Appendix I

A Model for Assessing Incidental Take of Manatees
Due to Watercraft-related Activities

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1. Abstract

A stochastic population model was developed to forecast the effects of various levels of incidental take on manatee population dynamics in the four Florida stocks, and to assess whether current, or any proposed, levels of watercraft-related mortality could be classified as “negligible” under the Marine Mammal Protection Act. This population model includes annual variability in survival and reproductive rates, demographic stochasticity, effects of changes in warm-water carrying capacity, rare catastrophes, and effects of changes in watercraft-related mortality. Further, the model explicitly accounts for uncertainty in the parameter estimates. Based on the criteria presented in the Proposed Rule, the current levels of incidental take cannot be deemed negligible for any of the four manatee stocks, even if those levels of take are held constant over time. The same conclusion is reached with two other methods for defining negligible (the “fraction of excess growth” criterion, and the potential biological removal method). The levels of incidental take that would be considered negligible based on the criteria in the Proposed Rule are <1 manatee/yr in the Atlantic, Upper St. Johns, and Northwest regions, and 0 manatees/yr in the Southwest region (the latter because the growth rate is expected to be negative even in the absence of incidental take). Of the three definitions of negligible considered, the potential biological removal method allows the highest levels of incidental take, at 5.6/yr in the Atlantic region, 0.6/yr in the Upper St. Johns, 1.5/yr in the Northwest, and 5.5/yr in the Southwest. In the Upper St. Johns and Northwest regions, allowable incidental take is limited because of the small population sizes; in the Atlantic and Southwest regions, allowable incidental take is limited because of low growth rates even in the absence of take. In the absence of any new management action, that is, if boat mortality rates continue to increase at the rates observed since 1992, the situation in the Atlantic and Southwest regions is dire, with no chance of meeting recovery criteria within 100 yrs; in the Upper St. Johns and Northwest regions, the probabilities of significant (>10%) delay in recovery time are 10 and 62%, respectively, compared to the case of no watercraft-related mortality. The results of these assessments are likely sensitive to (a) the fraction of carcasses recovered in the salvage program; (2) the model for future warm-water carrying capacity; (3) the fraction of mortality due to watercraft, as estimated from the carcass data; and (4) the model for change in watercraft-related mortality under the “no action” scenario.

2. Background and Purpose

A stochastic matrix-based model of Florida manatee (*Trichechus manatus latirostris*) population dynamics was used to make an assessment of levels of watercraft-related incidental take that could be considered negligible under the Marine Mammal Protection Act (MMPA). To be considered negligible, "The impact cannot be reasonably expected to, and is not reasonably likely to, adversely affect the species through effects on annual rates of recruitment or survival" (MMPA 50 C.F.R. 18.27). Several principles underlie the development of this model: (a) it is based on the best currently available information about manatee population dynamics; (b) it explicitly incorporates uncertainty about dynamics and population parameters, and where the uncertainty cannot be made mathematically explicit, precautionary assumptions are made; and (c) it meets the standards specified by, implied by, or interpreted from the MMPA.

The purpose of the model is to calculate for each of the four Florida manatee stocks, through stochastic simulations, whether a given level of authorized take is expected to meet the criteria for having a negligible impact. Thus, the input for the model is a proposed level for annual authorized take, as measured by observed watercraft-related deaths. The outputs of the model are: the probabilities of having achieved recovery (defined below) within 50 and 100 years, given the proposed level of incidental take; and the probability of recovery being delayed by ≥10% with the proposed level of take, compared to the case where there was no take. For a proposed level of take to be considered negligible, the probability of a 10% or greater delay in time to recovery must be less than or equal to 5%.

To determine whether a simulated population achieved recovery, the recovery criterion in the 3rd revision of the Florida Manatee Recovery Plan (USFWS 2001) was used, specifically, statistical confidence (of 95%) that the twenty-year mean annual growth rate was nonnegative.

Two other standards for defining negligible were considered. The Fraction of Excess Growth (FEG) criterion considers the expected growth rate (λ), calculates the "excess growth rate" (λ–1) in the absence of take, and determines what fraction of that excess growth is removed by a proposed level of incidental take. If the fraction of excess growth removed is less than 10%, the incidental take is deemed negligible. The Potential Biological Removal (PBR) criterion calculates a threshold level for incidental take that would be deemed negligible, by finding the product of the minimum population size, one half the maximum growth rate, and a recovery factor, as described in the MMPA, 16 USC 1362(20) and 16 USC 1386. Note that the FEG criterion required use of the model described herein, while the PBR criterion did not.

Several scenarios for future incidental take in each region were examined, including: no take; various levels of a fixed *rate* of take (relative to population size) over the next 100 yrs; various levels of fixed *absolute* take over the next 100 yrs; and continued increase in incidental take at the rates observed since 1992. Two primary questions were addressed: (1) are current levels of take negligible, as defined by the various criteria; and (2) if not, what levels of incidental take would be deemed negligible for each region?

3. Model Structure

3.1. Core Stage-structured Model

The core of the model (Fig. 1) is a matrix-based description of *female* manatee population dynamics. The model centers on females because their survival and reproduction directly control population growth. Manatees have a promiscuous mating system. A single male can inseminate multiple females (Hartman 1979:100); therefore males do not directly limit population growth. The core model is expanded below to include males. In the core model, the manatee population is broken into 7 classes of females:

First-year calves (0.5-yr-old). Manatee population monitoring focuses on the winter aggregation sites. Calves, however, are born during the spring and summer (Marmontel 1995, Rathbun *et al.* 1995, O'Shea and Hartley 1995, Reid *et al.* 1995). The first reliable data on reproduction is collected when a female with a dependent nursing calf returns to the winter aggregations in fall and winter. Calves are ca. 3-9 months old at this time. Thus a first-year calf represents successful pregnancy, birth, and survival to ca. age 0.5. There currently are no reliable means to monitor pregnancy or births in the wild (Rathbun *et al.* 1995).

Second-year calves (1.5-yr-old). Data on second-year calves (denoted as age-class 2) are collected the following year at the aggregation site. Second year calves are primarily identified by size—they are larger than first-year calves, but smaller than subadults. They may or may not be weaned and independent of their mothers. There is considerable variation among individuals as to whether a calf will nurse for one or two years (Rathbun *et al.* 1995, O'Shea and Hartley 1995, Reid *et al.* 1995).

Third-year subadults (2.5-yr-old, age class 3). At three years of age, individuals are independent but only rarely sexually mature and capable of reproducing (Marmontel 1995, O'Shea and Hartley 1995).

Fourth-year subadults (3.5-yr-old, age class 4) and *Pre-breeders* (≥ 4.5-yr-old, state P). Pre-breeders are individuals 4.5 years old or older that have not yet successfully reproduced. This model assumes that the earliest a female can breed is in her fourth year (at age ~3.5 yr), thus, the earliest first appearance with a calf can occur is age 4.5 yr. Based on winter observations, the earliest that a female manatee has been observed with a dependent calf is four winters after she herself was observed as a new calf, that is, at ca. 4.5 yr (Rathbun *et al.* 1995, O'Shea and Hartley 1995). However there is considerable individual variation in the age of first successful reproduction (Marmontel 1995, O'Shea and Hartley 1995); this is reflected in females that remain in the pre-breeder class for some time.

Adults with first-year calves (denoted as state C) and *Breeders* (state B). Sexually mature females that are accompanied by a dependent first-year calf, or that have previously produced a calf are classified as "with a 1st-yr calf" or as a "breeder," respectively. Mature females accompanied by a not-yet-weaned second-yr calf are considered "breeders," since the attendant calf was not born during the current year.

Two types of life-history parameters describe the transitions between the classes in the model: survival rates (s) and breeding rates (γ). For instance, s_1 is the probability a first-year calf survives to become a second-year calf; γ_P is the probability that an adult female that has not yet given birth to a calf, breeds and successfully gives birth within the next year, given survival until that time. Pre-breeders that survive either give birth to a calf (with probability γ_P) or remain as pre-breeders. Females with a first-year calf that survive become breeders the next year (with probability = 1.0), regardless of whether they wean the calf after the first year. That is, the model does not allow females to have calves two years in a row—this constraint reflects the physiological limitations imposed by the length of pregnancy (12-13 months, Rathbun *et al.* 1995, O'Shea and Hartley 1995, Reid *et al.* 1995) and early dependence of the calf. Breeders (without calves) that survive to the next year either give birth to a calf (with probability γ_B) or remain as breeders. A female with a first-year calf gives rise to a second-year calf (weaned or not weaned) in the next year with probability $s_1/2$, reflecting the probability of calf survival and an even primary sex ratio (recall this is a model for the female segment of the population, and only half the calves are expected to be female). Note that in this model, the litter size is assumed to be 1 calf. While twinning is possible in nature, it is rare (Marmontel 1995, Rathbun *et al.* 1995, O'Shea and Hartley 1995).

This life history diagram (Fig. 1) can be expressed in matrix form as

$$\begin{bmatrix} N_2 \\ N_3 \\ N_4 \\ N_P \\ N_C \\ N_B \end{bmatrix}_{t+1} = \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{1}{2}s_1 & 0 \\ s_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & s_3 & 0 & 0 & 0 & 0 \\ 0 & 0 & s_4(1-\gamma_4) & s_P(1-\gamma_P) & 0 & 0 \\ 0 & 0 & s_4\gamma_4 & s_P\gamma_P & 0 & s_A\gamma_B \\ 0 & 0 & 0 & 0 & s_A & s_A(1-\gamma_B) \end{bmatrix} \begin{bmatrix} N_2 \\ N_3 \\ N_4 \\ N_P \\ N_C \\ N_B \end{bmatrix}_t \tag{1}$$

where the N_i represent the number of manatees in class i at a given point in time. In the matrix formulation, first-year calves are not counted separately, as they are assumed to be dependent on their mothers, although their numbers can be inferred from the number of females with calves (N_C). New births first appear in the population model as second-year calves. The total female population size at time t can be calculated as:

$$N_{Total} = N_2 + N_3 + N_4 + N_P + 1.5N_C + N_B \tag{2}$$

where the number of females with first-year calves is multiplied by 1.5 to include both the mothers and their *female* calves in the total.

To expand the core model to include males, four additional classes of animals are added. The matrix formulation is

$$\begin{bmatrix} N_2 \\ N_3 \\ N_4 \\ N_P \\ N_C \\ N_B \\ N_2^M \\ N_3^M \\ N_4^M \\ N_A^M \end{bmatrix}_{t+1} = \left[\begin{array}{cccccc|cccc} 0 & 0 & 0 & 0 & \frac{1}{2}s_1 & 0 & 0 & 0 & 0 & 0 \\ s_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & s_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & s_4(1-\gamma_4) & s_P(1-\gamma_P) & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & s_4\gamma_4 & s_P\gamma_P & 0 & s_A\gamma_B & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & s_A & s_A(1-\gamma_B) & 0 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & \frac{1}{2}s_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & s_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & s_3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & s_4 & s_A \end{array}\right] \begin{bmatrix} N_2 \\ N_3 \\ N_4 \\ N_P \\ N_C \\ N_B \\ N_2^M \\ N_3^M \\ N_4^M \\ N_A^M \end{bmatrix}_t \quad (3)$$

where the four new classes keep track of the second-year, third-year, fourth-year, and adult males, respectively. There is no evidence that survival rates differ between males and females (Langtimm et al. 1998), so the same survival rates are used for corresponding male and female age-classes. The total population size can be written as

$$N_{Total} = N_2 + N_3 + N_4 + N_P + 2N_C + N_B + N_2^M + N_3^M + N_4^M + N_A^M \quad (4)$$

with the females with first-year calves now multiplied by two to include both the mothers and their calves (of either sex) in the total.

3.2. Environmental Stochasticity

Variation in life-history parameters (survival and reproductive rates) due to uncontrolled factors in the environment is called environmental stochasticity. Manatees experience environmental stochasticity due to a number of factors, for example, red tide (O'Shea et al. 1991, Bossart et al. 1998), severe cold (Buergelt et al. 1984), and hurricanes (Langtimm and Beck 2003). Two types of environmental stochasticity are often distinguished: "normal" variation, which causes the life-history parameters to fluctuate on an annual basis; and catastrophes, rare events that have strong negative effects. In this model, the effects of red tide and virulent, infectious disease are treated as catastrophes, while the effects of cold, hurricanes, and other factors are treated as "normal" variation. In the remainder of this document, "environmental stochasticity" refers to the "normal" variation, while catastrophes are identified specifically.

The time series of observations used to estimate survival and reproduction include "normal" variation, and so the estimated life-history parameters integrate stochasticity from the corresponding sources, but catastrophes of the sort described below are assumed not to have occurred during the time period of observation used for the parameter estimation.

In this model, environmental stochasticity is represented by probability distributions for the annual values for the life-history parameters. All of the parameters in the model are probabilities (survival probabilities, s; breeding probabilities, γ) and thus must be in the interval [0,1].

Variation in these parameters is modeled with logit-normal distributions. The logit-normal distribution is a transformation of the normal distribution that confines the values of the variables to the interval (0,1). Since the parameters in question must lie in this interval, this distribution is natural since it allows only biologically permissible values. The logit transformation is

$$x = \ln\left(\frac{p}{1-p}\right) \tag{5}$$

and if x is normally distributed, then p is said to follow a logit-normal distribution. Specification of a logit-normal distribution requires a mean (μ) and variance (σ^2) for the transformed variable (i.e, x).

The year-specific values for each life-history parameter are sampled from the appropriate logit-normal distribution. Thus, the first-year calf survival rate in year t has the distribution such that

$$\ln\left(\frac{s_{1,t}}{1-s_{1,t}}\right) \sim Normal\left(\mu_{s_1}, \sigma^2_{s_1}\right). \tag{6}$$

The survival rates are assumed to vary together, since it is likely the same environmental factors will affect subadult survival rates as affect adult survival rates. To model this, the same standard normal deviate is used to generate each of the survival rates. This method produces perfect temporal correlation among the survival rates sampled in this manner.

The breeding probabilities, γ, are also assumed to vary together. This implies that the same set of environmental factors affects all three breeding probabilities (γ_P, γ_C, and γ_B). The survival rates and breeding probabilities were assumed to vary together with a positive correlation of 0.5. This implies that the set of environmental factors affecting reproduction is similar, but not identical to the set of factors affecting annual survival. In the simulations, this correlation was accomplished by generating a pair of values from a standard bivariate normal distribution with correlation of 0.5, and using one of these values to generate the survival rates, the other to generate the breeding probabilities.

3.3. Catastrophes

Two types of catastrophes were considered, following the structure of the population viability analysis conducted by the state of Florida in its 2002 status review (FMRI 2002): the emergence of a virulent, infectious disease (Type 1); and severe red tide (Type 2). Large-scale mortality events caused by disease or toxins occur occasionally in marine mammals and have the potential to greatly reduce population size (Harwood and Hall 1990)—the Type 1 catastrophes describe this occurrence. These catastrophes were characterized in the model by an annual probability of occurrence of 0.01, a reduction of all survival rates by 25%, and a reduction of all breeding probabilities by 20% (FMRI 2002). Type 2 catastrophes (red tide mortality) were assumed to occur only in two of the four regions: in the Northwest with an annual probability of occurrence of 0.018, a reduction in all survival rates by 5%, and a reduction in all breeding probabilities by

5%; and in the Southwest with an annual probability of occurrence of 0.036, a reduction in all survival rates by 10%, and a reduction in all breeding probabilities by 5%. These probabilities of occurrence and effect sizes are drawn from the population viability analysis developed by the state of Florida (FMRI 2002).

3.4. Demographic Stochasticity

Demographic stochasticity is the variation due to applying probabilistic life-history parameters to individuals. For example, suppose the survival rate in a population is 0.5. If there are 10 animals in the population, 5 are expected to survive, but the number that actually survive can vary, since each animal flips its own "survival coin." Since all the life-history parameters in the model are probabilities with binary outcomes (survive vs. not-survive, breed vs. not-breed), an appropriate distribution for the demographic stochasticity is the binomial distribution (the binomial is the "coin-flip" distribution—e.g., if I flip 100 weighted coins, each with a certain probability of landing heads, what's the probability that, say, 65 of them are heads?). Thus, for each class in the population model, the number that survive or breed is drawn from a binomial distribution with success probability equal to the year-specific value for the appropriate life-history parameter.

For example, suppose in a given year, there are 100 adult males; the mean adult male survival rate is 2.75 on the logit-scale (this corresponds to a mean survival rate of ~0.94), and the standard deviation on the logit-scale is 0.75. The year specific annual survival rate is

$$\ln\left(\frac{s_{A,t}^{M}}{1-s_{A,t}^{M}}\right) \sim Normal(2.75, 0.75^2)\,.$$

Let's say a draw is made from this distribution and the value is 0.88. Then, the actual number of adult males that survive has the distribution

$$binomial(100, 0.88)\,.$$

Let's say a draw is made from this distribution and the value is 91. Thus, of the 100 adult males alive in year *t*, 91 survived to the next year.

Because demographic stochasticity represents the application of life-history parameters to individuals, it is calculated independently for each class in the model (this is equivalent to calculating it independently for each individual in the population).

The sex ratio in the first-year calves is assumed to be 0.50, there being no evidence of a skewed primary sex ratio or differential neonatal survival by sex (O'Shea and Hartley 1995, Reid et al. 1995). The number of first-year calves is determined by the number of females with calves. The number of *female* first-year calves is sampled from a binomial distribution with success probability 0.50. The number of male first-year calves is then found by subtraction.

Several other instances of demographic stochasticity are included in the model. These are described below in the *Outline of the Modeled Annual Cycle*.

3.5. Density-dependence

The model shown in equation (3) is an exponential population model, and the addition of stochastic effects doesn't change that. No real population can grow exponentially for an indefinite period of time—at some point, some resource becomes limiting and survival and/or reproductive rates must decrease.

Density effects on life-history parameters in manatees have not yet been documented or estimated in the literature. Four possible reasons for this are: (1) manatee densities may be too low to have shown any strong density-dependent effects; (2) since robust monitoring programs have been in place, manatee densities may not have varied over a wide enough range to allow detection of density-dependent effects; (3) appropriate monitoring programs specifically geared to detect density-dependent effects have not been developed; and (4) the relevant limiting factors may be unknown and/or may change over time and space, making detection of the effects of limitation difficult.

One of the major limiting factors for manatee population growth is presumed to be warm-water refugia (USFWS 2001). As the older power plants that currently provide warm-water are phased out of use, it is possible that manatee populations, particularly in the Atlantic and Southwest regions, will experience a reduction in the carrying capacity of their environments. In addition, reduction of spring flows due to increasing human reduction of aquifer capacity is decreasing the availability of warm-water at natural springs. Whether these factors affect long-term recovery of manatees will depend on the extent to which this loss of warm-water can be mitigated by other management measures.

For each region, three scenarios are possible regarding density-dependence acting through limitation in capacity of warm-water refugia during the winter. (1) No density-dependence over the next 100 years. This could be the case if manatees can adapt to changes quickly enough, or if management actions can be swift enough, to effectively increase the carrying capacity faster than any increase in the population size. (2) Stable carrying capacity. Current winter warm-water carrying capacity will remain constant over the next 100 years. This would be the case if there were no changes to warm-water sites, or if mitigating measures were implemented. (3) Declining carrying capacity over time. This scenario would reflect substantial loss of warm-water refugia over the next 100 years, due to closure of power plants and/or reduced spring flow. In the model, each of these scenarios, in each region, is assigned a probability to reflect uncertainty about future changes in warm-water carrying capacity.

For the third scenario of a decline in carrying capacity, a model for the magnitude and timing of the decline is needed. Here, carrying capacity is interpreted as the number of manatees that can fit into suitable warm-water habitat during prolonged cold periods, and so escape death due to cold stress.

Atlantic Region. In the Atlantic region, the likely decline in the warm-water carrying capacity can be described with a logistic curve (Fig. 2). The current carrying capacity (k_1) is likely to be maintained for at least 3 years, after which it will decline, then stabilize at some lower level (k_0) by 50 years from now. This drop will largely be a result of intermittent operation then permanent loss of industrial thermal plumes, forcing manatees south of the historical winter limit (around Sebastian Inlet). The timing of the drop is governed by the paramater c, which is roughly the time at which half of the vulnerable capacity is lost. The speed at which the loss occurs is governed by the paramater m. This curve can be described mathematically as

$$y = s_0 + \frac{(s_1 - s_0)}{1 + e^{m(x-c)}} \tag{7}$$

where y is the warm-water carrying capacity and x is time (in years). By setting

$$s_0 = \frac{(k_0 - k_1) + e^{-mc}\left(k_0 e^{mb} - k_1 e^{ma}\right)}{e^{-mc}\left(e^{mb} - e^{ma}\right)} \text{ and} \tag{8}$$

$$s_1 = s_0 + (k_1 - k_0)\frac{\left(1 + e^{m(a-c)}\right)\left(1 + e^{m(b-c)}\right)}{e^{-mc}\left(e^{mb} - e^{ma}\right)} \tag{9}$$

the curve can be made to pass through the points (a, k_1) and (b, k_0), where a and b are set at 3 and 50, respectively.

Upper St. Johns and *Northwest Regions*. In the Upper St. Johns and Northwest regions, if a decline in winter carrying capacity does occur, it is likely to occur in a gradually declining fashion as spring flow is reduced (Fig. 3). If the current carrying capacity is given by s_1 and the long-term carrying capacity is given by s_0, this curve can be described mathematically as

$$y = s_0 + (s_1 - s_0)e^{-mx}. \tag{10}$$

The half-life of the reduction from s_1 to s_0 can be used to calculate the rate parameter, m, as

$$m = \frac{\ln 2}{t_{1/2}}. \tag{11}$$

The Upper St. Johns and Northwest regions are described in the model with their own sets of parameters for equation 10.

Southwest Region. In the Southwest region, unless the plants in Ft. Myers and Tampa Bay stay in operation for a very long time, the loss of winter carrying capacity is likely to occur in two ways: a sharp loss when the Ft. Myers plant ceases to operate; and a more gradual decline with the intermittent operation and loss of other sources of warm water (Fig. 4). The current carrying capacity (k_1) is likely to be maintained for at least 3 years, after which it will decline, then stabilize at some lower level (k_0) by 30 years from now. The carrying capacity in the Southwest that will be lost can be divided into two components, the Ft. Myers capacity, k_M, and the remaining additional capacity, k_X, where

$$k_X = k_1 - k_0 - k_M \,. \tag{12}$$

The loss of this additional capacity can be described with an exponential decay function, as in equation 10. By setting

$$s_0 = k_X - \frac{k_X e^{-ma}}{e^{-ma} - e^{-mb}} \text{ and} \tag{13}$$

$$s_1 = k_X + \frac{k_X\left(1 - e^{-ma}\right)}{e^{-ma} - e^{-mb}} \tag{14}$$

the curve can be made to pass through the points (a, k_X) and (b, 0) (Fig. 5). The winter carrying capacity in the Southwest, then, can be expressed as the sum of the long-term carrying capacity, the Ft. Myers carrying capacity (if it is still operating), and the exponentially decaying additional capacity. That is,

$$y = k_0 + k_M I_{x<c} + k_X - \frac{k_X e^{-ma}}{e^{-ma} - e^{-mb}} + \frac{k_X e^{-mx}}{e^{-ma} - e^{-mb}} \tag{15}$$

for $a \le x \le b$, where

$$I_{x<c} = \begin{cases} 1 & \text{if } x < c \\ 0 & \text{if } x \ge c \end{cases} \tag{16}$$

indicates whether Ft. Myers is still operating (c is the time when Ft. Myers ceases to operate).

Effects of Exceeding Carrying Capacity. In the event that the population in a particular region exceeds its warm-water carrying capacity, what are the consequences? Presumably, animals outside the warm-water refugia face greater mortality due to cold stress, but the consequences are likely to be different depending on the age of the animal and the severity of the winter. Calves are more vulnerable than adults to the effects of cold, for two reasons: lower body mass, hence greater heat loss; and, for independent calves, lack of experience finding suitable wintering sites. This model consider two levels of severity in winter, “normal” and “cold”, where a “cold” winter occurs 20% of the time, and is determined from the standard normal deviate that governs environmental stochasticity in survival rates (that is, cold winters and “bad” years for survival are assumed to coincide). A cold winter is one in which there are multiple, prolonged cold spells. The effect of exceeding the carrying capacity and/or enduring a cold winter can be expressed as an additional source of mortality. If the population size is less than the carrying capacity, all animals are presumed to be “inside refugia.” If the population size is greater than the carrying capacity, the difference constitutes the animals that are “outside refugia,” who face additional mortality. Four cold-related mortality parameters are needed for animals that are outside refugia: for adults (including subadults) and calves, in cold years and in normal years. In addition, a fifth parameter describes cold-related mortality for calves inside refugia during cold years. Note that since the Incidental Take Model is a winter-to-winter model, the cold stress mortality is applied first. Those animals that survive are then subject to the annual class-specific survival rates, as described above.

Effects of Approaching Carrying Capacity. In addition to the sharp effect of exceeding carrying capacity during cold years, the model includes a more gradual density-dependent component. As the population approaches carrying capacity, reproductive rates (the breeding probabilities, γ) are reduced, due to presumed crowding and displacement from prime habitat. Each breeding probability is multiplied by

$$1-\alpha\left(\frac{N_{Total}}{K}\right)^{\beta} \qquad (17)$$

where α is the fraction by which reproduction is reduced when the population is at carrying capacity, and β controls how close the population size has to be to K (the carrying capacity) before the density-dependent effects are felt.

3.6. The Effect of Watercraft-related Mortality

The crux of the model is the link between the life-history parameters and the number of watercraft-related mortalities observed in the carcass recovery program each year. (See Ackerman et al. 1995 for a description of this program.)

The survival rates estimated from mark-recapture field observations (see **Parameter Estimates and Uncertainty**, below) include the effects of watercraft-related mortality in those regions over the time frame the estimates were made. To estimate the region-specific survival rates *in the absence of* watercraft mortality, the mortality rates are decreased by the fraction of mortality due to watercraft (as estimated by the fraction of carcasses for which the cause of death is watercraft-related). For example, suppose 35% of the carcasses were due to watercraft-related-mortality and the observed survival rate was 0.92, then the survival in the absence of watercraft-related mortality is found by increasing the observed survival rate 35% of the way toward 1.00, that is, to 0.948.

The key input for this model is the observed number of annual mortalities attributed to watercraft-related causes. Two adjustments need to be made to this number to translate it into the actual number of mortalities due to watercraft. First, the number needs to be inflated to reflect the fraction of watercraft-related mortalities that are not identified as such in the recovered carcasses (i.e., watercraft-related mortalities that are identified as “undetermined”). Second, the number needs to be inflated to account for the fact that not all carcasses are recovered.

The survival-rates-in-the-absence-of-take are applied to the population first, in the manner described above (under *Environmental Stochasticity* and *Demographic Stochasticity*). Then the watercraft-related take, adjusted to account for recovery rate and misclassification, is removed from the population by subtraction.

3.7. Outline of the Modeled Annual Cycle

The components of the model described in the preceding sections are assembled in the manner described below. In this outline, "DEM" refers to an element of demographic stochasticity, "ENV" refers to an element of "normal" environmental stochasticity, and "CAT" refers to a catastrophe.

1. Input: population vector at start of annual cycle (mid-winter), warm-water carrying capacity for that winter, observed mortality attributed to watercraft for that year.
2. Calculate effect of exceeding warm-water carrying capacity.
    a. [ENV] Determine if it is a "cold" or "normal" year, based on the standard normal variate used for the annual survival rates (see 3.a. below).
    b. [DEM] If N_{Total} exceeds K, distribute each stage class to "inside" or "outside" the warm-water refugia using a multivariate hypergeometric distribution.
    c. [DEM] Apply the appropriate cold-related mortality rates to the animals in each stage class, depending on whether it is a cold or normal year, whether they are inside or outside refugia, and whether they are calves or older. A binomial distribution is used to determine how many in each stage class survive the winter into spring.
3. Calculate survival and reproductive rates for the remainder of the year
    a. [ENV] Generate annual survival rates and breeding probabilities by sampling from the appropriate logit-normal distributions.
    b. Remove from the mortality rates the fraction of mortality that is due to watercraft-related take, in order to calculate survival rates in the absence of take.
    c. [CAT] Determine if a virulent disease strikes the population. If so, reduce the survival and recruitment rates accordingly.
    d. [CAT] Determine if a red tide event strikes the population. If so, reduce the survival and recruitment rates accordingly.
    e. Calculate the density-dependent reduction in breeding probabilities (using the spring population size relative to the carrying capacity).
4. Adjust and distribute the watercraft-related take
    a. [DEM] Determine how many of the observed watercraft-related mortalities are first-year calves, using a binomial distribution.
    b. [DEM] Correct the calf and older watercraft-related mortalities to account for "undetermined" carcasses, using a negative binomial distribution.
    c. [DEM] Correct the calf and older watercraft-related mortalities to account for unrecovered carcasses, using a negative binomial distribution.
    d. [DEM] Distribute the non-first-yr-calf watercraft-related mortalities into stages, using a multinomial distribution.
5. Apply the life-history parameters and subtract the take
    a. [DEM] Calculate the number of animals in each stage that survive to the next year, using a binomial distribution with the appropriate survival probability (in the absence of take).
    b. Subtract the watercraft-related take from each stage class.

   c. [DEM] Calculate the number of the surviving females in each stage that successfully produce young, using binomial distributions.
   d. [DEM] Calculate the number of surviving first-year calves that are female, using a binomial distribution. Calculate the number of males by subtraction.
6. Advance the age-classes and make the appropriate stage transitions to produce a resulting population vector.

4. Parameter Estimates and Uncertainty

The parameters used in the model are shown in Tables 1-8. These parameter estimates come from several types of sources: published peer-reviewed literature, manuscripts that are currently in review, recent unpublished analyses, and consensus views of expert panels. In the latter two cases, the methods for deriving the parameter estimates are described in some detail below.

4.1. Uncertainty

A concerted effort is made throughout to explicitly characterize the uncertainty associated with the parameter estimates. This uncertainty is then integrated into the simulations so that the results appropriately reflect the state of current knowledge. There are two primary ways that uncertainty was characterized. In the case of parameters that could be estimated through formal statistical analyses, the uncertainty is expressed as the sampling distribution for the estimate (e.g., the confidence interval for a survival rate appropriately expresses the uncertainty in the mean value for that rate). In the case of parameters that were elicited from expert panels, low, median, and high values were derived by consensus. The uncertainty in the corresponding parameter was expressed as a two-phase uniform distribution having the specified low, median, and high values (Fig. 6). In the sections that follow, the uncertainty in the parameter values is discussed along with the point estimates.

4.2. Survival and Reproductive Rates

The mean annual survival rates and breeding probabilities are shown in Table 1, along with confidence intervals that express the uncertainty in those values. The survival rates are derived from analysis of mark-recapture photo-ID data (Langtimm et al., *in review*). Direct estimates of adult survival rates are available for all four regions. Direct estimates of survival rates for the younger age classes are only available for the Upper St. Johns region; indirect estimates for the other regions were found by assuming the ratios of younger to adult survival rates are the same as in the Upper St. Johns region (Runge et al., *in review*). The breeding probabilities for females that have previously bred (γ_B) are derived from the reproductive histories of known females. In the Atlantic and Northwest regions, formal mark-recapture analysis was used to estimate these breeding probabilities (Kendall et al., *in press*; Kendall et al., *in review*). In the other regions, and for the other breeding probabilities (γ_P and γ_4), estimates were obtained by calculating binomial proportions from the observed stage transitions of known, marked females (Runge et al., *in review*). In the Southwest, this involved a reexamination of reproductive histories of marked animals in Sarasota Bay (Koelsch 2001).

The uncertainty in the mean survival rates and breeding probabilities was assumed to follow a logit-normal distribution. The parameters of this distribution (mean and standard deviation on the logit-scale) were estimated from the desired mean and standard deviation on the nominal scale, using the first-order estimates in equations (18) and (19) of Runge and Moen (1998). The resulting values are shown in Table 2.

4.3. Temporal Variance

Temporal variance is the annual fluctuation in survival and reproductive rates due to all factors except those specified as catastrophes (i.e., "normal" environmental stochasticity). The temporal variance for the adult survival rates (Table 3) was estimated from the year-specific estimates of survival over the years 1990-1999 (Langtimm et al., *in review*), using the variance components methods of Burnham et al. (1987:260-266). The distribution of the estimate for the variance ($\hat{\sigma}^2$) is such that

$$\frac{SSQ}{\hat{\sigma}^2 - \hat{\mathrm{var}}} \sim \chi^2_{n-1} \qquad (18)$$

where SSQ and $\hat{\mathrm{var}}$ are derived from the data as described in equations (4.9) and (4.10) of Burnham et al. (1987:265). This distribution was used to characterize the uncertainty in the variance, values less than 0 were truncated to 0, and the square root was taken. The 95% confidence interval for the standard deviation, as generated by this distribution, is shown in Table 3. The subadult survival rates were assumed to have the same variance as the adult survival rates.

Direct empirical estimates of temporal variance were not available for the two calf survival rates in each region. Indirect estimates were found by setting the coefficient of variation to be roughly twice that in the adult survival rates. For adult survival rates in each region, the mean (and 95% confidence interval) for the coefficient of variation were: Atlantic, 1.26% (0 – 5.6%); Upper St. Johns, 0% (0 – 0%); Northwest, 1.35% (0 – 5.6%); Southwest, 0% (0 - 10.3%). Assuming that calves are approximately twice as vulnerable to environmental variation as adults, the desired coefficients of variation for calf survival rates were: Atlantic, 2.5% (0 – 10%); Upper St. Johns, 0% (0 - 5%); Northwest, 2.5% (0 – 10%); Southwest, 0% (0 – 20%). These coefficients of variation were converted to values for standard deviation on the logit-scale (Table 3). The point estimate and range were treated as the median, low and high of a two-phase uniform distribution, in order to characterize uncertainty in the temporal variance of calf survival rates.

A direct estimate of temporal variance of γ_B could be obtained for the Northwest and Atlantic regions using year-specific estimates from a mark-recapture analysis of photo-ID data (Kendall et al., *in review*), using the methods of Burnham et al. (1987), as described above. The uncertainty was characterized using equation 18. In the Upper St. Johns region, γ_B was assumed not to vary, based on the very low estimate of variance in the Atlantic region, and the protected nature of the Upper St. Johns region. For the Southwest region, the temporal variance in γ_B was assumed to be the same as in the Northwest region. The temporal variance of the breeding probability of the pre-breeders (γ_P) was assumed to have the same distribution on the nominal scale as that of the breeders (γ_B). The breeding probability of four-year-olds (γ_4) was assumed not to vary temporally.

4.4. Catastrophes

The probabilities of Type 1 and Type 2 catastrophes, and the magnitude of the corresponding effects on survival and reproduction are summarized in Table 4. These estimates match those used by the state of Florida in their 2002 Status Review (FMRI 2002).

4.5. Warm-water Carrying Capacity

Currently, there are no comprehensive estimates for manatee carrying capacity published in the literature, nor are there quantitative projections of how that carrying capacity may change in the future. The estimates used in this model were derived from discussions with the Warm Water Task Force, a multi-agency, multi-stakeholder group of experts formed under the auspices of the Manatee Recovery Team to address the issues associated with manatees and warm water. The Task Force met on December 9, 2002 at the Florida Marine Research Institute in St. Petersburg. During that meeting and through detailed follow-up conversations with several of the members, the model for change in warm-water carrying capacity described above (in section 3.5), and the parameters associated with it, were elicited. Because of the intuitive nature of this expert opinion, a careful effort was made to have the panel discuss their degree of uncertainty in all of the aspects of the carrying capacity model. After that meeting, the properties of the inferred model were worked out in detail. However, the Task Force has not yet had the opportunity to thoroughly review those results, suggest revisions, nor endorse the quantitative articulation of the expert panel discussion.

Concerning the three potential scenarios in each region (no density-dependence, stable carrying capacity, or declining carrying capacity), the panel felt that there was no likelihood of the first, since it would mean the carrying capacity would have to increase faster than the population size. The panel felt the likelihood of the other two scenarios differed by region. In the Atlantic region, the expert panel felt that warm-water carrying capacity would decline over the next 100 years and that there was little chance it would remain stable. In this region, manatees currently rely heavily on several power plants that are likely to be decommissioned within this time frame. In the Upper St. Johns region, manatees rely entirely on spring flows for warm-water refugia. The panel felt there was a small likelihood (20%) that the carrying capacity in this region would remain stable, if water use was managed to stabilize spring flows, but felt it was more likely (80%) that warm-water carrying capacity would decline. In the Northwest region, manatees rely primarily on spring flows. The expert panel viewed the likelihood of decline in carrying capacity as higher here than in the Upper St. Johns region (90%). In the Southwest region, the panel felt that the decline in carrying capacity was even more likely (95%), since, like the Atlantic region, a substantial portion of current warm-water resources are tied to aging power plants. It is important to note that these probabilities do not factor in the effects of all potential mitigation. In fact, the Task Force was formed specifically to look for ways to reduce the consequences to manatees of loss of spring flow and reduction of thermal outfalls. For the purposes of this model, however, anticipated mitigation was distinguished from committed mitigation, and the probabilities as described above were used.

For the third scenario, decline in carrying capacity, estimates of the magnitude and timing of the decline were elicited from the expert panel. There was considerable uncertainty about these values—that uncertainty was expressed by identifying a median value for each parameter (the consensus middle value), a low value and a high value. The lowest and highest values suggested by anyone on the panel were taken as the possible extremes. So the range of uncertainty encompasses all the values that the panel thought were possible, with a median indicated to locate the more probable center of the distribution. The values for the parameters in equations 7 through 16 are shown in Table 5, and explained in the following four paragraphs.

Atlantic Region. The current carrying capacity (k_1) was estimated to be 2000 (range 1200-5000). During the 2001 synoptic survey, 1408 manatees were observed in the Atlantic region, suggesting that the current carrying capacity is at least that. However, 2001 was a relatively mild winter, so manatees may have escaped the effects of a severe winter, thus, it is conceivable that the carrying capacity is slightly less than the 2001 observed minimum population size. Several of the experts felt that the current carrying capacity might be substantially higher than current population levels, reflecting the possibility that there are suitable warm-water sites that we do not know about, or which are not currently used, because other, better ones are available. To estimate the long-term carrying capacity (k_0), the panel considered how many manatees could be sustained through a very cold winter if all of them were located south of Sebastian Inlet. This capacity was estimated to be 750 (range 600-900). Regarding the timing of the decline, the panel felt that half of the decline will occur within about 15 years (range 10-20 yr). The rate of the decline could be very slow (nearly linear between k_1 at 3 yr and k_0 at 50 yr) or quite precipitous (say, if there were simultaneous loss of both power plants in Brevard County).

Upper St. Johns Region. The panel estimated that the current carrying capacity (s_1) is 325 animals (range 150-500); reasoning that Blue Spring has been observed to provide warm-water habitat for about 120 animals, but could likely hold more (perhaps 250); DeLeon springs could hold about 50 animals; and there are several other sites (like Silver Glen) that could potentially provide habitat for manatees. The carrying capacity in this region could decrease to 80% (range 50-90%) of its current value due to decrease in spring flow. The best-case reduction (only 10%) would correspond to a 10% flow reduction, the goal that water managers are striving for. The worst-case reduction (50%) would represent substantial decreases in spring flow because of continued human population growth. The half-life of the loss of carrying capacity in this region was estimated to be 20 yr (range 15-30 yr).

Northwest Region. The current carrying capacity (s_1) is estimated to be 1200 animals (range 750-3000). A maximum of nearly 400 animals have been detected during aerial surveys of this region, but biologists familiar with the area feel that many more animals could make use of the warm water during cold events, perhaps on the order of 2-3 times more than are currently using the area. Spring flows have decreased sharply at Homosassa Springs over the past two decades, and reductions have also been observed at the many other springs in the region. The reductions are expected to continue with increases in the human population. In some areas (e.g., Homosassa Springs, Manatee Springs), carrying capacity could be increased through enhancement projects, but this is not likely to be enough to offset the losses in capacity due to spring flow reduction. The carrying capacity in this region could decrease to 70% (range 50-90%) of its current value due to decrease in spring flow. The best-case reduction (only 10%) would correspond to minimal flow reduction, through conservation measures, with simultaneous enhancement of a number of sites. The worst-case reduction (50%) would represent substantial losses of spring flow with few mitigating management actions taken. The loss of carrying capacity in this region might be at the same rate as in the Upper St. Johns region, with a half-life of 20 yr (range 10-40 yr), but there is greater uncertainty about this parameter.

Southwest Region. The current carrying capacity (k_1) was estimated to be 1500 (range 1200-3000). During the 2001 synoptic survey, 1379 manatees were counted in the Southwest region, suggesting that the current carrying capacity is at least that; but again, that winter was mild, so perhaps some manatees escaped the effects of a severe winter. As with the Atlantic region, several experts felt that there might be other sites we are not aware of, but which manatees might use if the density were higher, suggesting a much higher carrying capacity. To estimate the long-term carrying capacity (k_0), the panel considered what natural sources would be available to manatees if all the industrial warm-water disappears, and the manatees shift to using southern areas in the region (Charlotte Harbor and south). There was greater uncertainty about this question compared to the corresponding question in the Atlantic region because of uncertainty about the effects of the Comprehensive Everglades Restoration Plan on freshwater sources. There was also concern about the greater vulnerability to weather patterns that track easterly. The long-term carrying capacity was estimated to be 850 (range 500-1100). The carrying capacity of the Ft. Myers plant (k_M) was estimated to be between 400 and 500 animals, and the loss of that capacity will occur not sooner than 20 yrs but not later than 30 yrs from now. The rate parameter (m) was thought to be between 0 (linear decline) and 0.1 (half-life of about 7 yrs).

4.6. Effects of Carrying Capacity

The potential effects of exceeding warm-water carrying capacity during severely cold years was discussed at a meeting of an expert panel convened to provide input to the State's population viability analysis, August 16, 2002 at the Florida Marine Research Institute. As in the case of forecasting warm-water carrying capacity, there are few published analyses to provide guidance; instead the consensus view of the expert panel was sought, with due consideration given to expressing uncertainty. The estimated mortality rates associated with cold-stress are shown in Table 6. Where a range is provided to express uncertainty, the three values are used as the median, low, and high values in a two-phase uniform distribution.

The parameters associated with the density-dependent decline in reproductive rates (equation 17) were initially drawn from Florida's Status Review (FMRI 2002), then modified based on investigation of their implications, and bounded by a range of values that produced biologically reasonable properties. The uncertainty in both parameters was characterized with two-phase uniform distributions. The median value for α was 0.25 (range 0.15-0.50). The median value for β was 2 (range 1-4).

4.7. Watercraft-related Mortality

To estimate the fraction of mortality in each region that is watercraft-related, data from the carcass recovery program were obtained (Tom Pitchford, FMRI, *personal communication*). The data, for the period 1990-1999, consisted of the total number of carcasses recovered, the number attributed to watercraft-related causes, the number for which the cause could not be determined, and the number of those undetermined cases that had the phrase "suspect watercraft" in the narrative, with each category broken down by sex, size, and region. Three ways of calculating the fraction of mortality due to watercraft were devised, which reflect three different assumptions about the causes of death in the undetermined category. (1) The minimum value for the fraction of mortality due to watercraft, f_1, assumes that none of the mortalities in the undetermined category are due to watercraft. (2) A second value for the fraction of mortality due to watercraft, f_2, assumes that all the carcasses for which the pathologists indicated "suspect watercraft" were, in fact, the result of a watercraft-related mortality. (3) The largest value considered for the fraction of mortality due to watercraft, f_3, assumes that the fraction of watercraft-related mortalities in the undetermined category is the same as the fraction in the determined categories. The fraction of mortality due to watercraft did differ between these three methods, and between first-year calves (≤175 cm total length) and large animals, but did not differ by sex, or among size classes > 175 cm. The fractions of mortality due to watercraft, for calves and larger animals, by region, using the three methods are shown in Table 7. To express uncertainty in this fraction, f_2 was taken as the median of a two-phase uniform distribution, with f_1 and f_3 constituting the low and high values.

To inflate the observed level of incidental take to include the portion of the undetermined category that is actually due to watercraft (see above, section 3.7, step 4.b.), the probability of a watercraft-related mortality being identified as such in a carcass was calculated by dividing f_1 by the realized value of f (from the two-phase uniform distribution). This probability was then used in the negative binomial distribution.

To estimate the recovery rate of carcasses, by region, results were integrated from the survival analyses (Langtimm et al., *in review*), matrix population analysis, carcass recovery program, and synoptic surveys. First, the population size in each region was back calculated to 1990, beginning with the minimum population sizes for 2001 (from the synoptic survey) and using the estimated regional growth rates (Runge et al., *in review*). The average population size for the period 1990-1999 in each region was calculated. Second, a weighted survival rate for all animals except 1st year calves was calculated, using the survival rates in Langtimm et al. (*in review*), and weighting by the stable class distribution (Table 8, Runge et al., *in review*). Mortality rates for each region were calculated from these weighted survival rates. Third, using the stable stage distribution, 1st-year calves were removed from the minimum population size in each region. Fourth, the expected number of mortalities (of all causes) were calculated, based on the population size and mortality estimates. Finally, the expected number of mortalities were compared to the mean number of carcasses recovered per year in each region, from which recovery rates were calculated. These recovery rates are shown in Table 7.

5. Simulation

5.1. *Initial Population Size and Structure*

The synoptic survey count of January 5-6, 2001 was used as the baseline for all the simulations (Table 9, for description of the surveys see Ackerman 1995). While there is substantial disagreement about whether these counts represent an unbiased estimate of the current population size, there is better agreement that these counts at least represent minimum population sizes (Ackerman 1995). In keeping with the precautionary approach of the MMPA, then, this model uses the count for each Region as a conservative estimate of the initial population size.

For each region, the expected population structure (the fraction of the population in each sex/stage class) was found from the stable stage distribution (Table 8). In matrix population models, the fraction of animals in each stage class is known to stabilize after some period of time, even if the population continues to grow or decline (Caswell 2001). This set of fractions is called the stable stage distribution, and is found mathematically from the dominant eigenvector of the projection matrix. In this model, the expected initial population structure was the eigenvector of the projection matrix found in equation (3), using the mean values for each life-history parameter. This expected population structure was then used as the set of probabilities in a multinomial distribution. For each replicate of a simulation, the initial population structure was drawn randomly from this multinomial distribution, with the total population size given in Table 9. This means that the starting population size was the same for all replicates in a simulation, but the population structure varied, to reflect uncertainty about the actual structure of the population in 2001.

5.2. Simulated Management Strategies

The purpose of this simulation model is to investigate the effects of different levels of incidental take on the manatee population trajectory in each region over 100 yrs. Two fundamentally different ways of interpreting the "different levels of take" were considered. (1) *Proportional strategy*. In the first management strategy, the specified levels of observed incidental take were considered to be proportional to current population size. That is, if the incidental take were specified as 4 manatees/yr for a population of size 400, then it was assumed the incidental take would drop to 2/yr if the population decreased to 200. This strategy reflected two likely processes: first, all other things being equal, at lower population sizes, fewer watercraft-related mortalities can be expected, since fewer interactions between boats and manatees will occur; and second, future specifications of negligible levels of incidental take are likely to be adjusted in proportion to the population size. (2) *Fixed strategy*. In the second management strategy, the specified levels of observed incidental take were considered to be fixed over the time frame of the simulation (100 yrs). That is, if the incidental take were specified as 4 manatees/yr, it was assumed that many manatees would be taken each year, regardless of changes in the population size. This strategy asks a different question, namely, what would be the long-term effect of removing this fixed number of manatees per year (rather than removing manatees at a particular rate relative to the population size). What this strategy does recognize is the difficulty of reducing authorized levels of take once specified, but it does not account for the natural reduction in take that would occur with significantly decreased population size.

For each strategy, different levels of take were considered in parallel. Three situations can be distinguished: no take, various levels of authorized take, and no action. (1) Under the "no take" scenario, the watercraft-related mortality was set to 0. Under the MMPA, this is the goal for incidental take, and is the scenario to which others need to be compared. (2) The "authorized take" scenarios assume that the level of watercraft-related mortality will be held at some particular level (either proportional or fixed, as described in the preceding paragraph). Different levels were examined to determine what meets the criteria for "negligible." (3) Under the "no action" scenario, watercraft-related take began at the levels recently observed, and continued to increase at recent rates. This is the situation that is presumed to occur if there are no changes to current management, and is the baseline alternative in the EIS. For the purposes of this scenario, current levels of take and the current rate of increase were estimated by fitting an exponential curve to the observed watercraft-related mortality in each region for the period 1992-2002 (Table 10). The rate of increase in observed take was corrected for the estimated growth rate in each region (Runge et al., *in review*).

The simulations of different levels of take were performed in parallel, that is, by using the same values for environmental stochasticity and the same realizations of the uncertainty distributions for a given replicate for each of the levels of take. Thus, within a replicate, the only difference between a set of parallel simulations was the level of watercraft-related incidental take. This "pairwise" design to the simulations allowed a more powerful investigation of the effect of take.

5.3. Outline of the Simulation Structure

Each simulation consisted of 1000 replicates of the 100-yr time series at each of a number of different levels of incidental take. The structure of each simulation is outlined below.

1. Set the region, the type of management strategy (proportional or fixed), and the levels of incidental take to evaluate.
2. Set the hyperparameters (the values that describe the uncertainty distributions for all the parameters), as given in Section 4, above.
3. Loop over replicates (n = 1000)
    a. Sample all parameters from their uncertainty distributions
        i. Sample annual survival rates and breeding probabilities
        ii. Sample standard deviations for temporal variance
        iii. Sample cold-related mortality parameters
        iv. Sample fraction of mortality due to watercraft
        v. Sample warm-water carrying capacity parameters
    b. Calculate warm-water carrying capacity for t = 1 to 100 yr
    c. Generate variates that govern environmental stochasticity and catastrophes (4 variates for each of 100 yrs—2 variates from a bivariate normal distribution for the environmental stochasticity in survival rates and breeding probabilities,

   and two uniform variables for the occurrence of Type 1 and Type 2 catatstrophes.
   d. [DEM] Distribute the initial population size across stage classes, using a multinomial distribution.
   e. Loop over the specified levels of incidental take
      i. Set the initial ($t = 0$) population vector
      ii. Loop over time ($t = 1$ to 100)
         1. Calculate the one-year change in the population vector
      iii. End loop over time
   f. End loop over levels of take
4. End loop over replicates
5. Calculate summary metrics (see section 5.4, below).

5.4. Summary Metrics

The results of the simulations were replicate trajectories over time of the population size and structure, for different levels of observed incidental take. The following calculations were made, in order to derive summary metrics to describe the simulations.

Realized growth rates. For each replicate, level of take, and year, the population vector was summed to come up with a total population size. Then the realized growth rate for each year was calculated by dividing the population size in year t+1 by the population size in year t.

Actual mean 20-yr growth rates. For each 20-yr period, the mean growth rate was calculated. The mean growth rate at year 20 was calculated from the growth rates for years 1 through 20; the mean growth rate at year 21 was calculated from the growth rates for years 2 through 21; etc. In addition, the standard errors over these 20-yr periods were calculated.

Observed mean 20-yr growth rates. The recovery criterion in the Recovery Plan (USFWS 2001) specifies that the 95% confidence interval for the mean 20-year growth rate be above 1. The confidence interval for the mean growth rate reflects both natural variation (process variance) and observation error (sampling variance). The sampling variance for the mean 20-yr growth rates was calculated by halving the sampling variance for the mean 10-yr growth rates found in Runge et al. (*in review*). This essentially assumes that the sampling effort for survival and reproductive parameters, and hence, the uncertainty in the calculated growth rates, will remain constant over time. The observed mean 20-yr growth rates were calculated from the actual mean 20-yr growth rates by adding a normal random deviate (with mean 0 and variance equal to the appropriate region-specific sampling variance). The standard errors for the mean growth rates were inflated to include the sampling variance.

Evaluate the recovery criterion. At each point in time, to evaluate the recovery criterion, a confidence interval was formed from the observed mean 20-yr growth rate and the corresponding standard error. If the lower end of the confidence interval was greater than 1, then the population was considered to have met the recovery criteria at that point in time. Once a population first met the recovery criteria, it was assumed to stay “recovered”, even if the growth rate subsequently dipped below 1. The way the recovery criterion is structured, it cannot be met forever, since eventually a population will reach its carrying capacity and the growth rate will no longer be above 1.

Time to recovery. For each replicate, at each level of incidental take, the time to recovery was calculated. The probability of recovery in 50 years (R_{50}) was then calculated from the proportion of the replicates in which the population had achieved recovery within the first 50 yrs. Likewise, the probability of recovery in 100 years (R_{100}) was calculated from the proportion of replicates in which recovery was achieved within 100 yrs. Finally, the mean time to recovery was found by taking the average over all replicates for which recovery did occur. These metrics were calculated separately for each level of incidental take.

Delay in time to recovery. The delay in time to recovery for a particular replicate was calculated by comparing the time to recovery for a particular level of take to the time to recovery in the parallel simulation with no take. This delay is reported as the fractional increase in recovery time in the case of take relative to the case of no take. The delay in time to recovery was calculated for each replicate. The probability of a delay of a certain magnitude or greater was calculated by finding the proportion of replicates for which the delay was greater than the desired level. The probability of a delay of greater than 10% is the critical criterion for determination of whether a given level of take is negligible, as described in the Proposed Rule.

Fraction of Excess Growth. For each replicate, the actual mean growth rate over the first 20 yrs with incidental take was compared to the growth rate in the parallel simulation without take. The fraction of excess growth removed as a result of incidental take was calculated as

$$\frac{\lambda_i^0 - \lambda_i^{Take}}{\lambda_i^0 - 1} \tag{19}$$

where the λ's are mean growth rates over the first 20 yrs, i refers to a particular replicate, λ^0 is the growth rate in the absence of take, and λ^{Take} is the growth rate with the proposed level of incidental take. The mean over all replicates was then found.

Potential Biological Removal. The Potential Biological Removal (PBR) level was found for each region using the formula

$$PBR = \tfrac{1}{2} N_{\min} r_{\max} F_R \tag{20}$$

with the synoptic survey results of 2001 (Table 9) interpreted as $N_{\min}$, the maximum growth rate at low density, $r_{\max}$, set at 8%, and the recovery factor, F_R set to 0.1, as specified for an endangered species. Note that this calculation did not require use of the Incidental Take model.

6. Results and Discussion

6.1. Trends in Watercraft-related Mortality

There has been an increasing trend in watercraft-related mortality in all four regions over the past decade (Table 10). This is reflected in increases in the average annual number of watercraft-related mortalities as the period over which the average is taken becomes more recent. For instance, in the Atlantic region, the mean observed mortality due to watercraft was 25.8/yr for the period 1990-1999, 29.8/yr for the period 1993-2002, and 37.0/yr for the most recent 5-yr period. This trend is statistically significant in all four regions. The slope of the increase (as fit to the period 1992-2002) does not differ between the Upper St. Johns and Northwest regions (5.96%), nor does it differ between the Atlantic and Southwest regions (9.53%). To interpret these rates of increase, however, it is important to compare them to the historic growth rates (1990-1999) in each region, to account for the increase in watercraft-related mortalities that would be expected due to increases in manatee population size. In the Atlantic and Southwest regions, the rate of increase in watercraft-related mortality over that period far outstripped the estimated growth rate of those populations (by 8.5% in the Atlantic and 10.6% in the Southwest). In the Northwest region, the rate of increase in mortality (6.0%) is somewhat larger than the estimated growth rate (3.6%). In the Upper St. John's region, the increase in boat-related mortality can be completely explained by the estimated increase in the population size.

6.2. Proportional vs. Fixed Strategy

The results for the simulations in each region are shown in Tables 11-18, and summarized in Table 19. Two tables are shown for each region, one with the results from implementing the proportional strategy, one from implementing the fixed strategy. In general, the differences are not very noticeable at low levels of incidental take, but become more pronounced at higher levels. The effects depend on whether a population is increasing or decreasing. In an increasing population, a proportional level of take has a more profound effect, because as the population size increases, the incidental take increases accordingly. For example, in the Upper St. Johns region (Tables 13 and 14), a fixed level of incidental take of 5/yr causes a >10% delay in time to recovery 21% of the time; but a proportion level of take equivalent to 5/yr at current population levels causes such a large delay 33% of the time. In a decreasing population, however, a fixed level of take has a more profound effect than a proportional level of take, because as the population size decreases, the fixed take becomes a larger and larger fraction of the population. This has the effect of leading the population into a sharp decline. For example, in the Southwest region (Tables 17 and 18), a proportional level of take equivalent to 20/yr results in a 79% chance of significant delay in recovery, while a fixed level of take of 20/yr causes such a delay with 96% probability.

The proportional strategy reflects two dynamics about future mortality and regulations. First, it assumes that watercraft-related mortality will fluctuate with changes in population size—if the population size decreases, watercraft-related mortality should also decrease, since the likelihood of a boat and a manatee being colocated will decline. Second, it recognizes that incidental take regulations will be reevaluated periodically (at least every 5 yr), so that if take is authorized, the level at which it is authorized is likely to change as updated estimates of the population size become available. Note that the proportional strategy behaves in the same way that PBR does—it is readjusted as the population size changes. In the remaining presentation, only the proportional strategy is discussed in any detail.

6.3. Atlantic Region

In the Atlantic region, the expected growth rate (λ) in the absence of incidental take is just barely above 1 (Table 11), where growth rate is interpreted as the ratio of population sizes in subsequent years, thus a growth rate of 1 indicates a stable population. Many of the simulated scenarios did not exhibit an initial growth rate above 1, even in the absence of take. In fact, the probability of meeting the recovery criterion (of statistical confidence of positive growth over any 20 year period) within 100 years was only 59%. Thus, even in the absence of take, the Atlantic stock may not fare well. A significant delay in recovery time and a significant decrease in excess growth are felt even at very low levels of incidental take (1-2 manatees/yr). If "no action" is taken, and watercraft-related mortalities continue to increase at current rates, there is an extremely low likelihood that this population will ever meet the criteria for recovery. The current levels of take (37.0/yr), even if prevented from increasing, are far above what would be deemed negligible by any of the alternative criteria considered. Only the PBR method suggests that any take could be allowed; according to the other methods, even 1 manatee/yr would have a more than negligible impact. Since the population won't grow very quickly, even in the absence of take, it is certainly not able to progress toward OSP at an acceptable rate. Thus, there is no net productivity that can be allocated to incidental take.

6.4. Upper St. Johns Region

In the Upper St. Johns region, the expected growth rate in the absence of incidental take is 1.05 (Table 13), that is, the population could be expected to grow at 5% per year on average over the next 20 years. However, even incidental take of 1 manatee/yr shaves 9.1% off this excess growth, and take of 2 manatees/yr reduces the excess growth by 19%. Thus, based on the FEG criterion for negligible (<10% decrease in excess growth), 1 manatee/yr could be authorized, but not 2/yr. The probability of a 10% or greater delay in time to recovery is 6.1% at 1 manatee/yr, 8.5% at 2 manatees/yr. In the Proposed Rule, the suggested threshold for this probability was 5% (95% probability that delay is <10%), thus, 1 manatee/yr is slightly above the negligible level. The main factor driving these low levels for negligible impact is the small size of the population in this region—with only ~150 animals, take of 1-2 manatees/yr is a mortality rate of ~1%, which is significant in a mammal with such low natural mortality rates. Under the "No Action" scenario, there is a 10% chance of a significant delay in recovery time, and 23% of the excess growth is expected to be removed. Thus, under current conditions, the incidental take in this region does not meet any of the criteria for negligible.

Despite the high expected growth rate, the probability of achieving recovery within 100 yr, even in the absence of incidental take, is only 88%. The reason for this points to one of the fundamental problems with the recovery criteria currently in the Recovery Plan. Under some of the simulated replicates, this population grows "too fast" and reaches the carrying capacity within 20 years. As soon as it reaches carrying capacity, the growth rate drops to near 1 (by definition); then the mean growth rate over 20 years may not be demonstrably above 1. So, in about 12% of the cases, the population reaches its carrying capacity, but because it does so too quickly, it does not meet the criteria for having "recovered." Low levels of incidental take actually *increase* the probability of achieving recovery, because they reduce the growth rate just enough so that the population doesn't reach carrying capacity within 20 yrs.

If the threshold probability for a >10% delay in recovery is moved from 5% to 25%, an incidental take of 4 manatees/yr could be considered negligible in this region. This would actually be an increase over current levels of take (contrast take of 4/yr vs. No Action). However, proportional take of 4/yr would remove 43% of the excess growth, reducing the expected growth rate over the next 20 yr to 1.029.

6.5. Northwest Region

In the Northwest Region, the expected growth rate over the next 20 yrs, in the absence of take is 1.043 (Table 15). Incidental take of 1 manatee/yr removes 18% of the excess growth, and has a 12% probability of delaying recovery time by more than 10%, thus it cannot be considered negligible under the PR and FEG criteria. The probabilities of recovery within 100 yrs are very high, even for levels of incidental take up to 3-4/yr. Under current levels of take, with current increases in watercraft-related mortality, the probability of recovery in 100 yrs is 54%, and the probability of a significant delay in time to recovery is 62%. Nearly 80% of the excess growth over the next 20 yr is expected to be removed if current trends in take continue.

The results for this region are highly sensitive to the carcass recovery rate, which is lowest in this region (41%, Table 7). What this means is that for every 2 carcasses collected and documented to be due to injury from watercraft, 3 more were not recovered. If the estimate for the carcass recovery rate is negatively biased, then the assessment of incidental take in this region is too conservative. Additional work needs to be done to assess carcass recovery rates.

If the threshold probability for a >10% delay in recovery is moved from 5% to 25%, an incidental take of 2 manatees/yr could be considered negligible in this region. However, the expected reduction in the excess growth rate is 35% at this level of proportional take. Note also that the current levels of take (with continued increase) are not made negligible by this change in the criterion.

6.6. Southwest Region

In the Southwest region, the estimated historical growth rate for the period 1990-1999 was *negative* 1.1% (Table 10, Runge et al., *in review*). Even in the absence of incidental take, the growth rate over the next 20 yr is not expected to be positive (Table 17). Thus, in the Southwest region, there is no excess growth, no net productivity, that can be allocated to incidental take. Incidental take levels even as low as 1-2 manatees/yr result in a 37% probability that recovery (if it happens) will be delayed by > 10%. The probability of recovery in 100 yrs is only 63% in the absence of harvest, 16% if incidental take is held at a proportional rate of 25/yr, and 0% if current trends in take continue. This is an important point—while these simulations indicate that the population in this region is not expected to exhibit healthy growth even in the absence of incidental take, the incidental take is having a significant impact that is further delaying recovery, perhaps preventing it.

The carcass recovery rate in this region is also quite low (58%, Table 7), but contrary to the situation in the Northwest region, this alone is not enough to change the assessment of incidental take. The growth rate and probability of recovery in the absence of take are not affected by the carcass recovery rate. Even if the carcass recovery rate in this region were 100%, no level of take could be considered negligible, since there isn't any excess growth.

All of the life-history parameters are least well known in this region. The time series of photo-ID data is shorter here than in other regions (Langtimm et al., *in review*), reproductive parameters have been studied only in Sarasota Bay (Koelsch 2001), and little is known about survival rates of younger animals. The confidence interval for the historical growth rate is wide (–5.4 to 2.4%), and does include some positive values (Table 19, Runge et al., *in review*). Nevertheless, while there is considerable uncertainty about the status of this population, the best available science indicates that it is not increasing; and the results of this simulation model suggest that watercraft-related mortality, in conjunction with other factors, is having an important impact.

6.7. Summary of Results

A summary of these results and a comparison among regions is found in Table 19. The historic adult survival and population growth rates were highest in the Upper St. Johns and Northwest regions. These regions also have positive expected growth rates over the next 20 yrs even if increasing trends in watercraft-related mortality continue. In the Atlantic and Southwest regions, the historic growth rates, as estimated from a deterministic stage-based population model (Runge et al., *in review*), are not convincingly positive, and the projected growth rates are negative if watercraft-related mortality continues to increase. For all four regions, the projected growth rates over the next 20 yrs are lower than the historic growth rates. In the Upper St. Johns and Northwest regions, this is largely because the populations may approach their carrying capacity in that time frame, and hence, slow their growth. In the Atlantic and Southwest regions, the projected growth rates are lower than historic growth rates largely because of the anticipated continued increase in the watercraft-related mortality rate. In the Upper St. Johns and Northwest regions, if no action is taken, the probabilities of significant delay (>10%) in time to recovery are 10% and 62%, respectively. In the Atlantic and Southwest regions, if no action is taken, the probability of achieving recovery within 100 yrs is 0, thus the expected probability of a delay in recovery is 100%.

Based on the criterion for negligible described in the Proposed Rule, the level of incidental take that could be authorized is <1/yr in the Atlantic, Upper St. Johns, and Northwest regions, and 0/yr in the Southwest region. In the Southwest region, since the population is not expected to grow, even in the absence of incidental take, then it cannot be said to be moving toward OSP. Thus, it does not meet the criteria in the MMPA for authorization of incidental take. The negligible levels of incidental take based on the FEG criterion are essentially the same as those based on the PR criterion: 1/yr or <1/yr in the Atlantic, Upper St. Johns, and Northwest regions; and 0/yr in the Southwest. Of the 3 criteria considered for negligible impact, the PBR criterion affords the highest levels of incidental take overall: 5.6/yr in the Atlantic; 0.6/yr in the Upper St. Johns; 1.5/yr in the Northwest; and 5.5/yr in the Southwest.

On an absolute scale, net productivity is low in all 4 regions, which is why so little incidental take can be allowed. In the Upper St. Johns and Northwest regions, net productivity, hence allowable take, is limited because the populations are small. Even though the growth rates are healthy, there is not a large production of new animals each year. For example, with a population size of ~140 in the Upper St. Johns region and a growth rate of ~6%, the net productivity is ~8.4 manatees/yr. Even a few animals removed by incidental take will reduce net productivity substantially. In the Atlantic and Southwest regions, net productivity, hence allowable take, is limited because the growth rates are so low. In fact, in the Southwest, there appears not to be any net productivity at all.

6.8. No Action vs. Authorized Take in 2 Regions

As noted above (in 6.4 and 6.5), by making the decision to tolerate a higher probability of significant delay in time to recovery than that established in the Proposed Rule, it could be argued that current levels of watercraft-related mortality in the Upper St. Johns region are negligible, and that take in the Northwest region could be made negligible if it were reduced to 2 manatees/yr. What are the predicted effects on the populations if incidental take were authorized at proportional levels of 4/yr and 2/yr in the Upper St. Johns and Northwest regions, respectively? Table 20 shows a contrast between this scenario and the no action scenario.

In the Northwest region, if this authorization succeeded in decreasing incidental take, it would have several positive effects: the growth rate over the next 20 yrs would increase, less of the net productivity would be allocated to incidental take, and the probability of a delay in recovery time would decrease. However, the fraction of excess growth removed by incidental take (35%) would still be high.

In the Upper St. John’s region, authorization of incidental take at 4/yr would have a negative effect, if it meant that take would increase over current levels. If current regulation and enforcement of boat traffic, however, were held steady, it seems more likely that such authorization would be no different than the no action scenario. Note again, however, that the fraction of excess growth removed by incidental take (43%) is predicted to be high, as is the probability of a significant delay in time to recovery.

7. Further Considerations

7.1. Recovery Criteria

The articulation of quantitative recovery criteria in the most recent revision of the Manatee Recovery Plan (USFWS 2001) was a very positive step forward, as it continued a commitment to establish objective, transparent measures by which to evaluate population status. However, as noted above (section 6.4) and discussed by Runge et al. (*in review*), the current recovery criteria pose some conceptual difficulties. In particular, requiring that a positive growth rate be sustained over a long period of time only makes sense in a severely depleted stock; it does not make sense for a population that is nearing its carrying capacity. Since there is considerable uncertainty about what the carrying capacity is in each region, it is difficult to know whether this criterion is currently appropriate. The results of the simulation for the Upper St. Johns region suggest that it may not be an appropriate criterion for that stock.

Further, because the growth rate recovery criterion depends only on the value of the lower end of the confidence interval, it means that the goals for recovery depend on the sampling effort exerted to monitor the population. That is, a lower level of growth could be tolerated if the sampling effort were higher (and hence, the confidence interval were narrower). It makes sense to want high confidence that a depleted population is growing toward an optimal level, thus it makes sense to have some expectation about the level of sampling effort. However, a useful criterion should have an expectation about the speed or magnitude of recovery, in addition to an expectation about sampling effort. That is, in addition to a lower confidence bound, a mean should also be specified.

With regard to the definition of negligible being tied to this particular recovery criterion (95% confidence that the growth rate is above 1), there is the potential to allow a significant level of net productivity to be allocated to incidental take, while still achieving recovery. For instance, in the Northwest region (Table 15), the probability of recovery within 100 yrs with an incidental take of 4 manatees/year is quite high (95%), but 74% of the excess growth is removed.

While the recovery criterion itself is problematic, the *delay* in time to recovery, as a standard for "negligible", appears to be more useful. It is certainly reassuring that all three standard for negligible (delay in time to recovery, FEG, and PBR) provided very similar assessments of the tolerable level of incidental take in all four regions.

7.2. Sensitivity Analysis

A sensitivity analysis is a formal approach to asking "what if" questions about the results of a model. Many such questions can be asked of the Incidental Take model presented herein. What if carrying capacity doesn't decline so sharply? What if the estimates of carcass recovery rates are biased? What if the survival rates in the Southwest are biased by emigration? Which parameters are the results most sensitive to? Which parameters are largely irrelevant to the determination of negligible impact? The advantage of a comprehensive sensitivity analysis is that it indicates which components of the model have the strongest effects on the outcomes, and hence which need to be most strongly supported. A full sensitivity analysis had not yet been completed for this model.

7.3. Development of Specific Components

Several of the components of the Incidental Take model are the result of very recent analyses, and have not had the opportunity to undergo thorough peer review. Review of the following components is underway, and development is intended.

Warm-water carrying capacity submodel. The Warm-water Task Force served as an expert panel for the development of the submodel used to project changes in the carrying capacity of warm-water habitat. However, the Task Force has not yet had the opportunity to fully review the quantitative articulation of their discussions, nor have they yet offered their endorsement of the submodel. Within six months, several meetings of the Task Force will be convened to review this submodel in more depth, revise it as appropriate, and seek formal endorsement.

Analyses of carcass recovery rate and fraction of mortality due to watercraft. The carcass recovery rate (the fraction of dead manatees recovered by the carcass salvage program) has a strong influence on the calculation of negligible impact, because it serves as the link between the numbers of *observed* and *actual* watercraft-related mortalities. The fraction of mortality due to watercraft also has an important influence on the determination of negligible impact because it is used to calculate the survival rate in the absence of take, hence the degree to which take-reduction could increase the population growth rate. Both of these quantities have only recently been estimated, and have not had the opportunity to undergo peer review. Further, only a point estimate for recovery rate in each region is available; a fuller analysis needs to be completed to estimate the uncertainty in this parameter.

7.4. Ongoing Work

There is ongoing work by scientists at Federal and State agencies, academic institutions, and non-profit organizations that will enhance the modeling effort described herein. Included among the projects currently underway: new analyses of survival rates in the Atlantic and Southwest regions; formal mark-recapture analyses of reproductive rates in the Upper St. Johns and Southwest regions; investigation of migration between the Northwest and Southwest populations; integration of photo-ID, aerial survey, and carcass recovery data; estimation of detection probabilities for manatee aerial survey techniques; and estimation of population size at and site fidelity to several industrial warm-water effluents. The Incidental Take model will be revised appropriately as new information becomes available.

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Table 1. Parameter estimates for Florida manatees in the four regions. Values in **bold** are direct estimates of the appropriate parameter from published studies or recent analyses. Values in roman type are inferred. The "uncertainty" column represents a range of potential values for each parameter; in general, this is the 95% confidence interval for the parameter estimate.

Parameter	Atlantic		Upper St. Johns		Northwest		Southwest	
	Estimate	Uncertainty	Estimate	Uncertainty	Estimate	Uncertainty	Estimate	Uncertainty
s_1	0.791	(.650, .885)	**0.810**	**(.727, .873)**	0.807	(.673, .895)	0.765	(.616, .869)
s_2	0.893	(.712, .966)	**0.915**	**(.827, .960)**	0.911	(.751, .972)	0.864	(.654, .955)
s_3	0.936	(.923, .949)	**0.961**	**(.915, .983)**	0.956	(.943, .969)	0.906	(.867, .944)
s_4	0.936	(.923, .949)	**0.961**	**(.915, .983)**	0.956	(.943, .969)	0.906	(.867, .944)
s_P	**0.936**	**(.923, .949)**	**0.960**	**(.937, .982)**	**0.956**	**(.943, .969)**	**0.906**	**(.867, .944)**
s_A	**0.936**	**(.923, .949)**	**0.960**	**(.937, .982)**	**0.956**	**(.943, .969)**	**0.906**	**(.867, .944)**
γ_4	0.0	(.0, .3)	**0.208**	**(.071, .422)**	**0.000**	**(.000, .285)**	0.0	(.0, .3)
γ_P	0.304	(.132, .529)	**0.610**	**(.505, .709)**	**0.381**	**(.181, .616)**	**0.304**	**(.132, .529)**
γ_B	**0.381**	**(.292, .470)**	**0.610**	**(.505, .709)**	**0.429**	**(.217, .541)**	**0.595**	**(.421, .752)**

Table 2. Logit-normal distributions used to represent uncertainty in the mean values for the survival rates and breeding probabilities. The parameters given are the mean (and standard deviation) on the logit-scale. Normal random variables were generated on this scale, and then back-transformed to the nominal scale. These values were chosen to closely match the means and confidence intervals shown in Table 1.

Parameter	Atlantic	Upper St. Johns	Northwest	Southwest
s_1	1.327 (0.362)	1.453 (0.242)	1.431 (0.362)	1.180 (0.362)
s_2	2.115 (0.622)	2.377 (0.415)	2.328 (0.622)	1.846 (0.622)
$s_3 = s_4$	2.678 (0.110)	3.170 (0.293)	3.069 (0.156)	2.263 (0.230)
$s_A = s_P$	2.678 (0.110)	3.170 (0.293)	3.069 (0.156)	2.263 (0.230)
γ_4	–6.907 (3.055)	–1.337 (0.503)	–6.907 (3.055)	–6.907 (3.055)
γ_P	–0.828 (0.453)	0.452 (0.210)	–0.485 (0.450)	–0.828 (0.453)
γ_B	–0.486 (0.193)	0.452 (0.210)	–0.285 (0.233)	0.385 (0.335)

Table 3. Median and range for temporal standard deviation for the survival rates and breeding probabilities. These values are used to generate the magnitude of normal environmental stochasticity. For s_1 and s_2, the values are *on the logit-scale* and the range shows the low and high values considered for the standard deviation; for the other parameters, the values are *on the nominal scale* and the range shows the 95% confidence interval for the standard deviation.

Parameter	Atlantic	Upper St. Johns	Northwest	Southwest
$\sigma(s_1)$	0.104 (0, 0.417)	0 (0, 0.263)	0.128 (0, 0.518)	0.106 (0, 0.851)
$\sigma(s_2)$	0.233 (0, 0.935)	0 (0, 0.589)	0.281 (0, 1.124)	0.184 (0, 1.472)
$\sigma(s_3) = \sigma(s_4)$, $\sigma(s_A) = \sigma(s_P)$	0 (0, 0.039)	0 (0, 0)	0.018 (0, 0.048)	0 (0, 0.082)
$\sigma(\gamma_4)$	0	0	0	0
$\sigma(\gamma_P) = \sigma(\gamma_B)$	0 (0, 0.062)	0	0.076 (0, 0.213)	0.076 (0, 0.213)

Table 4. Probabilities of catastrophes and magnitudes of associated effects. A Type 1 catastrophe is associated with a virulent, infectious disease. Type 2 catastrophes are associated with red tide events.

Parameter	Atlantic	Upper St. Johns	Northwest	Southwest
Type 1				
Probability	0.01	0.01	0.01	0.01
Reduction in s	0.25	0.25	0.25	0.25
Reduction in γ	0.20	0.20	0.20	0.20
Type 2				
Probability	0	0	0.018	0.036
Reduction in s	--	--	0.05	0.10
Reduction in γ	--	--	0.05	0.05

Table 5. Parameters governing the projections of warm-water carrying capacity for Florida manatees in the four regions. Each parameter is described with a low, median, and high value. The values marked "--" are not applicable for that region.

Parameter		Atlantic	Upper St. Johns	Northwest	Southwest
k_1	low	1200	--	--	1200
	median	2000	--	--	1500
	high	5000	--	--	3000
k_0	low	600	--	--	500
	median	750	--	--	850
	high	900	--	--	1100
s_1	low	--	150	750	--
	median	--	325	1200	--
	high	--	500	3000	--
s_0	low	--	0.5 s_1	0.5 s_1	--
	median	--	0.8 s_1	0.7 s_1	--
	high	--	0.9 s_1	0.9 s_1	--
m	low	0	--	--	0.00
	median	1	--	--	0.05
	high	5	--	--	0.10
$t_{1/2}$	low	--	15	10	--
	median	--	20	20	--
	high	--	30	40	--
c	low	10	--	--	20
	median	15	--	--	25
	high	20	--	--	30
k_M	low	--	--	--	400
	median	--	--	--	450
	high	--	--	--	500

Table 6. Mortality due to cold stress for animals inside and outside warm-water refugia. The numbers in brackets refer to ranges that express uncertainty about the mortality rate. The adult category includes subadults. The calf category includes both first-year and second-year calves. In the model, these parameters do not differ by region.

		Inside Refugia	Outside Refugia
Adults	Normal year	0 %	1 %
	Cold year	0 %	50 % [30-75]
Calves	Normal year	0 %	5 % [2.5-10]
	Cold year	15 % [10-20]	100 % [90-100]

Table 7. Watercraft-related mortality parameters. The first three values are the low, median, and high values for the fraction of calf mortality due to watercraft; the second three values are the low, median, and high values for the fraction of subadult/adult mortality due to watercraft. The last parameter is the carcass recovery rate.

Parameter	Atlantic	Upper St. Johns	Northwest	Southwest
$f_{1,\text{calf}}$	0.0217	0	0.0526	0.0349
$f_{2,\text{calf}}$	0.0217	0	0.0526	0.0349
$f_{3,\text{calf}}$	0.0233	0	0.0588	0.0386
$f_{1,\text{adult}}$	0.352	0.452	0.404	0.301
$f_{2,\text{adult}}$	0.362	0.452	0.423	0.311
$f_{3,\text{adult}}$	0.500	0.667	0.500	0.475
r	0.8625	0.8242	0.4069	0.5837

Table 8. Stable stage distributions derived from the eigenvectors of a deterministic population matrix (equation 3) formed from the mean values of the life-history parameters. The distribution expresses the stable fraction of the population in each stage.

Stage	Atlantic	Upper St. Johns	Northwest	Southwest
N_2	0.0386	0.0512	0.0418	0.0454
N_3	0.0341	0.0440	0.0366	0.0396
N_4	0.0316	0.0397	0.0337	0.0361
N_P	0.0822	0.0437	0.0720	0.0903
N_C	0.0988	0.1345	0.1075	0.1178
N_B	0.2147	0.1869	0.2083	0.1707
N_2^M	0.0386	0.0512	0.0418	0.0454
N_3^M	0.0341	0.0440	0.0366	0.0396
N_4^M	0.0316	0.0397	0.0337	0.0361
N_A^M	0.3957	0.3651	0.3880	0.3790

Table 9. Regional counts from the synoptic aerial survey, January 5-6, 2001.

Region	**Count**
Atlantic	1408
Upper St. John's River	112
Northwest	377
Southwest	1379
Total	*3276*

Table 10. Trends in watercraft-related mortality of manatees in the four regions, 1992-2002, based on recovery of carcasses and documentation of cause of death (*Source of data:* Florida Marine Research Institute). The fitted values and slope were found by regressing ln(W+1) against time; a common slope was found for the Atlantic and Southwest regions, and for the Upper St. Johns and Northwest regions. The manatee population growth rates are take from Runge et al. (*in review*).

	Atlantic	Upper St. Johns	Northwest	Southwest
1992	22	1	3	12
1993	18	1	1	15
1994	21	1	2	25
1995	18	1	0	23
1996	31	1	3	26
1997	25	1	2	26
1998	31	3	5	27
1999	34	1	4	43
2000	35	2	5	36
2001	33	5	1	42
2002	52	1	4	38
Mean, 1990-1999	25.8 /yr	1.4 /yr	2.3/yr	23.2 /yr
Mean, 1993-2002	29.8	1.7	2.7	30.1
Mean, 1998-2002	37.0	2.4	3.8	37.2
Fitted value, 2001	41.1	2.1	3.2	39.5
Slope	9.53 %/yr	5.96 %/yr	5.96 %/yr	9.53 %/yr
Estimated Population Growth Rate (ln λ), 1990-1999	1.0 %/yr	6.0 %/yr	3.6 %/yr	–1.1 %/yr

Table 11. Analysis of effects of incidental take in the Atlantic Region, proportional strategy. Various metrics (see notes) are compared for a range of levels of *observed* watercraft-related mortality. Three definitions of "negligible" are considered, and the quantitative criteria are used to evaluate whether these definitions are met for the different levels of mortality. The PBR calculation indicates a negligible level of incidental take of 5.6 manatees/yr in the Atlantic region.

Take	$p(R_{50})$	$p(R_{100})$	$p(\Delta>10\%)$	$E[\lambda]$	$\%\downarrow\lambda$	PR?	FEG?	PBR?
0 / yr	23%	59%	0%	1.003	0%	Y	Y	Y
1	22	60	28	1.002	17	N	N	Y
2	23	60	28	1.002	36	N	N	Y
5	19	57	32	1.000	95	N	N	Y
10	16	56	35	0.996	>100	N	N	N
15	14	53	44	0.994	>100	N	N	N
20	11	49	48	0.991	>100	N	N	N
25	8	40	59	0.989	>100	N	N	N
No Action	0	0	100	0.932	>100	N	N	N

Notes:

(1) **$p(R_{50})$** and **$p(R_{100})$** are the probabilities that the recovery criteria will be met within 50 and 100 years.

(2) **$p(\Delta>10\%)$** is the probability that the delay in time to recovery compared to the case of no watercraft mortality is greater than 10%.

(3) **$E[\lambda]$** is the mean value of the growth rate over the first 20 years.

(4) **$\%\downarrow\lambda$** is the percent decrease in "excess" growth, that is, the fraction of the growth rate above 1 that is lost due to the effects of watercraft mortality.

(5) **PR?**, **FEG?**, and **PBR?** indicate whether the **P**roposed **R**ule, **F**raction of **E**xcess **G**rowth, and **P**otential **B**iological **R**emoval criteria for negligible are met.

Table 12. Analysis of effects of incidental take in the Atlantic Region, fixed strategy. See *Notes* in Table 11 for explanation of metrics. The "No Action" scenario was not calculated for the fixed strategy.

Take	$p(R_{50})$	$p(R_{100})$	$p(\Delta>10\%)$	$E[\lambda]$	$\%\downarrow\lambda$	PR?	FEG?	PBR?
0 / yr	23%	59%	0%	1.002	0%	N	Y	Y
1	22	60	28	1.001	27	N	N	Y
2	23	60	28	1.001	59	N	N	Y
5	19	57	32	0.999	>100	N	N	Y
10	18	46	48	0.998	>100	N	N	N
15	14	27	68	0.995	>100	N	N	N
20	11	14	81	0.992	>100	N	N	N
25	8	9	89	0.989	>100	N	N	N

Table 13. Analysis of effects of incidental take in the Upper St. Johns Region, proportional strategy. See *Notes* in Table 11 for explanation of metrics. The PBR calculation indicates a negligible level of incidental take of 0.6 manatees/yr in this region.

Take	p(R_{50})	p(R_{100})	p(Δ>10%)	E[λ]	%$\downarrow\lambda$	PR?	FEG?	PBR?
0 / yr	86%	88%	0%	1.050	0%	Y	Y	Y
1	87	90	6.1	1.046	9.1	N	Y	N
2	88	91	8.5	1.041	19	N	N	N
3	89	92	14	1.035	30	N	N	N
4	89	92	21	1.029	43	N	N	N
5	87	92	33	1.022	56	N	N	N
No Action	85	88	10	1.038	23	N	N	N

Table 14. Analysis of effects of incidental take in the Upper St. Johns Region, fixed strategy. See *Notes* in Table 11 for explanation of metrics. The "No Action" scenario was not calculated for the fixed strategy.

Take	p(R_{50})	p(R_{100})	p(Δ>10%)	E[λ]	%$\downarrow\lambda$	PR?	FEG?	PBR?
0 / yr	86%	88%	0%	1.050	0%	Y	Y	Y
1	87	89	6.1	1.048	5.1	N	Y	N
2	88	90	7.2	1.045	11	N	N	N
3	89	92	9.2	1.041	18	N	N	N
4	89	91	14	1.036	29	N	N	N
5	88	90	21	1.030	41	N	N	N

Table 15. Analysis of effects of incidental take in the Northwest Region, proportional strategy. See *Notes* in Table 11 for explanation of metrics. The PBR calculation indicates a negligible level of incidental take of 1.5 manatees/yr in this region.

Take	$p(R_{50})$	$p(R_{100})$	$p(\Delta>10\%)$	$E[\lambda]$	$\%\downarrow\lambda$	PR?	FEG?	PBR?
0 / yr	99%	99%	0%	1.043	0%	Y	Y	Y
1	98	99	12	1.038	18	N	N	Y
2	96	99	21	1.031	35	N	N	N
3	94	98	33	1.025	53	N	N	N
4	86	95	48	1.018	74	N	N	N
5	76	89	64	1.012	93	N	N	N
No Action	54	54	62	1.014	79	N	N	N

Table 16. Analysis of effects of incidental take in the Northwest Region, fixed strategy. See *Notes* in Table 11 for explanation of metrics. The "No Action" scenario was not calculated for the fixed strategy.

Take	$p(R_{50})$	$p(R_{100})$	$p(\Delta>10\%)$	$E[\lambda]$	$\%\downarrow\lambda$	PR?	FEG?	PBR?
0 / yr	98%	99%	0%	1.043	0%	Y	Y	Y
1	98	99	7.4	1.039	9.5	N	Y	Y
2	96	98	16	1.034	21	N	N	N
3	95	97	26	1.029	34	N	N	N
4	91	94	38	1.022	48	N	N	N
5	81	86	54	1.014	67	N	N	N

Table 17. Analysis of effects of incidental take in the Southwest Region, proportional strategy. See *Notes* in Table 11 for explanation of metrics. The PBR calculation indicates a negligible level of incidental take of 5.5 manatees/yr in this region. For this region, the percent decline in lambda is not applicable ("N/A") since there is no excess growth in the absence of take.

Take	$p(R_{50})$	$p(R_{100})$	$p(\Delta>10\%)$	$E[\lambda]$	$\%\downarrow\lambda$	PR?	FEG?	PBR?
0 / yr	25%	63%	0%	0.998	0%	N	N	Y
1	24	62	37	0.997	N/A	N	N	Y
2	22	63	37	0.996	N/A	N	N	Y
5	19	58	43	0.993	N/A	N	N	Y
10	17	49	55	0.988	N/A	N	N	N
15	12	39	66	0.983	N/A	N	N	N
20	7	26	79	0.977	N/A	N	N	N
25	4	16	88	0.972	N/A	N	N	N
No Action	0	0	100	0.851	N/A	N	N	N

Table 18. Analysis of effects of incidental take in the Southwest Region, fixed strategy. See *Notes* in Table 11 for explanation of metrics. The "No Action" scenario was not calculated for the fixed strategy.

Take	$p(R_{50})$	$p(R_{100})$	$p(\Delta>10\%)$	$E[\lambda]$	$\%\downarrow\lambda$	PR?	FEG?	PBR?
0 / yr	25%	63%	0%	0.997	0%	N	N	Y
1	24	58	39	0.996	N/A	N	N	Y
2	22	55	42	0.995	N/A	N	N	Y
5	19	40	60	0.992	N/A	N	N	Y
10	13	21	78	0.985	N/A	N	N	N
15	7	9	91	0.976	N/A	N	N	N
20	4	4	96	0.963	N/A	N	N	N
25	2	2	98	0.946	N/A	N	N	N

Table 19. Summary of Results. Historic survival and historic and projected Growth Rates, probability of recovery , probability of delay in recovery, historic observed watercraft-related mortality, and negligible levels of take, by stock (Langtimm et al., *in review*; Runge et al., *in review*; previous tables). NA refers to "No Action", namely, continued increase in boat-related mortality. In all cases, the results in this table refer to the proportional management strategy.

Parameter	Atlantic	Upper St. Johns	Northwest	Southwest
Historic Adult Survival Rate (1990-1999)	**93.6%** (92.3% - 94.9%)	**96.0%** (93.7% - 98.2%)	**95.6%** (94.3% - 96.9%)	**90.6%** (86.7% - 94.4%)
Historic Growth Rate (1990-1999)	**1.0%** (–1.2% to 2.9%)	**6.2%** (3.7% to 8.1%)	**3.7%** (1.6% to 5.6%)	**–1.1%** (–5.4% to 2.4%)
Projected Growth Rate (No Action)	**–6.8%** (–9.4% to –4.5%)	**3.8%** (1.0% to 6.2%)	**1.4%** (–1.8% to 3.8%)	**–14.9%** (–19.2% to –11.4%)
$p(R_{50})$	Take/yr p 0 23% 5 19% 25 8% NA 0%	Take/yr p 0 86% 2 88% 4 89% NA 85%	Take/yr p 0 99% 2 96% 4 86% NA 54%	Take/yr p 0 25% 5 19% 25 4% NA 0%
$p(R_{100})$	Take/yr p 0 59% 5 57% 25 40% NA 0%	Take/yr p 0 88% 2 91% 4 92% NA 88%	Take/yr p 0 99% 2 99% 4 95% NA 54%	Take/yr p 0 63% 5 58% 25 16% NA 0%
p(Delay > 10%), No Action	100%	10%	62%	100%
Observed Annual Incidental Take (1998-2002)	37.0	2.4	3.8	37.2
Negligible Take, PR	<1 /yr	<1 /yr	<1 /yr	0 /yr
Negligible Take, FEG	<1	1	<1	0
Negligible Take, PBR	5.6	0.6	1.5	5.5

Table 20. Comparison of No Action and Authorization of Take in USJ and NW. Note, in the last column, the results for the Atlantic and SW stocks are the same as for No Action.

	No Action	**Authorize USJ and NW**
% Popn Benefited	None	15%
Projected growth rate (95% CI), by stock	USJ: 3.8 % (1.0, 6.2) NW: 1.4 % (–1.8, 3.8) Atl: –6.8 % (–9.4, –4.5) SW: –14.9 % (–19.2, –11.4)	USJ: 2.9 % (0.3, 5.2) NW: 3.1 % (0.0, 5.4)
Decrease in excess growth, compared to no take (with 95% CI)	USJ: 23 % (5.3, 51) NW: 79 % (32, 181) Atl: >>100 % SW: N/A (no excess growth)	USJ: 43 % (15, 86) NW: 35 % (8, 94)
Probability of >10% delay in time to recovery	USJ: 10 % NW: 62 % Atl: 100 % SW: 100 %	USJ: 21 % NW: 21 %
Probability of >50% delay in time to recovery	USJ: 6.3 % NW: 47 % Atl: 100 % SW: 100 %	USJ: 8.8 % NW: 8.2 %
Probability of >100% delay in time to recovery	USJ: 5.4 % NW: 45 % Atl: 100 % SW: 100 %	USJ: 4.4 % NW: 4.5 %
Authorized level of take	None, but unauthorized take will continue to increase	USJ: 4/yr NW: 2/yr

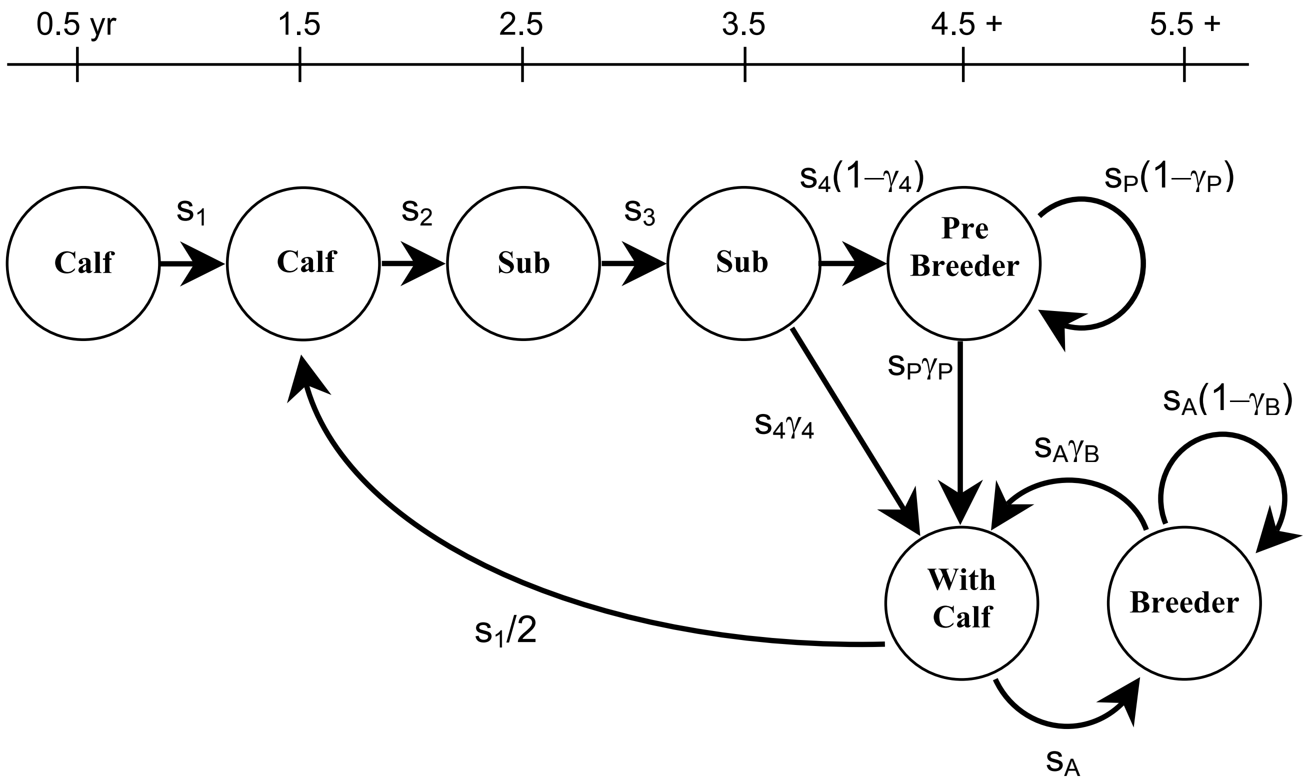

Fig. 1. Life-history diagram for the manatee population model. Note that calves enter the population as separate entities at 1.5 yr. The first circle is shown for completeness.

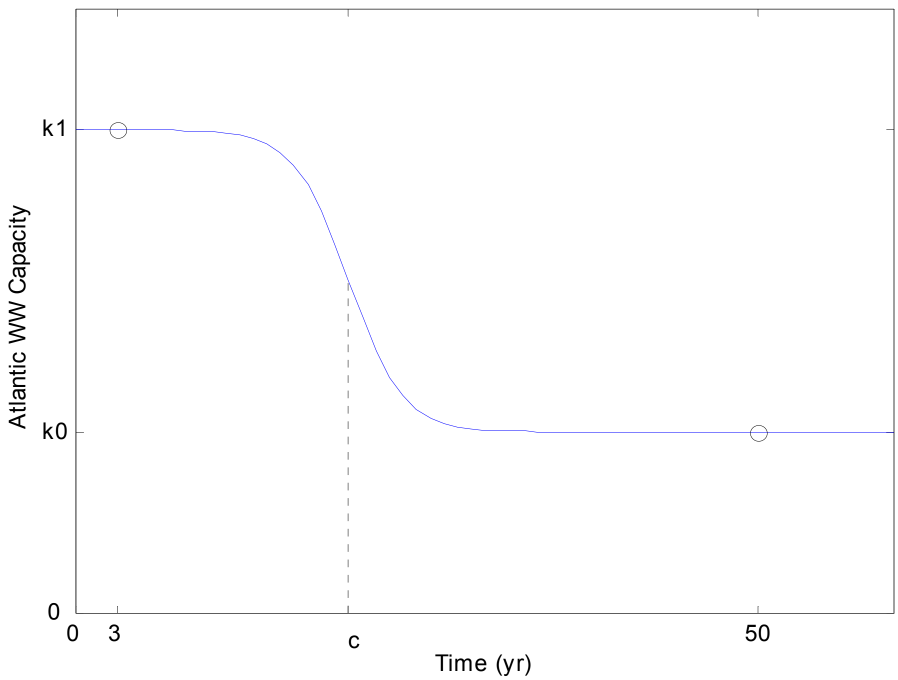

Fig. 2. Logistic curve to describe the change in warm-water carrying capacity in the Atlantic region.

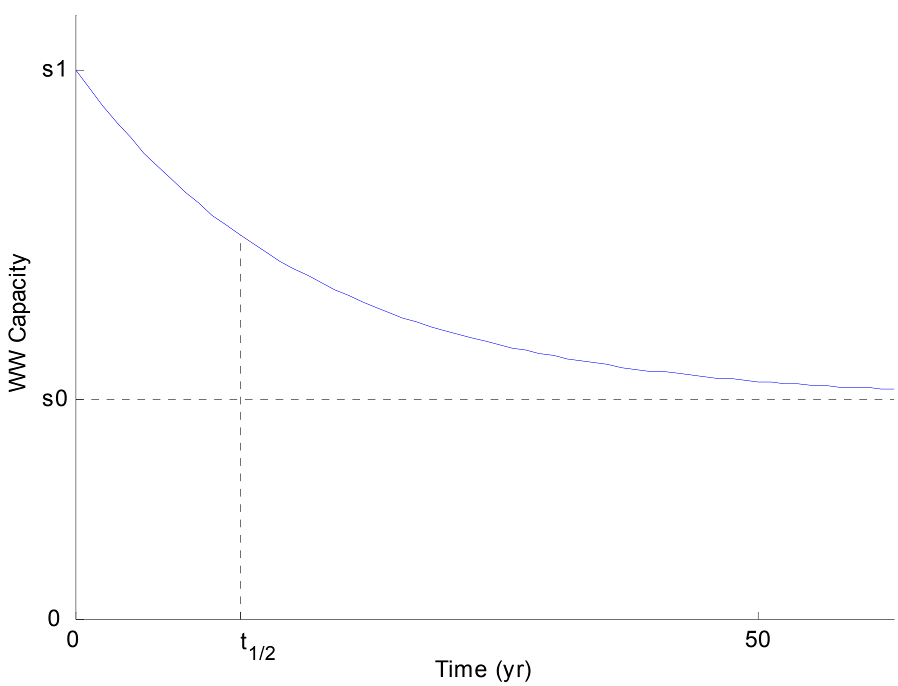

Fig. 3. Exponential curve to describe the changes in warm-water carrying capacity in the Upper St. Johns and Northwest regions. The current carrying capacity is given by s_1 and the long-range carrying capacity is given by s_0.

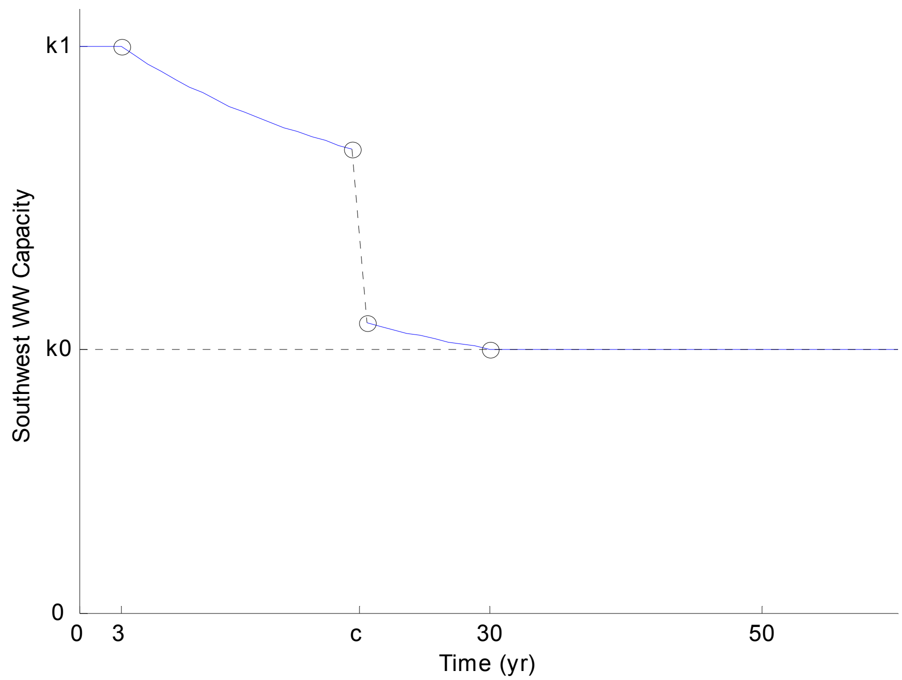

Fig. 4. Trajectory of warm-water carrying capacity in the Southwest region. The curve combines an exponential decline with an instantaneous loss of capacity when the Ft. Myers plant ceases to operate.

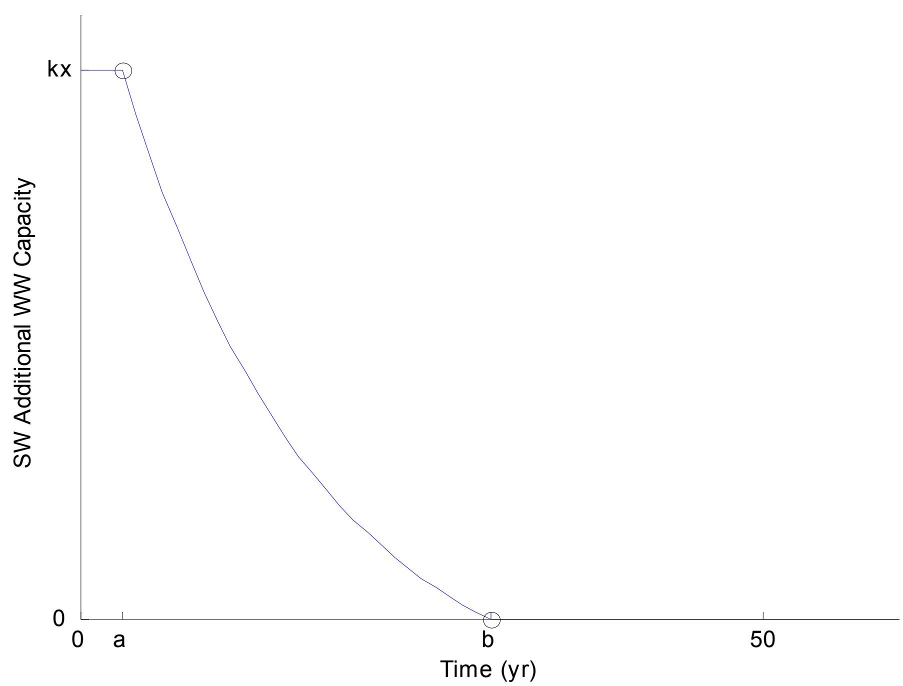

Fig. 5. Exponential component of the carrying capacity loss in the Southwest region. Of the carrying capacity that will eventually be lost, the component *not* associated with Ft. Myers is labeled k_X. This capacity declines exponentially, passing through the points (a, k_X) and (b, 0).

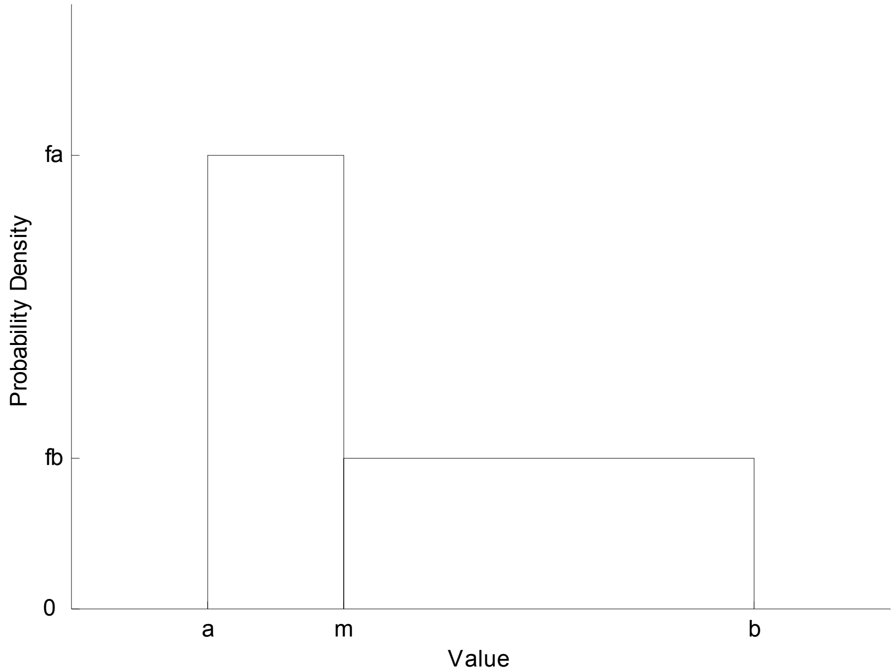

Fig. 6. Two-phase uniform distribution. Half of the density is found between the low value (a) and the median (m) and half is found between the median and the high value (b). Thus, the probability density is f_a for $a < x < m$, and f_b for $m < x < b$; and $f_a(m–a) = f_b(b–m) = 0.5$.