanford (Lake Monroe), the pertinent simulated stages tend to be high for the rarer events and low for the more frequent events, but they are within the calibration criterion of ±0.5 ft.

Minimum average stages. In the context of MFLs, minimum 180-day average stages (see Appendix A for some explanation of frequency analysis) are used in the establishment of the Minimum Average level. Therefore, comparison of measured and simulated 180-day average stages should indicate the model's suitability for representing the MSJR at this particular level. For the SJR at SR 44 near DeLand, simulated stages are within ±0.1 ft, well within the calibration criterion of ±0.5 ft (Table 12, Figure 31). For the SJR near Sanford (Lake Monroe),

Table 11. Differences in measured and simulated monthly stage duration curves for the MSJR SSARR model (values in feet); values correspond to the gage model

Month	Percent Chance of Exceedence				
	100%	90%	50%	10%	0%
SJR Near Sanford (Lake Monroe)					
January	0.4	–0.1	0.0	0.1	1.6
February	0.4	0.1	–0.1	0.2	0.0
March	0.4	0.1	0.1	–0.1	–0.2
April	0.2	0.0	0.1	0.0	–0.2
May	–0.2	–0.2	–0.1	0.3	0.6
June	0.0	–0.2	–0.1	–0.1	–0.8
July	0.2	0.1	0.2	–0.1	0.6
August	0.6	0.1	0.2	0.7	0.2
September	0.0	–0.1	0.0	0.4	0.0
October	–0.2	–0.4	–0.2	0.2	0.6
November	–0.2	–0.5	–0.3	0.0	1.4
December	0.0	–0.3	–0.1	0.6	1.6
SJR at SR 44 Near DeLand					
January	0.4	0.1	0.1	0.2	0.8
February	0.4	0.2	0.0	0.3	0.0
March	0.6	0.2	0.2	0.1	0.0
April	0.4	0.1	0.2	0.3	–0.4
May	0.2	0.0	–0.1	0.3	0.6
June	0.2	0.0	–0.1	–0.1	0.0
July	0.4	0.2	0.2	0.0	0.6
August	0.6	0.2	0.3	0.4	–0.2
September	0.0	–0.1	–0.1	–0.1	–0.6
October	0.0	–0.4	–0.3	–0.1	–0.2
November	0.0	–0.4	–0.3	0.0	0.6
December	0.2	–0.2	0.0	0.4	0.6

Note: MSJR = Middle St. Johns River
SJR = St. Johns River
SR = state road

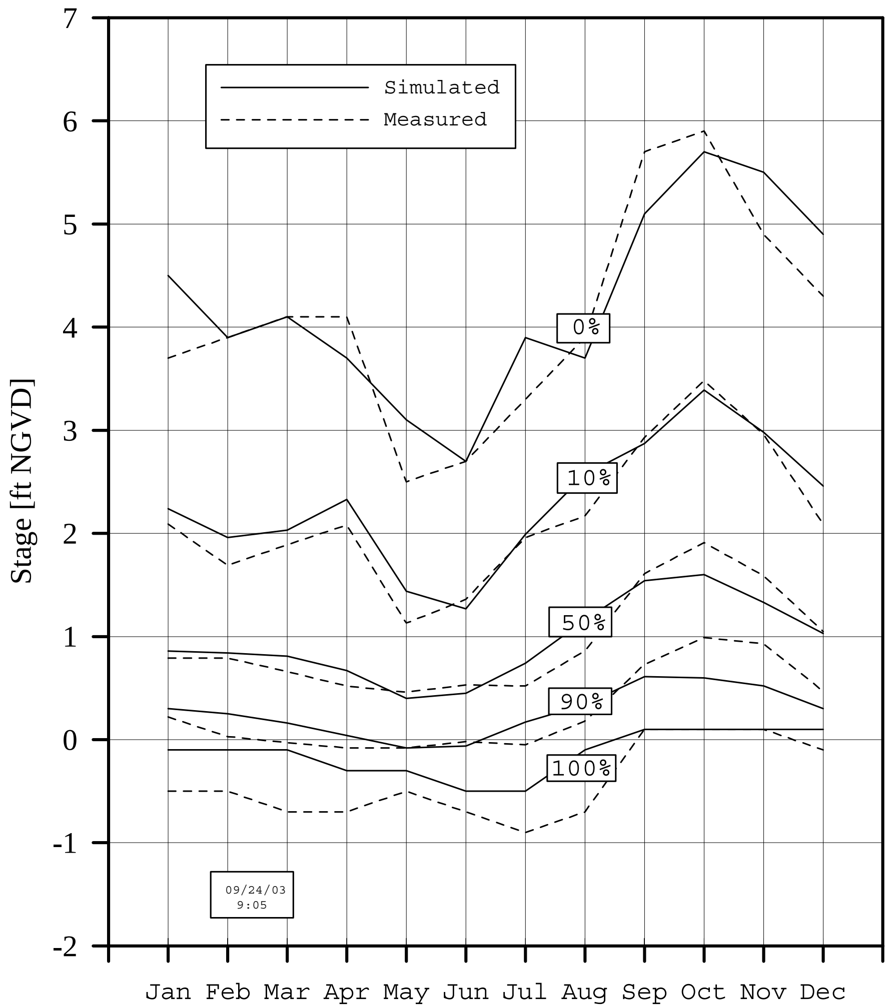


Figure 26. Measured and simulated monthly stage duration curves for the SJR at SR 44 near DeLand; results correspond to the gage model (see p. 29)

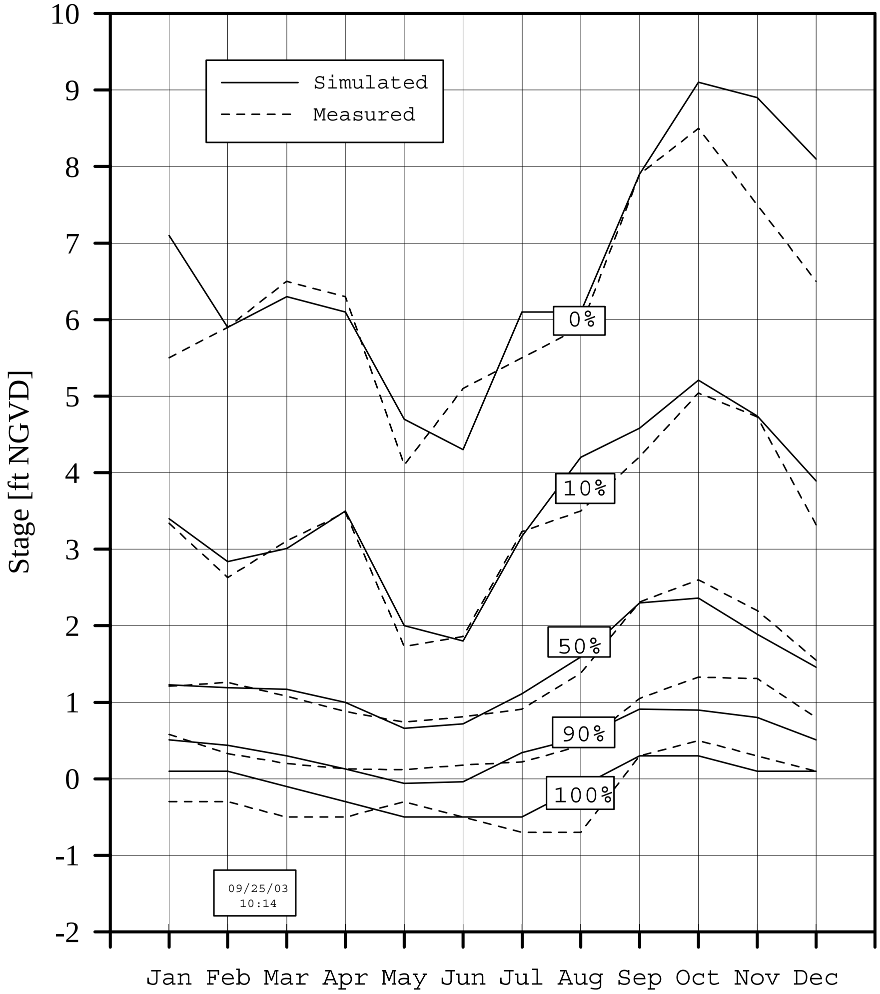


Figure 27. Measured and simulated monthly stage duration curves for the SJR near Sanford (Lake Monroe); results correspond to the gage model (see p. 29)

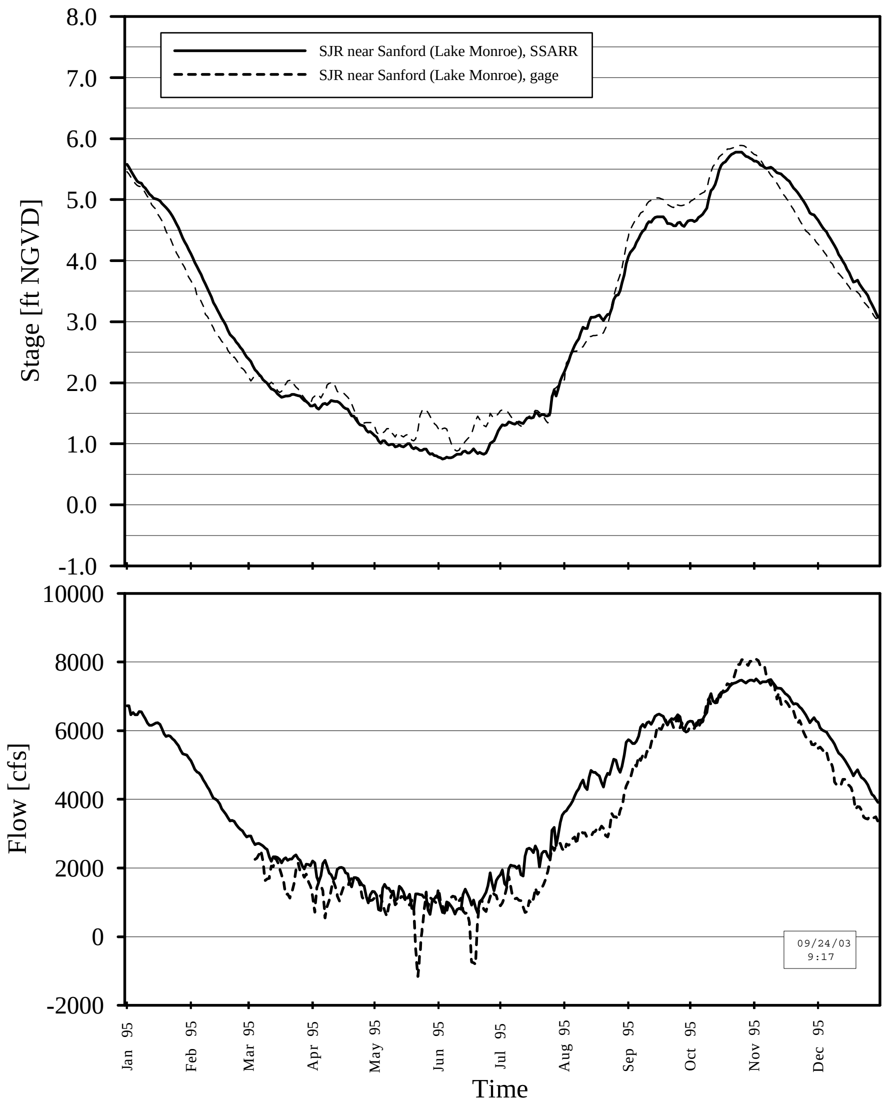


Figure 28. Measured and simulated stage and flow hydrographs for the SJR near Sanford (Lake Monroe); hydrographs correspond to the simulation for the year 1995 and the gage model (see p. 29)

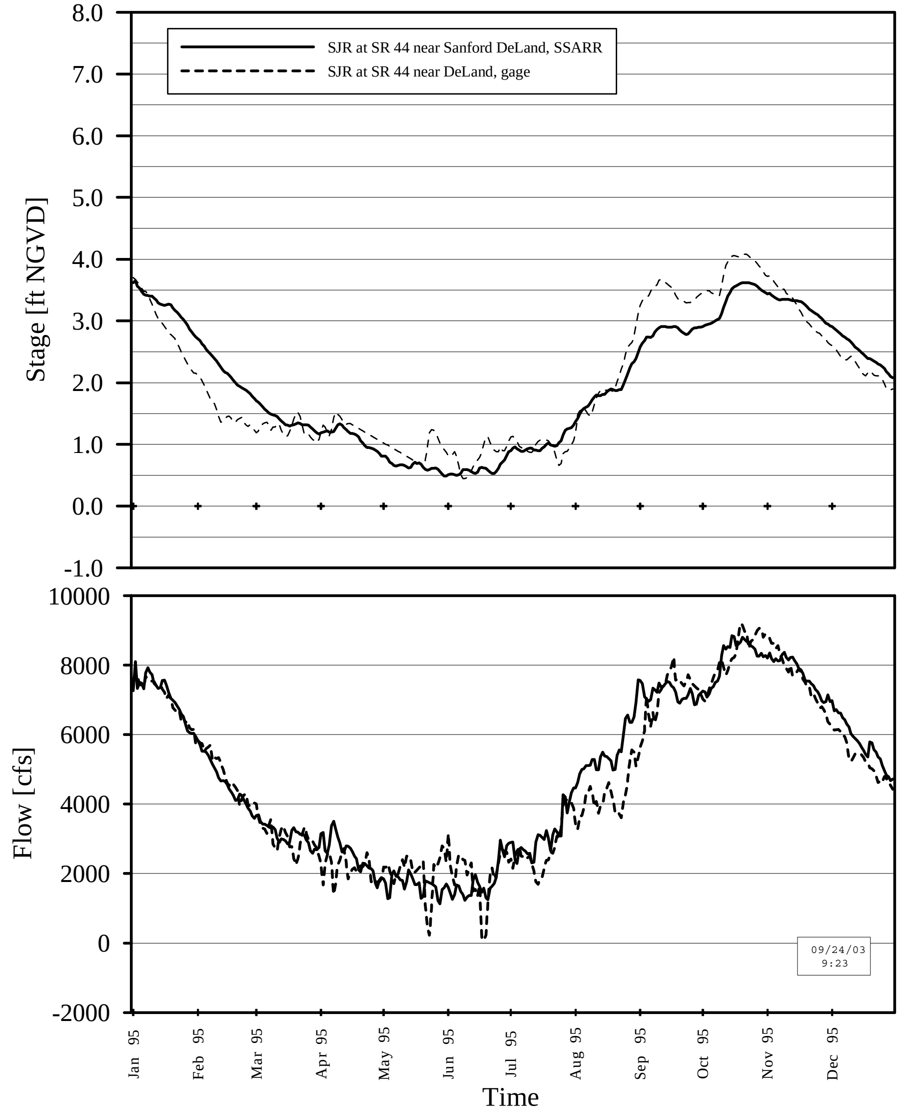


Figure 29. Measured and simulated stage and flow hydrographs for the SJR at SR 44 near DeLand; hydrographs correspond to simulations for the year 1995 and the gage model (see p. 29)

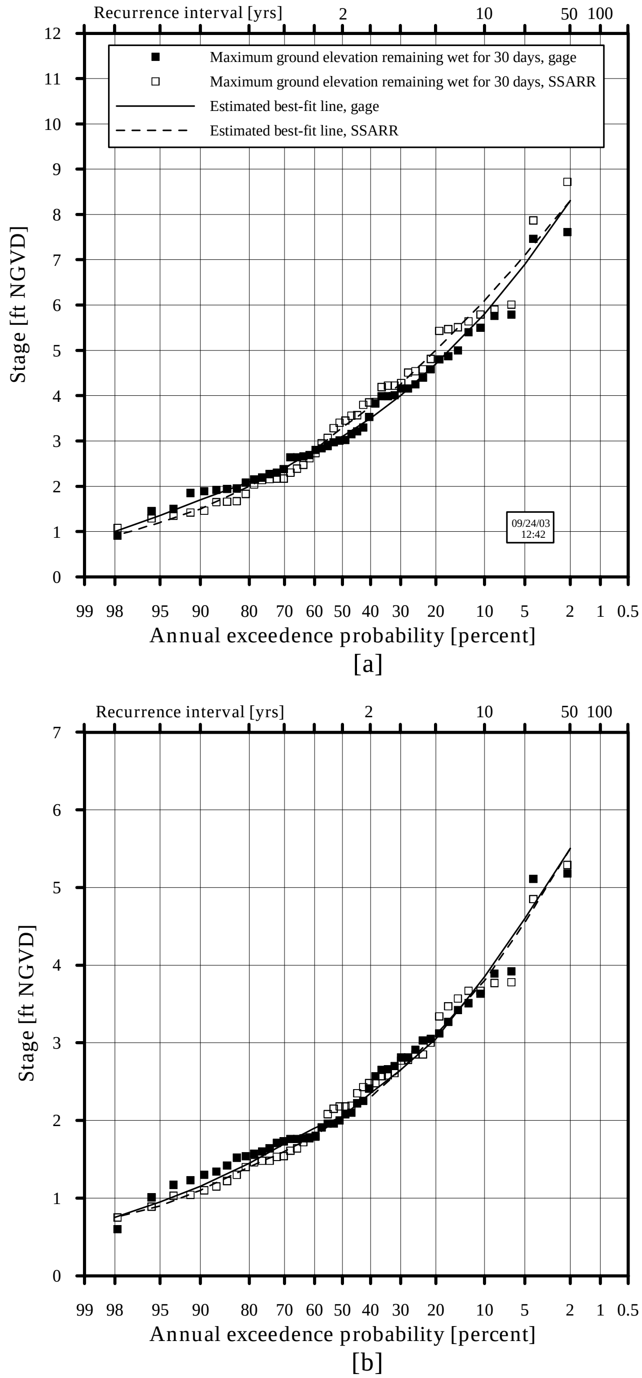


Figure 30. Comparison of measured and simulated maximum elevations remaining wet for 30 days for (a) the SJR near Sanford (Lake Monroe) and (b) the SJR at SR 44 near DeLand. This particular statistic is pertinent to the Minimum Frequent High level.

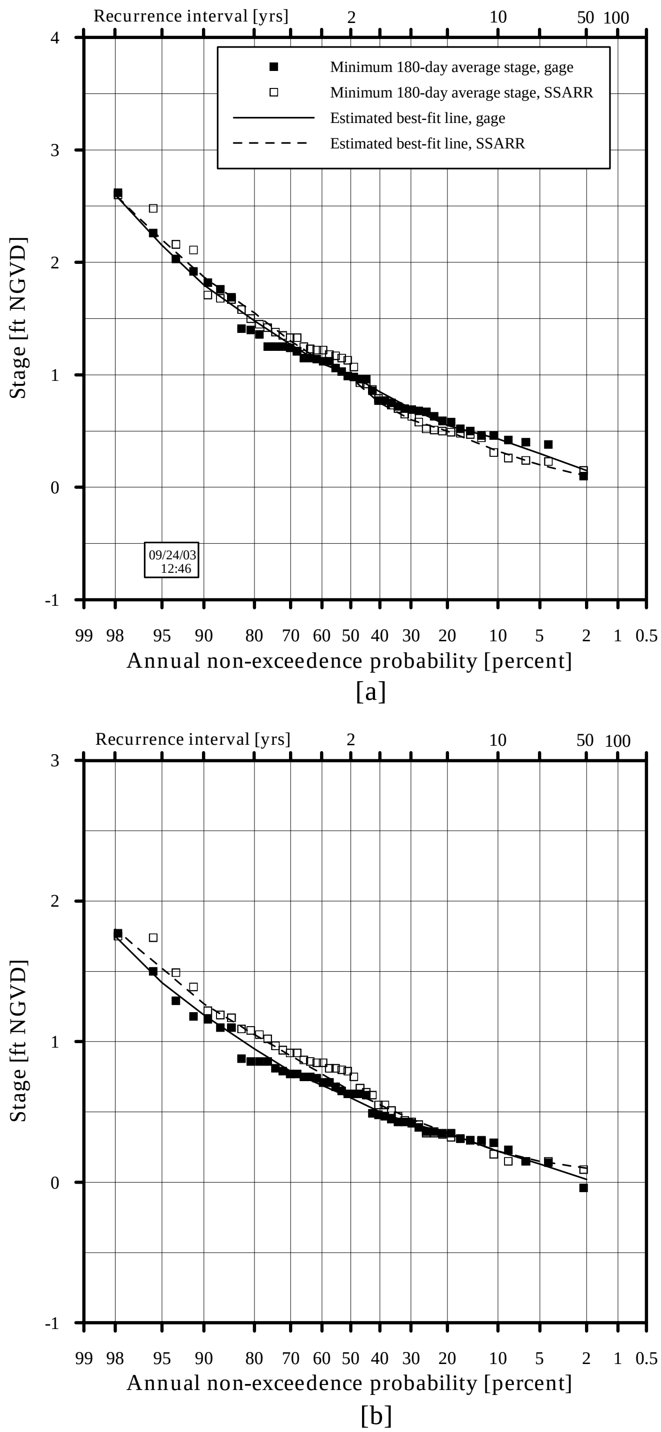


Figure 31. Comparison of measured and simulated minimum 180-day average stages for (a) the SJR at Sanford (Lake Monroe) and (b) the SJR at SR 44 near DeLand. This particular statistic is pertinent to the Minimum Average level.

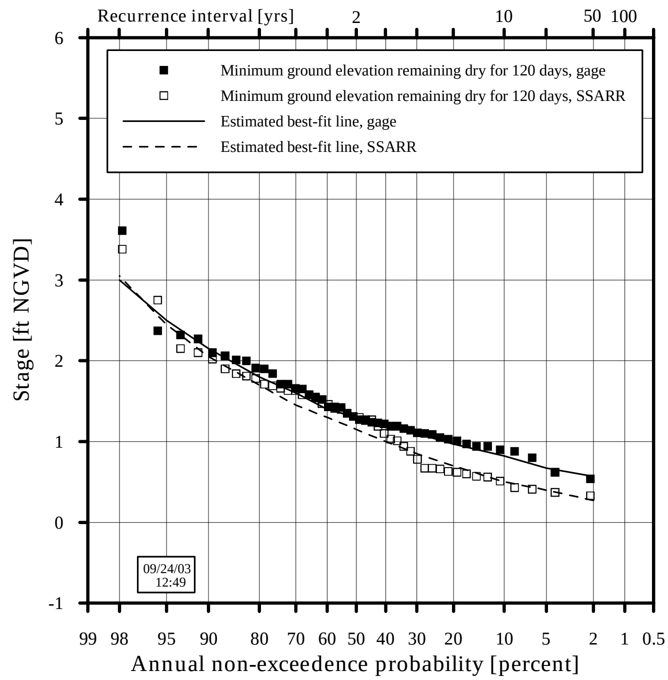
Table 12. Differences in measured and modeled stage frequencies (values in feet); values correspond to the gage model

Annual Probability of Exceedence	Maximum Remaining Wet for 30 Days		Minimum 180-day Average Stage		Minimum Remaining Wet for 120 Days	
	SJR at SR 44 Near DeLand	SJR Near Sanford (Lake Monroe)	SJR at SR 44 Near DeLand	SJR Near Sanford (Lake Monroe)	SJR at SR 44 Near DeLand	SJR Near Sanford (Lake Monroe)
2	0.0	0.0	0.1	–0.1	–0.3	–0.3
5	0.0	0.2	0.0	–0.1	–0.3	–0.3
10	–0.1	0.3	0.0	–0.1	–0.3	–0.3
20	0.1	0.3	0.0	–0.1	–0.3	–0.3
30	0.0	0.3	0.0	–0.1	–0.3	–0.3
40	–0.1	0.3	0.1	–0.1	–0.3	–0.2
50	0.0	0.2	0.1	0.0	–0.3	–0.2
60	–0.1	0.0	0.1	0.0	–0.3	–0.1
70	–0.1	0.0	0.1	0.0	–0.2	–0.2
80	–0.1	–0.1	0.1	0.1	–0.2	–0.1
90	0.0	–0.2	0.1	0.1	–0.2	–0.1
95	0.0	–0.2	0.1	0.1	–0.2	0.0
98	0.0	–0.1	0.1	0.0	0.0	0.0

Note: SJR = St. Johns River
SR = state road

the pertinent simulated stages are within ±0.1 ft, well within the calibration criterion of ±0.5 ft.

Minimum stages continuously not exceeded. In the context of MFLs, minimum stages continuously not exceeded for 120 days (see Appendix A for some explanation of frequency analysis) are used in the development of the Minimum Frequent Low level. Therefore, comparison of simulated and measured stages continuously not exceeded for 120 days should indicate the model's suitability for representing the MSJR at this particular level. For the SJR at SR 44 near DeLand, although simulated values are nearly all too low (approximately −0.3 ft), they are still within the calibration criterion of ±0.5 ft (Table 12, Figure 32). For the SJR near Sanford (Lake Monroe), the pertinent simulated stages tend to be low, especially for the rarer events. However, they are all still within the calibration criterion of ±0.5 ft. In any event, systematically low values will be conservative when it comes to assessing the Minimum Frequent Low.



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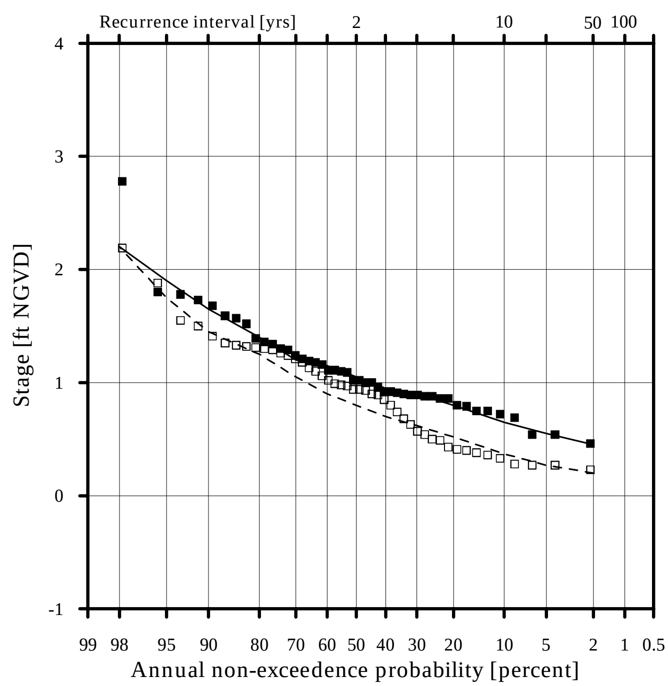


[b]

Figure 32. Comparison of measured and simulated minimum elevations remaining dry for 120 days for (a) the SJR at Sanford (Lake Monroe) and (b) the SJR at SR 44 near DeLand. This particular statistic is pertinent to the Minimum Frequent Low level.

Spring flow. Based on the MSJR SSARR model simulations, spring flow constitutes about 13% of the average annual flow for the SJR at SR 44 near DeLand (Table 13) and about 22% of the outflow from Lake George. Therefore, it is important to evaluate the ability of the spring simulation model (see pp. 22–27) to provide reasonable estimates of spring flow in the MSJR.

Table 13. Percentage of spring flow at DeLand and Lake George; values correspond to the complete model

Location	Total Simulated Annual Flow Volume (acre feet/year)	Total Simulated Spring Flow (acre feet/year)	Spring Flow as a Percentage of Total
SJR at SR 44 near DeLand	2,229,000	284,000	13
Lake George	2,633,000	570,000	22

Note: SJR = St. Johns River
SR = state road

The mean residuals for the power relationship springs (see p. 25) tend to be negative, indicating a possible bias towards underestimating spring flow (Table 14). The standard deviations of the residuals range from ±4% and ±30% of mean flow of the springs.

The most complete record among the springs is for Blue Spring (Table 14). The springflow model closely simulates the cumulative flow volume at Blue Spring (Figure 33) for the period of flow records. The low R^2 of 0.28 for simulation of yearly flow volumes for Blue Spring (Figure C7) is misleading because the coefficient calculation is limited by the minimum values involved. If the regression line is forced through the origin, the R^2 increases to 0.98.

A comparison of simulation results should provide some indication of the appropriateness of using the power fit relationships for simulation of spring flow (see pp. 22–27). The fit of simulated to measured annual flow volumes for Blue Spring using the power relationship (see Figure C7) is much better than that generated by using the linear relationship (see Figure C8). In consequence, the scatter of residuals is wider with the linear relationship model than with the power relationship model.

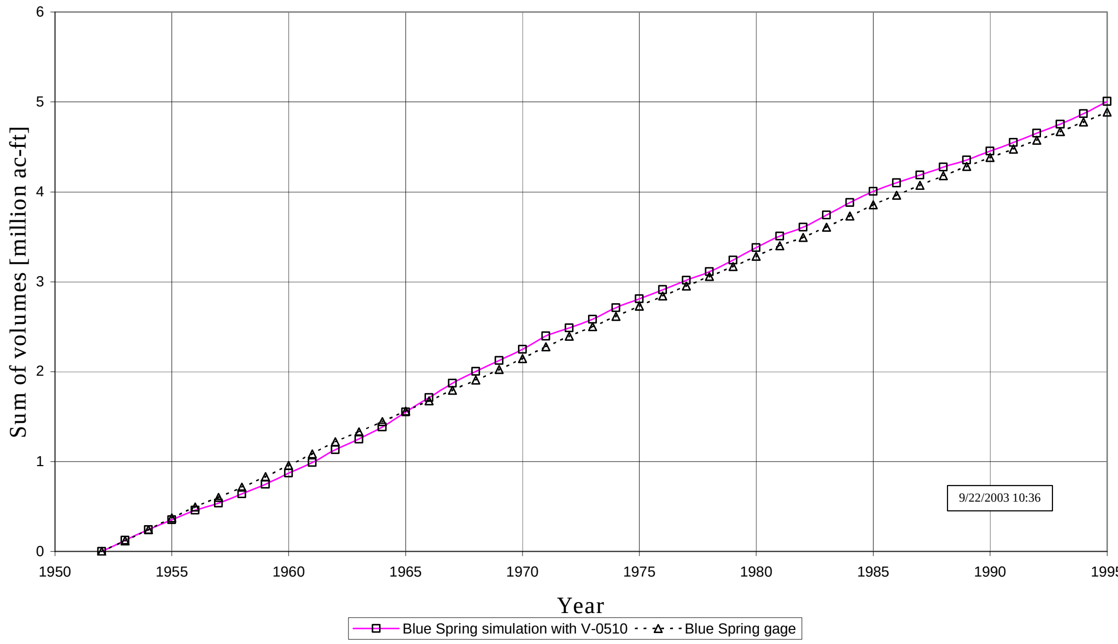


Figure 33. Measured and simulated cumulative flow volumes for Blue Spring

Table 14. Residual analysis statistics for springs included in the MSJR SSARR model

Spring Name	Mean Flow[1] (cfs)	Mean Residual (cfs)	Standard Deviation (cfs)	*n*
Power Relationship Springs				
Blue	158	–8.2	±36.5 (±23%)[2]	464
Ponce de Leon	28	–0.7	±5.6 (±20%)	221
Silver Glen[3]	107	–7.0	±27.9 (±26%)	36
Juniper and Fern Hammock[3]	23	–1.8	±6.6 (±29%)	37
Alexander[3]	110	–7.1	±33.0 (±30%)	90
Salt[3]	81	–6.8	±23.4 (±29%)	38
Linear Relationship Springs				
Wekiva River springs	178	0.0	±16.1 (±9%)	34
Black Water Creek springs	49	–0.1	±2.0 (±4%)	9

Note: cfs = cubic feet per second
MSJR = Middle St. Johns River

[1]See Table 7
[2]Standard deviation as percentage of mean flow
[3]Modeled as Lake George springs

Spring flow provides most of the base flow for the Wekiva River. Assuming that spring flows provide most if not all flow during the driest times, an indirect measure of the accuracy of the springflow simulation model would be provided by comparing the measured and simulated flow duration curves of the Wekiva River near Sanford (Figure 34). Although the comparison of curves indicates an underestimation of lower flows at this gage location, much of the deficit would be accounted for by the unnamed springs in the basin that were not included in the MSJR SSARR model.

Average annual runoff. Average annual runoff can be expressed as the depth of water uniformly distributed over a drainage basin, computed as the average annual flow volume divided by the drainage area. For the MSJR SSARR model, the amount of runoff was dictated by the particular rainfall station used and the SMI-ROP relationships (Figure 2) developed for each individual basin. The accuracy of simulated runoff amounts also depends on the correct determination of the contributing basin runoff area. For the 47 years of simulation, the average runoff from the different basins within the MSJR SSARR model varied between 8.6 and 19 inches (Table 15) but was generally between 11 and 15 inches. These amounts generally fall within the range of the 10–15 inches published for this region (ISPA 1998, p. 69).

Table 15. Simulated average annual runoff for the MSJR SSARR model (1952–98)

SSARR Basin Name	Average Annual Runoff (inches)
B01V	12
B02V	8.6
B00V	8.6
B01U	19
B00U	19
B00E	14
B00H	12
B00J	11
B00M	11
B00W	15
B00B	14
B00D	14
B00F	14
B00G	11

Note: MSJR = Middle St. Johns River

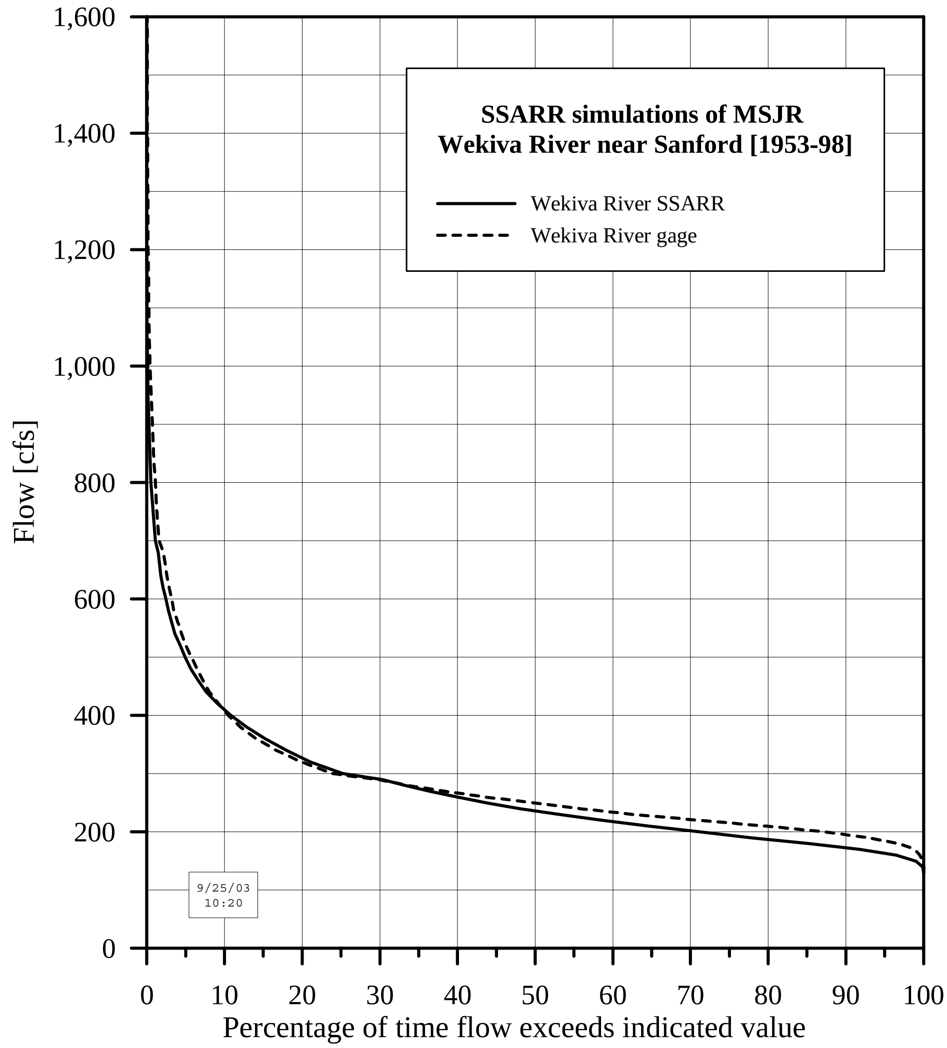


Figure 34. Measured and simulated flow duration curves for the Wekiva River near Sanford

APPROPRIATENESS OF MODELING ASSUMPTIONS

The ability of the MSJR SSARR model to replicate important hydrologic characteristics indicates the suitability of the hydrologic assumptions contained in the model. Most comparisons of measured and simulated stages fall within the calibration criterion of ±0.5 ft. In particular, simulation of stage durations and stage frequency are generally within ±0.5 ft and often within ±0.1 ft.

A number of assumptions (see p. 27) were made in order to provide for a practical application of the MSJR SSARR model. In particular, the following assumptions appear justified: modeling the DeLand and Christmas reaches of the river as lakes, the relative homogeneity of the gage record, and the temporary and localized character of negative flows.

The MSJR SSARR model should provide a useful tool for comparing water management alternatives for the MSJR, based on the good performance of the model relative to a variety of long-term hydrologic statistics. Given this good performance, and especially given the amount and type of data available, a more sophisticated model is not warranted at this time.

HYDRAULIC MODEL OF THE MIDDLE ST. JOHNS RIVER

INTRODUCTION

The principal model used in the assessment of the MSJR in the context of MFLs was the MSJR SSARR model. The assumptions, setup, and calibration of this model are described in the preceding chapter of this document. The MSJR SSARR model simulates the river segment between Lake Monroe and Lake George as a series of lakes. The MSJR SSARR model was successfully calibrated to three gaging stations bracketing the area of interest: the SJR near Sanford (Lake Monroe), the SJR at SR 44 near DeLand, and Lake George.

SJRWMD personnel have adopted three MFLs for the MSJR at SR 44 near DeLand (Mace 2003). These levels are composites of levels determined at four sites along the MSJR: Lake Woodruff, Pine Island, North Emmanuel Bend, and lower Wekiva River (Mace 2003). Except for Lake Woodruff, these sites do not correspond to specific SSARR model locations. Therefore, some method was needed to determine stages at the Pine Island, North Emmanuel Bend, and lower Wekiva River sites.

Individual events along the MSJR, as opposed to continuous simulations, can be modeled as one-dimensional, steady, gradually varied flow. A model developed for this type of flow, the U.S. Army Corps of Engineer's Hydrologic Engineering Center's River Analysis System (HEC-RAS), has been adopted for use along the MSJR. A description of the theoretical basis of HEC-RAS is beyond the scope of this report, but a more in-depth discussion of the technique used in the model (standard-step backwater method) is available in the model manual (USACE 1997) or a standard textbook on open channel hydraulics (Chow 1959; Henderson 1966).

The following topics will be discussed in this chapter:

- Calibration criteria for the MSJR HEC-RAS model
- Development and calibration of the MSJR HEC-RAS model
- Using HEC-RAS to interpolate intermediate stages along the MSJR

Calibration Criteria for the MSJR HEC-RAS Model

Calibration of a water surface profile model is a standard procedure in which measured and simulated stages are compared. Given the geometry of a river channel, flow resistance coefficients are adjusted in order to obtain the best possible agreement between measured and simulated stages.

Calibration criteria, used to judge the adequacy of a model, are determined before model calibration. In the case of the MSJR HEC-RAS model, the calibration goal was to maximize the number of simulated values lying within ±0.5 ft of the corresponding measured values for a wide range of flows.

Development and Calibration of the MSJR HEC-RAS Model

The MSJR HEC-RAS model was constructed using channel geometry and flow resistance factors at 52 cross sections (Figures 35, 36, and 37). Data for these cross sections were obtained from the Corps of Engineers and from surveys contracted by SJRWMD (pers. com., David Clapp, SJRWMD). The model was calibrated with stages (Figure 37) and flows (Figure 38) from several events recorded at USGS gages along the river. The downstream boundary condition was supplied by the stage measured at the USGS gage on Lake George.

Stages at cross-section 150.53, at the MSJR gage near Blue Spring Run, were calculated from an equation that relates stages near Blue Spring to stages at the DeLand gage:

$$H_{bs} = (H_{del} + 0.0936) \times 1.169 \tag{6}$$

where

H_{bs} = stage at the MSJR gage at Blue Spring Run

H_{del} = stage at the MSJR gage near DeLand

Equation 6 was developed previously by SJRWMD (pers. com., Robert Freeman, SJRWMD).

The MSJR HEC-RAS model was calibrated by adjusting Manning's *n* values (roughness coefficients) (Chow 1959; Henderson 1966) to obtain the best possible fit. A wide range of flows was used to increase confidence in model results. Table 16 lists the final *n* values. The channel *n* values for the downstream reaches (0.014 and 0.01) are very low for natural channels. These low *n* values are most

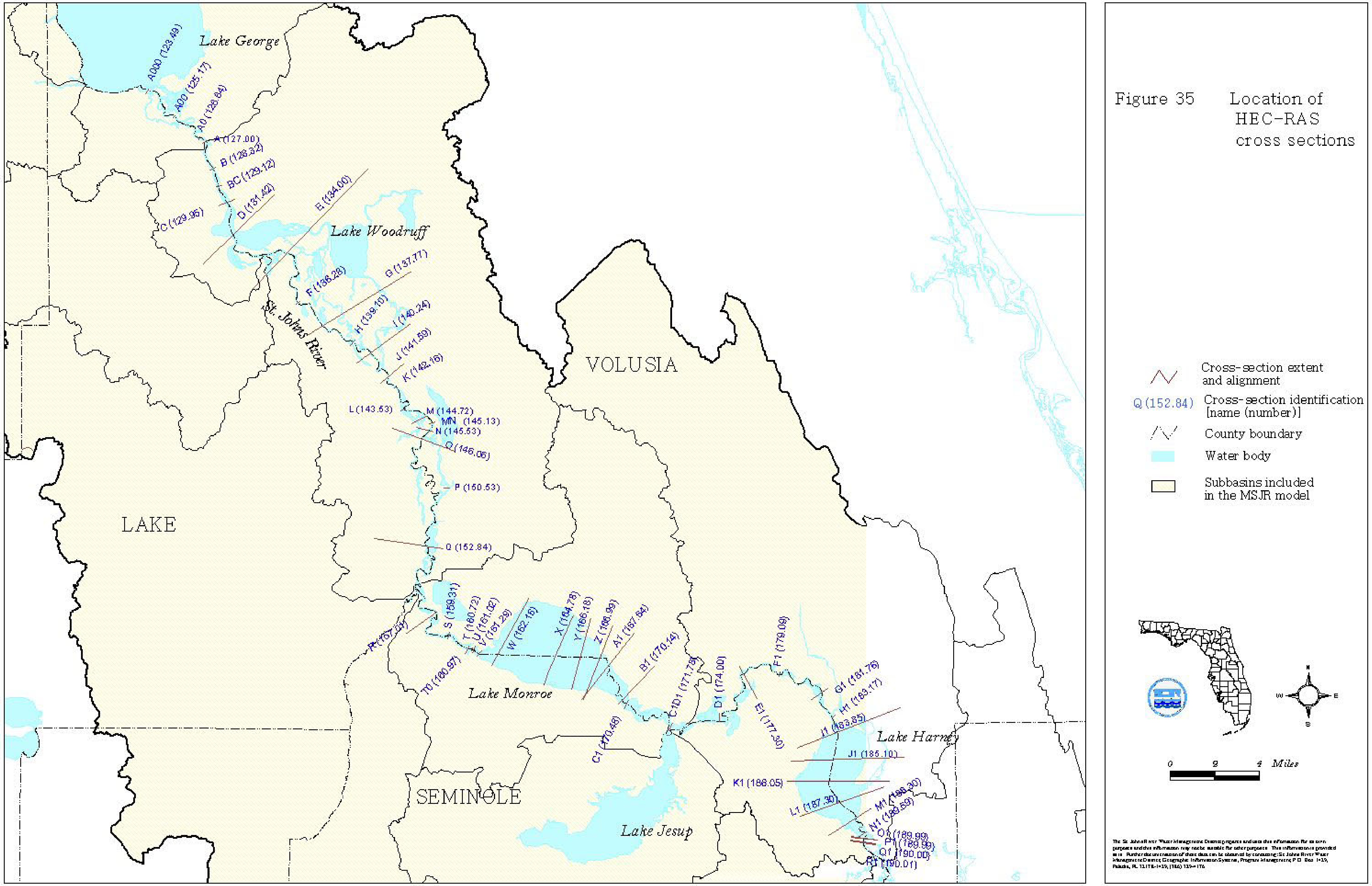


Figure 35 Location of HEC-RAS cross sections

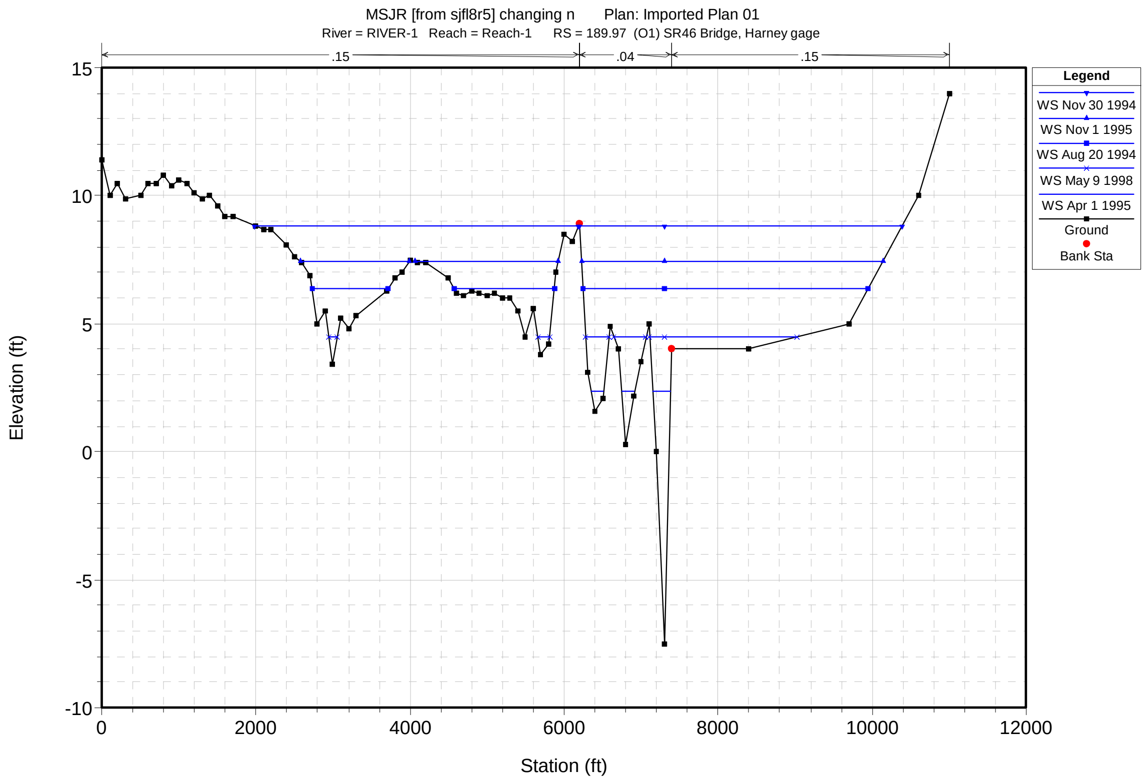


Figure 36. Cross-section 189.97 at the SR 46 bridge over the St. Johns River, upstream of Lake Harney, with superimposed flood events

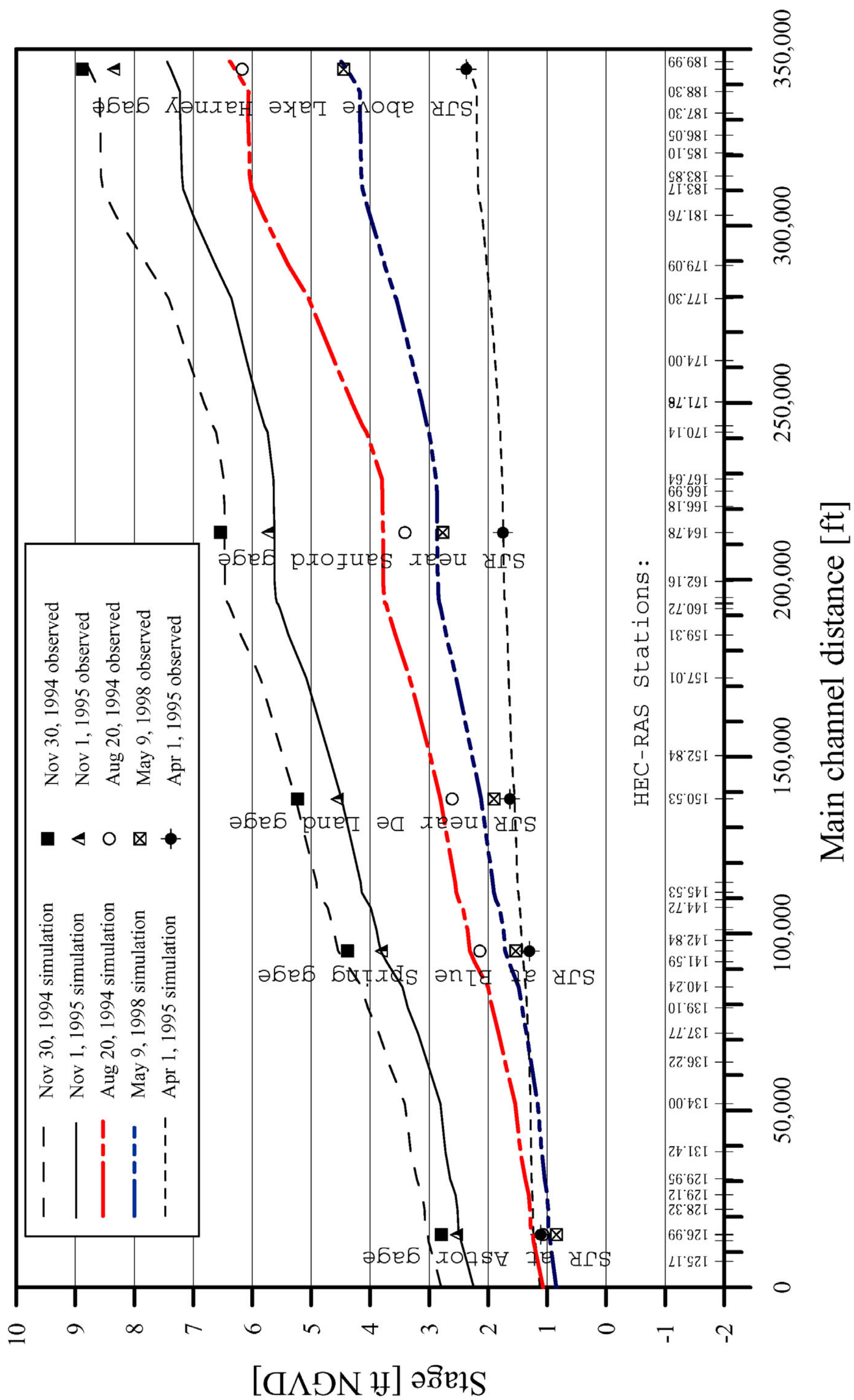


Figure 37. Water surface profiles simulated by the calibrated MSJR HEC-RAS model

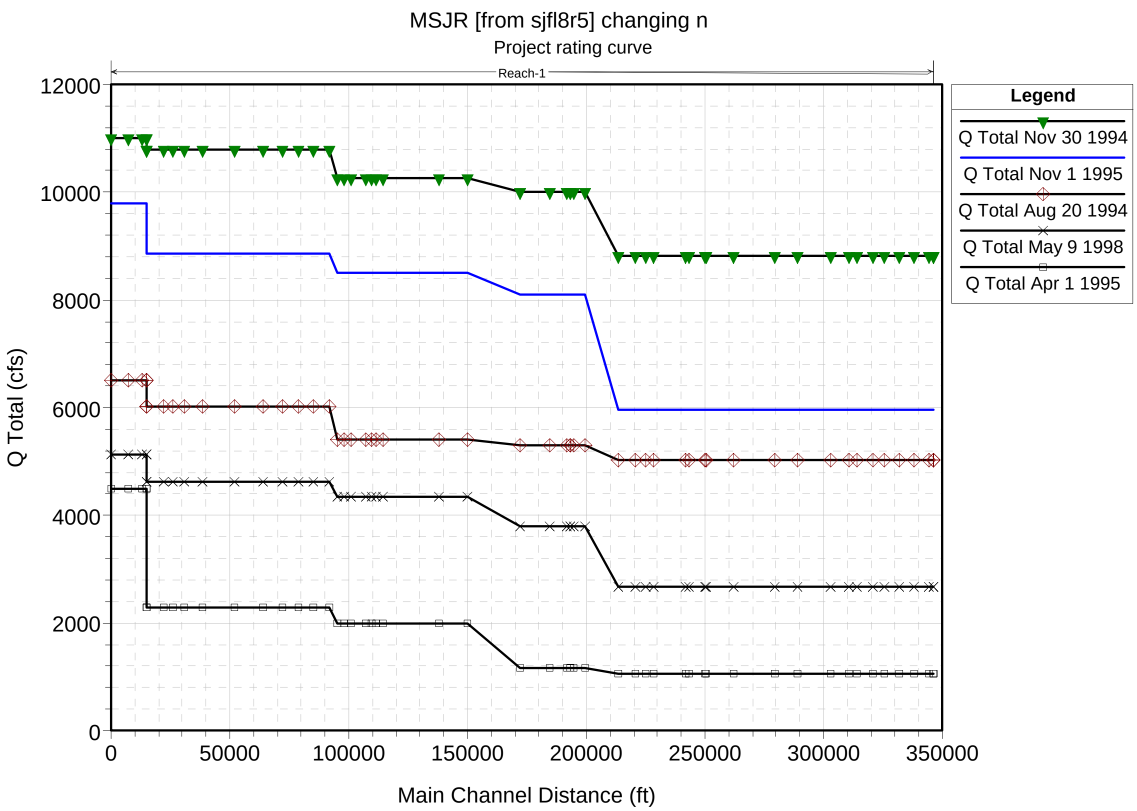


Figure 38. River flows used in calibration of the MSJR HEC-RAS model

Table 16. Final Manning's *n* values for the MSJR HEC-RAS model

River Station Interval	Left-Bank *n* Value	Channel *n* Value	Right-Bank *n* Value
189.99–170.14	0.15	0.04	0.15
167.64–152.84	0.15	0.03	0.15
150.53–131.42	0.15	0.014	0.15
129.95–123.49	0.15	0.01	0.15

Note: MSJR = Middle St. Johns River

likely due to lack of detail in the cross-sectional geometry. More-detailed surveying should bring these values more in line with standard values.

Except for one instance (Table 17), HEC-RAS replicates measured stages (Figure 37) within the calibration criterion of ±0.5 ft. For the May 9, 1998, event, the model was 0.97 ft lower than the gage value. One possible reason for the underestimation for this particular event is an under-measurement of the true flow.

The MSJR HEC-RAS model was successfully calibrated across a wide range of flows, so this model should provide a reasonable estimate of stages between gages used in the MSJR SSARR model (see Figure 4).

USING HEC-RAS TO INTERPOLATE INTERMEDIATE STAGES ALONG THE MIDDLE ST. JOHNS RIVER

The MSJR SSARR model was used to simulate stages for the SJR at SR 44 near DeLand and for the SJR near Sanford (Lake Monroe). The MSJR HEC-RAS model was used to determine stages at the Pine Island, North Emmanuel Bend, and lower Wekiva River sites. Based on the HEC-RAS results (Figure 37), it is reasonable to use direct interpolation between the SJR near DeLand gage site (cross-section 142.84, main channel distance (MCD) = 95,000 ft) and Lake Monroe (cross-section 160.72, MCD = 190,000 ft) to determine stages or stage durations at intermediate locations. The process of interpolation is based on the principle of the proportionality of right triangles. This principle states that the proportion of the heights (differences in stages, in this case) of two right triangles with a common angle is equal to the proportion of the respective bases (differences in MCDs, in this case). This proportionality can be written

Table 17. Differences between measured and modeled stages from calibration of the MSJR HEC-RAS model

Gage	HEC-RAS Stage (feet)	Measured Stage (feet)	Difference (feet)
November 30, 1994, Event			
SJR at Astor	1.22	1.11	0.11
SJR at Blue Spring	1.42	1.30	0.12
SJR near DeLand	1.55	1.63	–0.08
SJR near Sanford	1.74	1.75	–0.01
SJR above Lake Harney	2.30	2.37	–0.07
November 1, 1995, Event			
SJR at Astor	0.97	0.84	0.13
SJR at Blue Spring	1.71	1.53	0.18
SJR near DeLand	2.12	1.90	0.22
SJR near Sanford	2.87	2.77	0.10
SJR above Lake Harney	4.39	4.45	–0.06
August 30, 1994, Event			
SJR at Astor	1.26	1.07	0.19
SJR at Blue Spring	2.31	2.14	0.17
SJR near DeLand	2.81	2.61	0.20
SJR near Sanford	3.78	3.41	0.37
SJR above Lake Harney	6.29	6.17	0.12
May 9, 1998, Event			
SJR at Astor	2.50	2.54	–0.04
SJR at Blue Spring	3.82	3.81	0.01
SJR near DeLand	4.48	4.56	–0.08
SJR near Sanford	5.62	5.74	–0.12
SJR above Lake Harney	7.38	8.35	–0.97
April 1, 1995, Event			
SJR at Astor	3.04	2.79	0.25
SJR at Blue Spring	4.54	4.38	0.16
SJR near DeLand	5.26	5.23	0.03
SJR near Sanford	6.47	6.54	–0.07
SJR above Lake Harney	8.76	8.88	–0.12

Note: MSJR = Middle St. Johns River
SJR = St. Johns River

$$\frac{S_x - S_{del}}{S_{mon} - S_{del}} = \frac{MCD_x - MCD_{del}}{MCD_{mon} - MCD_{del}} \quad \textbf{(7)}$$

where

S_x = stage at intermediate site x
S_{del} = stage at SR 44 near DeLand
S_{mon} = stage at Lake Monroe
MCD_x = MCD at intermediate site x
MCD_{del} = MCD at SR 44 near DeLand
MCD_{mon} = MCD at Lake Monroe

Solving Equation 7 for S_x:

$$S_x = (S_{mon} - S_{del})\frac{(MCD_x - MCD_{del})}{(MCD_{mon} - MCD_{del})} + S_{del} \quad \textbf{(8)}$$

Table 18 summarizes the calculation of the MCD factors at the three MFLs sites along the MSJR. Two examples of interpolation follow:

If the stage for a given event is 2.00 ft NGVD on the MSJR at SR 44 near DeLand and 2.50 ft NGVD at Lake Monroe, then the stage at Pine Island is interpolated as follows:

$$S_{pi} = (S_{mon} - S_{del}) \times 0.53 + S_{del} = (2.50 - 2.00) \times 0.53 + 2.00 = 2.26\,ft \quad \textbf{(9)}$$

where

S_{pi} = stage at Pine Island MFLs site

Likewise, if the stage exceeded 10% of the time is 2.30 ft NGVD on the MSJR near DeLand and 3.40 ft NGVD at Lake Monroe, then the stage exceeded 10% of the time at North Emmanuel Bend is interpolated as follows:

$$S_{neb} = (S_{mon} - S_{del}) \times 0.64 + S_{del} = (3.40 - 2.30) \times 0.64 + 2.30 = 3.00\,ft \quad \textbf{(10)}$$

where

S_{neb} = stage at North Emmanuel Bend MFLs site

Table 18. Calculation of interpolation factors for different MFLs sites along the MSJR

Location	Description	Main Channel Distance[1] (feet)	Calculation of MCD Interpolation Factor
Pine Island	Midway between cross sections 150.53 and 152.84	145,000	$\frac{MCD_x - MCD_{del}}{MCD_{mon} - MCD_{del}} =$ $\frac{145{,}000 - 95{,}000}{95{,}000} = 0.53$
North Emmanuel Bend	Midway between cross section 150.53 and the Wekiva River confluence	156,000	$\frac{156{,}000 - 95{,}000}{95{,}000} = 0.64$
Lower Wekiva River	Distance equal to midway between Wekiva River confluence (162,000 feet) and cross section 157.01	167,000	$\frac{167{,}000 - 95{,}000}{95{,}000} = 0.76$

Note: MFLs = minimum flows and levels
MSJR = Middle St. Johns River

For cross-section numbers and locations, refer to Figures 35 and 37

[1]See Figure 37

Although the lower Wekiva River MFLs site is located on the Wekiva River, it is also within the MSJR floodplain. Thus, it was assumed that stages at this location would be dominated by the MSJR at the confluence of the two rivers.

Lake Woodruff stages were simulated directly by the hydrologic model. Therefore, pertinent minimum levels were transferred between Lake Woodruff and the SJR at SR 44 (and vice versa), assuming that the level at one location corresponded to a level with the same percent chance of exceedence at the other.

ASSESSMENT OF EXISTING HYDROLOGIC CONDITIONS OF THE MIDDLE ST. JOHNS RIVER AT SR 44 NEAR DELAND IN THE CONTEXT OF MINIMUM FLOWS AND LEVELS

INTRODUCTION

The SJRWMD MFLs program relies on results of long-term hydrologic simulations to determine if MFLs are being met. The purpose of these simulations is to assess the characteristics of a water body over a wide variety of hydrologic conditions. Modeling results are compared to adopted MFLs to determine if water levels and flows are likely to fall below the adopted MFLs. It should be emphasized that the assumption inherent in this analysis is that the 46-year (1953–98) data record used in the MSJR SSARR model is a statistically realistic representation of the hydrology, absent significant anthropogenic or climatological changes over the next 46 years. This chapter will address the following:

- The existing hydrologic conditions at the MSJR MFLs site at SR 44 near DeLand, assessed in the context of MFLs
- Determination of minimum flows corresponding to each of the minimum levels

ASSESSMENT OF EXISTING HYDROLOGIC CONDITIONS OF THE MIDDLE ST. JOHNS RIVER AT SR 44 NEAR DELAND IN THE CONTEXT OF MINIMUM FLOWS AND LEVELS

SJRWMD personnel have determined three MFLs on the MSJR at SR 44 near DeLand (Mace 2003): a Minimum Frequent High (MFH), a Minimum Average (MA), and a Minimum Frequent Low (MFL). Each of these MFLs is tied to characteristic durations and frequencies of occurrence. A more detailed description of the hydrologic analyses required to determine these frequencies and durations can be found in Appendix A of this report.

SJRWMD has determined the characteristic return period for the MFH level to be between 2 and 3 years (Section 40C-8.021, *Florida Administrative Code* [*F.A.C.*]). Ground at the MFH level should remain flooded or inundated (“wet”) for some period between 30 and 90 days. The preliminary MFH level for the MSJR at SR 44 near DeLand is 1.9 ft NGVD. Based on modeling results, under existing conditions ground at 1.9 ft NGVD is expected to remain continuously flooded for 90 days on average one in 3 years (Figure 39). Ground at 1.9 ft NGVD is expected to remain continuously flooded for 30 days on average one in 1.7 years. The MFH level and vertical lines corresponding to return periods of 2 and 3 years bound the crosshatched box on Figure 39. If model results show that the pertinent events will not occur often enough, the corresponding values will all appear outside of the box, indicating the MFH level would no longer be met.

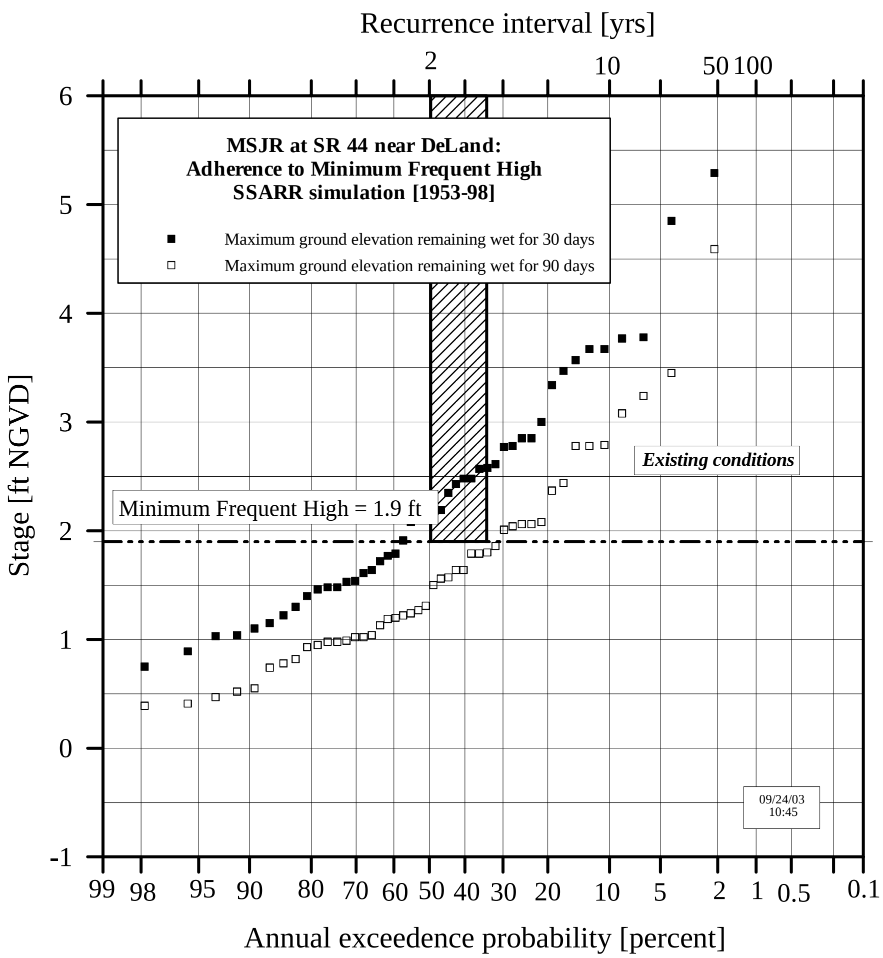


Figure 39. The Minimum Frequent High (MFH) level of the SJR at SR 44 near DeLand, as it relates to results of existing conditions SSARR simulation

SJRWMD has determined the characteristic return period for the MA level to be between 1.5 and 3 years (Section 40C-8.021, *F.A.C.*). The river should maintain an average stage at the MA level for some period between 120 and 180 days. The preliminary MA level for the MSJR at SR 44 near DeLand is 0.8 ft NGVD. Based on modeling results, under existing conditions the river is expected to maintain a 120-day average stage of 0.8 ft NGVD on average one in 1.3 years (Figure 40). The river is expected to maintain a 180-day average stage of 0.8 ft NGVD on average one in 2 years. The MA level and vertical lines corresponding to return periods of 1.5 and 3 years bound the crosshatched box on Figure 40. If model results show that the pertinent events will occur too often, the corresponding values will all appear outside of the box, indicating the MA level would no longer be met.

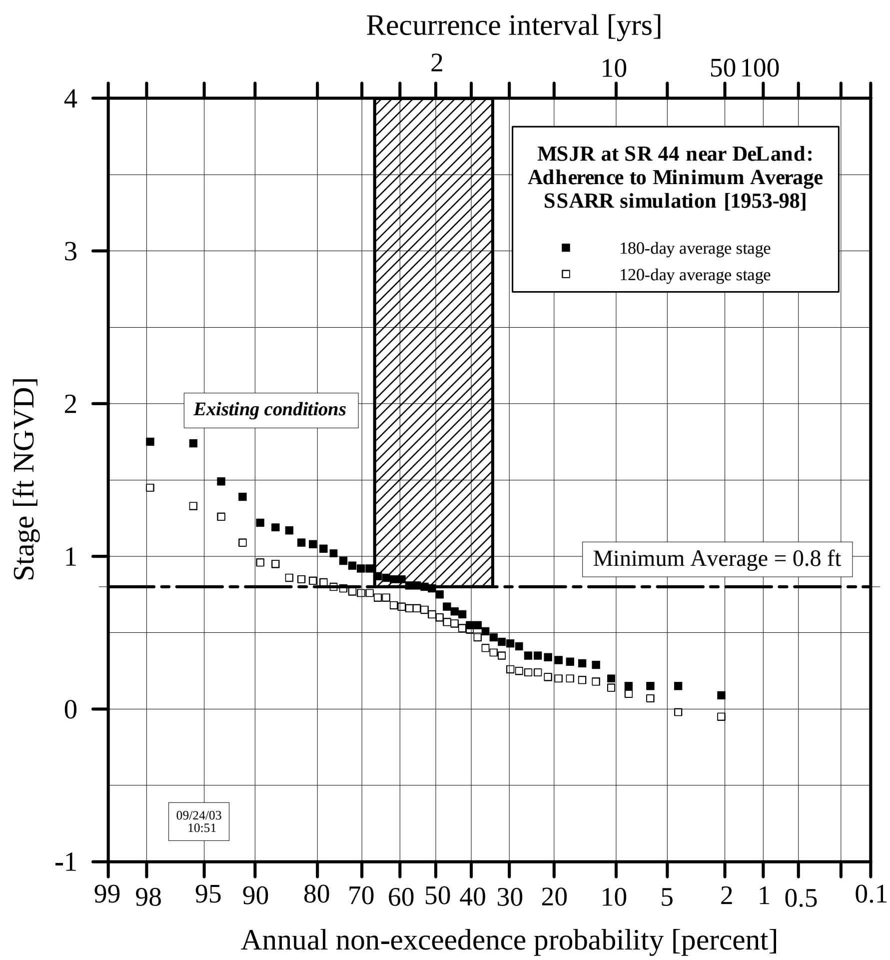


Figure 40. The Minimum Average (MA) level of the SJR at SR 44 near DeLand, as it relates to results of existing conditions SSARR simulation

SJRWMD has determined the characteristic return period for the MFL level to be between 5 and 10 years (Section 40C-8.021, *F.A.C.*). Ground at the MFL level should remain dewatered (“dry”) for some period between 60 and 120 days. The preliminary MFL level for the MSJR at SR 44 near DeLand is 0.3 ft NGVD. Based on modeling results, under existing conditions ground at 0.3 ft NGVD is expected to be dewatered continuously for 120 days on average one in 10 years (Figure 41). Ground at 0.3 ft NGVD is expected to be dewatered continuously for 60 days on average one in 4 years. The MFL level and vertical lines corresponding to return periods of 5 and 10 years bound the crosshatched box on Figure 41. If model results show that the pertinent events will occur too often, the corresponding values will all appear outside of the box, indicating the MFL level would no longer be met.

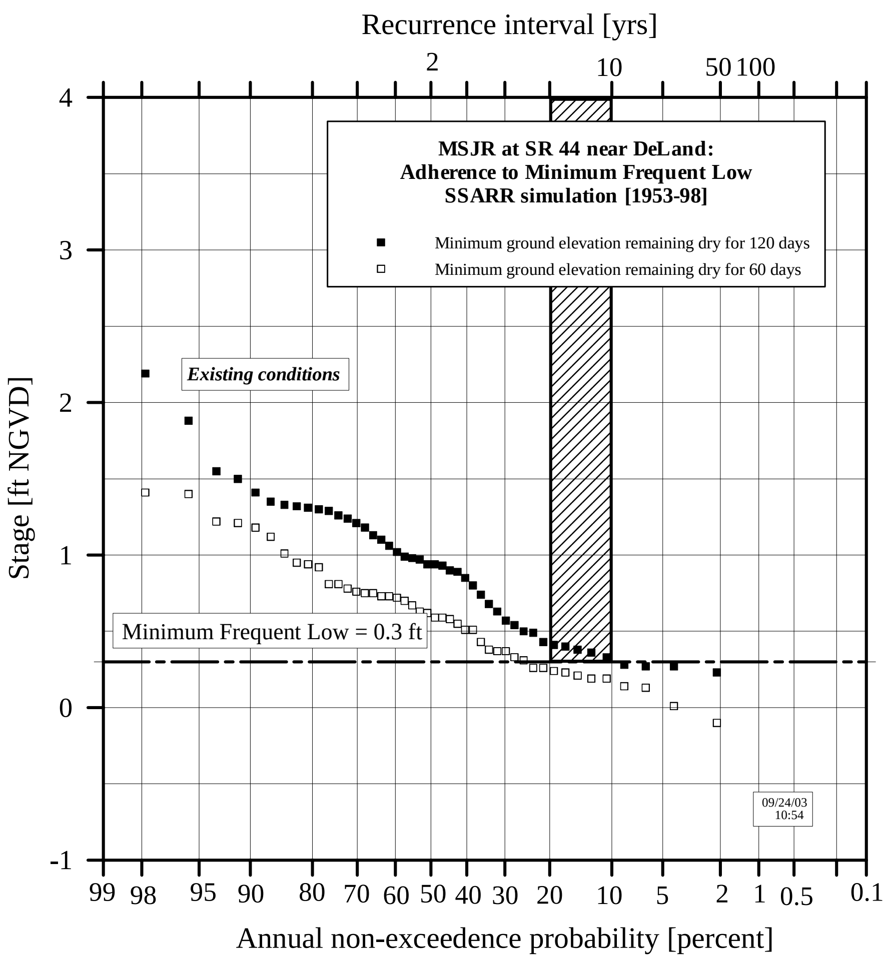


Figure 41. The Minimum Frequent Low (MFL) level of the SJR at SR 44 near DeLand, as it relates to results of existing conditions SSARR simulation

DETERMINATION OF MINIMUM FLOWS CORRESPONDING TO EACH MINIMUM LEVEL FOR THE MIDDLE ST. JOHNS RIVER AT SR 44 NEAR DELAND

MFLs usually are based on stages or water levels. However, in the case of a river system, each of these minimum levels can be associated with a minimum flow. While water resource decisions can be made based on minimum levels alone, pairing each of them with a corresponding minimum flow aids in a better understanding of the effects of changes to a hydrologic system.

As has been discussed previously (see Figures 6 and 7), a given water level in the DeLand area of the MSJR does not correspond to a unique flow. However, flows are subject to the same statistical analyses as stages. Each of the minimum levels is associated with a duration, a return period, and a description of whether that particular level should be continuously exceeded, be continuously not exceeded, or constitute an average condition. If flows of similar statistical characteristics can be assumed to be associated with each of the minimum levels, then minimum flows can be determined.

For example, the MFH level (Figure 39) of 1.9 ft NGVD is exceeded for 30 days slightly less often than the 60% annual exceedence probability. That particular characteristic corresponds to a flow of approximately 4,600 cfs (Figure 42).

The MA level of 0.8 ft NGVD (Figure 40) corresponds to a 180-day average stage slightly more often than the 50% annual non-exceedence probability. That particular set of characteristics corresponds to a flow of approximately 2,050 cfs (Figure 43).

Finally, the MFL level of 0.3 ft NGVD (Figure 41) is not exceeded for 120 days approximately one out of 10 years. This particular set of characteristics corresponds to a flow of approximately 1,100 cfs (Figure 44). As demonstrated in Figures 42–44, the MSJR SSARR model indicates that all three minimum flows are being met under existing hydrologic conditions.

The assumption that minimum flows can be associated with minimum levels of similar statistical characteristics can be evaluated when assessing a change in the existing conditions hydrology of the MSJR. For example, if the MSJR SSARR model indicates that a given minimum level and corresponding minimum flow cease to be met at the same level of surface water withdrawals, then the assumption is appropriate.

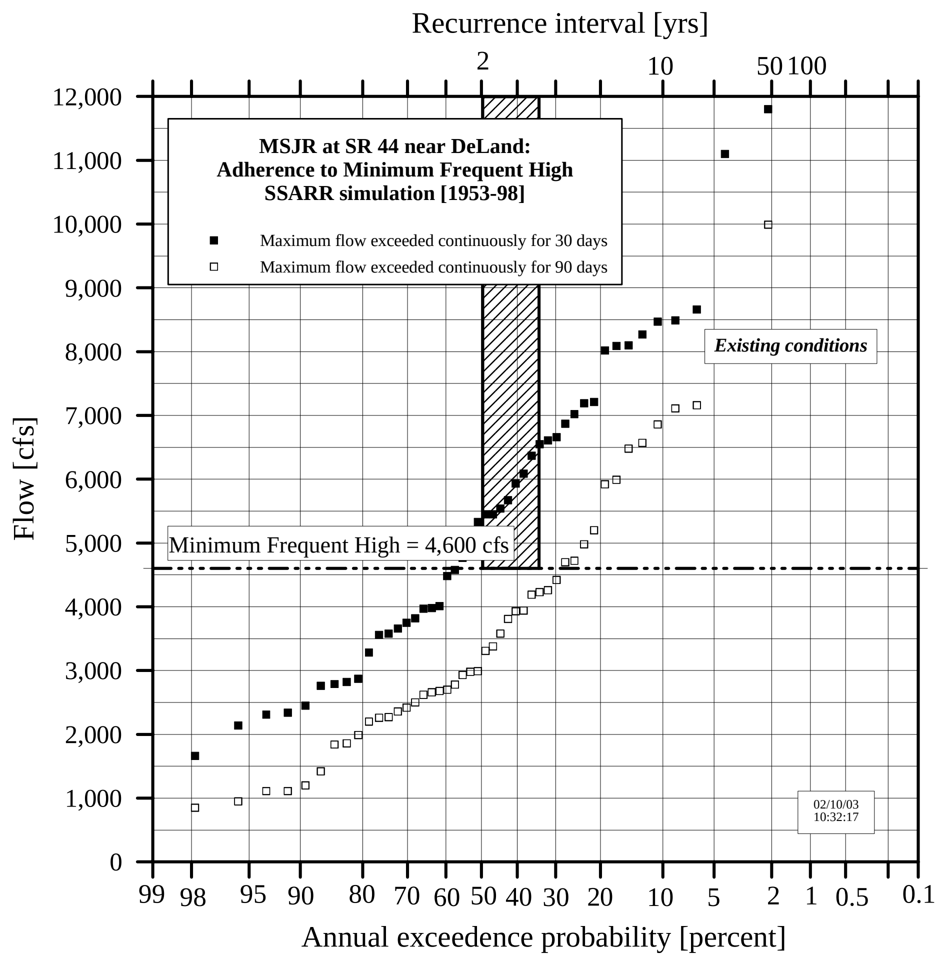


Figure 42. The Minimum Frequent High (MFH) flow of the SJR at SR 44 near DeLand, as it relates to results of existing conditions SSARR simulation

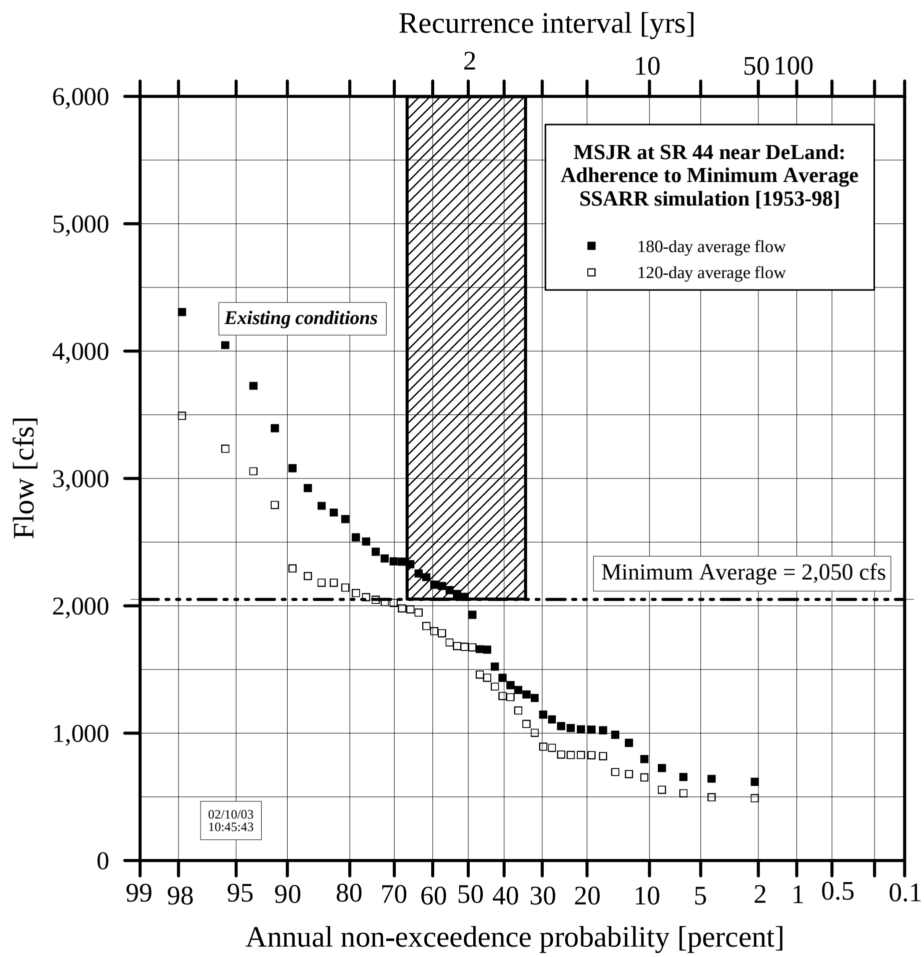


Figure 43. The Minimum Average (MA) flow of the SJR at SR 44 near DeLand, as it relates to results of existing conditions SSARR simulation

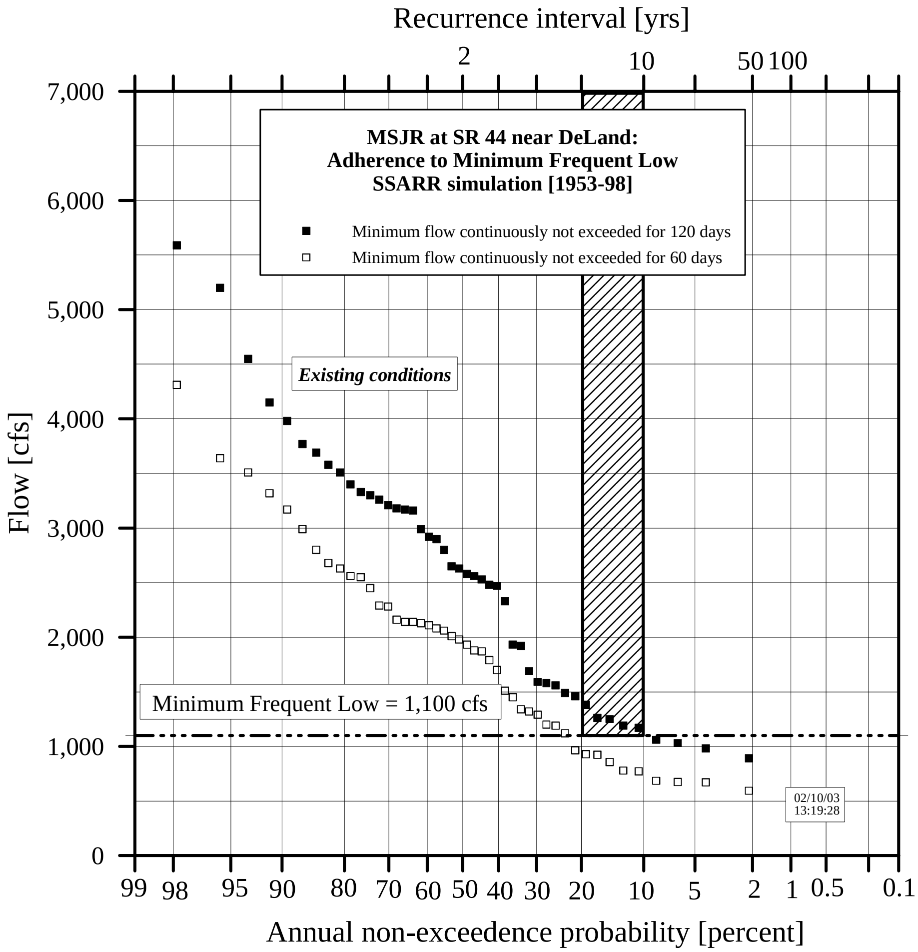


Figure 44. The Minimum Frequent Low (MFL) flow of the SJR at SR 44 near DeLand, as it relates to results of existing conditions SSARR simulation

ASSESSMENT OF HYPOTHETICAL SURFACE WATER WITHDRAWALS FROM THE MIDDLE ST. JOHNS RIVER IN THE CONTEXT OF MINIMUM FLOWS AND LEVELS

INTRODUCTION

The MSJR SSARR model described in this report will be used to assess the hydrologic effects of direct surface water withdrawals from the MSJR in the context of MFLs. This chapter will examine a number of alternatives for surface water withdrawals from the MSJR in the vicinity of DeLand. The assumption inherent in this analysis is that the 46-year (1953–98) data record used in the SSARR model is a statistically realistic representation of the hydrology, absent significant anthropogenic or climatological changes over the next 46 years.

ASSESSMENT OF HYPOTHETICAL SURFACE WATER WITHDRAWALS FROM THE MIDDLE ST. JOHNS RIVER NEAR DELAND IN THE CONTEXT OF MINIMUM FLOWS AND LEVELS AT SR 44 NEAR DELAND

The following assumptions were used in the withdrawal analysis:

1. A set amount of water is withdrawn from the “lake,” which represents the area of the MSJR in the vicinity of DeLand (Figure 4).

2. Withdrawals cease only under low-flow conditions.

3. The operating schedule for surface water withdrawals (Figure 45) depends on simulated SJR stages at SR 44 near DeLand:

   - The initiation of pumping corresponds to a selected percent exceedence stage under existing conditions (Figure 46).

   - The withdrawal amount gradually increases to the maximum upon reaching a selected percent exceedence stage under existing conditions.

The determination of a surface water withdrawal capacity of the MSJR in the context of MFLs involved a trial-and-error process. Withdrawal amounts (Figure 45) were increased, with the resulting hydrologic conditions compared to

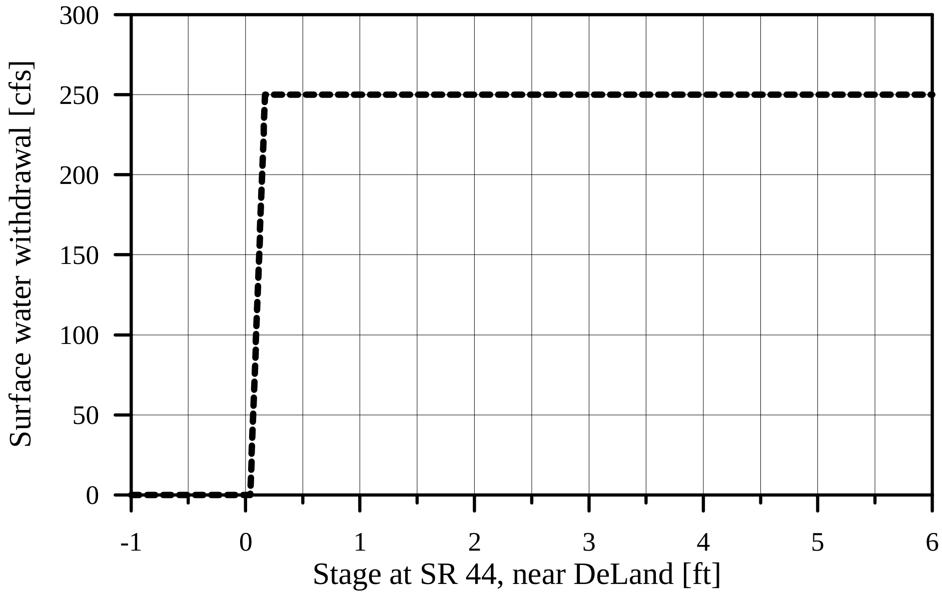


Figure 45. Hypothetical operating schedule for surface water withdrawals from the MSJR near DeLand. This particular schedule was that used for Alternative 1.

the MFLs. The withdrawal capacity was reached when the model results indicated that one of the MFLs would not continue to be met.

Five different water withdrawal alternatives (Table 19) were examined for the present report. The first four alternatives were of the type illustrated in Figure 45. Alternative 5 consisted of a constant withdrawal at all times, regardless of conditions on the MSJR.

To illustrate the effects withdrawals would have in the context of MFLs, Alternative 4 (Table 19) will be examined in more detail. A surface water withdrawal greater than 430 cfs (278 million gallons per day [mgd]) was found to cause water levels at SR 44 near DeLand (Figure 47) to fall below the adopted MA level, under the parameters set for Alternative 4. The MFL level at SR 44 near DeLand would still be met at this rate of withdrawal (Figure 48). The MFH level at SR 44 near DeLand would still be met (Figure 49) at this rate of withdrawal. With respect to flows, the MA flow (2,050 cfs) was also just met for a withdrawal of 430 cfs (Figure 50). This appears to lend credence to the assumptions made

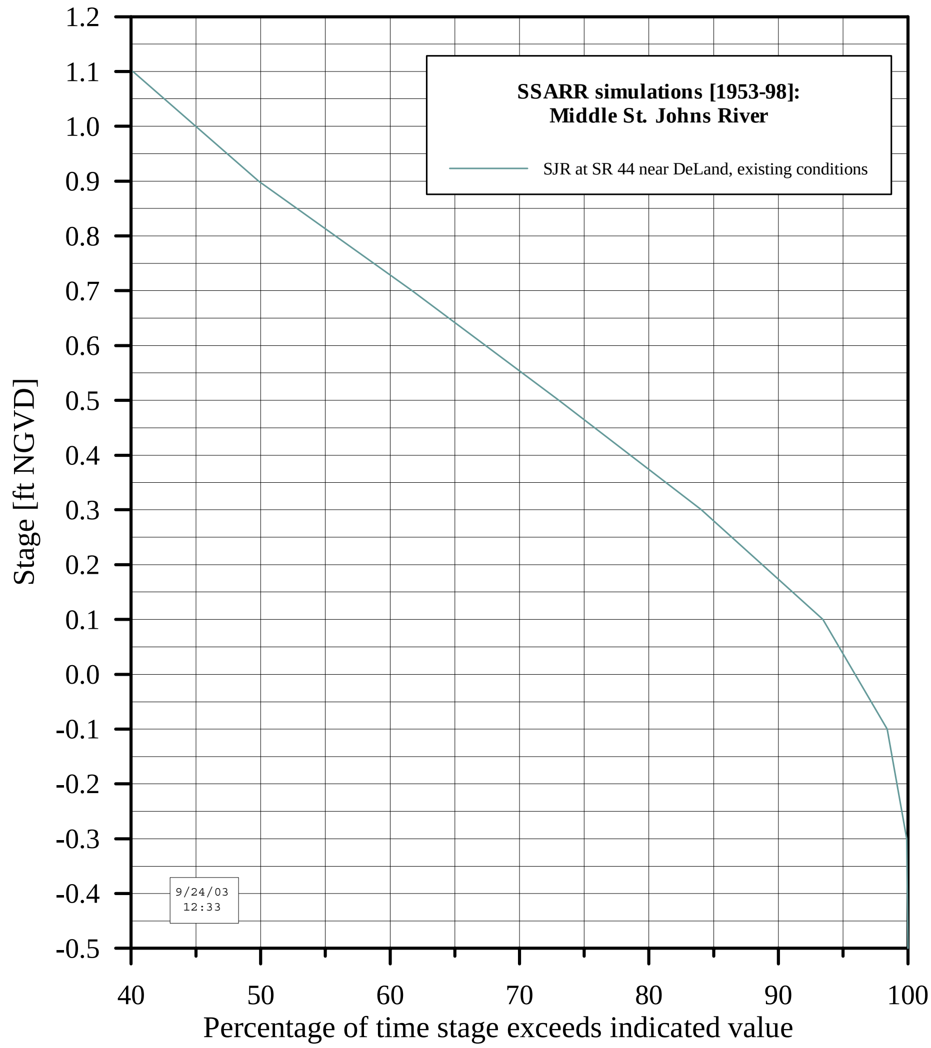


Figure 46. Stage duration curve for the MSJR SSARR simulation of existing hydrologic conditions at SR 44 near DeLand

about the linking of levels and flows (see p. 81). The MFL flow (Figure 51) and the MFH flow (Figure 52) would both still be met under Alternative 4.

From the point of view of stage duration, the effect of surface water withdrawals can be assessed from two perspectives: (1) given an exceedence percentile, how does the corresponding stage change and (2) given a stage, how does the exceedence percentile change. Stages would be drawn down at SR 44 near DeLand, due to decreased flow (Figure 53); at Lake Monroe, stages would be

Table 19. Water withdrawal parameters

Alternative	Pumping at Maximum		Pumping Ceases		Maximum Withdrawal (cfs [mgd])	Average Withdrawal (cfs [mgd])	Percent of Annual Flow at SR 44
	Percent of Time Stage at SR 44 Exceeded Under Existing Conditions	Stage (feet)	Percent of Time Stage at SR 44 Exceeded Under Existing Conditions	Stage (feet)			
1	90	0.17	95	0.04	250 (162)	236 (153)	7.7
2	80	0.37	85	0.28	260 (168)	221 (143)	7.2
3	70	0.55	75	0.47	320 (207)	238 (154)	7.7
4	60	0.73	65	0.64	430 (278)	271 (175)	8.8
5	NA	NA	NA	NA	240 (155)	240 (155)	7.8

Note: cfs = cubic feet per second
mgd = million gallons per day
NA = not applicable
SR = state road

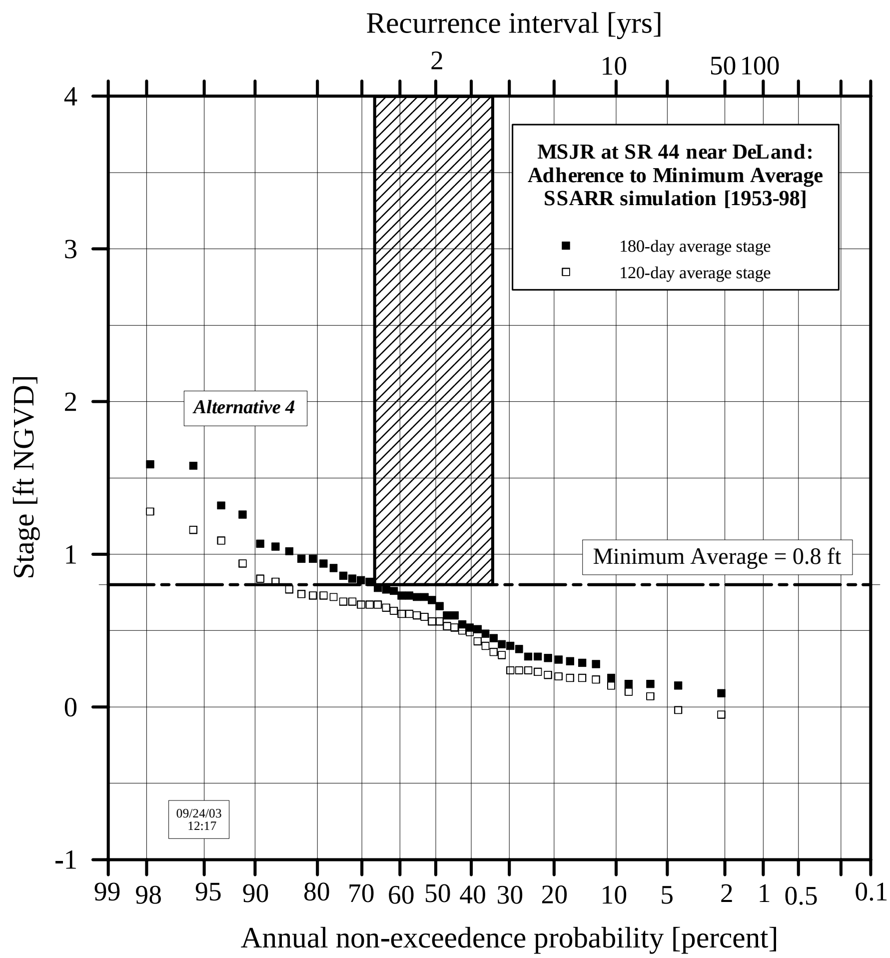


Figure 47. The Minimum Average (MA) level of the SJR at SR 44 near DeLand, as it relates to results of the Alternative 4 SSARR simulation. Model results illustrated here indicate that a maximum withdrawal larger than 430 cfs would violate this minimum level under the parameters set for Alternative 4 (see Table 19).

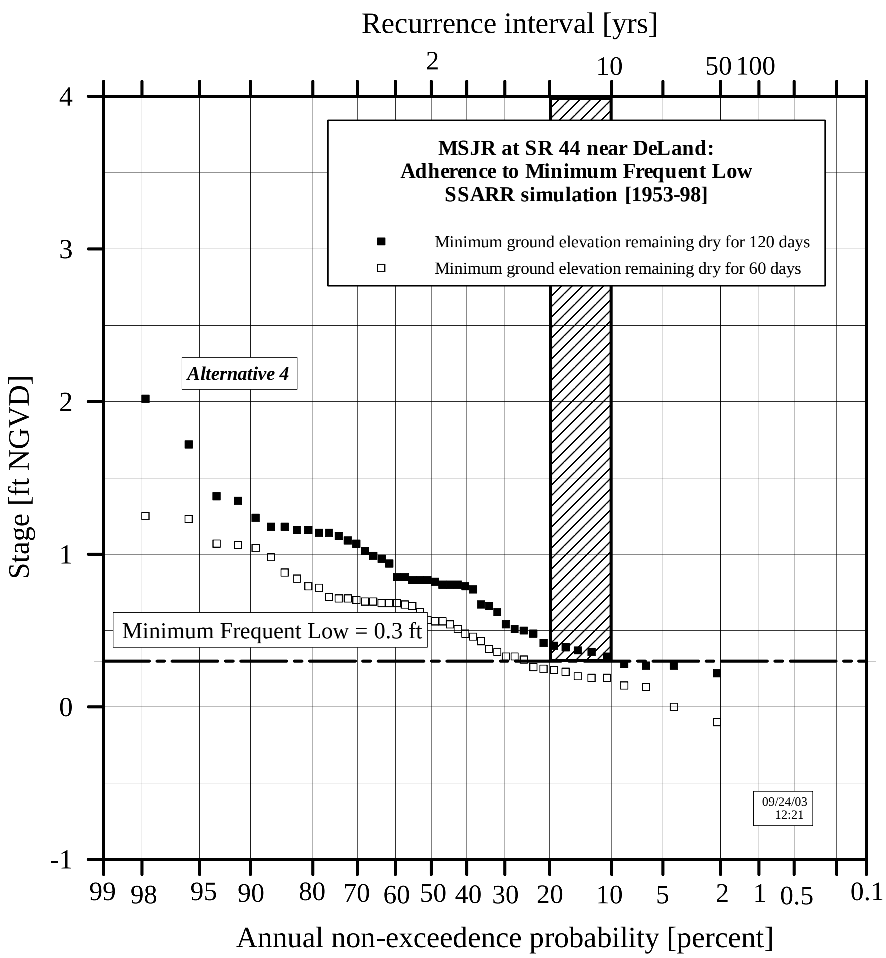


Figure 48. The Minimum Frequent Low (MFL) level of the SJR at SR 44 near DeLand, as it relates to results of the Alternative 4 SSARR simulation. Model results illustrated here indicate that this minimum level is being met under the parameters set for Alternative 4 (see Table 19).

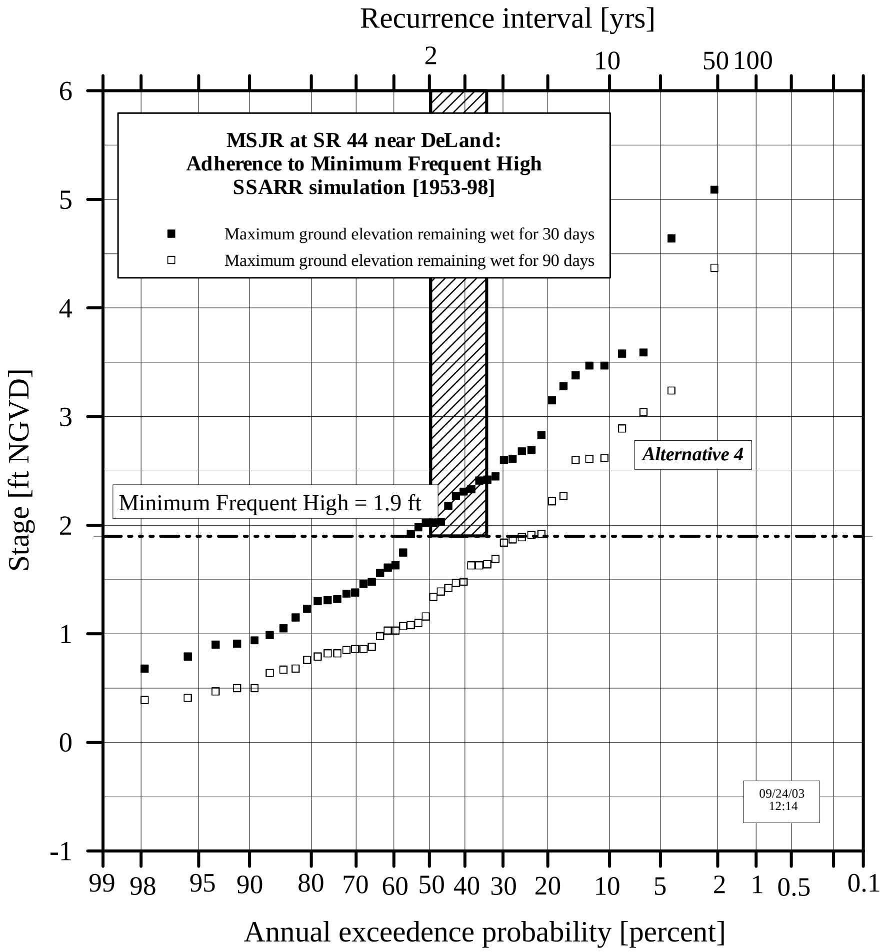


Figure 49. The Minimum Frequent High (MFH) level of the SJR at SR 44 near DeLand, as it relates to results of the Alternative 4 SSARR simulation. Model results illustrated here indicate that this minimum level is being met under the parameters set for Alternative 4 (see Table 19).

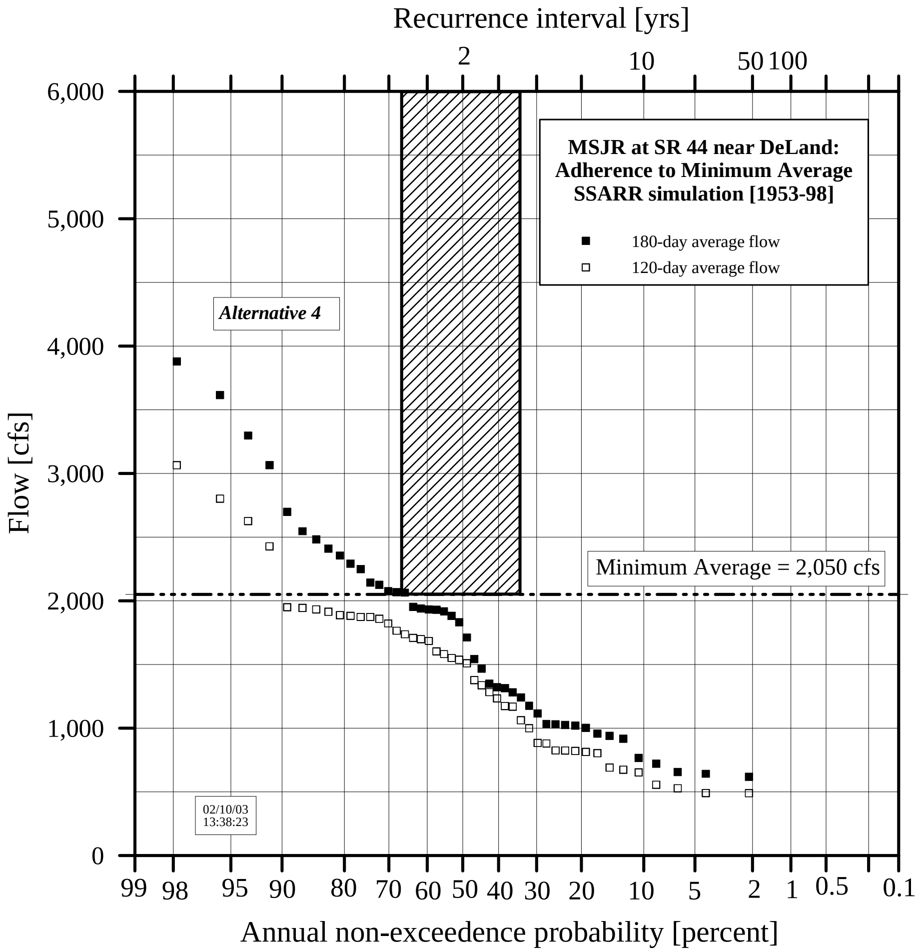


Figure 50. The Minimum Average (MA) flow of the SJR at SR 44 near DeLand, as it relates to results of the Alternative 4 SSARR simulation. Model results illustrated here indicate that a maximum withdrawal larger than 430 cfs would violate this minimum flow under the parameters set for Alternative 4.

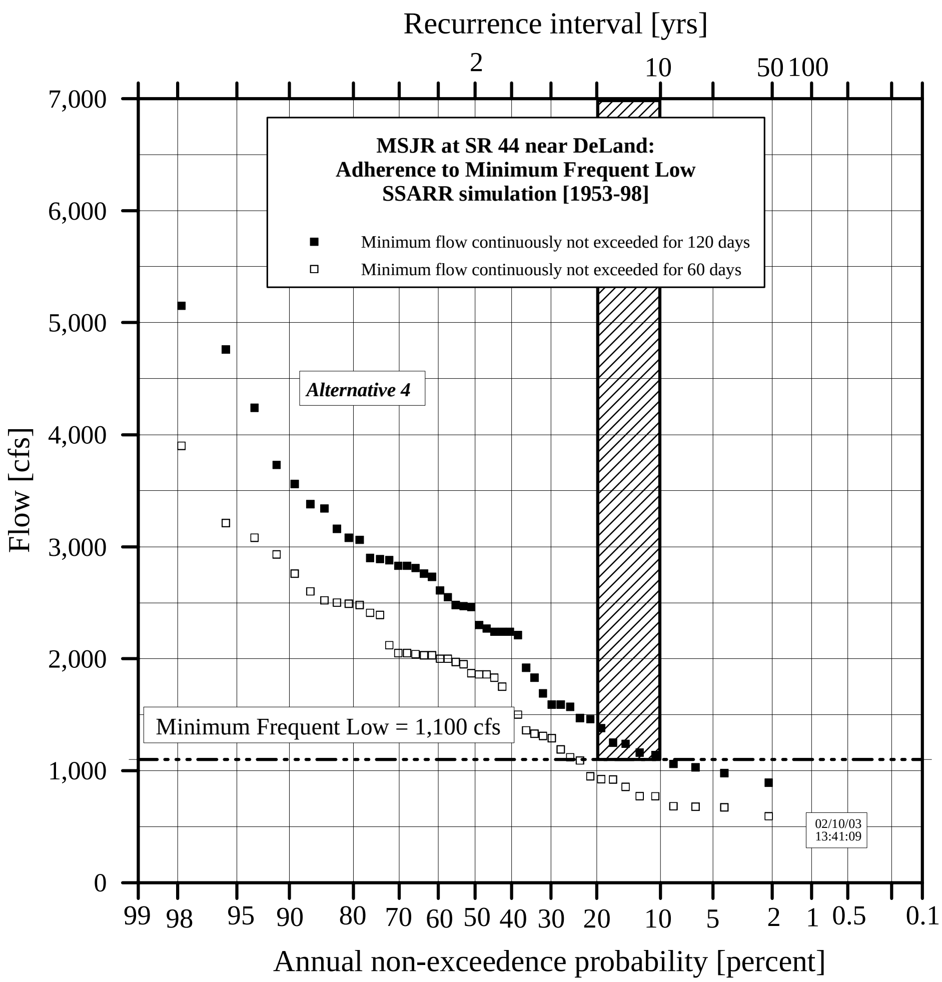


Figure 51. The Minimum Frequent Low (MFL) flow of the SJR at SR 44 near DeLand, as it relates to results of the Alternative 4 SSARR simulation. Model results illustrated here indicate that this minimum flow is being met under the parameters set for Alternative 4 (see Table 19).

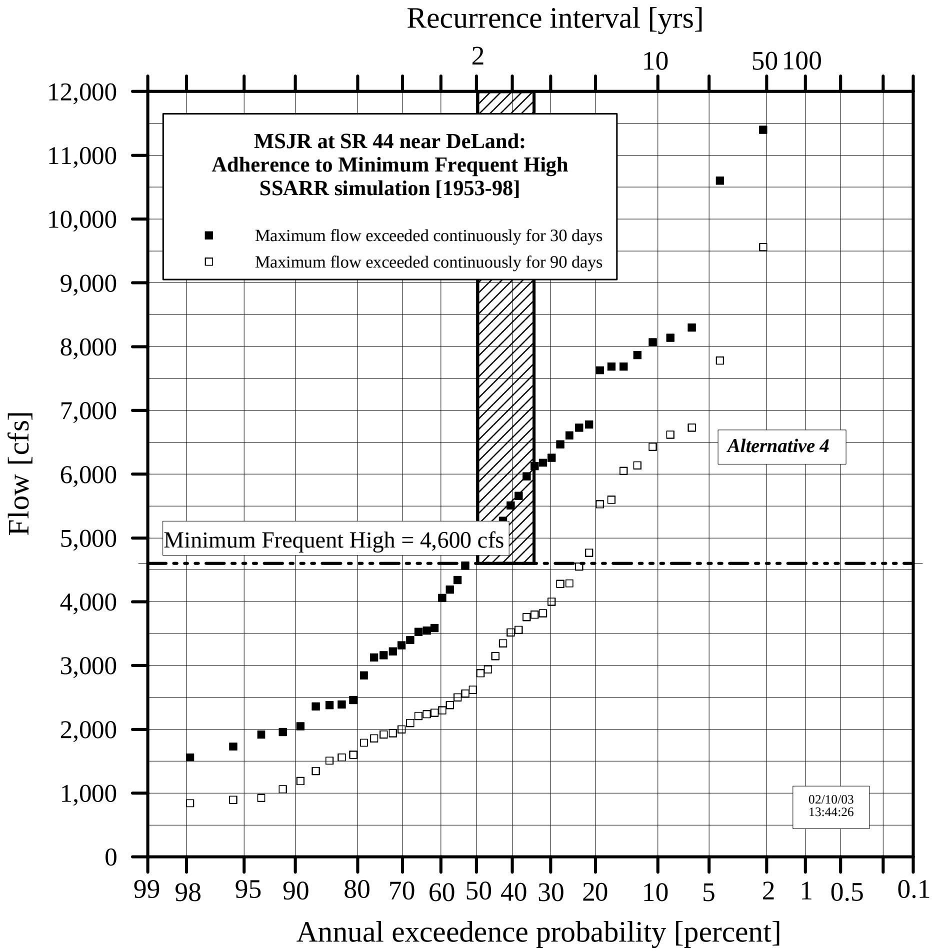


Figure 52. The Minimum Frequent High (MFH) flow of the SJR at SR 44 near DeLand, as it relates to results of the Alternative 4 SSARR simulation. Model results illustrated here indicate that this minimum flow is being met under the parameters set for Alternative 4 (see Table 19).

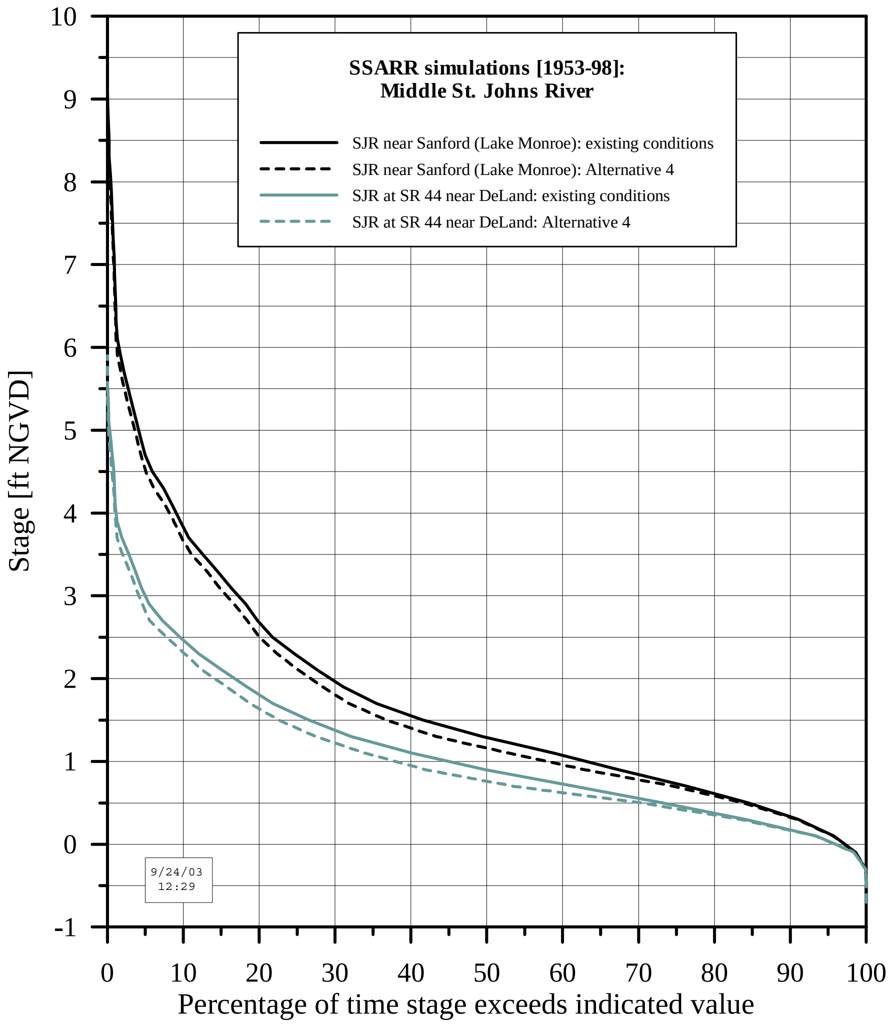


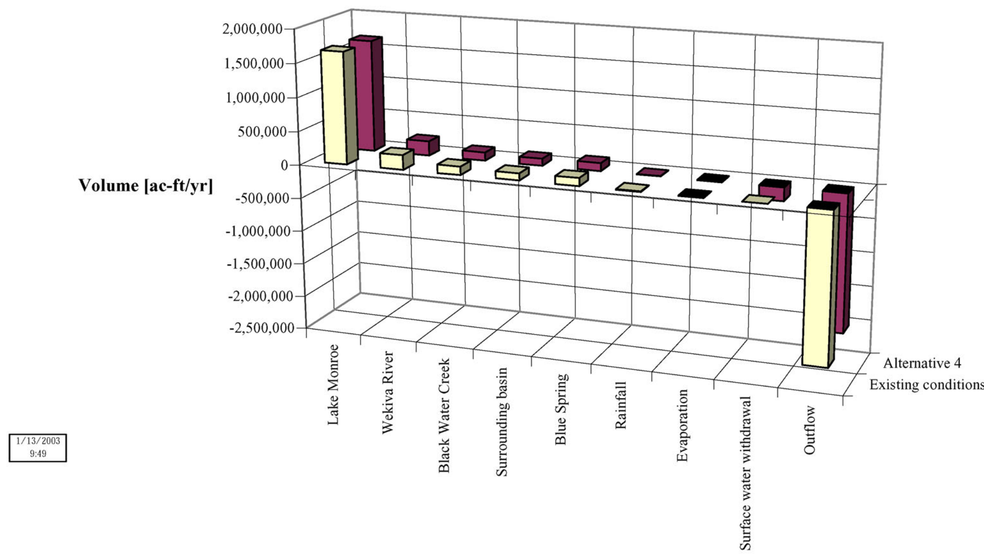
Figure 53. Stage duration curves for the MSJR SSARR simulations of existing hydrologic conditions and surface water withdrawal Alternative 4

drawn down due to the lower stages downstream. At high exceedence percentiles, the effects of withdrawals are nearly imperceptible at both locations. At a 50% chance of exceedence, stages are drawn down on the order of 0.1 ft. Because withdrawals are suspended when stages are low, stages at a 100% chance of exceedence do not change. At high stages, the effects of withdrawals are nearly imperceptible at both locations. At a stage of approximately 1 ft, percent chances of exceedence are reduced on the order of 5%. Because withdrawals are suspended when stages are low, the lowest stages have the same chance of exceedence (100%) with and without withdrawals.

The effect of any withdrawals can also be assessed in the context of a water budget. Based on the MSJR SSARR model, Alternative 4 would provide an average of about 196,000 acre-feet per year (Table 19, Figure 54) of water—175 mgd. This constitutes approximately 8.8% of the annual average flow for the MSJR at SR 44 near DeLand. Flows from Lake George to the lower St. Johns River can also be simulated with the SSARR model of the MSJR (Figure 55). On an average annual basis, the flow from Lake George would be reduced 7.4% under Alternative 4.

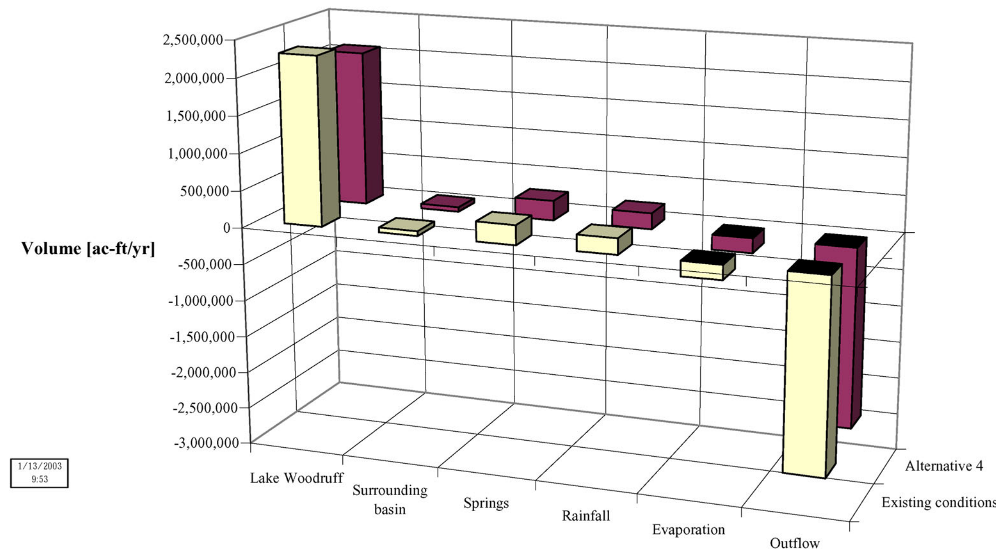
In the same manner described above, other withdrawal alternatives can be assessed with the MSJR SSARR model. In particular, increasing withdrawals at high flows to be stored for use during low-flow periods might be of interest.

It should be emphasized that the withdrawal scenarios included in this report are examples of application of the calibrated models and are not meant to provide a comprehensive analysis of the potential water supply yield of the SJR near DeLand. Additional analyses will be performed as part of a comprehensive investigation of the potential water supply yield of the MSJR, given the proposed MFLs.



	Lake Monroe	Wekiva River	Black Water Creek	Surrounding basin	Blue Spring	Rainfall	Evaporation	Surface water withdrawal	Outflow
Existing conditions	1,664,000	216,000	124,000	106,000	118,000	7,000	-6,000	0	-2,229,000
Alternative 4	1,664,000	216,000	124,000	106,000	118,000	6,000	-6,000	-196,000	-2,032,000

Figure 54. Comparison of water budgets from SSARR simulation of the SJR at SR 44 near DeLand, under existing conditions and surface water withdrawal Alternative 4



	Lake Woodruff	Surrounding basin	Springs	Rainfall	Evaporation	Outflow
Existing conditions	2,286,000	65,000	266,000	217,000	-200,000	-2,633,000
Alternative 4	2,091,000	65,000	266,000	216,000	-200,000	-2,438,000

Figure 55. Comparison of water budgets from SSARR simulation of Lake George under existing conditions and surface water withdrawal Alternative 4

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APPENDIX A—THE USE OF HYDROLOGIC STATISTICS IN MINIMUM FLOWS AND LEVELS

The objective of minimum flows and levels (MFLs) is to establish limits to allowable hydrologic change in a water body, in order to prevent significant harm to the water resources or ecology of an area. Hydrologic changes within a water body may result from an increase in the consumptive use of water or the alteration of basin characteristics, such as down-cutting outlet channels or constructing outflow structures.

MFLs define a series of minimum high and low water levels and / or flows of differing frequencies and durations required to protect and maintain aquatic and wetland resources. MFLs take into account the ability of wetlands and aquatic communities to adjust to changes in hydrologic conditions. MFLs allow for an acceptable level of change to occur relative to existing hydrologic conditions, without incurring significant ecological harm to the aquatic system.

Before MFLs can be applied, the minimum hydrologic regime must be defined or characterized statistically. Resource management decisions can then be made predicated on maintaining at least these minimum hydrologic conditions as defined by the appropriate statistics.

One way to understand how changes within a watershed alter a hydrologic regime and, therefore, how the aquatic and wetland resources might be affected, is by simulating the system with a hydrologic model. Significant harm can be avoided by regulating hydrologic changes based on the comparison of statistics of the system with and without changes.

The middle St. Johns River (MSJR) MFLs determination is based on a philosophy of maintaining duration and return period of selected stages and / or flows. Thus, stages on the MSJR can fall below a minimum level, but if they do so too often and / or for too long, then that minimum level would no longer be met.

Statistical analysis of model output provides a framework upon which to summarize the hydrologic characteristics of a water body. St. Johns River Water Management District (SJRWMD) MFLs primarily require two types of statistical analysis: duration analysis and frequency analysis.

DURATION ANALYSIS

Certain hydrologic characteristics are of interest in the context of MFLs. Among these hydrologic characteristics are

- The expected maximum stage (or flow)
- The expected minimum stage (or flow)
- The expected total range of water surface fluctuation
- The expected percentage of time a given ground elevation will be wet
- The expected percentage of time a given ground elevation will be dry
- The expected percentage of time a given flow will be exceeded
- The expected percentage of time a given flow will not be exceeded

Stage characteristics of a water body are summarized in what is referred to as a stage duration curve (Figure A1). A stage duration curve is simply the graphical representation of the cumulative distribution function that represents the expected percentage of time that a given stage will be exceeded or not exceeded. A stage duration curve can also be thought of in terms of representing the cumulative distribution function of the expected percentage of time that a given ground elevation will be above the water level (dry) or below it (wet).

Flow characteristics of a river or a stream are summarized in what is referred to as a flow duration curve (Figure A2). A flow duration curve is simply the graphical representation of the cumulative distribution function that represents the expected percentage of time that a given flow will be exceeded or not exceeded.

FREQUENCY ANALYSIS

As discussed previously, aquatic resources are sustained by a certain hydrologic regime. Depending on the resource in question, a selected ground elevation might need to

- Remain wet for a certain period of time with a certain frequency
- Remain dry for a certain period of time with a certain frequency
- Be under a given minimum depth of water for a certain period of time with a certain frequency

A stage duration curve tells us nothing about these statistics; instead, a statistical process referred to as frequency analysis is used. Frequency analysis estimates how often, on average, a given event will occur. If annual series data are used to generate the statistics, frequency analysis estimates the probability of a given hydrologic event happening in any given year.

A simple example illustrates some of the concepts basic to frequency analysis. A frequently used statistic with respect to water level is the yearly peak stage of a water body. If a gage has been monitored for 10 years, then there will be 10 yearly 1-day peaks $S_1, S_2, \cdots, S_{10}$. Once sorted and ranked, these events can be written as $\hat{S}_1, \hat{S}_2, \cdots, \hat{S}_{10}$, with $\hat{S}_1$ being the highest peak. Based on this limited sample, the estimated probability of the peak being greater than or equal to $\hat{S}_1$ in any year would be

$$P(S \geq \hat{S}_1) = \frac{1}{n} = \frac{1}{10} = 0.1, \qquad \textbf{(A1)}$$

where n = the total number of events,

the probability of the peak stage in any year being greater than $\hat{S}_2$ would be

$$P(S \geq \hat{S}_2) = \frac{2}{10} = 0.2, \qquad \textbf{(A2)}$$

and so on. The probability of the stage equaling or exceeding $\hat{S}_{10}$ would be

$$P(S \geq \hat{S}_{10}) = \frac{10}{10} = 1.0 \qquad \textbf{(A3)}$$

Since this system of analysis precludes any peak stage from being lower than $\hat{S}_{10}$, the usual convention is to divide the stage continuum into 11 parts: nine between each of the ten peaks, one above the highest peak, and one below the lowest peak (n – 1 + 2 = n + 1 = 11). This suggests what is known as the Weibull plotting position formula:

$$P(S \geq \hat{S}_m) = \frac{m}{n+1} \qquad \textbf{(A4)}$$

where

$P(S \geq \hat{S}_m) =$ probability of S equaling or exceeding $\hat{S}_m$

$m =$ rank of the event

Thus, in the example, the probability of the peak in any year equaling or exceeding $\hat{S}_1$ would be

$$P(S \geq \hat{S}_1) = \frac{1}{n+1} = \frac{1}{11} = 0.0909 , \tag{A5}$$

the probability of the peak stage in any year being greater than $\hat{S}_{10}$ would be

$$P(S \geq \hat{S}_{10}) = \frac{10}{11} = 0.9091 , \tag{A6}$$

and so on. The probability that the stage in any year is smaller than $\hat{S}_{10}$ would be

$$P(S < \hat{S}_{10}) = 1 - P(S \geq \hat{S}_{10}) = 1 - \frac{10}{11} = 1 - 0.9091 = 0.0909 \tag{A7}$$

The return period (in years) of an event, T, is defined as

$$T = \frac{1}{P} \tag{A8}$$

so the return period for $\hat{S}_1$ would be

$$T(\hat{S}_1) = \frac{1}{P(S \geq \hat{S}_1)} = \frac{1}{\frac{1}{11}} = 11 \tag{A9}$$

Said another way, $\hat{S}_1$ would be expected to be equaled or exceeded, on average, once every 11 years.

As the size of the sample increases, the probability of $\hat{S}_1$ being exceeded decreases. Thus, with n = 20,

$$P(S \geq \hat{S}_1) = \frac{1}{n+1} = \frac{1}{21} = 0.048 \tag{A10}$$

and

$$T(\hat{S}_1) = \frac{1}{P(S \geq \hat{S}_1)} = 21 \tag{A11}$$

The stage or flow data for a water body can be summarized using the Weibull plotting position formula and a frequency plot. For example, Figure A3 shows a flood frequency plot generated from annual peak flow data collected at the U.S. Geological Survey (USGS) gage on the Wekiva River.

Minimum events are treated in much the same way as maximum events, except with minimums, the events are ranked from smallest to largest. Thus $\hat{S}_1$ is the smallest or lowest event in a sampling. The minimum stage or flow data for a water body can be summarized using the Weibull plotting position formula and a frequency plot. For example, Figure A4 shows a drought frequency plot generated from a hydrologic simulation of the MSJR.

One of the purposes of performing this process of sorting, ranking, and plotting events is to estimate probabilities and return periods for events larger than $\hat{S}_1$, events smaller than $\hat{S}_n$, or any event between sample points. There are two methods of obtaining these probabilities and return periods. The first method is to use standard statistical methods to mathematically calculate these probabilities and return periods (Figure A5). This method is beyond the scope of this appendix; the reader is referred to a standard hydrology text (Bedient and Huber 1988, Ponce 1989, Linsley et al. 1982) or the standard flood frequency analysis text, Bulletin 17B (USGS 1982).

With the second method, interpolated or extrapolated frequencies and return periods can also be obtained by the graphical method. Once the period-of-record or period-of-simulation events have been sorted and ranked, they are plotted on probability paper. Probabilities and return periods for events outside of the sampled events can be estimated by drawing a line through the points on the graph to obtain an estimated best fit (Figure A6).

Frequency analysis is also used to characterize hydrologic events of durations longer than 1 day. Frequency analysis encompasses four types of events: maximum average stages or flows, minimum average stages or flows, maximum stages or flows continuously exceeded, and minimum stages or flows continuously not exceeded.

Maximum average stages or flows. In this case, an event is defined as the maximum value for a mean stage or flow over a given number of days. For example, if the maximum yearly values for a 30-day average are of interest, the daily value hydrograph is analyzed by using a moving 30-day average. Therefore, a 30-day event would have 336 (365 – 30 + 1 = 336) different values for a 30-day average. These 336 values are searched, and the highest is saved. After performing this analysis for each year of the period of record or period of simulation, the events are sorted and ranked. The analytical process is then the same as for the 1-day peaks.

Minimum average stages or flows. In this case, an event is defined as the minimum value for a mean stage or flow over a given number of days. For example, if the minimum yearly values for a 30-day average are of interest, the daily value hydrograph is analyzed by using a moving 30-day average. Therefore, a 30-day event would have 336 (365 – 30 + 1 = 336) different values for a 30-day average. These 336 values are searched, and the lowest is saved. After performing this analysis for each year of the period of record or period of simulation, the events are sorted and ranked. The process is then the same as for the 1-day low stages.

Maximum stage or flow continuously exceeded. In this case, an event is defined as the stage or flow that is exceeded continuously for a set number of days. For example, if the maximum yearly ground elevation that continuously remains under water for 60 days is of interest, the stage hydrograph of each year is analyzed by taking successive 60-day periods and determining the stage that is continuously exceeded for that period. This is repeated for 306 (365 – 60 + 1 = 306) periods of 60 days. The maximum stage in those 306 values is saved. Once that operation is performed for all years of record or of simulation, the results are sorted and ranked as for the 1-day peaks.

Minimum stage or flow continuously not exceeded. In this case, an event is defined as the stage or flow that is not exceeded continuously for a set number of days. For example, if the minimum yearly ground elevation that continuously remains dry for 60 days is of interest, the stage hydrograph of each year is analyzed by taking successive 60-day periods and determining the stage that is continuously not exceeded for that period. This is repeated for 306 (365 – 60 + 1 = 306) periods of 60 days. The minimum stage in those 306 values is saved. Once that operation is performed for all years of record or of simulation, the results are sorted and ranked as for the 1-day low stages.

In frequency analysis, it is important to identify the most extreme events occurring in any given series of years. Because high surface water levels (stages) in Florida generally occur in summer and early fall, maximum value analysis is based on a year that runs from June 1 to May 31. Conversely, because low stages tend to occur in late spring, the year for minimum events runs from October 1 to September 30.

HYDROLOGIC STATISTICS AND THEIR RELATIONSHIPS TO MSJR MFLS

This section will illustrate the process used to relate long-term hydrologic statistics generated by the MSJR SSARR model to the establishment of MFLs. SJRWMD has determined three MFLs on the MSJR at SR 44 near DeLand (Mace 2003): the Minimum Frequent High (MFH), the Minimum Average (MA), and the Minimum Frequent Low (MFL). The MFH level for this location will be used to illustrate how long-term hydrologic statistics of a river system relate to MFLs.

Each of the three MFLs is tied to characteristic stage durations and return frequencies. For example, the ground elevation represented by the MFH level is expected to remain wet continuously for a period of not less than 30 days and not greater than 90 days. This event is expected to occur, on average, once every two to three years.

The standard stage frequency analysis described previously in this appendix was performed on the results of the MSJR SSARR model simulations. In particular, simulated maximum river stages near DeLand continuously exceeded (ground elevations remaining wet) for 30 and for 90 days were determined, sorted, ranked, and plotted (Figure A7). The ground elevation of the MFH level can be superimposed on the plot (Figure A8) to demonstrate how the level is related to the pertinent hydrologic statistics. Finally, a box bounded by (1) the MFH level on the bottom, (2) a vertical line corresponding to a frequency of occurrence of once in every 2 years on the left, and (3) a vertical line corresponding to a frequency of occurrence of once in every 3 years on the right, is superimposed on the plot (Figure A9).

As surface water withdrawals are imposed on the MSJR system, the pertinent 30- and 90-day events will tend to occur less often. Therefore, the plotted events of Figure A9 will tend to shift to the right as conditions become drier. Given large enough withdrawals, eventually all 30-day values will shift outside of the box. In this case, based on modeling results, the MFH level will no longer be met. Similar analyses are done for the MA level and the MFL level.

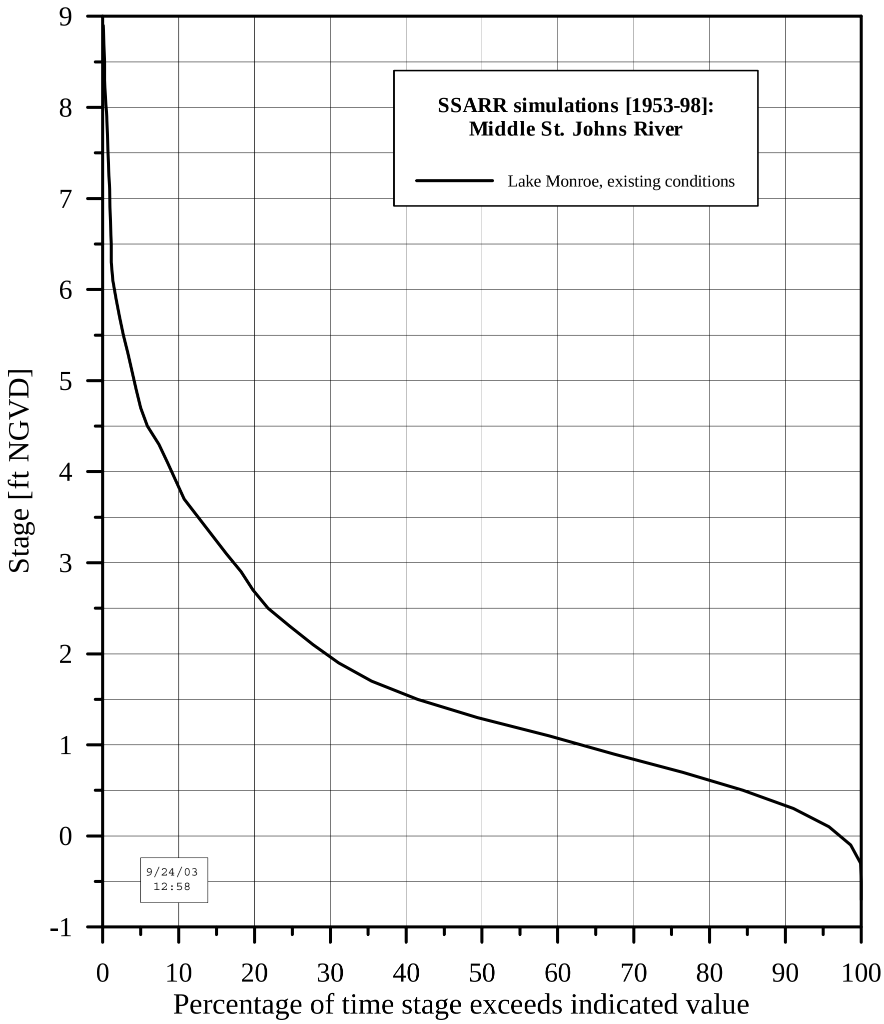


Figure A1. Simulated stage duration curve at Lake Monroe

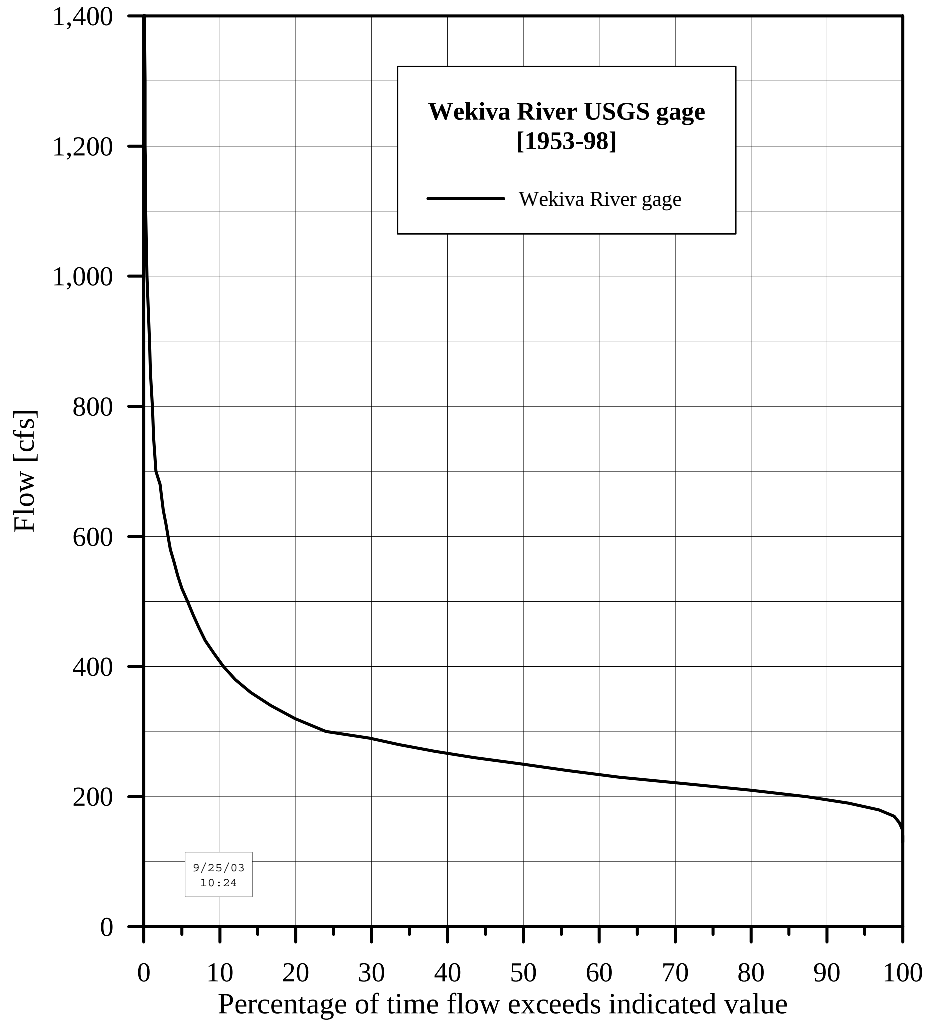


Figure A2. Flow duration curve for the Wekiva River at the USGS gage near Sanford, Florida

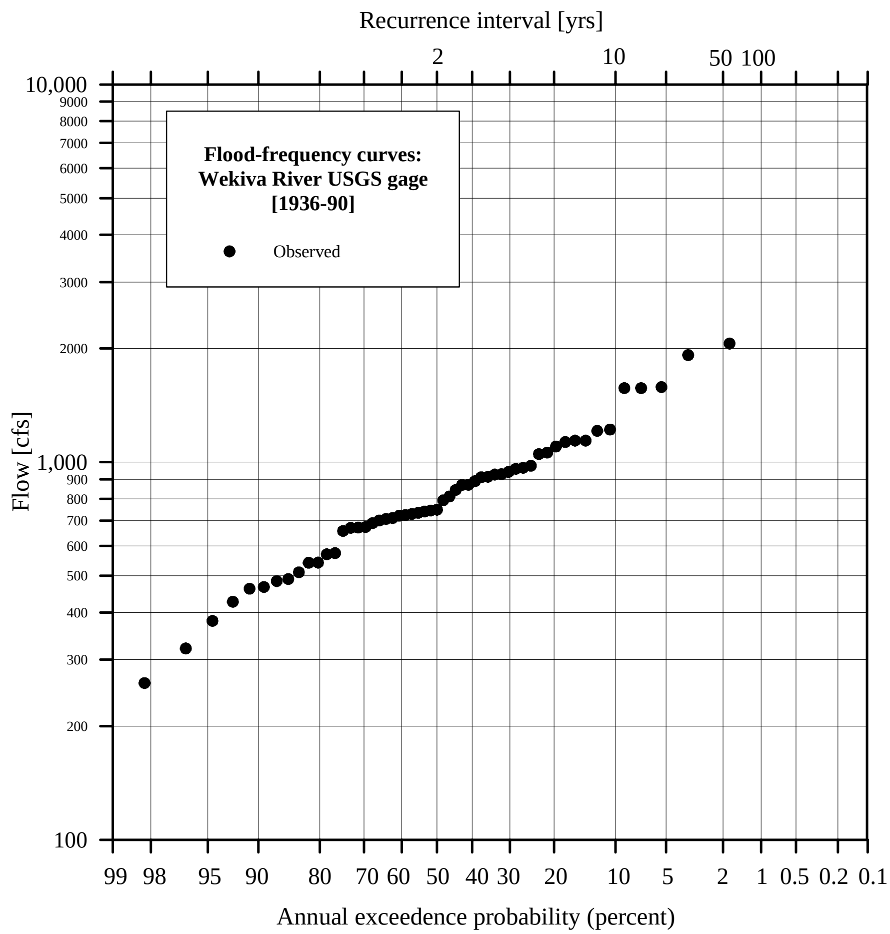


Figure A3. Flood frequencies for the Wekiva River at the USGS gage near Sanford, Florida. The 1-day peak flows have been sorted, ranked, and plotted according to the Weibull plotting position formula.

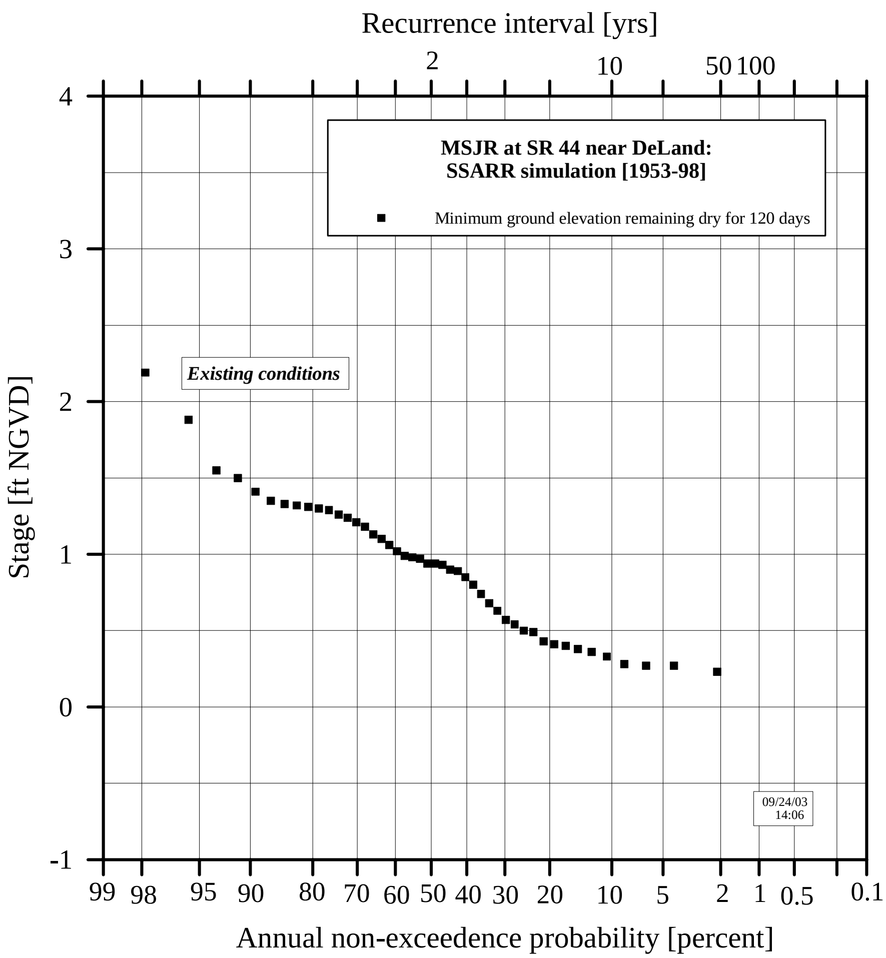


Figure A4. Drought frequencies computed using daily stages simulated by the MSJR SSARR model at SR 44 near DeLand. The minimum stages continuously not exceeded for 120 days have been sorted, ranked, and plotted according to the Weibull plotting position formula.

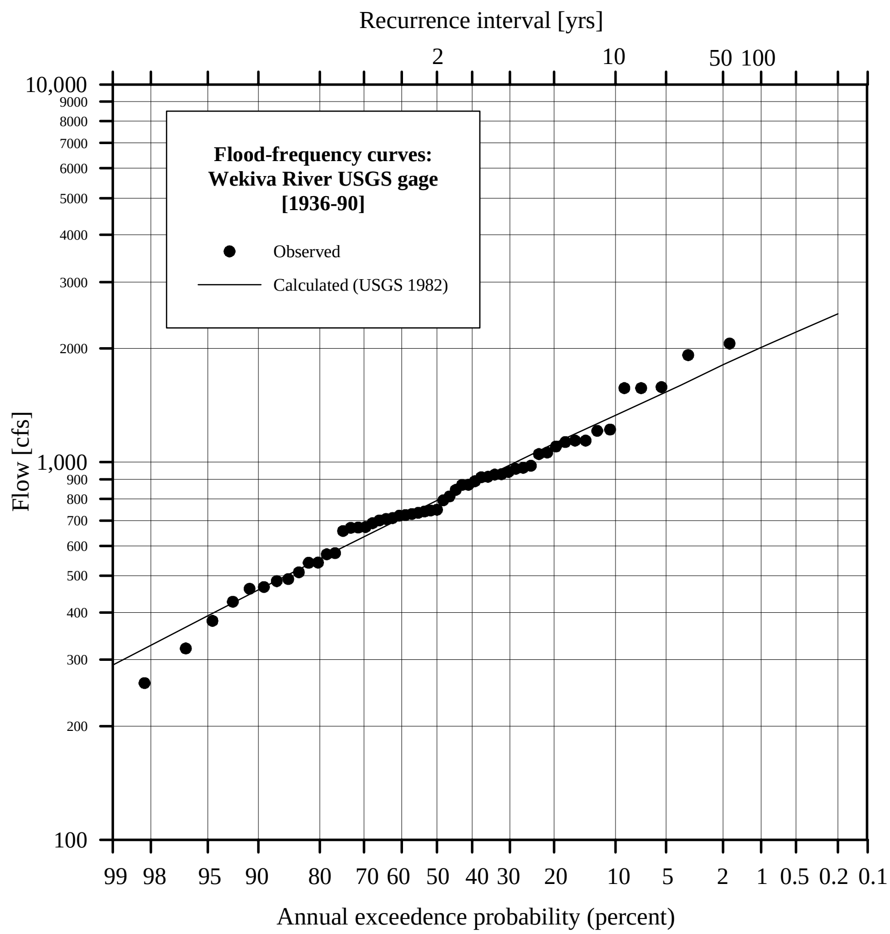


Figure A5. Flood frequencies for the Wekiva River at the USGS gage near Sanford, Florida, fitted by standard mathematical procedure

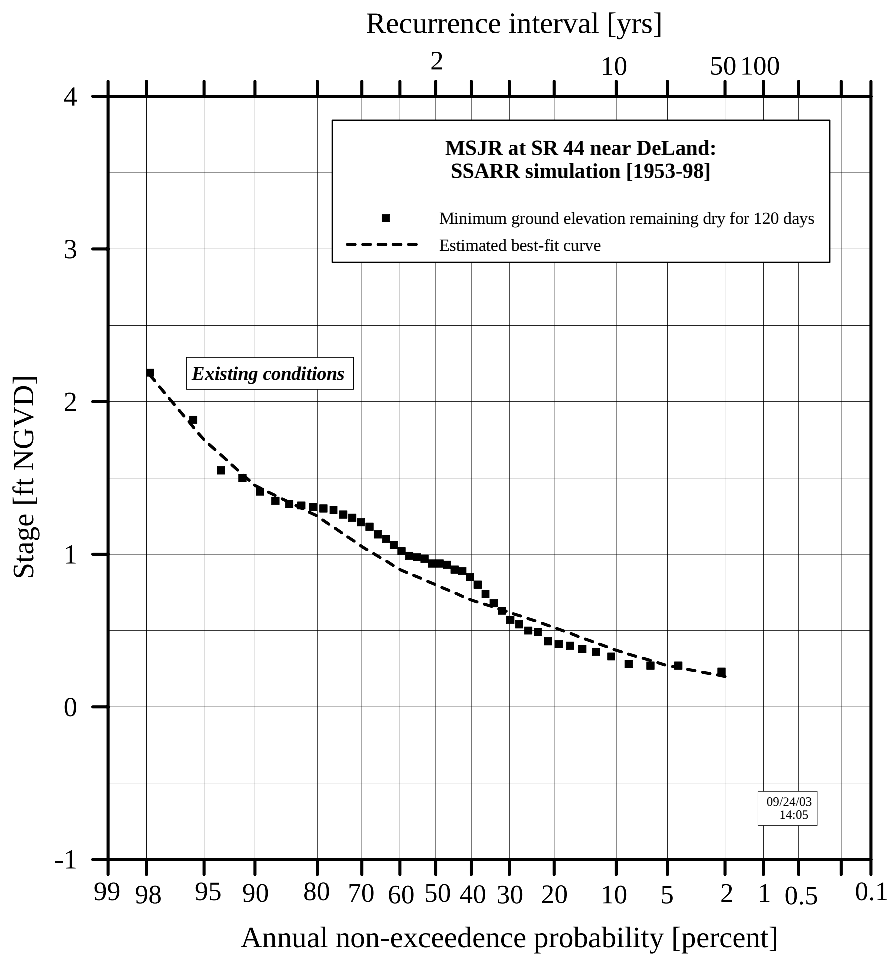


Figure A6. Drought frequencies computed using daily stages simulated by the MSJR SSARR model at SR 44 near DeLand, fitted by the graphical method

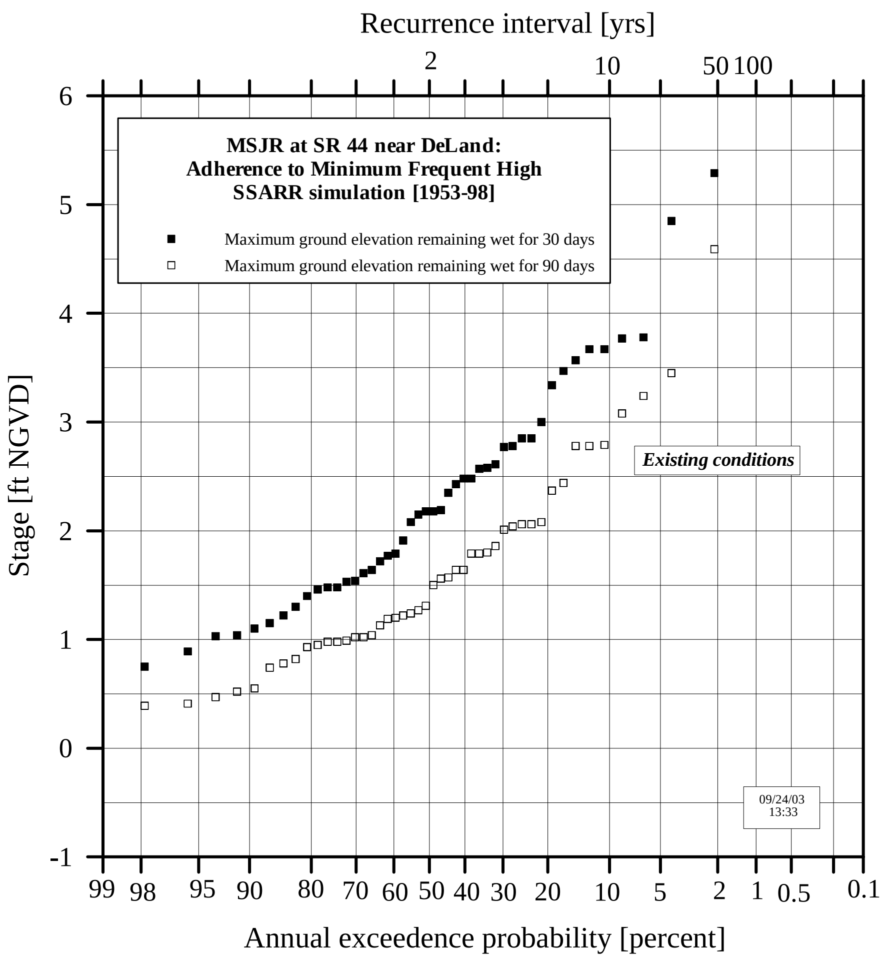


Figure A7. Flood frequencies computed using daily stages simulated by the MSJR SSARR model at SR 44 near DeLand for elevations continuously wet for 30 and 90 days

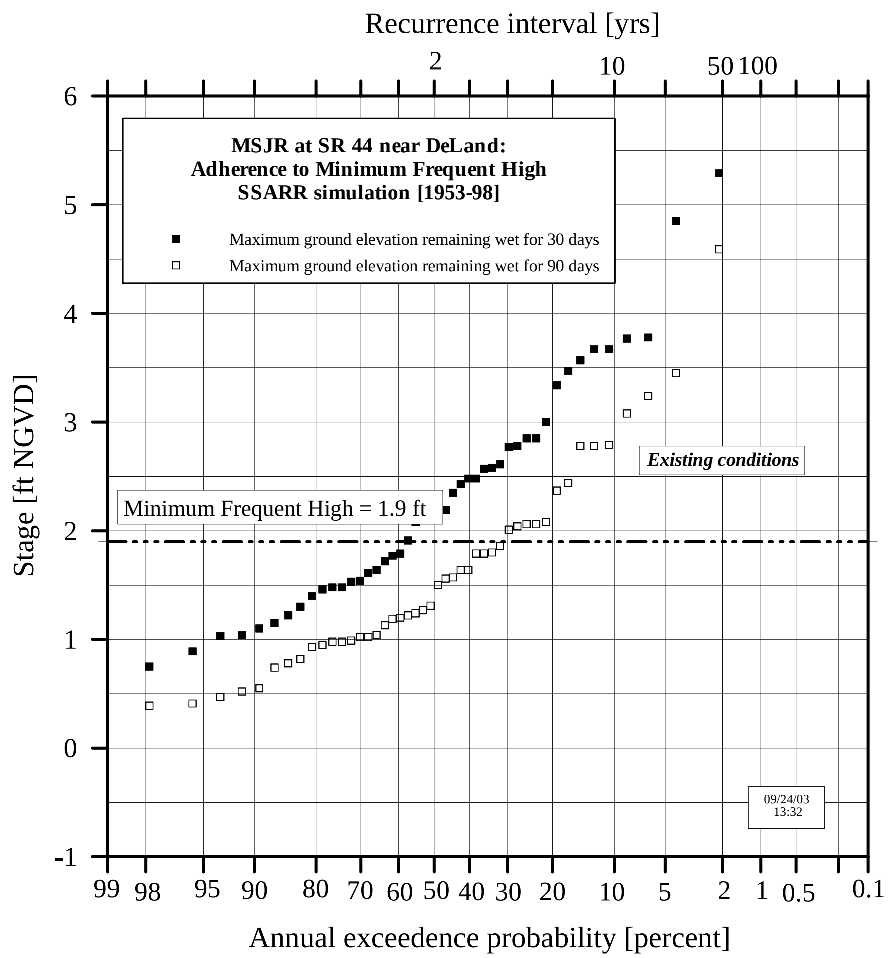


Figure A8. Flood frequencies computed using daily stages simulated by the MSJR SSARR model at SR 44 near DeLand for elevations continuously wet for 30 and 90 days with the Minimum Frequent High of 1.9 feet superimposed

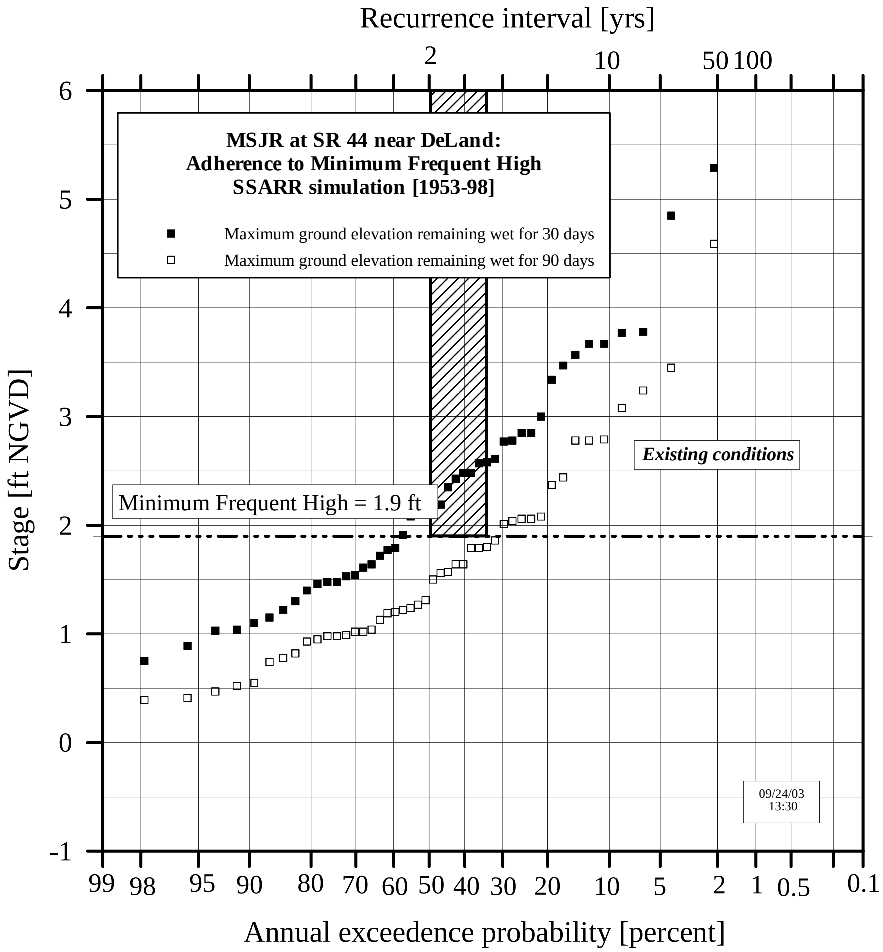


Figure A9. Flood frequencies computed using daily stages simulated by the MSJR SSARR model at SR 44 near DeLand for elevations continuously wet for 30 and 90 days with a superimposed box bounded by (1) the Minimum Frequent High, (2) a vertical line corresponding to a return period of 2 years, and (3) a vertical line corresponding to a return period of 3 years

APPENDIX B—MONTHLY RESIDUAL ANALYSES

One measure of model performance is provided by residual analysis. A residual represents the difference between a measured value and its corresponding modeled value. The magnitude and distribution of residuals can provide us with indications of the performance of a hydrologic model.

Residuals can be separated by month. Because hydrology is, to a large extent, dependent on the season of the year, results of monthly residual analyses can provide additional insights into model performance.

This appendix presents results of monthly residual analyses for SSARR simulation of stages for the St. Johns River at State Road 44 near DeLand and at Sanford (Lake Monroe). Also included are monthly residual analyses for SSARR simulation of flows for the St. Johns River at State Road 44 near DeLand.

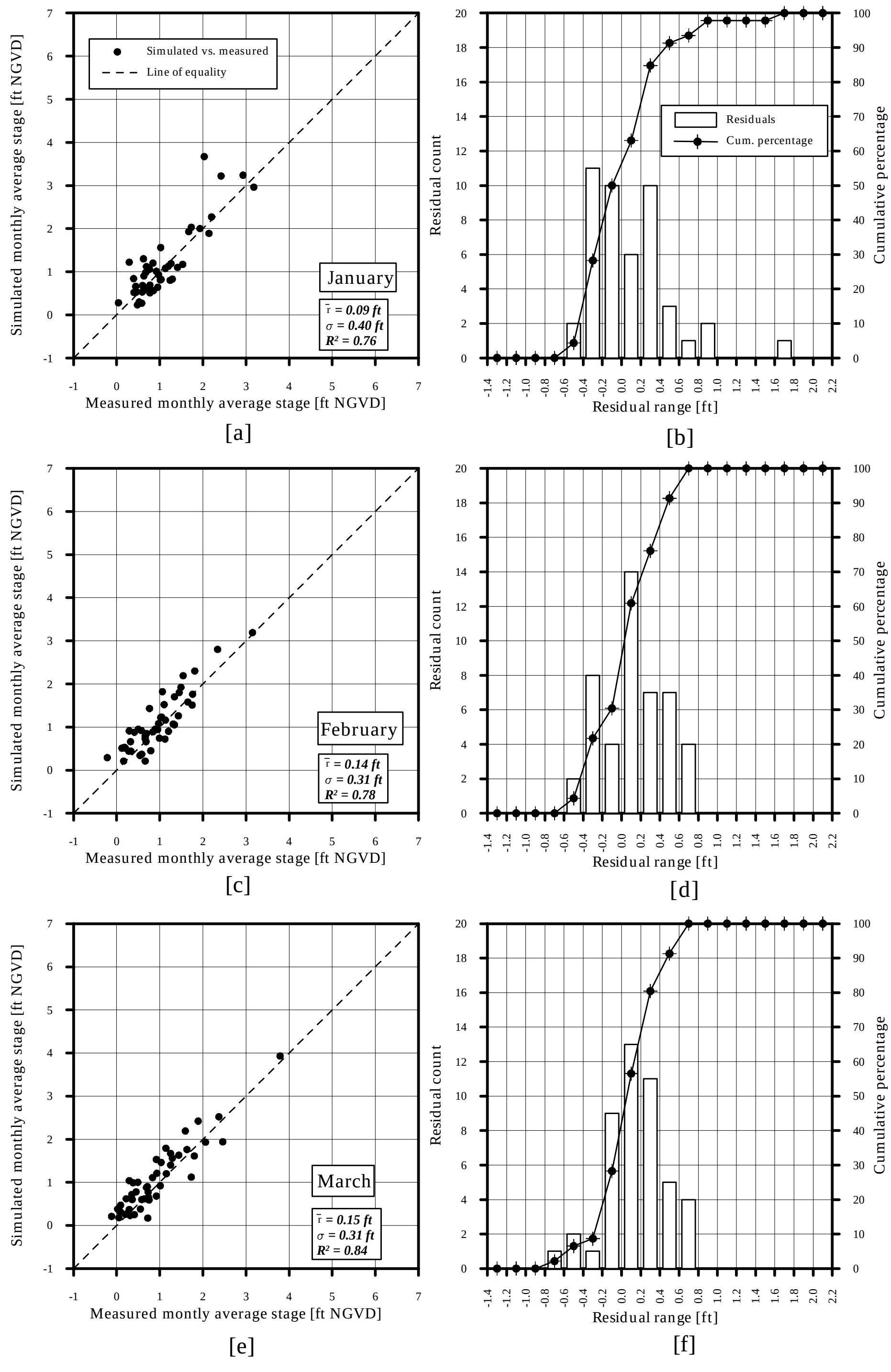


Figure B1. Monthly residual analysis of monthly average stages for the SJR at SR 44 near DeLand. Graphs correspond to January (a and b), February (c and d), and March (e and f).

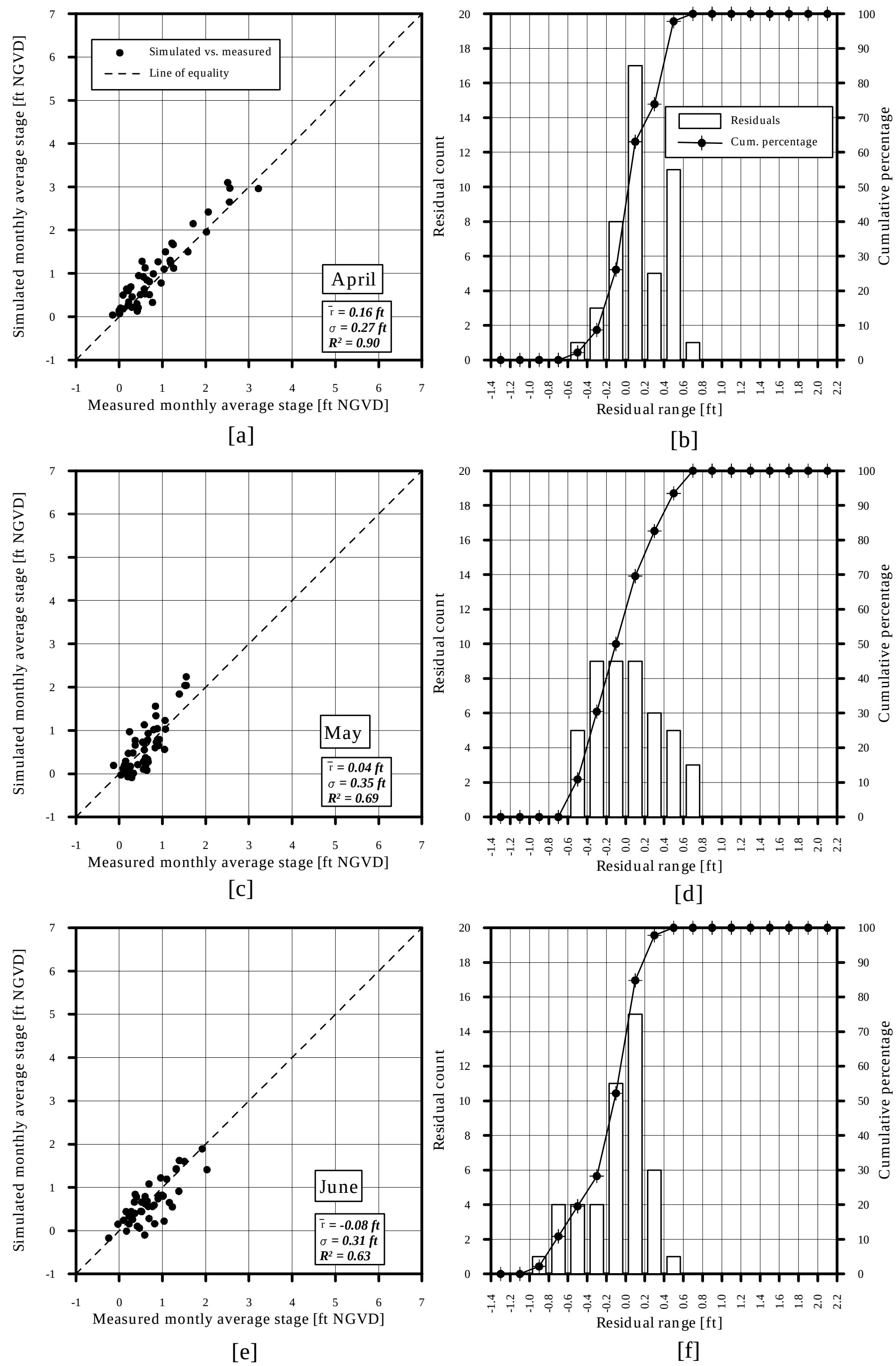


Figure B2. Monthly residual analysis of monthly average stages for the SJR at SR 44 near DeLand. Graphs correspond to April (a and b), May (c and d), and June (e and f).

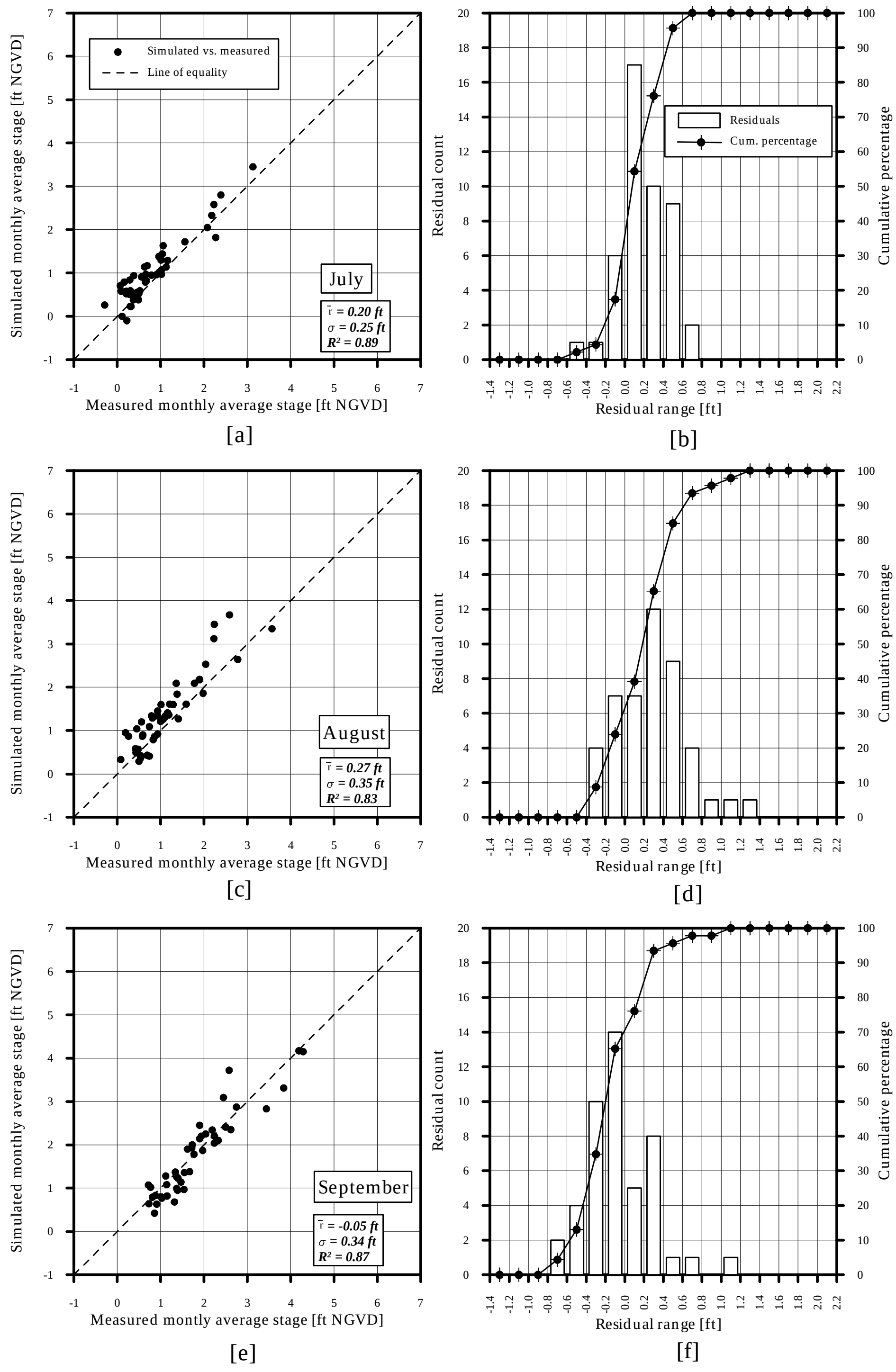


Figure B3. Monthly residual analysis of monthly average stages for the SJR at SR 44 near DeLand. Graphs correspond to July (a and b), August (c and d), and September (e and f).

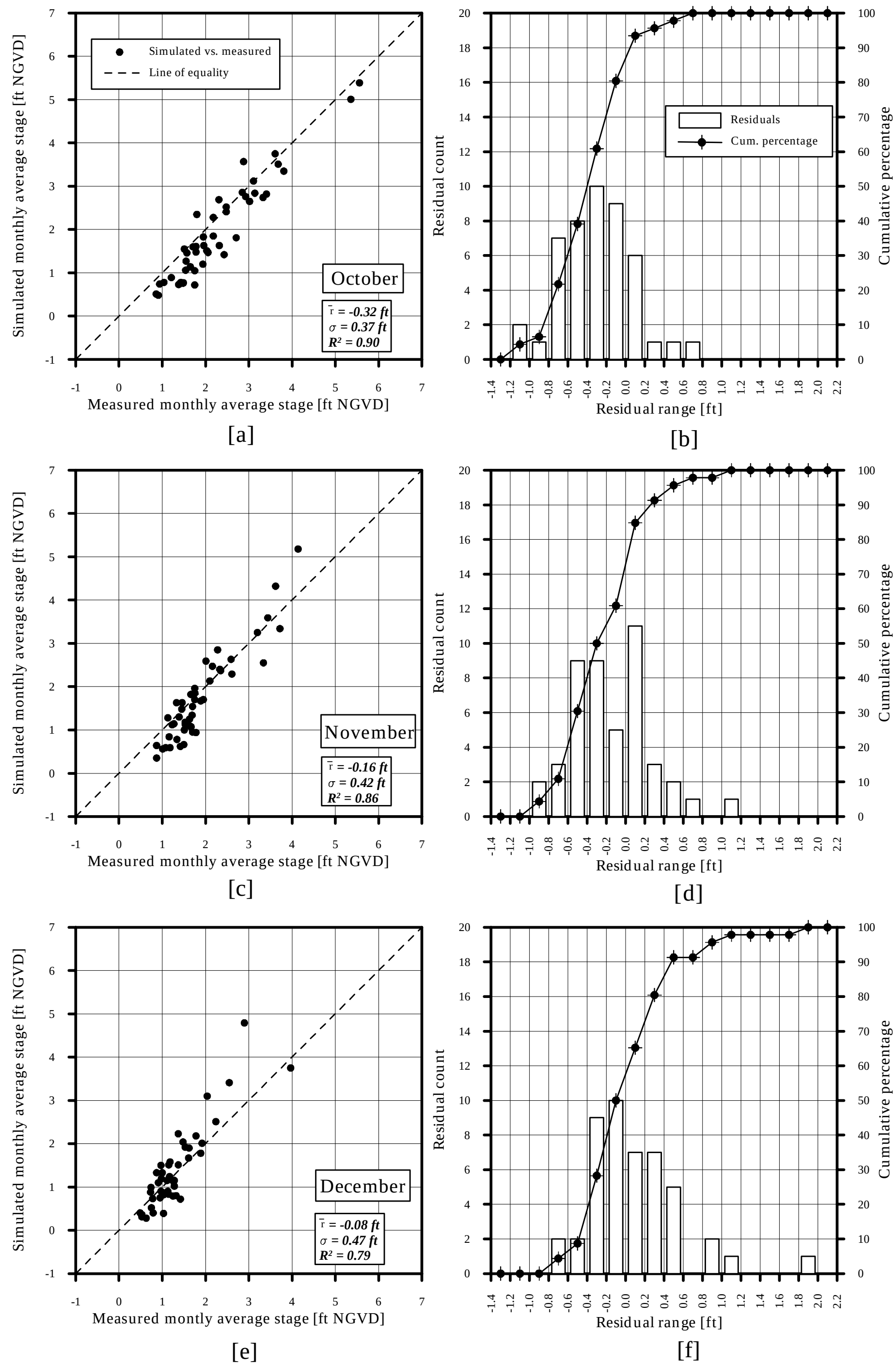


Figure B4. Monthly residual analysis of monthly average stages for the SJR at SR 44 near DeLand. Graphs correspond to October (a and b), November (c and d), and December (e and f).

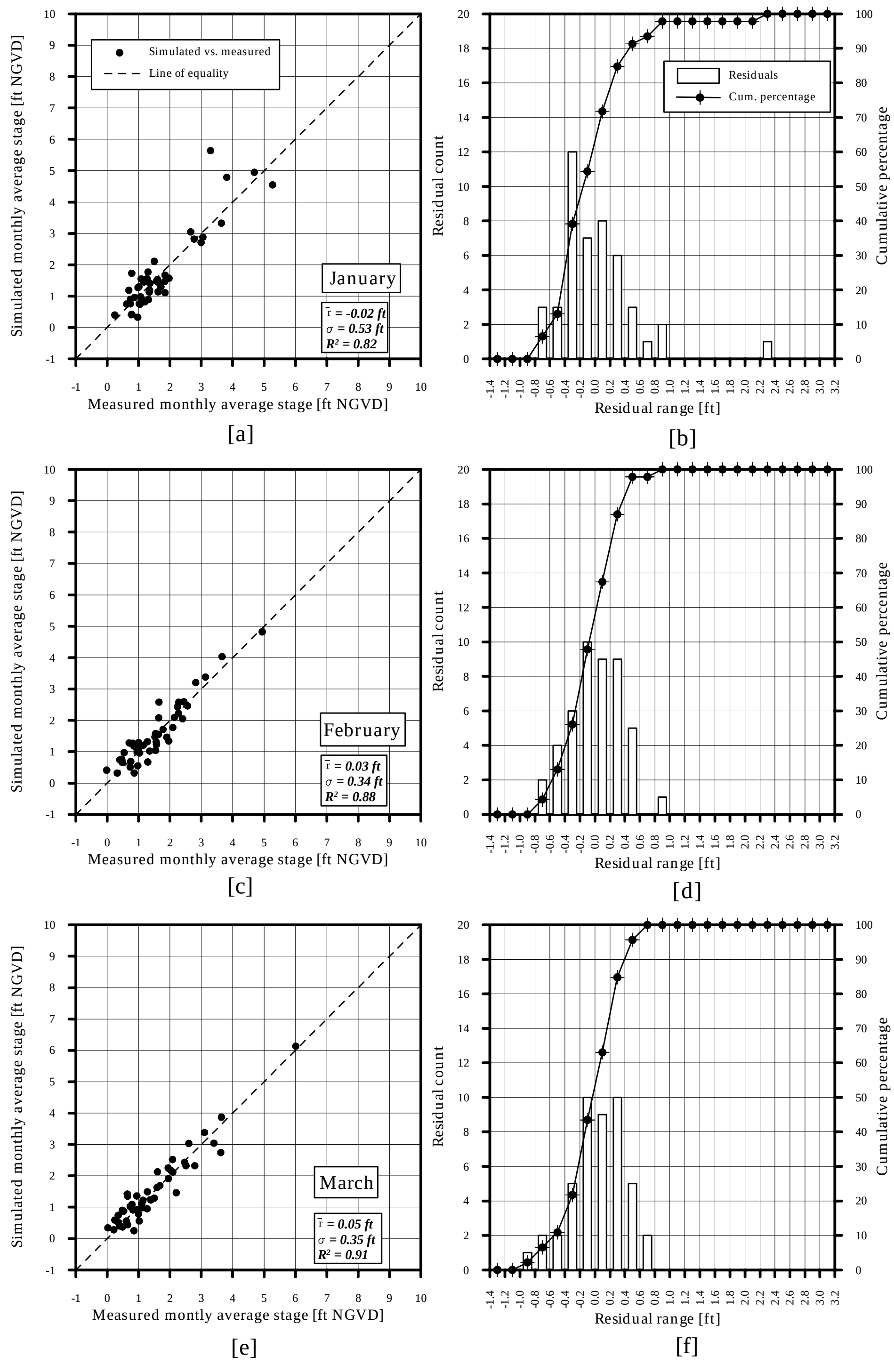


Figure B5. Monthly residual analysis of monthly average stages for the SJR near Sanford (Lake Monroe). Graphs correspond to January (a and b), February (c and d), and March (e and f).

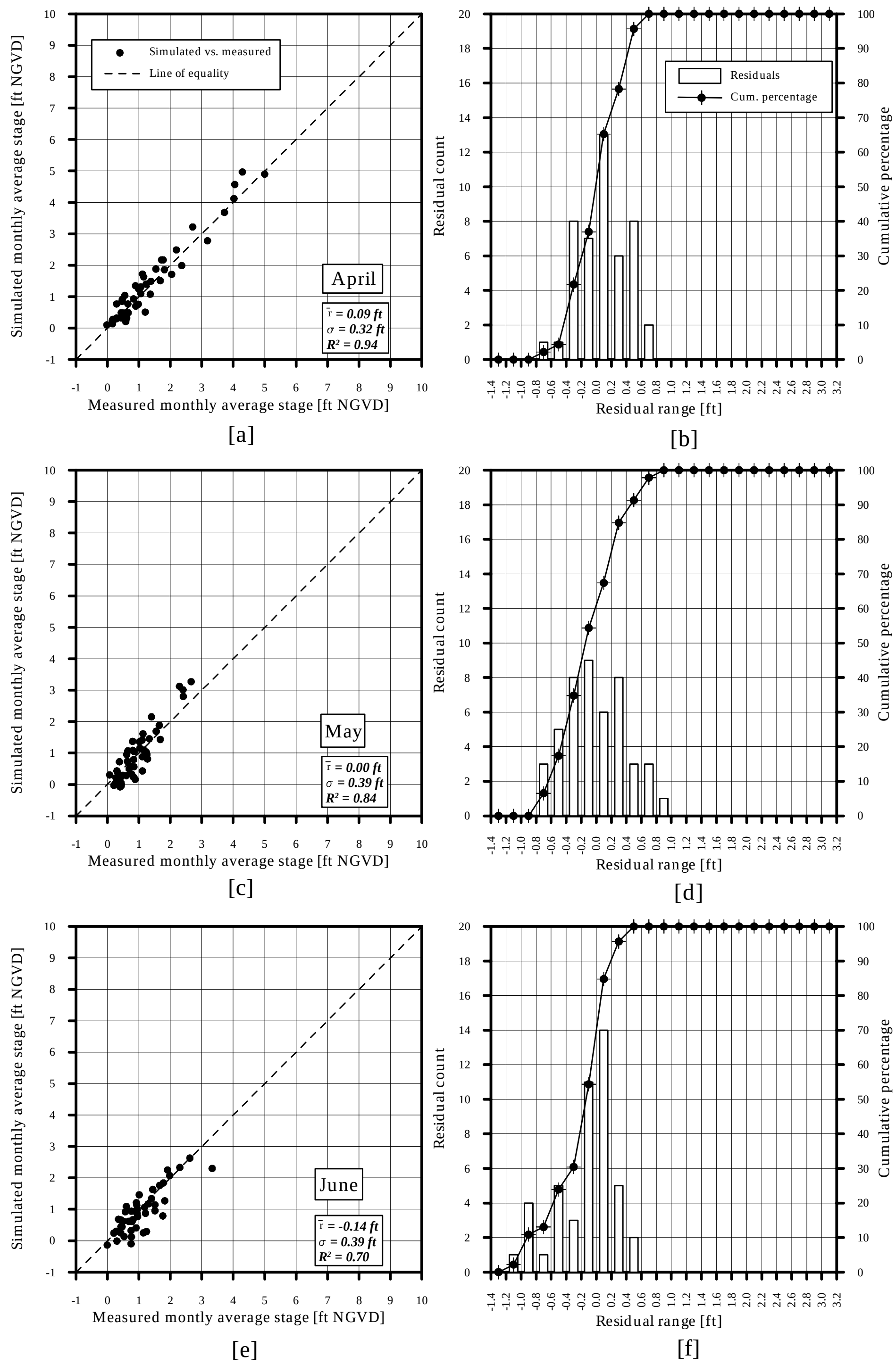


Figure B6. Monthly residual analysis of monthly average stages for the SJR near Sanford (Lake Monroe). Graphs correspond to April (a and b), May (c and d), and June (e and f).

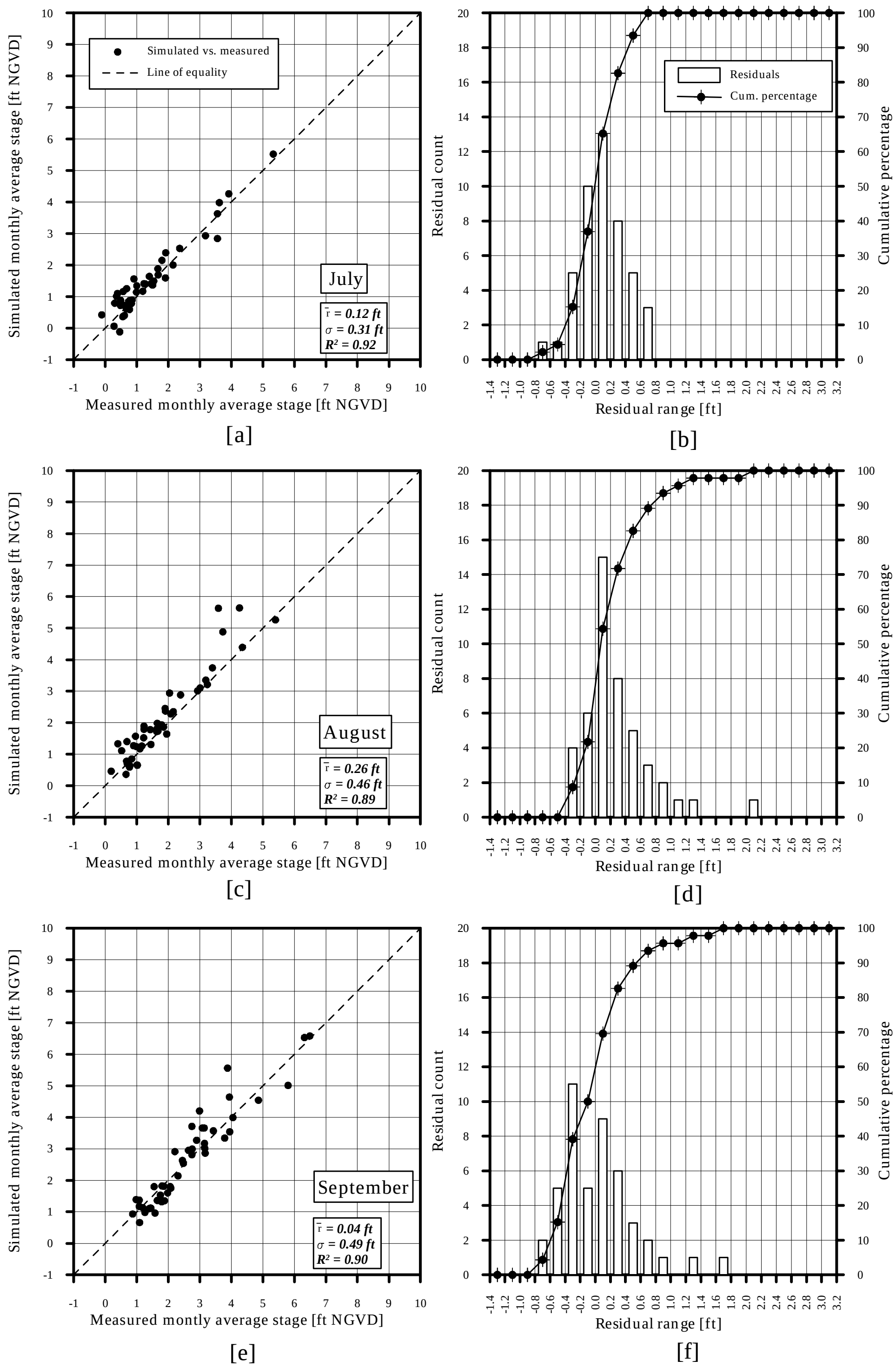


Figure B7. Monthly residual analysis of monthly average stages for the SJR near Sanford (Lake Monroe). Graphs correspond to July (a and b), August (c and d), and September (e and f).

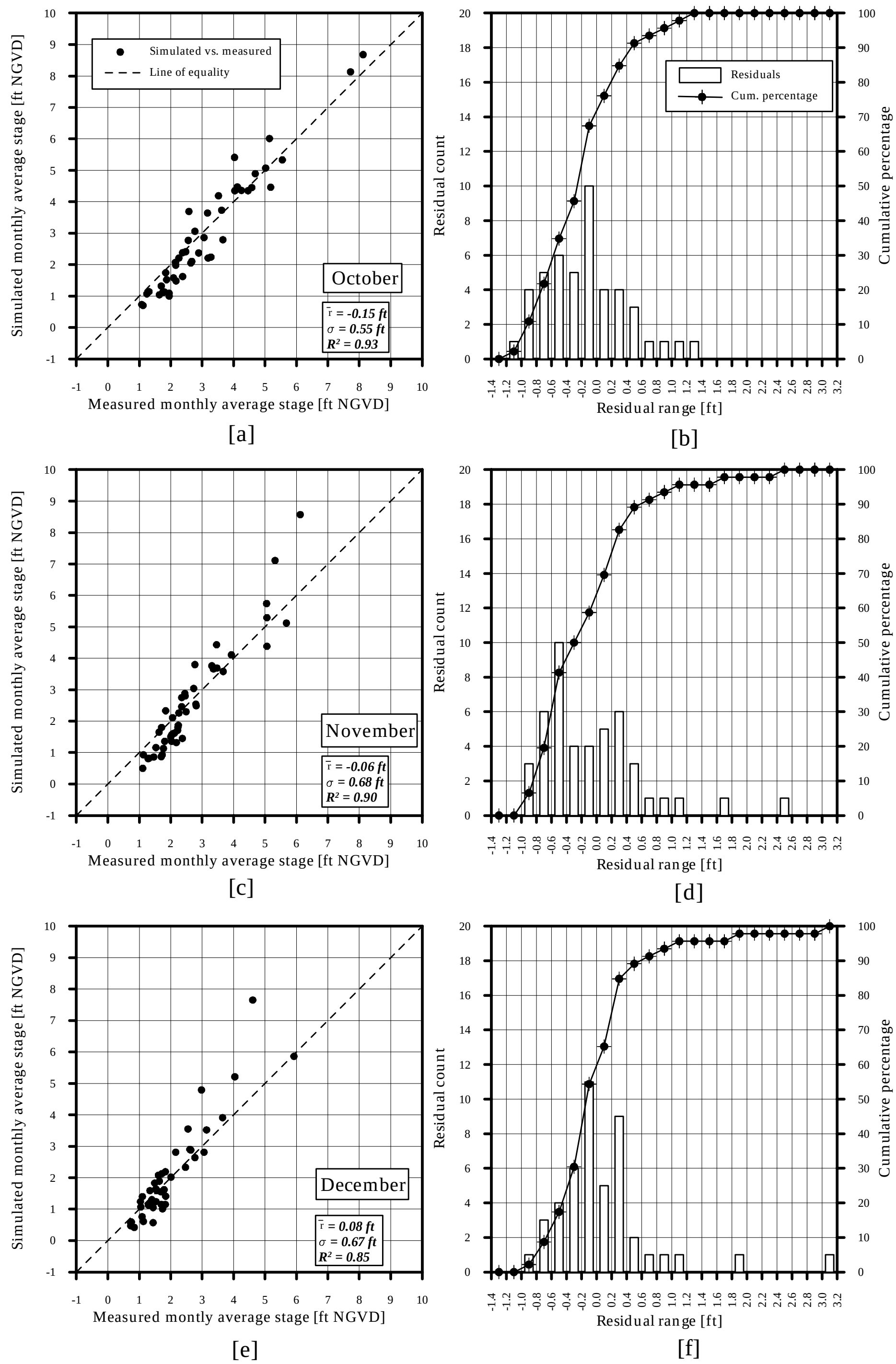


Figure B8. Monthly residual analysis of monthly average stages for the SJR near Sanford (Lake Monroe). Graphs correspond to October (a and b), November (c and d), and December (e and f).

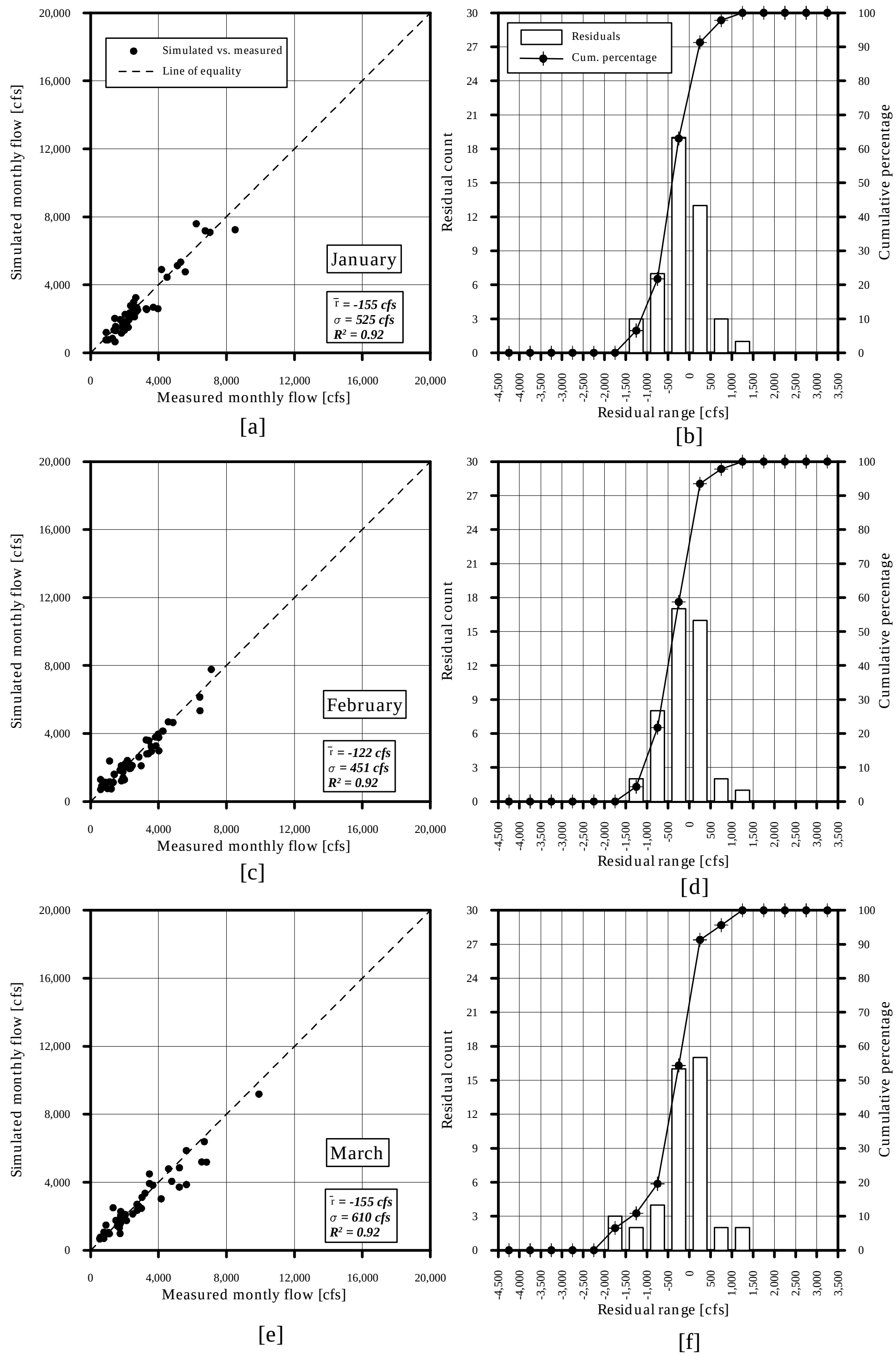


Figure B9. Monthly residual analysis of monthly average flows for the SJR at SR 44 near DeLand. Graphs correspond to January (a and b), February (c and d), and March (e and f).

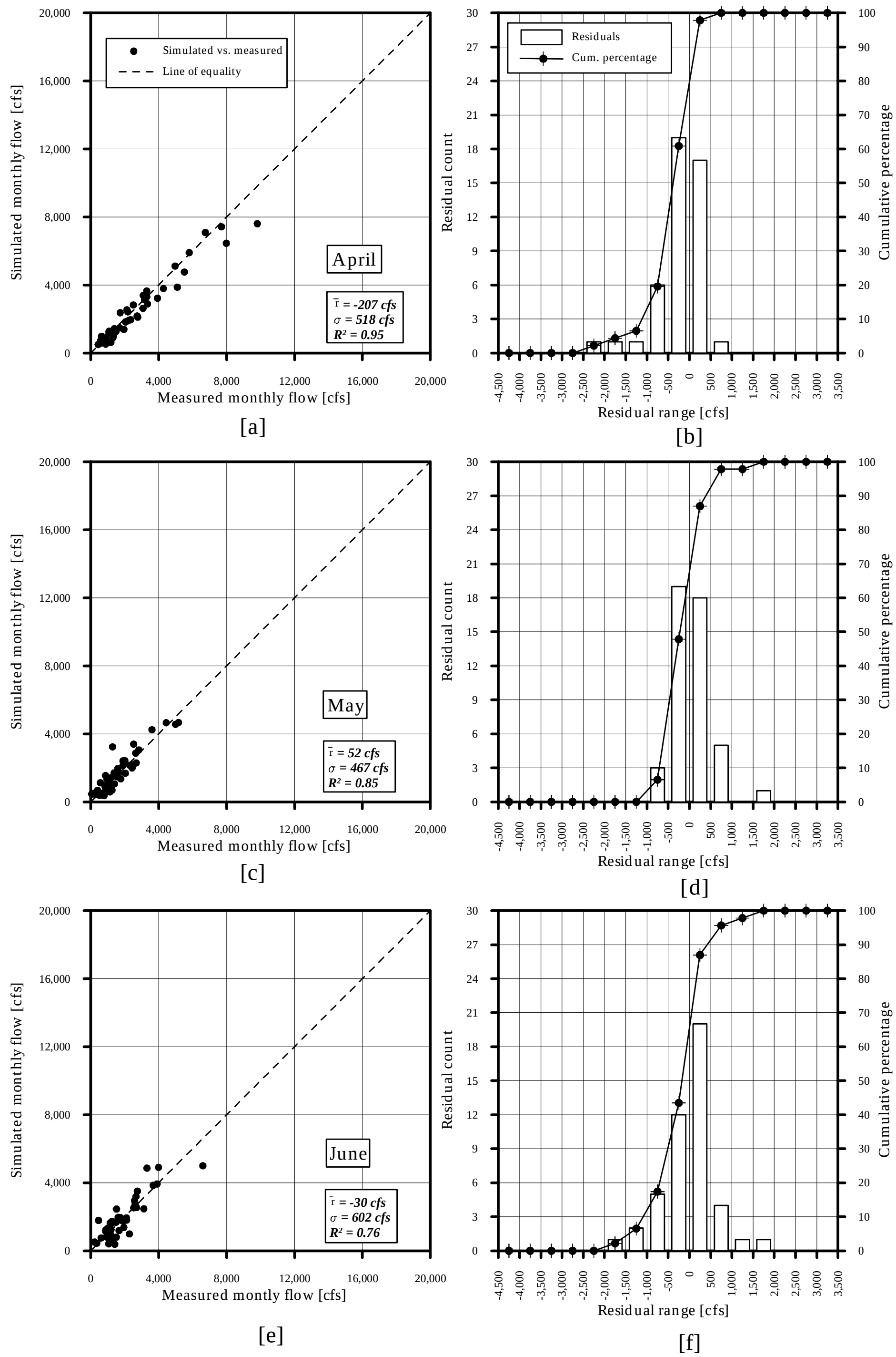


Figure B10. Monthly residual analysis of monthly average flows for the SJR at SR 44 near DeLand. Graphs correspond to April (a and b), May (c and d), and June (e and f).

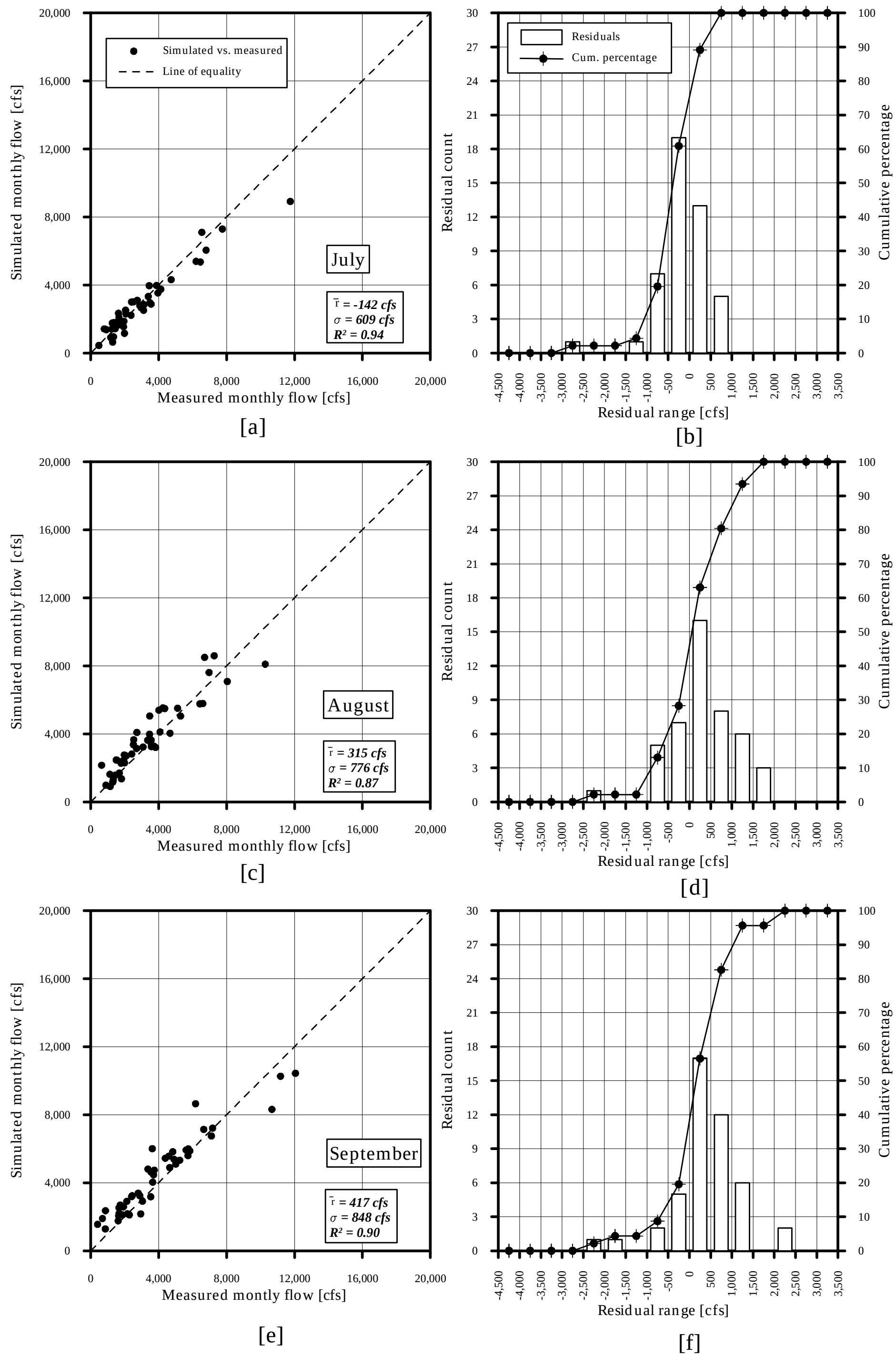


Figure B11. Monthly residual analysis of monthly average flows for the SJR at SR 44 near DeLand. Graphs correspond to July (a and b), August (c and d), and September (e and f).

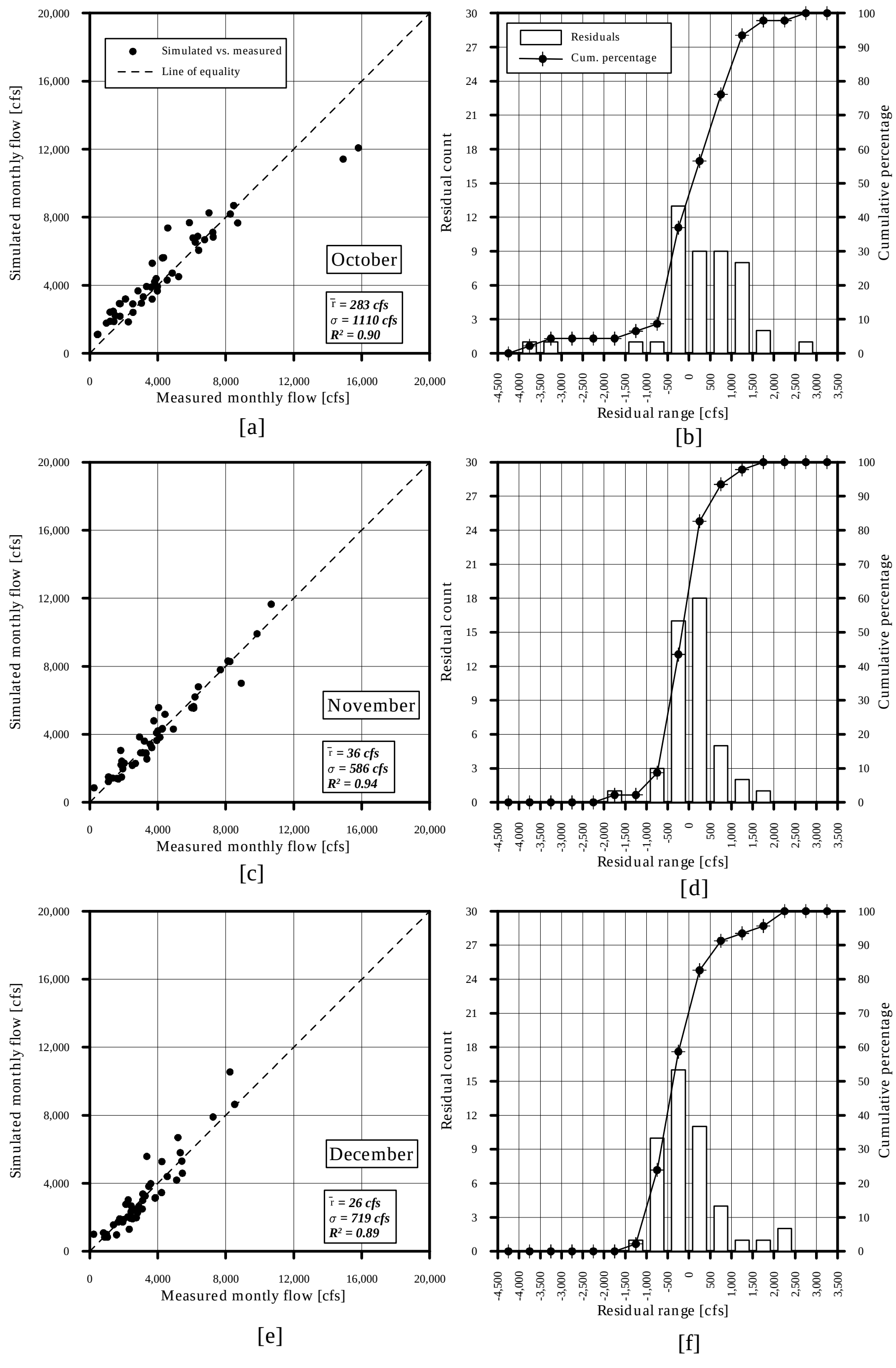
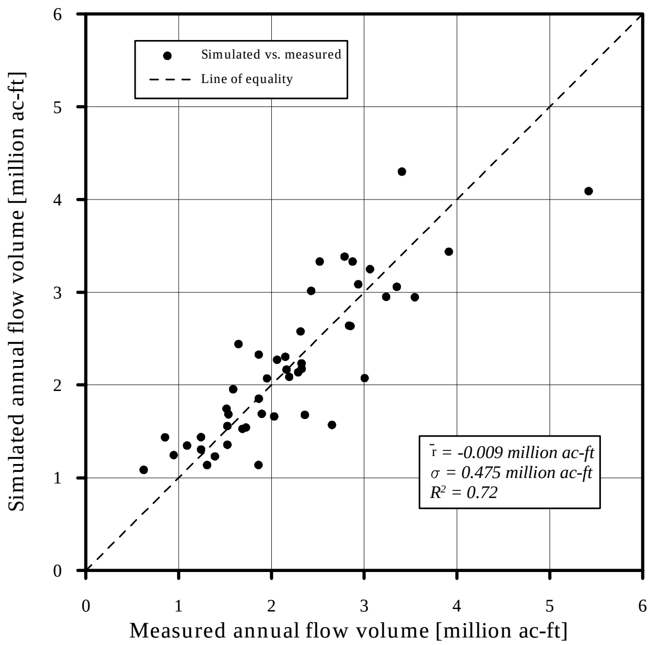


Figure B12. Monthly residual analysis of monthly average flows for the SJR at SR 44 near DeLand. Graphs correspond to October (a and b), November (c and d), and December (e and f).

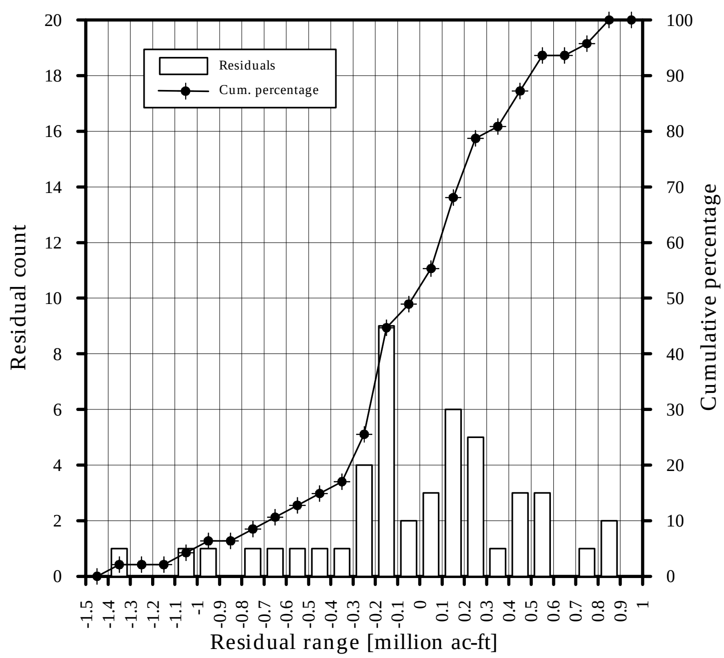
APPENDIX C—RESIDUAL ANALYSES OF ANNUAL FLOW VOLUMES

One measure of model performance is provided by residual analysis. A residual represents the difference between a measured value and its corresponding modeled value. The magnitude and distribution of residuals can provide us with indications of the performance of a hydrologic model.

This appendix presents results of residual analyses of annual flow volumes for calibration of the MSJR SSARR model.

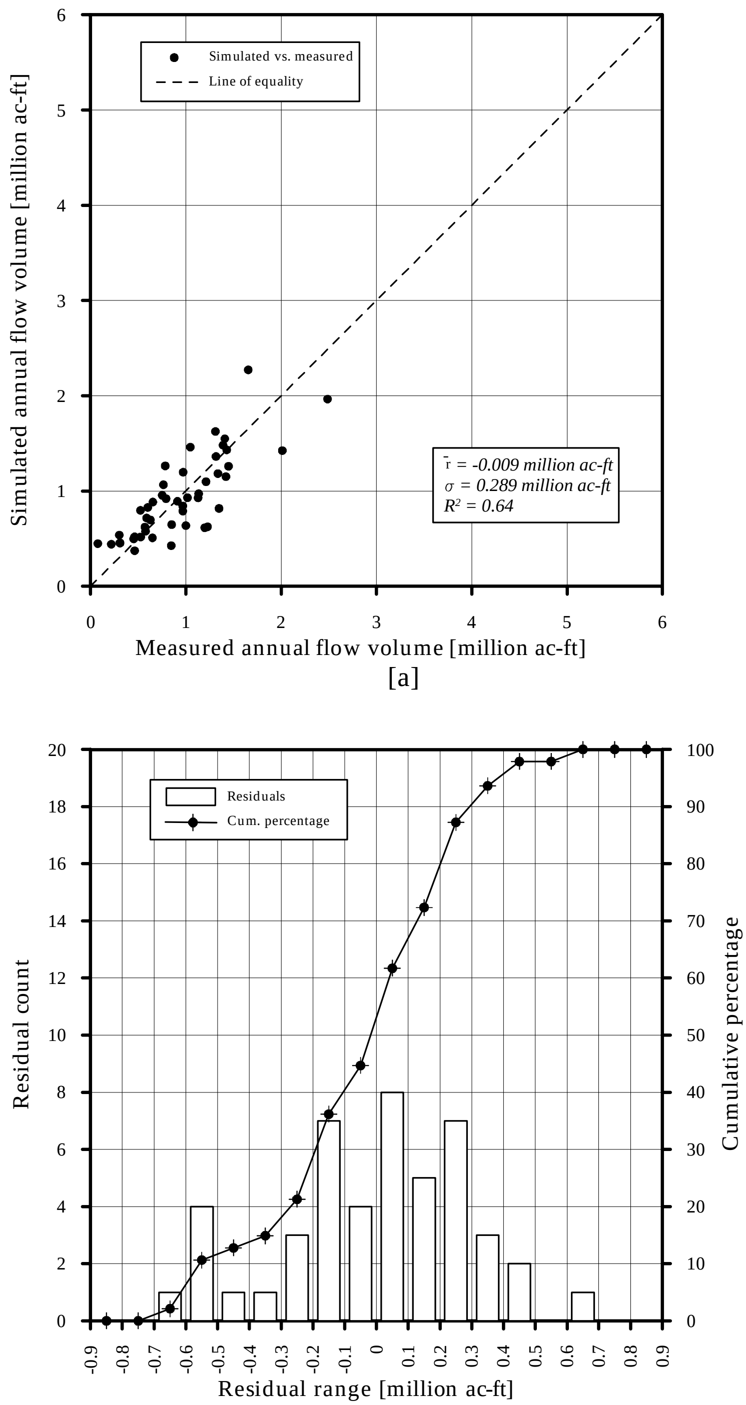


[a]



[b]

Figure C1. Residual analysis of annual flow volumes for the SJR at SR 44 near DeLand; results correspond to the complete model



[b]

Figure C2. Residual analysis of annual flow volumes for the SJR near Christmas

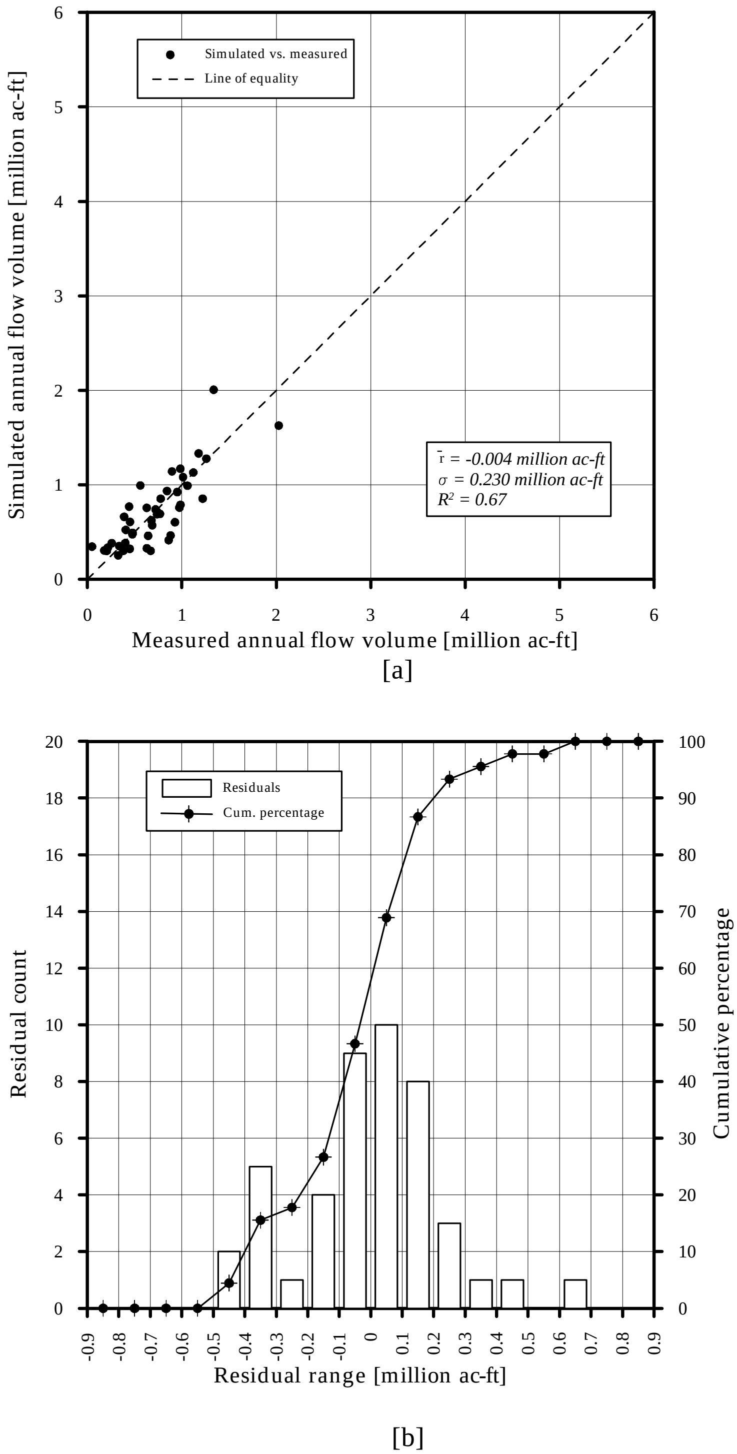


Figure C3. Residual analysis of annual flow volumes for the SJR near Cocoa (Lake Poinsett)

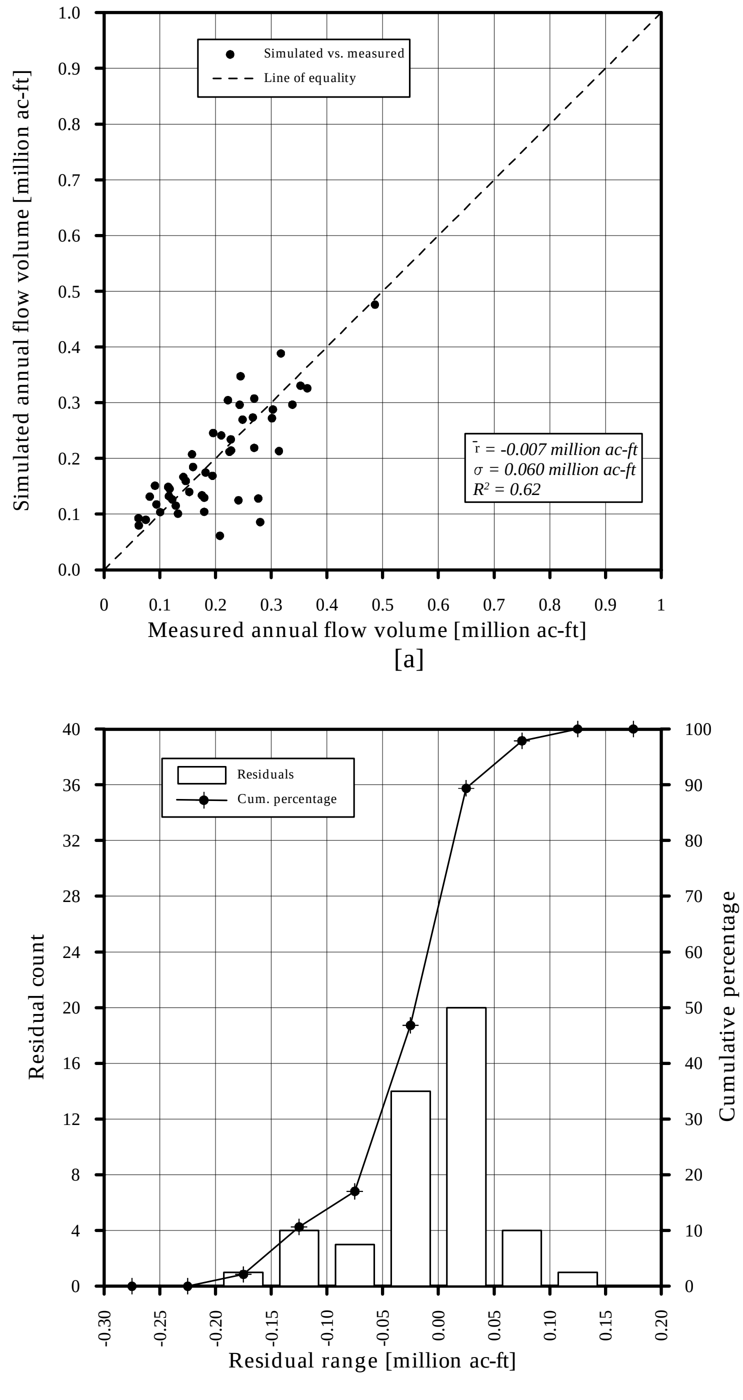


Figure C4. Residual analysis of annual flow volumes for the Econlockhatchee River near Chuluota

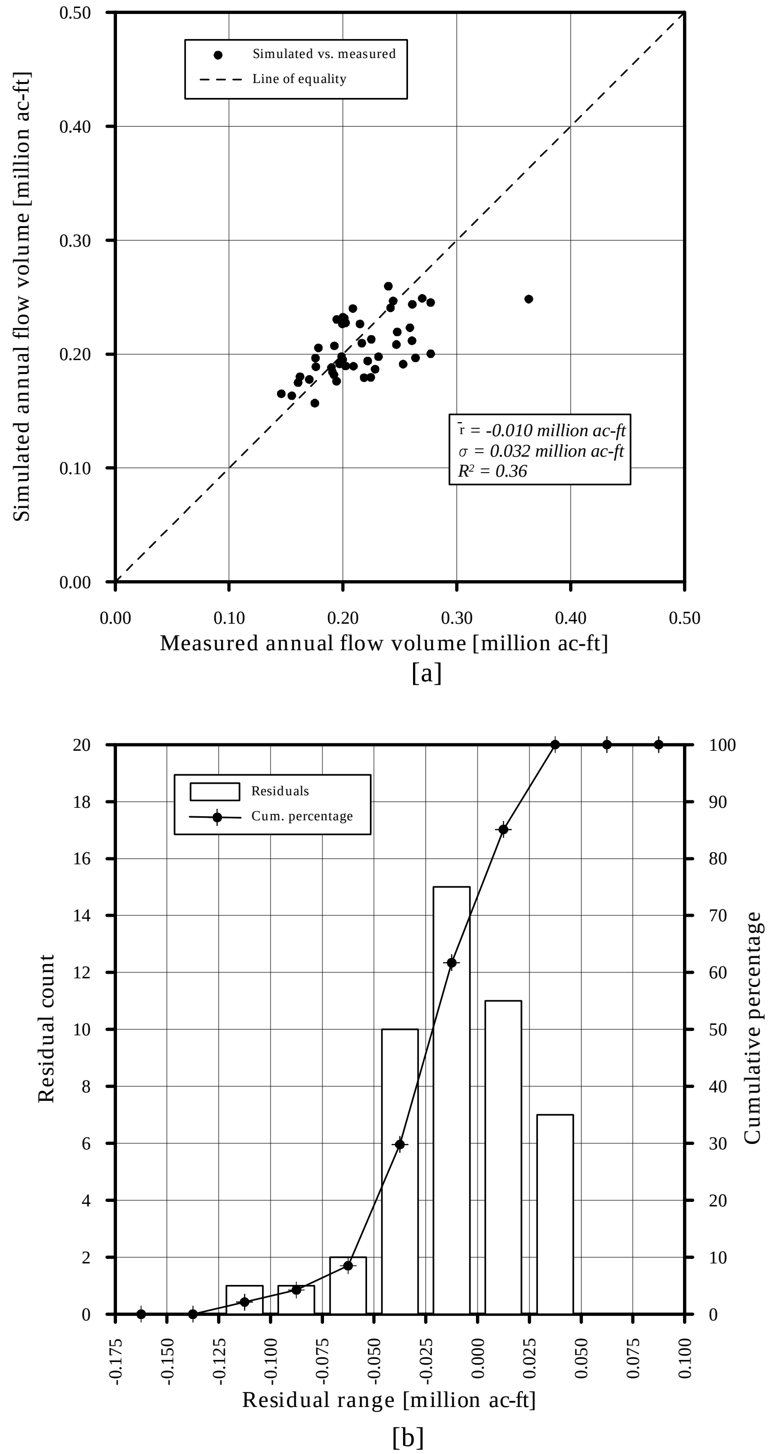
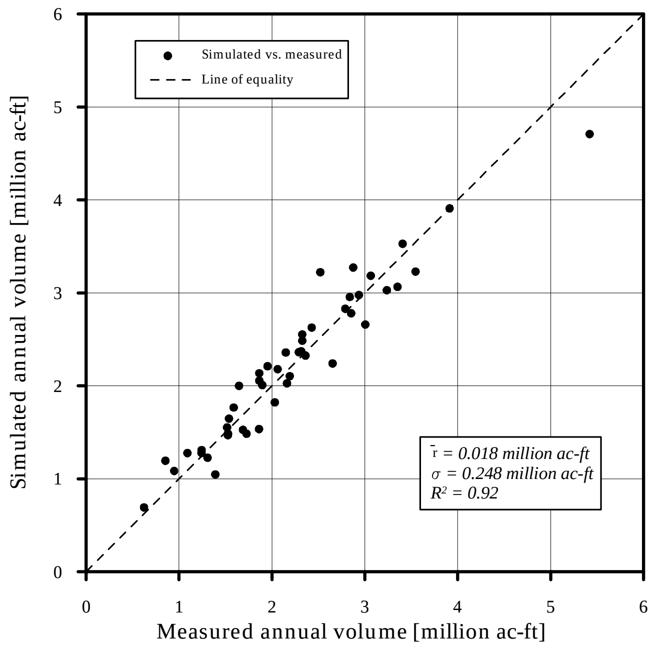
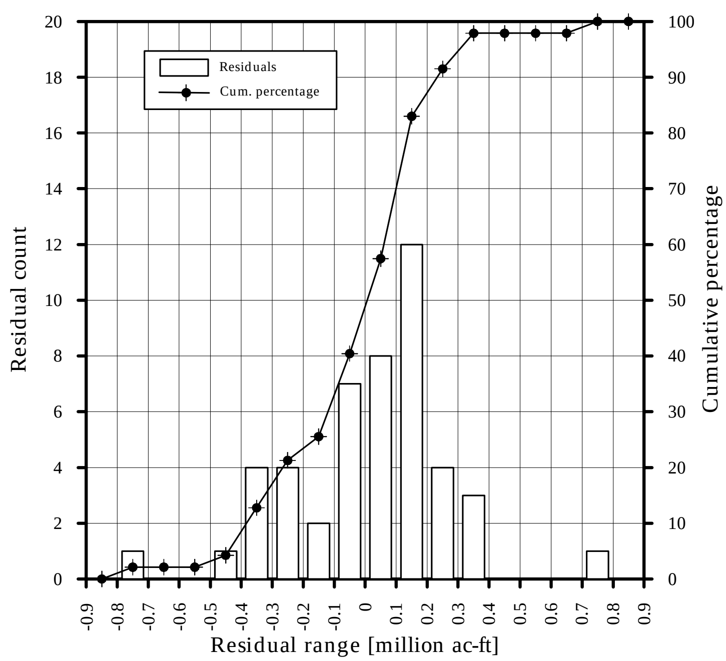


Figure C5. Residual analysis of annual flow volumes for the Wekiva River near Sanford

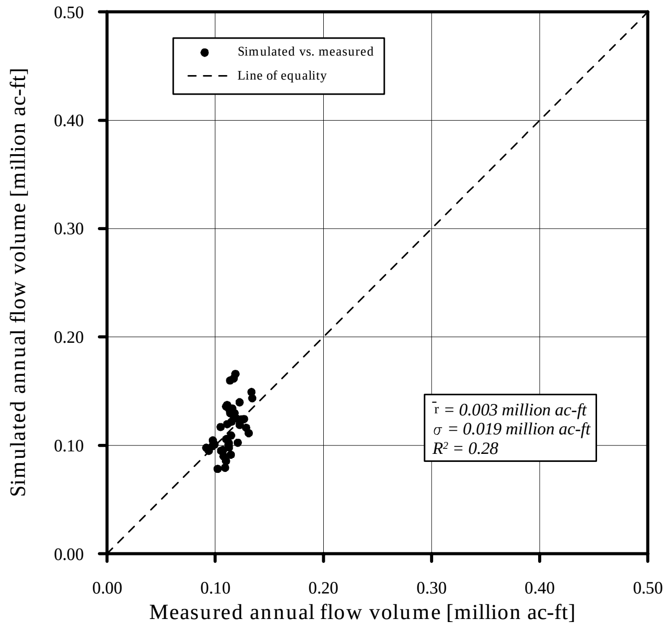


[a]

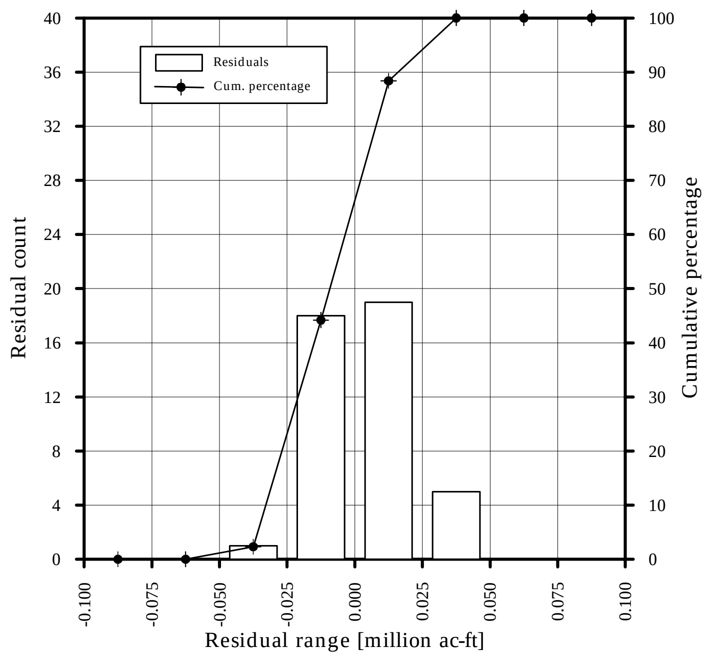


[b]

Figure C6. Residual analysis of annual flow volumes for the SJR at SR 44 near DeLand; results correspond to the gage model

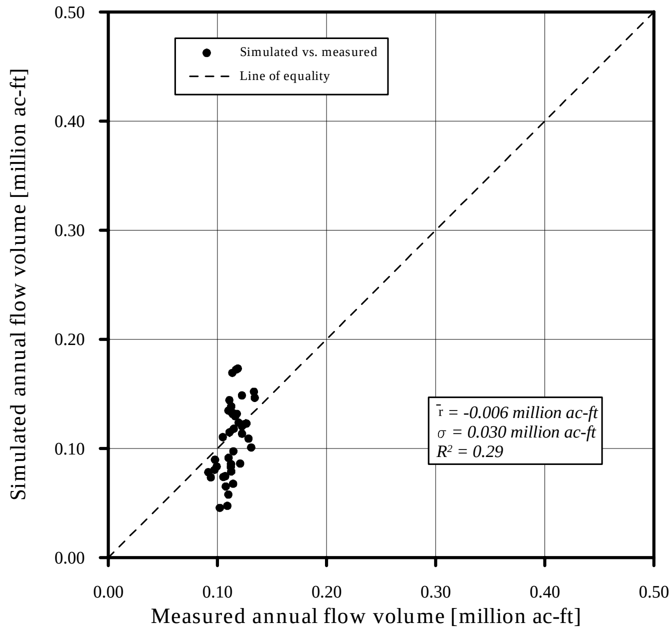


[a]

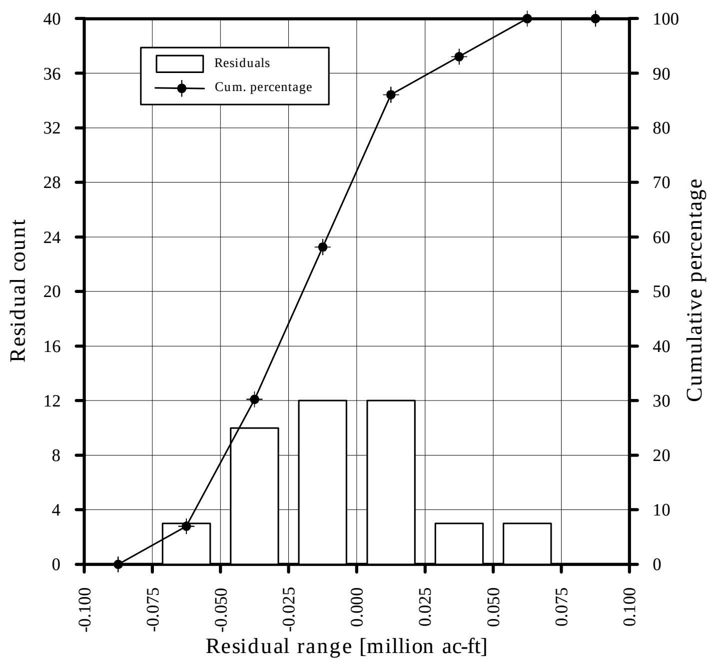


[b]

Figure C7. Residual analysis of annual flow volumes for Blue Spring using the power fit model



[a]



[b]

Figure C8. Residual analysis of annual flow volumes for Blue Spring using the linear fit model