MINIMUM FLOW DETERMINATION FOR BLUE SPRING, VOLUSIA COUNTY: THE RELATIONSHIP BETWEEN GROUND WATER DISCHARGE AND WINTER REFUGE FOR MANATEES

DRAFT 7

by

Peter Sucsy
Ric Hupalo
Bob Freeman

Department of Water Resources
St. Johns River Water Management District
Palatka, Florida

September, 1998

EXECUTIVE SUMMARY

This report recommends that the St. Johns River Water Management District (SJRWMD) establish a minimum average flow for Blue Spring, located near Orange City, Florida, in accordance with section 373.042, Florida Statutes. This statute directs the water management districts of Florida to establish minimum flow for surface watercourses. The statute further provides that these minimum flows shall be the limit at which further withdrawals would be significantly harmful to the water resources or ecology of the area. Blue Spring Run is a crucial warm-water winter refuge for manatees, an endangered species. The recommended minimum flow for Blue Spring was selected to maintain a reliable, warm-water winter refuge for the manatee population that relies on this spring.

Blue Spring Run is one of only three large, natural warm-water winter refuges for Florida manatees (*Trichechus manatus latirostris*) in north Florida. The other two refuges, springs associated with the Crystal and Homosassa rivers, are located on the west coast of Florida. Manatees are a tropical species: populations that overwinter in north Florida do so at the northern range of their distribution, and the availability of reliable, warm-water refuges are essential to the survival of these populations. Use of Blue Spring by manatees has grown exponentially since 1972 when the state began prohibiting boating and other human activity within a designated Manatee Refuge in the lower spring run. Some manatees also use artificial warm-water sources, primarily power plant discharges, as winter refuges. However, power plant discharges are unreliable, because plants occasionally shut down for maintenance, and can be phased out as plants age. Blue Spring Run, as a natural warm-water winter refuge, should be maintained

to ensure the survival of the manatee population inhabiting the St. Johns River.

Manatees seek refuge in the warmer waters of Blue Spring Run when the temperature of the St. Johns River drops below 68° F (20° C). The spring water remains a nearly constant 73° F (23° C) all year. Manatees cannot survive indefinitely in water colder than 61° F (16° C), and there are many documented cases of cold-induced manatee deaths during winter freezes throughout Florida. There exists the potential for catastrophic mortality within the St. Johns River manatee population if Blue Spring fails to maintain an adequate warm-water refuge for the duration of a hard freeze.

When the temperature of the St. Johns River is less than the temperature of Blue Spring Run, the denser river water intrudes into Blue Spring Run beneath the lighter spring water. The length of this cold-water intrusion is determined by the stage of the river, the temperature of the river, and the magnitude of the spring discharge. Higher river stage, colder river temperature, and lower spring discharge all increase the length of the cold-water intrusion into Blue Spring Run, resulting in a decrease of useable habitat for manatees.

We evaluated the effect of declining spring discharge on the intrusion of cold water into Blue Spring Run using a three-dimensional hydrodynamic model, EFDC (Environmental Fluid Dynamics Code), to simulate cold-water intrusion events. The results of the numerical simulations provide a comprehensive assessment of the intrusion of cold water into Blue Spring Run over a wide range of hydrodynamic conditions.

The recommended Minimum Average Flow for Blue Spring is 134 ft^3s^{-1} (3.8 m^3s^{-1}), 20% less than the historic average spring flow. The primary consideration for selecting a minimum average flow for Blue Spring was maintaining an adequate-sized winter refuge for manatees during large winter floods. Reduction of average spring flow below the recommended minimum average does not maintain the spring run as a reliable warm-water winter refuge for manatees during periods of cold weather, high river stage, and high manatee attendance.

CONTENTS

Executive Summary ii

List of Figures viii

List of Tables x

Acknowledgments xi

INTRODUCTION 1

SITE DESCRIPTION 3

OVERVIEW OF PROJECT COMPONENTS 6

THE USE OF BLUE SPRING RUN BY MANATEES 8

- Annual Trend of Manatee Use of Blue Spring Run 9
- Thermal Habitat Preferences of Manatees at Blue Spring Run . 10
- Potential for Cold-induced Mortality of Manatees at Blue Spring Run 12

GEOGRAPHIC, HYDRODYNAMIC, AND HYDROLOGIC DATA 15

- Bottom Elevation Data 15
- Shoreline Data 16
- Hydrodynamic and Hydrologic Data 17

HYDROLOGIC ANALYSES 19

Estimates of Daily Stage at Blue Spring 19
Long-term Trend in Rainfall/Discharge Ratio for Blue Spring 19
Correlation between River Stage and Spring Discharge 25

ANALYTIC MODEL OF COLD-WATER INTRUSION INTO BLUE SPRING RUN 26

Theory 26
Application to Blue Spring Run 29

SET-UP, CALIBRATION, AND VERIFICATION OF THE EFDC MODEL 31

Set-up of the EFDC Model 31
Model grid of Blue Spring Run 31
Boundary conditions 33
Calculation of intrusion length 34
Calibration and Verification of the EFDC Model 36

RESULTS OF EFDC MODEL SIMULATIONS 40

Test-set 1: Length of Cold-water Intrusion as a Function of River Stage and River Temperature at Constant Spring Discharge 43
Intrusion events greater than 400 m 43
Intrusion events greater than 280 m 45
Recurrence intervals of maximum annual intrusion length 48
Variability of spring discharge and recurrence of intrusion events 50
Test-set 2: Range of Cold-water Intrusions During Winter Flood Events 53
Intrusions greater than 500 m 54
Intrusions greater than 400 m 55

Intrusions greater than 280 m ... 55
Intrusions during recent winter floods ... 56
Test-set 3: Intrusion Duration Estimates for Blue Spring Run ... 57
Duration curves of intrusion length ... 57
Probability of cold-water intrusion for frequent intrusion events ... 57

DISCUSSION ... 61

Statutory and Policy Guidelines for Determining Minimum Average Flow ... 62
The Effect of Different Intrusion Events on Manatees in Blue Spring Run ... 64
Intrusion events exceeding 500 m ... 64
Intrusion events exceeding 400 m ... 65
Intrusion events exceeding 280 m ... 65
Intrusion events exceeding 80 m ... 66
Preventing Catastrophic Cold-water Intrusion Events ... 66
Maintaining Blue Spring Run as a Reliable Warm-water Refuge for Manatees ... 67
Preventing intrusions exceeding 400 m ... 67
Preventing intrusions exceeding 280 m ... 68

RECOMMENDATIONS ... 70

REFERENCES ... 71

FIGURES

Figure 1. Locator map for Blue Spring Run and surrounding area 4

Figure 2. Map of Blue Spring Run showing Manatee Refuge, Public Use Area, swimming area, spring boil, and boardwalk 5

Figure 3. Flow of information through project components 7

Figure 4. Manatee use at Blue Spring in the winters of 1970-72 and 1975-96 11

Figure 5. Relationship between river stage at Deland and Blue Spring 20

Figure 6. Annual average discharge of Blue Spring and annual rainfall at Deland, Florida for 1932–94 22

Figure 7. Rainfall-runoff mass for the period 1932–44 23

Figure 8. Discharge duration curves for Blue Spring 24

Figure 9. Definition of variables used for theoretical analysis of two-layer flow 28

Figure 10. Model grid of Blue Spring Run and adjacent St. Johns River 32

Figure 11. Simulated intrusion of cold water into Blue Spring Run 35

Figure 12. Isopleths of cold-water intrusion into Blue Spring Run as a function of stage and temperature of the St. Johns River for a constant discharge equal to the historical mean discharge (4.7 m^3s^{-1}) 44

Figure 13. Isopleths of cold-water intrusion into Blue Spring Run as a function of stage and temperature of the St. Johns River for a constant discharge equal to a 20% reduction of the historical mean discharge (3.8 m^3s^{-1}) 46

Figure 14. Isopleths of cold-water intrusion into Blue Spring Run as a function of stage and temperature of the St. Johns River for a constant discharge equal to a 30% reduction of the historical mean discharge (3.3 m^3s^{-1}) 47

Figure 15. Recurrence intervals of maximum annual intrusion length into Blue Spring Run given a range of constant spring discharges 51

Figure 16. Intrusion duration curves, Blue Spring Run, for a range of spring flow conditions 59

TABLES

Table 1. Hydrodynamic and hydrologic data assembled for modeling cold-water intrusion into Blue Spring Run 17

Table 2. Observed and simulated lengths of cold-water intrusion into Blue Spring Run for ten different intrusion events 38

Table 3. Statistical parameters of daily river temperature for each winter month 49

Table 4. Number of winters required to produce at least one intrusion greater or equal to a specified value for three different levels of probability 52

Table 5. Simulated intrusion lengths for a range of winter flood events at a constant river temperature of 12°C 56

Table 6. Statistical parameters used to randomly generate river stage and river temperature for winter conditions 57

Table 7. Percentage of intrusions exceeding a given value for successive reductions of spring flow 60

ACKNOWLEDGMENTS

This study would not have been possible without the cooperation and assistance of the staff at Blue Spring State Park, particularly Joe Kenner and Wayne Hartley. Their documentation of intrusion locations and manatee attendance, and observations concerning the Blue Spring manatee population were invaluable contributions to this study. Lynn Lefebvre, Ph.D. (USGS-Sirenia Project) provided many useful suggestions concerning manatee biology and behavior that were incorporated into this document.

INTRODUCTION

Blue Spring Run is one of only three large, natural warm-water winter refuges for Florida manatees (*Trichechus manatus latirostris*) in north Florida. The other two refuges, springs associated with the Crystal and Homosassa rivers, are located on the west coast of Florida. Manatees are a tropical species: populations that overwinter in north Florida do so at the northern range of their distribution, and the availability of reliable, warm-water refuges are essential to the survival of these populations. Some manatees use artificial warm-water sources, primarily power plant discharges, as winter refuges. However, power plant discharges are unreliable, because plants occasionally shut down for maintenance, and can be phased out as plants age. Blue Spring Run, as a natural warm-water winter refuge, should be maintained to ensure the survival of the manatee population inhabiting the St. Johns River.

Manatees seek refuge in the warmer waters of Blue Spring Run when the temperature of the St. Johns River drops below 20°C. The spring water remains a nearly constant 23°C all year. Manatees begin aggregating in Blue Spring Run in November and leave in March. Manatees use the spring run as a resting area, returning to the St. Johns River during the warmer period of the day to feed. Manatees generally aggregate just upstream of the interface between the warmer water from Blue Spring and the colder water of the St. Johns River.

When the temperature of Blue Spring Run exceeds that of the St. Johns River, the denser river water intrudes into the spring run beneath the lighter spring water. The length of this cold-water intrusion is determined by the stage and temperature of the river, and the magnitude of the spring discharge. Higher river stage, colder river temperature, and lower spring discharge all lengthen the cold-water intrusion into Blue Spring Run.

Declining discharge from Blue Spring could threaten Blue Spring Run as a reliable warm-water winter refuge for manatees. The St. Johns River Water Management District (SJRWMD) estimates that discharge from Blue Spring will decline 16% between 1988 and 2010 if water use increases as projected (Vergara, 1994). Decreased discharge from Blue Spring increases both the frequency and magnitude of cold-water intrusions into Blue Spring Run.

Cold-water intrusion events were simulated using a three-dimensional hydrodynamic model to evaluate the influence of declining spring discharge on the intrusion of cold water into Blue Spring Run. The hydrodynamic model was calibrated and verified with ten observed cold-water intrusion events. The calibrated model simulates steady-state intrusion length for a given combination of river stage, river temperature, and spring discharge.

Simulated cold-water intrusions, over a range of river stages and river temperatures, were analyzed to estimate and compare the magnitudes and probabilities of intrusion events into Blue Spring Run for different spring flow conditions. Duration curves of intrusion length for a range of spring flow conditions were also calculated using Monte Carlo simulation techniques (Maidment, 1993). The results of the Monte Carlo simulations were used to compare the frequency of occurrence of different intrusion events for a range of spring flow conditions.

The results of the numerical simulations provide a comprehensive assessment of the intrusion of cold water into Blue Spring Run over a wide range of hydrodynamic conditions. These results were used to determine the minimum average flow from Blue Spring that maintains Blue Spring Run as a reliable, warm-water winter refuge for manatees.

SITE DESCRIPTION

Blue Spring Run is located in Volusia County, Florida, west of Orange City (Figure 1). The spring run is 650 m long, 20–40 m wide, and discharges into the St. Johns River. The run has fairly steep banks and a channel of sand and fragmented shell nearly devoid of vegetation.

The spring run and surrounding property have been owned and managed by the Florida Department of Natural Resources and then the Florida Department of Environmental Protection (FDEP) since 1972. FDEP manages the lower 280 m of the run as a Manatee Refuge (Figure 2). The Manatee Refuge is that portion of the spring run set aside exclusively for use by Manatees as a winter refuge. Public use of the Manatee Refuge, such as for boating, fishing, or swimming, is prohibited. Manatees usually aggregate in the Manatee Refuge, although on occasion some are sighted farther upstream to the spring boil.

The upper 370 m of the spring run is designated as a Public Use Area. The Public Use Area includes a swimming area located immediately upstream of the Manatee Refuge. Divers use the spring boil to access a series of underground caverns. FDEP constructed a boardwalk along the south bank of the run that includes two observation decks for observing manatees. A fishing pier was constructed at the mouth of the run.

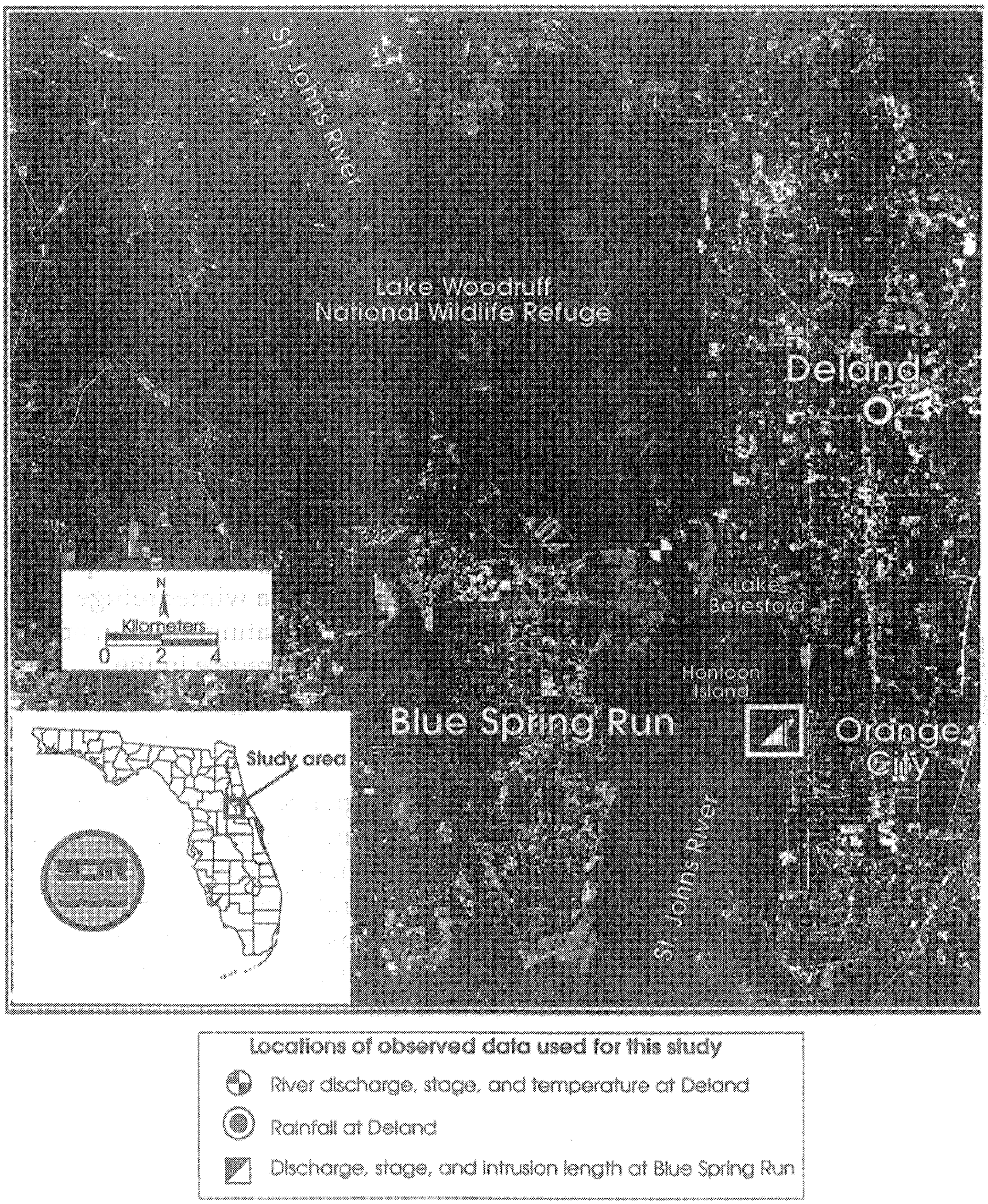

Figure 1. Locator map for Blue Spring Run and surrounding area

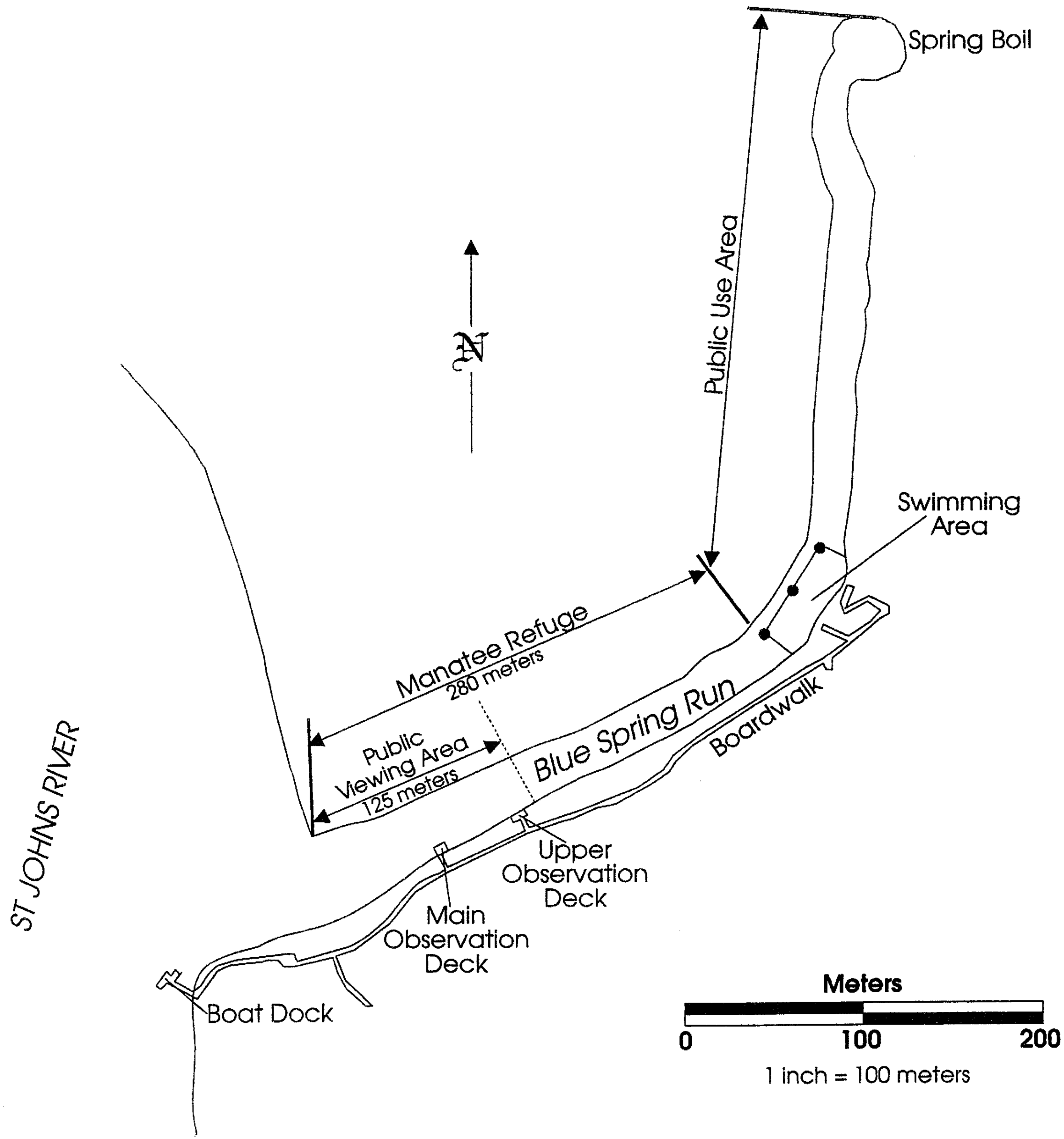

Figure 2. Map of Blue Spring Run showing manatee refuge, public use area, swimming area, spring boil, and boardwalk. Observation platforms allow public viewing of manatees in the lower 125 m of the run.

OVERVIEW OF PROJECT COMPONENTS

This study was designed to determine a minimum average flow for Blue Spring. A minimum average flow describes a spring flow condition that, although less than the historic flow, conserves key ecological functions associated with the historic flow. For Blue Spring Run, we needed to determine the minimum flow required to maintain Blue Spring Run as a reliable winter refuge for manatees. The project components, involving data collection and analysis, literature reviews, and numerical hydrodynamic modeling, that were used to meet this goal are described below and summarized in Figure 3.

After formulating the project goal, SJRWMD contracted with Post, Buckley, Schuh, and Jernigan, Inc. (PBS&J) to perform a bathymetric and shoreline survey of Blue Spring Run. For modeling purposes, SJRWMD staff collected temperature profiles within the spring run and also assembled a data set of concurrent river stage, river temperature, and spring flow describing ten cold-water intrusion events. These data were compiled from FDEP, United States Geological Survey (USGS) and SJRWMD.

An analytical model of cold-water intrusion was used to assess the sensitivity of intrusion length to the various factors affecting cold-water intrusion. The results of this analysis led to an additional bathymetric and shoreline survey around the mouth of Blue Spring Run. These additional data were used with the previously collected data to calibrate and verify a 3-D numerical temperature model of Blue Spring Run.

Long-period data sets of river temperature, stage, and spring discharge were assembled and analyzed to provide statistical parameters of each variable to the numerical model. A review of

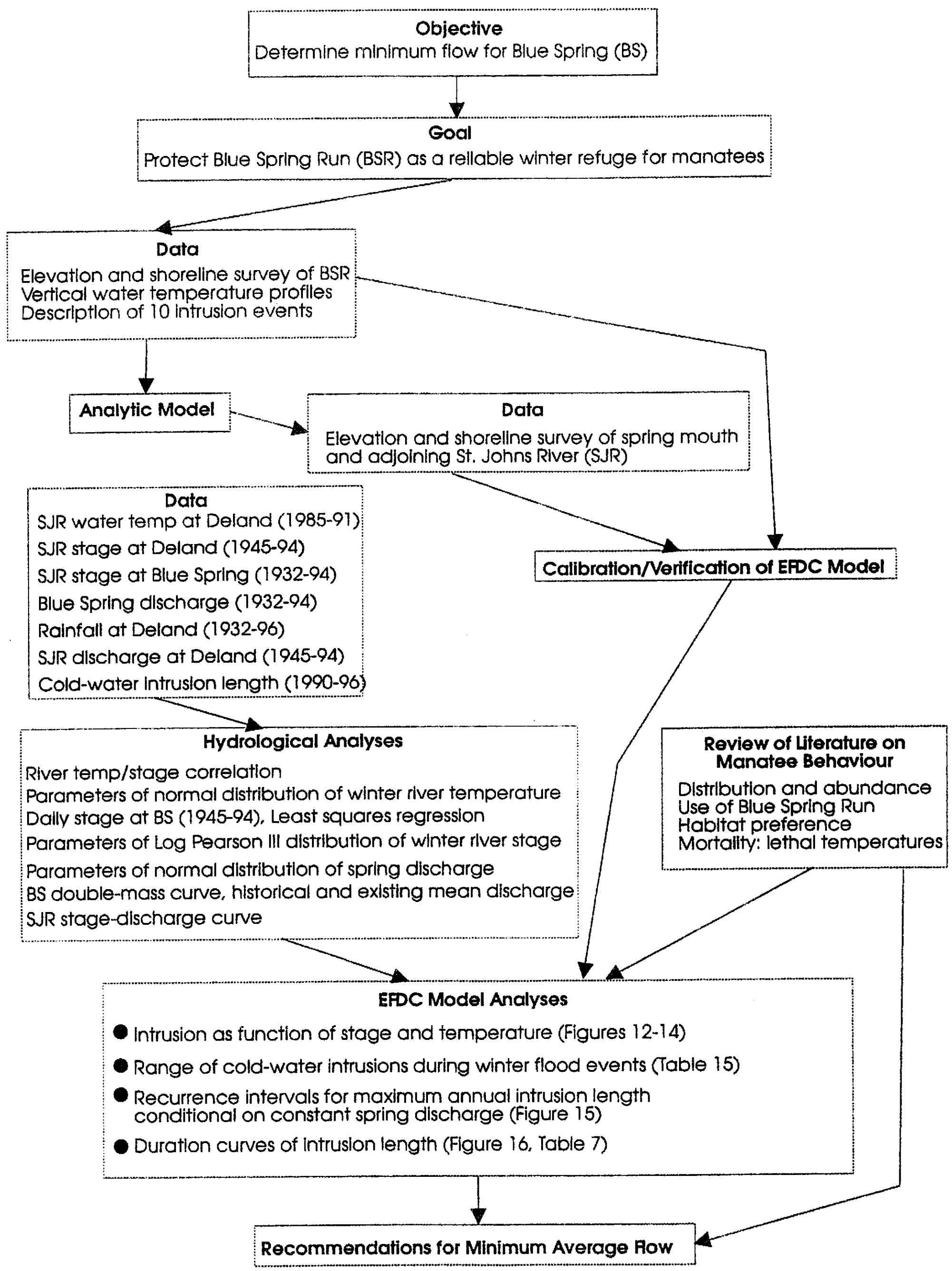

Figure 3. Flow of information through project components

literature on manatee behavior guided decisions on the use of the numerical model for analyzing different aspects of the effect of spring discharge on cold-water intrusion and its impact on the Florida Manatee.

THE USE OF BLUE SPRING RUN BY MANATEES

Manatees are members of a small group of tropical aquatic herbivorous mammals of the order Sirenia. The order Sirenia comprises three species of manatees (Family *Trichechidae*) and one species of dugong (Family *Dugondidae*). A second dugong, Steller's sea cow (*Hydrodamalis gigas*), was hunted to extinction within 25 years of its discovery in 1741 (O'Shea, 1994).

The West Indian manatee *(Trichechus manatus)*, ranges south to the West Indies and through coastal Gulf, Caribbean, and Atlantic waters from Mexico to northern Brazil (Hartman, 1978). The Florida manatee (*T. m. latirostris*) is a subspecies that occurs around peninsular Florida, although some individuals occasionally range north in summer to the Carolinas and Virginia (O'Shea, 1994). The manatee has been designated an endangered species by both the state of Florida and federal government. Seasonal migration to warm-water winter refuges is a unique behavioral characteristic of the Florida manatee that allows their survival in a temperate climate (Hartman, 1979).

Manatees occur in the St. Johns River from Jacksonville to Lake Monroe, although some manatees that use Blue Spring Run as a winter refuge range as far as Miami, 800 km to the south (Personal Communication: Lynn Lefebvre, 1997). Smaller warm-water refuges in the St. Johns River basin include an industrial discharge near Jacksonville; the Sanford and Enterprise power plant discharge canals on Lake Monroe; and Welaka, Silver Glen, and Croaker Hole springs. Small numbers (1–4) of manatees infrequently use these warm-water refuges while migrating to Blue Spring or during unseasonably cold temperatures (USFWS, 1981). Blue Spring Run is the only warm-water refuge in the St. Johns River that manatees, as a population, frequent regularly. Characteristics of Blue Spring Run not duplicated at other warm-water refuges in the region are the large volume of flow, depths of 3–4 m at the entrance to the spring run, and restricted access to recreational water craft (USFWS, 1981).

Most manatees that inhabit the St. Johns River spend non-winter periods foraging and raising calves in the Lake George and lower St. Johns River basins. The first arrival of manatees at Blue Spring occurs after the first cold spell, typically in November or December. Manatees aggregate in the spring run when minimum daily air temperature approaches 10°C and the temperature of the St. Johns River drops below 20°C (USFWS, 1981). Most manatees leave Blue Spring in March or April when minimum daily air temperatures exceed 10°C and the river temperature approaches 23°C (USFWS, 1981). Depletion of aquatic vegetation in the river near Blue Spring might occasionally force manatees to leave the area as early as late February, despite low temperatures (USFWS, 1981).

Annual Trend of Manatee Use of Blue Spring Run

Since 1970, Blue Spring State Park has recorded daily the number of manatees using the spring run, except during the winters of 1972–73 and 1973–74. The number of manatees using the spring run in winter exponentially increased at an average annual rate of 8.2% between 1970 and 1994 (Ackerman, 1995). The number of manatees observed in Blue Spring Run during winter for the period 1970–96 fits an exponential regression curve with an R^2 of 0.96 (Figure 4). The exponentially increasing population indicates that this population might not have yet reached the carrying capacity of the environment. Most of the annual increase of manatees at Blue Spring has been attributed to the reproduction and survival of resident (St. Johns River) animals. However, immigration and subsequent reproduction might explain about one-third of the annual increase (Ackerman, 1995).

Thermal Habitat Preferences of Manatees at Blue Spring Run

Manatees aggregate within Blue Spring Run during cold weather, with the number of manatees present being related to the river temperature (USFWS, 1981). Most foraging trips from the spring run to the river are partially nocturnal and last from 3 to 15 hours (Bengston, 1981). Heat produced metabolically while cruising probably enable the animals to tolerate water temperatures that would be unendurable during inactivity (Hartman, 1979).

Manatees frequent the lower half of the spring run because this portion of the run is (a) nearest to river feeding locations, (b) conducive to bottom resting because of the channel width and morphology, and (c) excluded from human activity. Manatees generally rest upstream of the thermocline between Blue Spring and the river (Bengston, 1981). When the temperature of the lower run drops below 20°C the manatees move farther upstream (Hartman, 1979). While in the spring run, manatees rest on the bottom about 85% of the time, primarily between the mouth of the run and the public swimming area (USFWS, 1981). The animals prefer to rest near mid-channel in 2–3 m of water, prone on the bottom, and facing into the current (USFWS, 1981). Manatees

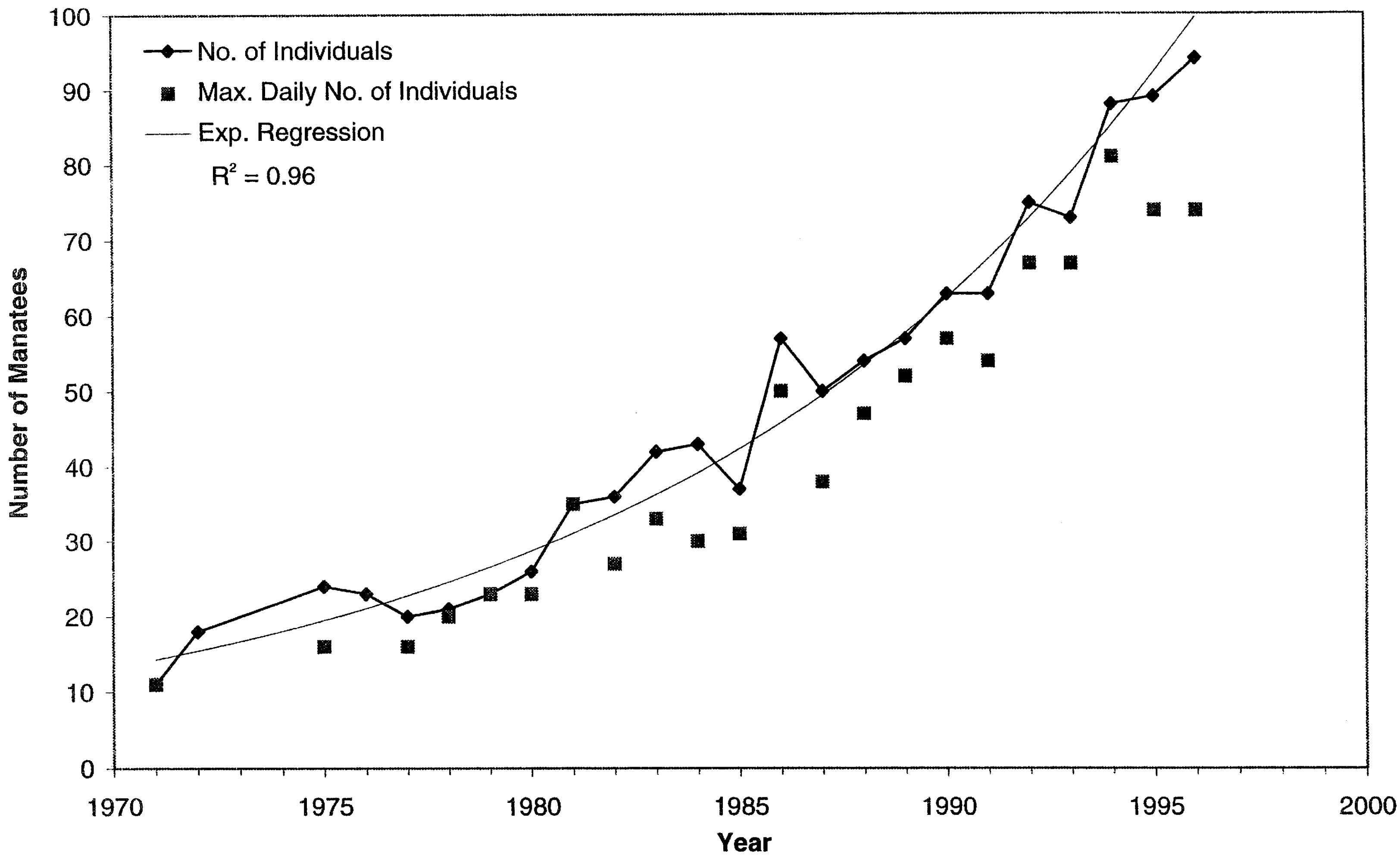

Figure 4. Manatee use at Blue Spring in the winters of 1970-72 and 1975-1996. The trend line (an exponential regression) was calculated from the total number of individual manatees observed in the spring run each winter. Also plotted for each year is the maximum number of animals observed in the spring run on a single day. The maximum number of manatees observed in the spring run on any day was 81 animals. Data are from Blue Spring State Park and are plotted after Ackerman (1995).

generally avoid shallow flats of less than a meter depth unless the flats are immediately adjacent to deeper water (Hartman, 1979).

High river stage following heavy rainfall during the early winter of 1976 caused an intrusion of river water into Blue Spring Run that forced the manatees farther up the spring run than observed in previous years (Waldron, 1981). Manatees have been observed on rare occasions, usually during severe cold spells, at the spring boil resting with their snouts pointed into the limestone cavern (USFWS, 1981; Bengston, 1981). This occurred on 20 January 1977 when the previous night's air temperature reached -6°C (Waldron, 1981). Measurement of water temperatures along the spring run that same morning showed that the temperature of the upper three-quarters of the run was 23°C (Waldron, 1981).

Potential for Cold-induced Mortality of Manatees at Blue Spring Run

The Florida manatee has an exceptionally low metabolic rate, only 15–22% of the rate expected for a mammal of its size. Biologists have speculated that the slow metabolism of a related species, the Amazon manatee (*T. inunguis*), is an evolutionary adaptation to sequential food availability (feast or famine) caused by seasonal flood-drought cycles (O'Shea, 1994).

Slow metabolism is a liability in cold water when manatees cannot metabolize energy fast enough to counter heat loss (O'Shea, 1994). Evidence from necropsies of Florida Manatee supports hypothermia as the primary cause of cold-induced mortality (O'Shea et al., 1985). Necropsies frequently describe cachexia marked by emaciation, severe atrophy of fat, and absence of food in the gastrointestinal tract. Winter mortality of Florida manatees occurs most commonly in late juvenile and subadult manatees (O'Shea et al., 1985). The susceptibility of subadult and juvenile manatees to cold could be related to inexperience finding migration routes, warm-water refuges, or foraging areas within their winter ranges, and is perhaps related to smaller body size and diminished nutritional status (O'Shea et al., 1985).

Manatees cannot survive indefinitely in water that is colder than 16°C (Ackerman et al., 1995). Manatees migrate to warm-water refuges when ambient water temperatures fall below 20°C and daily minimum air temperature falls below 10°C. Manatees rarely move voluntarily into water colder than 15°C (Ackerman et al., 1995). Hartman (1979) observed an estrous cow and seven bulls descend the Crystal River to waters of 15.7°C, whereupon they hesitated, then doubled back upstream. Only three times in Hartman's study did manatees enter water colder than 15°C, and only once did manatees enter water colder than 13.5°C (Hartman, 1979). Foraging trips by some manatees from Blue Spring Run to the St. John River might have occurred (implied by animals missing from consecutive surveys) when the river temperature receded to 12°C (USFWS, 1981). A rehabilitating animal died in a tank when the water temperature fell to 14°C. Feeding by captive manatees became irregular at 18–19°C and feeding and other activities ceased below 16°C (Ackerman et al., 1995).

Cold-related deaths accounted for 10% of all manatee mortality in northeastern Florida during 1986–92 and 2–4% in other Florida regions (Ackerman et al., 1995). State-wide accounting methods did not identify cold-related deaths as a separate mortality factor before 1986. In the winter of 1989–90, 56 cold-related deaths occurred in Florida, the largest recorded mortality from low temperatures. Most of these deaths followed a severe cold front on 24 December 1989. Of the 56 deaths that winter, 44 occurred in northeastern Florida; primarily in Brevard County (31 deaths) where warm-water refuges are unreliable.

Ackerman et al. (1995) reported 38, 30, and 34 cold-related manatee deaths in 1976–77, 1980–81, and 1983–84, respectively. The 38 deaths during 1976–77 occurred near the Florida Power and Light Company power generating plant at Titusville. Intake water temperatures during that winter reached a low of 8°C on 20 January 1977. Outlet water temperatures were below 21°C for most of the winter and dropped to 11°C and 13°C, respectively, during two partial shutdowns. Manatee carcasses were recovered between January and March 1977 and Ackerman et al. (1995) believed that the deaths were caused by low ambient water temperatures combined with further stress from the partial shutdowns.

Cold-related deaths are relatively uncommon near the springs of the Crystal River and Blue Spring because these springs are reliable warm-water refuges (Ackerman et al., 1995). However, the documented cases of cold-induced mortality elsewhere in the state shows the vulnerability of manatees to cold winter temperatures when warm-water refuges either do not exist or are unreliable. There exists the potential for catastrophic mortality within the St. Johns River manatee population if Blue Spring Run fails to provide an adequate warm-water winter refuge when the St. Johns River temperature is below a level tolerable to manatees.

GEOGRAPHIC, HYDRODYNAMIC, AND HYDROLOGIC DATA

Bottom Elevation Data

Bottom elevation data were required for the development of both an analytic model and numerical model of cold-water intrusion into Blue Spring Run. Bottom elevations for Blue Spring Run were obtained from the following two sources:

- A bathymetric survey by Post, Buckley, Schuh, and Jernigan, Inc. (PBS&J), Winter Park, Fla. on 9 June 1995.
- A bathymetric survey by SJRWMD staff around the mouth of the run and an adjacent portion of the St. Johns River on 17 May 1996.

The survey by PBS&J (contract #92G135B) consisted of 50 measurements of bottom elevation along the centerline of the run at approximately 15 m intervals and eight channel cross-sections of the run. Bottom elevation along a cross-section were measured at approximately 1.5 m intervals. All elevations were reported relative to NGVD of 1929.

The bathymetric survey by SJRWMD, around the mouth of the run, consisted of 334 observations of bottom elevation along 13 transects. There were six lateral transects and two longitudinal transects between the spring mouth and main observation deck. There were two longitudinal transects and three lateral transects within the St. Johns River adjacent to the mouth of the run.

Resource-grade GPS (Global Positioning System - Trimble Pathfinder Pro XL) with real-time correction was used to obtain horizontal positioning for the bathymetric survey. Soundings were measured with an Innerspace 448 fathometer and checked with a surveying rod. The horizontal and vertical measurements were correlated using chart-ticks on the fathometer and time-ticks in the GPS data files. Horizontal accuracy was 1–3 m at 95% confidence interval and vertical accuracy was 3 cm at 68% confidence interval (Personal Communication: Roy Wegner, 1997). A reference water level at the mouth of the run was determined from a staff gauge leveled to NGVD of 1929.

Shoreline Data

Shoreline data for Blue Spring Run were primarily obtained from the survey by PBS&J. SJRWMD staff also measured horizontal coordinates at six locations around the mouth of the run using GPS. Three locations were measured along the north shore and three locations were measured along the south shore of the run. Shoreline locations for the St. Johns River were digitized from a SPOT satellite image of 10 x 10 m resolution.

All bathymetry and shoreline data were assembled into a GIS database using ARC/INFO. The GIS database was used to construct the model grid for the three-dimensional numerical model.

Hydrodynamic and Hydrologic Data

The hydrodynamic and hydrologic data required to calibrate and verify the temperature models were obtained from several sources (Table 1). These data included model boundary conditions used to simulate observed intrusion events, and long-term hydrologic data for statistical analyses.

Table 1. Hydrodynamic and hydrologic data assembled for modeling cold-water intrusion into Blue Spring Run

Data Type[1]	Collecting Agency[2]	Period of Record	Interval between Observations
River stage at Blue Spring Run	USGS	1932–present	1–2 months
River stage at Deland	USGS	1945–present	Daily
Spring discharge at Blue Spring Run	USGS	1932–present	1–2 months
River discharge at Deland	USGS	1945–present	Daily
River temperature at Deland	USGS	11/85–9/92	Daily
Cold-water intrusion length at Blue Spring Run	FDEP	1990–present	Daily, winter only
Rainfall at Deland	NOAA	1932–present	Daily

[1]See Figure 1 for station locations
[2]USGS = U.S. Geological Survey; FDEP = Florida Department of Environmental Protection, NOAA = National Oceanic and Atmospheric Administration

Cold-water intrusion length is routinely recorded by park rangers during daily counts of manatees using the spring run. The rangers report plume locations relative to a series of landmarks along the spring run. Visual observation of the intrusion is possible because the intruding St. Johns River water is stained with tannin, while the overlying spring water is clear.

We confirmed that the thermocline between the spring and river water can be visually observed by measuring vertical profiles of temperature and dissolved oxygen within the run and river. The clear spring water had distinctly higher temperature and lower dissolved oxygen than the tannin-stained river water. On 31 January 1996, the surface temperature throughout the run was approximately 23°C and the surface dissolved oxygen was 1.1 mg L^{-1}, indicative of spring water. At the same time, the tannin-stained water within the St. Johns River and underlying the spring water within Blue Spring Run had a temperature of approximately 18°C and a dissolved oxygen concentration of 7.6 mg L^{-1}.

HYDROLOGIC ANALYSES

Estimates of Daily Stage at Blue Spring

Because the data set of river stage at Blue Spring is much sparser than the data set of river stage at Deland (7 river miles downstream), the Deland stage data were used to create a more complete stage record at Blue Spring. A linear, least squares regression was calculated between river stage at Blue Spring and Deland, and daily stage at Blue Spring was estimated from this linear relationship ($R^2 = 0.981$, Figure 5).

Long-term Trend in Rainfall/Discharge Ratio for Blue Spring

We examined the ratio between Blue Spring discharge and Deland rainfall for the period 1932–94 to define a range of discharge for modeling scenarios designed to examine cold-water intrusion into Blue Spring Run. Mean discharge for both historic and existing flow conditions was estimated using the results of a mass-curve of cumulative annual rainfall at Deland and cumulative annual discharge from Blue Spring. Because the mass-curve analysis indicates a declining trend in spring discharge since 1975, we used lower values of discharge in the modeling scenarios than at first seemed warranted under the assumption of no significant decline in Blue Spring discharge from historic levels.

The mass-curve analysis assumes that the Deland rainfall station accurately represents the spatial distribution of annual rainfall over

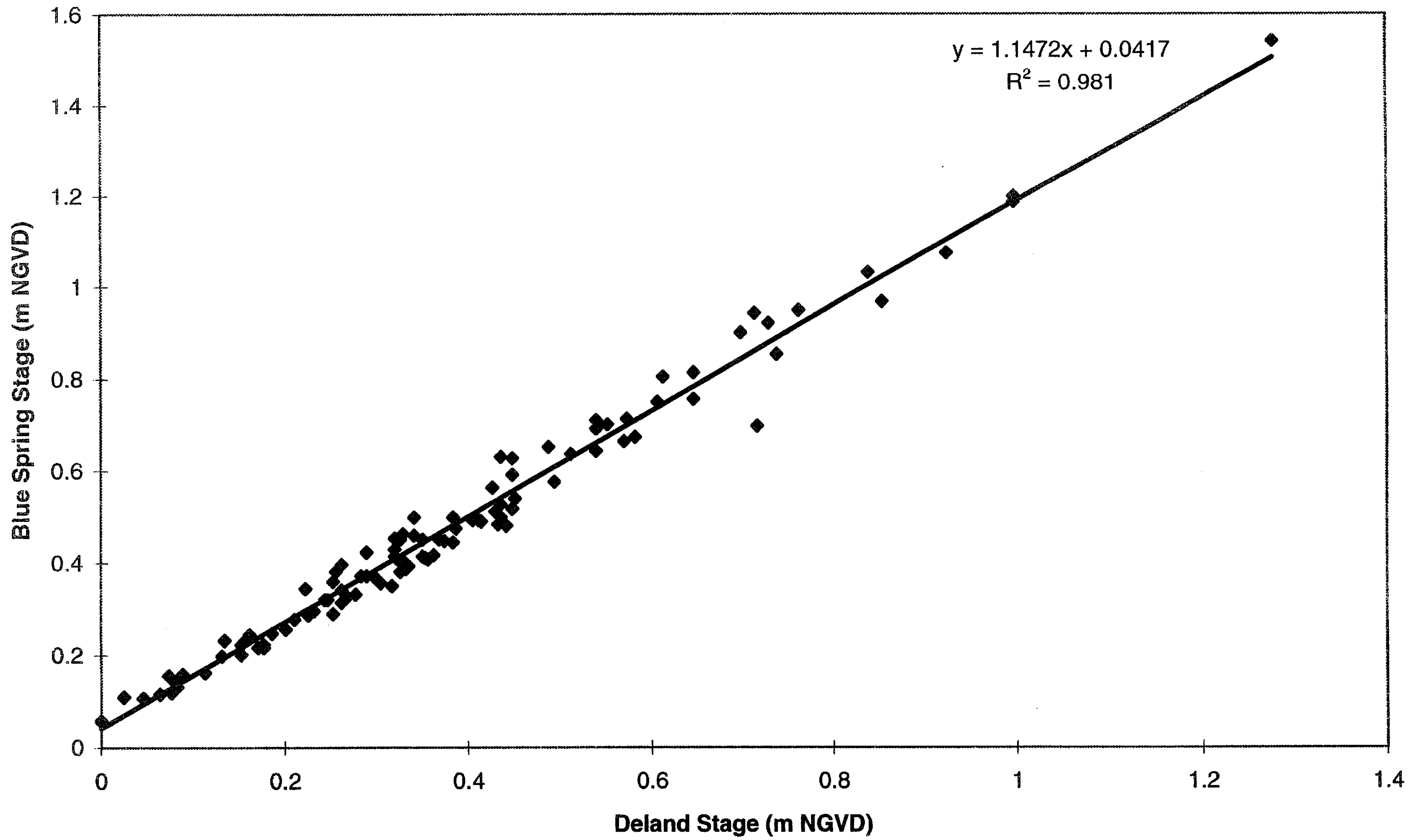

Figure 5. Relationship between river stage at Deland (SR 44) and at Blue Spring. The scatterplot and the coefficient of determination (R^2), calculated from the least squares regression of these data, indicate a strong linear relationship between stages at the two locations.

the recharge area of Blue Spring. This is a good assumption because the recharge area, as defined by Williams (1997) for a groundwater model of Volusia County, is fairly small (approximately 24 x 32 km), and the Deland rainfall gauge lies in an area of high recharge within the recharge area.

The mass-curve analysis was used to examine the trend between annual average discharge from Blue Spring and total annual rainfall at Deland (Figure 6). This analysis indicates that the ratio of spring discharge to rainfall has declined since about 1975 (Figure 7).

A comparison of discharge-duration curves for periods prior to and following 1975 also indicate that Blue Spring discharge has declined since 1975 (Figure 8). Discharges were generally lower during 1976–94 than during 1932–75. In addition, mean spring discharge during the more recent 10-year period of 1985–94 was lower than for the period 1932–75 even though average rainfall was greater. Mean discharge for the period 1932–75 was 4.58 m^3s^{-1} when average annual rainfall at Deland was 1.376 m. Mean discharge for the period 1985–94 was 3.98 m^3s^{-1} when average annual rainfall was 1.503 m.

Although this trend of declining discharge is important to the management of Blue Spring Run as a refuge for manatee, the absolute accuracy of our estimate for discharge decline does not affect our determination of a minimum flow for Blue Spring, which is based on absolute values of spring discharge. The assessment of existing Blue Spring flow relative to either historic flow or our recommended minimum flow is beyond the scope of this report.

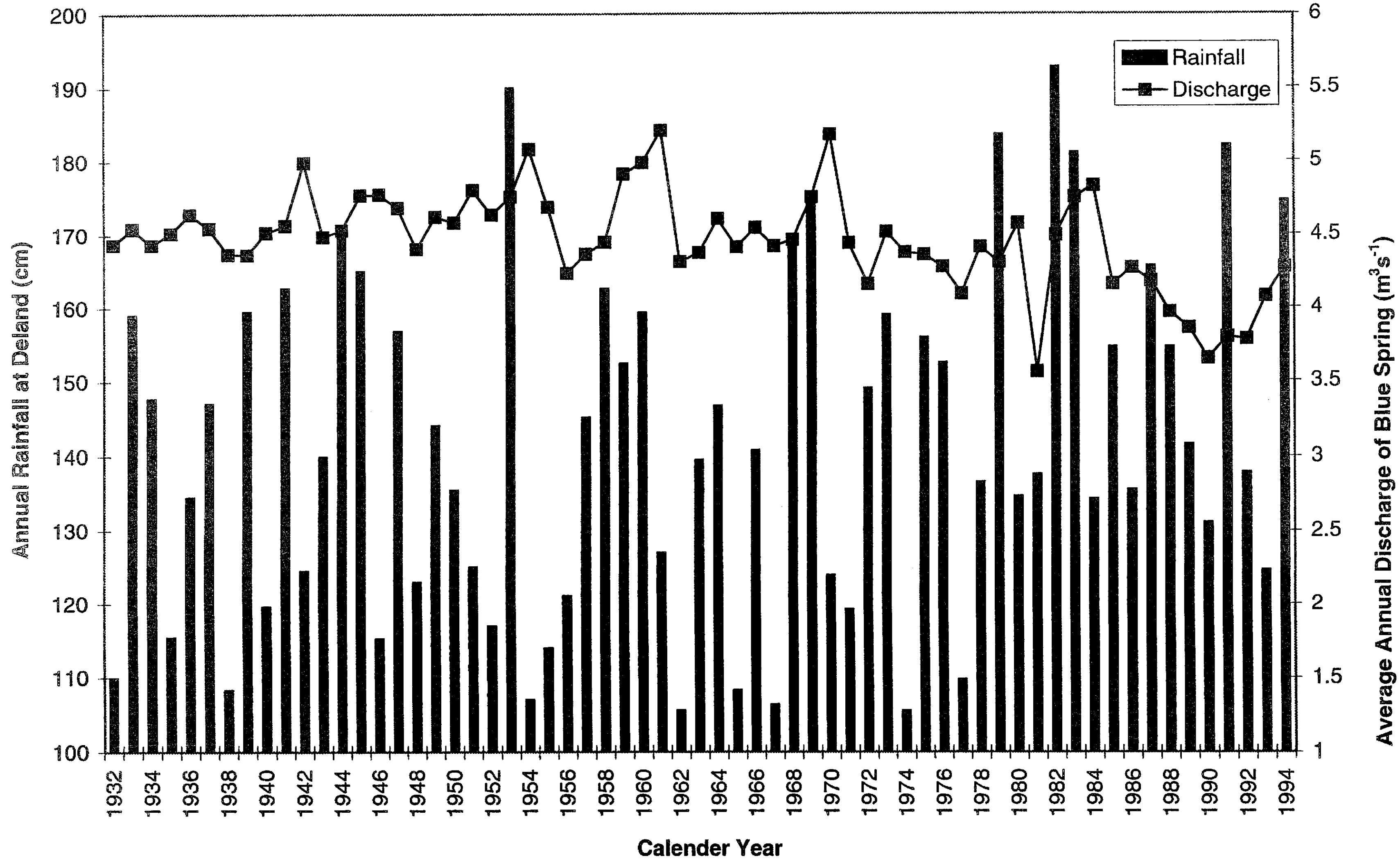

Figure 6. Annual average discharge of Blue Spring and annual rainfall at Deland, Fla. for 1932-94.

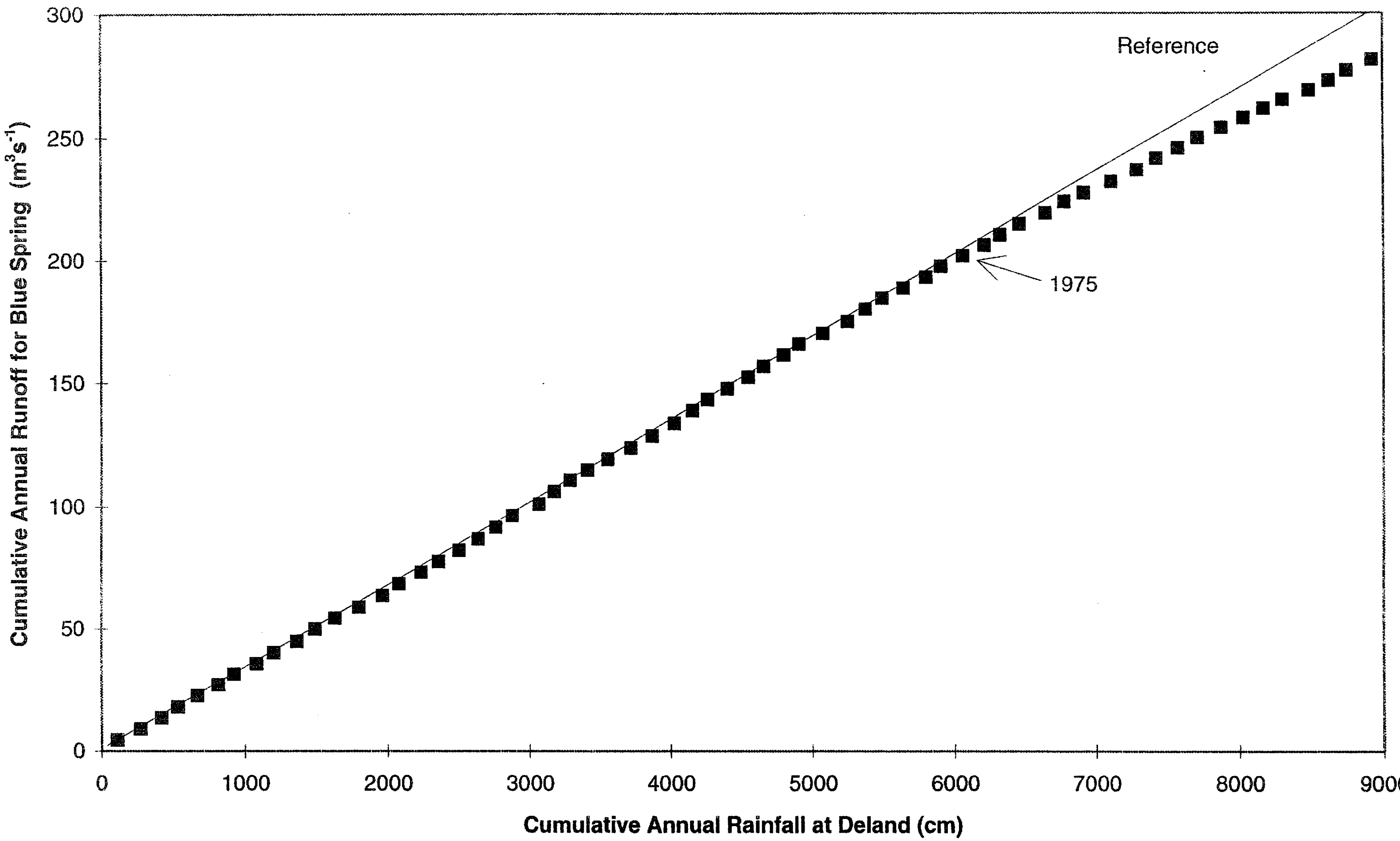

Figure 7. Rainfall - runoff mass curve for the period 1932-94. A straight reference line is added to aid in visually detecting changes in the relationship between the two variables over time. The downward deflection of the data series indicates a decline in annual spring discharge per unit of annual rainfall since 1975.

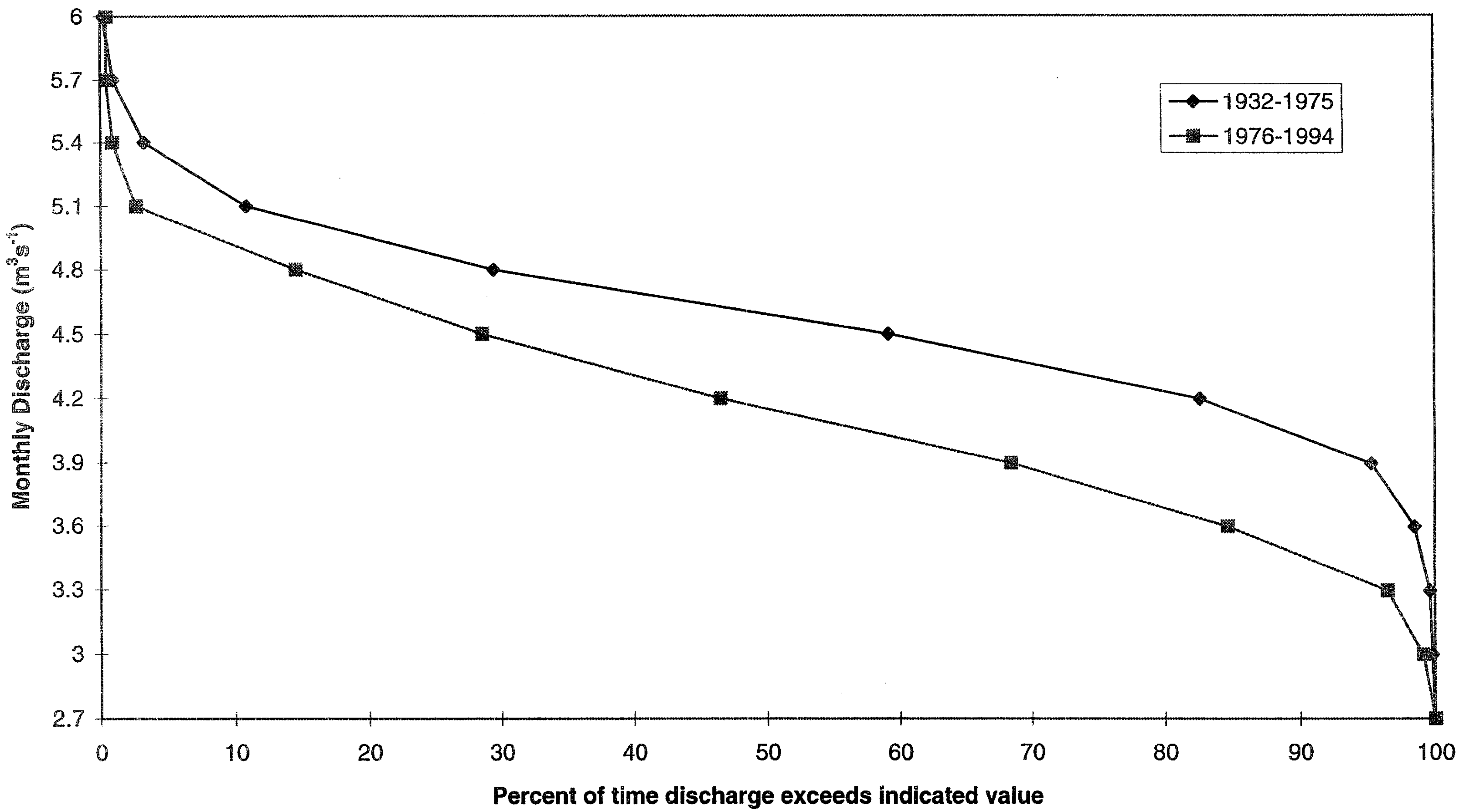

Figure 8. Discharge duration curves for Blue Spring. The percent of time that a discharge quantity is exceeded is shown for two time periods, 1932-75 and 1976-94. These curves show that, except for extreme events, discharges were lower during 1976-94 than during 1932-75.

Correlation Between River Stage and Spring Discharge

We found no correlation between river stage at Blue Spring and Blue Spring discharge. However, a sampling of instances where a change in river stage coincided with a reverse change in discharge, measured at 1–2 month intervals, were correlated (R^2=0.86, where a 10 cm rise in river stage corresponded to a 0.16 m^3s^{-1} decline in spring discharge). A rise in river stage, over 1–2 months, often corresponds to a decline in spring discharge and vice versa. Changes in river stage probably affect spring discharge by altering the head difference between the river and underlying aquifer. We did not include a model component for the effect of river stage on spring discharge due to a lack of sufficient long-period data to perform dynamic simulations of intrusion length.

ANALYTIC MODEL OF COLD-WATER INTRUSION INTO BLUE SPRING RUN

Theory

When intrusion of cold water into Blue Spring Run occurs, the denser, underlying river water and lighter, outflowing spring water form an arrested thermal wedge. This condition is a result of very low mixing between the river and spring water. The lack of mixing is visually observable since the river water is naturally tea-colored from dissolved organic compounds, while the spring water is clear.

The hydraulics of this type of two-layer flow was theoretically analyzed by Stommel and Farmer (1952) and Officer (1976) using the following simplifying assumptions:

- No mixing of the two water masses occurs across the interface.
- The surface layer flow produces a frictional stress on the bottom layer that is proportional to the square of the velocity of the surface layer.
- The velocity of the surface layer is constant.
- The velocity of the bottom layer is negligible compared to the velocity of the surface layer.
- The mouth of the spring run acts as a hydraulic control on surface flow.

Under these assumptions, the flow is governed by the following equations:

$$h_1^3 = \frac{q_1^2}{g\beta} \quad (1)$$

$$\frac{gh_1^3}{q_1^2}\frac{d\eta_1}{dx} + \frac{d\eta_2}{dx} = k \quad (2)$$

$$-\frac{gh_1^2 h_2}{\alpha q_1^2}[\alpha\frac{d\eta_1}{dx} + \beta\frac{d\eta_2}{dx}] = \frac{3}{2}k \quad (3)$$

Where:
ρ_1 = the density of the spring water
ρ_2 = the density of the river water
h_1 = the depth of the outflowing spring water at the mouth
q_1 = the spring discharge per unit width
g = the gravitational constant
k = an interfacial friction coefficient

$$\alpha = (\frac{\rho_1}{\rho_2})$$

$$\beta = \frac{\rho_2 - \rho_1}{\rho_2}$$

Other quantities are as defined in Figure 9.

These equations were applied to Blue Spring Run to solve for the surface-layer depth (h_1) and bottom-layer depth (h_2) given constant values of water density (ρ_1 and ρ_2) and surface-layer discharge (q_1). Intrusion length was calculated as the point where the bottom-layer depth equaled zero. We used a value of $1.1\text{x}10^{-4}$ for the interfacial friction factor, k. This value for the friction factor was determined, by trial-and-error, to provide the best match of calculated and observed intrusion length.

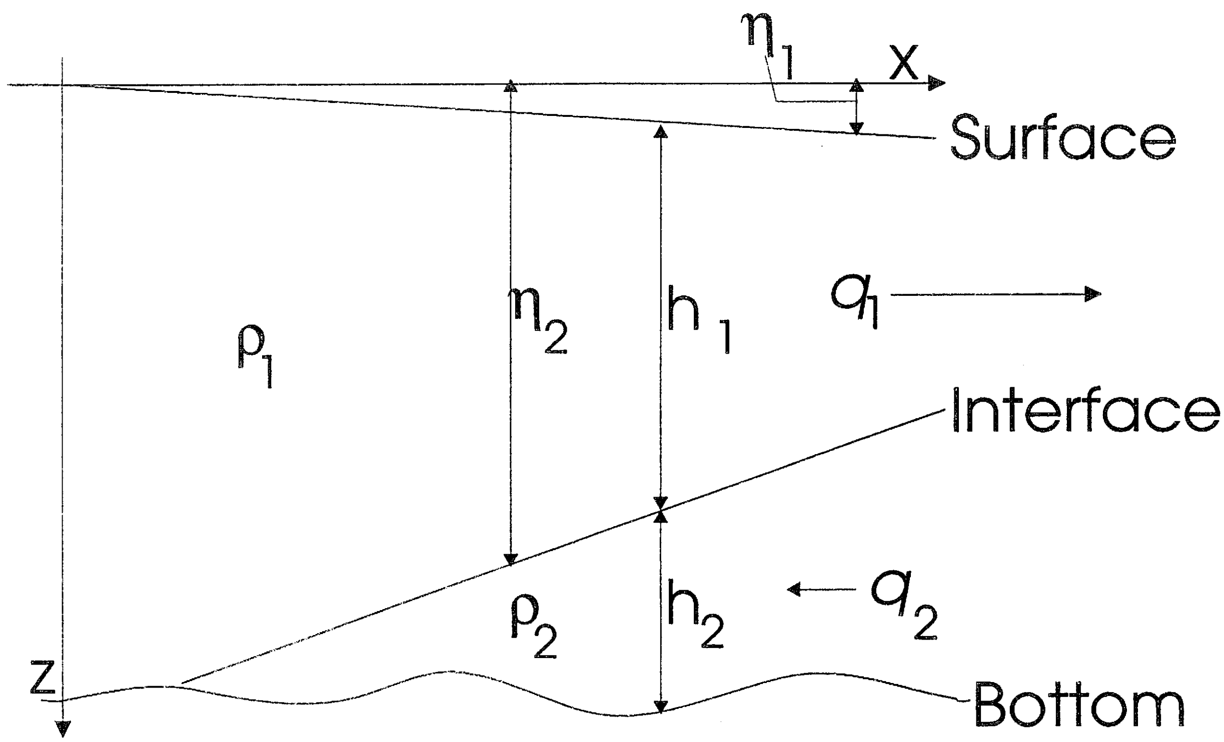

Figure 9. Definition of variables used for theoretical analysis of two-layer flow. *Two-layer flow develops in Blue Spring Run when the water of the St. Johns River cools in winter and becomes denser than the outflowing spring water.*

Application to Blue Spring Run

The analytic model showed that the length of intrusion of cold river water into Blue Spring Run is determined by river stage, spring discharge, and the difference in density between the river and spring water. The difference in density is primarily governed by river temperature because the spring water temperature is nearly constant. Differences in mineral content also contribute slightly to the density difference between the river and spring waters. The dissolved mineral content of the spring is about 0.5 parts per thousand greater than that of the river. This difference in weight of dissolved minerals is only significant for calculating density difference between the water masses when the river temperature is within a few degrees Celsius of the spring temperature.

A sensitivity test, using the analytic model, indicated that intrusion length is most sensitive to river stage. Intrusion length calculated with the analytic model varied 85 m over one standard deviation of river stage (0.3 m), 20 m over one standard deviation of river temperature (3° C), and 12 m over one standard deviation of spring discharge (0.4 m^3s^{-1}).

The assumption that the mouth of Blue Spring Run functions as a hydraulic control for the outflowing spring water implies that accurate geometry and bathymetry of the run mouth are essential for modeling the dynamics of the intrusion. Because the surface layer depth adjusts to allow maximum discharge per unit width at the hydraulic control (Equation 1), the solution for intrusion length upstream of the mouth (Equations 2 and 3) depends on correctly calculating the layer depths at the mouth.

An accurate estimate of discharge per unit width near the mouth is essential for calculating intrusion length. The estimation of discharge per unit width, in turn, depends on an accurate representation of the geometry of the run near the mouth.

Accurate depths within the run are similarly important for the calculation of intrusion length, because bottom layer depth is calculated from channel depths. Thus, a detailed set of bathymetric data was collected to define the geometry of the mouth. These data also proved essential for calibrating the numerical temperature model.

Although the analytic solutions of intrusion length agreed well with ten observed intrusion events (Table 2), we used a numerical 3-D temperature model, Environmental Fluid Dynamics Code (EFDC; Hamrick, 1992a), to predict intrusion length for this study. Reasons for using the EFDC Model over the analytic model are as follows:

- The analytic model is sensitive to the specified value of interfacial friction which may change under differing flow conditions. The EFDC Model calculates internal friction using a turbulence-closure scheme.
- The analytic model depends on specifying the location of the critical flow condition within the spring run. The location of critical flow may change under different flow conditions. The EFDC Model does not have this limitation.
- The analytic model assumes no mixing between layers. We could not be certain that this idealized assumption would apply to all combinations of parameters affecting the flow regime, some of which have not been observed. The EFDC Model includes the effects of vertical turbulent mixing processes.
- The analytic model assumes constant depth across each channel cross-section, whereas the EFDC Model allows for the effects of variable depth cross-sections.

SET-UP, CALIBRATION, AND VERIFICATION OF THE EFDC MODEL

Set-up of the EFDC Model

The EFDC Model (Hamrick, 1992a; 1992b) solves finite-differenced forms of the hydrostatic Navier-Stokes equations, together with transport equations, for salinity, temperature, turbulent kinetic energy and turbulent macroscale. The equations are solved horizontally on a curvilinear, orthogonal grid and vertically on a stretched, sigma grid. Vertical diffusion coefficients for momentum, mass, and temperature are determined by the second-momentum closure-scheme of Mellor and Yamada (1982) and Galperin et al. (1988). A complete description of the code's theoretical and computational aspects is presented in Hamrick (1992a).

Model Grid of Blue Spring Run

An irregular, orthogonal model grid (Figure 10) was applied to Blue Spring Run and a portion of the adjacent St. Johns River. The model grid contained 1670 cells (167 horizontal cells of 10 vertical layers apiece). Horizontal cell widths ranged from 6 m within Blue Spring Run to 90 m within the St. Johns River. We used three cells across the width of the spring run to simulate the shape of the cross-sectional depth profiles of the run. Vertical cell thickness depends on depth and ranged from 6–45 cm.

Model depths, relative to the National Geodetic Vertical Datum of 1929 (NGVD29), ranged from 0.58 m, in the upper portion of Blue

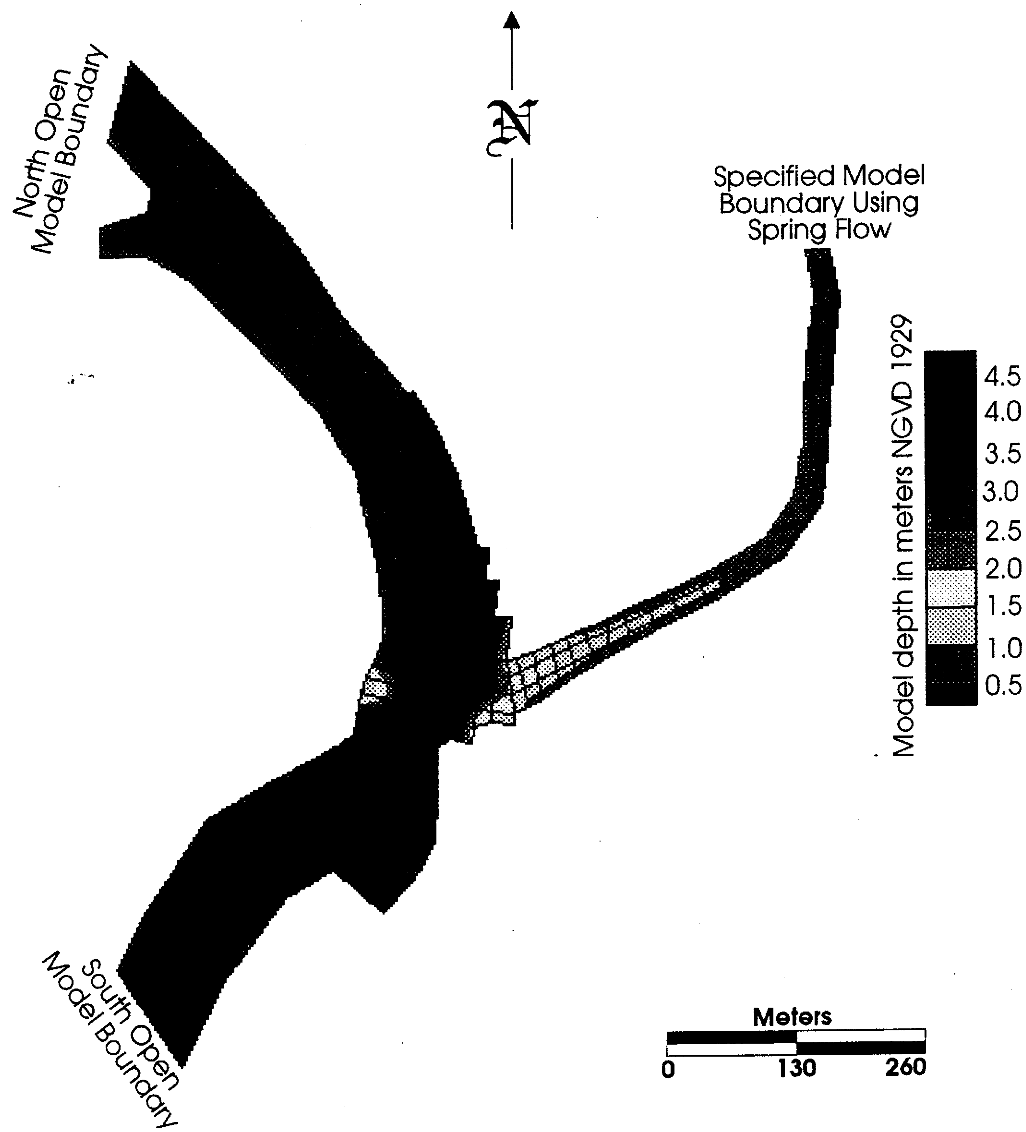

Figure 10. **Model grid of Blue Spring Run and adjacent St. Johns River.** *This model grid and associated model bathymetry were used to simulate cold-water intrusions into Blue Spring Run.*

Spring Run, to 4.4 m in the St. Johns River (Figure 10). Water surface elevation in Blue Spring Run is typically 0.3–0.6 m above NGVD29, so mean water depths within the run are greater than the depths shown in Figure 10. Centerline depths within the spring run were interpolated from the PBS&J survey. The depths of model cells along the shore margins of the spring run were adjusted so that observed and modeled cross-sectional areas agreed. The fine features of bathymetry near the mouth of the run are a result of the fairly extensive bathymetric survey within that area.

Boundary Conditions

External forces to the EFDC Model (Figure 10) were specified at three model boundaries: (a) the upstream boundary of the St. Johns River, (b) the downstream boundary of the St. Johns River, and (c) the head of Blue Spring Run, at the spring boil.

Constant values for river stage, temperature, and salinity were specified at the upstream river boundary. A constant value for river salinity of 0.5 PSS78 (Practical Salinity Scale 1978; Lewis, 1980) was used for all model runs. Temperature and stage were varied among model runs to simulate the river conditions for each specific model scenario.

Constant values of inflow, temperature, and salinity of the spring discharge were specified at the head of Blue Spring Run. Constant values for temperature and salinity of 23°C and 1.0 PSS78, respectively, were used for all model runs. Spring discharge was varied among model runs.

A constant outflow at the downstream model boundary was specified. The value of outflow was the sum of the estimated St. Johns River discharge and the discharge specified at the spring boil.

St. Johns River discharge was estimated from the stage specified at the upstream model boundary using a stage-discharge curve.

Calculation of Intrusion Length

Intrusion of cold water was simulated with the EFDC Model for various combinations of river stage, river temperature, and spring discharge. The input variables were held constant for each model run. The model was run to steady-state to obtain the length of cold-water intrusion into Blue Spring Run. A steady-state analysis was appropriate for this study, because the time to achieve steady-state conditions in Blue Spring Run is much less than the typical variability of the input parameters. Model tests showed that steady-state conditions in the run are achieved in less than six hours. River stage, river temperature, and spring flow all vary much more slowly—from days, for river temperature, to weeks, for spring flow.

The length of cold-water intrusion into Blue Spring Run was estimated from simulated bottom temperature. The cold-water intrusion length was defined according to bottom temperature, because manatees within Blue Spring Run usually rest on the bottom, often directly upstream of the bottom thermocline between river and spring water (USFWS, 1981a).

The upstream edge of the intrusion was operationally defined as the point where the bottom temperature equaled ($0.8T_{spring} + 0.2T_{River}$), where T_{spring} is the temperature of the spring water and T_{river} is the temperature of the river. This location was determined by linearly interpolating between cell nodes. This operational definition of intrusion length defines a spatial interface that is consistent with the observed resting locations of manatees just upstream of the thermocline. The upstream location of an intrusion, as defined above, lies upstream of the area where most mixing of river and spring water occurs (Figure 11).

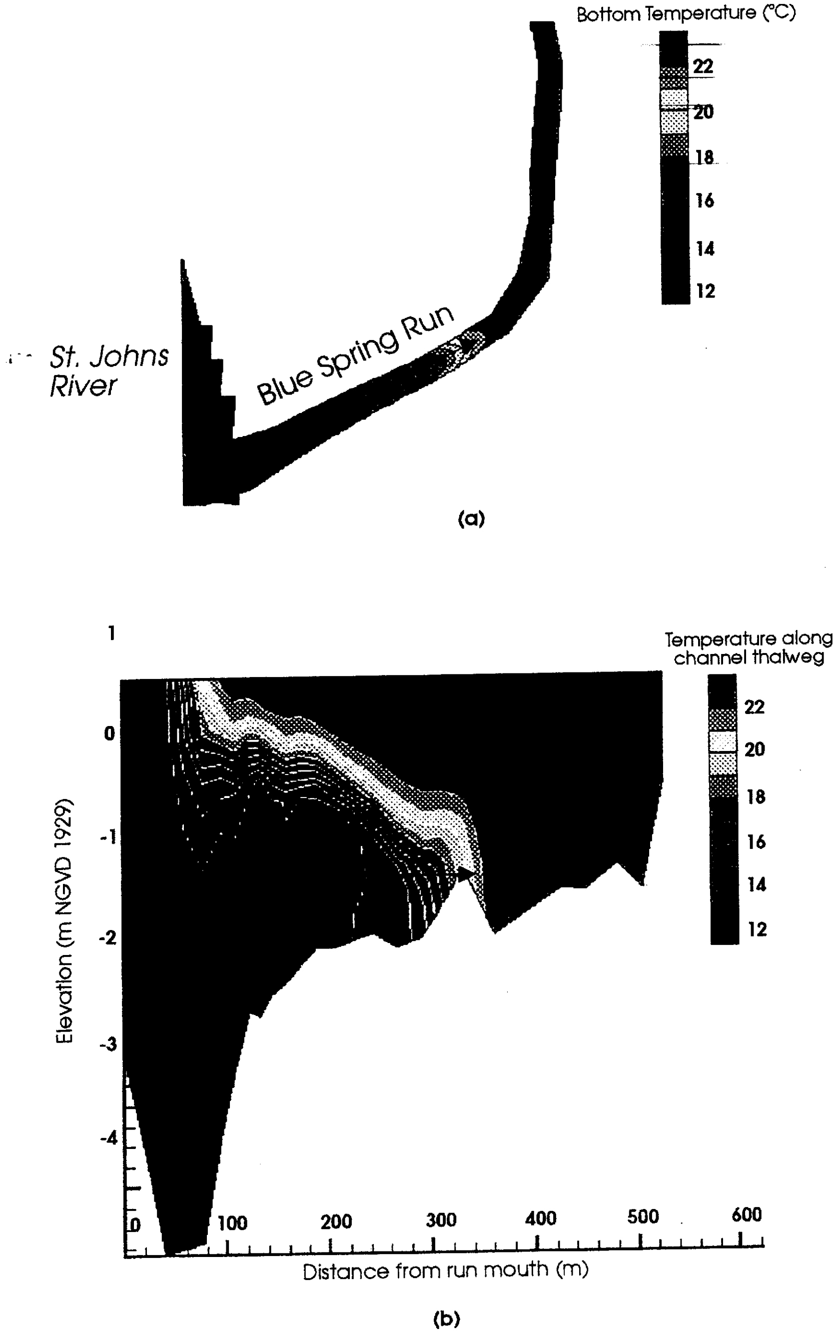

Figure 11. Simulated intrusion of cold water into Blue Spring Run. *The example shown is for a river stage of 1.0 m NGVD, a river temperature of 12°C, and a spring discharge of 3.6m³s⁻¹.*

Although the length of Blue Spring Run, including the spring pool, is approximately 650 m, the numerical model does not resolve intrusion lengths greater than 550 m because of inadequate grid resolution in the upper reaches of Blue Spring Run, where the run becomes narrow and shallow. However, any cold-water intrusion in excess of 500 m could potentially be catastrophic to manatees, so that resolution of intrusion events greater than 550 m is irrelevant for the purposes of this report.

Calibration and Verification of the EFDC Model

The EFDC Model was calibrated and verified by comparing observed and simulated lengths of cold-water intrusion for ten intrusion events. Event 1 was used for model calibration and the other nine intrusion events were used for model verification (Table 2). These intrusion events were selected from periods when observed values of river temperature, spring discharge, river stage, and intrusion length were concurrently available.

Calibration of the EFDC Model was accomplished by carefully modeling the bathymetry within the spring run and by adjusting the number of vertical layers used to simulate the vertical structure of the thermal wedge. Depths laterally across the spring run were adjusted so that the modeled cross-sectional areas matched surveyed cross-sectional areas. Ten vertical layers were used for the calibrated model. All simulations for the calibration and verification events used the following values:

- Salinity difference between spring and river of 0.5 PSS78
- Model bottom roughness of 1 cm
- Model time step of 9 s
- Temperature of spring water of 23°C

Simulated intrusion length, independently calculated using the EFDC Model, compared well with observed intrusion lengths for all ten events (Table 2). Observed intrusion lengths in Table 2 typically vary 20–40 m over the period of observation defining an intrusion event. Because river stage, temperature, and spring discharge were not always available on a daily basis, these values were assumed constant over the period of observation of intrusion length. Fluctuations of spring discharge and river stage and diurnal variation in river temperature over the period of observation might cause the observed variability of intrusion length. Wind effects and unsteady effects not included in the model simulations might also contribute to this variability.

Table 2. **Observed and simulated lengths of cold-water intrusion into Blue Spring Run for ten different intrusion events.** *For each event, both the EFDC Model and analytic model were used to independently simulate the length of cold-water intrusion using observed values of river stage, river temperature, and spring discharge.*

Event	Period of Observation	Spring Discharge (m^3s^{-1})	River Stage[1] (m)	River Temp (C)	Observed Intrusion Length[2] (m)	Simulated Intrusion Length, EFDC Model (m)	Simulated Intrusion Length, Analytic Model (m)
1	1/30–2/5/90	3.54	0.12	20.0	0–24	13	9
2	1/21–1/24/91	3.25	0.34	16.5	24–60	58	72
3	12/15–12/17/91	4.59	0.42	18.5	0–36	26	24
4	2/18–2/21/92	4.43	0.36	18.5	0–24	13	22
5	12/12–12/16/92	4.29	0.63	16.0	36–86	92	106
6	1/31–2/5/93	3.89	0.70	16.5	<86	74	106
7	11/1–11/3/93	3.93	0.51	19.5	14–24	26	11
8	12/12–12/17/93	3.95	0.41	15.5	24–60	58	89
9	11/16–11/27/95	4.38	1.06	17.0	86–124	131	149
10	1/14/96	4.38	0.83	11.0	156	151	149

[1]River stage is relative to NGVD of 1929
[2]Intrusion length of a single scenario often varied over the period of observation

The ten intrusion events illustrate the competing effects of spring discharge, river stage, and river temperature on intrusion length. For example, Events 1 and 3 each had intrusion lengths less than 30 m, although river stage was higher and river temperature lower during Event 3. As both these factors favor increased intrusion length, the fact that intrusion length did not increase between Events 1 and 3 was probably due to the larger spring discharge during Event 3. Events 2 and 8 similarly show the effect of spring discharge on intrusion length.

Discharge was the same for Events 9 and 10, which both occurred during the winter of 1995–96. Event 10, however, produced the greater intrusion length despite having a lower river stage. In this case, lower river temperature probably caused the greater intrusion length of Event 10 as compared to Event 9.

The largest intrusion lengths occurred for Events 5, 9, and 10. These events also coincide with the highest river stages and, in general, intrusion length was most sensitive to river stage.

RESULTS OF EFDC MODEL SIMULATIONS

Three different sets of numerical tests were performed, using the EFDC Model, to examine the relationship between spring discharge and cold-water intrusion into Blue Spring Run. Each test-set provided results that were used to examine the minimum flow requirements for Blue Spring Run. Different aspects of the problem of protecting manatee habitat were examined with each test-set.

The first test-set examined intrusion length as a function of river stage and river temperature for constant spring discharge. Intrusion length was simulated for several constant spring discharges by varying river stage and river temperature over the range of observed values of these parameters. The results of this analysis show first, how intrusion length is affected by river temperature and river stage, and second, how declining discharge alters intrusion length for different values of river temperature and stage. These results were further used to examine how well different values of constant spring discharge protect Blue Spring Run from cold-water intrusions.

The second test-set examined the range of cold-water intrusions into Blue Spring Run for specific winter flood events. Intrusion length was simulated for a range of spring flow conditions in conjunction with the mean annual, 5-, 10-, 50-, and 100-year winter flood events. River temperature was held constant at 12°C for each model run of this test set. The purpose of this test-set was to show how well different flow conditions maintain an adequate warm-water refuge during periods when winter floods accompany very cold river temperatures.

The third test-set examined the effect of spring flow reduction on the frequency of cold-water intrusions into the Manatee Refuge.

For this purpose, we developed duration curves of intrusion length for a range of flow conditions using results from Monte Carlo simulations. Each Monte Carlo simulation consisted of 1000 model runs, using randomly-generated values of river stage, river temperature, and spring discharge.

The numerical tests described for Test-Sets 1 and 2 focus on three specific cold-water intrusion events: (a) the intrusion event that inundates nearly the entire spring run (≥ 500 m), (b) the intrusion event that reduces the available warm-water refuge to a length less than 250 m (≥ 400 m), and (c) the intrusion event that inundates the entire Manatee Refuge (≥ 280 m).

Park staff estimate that 200–250 m of run length is required to hold the present winter manatee population within Blue Spring Run (personal communication, Wayne Hartley to Lynn Lefebvre, 1997). Intrusions greater than 500 m would reduce the available warm-water refuge to less than 150 m, considerably less than that required to hold the resident manatee population. Such an event could subject a substantial portion of the resident manatee population to cold water temperature and, depending on the severity and duration of the intrusion event, cause significant mortality of the population. We used an intrusion event greater than 500 m, then, to represent a worst-case or catastrophic event.

Intrusions greater than 400 m would decrease the available warm-water refuge to less than 250 m, just below the acceptable threshold for adequate refuge length. Intrusions events greater than 400 m, then, could seriously jeopardize manatees within the run. This event represents the largest acceptable intrusion length for this study.

Intrusions greater than 280 m completely inundate the state-designated Manatee Refuge. Although such an event probably does not jeopardize the manatees, it does force the manatees out of that portion of Blue Spring Run set aside by the state exclusively as a winter refuge for manatee.

The primary goal of this study is to determine the minimum flow for Blue Spring that maintains the run as a reliable warm-water refuge for manatees. We have taken this to mean that a cold-water intrusion exceeding 400 m should be an improbable event and an intrusion exceeding 280 m should be infrequent. Although terms such as "improbable" and "infrequent" are necessarily subjective, the following results quantify the probability of intrusion events for spring flow conditions ranging from the historic flow to successive percentages of reduction of spring flow. In this way, the probabilities of specific intrusion events can be directly compared and evaluated for different flow conditions.

Test-set 1: Length of Cold-Water Intrusion as a Function of River Stage and River Temperature at Constant Spring Discharge

Intrusion lengths were simulated over the observed range of winter river stage and temperature for constant spring discharges ranging from 4.7 to 2.3 m^3s^{-1}, corresponding to the historic mean discharge and up to a 50% reduction of historic flow. These simulations show the relative ability of each discharge to maintain an adequate warm-water refuge within Blue Spring Run for varying combinations of river temperature and stage.

Winter river stage (November–March) for 1945–95 ranged from -0.33–1.72 m NGVD29. A river stage of 1.72 m is approximately equivalent to a 100-year winter flood event. Winter river temperature for 1985–92 ranged from 10.7–26.1°C. The mean winter river temperature for the coldest months (December–February) was 18.2°C with a standard deviation of 2.7°C. We used a temperature range of 10–20°C for the model simulations, because cold-water intrusions are relatively small for river temperatures close to the temperature of the ambient spring water (23.0°C). This temperature range also spans the range where a physiological or behavioral response by manatees to cold water has been documented.

Intrusion Events Greater than 400 m

Given a spring discharge of 4.7 m^3s^{-1}, no combination of river temperature and stage within the ranges tested produced an intrusion greater than 400 m (Figure 12). At this discharge the run was maintained as a reliable warm-water refuge for up to the 100-year winter flood event. This result indicates that, at the historic

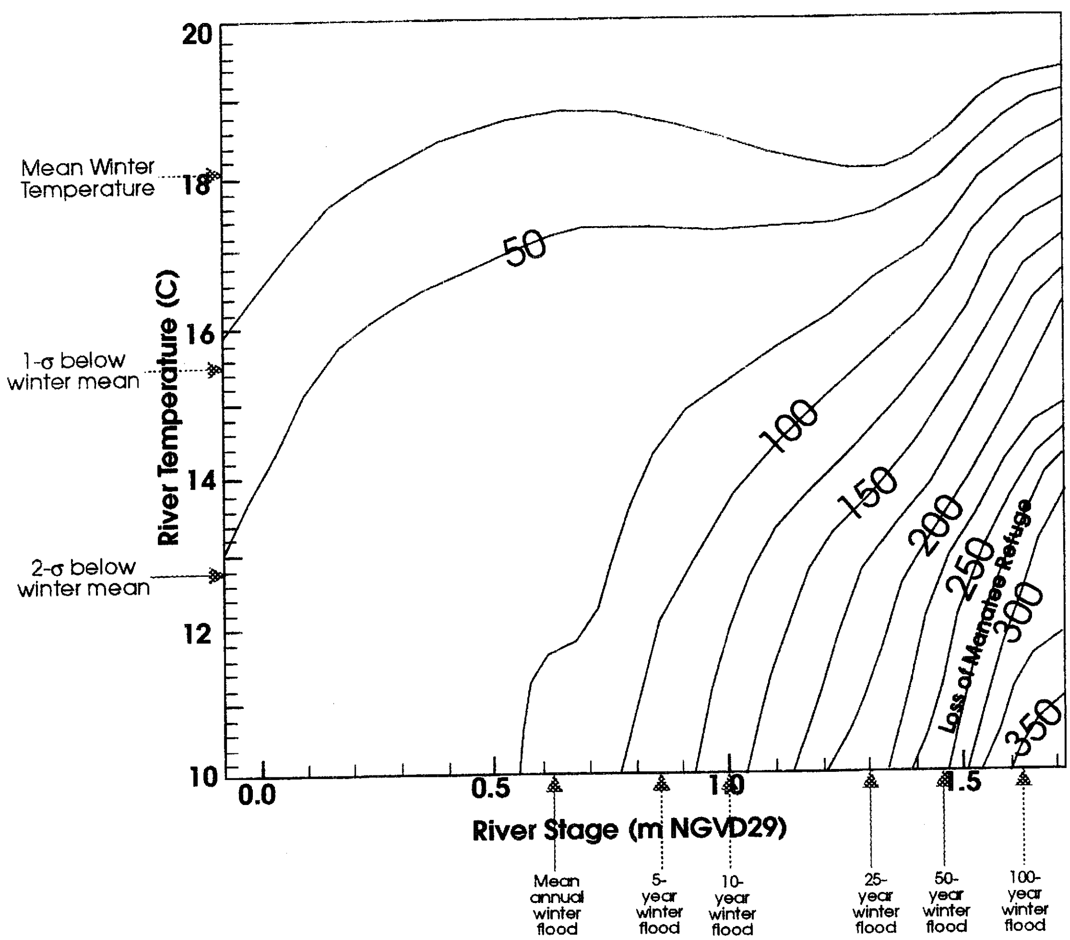

Figure 12. Isopleths of cold-water intrusion into Blue Spring Run as a function of stage and temperature of the St. Johns River for a constant spring discharge equal to the historical mean discharge (4.7 m^3s^{-1})

mean discharge, Blue Spring Run was a reliable warm-water refuge for manatees.

Given a spring discharge of 3.8 m^3s^{-1}, an intrusion exceeding 400 m can occur for winter floods exceeding a 50-year flood event when river temperatures are more than 1 standard deviation below the mean winter river temperature (Figure 13). The dependence of such an intrusion event on low river temperature means that an intrusion event greater than 400 m has a relatively low probability at a discharge of 3.8 m^3s^{-1}.

Given a spring discharge of 3.3 m^3s^{-1}, an intrusion greater than 400 m could occur during a 100-year winter flood if river temperatures are less than 1 standard deviation below the mean winter river temperature (Figure 14). When only moderate winter temperatures are required to produce a particular intrusion event for a given river stage, the probability of that intrusion event (based on the joint probability of river temperature and stage) approaches the probability of the stage event. The recurrence interval of a 400 m intrusion event, given a discharge 30% below the historic mean flow, then, is of the order of 100 years. Consequently, during a 100-year winter flood event a discharge of 3.3 m^3s^{-1} essentially provides no protection against loss of an adequate warm-water refuge for manatees, whereas a discharge of 3.8 m^3s^{-1} or greater does provide such protection.

Intrusion Events Greater than 280 m

Given a spring discharge of 4.7 m^3s^{-1}, an intrusion exceeding 280 m only occurs for river stages greater than a 50-year winter flood in concurrence with river temperatures more than 1 standard deviation below the mean winter river temperature (Figure 12). An intrusion event greater than 280 m, then, must have a recurrence greater than 50 years given a discharge of 4.7 m^3s^{-1}.

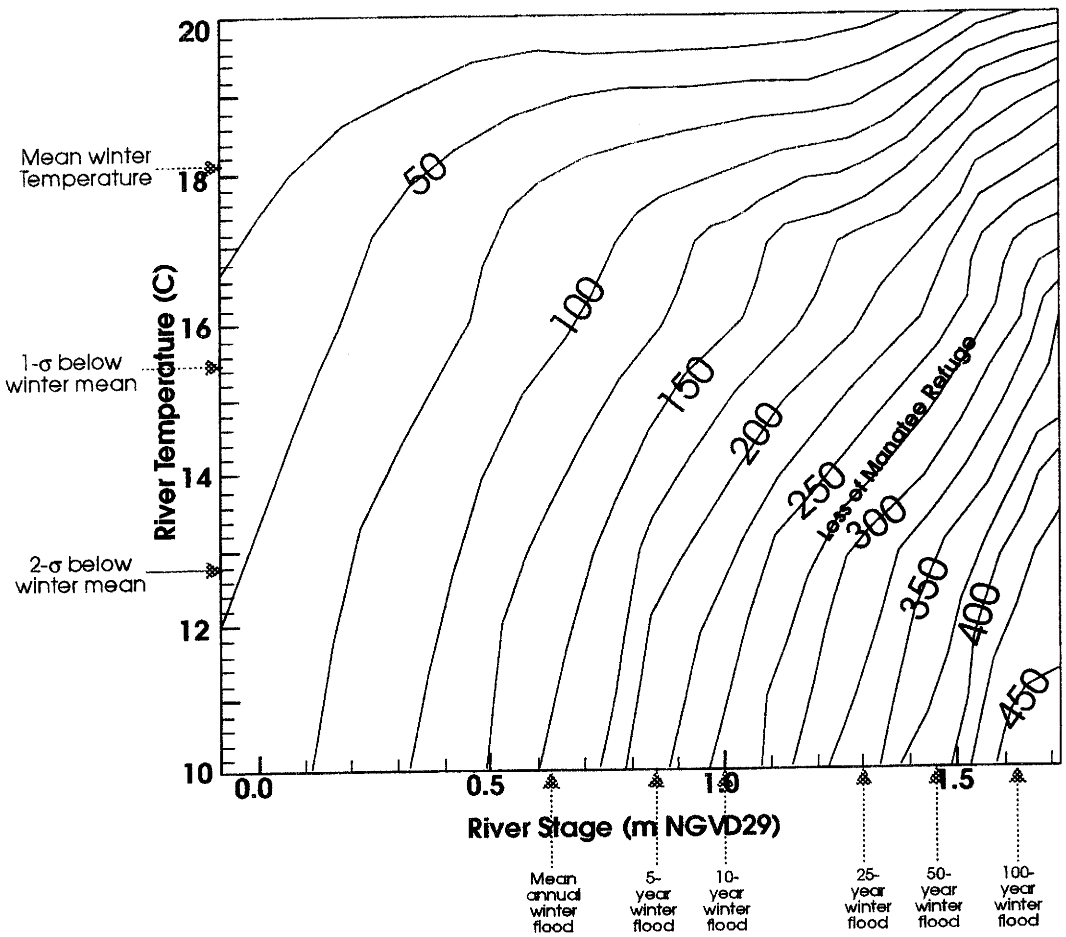

Figure 13. Isopleths of cold-water intrusion into Blue Spring Run as a function of stage and temperature of the St. Johns River for a constant spring discharge equal to a 20% reduction of the historical mean discharge ($3.8\ m^3s^{-1}$)

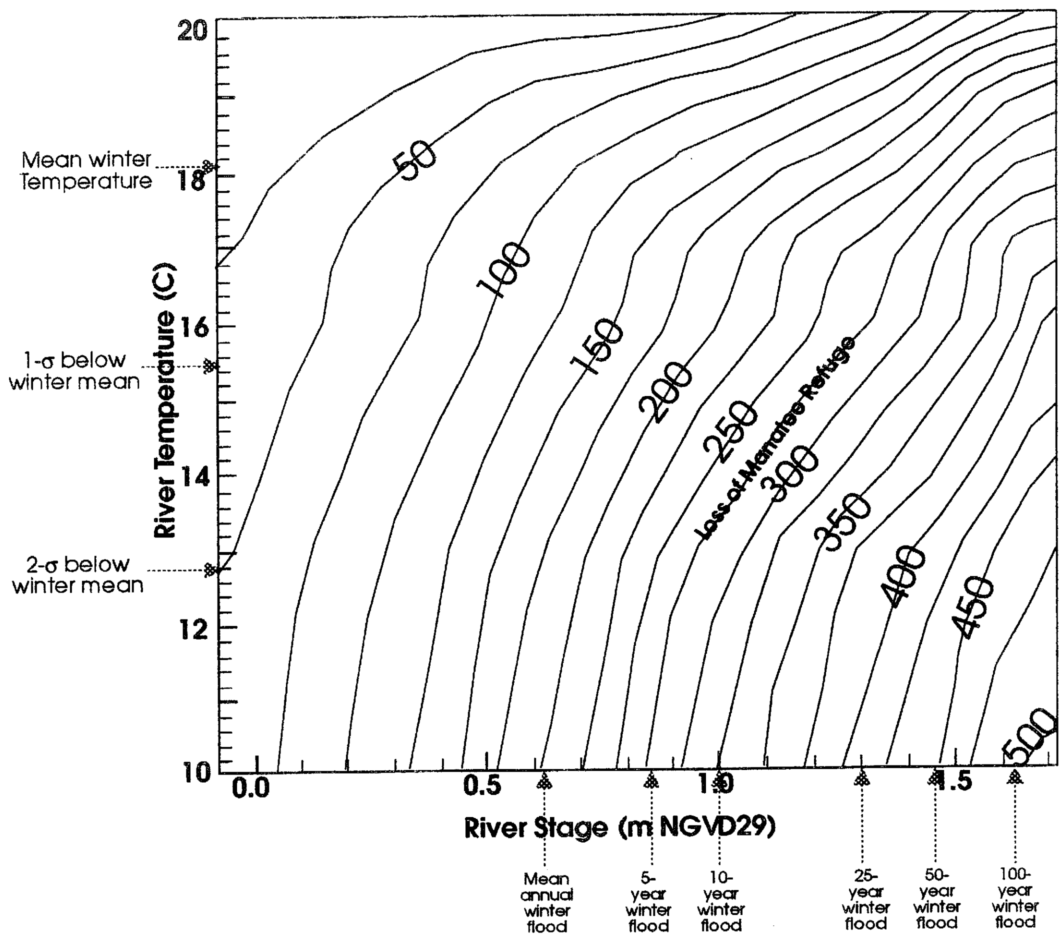

Figure 14. Isopleths of cold-water intrusion into Blue Spring Run as a function of stage and temperature of the St. Johns River for a constant spring discharge equal to a 30% reduction of the historical mean discharge (3.3 m^3s^{-1})

Given a discharge of 3.8 m^3s^{-1}, an intrusion event greater than 280 m occurs during a 100-year winter flood for river temperatures less than 1 standard deviation below the mean winter river temperature (Figure 13), and during a 25-year winter flood for river temperatures more than 1 standard deviation below the mean. This result indicates that the recurrence of an intrusion greater than 280 m, at a discharge of 3.8 m^3s^{-1}, is probably between 25 and 100 years.

Given a discharge of 3.3 m^3s^{-1}, an intrusion event exceeding 280 m occurs for a 25-year winter flood for river temperatures less than 1 standard deviation below the mean winter river temperature (Figure 14). This result indicates that the recurrence of an intrusion greater than 280 m, at a discharge of 3.3 m^3s^{-1}, is probably less than 25 years. During a 25-year winter flood event, then, a discharge of 3.3 m^3s^{-1} provides essentially no protection against loss of the Manatee Refuge, whereas a discharge of 3.8 m^3s^{-1} or greater does provide such protection. At a discharge equal to or greater than the historic mean discharge (4.7 m^3s^{-1}), the Manatee Refuge was well protected from inundation during a 25-year winter flood.

Recurrence Intervals of Maximum Annual Intrusion Length

To corroborate our estimates for the probability of intrusion events at constant spring discharge, we estimated recurrence intervals of maximum annual intrusion length, conditional on a constant discharge, from 50-year records (November-March) of simulated intrusion length. Intrusion length was simulated using observed daily river stage for the period 1945–95. Spring discharge was similarly varied between 2.2 and 4.7 m^3s^{-1} for these tests. A frequency analysis was performed on each 50-year set of simulated daily intrusion lengths to calculate maximum annual recurrence intervals of intrusion length for each constant discharge.

River temperature was randomly generated using the parameters of a normal distribution for each winter month. The monthly parameters of river temperature (Table 3) were calculated from eight years of observed daily values at Deland. Numerical tests showed no significant change in the calculated values of recurrence intervals using different sets of randomly-generated river temperatures.

Table 3. Statistical parameters of daily river temperature (°C) for each winter month. *These parameters were used to randomly generate river temperatures for the period 1945–95 for each winter month using a normal probability distribution.*

Month	Mean	Standard Deviation	Minimum Observed	Maximum Observed	Sample Size[1]
Nov	22.4	2.5	15.9	26.1	100
Dec	18.2	3.1	10.7	24.5	134
Jan	17.5	2.4	11.5	22.5	113
Feb	19.0	2.1	13.5	23.1	111
Mar	20.9	2.2	14.9	25.8	174

[1]Temperature data were collected at Deland during the period 1985–92.

A 50-year series of maximum annual intrusion length was obtained for each constant spring discharge tested. Each of these series was fit to a log-Pearson III distribution to calculate the mean annual, 5-, 10-, 25-, and 50-year recurrence interval of maximum annual intrusion length given a constant spring discharge.

The calculated conditional recurrence intervals for intrusion length corroborate our previous order-of-magnitude estimates of recurrence intervals for intrusion events greater than 280 m. As discussed in the previous section, the recurrence interval of a 280 m intrusion event was between 25 and 100 years given a discharge of 3.8 m^3s^{-1} and less than 25 years given a discharge of 3.3 m^3s^{-1}. The recurrence intervals developed from the 50-year simulations (Figure 15) indicate that a 280 m intrusion event has a recurrence of about 30 years given a discharge of 3.8 m^3s^{-1} and 15 years given a discharge of 3.3 m^3s^{-1}.

Variability of Spring Discharge and Recurrence of Intrusion Events

The preceding analysis of intrusion events assumes a constant spring discharge and does not account for the variability of discharge about a mean value. Although the historic mean discharge is 4.7 m^3s^{-1}, the observed discharge from 1932–96 ranged from 2.8 to 6.1 m^3s^{-1}. Our simulations of intrusion length for a constant discharge of 4.7 m^3s^{-1} (equivalent to the historic mean discharge) indicates that an intrusion greater than 400 m is essentially impossible for river stages less than or equal to the 100-year winter flood event (Figure 12). However, at the historic flow an intrusion greater than 400 m was possible under these same conditions of river stage and temperature when the spring discharge was significantly less than the mean discharge.

To account for the variability of spring discharge about a mean, we estimated the probabilities of various intrusion events by numerically integrating the joint probability distribution of river stage, river temperature, and spring discharge (under the assumption that these variables are mutually independent random variables) to obtain an estimate of the probability of an intrusion event for different spring flow conditions. The probability distributions of river temperature and spring discharge were assumed normal, and the probability distribution of winter river stage was estimated numerically from 50-years of observed winter stage at Deland (1945–95). Intrusion length was simulated using EFDC for a range of river stage (-0.08-1.72 m NGVD29), river temperature (10-30 °C), and spring discharge (0.0-6.5 m^3s^{-1}) at increments of 0.02 m, 1 °C, and 0.2 m^3s^{-1} for stage, temperature, and discharge, respectively.

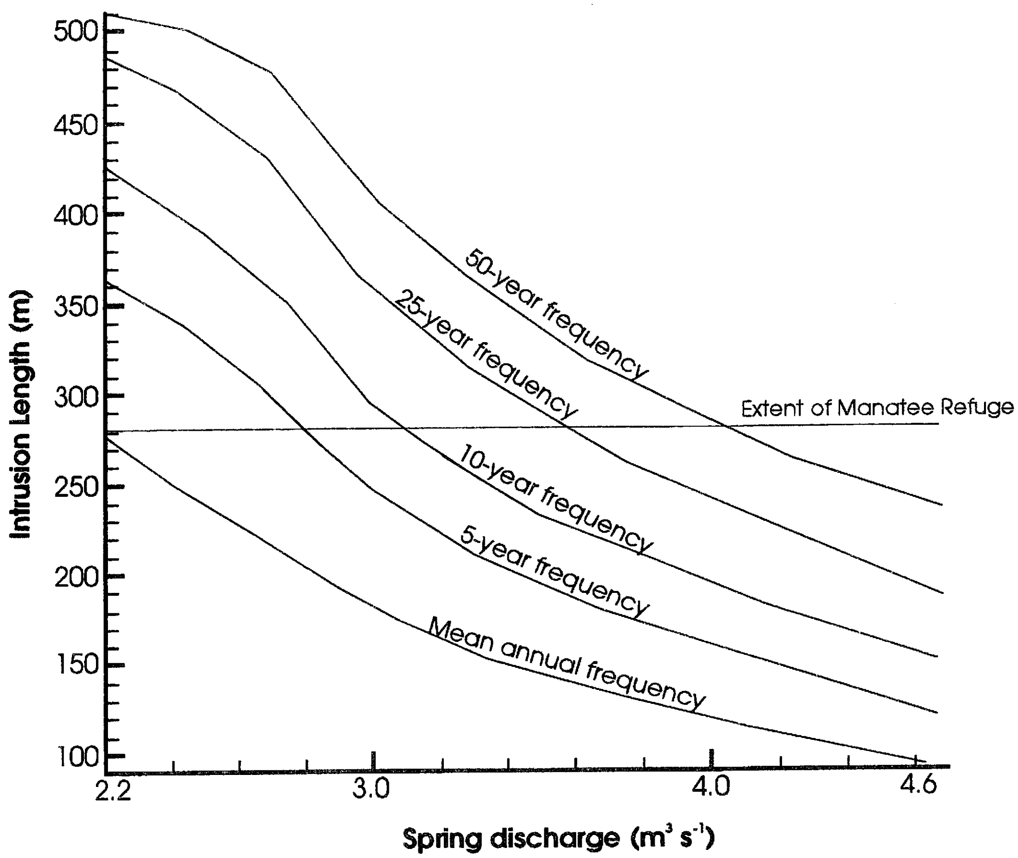

Figure 15. Recurrence intervals of maximum annual intrusion length into Blue Spring Run given a range of constant spring discharges.

This numerical integration of the probability distribution of intrusion length provided estimates of the probabilities of intrusion events greater or equal to a given value for five different spring flow conditions, corresponding to the historic spring flow and 10%, 20%, 30%, and 40% reductions of spring flow. The estimated probabilities of intrusion events were used to calculate the length of time (in winters) required to produce at least one such intrusion event at confidence levels of 99.9%, 99%, and 90% (Table 4). The calculations of the number of winters required to produce a given intrusion event assumes that daily intrusion events are independent, which is certainly not the case. However, the calculated results are reasonable order-of-magnitude estimates that are particularly pertinent for comparing different spring flow conditions.

Although the calculated values of the number of winters required to produce at least one intrusion event is not an estimate of annual recurrence, it did produce results in qualitative agreement with the previously calculated estimates of recurrence for a 280 m intrusion event (Figure 15). These results further show the relative probability of intrusion events for different flow conditions, while also accounting for stochastic variability of discharge.

Table 4. Number of winters required to produce at least one intrusion greater or equal to a specified value for three different levels of confidence.

	Intrusions ≥ 500 m			Intrusions ≥ 400 m			Intrusions ≥ 280 m		
Spring Flow Condition	99.9%	99%	90%	99.9%	99%	90%	99.9%	99%	90%
Historic (4.7 m^3s^{-1})	161,000	110,000	55,000	5000	3000	1500	250	175	90
10% reduction (4.2 m^3s^{-1})	120,000	13,000	6700	900	600	300	70	50	25
20% reduction (3.8 m^3s^{-1})	4000	3000	1500	250	175	90	40	20	10
30% reduction (3.3 m^3s^{-1})	600	400	200	65	40	20	9	6	3
40% reduction (3.0 m^3s^{-1})	250	160	80	30	20	10	5	3	2

Under the historic flow condition, an inundation large enough to threaten the manatee population as a whole (≥ 500 m) was very improbable. At a 30% flow reduction, however, there is about a 90% confidence that such an event would occur within 200 years. Similarly, a 400 m intrusion event occurred infrequently historically, but would likely occur within 65 years at a 30% reduction of spring flow.

At the historic flow, the manatee were seldom forced out of the Manatee Refuge. An intrusion exceeding 280 m had about a 90% probability of occurring within 90 years. This duration is reduced to 10 years at a 20% reduction of historic flow and to 3 years at a 30% reduction of historic flow. Historically, then the manatees were forced out of the Manatee Refuge every few centuries. At a 20% reduction of historic flow they would be forced out of the Refuge every few decades, and at a 30% reduction of historic flow they would be forced out every few years.

Test-set 2: Range of Cold-Water Intrusion During Winter Flood Events

To further examine how well different spring flow conditions protect Blue Spring Run from cold-water intrusion events, we simulated intrusion length for specific winter flood events for a range of spring discharges. Intrusion lengths were simulated for 5 river stages corresponding to the 100-year, 50-year, 10-year, 5-year, and mean annual winter flood event. For each of the winter flood events tested, we simulated intrusion length for a range of flow conditions. For each flow condition we tested 3 values of discharge: the mean discharge and discharges 1 standard deviation and 2 standard deviations below the mean.

River temperature was held constant at 12°C, approximately two standard deviations below the mean winter river temperature, for these simulations. A low value for river temperature was used because (a) this value produces a realistic upper bound for intrusion length, and (b) we wished to consider how well the spring run is protected from cold-water intrusions at low river temperatures because periods of cold river temperatures are precisely when manatees most require a warm-water refuge.

Intrusions Greater than 500 m

For the historic flow condition, no intrusion exceeded 500 m over the range of parameters tested. Even when river temperature and spring discharge were 2 standard deviations below the mean, intrusion length did not exceed 453 m for stages up to the 100-year winter flood (Table 5). For a 20% reduction of historic flow, an intrusion exceeding 500 m could occur during a 100-year winter flood, but only when both river temperature and spring discharge were at least 2 standard deviations below the mean. For a 30% reduction of historic flow, an intrusion exceeding 500 m could occur during a 100-year winter flood for spring discharges less than 1 standard deviation below the mean (Table 5).

A 20% reduction of historic flow, then, would protect Blue Spring Run from cold-water inundation during a 100-year winter flood except during periods when spring flow was more than two standard deviations below the mean flow (approximately 3.0 m^3s^{-1}). However, at a 30% reduction of historic flow the run is not well-protected from cold-water inundation during a 100-year winter flood.

Intrusions Greater than 400 m

Under the historic flow, intrusions exceeding 400 m required a river stage in excess of the 100-year winter flood and spring discharge of 1 standard deviation below the mean. Under a 20% reduction of historic flow, a 400 m intrusion event could occur during a 50-year winter flood with the same restrictions on discharge. Under a 30% reduction of historic flow, a 50-year winter flood, in conjunction with river temperatures near 12°C, always produced an intrusion greater than 400 m. A 30% reduction of flow, then, would probably not maintain an adequate warm-water refuge during a 50-year winter flood should river temperatures drop to 12°C.

Intrusions Greater than 280 m

Under the historic flow, intrusions exceeding 280 m required a river exceeding the 10-year winter flood. Under a 20% reduction of historic flow, a 280 m intrusion event could occur during a 5-year winter flood, but only when spring discharge was at least 2 standard deviations below the mean. At a 30% reduction of historic flow, a 280 m intrusion event could occur during a 5-year winter flood for spring discharge less than 1 standard deviation below the mean. There is a considerably greater probability of losing the Manatee Refuge under a 30% reduction of historic flow, then, as compared to a 20% reduction of historic flow.

Table 5. Simulated intrusion lengths for a range of winter flood events at a constant river temperature of 12°C. For each spring flow condition tested, intrusion lengths were simulated for the mean discharge and for discharges of 1 and 2 standard deviations below the mean. Recurrence intervals of winter stage were calculated from maximum December–January stage from the winters of 1932–94.

Recurrence Interval of Winter River Stage (Dec.–Jan.)	River Stage (m)	Historic Flow (4.7±0.5)			20% Reduction of Historic Flow (3.8±0.4)			30% Reduction of Historic Flow (3.3±0.35)		
		Mean	-1σ	-2σ	Mean	-1σ	-2σ	Mean	-1σ	-2σ
100-Year	1.62	338	402	453	444	478	505	486	506	526
50-Year	1.45	252	324	391	378	428	472	439	472	510
10-Year	1.01	129	190	255	242	295	347	308	347	396
5-Year	0.85	100	153	212	200	249	298	261	298	346
Mean Annual	0.64	83	117	155	147	180	214	188	214	251

Intrusions During Recent Winter Floods

Recent winter floods that occurred during November 1995 and January 1996 resulted in cold-water intrusion into Blue Spring Run. Fortunately, a relatively high discharge of 4.4 m^3s^{-1} during the winters of 1995–96 abated cold-water intrusion during these recent winter floods.

In November 1995, a 10-year winter flood was accompanied by a river temperature of 17°C. These conditions caused a cold-water intrusion of 124 m, which represents a 44% loss of the Manatee Refuge. Spring discharge during this flood was 4.4 m^3s^{-1}. Under these same conditions, a discharge of 2.6 m^3s^{-1} would have resulted in a loss of 85% of the Manatee Refuge.

During January 1996, a 5-year winter flood event was accompanied by a river temperature of 11°C. These conditions caused a cold-water intrusion of 156 m into Blue Spring Run, resulting in 56% loss of the Manatee Refuge. Again, spring discharge was 4.4 m^3s^{-1} during this flood. A spring discharge of 2.6 m^3s^{-1} would have resulted in a loss of 88% of the refuge.

Test-set 3: Intrusion Duration Estimates for Blue Spring Run

Duration curves of intrusion length were developed for a range of spring flow conditions using Monte Carlo simulation techniques. The two preceding test-sets focused on large, relatively infrequent intrusion events. This analysis best illustrates how declining spring discharge affects smaller, more frequent intrusions.

For each flow condition, we simulated intrusion length for 1000 randomly-generated sets of river stage, river temperature, and spring discharge. We then estimated the percentage of time that different intrusion lengths were exceeded for each set of simulated intrusion lengths. These results show the relative frequency of cold-water intrusion into the Manatee Refuge for different flow conditions.

River stage was randomly generated from a log-Pearson III probability distribution. River temperature and spring discharge were randomly generated from normal distributions. Table 6 lists the statistical parameters used to randomly generate river stage and temperature for the Monte Carlo simulations.

Table 6. Statistical parameters used to randomly generate river stage and river temperature for winter conditions. *These variables, together with spring discharge, were used to generate a PDF for intrusion length using 1000 points.*

Hydrodynamic Variable	Mean	Standard Deviation	Skewness [1]	N	Assumed PDF
Winter river stage	0.47 m	0.30 m	1.00 m^3	7591	Log Pearson III
Winter river temperature	19.6°C	3.0°C	N/A	632	Normal

[1]Skewness was not used to generate river temperature because a normal distribution was assumed.

Duration Curves of Intrusion Length

Duration curves for intrusion length for a representative range of flow conditions are shown in Figure 16, with intrusion length scaled by the resolution of the numerical model (approximately 550 m). Regardless of flow, no intrusions occur for approximately 42% of the winter (a winter, here, is November-March, or approximately 150 days) when river temperature exceeds spring temperature. Some intrusion occurred for about 50% of the winter, under all flow conditions.

Probability of Cold-Water Intrusion for Frequent Intrusion Events

The intrusion duration curves show that for all flows tested an intrusion event exceeding 280 m is relatively infrequent. Less than 1% of intrusions would exceed 280 m even for flow reductions as much as 30% below the historic flow (Figure 16). Most intrusions only affect the present Manatee Refuge. Historically, 99% of intrusions did not exceed 150 m.

Using our previous assumption that the present manatee population requires 200-250 m of run length for an adequate warm-

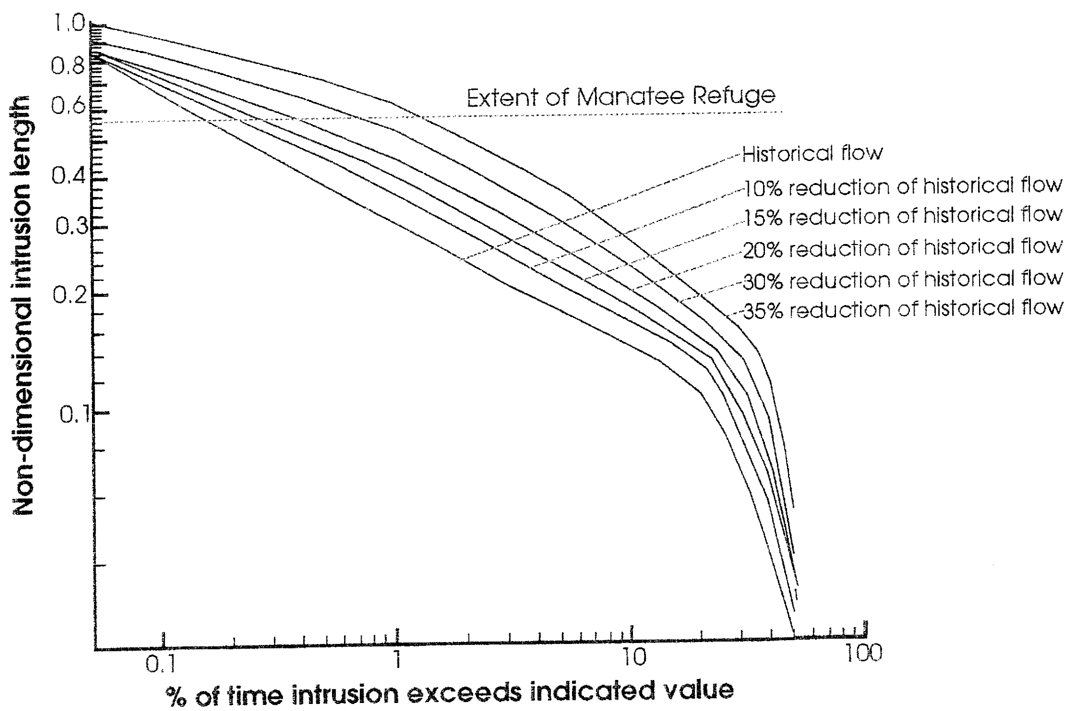

Figure 16. Intrusion duration curves, Blue Spring Run, for a range of spring flow conditions. Intrusion length is scaled to the resolution limit of the numerical model

water refuge, intrusions exceeding 80 m could force some manatees out of the Refuge. The percentage of intrusions exceeding 80 m approximately doubled when discharge is reduced 20% from historic levels (Table 7).

Table 7. Percentage of intrusions exceeding a given value for successive reductions of spring flow

Intrusion Length (m)	Historic Flow	10% Reduction of Historic Flow	20% Reduction of Historic Flow	30% Reduction of Historic Flow	40% Reduction of Historic Flow
50	25.2	29.1	36.3	42.2	43.8
80	8.9	12.1	18.6	23.4	30.6
100	3.0	6.5	10.1	14.6	21.3
125	1.7	2.3	5.5	8.9	15.1
150	0.9	1.3	3.4	5.5	9.5

Finally, the Monte Carlo analysis shows that both the mean length and variability of intrusions increase with decreasing spring flow. The mean length and standard deviation of intrusions for the historic flow and 10%, 20%, 30%, and 40% reduction of historic flow are 28.7±40.5, 32.5±42.6, 39.8±52.1, 48.5±64.7, 57.7±77.5 m, respectively.

DISCUSSION

The recommended Minimum Average Flow for Blue Spring is 3.8 m^3s^{-1} (134 ft^3s^{-1}), 20% less than the historic spring flow. Reduction of spring flow below the recommended minimum average does not maintain the spring run as a reliable warm-water winter refuge for manatees during periods of cold weather, high river stage, and high manatee attendance.

Adequate spring flow and a corresponding Floridan aquifer potentiometric level are the crucial hydrologic elements for maintaining a warm-water refuge for manatees at Blue Spring. A surface water minimum level is unnecessary because the majority of the spring run is relatively deep and the water level is hydraulically determined by the St. Johns River.

In recommending a minimum average flow for Blue Spring Run we considered the following factors:

- The spring flow conditions that protect Blue Spring Run from complete cold-water inundation, and thus catastrophic loss of the run as a warm-water refuge for manatees, during winter floods
- The spring flow conditions under which Blue Spring Run can be considered a reliable warm-water refuge for manatees
- The spring flow conditions required to maintain the Manatee Refuge as the principle warm-water refuge within Blue Spring Run

These factors, along with the results from the previous modeling analyses, are discussed below to show how our recommended minimum flow for Blue Spring protects the unique resources of Blue Spring Run and the adjacent St. Johns River.

Statutory and Policy Guidelines for Determining Minimum Average Flow

SJRWMD is directed by Florida Statute (F.S.) section 373.042 to use the best available information to calculate minimum flows and minimum water levels, reflecting seasonal variations when appropriate. The minimum flow for a watercourse is defined by F.S. section 373.042 as "the limit at which further withdrawals would be significantly harmful to the water resources or ecology of the area."

To further define the concept of "significant harm" within the framework of F.S. section 373.042, we used a definition of unacceptable hydrologic harm to natural systems proposed by Lowe (1994) as part of work by the Subcommittee on Impacts to Natural Systems (SINS). Lowe (1994) defines unacceptable harm to natural systems as: "Anthropogenic effects on hydrology which have caused, or are expected to cause, directly or indirectly, singly or cumulatively, by their extensiveness, intensity, duration, or frequency for more than five years ... an on-site, local, or regional reduction in abundance or reproductive success of a listed, endemic, or regionally rare native species".

Under this definition, failure to maintain a warm-water refuge within Blue Spring Run due to an anthropogenic reduction of spring discharge constitutes unacceptable harm to the ecology of the St. Johns River, because the St. Johns River manatee population would be adversely affected for more than five years if the warm-water refuge at Blue Spring failed. Our reasons for concluding that a catastrophic cold-water intrusion event would adversely affect the manatee population for more than five years are as follows:

- Should a catastrophic cold-water intrusion occur, most of the manatee population would be aggregated in the spring run, thus the number of deaths could be large relative to the total population.
- Population recovery following a large loss of manatees would be much greater than 5 yr, due to low fecundity and a low rate of calf survival.

A 15-year study of the Blue Spring manatee population by O'Shea and Hartley (1995) found that (a) the average age of first successful reproduction is 5.4 yr (±0.98 yr), (b) the average interval between births is 2.6 yr (±0.81 yr), (c) the typical litter size is one calf, and (d) 40% of the young calves (neonatal to six months) do not survive to the first winter.

Although winter mortality rates in subadult Florida manatees is fairly high (O'Shea et al., 1985), factors causing this age-skewed mortality distribution do not apply to the failure of a major warm-water refuge. Loss of Blue Spring as a warm-water refuge when the temperature of the St. Johns River was below a threshold tolerable to manatees could result in the deaths of reproductive adult as well as subadult manatees. The loss of reproductive adults from the St. Johns River manatee population would lengthen the population recovery as compared to losing only subadults.

The Effect of Different Intrusion Events on Manatees in Blue Spring Run

This study focused on four specific intrusion events that differ in their effect on manatees using Blue Spring Run as a warm-water refuge. The four events were (a) intrusions exceeding 500 m, (b) intrusions exceeding 400 m, (c) intrusions exceeding 280 m, and (d) intrusions exceeding 80 m. The increased occurrence with decreasing discharge for each of these intrusion events was considered for establishing a minimum flow for Blue Spring, although greater weight was placed on the largest intrusion events, because these events have the potential for the greatest detriment to manatees.

Intrusion Events Exceeding 500 m

A cold-water intrusion event exceeding 500 m could cause significant mortality of manatees depending on the severity of the river temperature and duration of the event because such an intrusion does not allow an adequately-sized warm-water refuge for manatee. Park staff who conduct the daily manatee count estimate that the current Blue Spring winter manatee population needs 200–250 m of spring run to hold all the animals at one time (personal communication: Wayne Hartley to Lynn Lefebvre, 1997). Because Blue Spring Run, including the spring boil, is 650 m long, an event exceeding 500 m leaves less than 150 m of spring run available as a warm-water refuge.

The potential for significant mortality during a 500-meter intrusion event, coupled with a slow population recovery, means that spring flow should be maintained to prevent the occurrence of such an event.

Intrusion Events Exceeding 400 m

Maintaining Blue Spring Run as a reliable warm-water refuge requires maintaining sufficient spring flow to prevent intrusions exceeding 400 m during winter floods and low river temperatures, because an intrusion of 400 m is the smallest intrusion that preserves at least 250 m of the 650 m spring run as a warm-water refuge for manatees.

Intrusion Events Exceeding 280 m

A cold-water intrusion exceeding 280 m would force the manatees out of the state-designated Manatee Refuge and into less-desirable habitat in the upper run. Most of the upper 100 m of the spring run is narrower and shallower than the lower run and, as a result, has a swifter current. Manatees might have difficulty resting in this portion of the run because of the swifter current, although manatees have been observed passing through this reach to use the spring pool. For this reason we consider that this portion of the run is less suitable for manatees as a winter refuge, although they would likely use it as a warm-water refuge if the lower run were not available (personal communication: Lynn Lefebvre, 1997). In addition, the Manatee Refuge is preferred by manatees probably because this portion of the run is nearest to river feeding locations and excluded from human activity. Forcing the manatees into the upper spring run, then, would likely place additional stress on the animals.

To avoid forcing manatees into the less suitable habitat of the upper run, while still maintaining a 250 m run refuge length, requires that intrusions not exceed about 300 m. Because this intrusion limit is close to the limit of the Manatee Refuge (280 m) we chose to evaluate intrusion lengths exceeding 280 m as the event satisfying the above requirements. Cold-water inundation of the Manatee

Refuge, then, approximately coincides with the minimum intrusion length required to prevent forcing the manatees into unsuitable habitat in the upper spring run.

Intrusion Events Exceeding 80 m

Intrusions exceeding 80 m would reduce the 280 m Manatee Refuge to less than 200 m and possibly force some manatees out of the Refuge.

Preventing Catastrophic Cold-Water Intrusion Events

We determined that a catastrophic cold-water intrusion event is an intrusion exceeding 500 m. Such an event could subject a large number of manatees to intolerable water temperatures and possibly cause significant mortality to the St. Johns River manatee population. Under the historic spring flow condition, with mean discharge of 4.7 m^3s^{-1}, a catastrophic cold-water intrusion event was very improbable. Cold-water intrusion did not exceed 500 m during a 100-year winter flood for spring discharge of two-standard deviations below the historic mean even when river temperature was as low as 12°C.

For a 30% reduction of historic flow our results show the distinct possibility of a catastrophic intrusion event during a 100-year winter flood. Under this flow condition, a 100-year winter flood accompanied by a river temperature of 12°C nearly produces a 500 m event even for the mean discharge (Table 5, Figure 14). This means that at a 30% reduction of historic flow, the spring run is not protected from complete inundation during a 100-year winter flood when manatees would most require a warm-water refuge.

A 20% reduction of historic flow, with a mean discharge of 3.8 m^3s^{-1}, was the lowest spring flow evaluated that protects the spring run from cold-water inundation for a realistic range of river stage, spring variability, and river temperature. At a constant mean discharge of 3.8 m^3s^{-1}, no intrusion exceeded 500 m for river stage up to the 100-year winter flood and river temperatures as low as 10°C (figure 13).

Maintaining Blue Spring Run as a Reliable Warm-Water Refuge for Manatees

Fundamentally, maintaining Blue Spring Run as a reliable warm-water winter refuge for manatees requires that spring discharge be sufficient to maintain at least 250 m of run length for a warm-water refuge during winter floods and cold river temperatures. Intrusions exceeding 400 m, then, are the largest allowable cold-water intrusions that still maintain adequate run length. However, the upper 100 m of spring run is less desirable as manatee habitat and preventing intrusions greater than 280 m is therefore preferred under all but the most extreme scenarios. In this section, then, we examine both these intrusion events as the upper and lower bounds for providing a reliable winter refuge for manatees.

Preventing Intrusions Exceeding 400 m

At the historic mean discharge of 4.7 m^3s^{-1}, intrusion lengths did not exceed 400 m for river stages up to the 50-year winter flood even for river temperatures as low as 12°C and spring discharge two standard deviations below the mean (Table 5). An intrusion exceeding 400 m was only possible when river stage equaled or exceeded the 100-year winter flood, river temperature was at or below 12°C, and spring discharge was at least 1 standard deviation below the mean.

For a 20% reduction of historic spring flow, an intrusion exceeding 400 m could occur for a 50-year winter flood, but only if river temperatures were at or below 12°C and spring discharge was at least 1 standard deviation below the mean (Table 5). However, at the mean discharge of 3.8 m^3s^{-1}, the cold-water intrusion during a 100-year winter flood when river temperature was near 12°C would approach 450 m. Still, the conditions at which a cold-water intrusion exceeding 400 m could occur under a 20% reduction of spring flow remain reasonably extreme.

At a 30% reduction of historic flow, an intrusion exceeding 400 m would occur during a 50-year winter flood at the mean discharge of 3.3 m^3s^{-1} when river temperatures are near 12°C. We estimated that, at this spring flow, there is a 90% probability of at least one intrusion exceeding 400 m in only 20 winters. We cannot accept a 30% reduction of spring flow, then, as an adequate flow for maintaining Blue Spring Run as a *reliable* winter refuge for manatees.

Preventing Intrusions Exceeding 280 m

Intrusions exceeding 280 m would force the manatees out of the Manatee Refuge and into less-desirable habitat in the upper run. We felt that such an event should not occur for more frequent flood events, and we thus examined the possibility of losing the manatee refuge during floods with annual recurrence of 10 years or less. The most recent 10-year winter flood occurred during January 1998.

At the historic mean flow, loss of the Manatee Refuge did not occur for river stages less than a 50-year winter flood (Figure 12), so the Refuge was well-protected from cold-water inundation at this discharge. At a 20% reduction of historic mean flow, the Refuge remains protected from a 10-year winter flood (Figure 13), but is not protected from a 10-year winter flood at a 30% reduction of historic mean flow (Figure 14). Loss of the Manatee Refuge would occur at a 30% reduction of historic mean flow during a 10-year winter flood even for river temperatures as high as 14°C.

During a 10-year winter flood, an intrusion exceeding 280 m could occur at a 20% reduction of historic flow, but only if spring discharge was at least 1 standard deviation below the mean and river temperature was at least 12°C (Table 5). For a 30% reduction of historic flow, a 280 m intrusion would occur during a 10-year winter flood at the mean discharge if river temperature were 12°C. A 30% reduction of spring flow, then, provides no protection of the Manatee Refuge during a 10-year winter flood at cold river temperatures. Even during a 5-year winter flood at the mean discharge, a 30% reduction of historic spring flow would allow an intrusion of 261 m, nearly inundating the Manatee Refuge. As a result, for a 30% reduction of historic flow there is approximately a 90% probability of at least one intrusion exceeding 280 m in 3 winters, whereas for a 20% reduction of historic flow the equivalent duration is 10 winters.

RECOMMENDATIONS

The recommended Minimum Average Flow for Blue Spring is 3.8 m^3s^{-1} (134 ft^3s^{-1}). At this average discharge Blue Spring Run is protected from a catastrophic intrusion event during a 100-year winter flood and maintains an adequate warm-water refuge for a 50-year winter flood even for river temperatures as low as 12°C. This flow condition was also the lowest flow condition that prevented frequent inundation of the Manatee Refuge.

REFERENCES

Ackerman, B.B. 1995. Aerial Surveys of Manatees: A Summary and Progress Report. In *Population Biology of the Florida Manatee; Information And Technology Report I.* T.J. O'Shea, B.B Ackerman, and H.F. Percival (*eds*). U.S. Department of the Interior, National Biological Service. Washington, D.C. pp. 13–33.

Ackerman, B.B., S.D. Wright, R.K. Bonde, D.K. Odell, and D.J. Banowetz. 1995. Trends and Patterns in Mortality of Manatees in Florida, 1974–92. In *Population Biology of the Florida Manatee; Information And Technology Report I.* T.J. O'Shea, B.B Ackerman, and H.F. Percival (*eds*). U.S. Department of the Interior, National Biological Service. Washington, D.C. pp. 223–258.

Bengtson, J.L. 1981. Ecology of Manatees (*Trichechus manatus*) in the St. Johns River, Florida. Doctoral Dissertation for the University of Minnesota. University Microfilms International, Ann Arbor, Mich. 126 pp.

Galperin, B., L.H. Kantha, S. Hassid, and A. Rosati. 1988. A quasi-equilibrium turbulent energy model for geophysical flows. *J. Atmos. Sci.,* 45: 55–62.

Hamrick, J.M. 1992a. A three-dimensional environmental fluid dynamics computer code: Theoretical and computational aspects. Special Report 317. The College of William and Mary, Virginia Institute of Marine Sciences, Va.

Hamrick, J.M. 1992b. Estuarine environmental impact assessment using a three-dimensional circulation and transport model. In *Estuarine and Coastal Modeling, Proceedings of the 2nd International Conference,* M.L. Spaulding, ed. American Society of Civil Engineers. N.Y.

Hartman, D.S. 1978. Species Account: West Indian Manatee. In *Rare and Endangered Biota of Florida: Volume One Mammals*. J. N. Layne and P.C. Pritchard (*eds*). Florida Committee on Rare and Endangered Plants and Animals. University Presses of Florida. Gainesville, Fla. pp. 27–30.

Hartman, D.S. 1979. Ecology and Behavior of the Manatee (*Trichechus manatus*) in Florida. Special Publication No. 5, The Am. Soc. of Mammalogists. Carnegie Museum of Natural History, Pittsburgh, Pa. 153 pp.

Lewis, E.L. 1980. The Practical Salinity Scale 1978 and its antecedents. IEEE J. of Ocean. Eng., OE-5(1), 3–8.

Lowe, E.F. 1994. District Water Management Plan - Conventions Subcommittee on Impacts to Natural Systems. Final Report, August 1994. St. Johns River Water Management District, Palatka, Fla. 119 pp.

Maidment, D.R. 1993. *Handbook of Hydrology*. McGraw-Hill, Inc., N.Y.

Mellor, G.L. and T. Yamada. 1982. Development of a turbulence closure model for geophysical fluid problems. *Rev. Geophys. Space Phys.,* 20(6): 851–875.

Officer, Charles B. 1976. *Physical Oceanography of Estuaries.* John Wiley & Sons, N.Y.

O'Shea, T.J. 1994. Manatees. Scientific American. July: 66–72.

O'Shea, T.J. and W.C. Hartley. 1995. Reproduction and early-age survival of manatees at Blue Spring, Upper St. Johns River, Florida. In *Population Biology of the Florida Manatee; Information And Technology Report I.* T.J. O'Shea, B.B Ackerman, and H.F. Percival (*eds*). U.S. Department of the Interior, National Biological Service. Washington, D.C. pp. 157–170.

O'Shea, T.J., C.A. Beck, R.K. Bonde, H.I. Kochman, and D.K. Odell. 1985. An analysis of manatee mortality patterns in Florida, 1976–81. J. Wildl. Manage. 49(1):1–11.

Stommel, H. and H.G. Farmer. 1952. Abrupt change in width in two-layer open channel flow. *J. of Marine Res.*, 11: 205–214.

U.S. Fish and Wildlife Service. 1981. Summary of U.S. Fish and Wildlife Service Manatee Research at Blue Spring Run, 1970–81, Volumes 1–3. Sirenia Project, Denver Wildlife Research Center - Gainesville Field Station. Gainesville, Fla. 449 pp.

Vergara, Barbara. 1994. Water supply needs and sources assessment. Tech. Publication SJ94-7, SJRWMD, Palatka, Fla.

Waldron, J.C. 1981. 1976–77 winter field study of the Florida Manatee at Blue Spring State Park, Volusia Co., FL. *In* Summary of U.S. Fish and Wildlife Service Manatee Research at Blue Spring Run, 1970–81, Volumes 1–3. Sirenia Project, Denver Wildlife Research Center - Gainesville Field Station. Gainesville, Fla. pp 176–185.

Williams, Stanley A. 1997. A regional flow model of the Volusia ground water basin. Tech. Publication SJ97-3, SJRWMD, Palatka, Fla.