This PDF is available from The National Academies Press at http://www.nap.edu/catalog.php?record_id=13052

Review of the St. Johns River Water Supply Impact Study: Report 3

ISBN
978-0-309-16404-7

41 pages
8 1/2 x 11
2010

Committee to Review the St. Johns River Water Supply Impact Study; National Research Council

More information

Find similar titles

Share this PDF

Visit the National Academies Press online and register for...

- Instant access to free PDF downloads of titles from the
  - NATIONAL ACADEMY OF SCIENCES
  - NATIONAL ACADEMY OF ENGINEERING
  - INSTITUTE OF MEDICINE
  - NATIONAL RESEARCH COUNCIL
- 10% off print titles
- Custom notification of new releases in your field of interest
- Special offers and discounts

Distribution, posting, or copying of this PDF is strictly prohibited without written permission of the National Academies Press.
Unless otherwise indicated, all materials in this PDF are copyrighted by the National Academy of Sciences.
Request reprint permission for this book

Copyright © National Academy of Sciences. All rights reserved.

THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

Review of the St. Johns River Water Supply Impact Study: Report 3

Committee to Review the St. Johns River Water Supply Impact Study

Water Science and Technology Board

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

PREPUBLICATION COPY

Copyright © National Academy of Sciences. All rights reserved.

THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the panel responsible for the report were chosen for their special competences and with regard for appropriate balance.

Support for this study was provided by the St. Johns River Water Management District under grant SLOC-25123. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number X-XXX-XXXXX-X
Library of Congress Catalog Card Number XX-XXXXX

Additional copies of this report are available from the National Academies Press, 500 5th Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu.

Copyright 2010 by the National Academy of Sciences. All rights reserved.

Printed in the United States of America.

Copyright © National Academy of Sciences. All rights reserved.

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

PREPUBLICATION COPY

Copyright © National Academy of Sciences. All rights reserved.

PREPUBLICATION COPY

Copyright © National Academy of Sciences. All rights reserved.

COMMITTEE TO REVIEW THE ST. JOHNS RIVER WATER SUPPLY IMPACT STUDY

PATRICK L. BREZONIK, *Chair*, University of Minnesota, Minneapolis
M. SIOBHAN FENNESSY, Kenyon College, Gambier, Ohio
BEN R. HODGES, University of Texas, Austin
JAMES R. KARR, University of Washington, Seattle
MARK S. PETERSON, University of Southern Mississippi, Ocean Springs
JAMES L. PINCKNEY, University of South Carolina, Columbia
JORGE I. RESTREPO, Florida Atlantic University, Boca Raton
ROLAND C. STEINER, Washington Suburban Sanitary Commission, Laurel, Maryland
J. COURT STEVENSON, University of Maryland, Cambridge

STAFF

LAURA J. EHLERS, Study Director
MICHAEL J. STOEVER, Research Associate

Copyright © National Academy of Sciences. All rights reserved.

WATER SCIENCE AND TECHNOLOGY BOARD

DONALD I. SIEGEL, *Chair*, Syracuse University, New York
LISA ALVAREZ-COHEN, University of California, Berkeley
MARK M. BRINSON, East Carolina University, Greenville
YU-PING CHIN, The Ohio State University, Columbus
OTTO C. DOERING, Purdue University, West Lafayette
GERALD E. GALLOWAY, University of Maryland, College Park
GEORGE R. HALLBERG, The Cadmus Group, Inc., Waltham, Massachusetts
KENNETH R. HERD, Southwest Florida Water Management District, Brooksville
GEORGE M. HORNBERGER, Vanderbilt University, Nashville
KIMBERLY L. JONES, Howard University, Washington, DC
MICHAEL J. MCGUIRE, Michael J. McGuire, Inc., Santa Monica, California
DAVID H. MOREAU, University of North Carolina, Chapel Hill
DENNIS D. MURPHY, University of Nevada, Reno
MARYLYNN V. YATES, University of California, Riverside

STAFF

STEPHEN D. PARKER, Director
JEFFREY W. JACOBS, Scholar
LAURA J. EHLERS, Senior Program Officer
STEPHANIE E. JOHNSON, Senior Program Officer
LAURA E. HELSABECK, Program Officer
M. JEANNE AQUILINO, Financial and Administrative Associate
ELLEN A. DE GUZMAN, Senior Program Associate
ANITA A. HALL, Senior Program Associate
MICHAEL J. STOEVER, Research Associate
SARAH E. BRENNAN, Program Assistant

Copyright © National Academy of Sciences. All rights reserved.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

MARK M. BRINSON, East Carolina University
WENDY D. GRAHAM, University of Florida
WAYNE HUBER, Oregon State University
MICHAEL C. KAVANAUGH, Geosyntec, Inc.
JAYANTHA OBEYSEKERA, South Florida Water Management District

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Jerome B. Gilbert. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Copyright © National Academy of Sciences. All rights reserved.

Copyright © National Academy of Sciences. All rights reserved.

Contents

Copyright © National Academy of Sciences. All rights reserved.

Copyright © National Academy of Sciences. All rights reserved.

Summary

The St. Johns River Water Management District in northeast Florida is studying the feasibility of withdrawing water from the St. Johns River for the purpose of augmenting future public water supply. The District requested that its Water Supply Impact Study (WSIS) be reviewed by a committee of the National Research Council (NRC) as it progresses. This third report from the NRC committee focuses on the hydrology and hydrodynamics workgroup. A brief summary of the report's major conclusions and recommendations is presented below.

The main output of the hydrologic and hydrodynamic models is to predict stage, flow, and salinity at various points along the river given potential changes in water withdrawals—information which will then be used by the six ecological workgroups to better understand impacts. The committee is generally satisfied that the modeling approach of the hydrology and hydrodynamics workgroup reflects the state of the science and available data and information. As in previous reports, the criticisms mentioned in this report are intended to improve the workgroup's efforts as the modeling evolves to support future water supply planning in an adaptive management framework.

Modeling of the St. Johns River watershed, which is integral to understanding the hydrologic response of the river to changes in water withdrawal, relies heavily on accurate estimates of future land use. The committee cautions that the land use relationships developed for the current WSIS may not hold in the future, especially if the actual rate of population increase or its impact on the hydrologic response of the resulting change in land use is significantly different from the current forecast. It is strongly recommended that the District revisit and update the population and resulting land use projections in future periodic reviews.

The hydrologic model was calibrated using observed meteorology with fixed (1995) land use over the decade 1995 to 2006, such that the model's reliability is limited outside its calibrated time span (e.g., for the 2030 conditions). Because insight can be obtained by a quantitative evaluation of the model outside its calibration range using newer data, it is recommended that the District apply the model (without further calibration) to 2009–2010 land use conditions and 2009–2010 observed rainfall and streamflow to provide a basic understanding of how the model behaves for a case outside the calibration range. In addition, whether the hydrologic model can adequately quantify confounding processes outside the calibration range is unknown. Confounding processes are processes whose effects are large but in the opposite direction such that they tend to cancel each other out. Even with the best possible model, confounding processes outside the calibration range can lead to uncertainty in the prediction that is larger than the magnitude of the predicted impact. The District's analysis of model results

Copyright © National Academy of Sciences. All rights reserved.

across the scenarios should carefully consider which scenarios have confounding processes and which do not.

The hydrologic and hydrodynamic models provide reasonable approximations of the major fluxes through the watershed, with the exception of some wetlands hydrologic processes. The following concerns are noted. First, the District should consider supplementing rain gage data with NEXRAD Doppler data for scenario testing. Second, due to a changing climate, decisions based on model predictions using historic rainfall conditions should be revisited as the state-of-the-science improves. Finally, as computational power increases over the next decade, the grid resolution of the hydrodynamic model should increase to 4X or even 16X in order to not limit the model's ability to represent physical/ecological dynamics driven by salinity gradients.

For reasons detailed in the report, the HSPF model used to predict hydrologic changes for the different water withdrawal scenarios has limited value for wetlands. The District is urged to continue developing the Hydroperiod Tool and analyzing the empirical water level data available from minimum flow and levels (MFL) transects in order to determine the correspondence between river stage and wetland hydroperiod. These tools and data have the potential to provide considerable insight into the response of the different wetland types to water withdrawals.

Results of the hydrologic/hydrodynamic simulations, expressed in terms of changes in flow and water stage, were generated for various scenarios at two locations in the watershed. The modeling revealed that flow and stage would generally increase under the proposed full withdrawal condition, assuming management of the upper basin to bring water back into the system and the 2030 land use condition (which would increase the contribution of stormwater to river flow). Given these results, which were unexpected at the onset of the WSIS, the committee urges that as much attention be given to potential water quality and other environmental impacts of future increases in flows and levels and in the temporal distribution and routing of flows as to the potential for decreases in flow and levels.

Copyright © National Academy of Sciences. All rights reserved.

Chapter 1

Introduction

With a length of about 310 miles (500 kilometers), the St. Johns River is by far the longest river in Florida. Its drainage basin of 31,954 square kilometers (km^2) or 12,283 square miles (mi^2) represents 23 percent of the total area of Florida and occupies the northeast quadrant of the state. Two of the state's largest urban centers lie wholly (Jacksonville) or mostly (Orlando) within the drainage basin, and 110 other municipalities exist within the basin. The population of the basin currently is about 4.4 million people (21 percent of the state's population) and is expected to grow to more than 7.2 million people by 2030.

Additional water supply demands from the increased population will not be met by further withdrawals from groundwater supplies in the basin because those supplies are reaching their sustainable limits. Moreover, a joint action plan of the three Florida water management districts responsible for water management in central Florida capped groundwater withdrawals at the level of the 2013 demand. The St. Johns River Water Management District (the District) is thus studying the feasibility of withdrawing water from the St. Johns River and its major tributary, the Ocklawaha River. The District requested that their study, called the Water Supply Impact Study (WSIS), be reviewed by a committee of the National Research Council (NRC) as it progresses. This is the third report from the NRC committee, and it focuses primarily on the work and results stemming from the hydrology and hydrodynamics workgroup of the WSIS. It also considers related activities of the wetlands workgroup and the role of stormwater management in how the hydrologic and hydrodynamic modeling results should be interpreted. The NRC committee's statement of task is presented in Box 1-1.

This report is primarily a review of Cera et al. (2010), Sucsy (2010), and Belaineh et al. (2010)—District publications/presentations describing the recent progress of the hydrology and hydrodynamics workgroup. This report also reflects knowledge gained by the committee during numerous District presentations at meetings and conversations with District staff regarding their modeling approach, and by reviewing relevant references and other outside reviews of the District's work. Because the primary audience of this report is the District staff and outside experts, details of the hydrology and hydrodynamic modeling are not repeated here, including evidence provided by the District showing that the model simulations closely matched measured outcomes. The reader is referred to Cera et al. (2010) and SJRWMD (2008) for such information. Rather, this report focuses on the committee's concerns about the Cera et al. (2010) report where they existed and suggests improvements for future work.

The positive statements affirming the District's approach found throughout this report reflect the committee's best professional judgment as it analyzed the District's attempts to do state of the science hydrologic and hydrodynamic modeling. Detailed discussion is provided

Copyright © National Academy of Sciences. All rights reserved.

Box 1-1
Statement of Task

An NRC committee overseen by the Water Science and Technology Board of the National Academies will review the progress of the St. Johns River Water Supply Impact Study (WSIS). Communities in the St. Johns River watershed in east central Florida are facing future drinking water supply shortages that have prompted the St. Johns River Water Management District to evaluate the feasibility of surface water withdrawals. At the current time, drinking water is almost exclusively supplied by withdrawals from groundwater. Reliance on groundwater to meet the growing need for public supplies is not sustainable. The St. Johns River and the Lower Ocklawaha River are being considered as possible alternatives to deliver up to 262 million gallons of water per day (MGD[1]) to utilities for public supply. In January 2008, the District began an extensive scientific study to determine the feasibility of using the rivers for water supply, and it has requested the advice of the National Academies as the study progresses.

The WSIS is composed of six major tasks, being carried out by District staff scientists aided by a suite of outside experts, each with national standing in their scientific discipline. These activities include modeling of the relevant river basins, determining what criteria should be used to evaluate the environmental impacts of water withdrawals, evaluating the extent of those impacts, coordinating with other ongoing projects, and issuing a final report. The NRC committee will review scientific aspects of the WSIS, including hydrologic and water quality modeling, how river withdrawals for drinking water will affect minimum flows and levels in the two rivers, the impact of removing old and introducing new wastewater streams into the rivers, the cumulative impacts of water withdrawals on several critical biological targets, and the effects of sea level rise. Potential environmental impacts being considered by the District include altered hydrologic regimes in the river, increased pollutant concentrations in the rivers (e.g., sediment, salinity, nutrients, temperature), associated habitat degradation, and other direct effects on aquatic species due to the operation of the new water supply facilities.

only for those issues where improvements could be made to the modeling efforts as they evolve to support water supply planning. The reader is referred to previous reports of the committee (NRC, 2009a, b) for considerable background on the basin, the origins of the WSIS, and the District's WSIS Phase I activities. These reports are available online at http://sjrwmd.com/surfacewaterwithdrawals/NRC_Phase1Report_review.html.

WATERSHED AND RIVER DESCRIPTION

The St. Johns river flows in a northerly direction for most of its length—from its origins in headwater wetlands west of Vero Beach (Indian River County) until it reaches Jacksonville, where it turns east and flows another 25 miles before reaching the Atlantic Ocean at Mayport (Figure 1-1). In spite of its length, the river elevation drops only about nine meters (~30 feet) from its headwaters to the ocean (an average of about 1.1 inches per mile or less than 2 cm per km), and most of the elevation drop occurs in the upper third of the river channel. As a result, a large fraction of the river is influenced by oceanic tides, and as a whole the river is a low-gradient, slow-moving ("lazy") river. The present river evolved from an ancient intracoastal lagoon system into a river channel that has three hydrologically distinct parts: the upper, middle, and lower St. Johns River (see Figure 1-1 for boundaries of the subbasins).

---

[1] 1 MGD = 0.645 cubic feet per second (cfs)

Copyright © National Academy of Sciences. All rights reserved.

Before drainage activities began in the early 20th century to enable the development of agriculture, the upper St. Johns basin had an extensive floodplain with large expanses of freshwater marsh and interconnected shallow lakes, and the river flow was not always in a distinct channel. Further drainage activities for flood-control in the middle of the 20th century ultimately claimed about 70 percent of the original floodplain, created several large reservoirs, and channelized parts of the river. In addition, several large areas were removed from the St. Johns basin, and runoff from these areas was pumped into manmade canals that flowed directly into the Atlantic Ocean via the Indian River Lagoon. Because of environmental concerns, wetland restoration has been underway in the upper basin since the 1980s, and several large projects are reconnecting parts of the upper drainage basin that had been transferred out of the basin by levees, canals, and pumping systems (see below).

The middle St. Johns River is a relatively short segment—approximately 60 km (37 miles)—with several large lakes and springs. It generally is considered to begin above Lake Harney and end below the outlet of Lake Monroe. The basin covers about 3,120 km^2 (1,200 mi^2), including some heavily urbanized areas northeast of Orlando. The Econlockhatchee River is a major tributary in this segment, and several large springs also contribute to the river flow. Lakes Harney and Monroe are widened areas in the main channel of the river, and Lake Jesup is a shallow off-channel lake between Harney and Monroe.

The lower St. Johns River, the longest of the three segments, is defined as the stretch of the river that is tidally influenced. It is divided into a freshwater segment, which extends down-river approximately to Green Cove Springs (river mile 48 from the ocean) and an estuarine segment, which exhibits increasing salinity as the river approaches the ocean. In turn, the freshwater segment is divided into two sub-reaches, one including Lake George, and a second including the freshwater reach downstream of the confluence of the Ocklawaha River (see Figure 1-1).

With a drainage basin of 7,170 km^2 (2,769 mi^2)—almost one-fourth of the entire St. Johns drainage basin—the Ocklawaha River is by far the largest tributary of the St. Johns River. The river starts as a series of large, shallow lakes (Apopka, Dora, Harris, Eustis, and Griffin) to the northwest of Orlando. The Silver River, which originates at Silver Springs, near Ocala, also contributes substantially to the river flow. Water from the Ocklawaha contributes significantly to the flow of the lower St. Johns River, and more than 40 percent of the surface water withdrawals being considered for water supply purposes in the current WSIS (i.e., 107 MGD out of a total of 262 MGD) is from the Ocklawaha River. Effects of this water withdrawal on the Ocklawaha River itself are not being considered in the current WSIS, although the ecological and hydrological effects on the St. Johns River of decreased flow from the Ocklawaha resulting from the withdrawal are being considered. (For further discussion of the Ocklawaha and its role in the WSIS, the reader is referred to NRC, 2009a).

As a whole, the St. Johns River drainage basin has very limited topographic relief, and as a result the river has extensive riparian wetlands. In the upper basin, the wetlands primarily are marshes, but in the middle and lower basins, hardwood swamps predominate. The highest elevations within the basin (up to 150-200 feet above sea level) occur to the west of the river, mainly in the sand hill region east of Gainesville, which has numerous soft-water lakes, and in the Ocala National Forest in the northern part of the Ocklawaha River basin.

Although agriculture is an important activity within the St. Johns basin, a larger fraction of the drainage basin, particularly in the middle and lower basins, is forested. Much of the upland forest is in pine plantations grown for pulp and paper production (see Table 1-1 for

Copyright © National Academy of Sciences. All rights reserved.

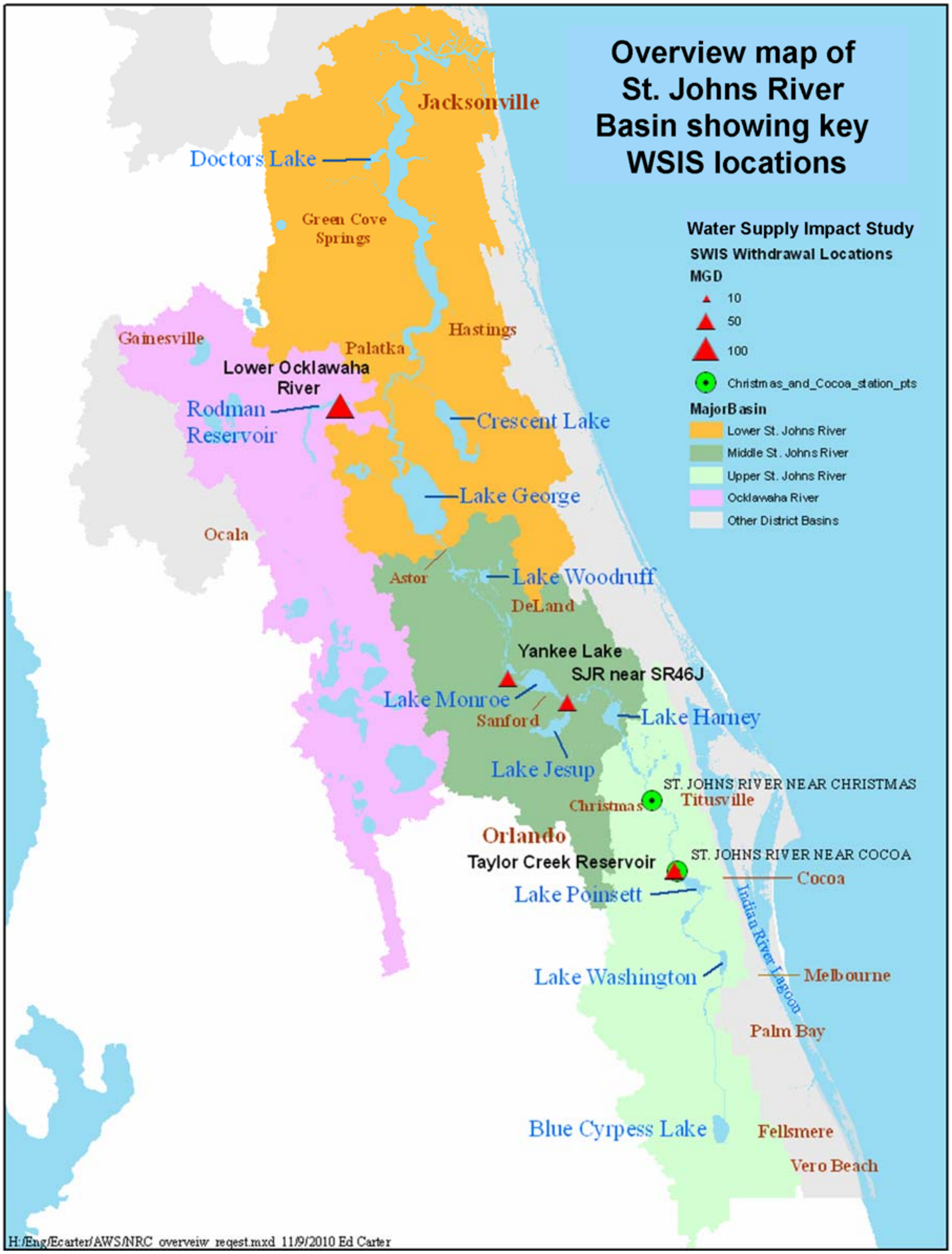


FIGURE 1-1 A map showing the surface water basins of the St. Johns River, major lakes along the main stem, relevant towns and cities including Cocoa and Christmas where model simulations were run, and the location of four potential surface water withdrawal sites.
SOURCE: Tom Bartol and Ed Carter, SJRWMD, personal communication, 2010.

Copyright © National Academy of Sciences. All rights reserved.

TABLE 1-1 1995 and predicted 2030 land use in the St. Johns River Basin.

HSPF Land Use Group	1995 Land Use (acres)		2030 Land Use (acres)	
1. Low Density Residential	263,841	4.9%	787,264	14.7%
2. Medium Density Residential	247,710	4.6%	540,955	10.1%
3. High Density Residential	78,947	1.5%	169,659	3.2%
4. Industrial and Commercial	140,282	2.6%	301,998	5.6%
5. Mining	20,515	0.4%	14,973	0.3%
6. Open and Barren Land	112,207	2.1%	58,512	1.1%
7. Pasture	505,701	9.4%	343,102	6.4%
8. Agriculture General	267,970	5.0%	148,201	2.8%
9. Agriculture Tree Crops	144,268	2.7%	72,500	1.3%
10. Rangeland	272,895	5.1%	136,985	2.5%
11. Forest	1,659,119	30.9%	1,139,307	21.2%
12. Water	286,016	5.3%	286,016	5.3%
13. Wetlands	1,374,656	25.6%	1,374,656	25.6%
Total	5,374,127	100.0%	5,374,127	100.0%

SOURCE: Cera et al. (2010).

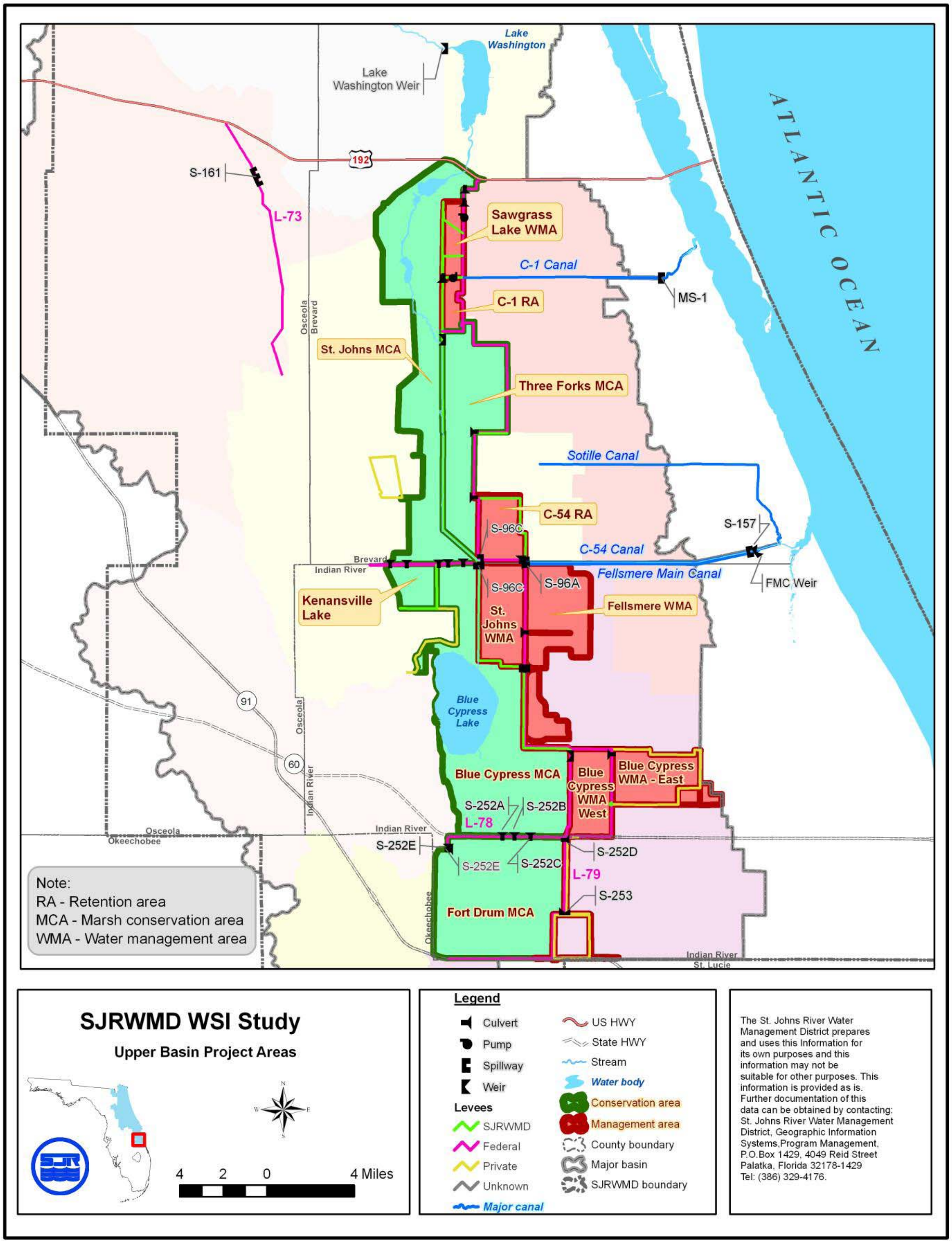
summary information on land use and land cover in the St. Johns basin, including its major subbasin, the Ocklawaha). Cattle grazing, horse farms, citrus groves, and vegetable production (e.g., potatoes, winter vegetables) are the major farming activities within the large and agriculturally diverse basin.

Because of the extensive wetlands throughout the drainage basin, the St. Johns River is highly stained (brown) with humic color. Water in the river generally is quite hard—high in calcium, magnesium and alkalinity—as a result of inflows from groundwater and artesian springs connected to the calcareous Floridan Aquifer. Chloride concentrations also are high, even in the freshwater portions of the river, because of the influx of groundwater with high chloride levels. These characteristics provide challenges in treating the water for potable purposes. The river and its tributaries are rich in nutrients (nitrogen and phosphorus) as a result of runoff from agricultural and urban areas, as well as inflows of treated municipal wastewater. The nutrient levels promote luxurious growths of aquatic plants along the river edge and cause algal blooms in the major in-channel lakes, especially in the middle and lower St. Johns River.

Upper Basin Projects

Three upper basin diversion projects—Three Forks, C-1 basin, and Fellsmere—are underway to return tens of thousands of acres of land to the St. Johns River drainage basin (see Figure 1-2). The three projects were selected from a larger number of potential projects that had been investigated by the District and U.S. Army Corps of Engineers for several years prior to their approval in 1987. Federal funding for the projects was not forthcoming until 2006, when construction began, and they are expected to be completed by 2015. This timeframe is well ahead of the first anticipated water withdrawals (in 2020) considered in the WSIS. The projects involve re-diverting some of the water in the three subbasins from its current destination (the

Copyright © National Academy of Sciences. All rights reserved.



The St. Johns River Water Management District prepares and uses this Information for its own purposes and this information may not be suitable for other purposes. This information is provided as is. Further documentation of this data can be obtained by contacting: St. Johns River Water Management District, Geographic Information Systems,Program Management, P.O.Box 1429, 4049 Reid Street Palatka, Florida 32178-1429 Tel: (386) 329-4176.

Author:jamoah, Source:Z:\review\GIS\Florida_sjrwmd_wsis.mxd, Time:06/26/2009 4:26:54 PM

FIGURE 1-2 Upper Basin Project areas: Phase I C-1, Three Forks Conservation Area (part of C-1 Basin), and Fellsmere Water Management Area.
SOURCE: Cera (2010).

Copyright © National Academy of Sciences. All rights reserved.

Indian River Lagoon) back to the St. Johns River, thus increasing flow in the river. As discussed later in this report, the additional flow is included in some of the WSIS scenarios.

In addition to returning the land areas of the upper basin projects to the St. Johns River drainage basin, the projects are intended to provide (1) temporary storage for floodwaters, (2) treatment for stormwater, and (3) open water and wetland habitat for wildlife in a more natural state than the prior use of the land (mostly as pasture). In particular, the marsh conservation areas (e.g., Three Forks) will provide temporary storage for floodwaters. Water management areas (e.g., Fellsmere) are being developed on former agricultural land that experienced considerable soil subsidence and thus provide deep water storage reservoirs to be used for irrigation of remaining agricultural land. The projects will be managed by a system of weirs and pumping stations to direct the water through canals and augment flow to the St. Johns River during normal and dry periods. By reducing the freshwater diversion to the Indian River Lagoon, water quality in the lagoon will be improved (i.e., salinity will be returned to more stable and natural levels).

In the WSIS hydrologic modeling studies, water inputs from operating the completed upper basin projects to the St. Johns River were provided as external time series that were produced from modeling complex management scenarios for the project structures. As discussed later, the combined mean annual contribution to flow in the St. Johns River at Cocoa and Christmas from the completed upper basin projects will be between 11 and 14 MGD.

BACKGROUND ON THE HYDROLOGY AND HYDRODYNAMICS WORKGROUP

Hydrodynamic and hydrology (H&H) studies undertaken for the St. Johns River WSIS are focused on developing models and linkages between models to characterize water flux through the watershed. The H&H effort has four principal parts:

1. Meteorological forcing (precipitation and potential evaporation)
2. Aquifer groundwater fluxes
3. Landscape water fluxes (watershed runoff)
4. River flows

Meteorological forcing and groundwater fluxes are the top and bottom boundary conditions for non-tidal water fluxes into and out of the basin. These fluxes primarily have external controls (e.g., climate, weather, geology), but secondary feedbacks from the basin (e.g., local changes in hydraulic head and changes in the landscape that affect transpiration) also influence them. Watershed hydrologic conditions and hydrodynamic constraints on river flows provide the immediate controls on water movement for any given set of meteorological and groundwater conditions. The District separated the analysis of meteorology, groundwater fluxes and the watershed hydrological/hydrodynamic modeling into distinct components as follows:

1. Data from a fixed period of record for precipitation and estimated potential evaporation were used to quantify the atmosphere/landscape interchange required by a watershed hydrological model.

2. Steady-state groundwater flow models based on MODFLOW were used to compute groundwater base flows along the river from the surficial aquifer system and the upper Floridan aquifer. The primary purpose of the groundwater component of the WSIS was to estimate the response of the underlying aquifer to potential water withdrawals in terms of discharge and

Copyright © National Academy of Sciences. All rights reserved.

aquifer head change, to provide boundary conditions for the mainstem hydrodynamic model, and to provide groundwater data for the water budget calculation.

3. A watershed hydrologic model called HSPF (which stands for hydrologic simulation program—Fortran) was calibrated for gauged sub-basins over the period of record (1995-2006) based on observed streamflow, rainfall, and 1995 land use conditions.
4. A hydrodynamic model of the main stem of the St. Johns River (the Environmental Fluid Dynamics Model or EFDC) was calibrated by varying bottom roughness to improve the fit of modeled flows to measured values.
5. Scenarios for various land use and water withdrawals were simulated with the models to estimate the effects on water levels, the magnitude of flows, and the timing peak and minimum flows throughout the basin.

The above approach is a reasonable use of the state-of-the-science for hydrological modeling, and it is reasonable within the context and goals of the WSIS. However, there are several levels of ambiguity inherent in this modeling process that should be acknowledged as the District moves to use the study results to formulate management plans. These issues (described in Chapter 3) are not criticisms of the District's approach, but rather serve as caveats to what science presently can discern; they should be considered in evaluating the model results.

A primary goal of the H&H workgroup is to send relevant data to the environmental workgroups of the WSIS to facilitate their impact analyses. The Committee requested, and received in June 2010, an informal cataloguing of these data to better understand the approaches that each environmental workgroup would be using for its impact analysis. These include data on river water level and salinity (for almost all workgroups), discharge (biogeochemistry, plankton, fish, and submersed aquatic vegetation or SAV workgroups), rainfall and wetland evapotranspiration data (biogeochemistry workgroup), water age and temperature (plankton workgroup), light attenuation (SAV workgroup), and shallow well water levels along some of the MFL transects (wetlands workgroup). In general, the Committee finds these categories of data, and the necessary detail with which they will be provided, as adequate, with the exception of shallow well data for the wetlands workgroup (as described in Chapter 3).

SCENARIOS TO BE MODELED

The District has decided upon four potential water withdrawal points: one within the upper St. Johns River basin, two in the middle basin, and one in the Ocklawaha River, which flows into the lower St. Johns River basin. The most southern withdrawal point is at the Taylor Creek Reservoir, where 55 MGD would be withdrawn from a canal on the west side of the St. Johns River just north of State Route 520. The first middle basin location is State Route 46, at which 50 MGD would be withdrawn at the northeast end of Lake Jesup. The second middle basin site is at the Yankee Lake project, where 50 MGD would be withdrawn from an intake location already sited on a canal, on the west side of the St. Johns River north of the I-4 crossing (near the outlet of Lake Monroe). The fourth withdrawal point is planned for the Ocklawaha River basin, where up to 107 MGD would be withdrawn upstream of the Rodman Reservoir at a location just north of Route 40 (according to a recent District map).

In conducting hydrologic simulations of water withdrawals and their effects on river hydrodynamics, the District considered various combinations of the four withdrawal points. In particular, the scenarios include "no withdrawal," a "half withdrawal" that corresponds to half

Copyright © National Academy of Sciences. All rights reserved.

the allotted amount from the three main-stem locations (77.5 MGD), a “full withdrawal” that corresponds to the full allotted amount from the three main-stem locations (155 MGD), and the full withdrawal plus the Ocklawaha withdrawal (262 MGD).

In addition to the amount of water withdrawn, the District is altering other variables as it develops scenarios that will reflect future conditions, including changes in land use from 1995 to 2030, changes in how the upper basin is managed, potential sea level rise, future wastewater treatment plant (WWTP) reuse, and dredging in the lower St. Johns River (although simulations that include the latter three issues were not available in time to be reviewed in this report). The three typical scenarios used in the District’s latest hydrology and hydrodynamics report (Cera et al., 2010) are (1) 1995 land use, (2) 1995 land use along with upper basin projects that put water back into the river system; and (3) 2030 land use with the upper basin projects added. For each of these scenarios, the District is simulating the “no withdrawal,” “half withdrawal” (77.5 MGD), “full withdrawal” (155 MGD), and “full withdrawal + Ocklawaha” (262 MGD) cases, for a total of 12 major simulations.

It should be kept in mind that each withdrawal scenario is more complicated than is implied by the single MGD value because withdrawals are restricted during low flow periods and then increase as flows increase. For example, the amount of water withdrawn from the river into the Taylor Creek Reservoir will range from 0 to 84 MGD depending on the flow and stage conditions at State Road 50. A constant 55 MGD will be diverted from the reservoir for water supply, while a constant 11 MGD will be released from the reservoir to satisfy minimum flow requirements. Both these reservoir outflows would be cut off when the river stage at State Road 50 drops below 30.0 ft NGVD.

Copyright © National Academy of Sciences. All rights reserved.

Chapter 2

Review of Modeling Methods and Results

This chapter briefly describes the major components of the hydrologic and hydrodynamic modeling, including groundwater modeling. Some discussion of improvements that would strengthen the analysis of the District is included, but the bulk of recommendations in this regard are found in Chapter 3. In addition, the results of model runs for particular scenarios are presented.

LAND USE/LAND COVER

1995 land use/land cover data, developed from interpretation of color-infrared aerial photography, was used as the baseline for the WSIS because it is the basis for current water supply planning conducted by the District. The 1995 land use data, together with data sets on precipitation, evaporation, and other drivers of the models from 1995-2005, were used to calibrate the HSPF models.

The District adopted 15 land use/land cover categories for modeling, as shown in Table 2-1. Runoff and other coefficients used in the hydrologic modeling were selected to reflect the differing characteristics of these land use/land cover categories. For use in the HSPF modeling, the District grouped the land-use categories according to similarities in hydrologic response—usually corresponding to degrees of imperviousness. The model employs a lumped parameter approach, such that all of the areas for a given land use within a subwatershed are summed and multiplied by the discharge expected from that type of land use.

Population growth is expected to be the main driver for changes in land use through the planning period (to the year 2030). Projected land use for the year 2030 (see Table 1-1) was developed by expanding 1995 conditions in relation to expected population growth. County-level population forecasts were prepared by the University of Florida Bureau of Economic and Business Research, and a consulting firm, GIS Associates, Inc., was retained to develop detailed spatial disaggregations based on the county-level forecasts (SJRWMD, 2009) in order to project future populations, and thus water demand, for public water supply utility service areas. Special algorithms were used at the parcel level to reallocate growth from high growth parcels having spatial constraints to lower growth parcels, while still conforming to the county-level projections.

As a result of the projected population growth, residential and commercial/industrial land use areas increased over the time period of interest, while open, range, forest, and agricultural land areas in the drainage basin decreased. Wetlands and water areas were generally kept at

Copyright © National Academy of Sciences. All rights reserved.

TABLE 2-1 Hydrologic Model Land Use Categories

Low density residential	Open land and barren land	Forest
Medium density residential	Pasture	Water
High density residential	Agriculture general	Wetlands
Industrial and commercial	Agriculture tree crops	Forest regeneration
Mining	Rangeland	Non-riparian wetlands

Note that there are extra land use categories here compared to Table 1-1. The committee found that the District was not consistent with respect to the number of land use categories presented in various documents.

1995 values[2]. As shown in Figure 2-1 for the lower St. Johns River basin, projections were made in five-year increments from 2005 to 2030.

The District has indicated that because of the recent economic downturn, the 2030 population estimates actually may be more accurate for 2033 or 2035, but this affects only the timing of growth and not the growth itself. Land use forecasts, however, are a function not only of population forecasts but also the nature of the population's impact on the landscape (e.g., the mix of housing densities and the degree and characteristics of imperviousness in developed lands). The relationships developed for the current WSIS may not hold in the future, especially if the actual rate of population increase or its impact on the hydrologic response of the resulting change in land use is significantly different from the current forecast. Indeed, the land use shown for 2004 in Figure 2-1 does not seem to reflect projected changes in population growth. Thus, although the Committee does not have any technical issues concerning the approach used by the District to estimate 2030 land use/land cover conditions, **it recommends that the District revisit and update the population and resulting land use projections in future periodic reviews (e.g., the District's water supply plans and the water supply assessments made by the District every five years).**

---

[2] The committee cautions that this assumption of wetlands acreage remaining the same is uncertain. This is because the predicted increases in stormwater discharge that will accompany the 2030 land use condition could result in stream channel deterioration that would reduce the surface area of riparian wetlands (discussed in Chapter 3). These losses would have to be offset by wetlands mitigation required under the Clean Water Act and/or restoration of the upper basin for the assumption to hold true.

Copyright © National Academy of Sciences. All rights reserved.

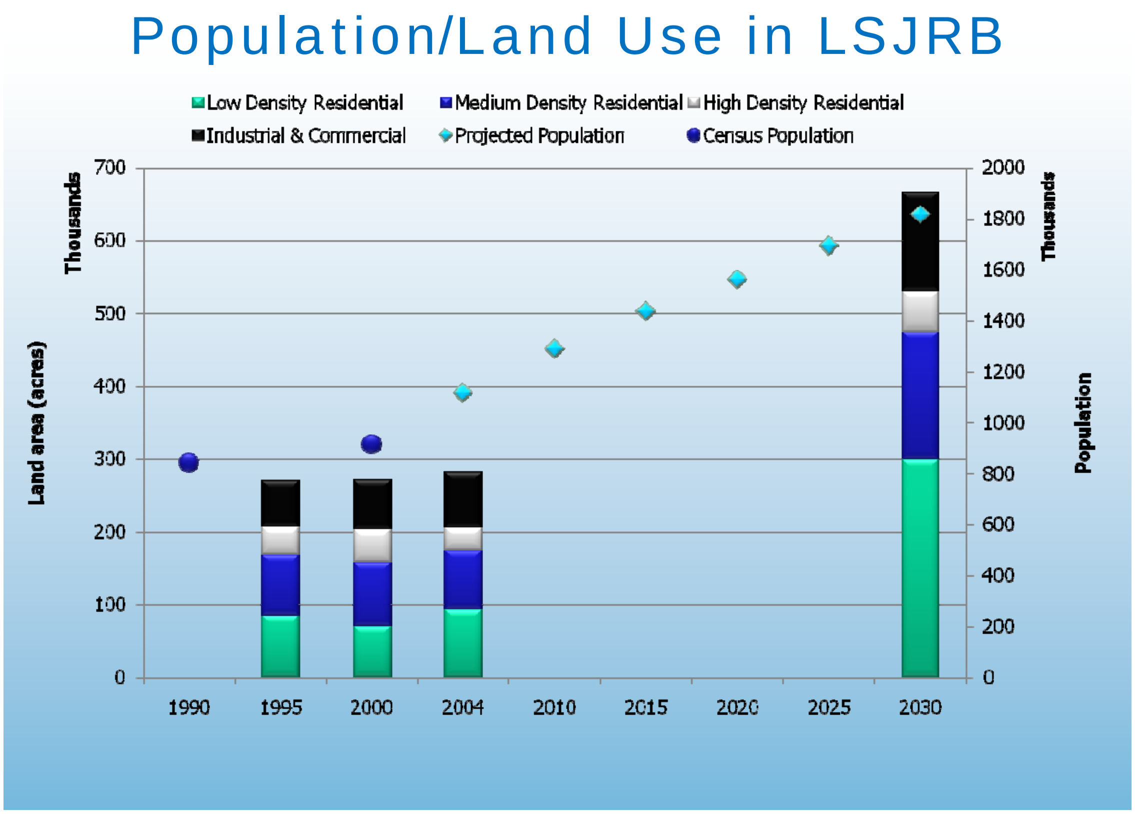


FIGURE 2-1 Population and Resulting Land Use Projections in the Lower St Johns River Basin for the Planning Period 1995–2030.
SOURCE: Cera et al. (2010).

METEOROLOGY

For the District's analyses, the required meteorological data consist of rainfall and potential evaporation (for a detailed description, see pp. 12-23 of Cera et al., 2010). Rainfall distribution across the catchment was modeled for historical data by taking National Weather Service (NWS) rain gage data and distributing them spatially using a network of Thiessen polygons. Gage data for rainfall accumulations for time periods larger than the hydrologic model time step (1 hour) were disaggregated using either nearby hourly data or (where no hourly data were available) by assuming that rain events of less than a half inch (1.3 cm) occur within an hour and that larger events were distributed with a triangular weighting over three to five hours. Missing data were estimated from the nearest available measured data. Where only daily rainfall records were available, disaggregation from daily to hourly values was accomplished using the software package WDMUtil, which is part of the EPA BASINS package and can be considered state-of-the-science. Although more comprehensive Doppler rainfall data are available, the District chose to use the rain gage data due to their longer period of availability.

Potential evaporation was modeled using the Hargreaves method, which requires only historical temperature data. Observed temperature data at meteorological stations were distributed across the basin using Thiessen polygons.

Copyright © National Academy of Sciences. All rights reserved.

Model Calibration and Uncertainty

The use of NWS data for rainfall does not require (or allow) any formal calibration. Distribution of rainfall across a watershed from point-based rain gage data introduces some uncertainty into the rainfall model that is difficult to quantify with only the point-based gages, but this is a problem inherent to hydrologic modeling at the watershed level and not a specific criticism of the District's approach.

The Hargreaves estimate of potential evaporation was calibrated based on satellite-based estimates of potential evaporation computed for three sites using the Penman method.

Model Capabilities and Limitations

The modeling approach is limited in its ability to represent small-scale convective storms and flashy rain events. This limitation, which is inherent in models that rely on data from point-based gages with no better than hourly data, may not be important for present conditions because the St. Johns is a heavily dampened system. It could become more important as the landscape urbanizes, however, because the model will be limited in its ability to predict runoff from the catchment during flashy events.

In the committee's opinion, the assumptions in the models presented are reasonable. We agree with the District that that Doppler and point rain gage data cannot be intermingled in a single model data set to drive a watershed hydrologic model. However, the existing Doppler radar sets that the District did not use in their hydrologic modeling efforts could be used to help quantify the uncertainty associated with distribution of point-gage rainfall data across the Thiessen network. A further criticism regarding the use of NWS rain gages is discussed below relative to the calibration of the watershed hydrology model.

WATERSHED HYDROLOGY

The watershed hydrology for the entire upper basin (including river reaches) and the middle and lower basins (excluding the main river stem) were modeled with the HSPF hydrological model. This model is a recognized, EPA-supported "lumped parameter" model that represents the relationship between infiltration, surface runoff, subsurface flow, and transpiration based on the fractions of a sub-watershed with pervious and impervious cover. "Lumped parameter" refers to models that use a set of calibrated coefficients to represent hydrologic behavior in each subbasin based on land use or land cover. This approach can be contrasted with other "distributed parameter" models that use small-scale grid cells to directly represent individual regions of pervious or impervious cover, their mechanical characteristics, and their spatially distributed connections. The District chose a reasonable approach in using the lumped parameter model. Although this approach renders the model highly dependent on calibration, a mechanistic distributed parameter model could not reasonably be supported for a basin the size of the St. Johns and with the available data.

Copyright © National Academy of Sciences. All rights reserved.

Model Calibration and Uncertainty

Model calibration was extensively presented in Cera et al. (2010). The calibration approach used historical rainfall and potential evaporation models (described above) for the period 1995 to 2006 and land-use data based on a 1995 study. The accepted "Parameter ESTimation" (PEST) software was used for calibration of eight of the 19 parameters used in the HSPF Common Logic Table (Appendix C, p. 209, Cera et al., 2010) and the "special actions" associated with a wetland storage-outflow model. Other parameters were fixed. The HSPF calibration modeling reported to date has been conducted carefully and thoughtfully, and the District is commended on this effort. The model has been demonstrated to provide reasonable results during the calibration period.

The District chose to use data from the NWS rainfall gages rather than NEXRAD Doppler radar data for their calibration study because they are using a 32-year NWS rainfall gage record for scenario analysis. However, to limit the influence of land use changes, model calibration was based only on the 1995-2006 period rather than the 32-year period. This approach is reasonable with some limitations. It should be recognized that the model response to rainfall outside the calibrated period is uncertain, and so statistics gathered from the model based on the larger 32-year data set will be reliable only if the weather patterns are similar to those in the 11-year data set. There is little reason to assume that a lumped parameter model will respond correctly to rainfall events that are significantly different than those in the calibration data set. The calibration data set thus should contain a reasonable approximation of all expected weather over the scenario testing data set. If there are significantly different weather patterns in the 32-year set than in the 11-year set, then the calibration approach may need to be reconsidered.

The District has not yet presented or proposed any methods to estimate the uncertainty associated with the HSPF model.

Model Capabilities and Limitations

The hydrologic model appears to provide reasonable approximations of the major fluxes through the landscape. The runoff values predicted to the river main stem are reasonable approximations of the observed flows. The principal limitation appears to be whether or not the approach to modeling wetlands (FTABLES) provides enough accuracy for evaluation of ecological impacts. Lumped-parameter hydrological models inherently perform better under high-flow conditions, where the modeled physical processes are strongly affected by the calibration coefficients. Under low-flow conditions that are often important to ecology, a lumped-parameter model may have significant hydrological flux uncertainty because of the difficulty of obtaining data and calibrating for such conditions. Thus, the model's ability to represent water retention times for short events (e.g., convective thunderstorms), flux rates through wetlands, and saturated soil fluxes in areas undergoing periodic immersion/drying cycles is more problematic.

The District may not be taking advantage of the best available rainfall data by relying on the NWS gage data rather than using NEXRAD Doppler data for scenario testing. The principal reason for the modeling work is to predict likely future catchment characteristics. The District likely will want to use this model for adaptive management and to monitor how well its decisions hold up under rainfall and land-use conditions that actually occur in the future. **Thus, using the**

Copyright © National Academy of Sciences. All rights reserved.

best available rainfall data (NEXRAD Doppler) is appropriate. As noted in the outside peer-review of modeling commissioned by the District (INTERA, 2009, page 16):

> *The District should consider calibrating the sub-watershed models with the shorter 1995 to present NEXRAD data set using the same approach and objective functions... [This] would provide the District an indication of how much the model underperformance is due to issues with the major forcing variable (rainfall) versus uncertainty in the model parameters such as vegetative cover and evaporation.*

The committee agrees with the above comment and recommends that the District consider conducting a secondary set of calibration runs.

The issue of how accurately wetlands are modeled under drying conditions is a principal concern and is discussed below in the section "Applicability of HSPF to Wetlands Hydrology.

The report section on "Scenario Simulations for Water Quantity" (Cera et al., 2010) is difficult to follow and understand. Different naming and numbering conventions were used to describe the scenarios and to present them in figures and tables. The withdrawal scenario for Taylor Creek Reservoir (p. 177) is particularly difficult to follow, and is presented without any reasoning for its development.

RIVER HYDRODYNAMICS

The District provided an extensive PowerPoint presentation on the river hydrodynamic model development and calibration. It is clear that they are proceeding carefully and analyzing how model implementation choices affect results. The Committee appreciates the level of detail provided and the development of graphs that clearly illustrate what the model can and cannot achieve.

For the lower SJR, where tidal oscillations are a dominant forcing, the District has conducted grid resolution tests to determine whether their 1X (coarse) model grid is consistent with results produced by a 4X (medium) and 16X (fine) model grid. This effort is a standard modeling exercise to establish that the coarser, more practical grid provides results that are sufficiently similar to the fine grid. The results are reasonable, showing very small percentage differences in the tidal amplitude in the lower reaches (where the amplitudes are larger). The only points that seem questionable are those near Lake George, where the absolute difference in the tidal amplitude between the models is small, but the percentage difference is large because the Lake George tidal amplitude is quite small. This problem may not be resolvable through calibration at the 1X grid scale, and so the District should analyze the differences to understand their effects on model predictions. It is likely that the differences are irrelevant at the upstream locations. Tidal phase differences were also examined by the District. Phase differences between results on the different grids are expected for this type of model, and the results shown appear well within the acceptable bounds. Overall, the grid resolution tests show that the coarse resolution model is adequate for this stage of the project and the available computer power. **However, as computational power increases over the next decade, continued modeling for adaptive management should plan on using the 4X or perhaps even the 16X grid.** It can be expected that as more data become available, the ability of the 1X model to distinguish finer detail will limit the model's utility.

The District analyzed oscillation frequencies in Crescent Lake using the hydrodynamic model and a field-deployed drifter, which provided confidence that the large-scale surface

Copyright © National Academy of Sciences. All rights reserved.

seiching of this lake is reasonably modeled, both in velocity magnitude and decay. The District is congratulated for this effort; numerical error in many models artificially damps the surface seiche and prevents representation of this behavior.

The District used the PEST software to calibrate the model by adjusting the bottom roughness height. In the main stem of the tidal river, the calibrated bottom roughness heights are sub-millimeter, which is an order of magnitude or more smaller than expected physical roughness heights. This result is not entirely surprising for the model using the 1X grid. It is well known that coarser model grids induce a damping error – "numerical dissipation" – that has the same effect on the model as the turbulent dissipation produced by the bottom boundary. The small bottom roughness height produced by calibration indicates that numerical dissipation is of the same order of magnitude or larger than physical dissipation produced by boundary-driven turbulence. From an academic modeling standpoint, this is not an ideal model formulation. It clearly would be better to have the energy dissipation developed through bottom boundary dissipation rather than the numerical dissipation. However, engineering efforts must always balance the ideal against the practical. In this case, the additional computational expense of moving to a 4X grid simply to decrease the numerical dissipation is not justified. The grid resolution study shows that the 1X model captures the bulk physical transport fairly well. Thus, it is unlikely that using a 4X grid to obtain better resolution of bottom turbulence will significantly alter the overall model results. However, the District should keep in mind that physical processes associated with the bottom boundary layer are poorly represented; it follows that any conclusions that depend on the vertical distributions in the water column driven by turbulent mixing may be suspect. In particular, these effects may limit the ability of the model to represent the physical/ecological dynamics driven by salinity gradients and resulting stratification in the Lower St. Johns River. The model predictions of salinity provided to the committee have reasonable comparison to field data; however, the amount of data available on vertical stratification is fairly sparse.

The hydrodynamic model results for the middle St. Johns River are quite satisfactory. The calibrated model captured daily discharge at various stations along the river. The model was calibrated based on a one-year subset of a 10-year data record, and performed equally well in the nine years outside of the calibration period. Not only did the model perform well over the longer time scale, but shorter time-scale (daily and hourly) discharge features were also reasonably represented. At the hourly scale, the model output has errors in phase and amplitude of smaller-scale oscillations that are not unexpected, but the overall characteristics are very similar to the observations. Modeled salinity in the Middle St. Johns River also compared well with both observed data and model results from HSPF.

The District provided some preliminary PowerPoint slides (Sucsy, 2010) and a draft report (Sucsy et al., 2010)[3] on sensitivity and uncertainty analyses. The combination of First-Order Error Analysis and Monte Carlo simulations were used to understand the major contributors to model sensitivity and uncertainty. The approach appears to be reasonable and well-considered.

---

[3] This document was received too late in the report preparation process to be thoroughly reviewed by the committee, but it appears to support the conclusions drawn from the District's PowerPoint presentation in March 2010.

Copyright © National Academy of Sciences. All rights reserved.

GROUNDWATER

Multiple interactions in the hydrologic cycle within the St. Johns basin involve groundwater. Along the main stem, the St. Johns River collects runoff, and shallow groundwater contributes to the base flow. At the same time, a multi-layered groundwater flow system has been grouped into three distinct hydrogeologic systems: the surficial aquifer (SAS), the Intermediate Confining Unit (ICU), and the Floridan Aquifer System. Recharge to the SAS is primarily from rainfall, although infiltration due to irrigation, reclaimed water, seepage from surface waterbodies, and septic tanks also make contributions. Discharge from the SAS occurs through evapotranspiration, from seepage into surface waterbodies, and from well withdrawals. In addition, the Floridan Aquifer System recharges to the SAS in areas where the potentiometric surface of the Upper Floridan Aquifer (UFA) is higher than the water table (otherwise, downward leakage from the SAS to the underlying UFA occurs). Springs discharging from the UFA exist throughout the basin and exert a significant influence upon the base flow in the river. Some of the above interactions are understood well and amenable to quantitative modeling (e.g., water movement in the Floridan Aquifer) or measurement (spring discharges), but others are poorly understood and difficult to model at the current state of understanding (e.g., exchange of water between the unconfined shallow aquifer and wetlands).

Using a single model to represent these hydrologic interactions would be a complicated task, to say the least, and consequently the District is using several independent models to represent the system: a GIS tool to identify wetlands, HSPF for surface water runoff from the watershed, the mainstem river hydrodynamic model EFDC, and the Eastern Central Florida (ECF) groundwater model, which is based on MODFLOW, a widely used groundwater flow model of the U.S. Geological Survey. One of the main criticisms of this approach is the limited extent to which HSPF can model wetland hydrology, including groundwater–surface water interactions in the riparian wetlands. This issue is discussed in Chapter 3. This section focuses on resolving comments made previously by the Committee about the assumption of constant chloride concentrations in groundwater input to the river channel over time and about the use of a steady state, non-density-dependent groundwater model.

Groundwater Salinity

An earlier criticism of the District's analysis of groundwater was their assumption of a constant average chloride concentration value for a given location in their groundwater modeling. As discussed in the Phase 1 report (SJRWMD, 2009), the District calculated the chloride load into the river by obtaining chloride concentration data from monitoring wells and from a chloride concentration map produced by the District. Then they used a GIS feature to distribute those concentration values to each ECF model grid. Those values were then multiplied by the groundwater flux from MODFLOW to get the chloride load contributed by the groundwater.

Upon being asked to show data that demonstrate the stability of the chloride concentration at more locations, District scientists presented chloride concentration data from eight wells from 1990 to 2009. The chloride concentrations across the eight wells ranged from a mean of about 5,300 mg/L over a 22-year period to a mean of only 9 mg/L. For any individual well, the highest temporal variability about the mean was 2.2 percent. Wet vs. dry years

Copyright © National Academy of Sciences. All rights reserved.

appeared to make little difference. Based on these findings, the committee no longer is concerned with the use of a temporally constant chloride concentration.

Density and Temporal Dependence of Models

In NRC (2009a), the District was criticized for employing a steady-state groundwater model (ECF) that was not density-dependent, which limits its ability to predict changes in salinity that might result from water withdrawals. District scientists considered both assumptions (steady state and density independence) to be valid, and they were asked to provide evidence for their opinions. To prove density independence, the District analyzed salt concentrations at three wells (S0025, V0083, and BR1526) in the Lake Harney area with high chloride concentrations and showed that converting real head data from these wells to their freshwater equivalent did not lead to a significant change in the potentiometric surface. When asked to address what criteria were used to determine whether changes were "significant," the District presented data suggesting that a change in head of 0.3 m or a change in chloride flux of 0.02 m^3/s was not significant. In Lake Harney, which has one of the highest chloride concentrations, the salinity change due to density stratification is only 0.012 practical salinity units or PSU (or 6.6 mg/L of chloride ion).

To determine that transience in groundwater flux is not important enough to forgo the use of steady state values in the modeling, the District analyzed how sensitive the river hydrodynamics model (EFDC) is to using transient vs. steady state groundwater input. Using well level and river stage data from four locations in the middle basin, the EFDC model was run with both the steady state and transient groundwater flux (using 10 years of transient groundwater discharge data). The change in water level or salinity predicted by the model when using steady state groundwater flux vs. transient flux was small (i.e., 95 percent of the time there was less than half a centimeter change in water level and less than 0.035 PSU change in salinity).

As a second line of evidence, the District argued that in absolute value terms river water storage and surface water discharge are much larger than groundwater discharge, such that the impact of groundwater on overall flow is not large. The committee accepts this statement as being generally correct, but notes that there are likely to be some occasions when groundwater is significant because there are times of zero surface water discharge. Of course, if such occasions (where groundwater is a major contributor to flow) happen once every 10 years, they are less important than if they occur several times a year.

SIMULATIONS FOR VARIOUS SCENARIOS AND FUTURE CONDITIONS

Results of the hydrologic/hydrodynamic simulations, expressed in terms of changes in flow and water stage, were generated for the 12 scenarios described earlier for two upper basin locations—Christmas and Cocoa. As shown in Table 2-2, several major results became evident. First, substantially more flow (51 MGD) was generated with the 2030 land use baseline scenario than with the 1995 land use baseline scenario because of the increase in impervious area over time. Second, the surface water restoration projects in the upper basin also increased the mean flow (by 11 MGD for case with no withdrawal) and stage over the 1995 baseline condition. Third, the effects of full and half withdrawal were more pronounced upstream at Cocoa than

Copyright © National Academy of Sciences. All rights reserved.

TABLE 2-2 Stage/Flow Modeling Results at Cocoa and Christmas for 9 Withdrawal Scenarios

Scenarios	**Cocoa Mean stage (ft NGVD)**	**Cocoa Mean flow (mgd)**	**% Change in Flow from 1995 Base Case**	**Christmas Mean stage (ft NGVD)**	**Christmas Mean flow (mgd)**	**%Change in Flow from 1995 Base Case**
1995 Base	11.88	568	NA	6.73	721	NA
1995 + Half SJR Withdrawal	11.77	545	-4.0%	6.65	693	-3.9%
1995 + Full SJR Withdrawal	11.7	524	-7.7%	6.57	669	-7.2%
1995 + USJB Projects	12.09	579	2.0%	6.85	732	1.5%
1995 + USJB Projects + Half SJR Withdrawal	11.97	556	-2.0%	6.76	705	-2.2%
1995 + USJB Projects + Full SJR Withdrawal	11.9	537	-5.5%	6.69	683	-5.4%
2030 Base + USJB	12.22	619	9.1%	7.02	793	9.9%
2030 + USJB + Half SJR Withdrawal	12.12	596	5.0%	6.93	765	6.1%
2030 + USJB + Full SJR Withdrawal	12.04	576	1.5%	6.87	741	2.8%

downstream at Christmas. **Thus, despite the initial (and intuitive) assumption that water withdrawals would reduce river flows and stage, the modeling revealed that both variables in fact would *increase* under the full withdrawal condition, assuming management of the upper basin to bring water back into the system and the 2030 land use condition.**

These results should not be interpreted to mean that stage and flow would *never* fall below the 1995 baseline condition, but rather that on average both variables would increase. Temporal changes in stage and flow were represented as the difference in stage at Cocoa between the 1995 land use baseline case for zero withdrawal vs. half or full withdrawal (see Figure 2-2). Each dot in the figure represents a day, such that lines of dots indicate “events.” Figure 2-2 indicates that a full withdrawal could, at times, lead to as much as 0.7 ft drop in stage around the 10-11 ft water level. It should be noted that there are smaller stage and flow differences on either side of the 10-11 ft mark because (1) when there is less water in the river, the full withdrawal is not permitted, and (2) when there is more water in the river, the effect of a withdrawal becomes less important on a relative scale.

Copyright © National Academy of Sciences. All rights reserved.

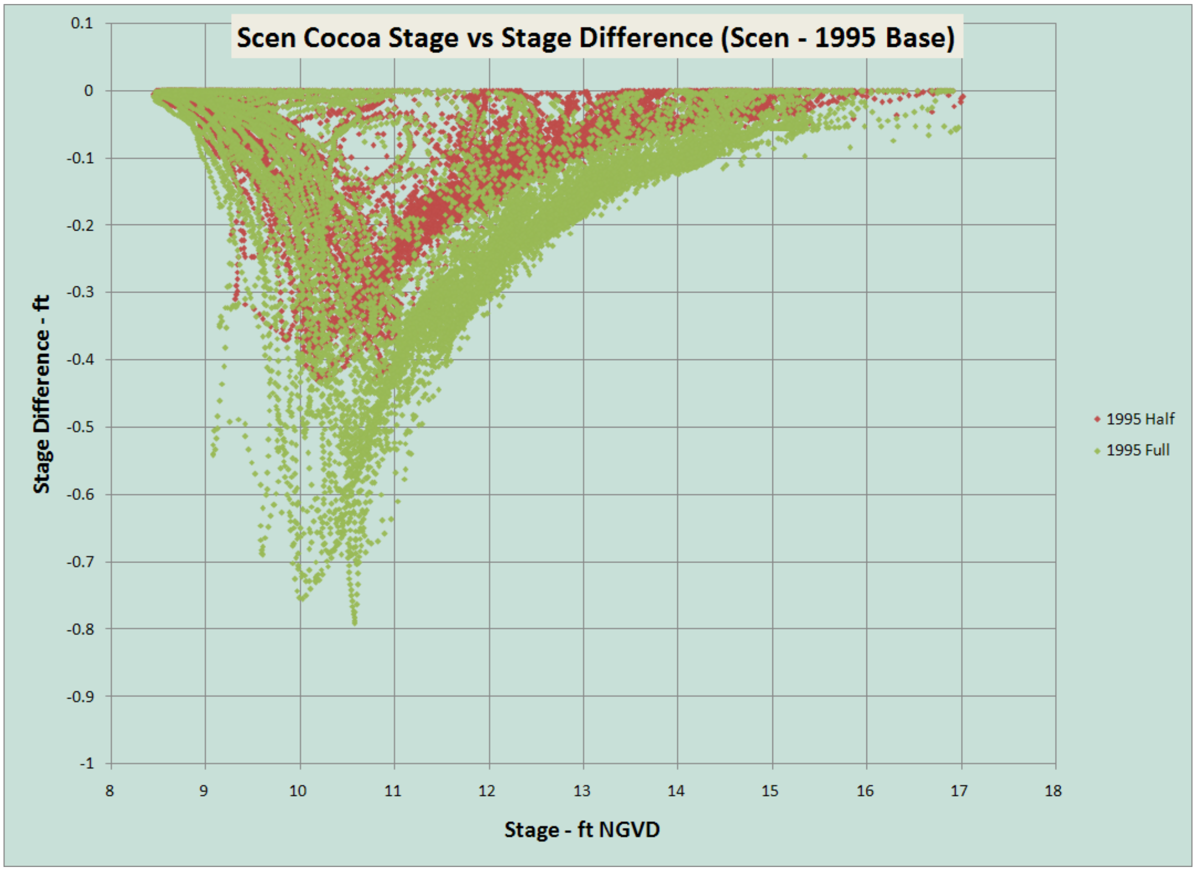


FIGURE 2-2 Changes in Stage Difference at Cocoa Under Various Water Withdrawal Scenarios assuming 1995 Land Use.
SOURCE: Jobes (2010).

The analysis shown in Figure 2-2 was repeated with the 2030 land use scenario, sea level rise, and upper basin project management included (Figure 2-3). This scenario brought so much water into the river that the effects on stage were reversed compared to Figure 2-2. For example, at Cocoa there was a 1.5-ft *rise* in stage at the 11-12 ft mark because the upper basin project and the 2030 land use more than compensated for any loss in stage from water withdrawal. The modeled results indicate that the effect of the upper basin projects would taper out as stage rises, because the projects will store water in the upper basin at high flows. As seen in Figure 2-3, there still would be some events where the water level drops below the baseline condition, but most of the curves are around zero. The same results were observed at Christmas, although the graphs are "noisier" at this location.

Copyright © National Academy of Sciences. All rights reserved.

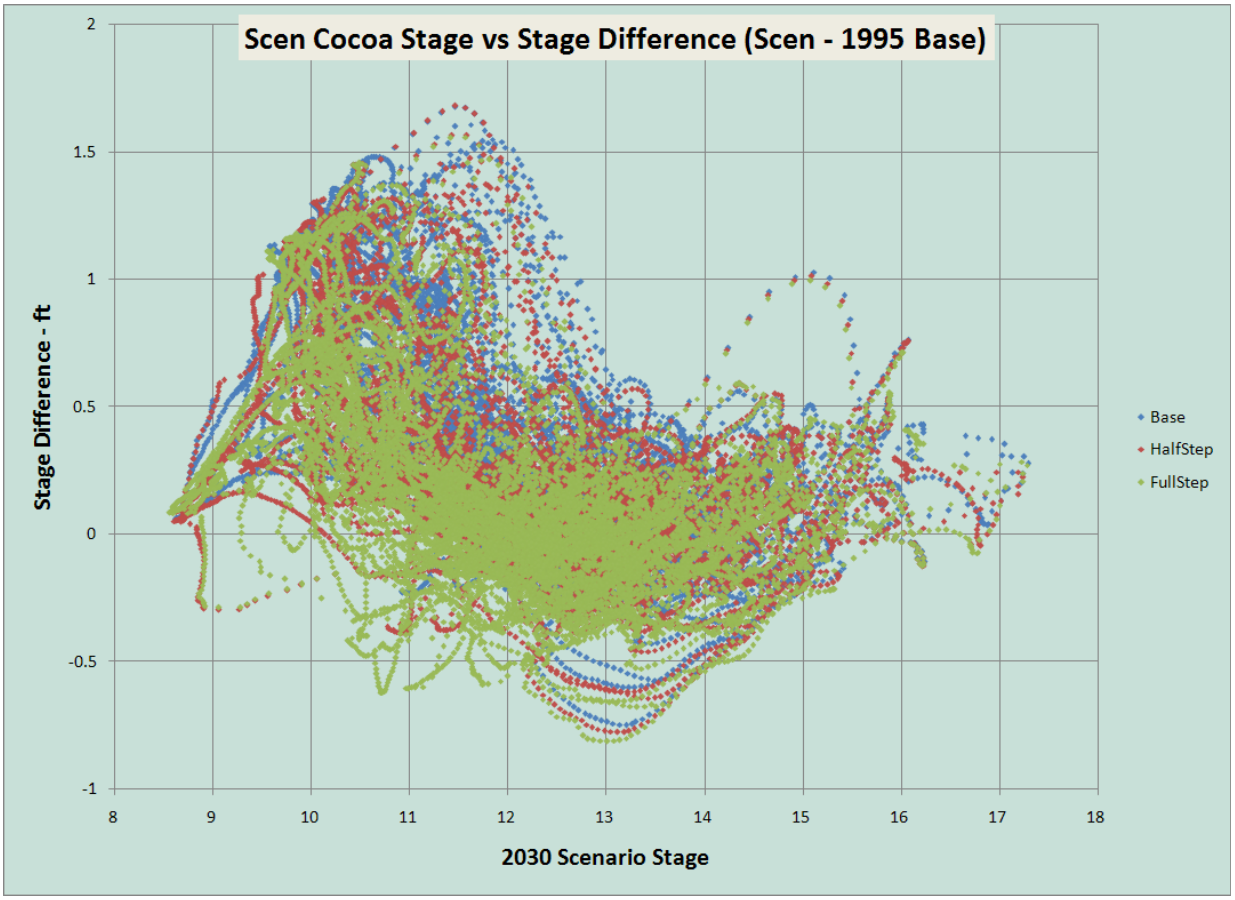


FIGURE 2-3 Changes in Stage Difference at Cocoa Under Various Water Withdrawal Scenarios assuming 2030 Land Use and Upper Basin projects.
SOURCE: Jobes (2010).

It should be noted that the modeling studies predicted that full withdrawal plus the Ocklawaha withdrawal would lead to a 9.3 percent decrease in flow in the Ocklawaha River basin compared to the 1995 baseline condition. However, the impacts of the reduction in flow to the Ocklawaha River at the Rodman Reservoir are not part of the WSIS and consequently are not analyzed further in this report.

Copyright © National Academy of Sciences. All rights reserved.

Chapter 3

Model Limitations and Other Recommendations

Several issues affect the ability of the models to accurately predict the hydrologic and hydrodynamic changes that will accompany proposed water withdrawals into the future, in particular climate change and limitations imposed by the calibration process, as discussed below. Not all the District's studies related to these topics have been completed, and the following discussion thus focuses on suggestions for addressing them.

In addition, the increased amounts of urban stormwater runoff that would be a major source of water compensating for the WSIS withdrawals have important implications with regard to both water quality in the St. Johns River and on water quantity—flow and stage, as predicted by the hydrologic modeling. These implications and the role of stormwater management in influencing future conditions in the river are discussed below.

CHANGING CLIMATE

Some comments are warranted on the likely limitations of the models in a changing climate, given its growing importance. The hydrologic model for the 2030 land-use conditions will be tested using rainfall/potential evaporation data based on historic records. Hydrological scientists presently are grappling with how to handle the non-stationarity of climate, and this remains an open and important research question. While it is unlikely that simply assuming future rainfall will be the same as past rainfall is valid, models or methods to predict reasonable future rainfall distributions do not exist. Indeed, one cannot even adequately discern the direction of the change, that is, whether rainfall will decrease or increase in the St. Johns River basin over the next 20 years. The District thus can do little directly to address impacts of climate change in the WSIS. District managers should keep in mind, however, that **decisions based on model predictions using historic rainfall conditions will need to be revisited as the state-of-the-science improves.** Water supply levels that have had demonstrably low impacts under historic conditions could prove to be ecologically problematic under conditions of a changing climate. Conversely, it is also possible that the climate change could make more water available without ecological harm. Adaptive management and ongoing scientific studies are a necessary part of making sure that future withdrawals from the St. Johns River are ecologically sustainable.

Copyright © National Academy of Sciences. All rights reserved.

CALIBRATION LIMITS

The hydrologic model was calibrated using observed meteorology and observed rainfall with fixed (1995) land use over the decade 1995 to 2006. Land-use changes that occurred over the decade of calibration and affected the measured runoff thus were subsumed into the calibration rather than represented explicitly in the calibration process. In effect, the model calibration knob for process 'A' was tweaked to account for changes in process 'B'. Inherently, this limits the reliability of the model outside its calibrated time span. There is little that the District can do about this problem, as developing year-by-year land use maps for use in calibration probably is impractical. The District, however, should acknowledge the ambiguity that this approach introduces into modeling results for the 2030 land use scenarios. There is no reason to expect that a calibration based on 1995 land use and 1995-2006 runoff, when applied to 2030 conditions, will result in a model with the same level of accuracy as that for the calibration period itself. The 2030 conditions move the model outside of its calibration range, and consequently the level of error is unknown. This was discussed in the outside peer review of the modeling approach (INTERA, 2009, page 7), where it was noted that:

> *Given the uncertainty in the calibration,... caution should be used in predicting contributions of future land use. This would be especially true given large swings in impervious land use... Exaggerating a small error when up-scaling to the future land use condition would erroneously allow the model to simulate more water is available.*

Some insight can be obtained by a quantitative evaluation of the model outside its calibration range using newer data. **It is recommended that the District apply the model (without further calibration) to 2009-2010 land use conditions and 2009-2010 observed rainfall and streamflow to provide a basic understanding of how the model behaves for a case outside the calibration range that has observed data.**

DEPENDENCY ON URBANIZATION AND RESULTING STORMWATER FLOW

A key problem inherent in water budget studies on urbanizing catchments is that increasing impervious surfaces tends to decrease water fluxes through the vadose zone and increase surface water flow. The net effect is to decrease transpiration losses and thus increase the surface water available for withdrawal. Taken to its logical (but absurd) extreme, an entirely paved catchment has the maximum harvestable water. It follows that the predicted land use may be the critical driver of the study results for flow and level impacts. The predicted land use is taken as a "given" in the District's study, however, rather than as a variable subject to study and analysis. **The District needs to evaluate how errors in land-use predictions affect the allowable withdrawals.**

More broadly, a review of how stormwater is considered in the WSIS is warranted. Post-development stormwater management requirements are specified in Chapter 40C-42 of the Florida Administrative Code and Section 10.2.1 of the St. Johns River Water Management District Applicants Handbook *Management and Storage of Surface Waters*. Future changes in land use are subject to specific requirements regarding the management of stormwater for quality and quantity impacts on receiving waters. At present, stormwater *quality* is primarily managed by the requirement of wet or dry detention or retention systems designed (depending on site conditions) to retain specified depths of rainfall/runoff from pervious and impervious areas, with

Copyright © National Academy of Sciences. All rights reserved.

the resulting storage volume being released later or recovered through soil infiltration within specified time limits. The effectiveness of detention/retention systems in removing the pollutants found in urban stormwater is variable (see Chapter 5 in NRC, 2009c). In general, such systems are moderately effective in removing suspended matter by simple settling processes, but they do a poor job removing pollutants present in the dissolved state or sorbed onto colloidal material.

The chemical composition and quality of urban stormwater is highly variable (e.g., Brezonik and Stadelmann, 2002; NRC, 2009c Chapter 3) and depends on numerous factors, including characteristics of the rainfall event (e.g., duration, intensity), nature of the land cover and land use activities in the drainage area, and geographic and seasonal factors. Six major categories of pollutants occur in urban stormwater: nutrients, suspended matter, heavy metals, organic contaminants (especially pesticides from lawns and gardens and polynuclear aromatic hydrocarbons from paved surfaces), chloride salts from street deicing (in northern climates), and (potentially pathogenic) microorganisms. Among the heavy metals, copper and zinc are of growing concern with regard to urban runoff quality because of the widespread nature of urban sources for these metals and their toxicity to aquatic organisms. Several of these categories of pollutants (especially nutrients) are already of concern with regard to water quality in the St. Johns River, and expansion of urban land with the consequent increase in stormwater runoff loading to the river could exacerbate water quality problems in the future.

Stormwater *flow* is managed by the implementation of temporary storage facilities for the attenuation of peak discharge to near pre-development rates (see Figure 3-1). Specific requirements are mandated for storms of various return periods and durations, depending on site conditions and location within the overall St. Johns River basin.

Although the *rate* of stormwater runoff is constrained by regulation to predevelopment values (and then only for certain sized storms), the *volume* of runoff from post-development land uses (residential, industrial, and commercial) is greater than that of the land covers (agriculture, forest, and range) they replace. This is because of lower infiltration and evapotranspiration from

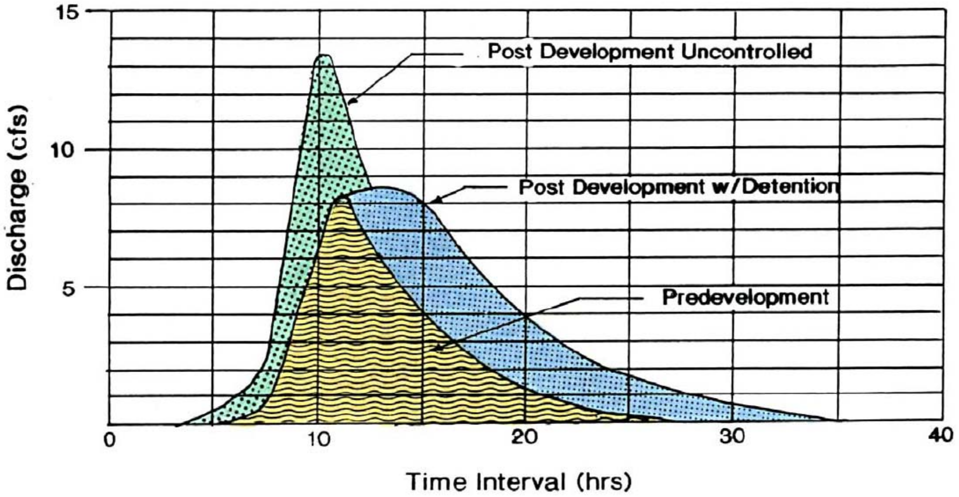


FIGURE 3-1 Example Predevelopment and Post-Development (Managed) Stormwater Hydrographs.
SOURCE: Tom Bartol, SJRWMD, personal communication, June 2010

Copyright © National Academy of Sciences. All rights reserved.

impervious surfaces than from surfaces covered with vegetation. The altered hydrologic regime that accompanies urbanization leads to a variety of well-known geomorphologic changes in streams, such that they have been named the Urban Stream Syndrome (NRC, 2009). The increase in stream flow and volume tends to mobilize sediment both on the land surface and within the stream channel, the latter leading to channel encision and degradation of riparian wetlands. The higher flow volumes and peak discharge caused by urbanization also tend to preferentially remove fine-grained sediment, leaving a lag of coarser bed material. The geomorphic outcome of these changes is a mix of enlargement of some stream reaches, significant sedimentation in others, and potential head-ward downcutting of tributaries. There is consequent deterioration of stream biogeochemical function and declines in species diversity and indices of biotic integrity in such streams. These effects are compounded by human actions to improve drainage, such as channel straightening and lining to reduce friction, increasing flow capacity, and stabilizing channel position. The potential deleterious impacts of these increased flows and volumes and changes in the temporal distribution of flows are not currently considered in the WSIS.

The net impact of modeled land-use change on mean flow of the river at Cocoa and Christmas would be approximately 40 and 60 MGD, respectively (compare the second and third set of rows in Table 2-2). By itself, this contribution to flow would more than replace water taken under the half withdrawal scenarios at both of these locations, as well as the full withdrawal scenario at Christmas. Moving in the downstream direction, the cumulative amount of population growth-driven land-use changes and the resulting runoff increase. In total, the mean daily flow increase due to modeled changes in land use between 1995 and 2030 would be 90 MGD in the upper St. Johns River basin, and additional increases of 86 and 193 MGD would occur in the middle St. Johns River basin and lower St. Johns River basin, respectively (derived from Table 73, Cera et al., 2010).

The modeling results thus indicate that future stormwater additions to mean flow of the river more than offset the proposed withdrawals. For model development, the stormwater management conditions in place in the 1995 base year are incorporated in HSPF implicitly via the calibration. The modeled stormwater impact on river flow as a result of forecast changes in land use during the planning period is based on those same calibrations.

As a result of concerns expressed by this Committee with respect to quantity and quality of increased stormwater runoff, the District performed a comparative case study (Cera et al., 2010). To create the case study, the HSPF model of the Little Econlockhatchee River was modified to explicitly incorporate the quantitative stormwater best management practices (BMPs) specified by Florida statute. The difference between using the 1995 calibration relationship and the case study is only 1 percent, which suggests that use of the prior calibration is an acceptable simplification of the explicit modeling of BMPs relative to water quantity issues.

To obtain an outside review of the District's use of HSPF for the WSIS, the firm Intera was retained to review the watershed modeling effort. Among the recommendations for improvement, several were concerned with the way stormwater management was considered (INTERA, 2009), and these concerns were addressed in subsequent model runs. In particular, the percentages of "directly connected impervious area" of residential and industrial land use were reduced to near the recommended values, and these results were made consistent throughout the entire basin. Impervious area retention storage was universally increased to 0.1 inch, and storage attenuation for both pervious and impervious land areas was taken into account.

Copyright © National Academy of Sciences. All rights reserved.

Given that the WSIS demonstrates that the population growth-driven changes in land use will more than offset the proposed withdrawals, **the Committee urges that as much attention be given to potential water quality and other environmental impacts of future *increases* in flows and levels and in the temporal distribution and routing of flows as to the potential for decreases in flow and levels.** In particular, water quality impacts of increased urbanization on downstream reaches need further study, with particular attention to effects of increased loadings and concentrations of nutrients, heavy metals, and pathogenic organisms. In addition, the effects of urbanization, including increases in impervious areas and changes in stream morphology resulting from altered flows, on the biotic integrity of streams in the drainage basin also need more attention.

CONFOUNDING PROCESSES

Whether the hydrological model can adequately quantify confounding processes outside the calibration range is doubtful. "Confounding processes" are processes whose effects are large but in the opposite direction such that they tend to cancel out, leaving a smaller residual effect. One might accept, for example, that the hydrologic model, calibrated for existing land use and rainfall, can reasonably predict impacts associated with a scenario for increased water withdrawals (reducing flows and levels). Likewise, one might accept that the calibrated model can be used to estimate the effect of a scenario for increasing urbanization (increasing flows and levels) for the existing withdrawals. These scenarios have confounding processes, however, because they have effects in opposite directions. Both scenarios have model errors that should be a fraction of the modeled impact. There is no reason to think, however, that the errors will be of similar magnitudes or opposite directions. It follows that the model error for a scenario combining withdrawal and urbanized land use may be much different than the predicted net impact.

To illustrate this problem, assume that a measurable impact of water removal on some flow condition is −5 ± 10%, and the impact of urbanization is +6 ± 10%. The net impact is *not* likely to be +1 ± 10%, but is instead likely to scale on the sum of absolute errors of the individual scenarios; e.g. −5 ± 0.5 and +6 ± 0.6, resulting in a net impact of +1 ± 1.1 or +1 ± 110%. Consequently, even though a model might predict the major impacts in a given direction by ± 10%, when processes are confounding, the error generally scales on the magnitude of the individual processes, not on the net effect. The error thus may be large relative to the estimated impact. Even with the best possible model, confounding processes outside the calibration range can lead to uncertainty in the prediction that is larger than the magnitude of the predicted impact. **The District's analysis of model results across the scenarios should carefully consider which scenarios have confounding processes and which do not.**

APPLICABILITY OF HSPF TO WETLANDS HYDROLOGY

The HSPF model that the District is using to predict hydrological changes for the different water withdrawal scenarios has limited value for modeling wetlands because HSPF output does not include water table elevation data. Essentially HSPF models water infiltration to the active groundwater, and this water either becomes base flow to the river or is "sunk" to the

Copyright © National Academy of Sciences. All rights reserved.

inactive groundwater (i.e., it leaves the system). The model does not include changes in water table elevations, it does not describe how the surficial groundwater interacts with wetlands as part of its output, it does not take into account water storage in wetlands, and it does not simulate wetland interactions with the river or with the unconfined water table aquifer. All of these are important components of the wetland's hydrologic signature. Floodplain wetlands in the watershed tend to be hydrologically "vertical," i.e., water moves up and down through the soil more rapidly than it moves horizontally. Groundwater inflows thus are an important water source when the floodplain is not inundated, and HSPF does not model this process adequately.

There are also issues of spatial resolution regarding use of HSPF for wetland impacts. The model is run for each of 411 subbasins that have been delineated in the watershed, but this does not provide enough spatial resolution to investigate wetland impacts. A key question that the wetlands workgroup has identified is how the duration of wetland inundation might be altered. To fully address this, spatially referenced wetland elevation and plant community data are needed. HSPF provides surface water level data in the subbasins but does not provide results on wetland hydrodynamics because the model cannot predict spatially variable changes in groundwater levels.

To help address the above issues and shortcomings of HSPF with regard to wetlands, the wetlands workgroup is adopting the Hydroperiod Tool from the South Florida Water Management District. This tool estimates daily water depth over an area by subtracting the ground surface elevation (obtained from a digital elevation model or DEM) from an interpolated water surface elevation model based on river stage, and it can be used to estimate hydroperiods. In essence the wetlands workgroup will take the output from the HSPF model and distribute it over the landscape. Where adequate DEMs are available, this approach should aid the workgroup in accomplishing its goal of analyzing the correspondence between river stage and wetland hydroperiod.

District scientists have made little progress in analyzing the empirical water level data available from transects established for previous work to establish minimum flow and levels (MFL) rules, and this lack of progress is hindering the progress of the wetlands workgroup. Having requested this analysis since May 2009, the committee is at a loss to understand the delay and urges the workgroup to undertake this analysis soon. These data have the potential to provide considerable insight into the response of the different wetland types to water withdrawals. When analyzed, these data should give the workgroup a much-improved understanding of floodplain wetland hydrodynamics.

Finally, the Committee has several concerns about the proposed plans for data analysis by the wetlands workgroup. First, there are inconsistencies in the data needs presented and the plans for using the data. For example, an informal District document outlining the hydrologic data needs of each workgroup (and requested by this committee) states that salinity data are required by the wetlands workgroup to assess the potential for changes to wetland plant communities due to altered salinity levels, but no plan is presented for how these data will be employed. To tackle this question, the wetlands workgroup could focus an analysis of the impacts of increasing salinity on different wetland community types where information on salinity stress exists (i.e., literature values that indicate at what salinity level will a given community, such as hardwood swamps, begin to show stress). In contrast, they might focus on the dominant species in a given community (for example, cypress trees in hardwood swamps). It should be noted that much about the plant's ability to tolerate salinity shifts will be tied to when the salinity peaks are experienced (season), for how long, and at what recurrence frequency.

Copyright © National Academy of Sciences. All rights reserved.

Second, questions remain about the GIS and STELLA modeling work planned by the wetlands workgroup in conjunction with the biogeochemistry workgroup. The groups propose to use DEM and vegetation maps in a STELLA model to project water elevations at certain locations. It is unclear whether the proposed STELLA model will be linked directly with the GIS database. In the committee's view, this is the only way to make the STELLA modeling output spatially explicit. Because the committee views this as an ambitious undertaking, it is unlikely to be an optimal use of staff resources at this point in the project, and may distract from the other efforts described above.

Copyright © National Academy of Sciences. All rights reserved.

References

Belaineh, G., et al., 2010. Estimation of Volume and Chloride Flux From the Upper Floridan Aquifer to the St. Johns River, Florida, in Support of the Water Supply Impact Study. Palatka, FL: St. Johns River Water Management District.

Brezonik, P. L., and T. H. Stadelmann. 2002. Analysis and predictive models of stormwater runoff volumes, loads, and pollutant concentrations from watersheds in the Twin Cities (Minnesota, USA) metropolitan area. Water Research 36:1743-57.

Cera, T. 2010. Hydrology of the St. Johns River Watershed. Presentation to the NRC Committee. St. Augustine, FL. March 29-31, 2010.

Cera, T., D. Smith, M. G. Cullum et al. 2010. Watershed Hydrology and Modeling of the St. Johns River Watershed. St. Johns River Water Management District, Palatka, Florida, 511 pgs.

INTERA. 2009. St. Johns River Watershed Water Supply Impact Study Model Review (for SJRWMD). Palatka, FL: St. Johns River Water Management District.

Jobes, T. 2010. WSIS USJRB Withdrawal Scenario Results. Presentation to the NRC Committee. St. Augustine, FL. March 29-31, 2010.

NRC. 2009a. Review of the St. Johns River Water Supply Impact Study: Report 1. Washington, D.C.: National Academies Press.

NRC. 2009b. Review of the St. Johns River Water Supply Impact Study: Report 2. Washington, D.C.: National Academies Press.

NRC. 2009c. Urban Stormwater Management in the United States. Washington, D.C.: National Academies Press.

SJRWMD. 2008. Alternative Water Supply Cumulative Impact Assessment, Interim Report-Draft. Lowe, E. F., L. E. Battoe, and T. Bartol (eds.). Palatka, FL: St. Johns River Water Management District.

SJRWMD. 2009. The Small Area Population Projection and Distribution Methodology of the St. Johns River Water Management District for the 2008 District Water Supply Assessment and the 2010 District Water Supply Plan, SJ2009-SP7, (by GIS Associates, Inc.). Palatka, FL: St. Johns River Water Management District. Stadelmann, T. H., and P. L. Brezonik. 2002. Analysis and predictive models of stormwater runoff volumes, loads, and pollutant concentrations from watersheds in the Twin Cities (Minnesota, USA) metropolitan area. Water Research 36: 1743-57.

Sucsy, P. 2010. Hydrodynamics of the Lower and Middle St. Johns River. Presentation to the NRC Committee. St. Augustine, FL. March 29-31, 2010.

Sucsy, P., E. Carter, D. Christian, K. Park, J. Stewart, and Y. Zhang. 2010. Development of a Hydrodynamic Model of the Lower and Middle St. Johns River. St. Johns River Water Management District, Palatka, Florida.

Copyright © National Academy of Sciences. All rights reserved.