Technical Note DOER-E4
December 1998

FISHFATE: Population Dynamics Models to Assess Risks of Hydraulic Entrainment by Dredges

PURPOSE: The interagency coordination process through which environmental windows are determined for individual dredging projects is frequently handicapped by a paucity of technical knowledge pertaining to important attributes of the fishery resource(s) of concern and potential conflicts resulting from the dredging event. Thus, in many cases, environmental windows are chosen in an unavoidably subjective manner. Few tools exist to facilitate or inject objectivity into the negotiation of reasonable, technically justified environmental windows. The subject of this Technical Note is the conceptual development of an integrated computer simulation package, called FISHFATE, that provides a capability to assess alternative environmental windows that arise from issues related to hydraulic entrainment of aquatic organisms.

To be an effective tool in facilitating dredging project coordination, modeling applications must: (a) make optimal use of existing data resources (i.e., not require expensive, time-consuming collection of extensive field data sets), (b) be capable of making conservative estimates of parameters where quantitative data are lacking, and (c) be adaptable to a wide range of dredging project scenarios. Since it is unlikely that comprehensive data on individual fishery resources will be available for evaluation of even a fraction of common dredging project scenarios, population dynamics models represent one of few options to objectively examine environmental windows. Given the above criteria, however, it is imperative that confidence limits for model outputs be known. To this end, FISHFATE is intended to express population risks due to entrainment in probabilistic terms.

BACKGROUND: The growth of the maritime shipping industry, coupled with the increasing size of military and commercial vessels, has necessitated many improvements to navigable coastal waterways, including widening and deepening of channels and basins. The U.S. Army Corps of Engineers (USACE) maintains many navigation channels and removes more than 150 million cubic yards of dredged material annually in the United States (Navigation Data Center 1998). Many of the affected areas also support important commercial and sport fisheries, and many of the associated estuaries are major nursery habitats that contribute substantially to the quality and stability of coastal marine fisheries populations. Navigation projects have the obvious potential of benefitting the commercial shipping and production sectors of the economy; however, dredging and related activities may also have deleterious impacts on key fishery resources and, to some extent, the fishing industry. The effects of dredging on aquatic resources have been an issue of strident environmental concern for decades. However, very little work has been done on the direct population-level effects of entrainment on mobile epibenthic macroinvertebrates or demersal fishes (Wainwright et al. 1992). In contrast, quantitative assessment of power plant entrainment and impingement effects on fish has generated a relatively large literature. Of the methods used in power plant assessments, the "equivalent adult loss" (Goodyear 1977a) and "production foregone" (Rago 1984) approaches may be transferable to the modeling of USACE dredging operations, provided sufficient quantities of quality biological, physical, and operational data are available. To predict the population-level consequences of entrainment by hydraulic dredges, a stochastic demographic model is needed that captures the essential population dynamics of the species in question. Such a model should serve at least three purposes: (a) to establish base-line population dynamics models to assess the likelihood and severity of any possible impacts due to entrainment by hydraulic dredges, (b) to evaluate those environmental windows that are "optimal" for dredging operations under the design constraints, and (c) to eventually couple the population dynamics models to broader hydrodynamic circulation and fate-and-transport models.

INTRODUCTION: This document focuses on entrainment of aquatic organisms by hydraulic dredges (e.g., cutterhead and hopper dredges) and the efficacy of protecting organisms important to fisheries through application of the "environmental windows" concept. The term "environmental windows" defines a period of each year which constrains dredging operations. Such periods differ by region and population type, but are formulated to coincide with times when dredging activities are least likely to deleteriously affect the dynamics and productivity of the populations associated with the entrainment processes. In contrast, the term "seasonal restriction" refers to that period in which dredging operations are disallowed. Concerns about impacts associated with entrainment are persistent and technically challenging to address. The issue encompasses a variety of hypothetical effects, ranging from entrainment of egg and larval forms (e.g., oyster and striped bass larvae in the Chesapeake Bay) and juvenile and adult forms (e.g., Dungeness crabs and juvenile salmonids in the Pacific Northwest) to protected threatened and endangered species (e.g., sea turtles and sturgeon throughout their respective ranges). Often these concerns have led to imposition of seasonal restrictions on dredging projects to avoid putting resources at risk. In several cases, operational measures have been devised to reduce potential impacts.

This paper's goal is to design a framework for the development of state-of-the-science modeling to assess population entrainment risks under alternative environmental windows using emerging modeling and visualization tools for predicting impacts on fishery resources. There has been an extensive review of the scientific and technical literature on modeling approaches and tools that are used to assess the impacts on fishery organisms from dredging, power plants, and other entrainment activities. Additional physical, hydrodynamic, transport-and-fate, and population models were also reviewed to determine the feasibility of evaluating dredge entrainment effects by use of a decision support framework fully integrated from a population risk assessment perspective. In the review and analyses, two outputs have been emphasized: (a) absolute rates of entrainment and (b) estimating population level consequences of mortality attributable to entrainment under differing environmental windows. This document summarizes a framework for integrating a broad variety of abiotic and biotic models, their sources, types of output, assumptions, and requirements for verification. Technical and logistical strengths and weaknesses (e.g., computational constraints, output sensitivity) and associated costs issues (e.g., system requirements) are also reviewed. To ultimately realize a unified and comprehensive decision support system for both environmental and fishery management, an "entrainment model package" is necessary because of the number and complexity of the interacting variables specific to the dredge entrainment-population dynamics problem. It will consist of all software necessary to evaluate the effects of hydraulic entrainment by dredges. The framework for development of such a package is outlined herein. The package must be usable in an administrative, as well as a technical, context and must be user-friendly in terms of implementation and interpretation of output. Ideally, the package will be capable of generic evaluations. A tiered modeling approach which is logically stratified by geography, taxon, and operational issues is necessary. A useful model package will provide initial screening of dredging projects, identifying projects according to high or low probabilities of significant entrainment impacts. Those in the former category would be subjected to more extensive modeling exercises and perhaps systematic field verifications.

Dredge Operational Issues: Development of a population model to assess environmental windows requires careful consideration of the regions of operation and the operational characteristics of the dredge plants (Figure 1). Operations will vary regionally due to discrete physical, biological, and administrative attributes of each region. As numerous dredge project sites can be located within a given watershed (e.g., the Baltimore District operations in the Chesapeake Bay (Earhart 1986)), one approach is to stratify the nation into several regions encompassing similar biotic and abiotic regimes related to entrainment effects. At least six biogeographic regions encompassed by USACE harbor maintenance operations can be identified in U.S. coastal waters: northwest, southwest, north central, northeast, southeast, and Gulf of Mexico. Dredge entrainment effects across these regions encompass a variety of taxa. These range from eastern oysters and striped bass in the northeast area (with main emphasis on egg and larval stages) to Dungeness crabs in the northwest (primarily juvenile and adult stages) to sea turtles, salmon, and sturgeon (species listed under the Endangered Species Act).

Administratively, there are 8 USACE divisions containing 38 districts that may deal with environmental window and entrainment issues. However, environmental window issues are not uniformly distributed across the country. Four of the top five districts, in terms of these issues, are located in the North Atlantic Division, with the New England and Baltimore Districts ranking first and second (Dickerson, Reine, and Clarke 1998). The fish species with the most environmental restrictions per USACE district are striped bass, American shad, Chinook salmon, and alewife. Environmental windows are in place for striped bass in eight districts and in at least five districts for the other three species (Reine, Dickerson, and Clarke 1998). In addition, environmental windows for sea turtles exist in four USACE districts, particularly within the North Atlantic and South Atlantic Divisions. In terms of invertebrates, six districts in the Atlantic and Gulf of Mexico areas have restrictions involving the eastern oyster. On the west coast, the Dungeness crab has received particular emphasis in USACE planning and has generated restrictions in two districts.

A variety of dredge plant types are used that involve differing surface platforms, cutterheads or dragheads, swinglines or tow tracks, production rates, and areal effects. Modeling of effects on fishery organisms will be based in part on whether the dredging pipeline platform is relatively stationary (cutterhead dredges) or mobile (hopper dredges). Pipeline platforms are used to excavate more than twice the volume of dredged material as hopper dredges (approximately 74 million yd^3 yr^{-1} versus 30 million yd^3 yr^{-1}) (Dickerson, Reine, and Clarke 1998). An important suite of gear attributes involves the structure and towing characteristics of the draghead or cutterhead. The Navigation Data Center at the Water Resources Support Center maintains a database of dredging platforms and their operational attributes within all USACE districts. Many of these data can be rapidly obtained through the Internet (http://www.wrsc.usace.army.mil). To obtain more detailed information on harbor- and channel-specific parameters when employing models to assess alternative environmental windows, direct communication with individual USACE district offices will be necessary. Through these contacts, access to more detailed information (hydrodynamic transport models, fate models, GIS data layers, etc.) will also be facilitated.

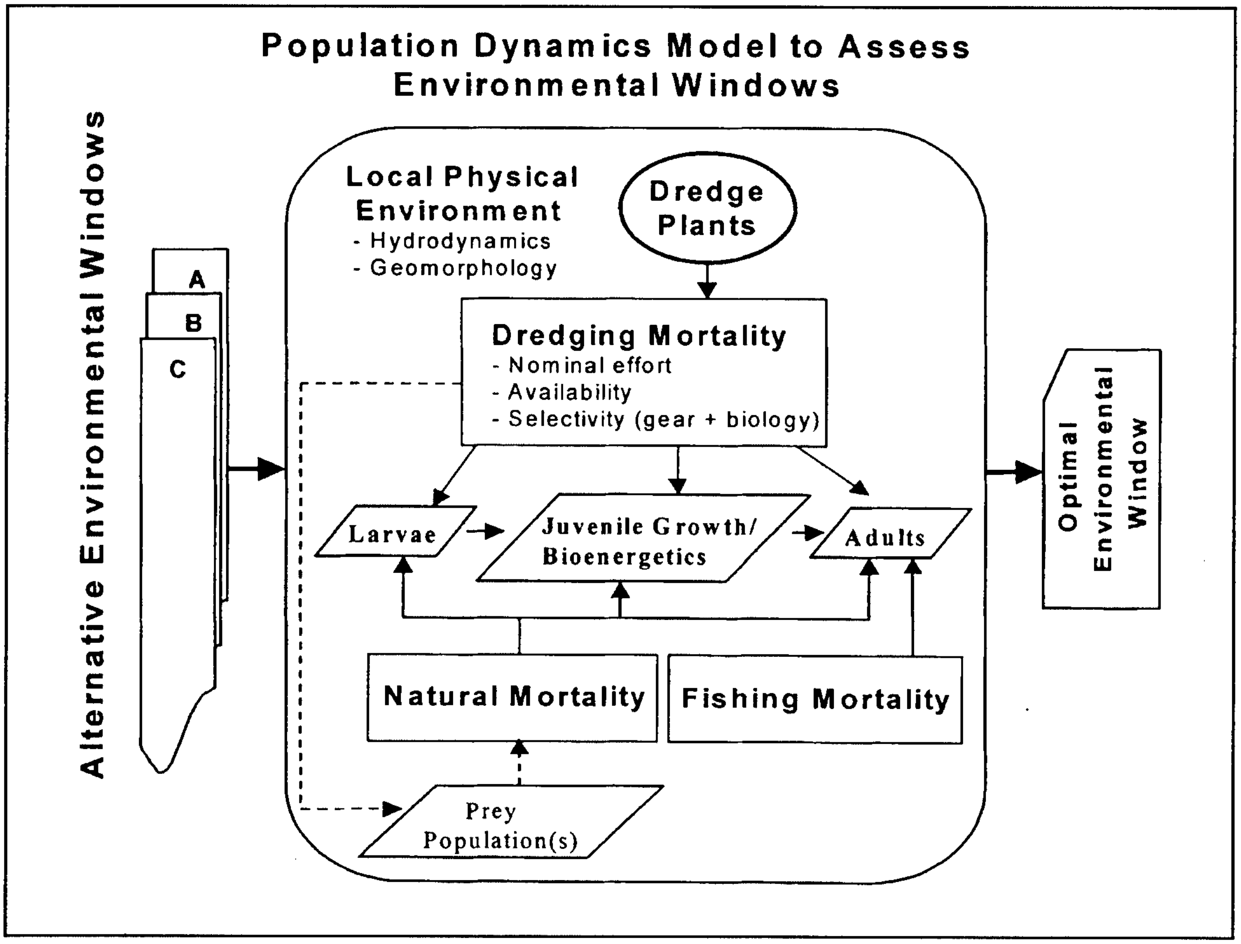

Figure 1. Population dynamics model outline for assessing dredge entrainment mortality relative to alternative environmental windows

Target Populations: Choice of target species for modeling studies will involve several criteria. These include economic value, susceptibility to effects, ecological significance, and magnitude of administrative concerns. There is a suite of species that meets these criteria and includes both motile and benthic forms (Table 1). Some representative invertebrates within this group include the eastern oyster (*Crassostrea virginicus*), the blue crab (*Callinectes sapidus*), and the Dungeness crab (*Cancer magister*). Representative fishes include striped bass (*Morone saxatilis*) and the coho/chinook salmon group (*Oncorhynchus kisutch* & *O. tshawytscha*). Reptiles include the loggerhead sea turtle (*Caretta caretta*).

Dredge Entrainment Processes: Entrainment may affect a substantial number of animals over a variety of size and age classes. The most conservative assumption is that 100 percent of all entrained animals die. However, entrainment processes may generate non-uniform mortalities, depending on the taxon, size, and age. This component is the core of the population risk assessment decision support system, and it requires the integration of population production functions (population dynamic and bioenergetic/movement models) with dynamic spatial model components (hydrodynamic and fate/transport models). Local hydrodynamics and geomorphology will influence these models, as well as biological effects of dredge-related stressors which vary according to life stage (Figures 2 and 3). Dredging operations generate at least three stressors that directly

Table 1
Examples of Target Populations and Selected Biological Attributes Relevant to Dredge Entrainment

	Life Stage	Eastern Oyster NE, SE, GM	Blue Crab NE, SE, GM	Loggerhead Turtle SE, GM	Striped Bass NW, NE, SE	Dungeness Crab NW	Coho/Chinook Salmon NW, NC
Month in Dredge Areas	L J A	5-8 6-10 1-12	5-8 6-10 7-12	5-9 5-11 5-12	4-9 5-10 6-12	4-8 5-9 5-10	6-9 7-11 6-2
Water Column Position	L J A	W B B	W B B	S S S or B	W W W	W B B	S W W
Dredge Avoidance Ability	L J A	Low Low Low	Low Low Mid	Low Mid Low-High*	Low Mid High	Low Low Mid	Low Mid High

Note: Life-stage parameters are preliminary estimates. NE = northeast region of U.S.; SE = southeast; NC = north central; GM = Gulf of Mexico; NW = northwest. L = larvae (hatchlings for loggerhead turtles); J = juveniles; A = adults. Peak months represented numerically (e.g., 1 = Jan., ..., 12 = Dec.). S = surface; W = throughout water column; B = bottom.
* Dependent on whether individual is burrowed in mud or free-swimming.

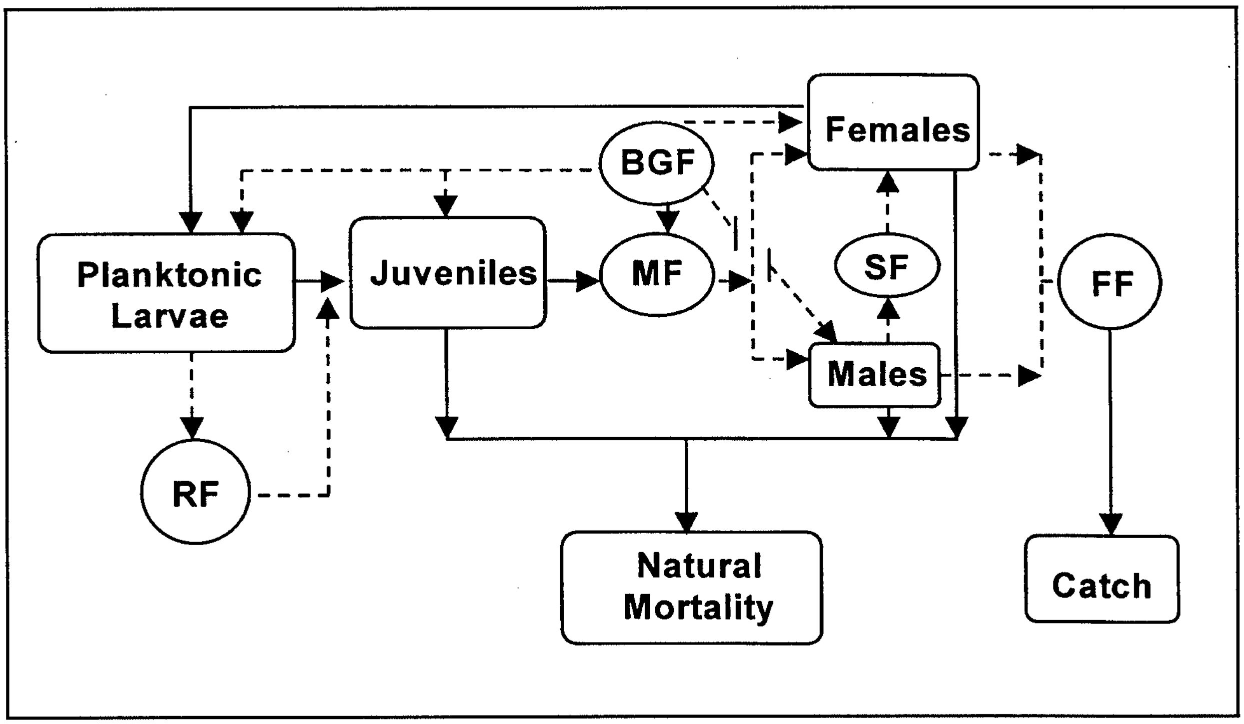

Figure 2. Population processes and dynamics of fishery organisms potentially affected by dredge entrainment. SF = spawning function; FF = fishing mortality function; BGF = bioenergetic growth function; MF = sex-specific maturation function; RF = recruitment function. Boxes represent state variable compartments, solid lines represent material flows, dashed lines represent information flows, and circles represent regulatory functions

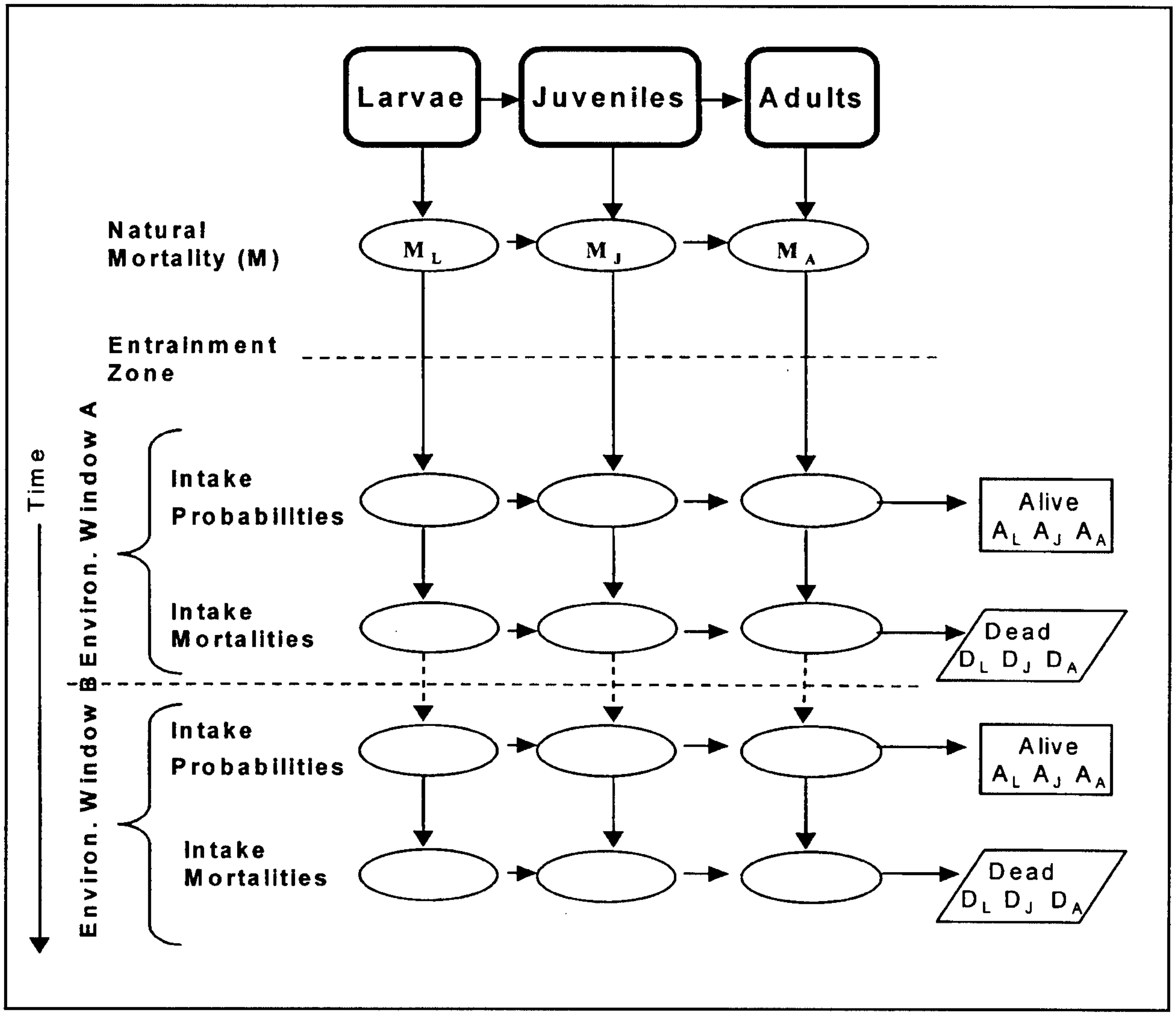

Figure 3. Diagrammatic representation of steps in entrainment mortality process estimation by life stage

influence environmental windows: (a) entrainment, (b) suspended sediments/turbidity, and (c) sedimentation. Although entrainment is the focus of the present study, future model packages may include estimators of other stressors. The evaluation of site-specific variation in entrainment is critical. The assessment must consider the spatial and temporal distribution of the stressor with respect to dredge locations and other relevant factors that influence entrainment effects. Direct information, or proxies, are needed on the volume and rate of water and sediment entrained, the spatial scales of cutterhead or draghead influence on flow fields, organismal distributions and abundances (including seasonal and diurnal variation), sediment characteristics, and other environmental characteristics such as bottom types and, possibly, micro-climate effects. The performance specifications of dragheads and their towing profiles provide important insight into which ecological components may be most exposed. Stressor distributions will also be influenced by historical dredging patterns, volumes and areas currently affected, hydrologic characteristics, and climate. These are essential to developing an accurate suite of effect scenarios which encompass the range of predicted results.

The potential biological effects of exposure to dredge entrainment processes depend on organismal responses to both abiotic and biotic perturbations. Effects can be acute or chronic. Acute effects occur within a few days, with the response being lethal (mortality) or sublethal (a change in growth or reproduction, or disruption of basic behavioral or physiological processes). Chronic effects occur over weeks, or longer, with the response being continued manifestation of sublethal effects that may ultimately result in decreased survivorship. Chronic effects are, to some extent, beyond the scope of the initial population risk assessment. Unlike some other stressors, entrainment effects are largely acute in nature, and, thus, the principal effects evaluated are from acute responses and their resultant effects on both short-term and longer-term productivity and yields, including lost recruitment and biomass production. Analyses of these effects have traditionally defied exhaustive empirical treatment; thus a broad quantitative analytical framework is needed to fully assess the risks of population exposure to entrainment effects. Extensive information on invertebrate entrainment exists for the Dungeness crab from the U.S. west coast. This species is primarily affected by hopper dredges. Entrainment rate estimates varied according to the distribution of dredging effort across the estuaries in question and ranged from 0.040-10.78 crabs/yd^3 of dredged material (Reine and Clarke 1998). The majority of studies on Dungeness crab mortality are based on entrainment rate estimates of less than 0.5 crabs/yd^3. In addition, mortality is differentially affected by life stages impacted and season of dredging. Dredge entrainment data on Atlantic invertebrates are mostly lacking. For example, there are no dredge entrainment estimates available for the blue crab (Reine and Clarke 1998) despite their wide geographic range, relatively high local abundances, and substantial economic value throughout many estuaries on the U.S. east coast and Gulf of Mexico.

Dredge entrainment rates for fishes have been summarized by LaSalle et al. (1991) and Reine and Clarke (1998). Given the dozens of substantial dredging projects annually, there is a paucity of data in most regions of the country. This derives from several logistical reasons, including inherent difficulties in accurate sampling of biological resources during large-scale dredging projects. In addition, many issues besides entrainment are responsible for environmental windows (Reine, Dickerson, and Clarke 1998), and, often, sampling efforts are focused not on entrainment but rather on turbidity, sedimentation, habitat modification, and water quality. In the northeastern and southwestern United States, a large number of studies focusing on power plant entrainment appear to have methodological applications that may be suitable to dredge entrainment modeling. However, actual entrainment and mortality rate data from power plants are not directly applicable to dredging activities due to many differences in placement, gear types, mobility, and timing of operations. Fewer than ten studies have comprehensively addressed fish entrainment by dredges. When quantitative estimates of dredge entrainment of fishes are available, rates are typically <0.01 individuals/yd^3. In the northwest United States, this situation is similar for a wide range of species (Reine and Clarke 1998). By applying ichthyoplankton survey data in an empirical transport model, Burton, Weisberg, and Jacobson (1982) estimated that <1 percent of striped bass larvae suffered mortality from dredge entrainment within the Delaware River estuary. However, there have been few other quantitative efforts to link local-scale dredge entrainment information to population-scale effects.

Assessing Dredging Alternatives: Ultimately, the model must serve as a tool for use at the District level (with initial training assistance). It must be usable with "best guess" estimates of parameters so that fieldwork is not a prerequisite. The tool is intended to screen individual dredging projects, not to be a justification for environmental windows in general. Assessments will take on three characteristic steps: (a)setting goals and objectives, (b) determining the primary objectives, and (c) defining the decision-making environment. The model should be used in a strategic format to help define the long-term target and the transitional behavior of the stock under a range of alternative environmental window scenarios. The modeling framework will be used to integrate parameter estimates in a concise way such that model outcome sensitivity to parameter ranges can be examined, and ultimately to provide insight into balanced dredging project management. Dredging effects will be assessed using "best" parameter estimates to determine if and when environmental windows may be reconfigured to improve dredging operations and minimize effects on key taxa. An assessment indicating minimal risk would support consideration of flexible window start and end dates. A "red flag" assessment (i.e., a model outcome indicating elevated risk of population effects) would substantiate the need for conservative environmental windows. Further evaluation of a "high risk" window would require sophisticated databases on the appropriate estimates in space and time of animal abundance, population dynamics, habitat, and physical systems. These are not to be expected routinely.

Various exposure scenarios should be evaluated in the physical and biotic context of the region in question. The approach consists of two elements. First, the spatial and temporal distribution of the stressor is measured or estimated. Second, the distribution of the biological component and its characteristics that influence exposure are evaluated. The two elements are combined to evaluate the co-occurrence of the stressor and the ecological component. Dredge locations and area covered are combined with distributional information on the target species to develop a probability ranking of dredge and biotic exposure scenarios. Other relevant criteria may be employed as well. Development of the scenario-consequence analysis is based on an internally consistent, plausible set of conditions that are designed to represent a range of possible dredge operations and seasonal criteria. Each scenario will provide a clear specification of the type, area coverage, timing, and location of a dredge operation, as well as the weather and hydrodynamic conditions at the time. A carefully developed set of scenarios should bound the range of plausible conditions and provide the more specific conditions necessary to conduct consequence assessments. Criteria for selection of the specific scenarios to use include: range of hydrodynamic conditions, range of weather conditions, range of locations, range of seasonal timing, other physical aspects deemed relevant to the potential location, and consequences of the operations on ecological systems (Table 1). For example, it will likely be important to hindcast dredging mortality rates that are likely to trigger population declines under scenarios developed with best-guess parameter estimates. In all the aforementioned scenarios, population results will be expressed as the probability of decline as a function of the magnitude of decline, or the predicted distribution of time that will pass before the population passes a particular threshold (Figures 4 and 5). This format allows accurate evaluation of population risks, with and without impact, and provides some definition of the maximal increase in population risks associated with dredge entrainment. Finally, the results of the population viability analysis will include: (a) the risk of partial population decline or loss to population productivity, (b) the risk threshold, and (c) the recovery chance. The model will help to focus on several key measures of "population health": (a) the probability that a decline will occur, (b) the amount of decline, if it does occur, (c) the time it will take the population to decline a specified amount, and (d) the recovery rate.

Uncertainty and Sensitivity: These models will be designed to address two sources of uncertainty, subjective uncertainty (measurement error or lack of information) and objective

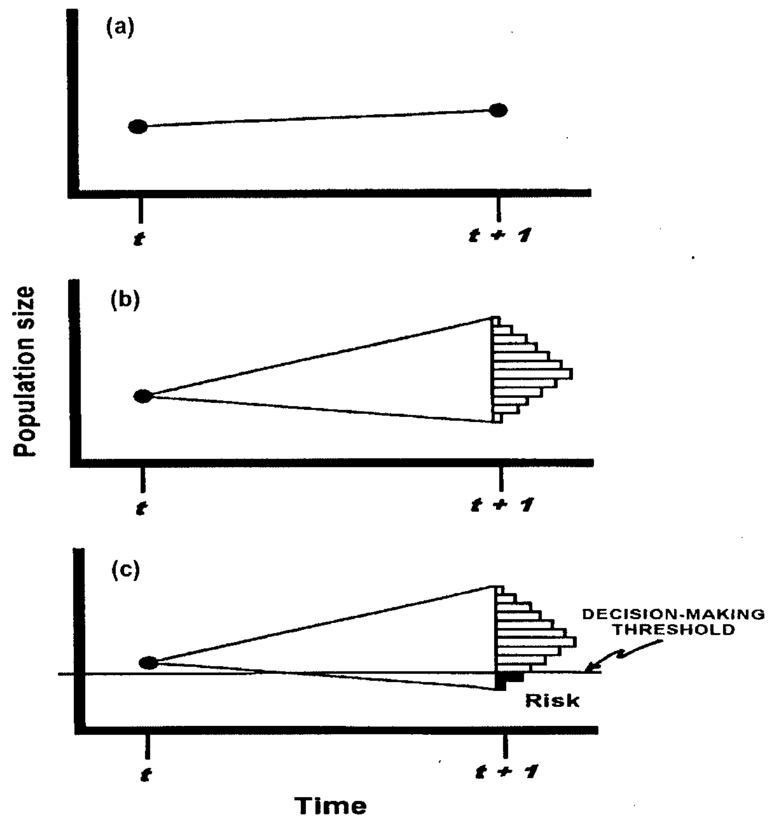

Figure 4. Summary of hypothetical population trajectories when the intrinsic rate of population growth is: (a) constant, (b) stochastically distributed over a given range, and (c) stochastically distributed with an imposed minimum threshold for decision-making

uncertainty (interannual variability and spatial heterogeneity). These issues need to be addressed in a population viability analysis when assessing the impacts of dredge entrainment on populations. Population viability analysis looks at the extent of perturbations to a population, quantifies the immediate effect in terms of acute mortalities, and assesses the chronic effects in terms of recovery probabilities and the time required to reach a specified recovery threshold. Many aspects of population viability analysis can be expressed in a suite of sophisticated population dynamics models. These models should be structured to incorporate demographic and environmental stochasticity. Demographic stochasticity refers to temporal and spatial variation in survivorship, growth, and fecundity due to age- or stage-specific fluctuations. Environmental stochasticity refers to temporal variation in the vital rate parameters due to fluctuations in environmental conditions. Stochastic population modeling, rather than using fixed demographic rates, will consider each element as a probability distribution. Density-dependent models will consider changes in the vital rates to be functions of population density. There are at least three advantages of stochastic population modeling: (a) it overcomes the general equilibrium assumptions because it minimizes the investigator's dependency upon stable age distribution, (b) it incorporates natural "observed" variability in the vital rates, and (c) it estimates the uncertainty involved in the endpoint of interest. These features facilitate expression of results in terms of population risk. Key decisions involve:

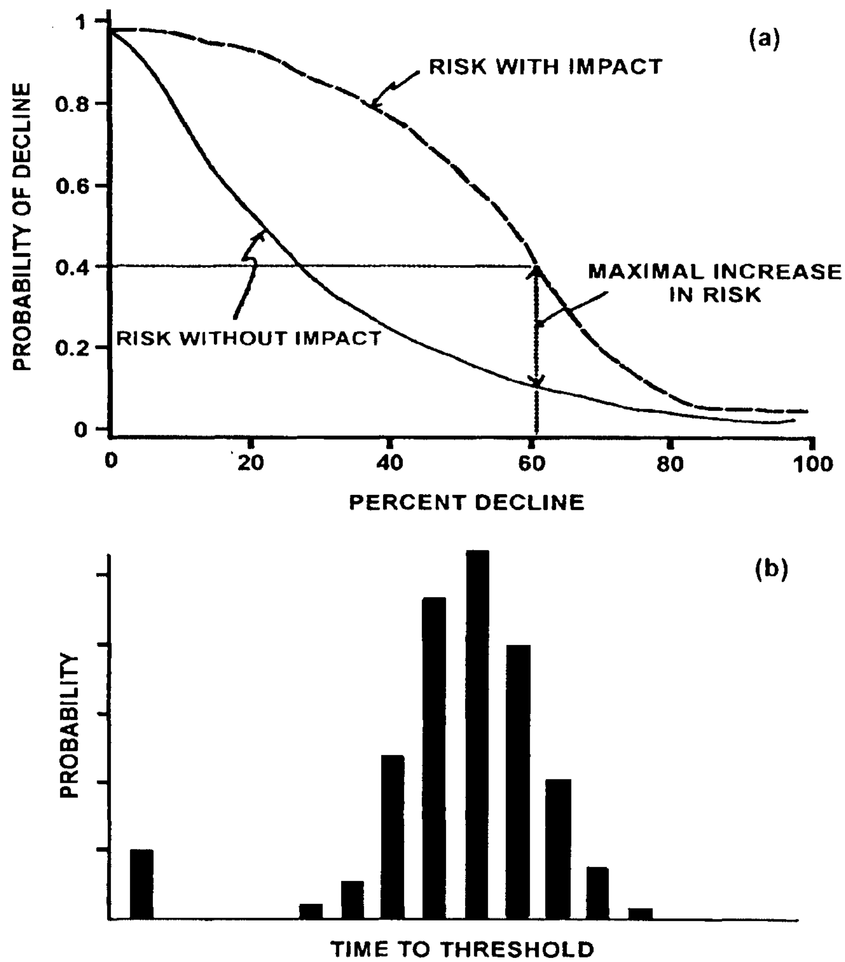

Figure 5. The predicted distribution of time that will pass before the population passes a particular threshold. Each vertical bar shows the probability of reaching the threshold at a particular time. (a) Probability of decline at the end of *t* years, (b) Probability of decline as a function of the magnitude of decline

(a) Which vital demographic rates depend on density? (b) What is the form of the recruitment function? and (c) What are the parameters of the model?

Population risk assessment is the process of qualitatively or quantitatively estimating the magnitude and probability of biological effects from exposure to stresses. The process evaluates two types of scientific information, ecological effects from co-occurrence with a stress and the spatial and temporal intensity and duration of the stress. Conducting a risk assessment is a complicated undertaking because of the complexity of the ecosystems of interest, limited data on fate-and-transport and biological effects, and geographic and phylogenetic variation in the nature of entrainment details and effects. Fortunately, a newly developed framework for ecological risk assessments provides a systematic structure for conducting assessments of consequences to the environment from human activities (Harwell, Ault, and Gentile 1995). Application of new population risk assessment tools directly applicable to assessing ecological effects of maintenance dredging operations will represent one of the earliest major applications of the framework to real-world problem solving.

A population risk assessment (i.e., directly comparing the relative risks to the environment from differing operational and seasonal parameters) may likely be best accomplished through an ecorisk framework using a "scenario/consequence analysis" approach (Harwell, Ault, and Gentile 1995). By using these new methodological tools, the scientific bases for making appropriate decisions are significantly enhanced.

A strong conceptual model will provide linkages necessary to combine the specified research tasks with the framework necessary to carry out the risk assessment. The model will address four specific areas: (a) definition of the specific scenarios to be evaluated and identification of the resources or taxa at risk, (b) selection of the endpoints required to conduct the assessment, (c) discussion on how the physical and biological models are to be combined to perform the full risk assessment, and (d) the physical and biological pathways that are to be evaluated in the risk assessment. The conceptual model also elucidates the extent to which information is available to conduct the ecorisk assessment and how integration is to be accomplished. The conceptual framework development will also define how the endpoints identified for the risk assessment depend on spatial and temporal scales for the stressors identified. The population model to assess dredge entrainment effects should be based on sound demographic principles with the most comprehensive life history information available. Model simulations should display patterns of abundance and variability similar to those known in nature, given the initial abundance of each age class, age-specific fecundity and survivorship estimates (with their respective year-to-year variations), maximum age, and sex ratio. Emigration and immigration, correlations among parameters, and density-dependent relationships among variables can be specified. The resulting probability distribution of outcomes gives an estimate of the likelihood of reaching a given abundance threshold within a specified time horizon. The distribution of risk measures the likelihood of population decline for all levels of forcing (Ault and Fox 1989; Harwell, Ault, and Gentile 1995).

In the proposed framework for analysis of environmental windows, we expect to evaluate a suite of scenarios associated with two regions involved in dredge activities. The kinds of endpoints will broadly involve short-term biological losses in two classes, mortality of organisms as a function of exposure and lost productivity. Complex problems like environmental windows involve multiple objectives. One of the most important problems in decision analysis concerns quantifying the decision-maker's preferences for the various objectives. To quantify these, we must obtain a utility function over all possible consequences. It is assumed that an individual or agency can choose from among the available alternatives in such a manner that the satisfaction derived from the choice is as large as possible. The desire is to obtain an objective function involving multiple measures of effectiveness to indicate the degree to which the various objectives are met. In effect, an individual's or group's utility function is a formal mathematical representation of the preference structure for outcomes. In this case, the alternatives involve temporal modifications to existing environmental windows that will not degrade resources or decrease dredging expenditures and will satisfy several different agencies. By specifying a group of alternatives differing slightly in some feature, we can conduct a sensitivity analysis of the probabilistic inputs. Also, we can conduct a sensitivity analysis of the preference structure by varying such parameters as the scaling constants in the decision-maker's multi-attribute utility function. In this way, different utility functions of the members of a decision-making group can be used to evaluate and rank the alternatives. This will clarify differences of opinion and suggest certain creative compromises.

Model Implementation and Software Development: FISHFATE will combine spatially explicit seascape modeling with scientific data visualization in response to the need to use an ecosystem approach. However, predictive success at the ecosystem level almost surely requires the inclusion of those physical and biological components that are forcing, or are significantly coupled to, the target species. New sensor, communication, and information technologies are making it possible using a "fish-eye view" to begin to identify and track in near real-time the state of such a "subecosystem" associated with a fishery resource. It also facilitates development of "environmental management systems" that use this information to improve strategic decision-making capabilities (Ault and Fox 1989; Rothschild, Ault, and Smith 1996). In dealing with subsystems related to single stock dynamics, the four basic tasks of sampling design, data analysis, model development, and model validation now involve time varying, spatially dependent variables for the populations, the physical environment, and those processes that couple these system components. Computer innovations and scientific data visualization provide an enhanced technical interface for decision-makers to evaluate technical issues. Eventually these will be complemented by numerical and computer-based linkages between hydrodynamic circulation, fate-and-transport, and ecological models at the individual, population, and landscape/seascape levels (Harwell, Ault and Gentile; Ault et al. 1998). A cornerstone information technology for our work is "scientific data visualization," which is the use of sophisticated computer graphics to gain insight and understanding into complex problems characterized by large data sets. Scientific data visualization is emerging as a strategic technology in the natural resource sciences, and this technology will be pivotal to our ability to work with the system's relatively high dimensionality. Documentation will be an essential element of the computer-based decision support model and parameter development.

Model Validation: In summary, a suite of viable approaches to the modeling of dredging project scenarios exists. These models can be effectively integrated within a population risk assessment modeling framework. Four fundamental model types have the potential to optimally achieve this goal: (a) hydrodynamic, (b) fate-and-transport, (c) coupled biophysical population-dynamic, and (d) bioenergetic models that are developed in a spatially explicit format. Several methods to integrate GIS and new spatial visualization tools to facilitate graphical animations of the coupled biophysical models in spatially explicit manners are available. Incorporation of these technological capabilities will enhance the feasibility of modeling dredge entrainment in terms of absolute rates at the local scale and population level effects among alternative environmental windows.

To accomplish full validation of the FISHFATE model, research and development of the population models to assess environmental windows should proceed in at least seven steps: (a) write out the mathematics appropriate for model development, (b) convert the mathematics to computer code, (c) collect and analyze existing databases on dredge entrainment activities, (d) parameterize the dredge entrainment population risks model, (e) calibrate the model to the various regional data sets, (f) run test scenarios based on actual dredging projects conducted in selected districts, and (g) iterate this process with an emphasis on hands-on utility at the USACE District and Division levels.

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APPENDIX I
PARAMETERS AND EQUATIONS FOR FISHFATE POPULATION DYNAMICS MODELS

ENTRAINMENT MORTALITY: Estimates of entrainment rates and mortality of biota (e.g., fish and shellfish life stages) required by FISHFATE are based on some measure of exposure to the effects of hydraulic entrainment. Exposure time is calculated from the time a target organism will be in a dredge "search area" (i.e., subject to influence of cutterhead or draghead intake flow fields) or by active or passive biotic movement into and out of the affected area using a diffusion-taxis spatial model (Rothschild, Ault, and Smith 1996; Ault et al. 1998). In turn, entrainment rates will be influenced at the gear/organism scale by flow fields, gear dimensions, operating characteristics, habitat types, and mechanical effects on life stages. End-of-the-pipe mortality is a function of several variables (e.g., extent of entrainment exposure, organism size, behavioral responses, etc.). We represent these relationships as follows:

$$D = f \cdot s_a \cdot a_d \cdot q \tag{I1}$$

where D is the instantaneous rate of dredge mortality, f is nominal dredge effort in time/volume units, s_a is selectivity at size/age, a_d is availability to dredge at size/age, and q is the "catchability coefficient" or the fraction of the stock affected per unit of nominal dredge effort. Many biotic and dredging operations parameters can influence D. Primary parameters for many of the target species and engineering factors are available from the peer-review and gray literature. A summary of some key population and entrainment parameters for proposed models is given in Table I1.

Table I1
Population Dynamics and Entrainment Process Parameters, Definitions, and Units Used in Numerical Modeling of Entrainment Rates and Effects on Target Species and Taxon

Population Dynamics			Entrainment Process		
Parameter	**Definition**	**Units**	**Parameter**	**Definition**	**Units**
W_∞	Ultimate weight	kg	A_d	Head surface area	m^2
L_∞	Ultimate length	mm	j	Median grain size	mm
t_λ	Oldest (largest) age	yr	d_f	Head penetration	m
L_λ	Largest (oldest) length	mm	d	Head diameter	m
K	Growth coefficient	yr^{-1}	h	Dredging depth	m
t_0	Age at which size = 0	yr	V_i	Intake velocity	$yd^3\ hr^{-1}$
$Fec_{(t)}$	Fecundity at age	No. eggs	V_t	Net head velocity	$m\ hr^{-1}$
t_m	Minimum age of maturity	yr	ρ	Density of water	g/l
t_E	Age at egg stage	yr	V_d	Volume of head	m^3
t_L	Age at larval stage	yr	D	Entrainment mortality	yr^{-1}
t_r	Age at recruitment	yr	s_a	Selectivity @ size/age	N/A*
t′	Minimum age of capture	yr	f_d	Nominal dredge effort	$m^3\ d^{-1}$
L′	Minimum size of capture	mm	q	Catchability	N/A*
M	Natural mortality rate	yr^{-1}			
F	Fishing mortality rate	yr^{-1}			
a_d	Availability to dredge	N/A*			

* Dimensionless parameters.

POPULATION DYNAMICS MODEL: For the foreseeable future, single population or species assessments (including all the spatial complexity as needed) will remain the most practical approach to population ecological risk assessment (Ginzburg 1994). Advantages of the single-species population-level model include: (a) it is better understood than higher-level models, (b) it requires less data to treat comprehensively, and (c) it has well-defined endpoints such as risk of decline or extinction. Legislation such as the Endangered Species Act has reduced the restrictive aspects of the single-species approach by focusing on species considered to be "indicators" of ecosystem stress (derivative of their threatened status) and as "umbrella species" (as a result of their large habitat requirements). A wide variety of studies have examined modeling of entrainment effects, but these have mostly focused on power plant entrainment issues (e.g., Goodyear 1978; EPRI 1981a,b; Jensen, Spigarelli, and Thommes 1982; Barnthouse and VanWinkle 1988; Nisbet, Murdock, and Stewart-Oaten 1996). However, some models of entrainment effects from maintenance dredging are also available (e.g., Armstrong et al. 1987) as are approaches to modeling multiple stressors (Vaughan, Kanciruk, and Breck 1982) and new modeling tools for Before-After analyses of effects (e.g., Schmitt and Osenberg 1996).

To achieve a better understanding of the dynamics of populations, their response to dredge entrainment, and the accuracy and precision of statistical estimates from the available data, we will develop an object-oriented computer simulation population dynamics model to assess dredge entrainment risks among alternative environmental windows. The model will contain fundamental population-dynamic processes of growth, mortality, and recruitment specific for regional populations of interest. The envisioned population effects model will operate at the ensemble individual level with a demographic perspective (e.g., survivorship, growth, and reproductive effort) and may be used to infer effects at the population level, for example, the chance of the perturbed population falling below certain thresholds of population size or reproductive effort. Analysis of population variability includes the following steps: (a) identification of key factors (e.g., separating natural variability from human impact), (b) statistical analysis of the data, (c) determination of the model structure to use, (d) parameter estimation, (e) modeling and risk analysis, (f) implementation of management options, and (g) long-term monitoring and evaluation. The actual population dynamics model to assess dredge entrainment risks will employ a network of strategic population models to encompass the range of mechanical and trophodynamic interactions involved in the broad scope of dredging operations at various regional locales.

Age/Size Structure and Life History Ontogeny: It is important to ascertain how a given stock distributes itself over the seascape and how it grows and matures. This will define how, when, and what life stages, such as eggs/larvae, juveniles or adults, are expected to interact with dredges. Although possessing different distributions and population demographic parameters, all of these stages are influenced by fundamentally similar bioenergetic processes (e.g., bioenergetic growth function in Figure 2). Bioenergetic growth functions serve as convenient and powerful linkages for modeling of spatially explicit population distributions and "spatial growth rate potential" fields (Ault et al. 1998). Other processes, such as maturation and spawning, are specific to certain life stages, but these are also interconnected to the spatial growth rate potential because per capita fecundity is directly tied to the size-at-age function. In well-studied species, entrainment mortality rates can show wide ontogenetic variation. For example, mortality of entrained Dungeness crabs can vary from 5 to 85 percent over a 60-mm growth interval (Wainwright et al. 1992). On the scale of individual life stages, mechanical and physiological effects of entrainment are not well known for many taxa. Conservative modeling assumptions will assume 100 percent mortality; however, the model will be configured to allow that figure to be adjusted as required. Development of the modeling package will require that the mean and standard error of all regional-specific biotic and dredge parameters relevant to these issues for the primary target species are specified (Table I1). It should be noted that it has been difficult and cost prohibitive to collect comprehensive data for a large number of taxa; thus, the modeling approach is necessary as the most tenable effort because of the flexibility of investigating population response to a range of realistic parameters as best understood by scientists and dredging project managers.

Growth: Animal growth will be modeled using a bioenergetic framework to facilitate explicit coupling with its prey-base and the physical and biological environment following Ault et al. (1998). Traditional models describe the growth of fish with respect to time as the difference between the rates of tissue synthesis (anabolism) and degeneration (catabolism). Both anabolic and catabolic rates are considered to be allometric functions of individual weight (Jobling1994). This allows age-structured growth to be written as a general conservation equation following Ault and Olson (1996):

$$\begin{aligned} dW &= [anabolism - catabolism]dt \\ &= \left[\lambda W(a,t)^m - \eta W(a,t)^n\right]dt \end{aligned} \qquad (I2)$$

where $W(a,t)$ is weight at age a and time t, and λ and η are scalar coefficients. The anabolism power coefficient, m, relates to the proportionality between gut surface area of digestion and body volume, whereas catabolism is assumed to be proportional to body volume (i.e., the von Bertalanffy model assumes $m = 2/3$ and $n = 1$). Equation I2 is in the form of the Chapman-Richards generalized growth equation (Gulland 1983), a form fundamental to many traditional fishery stock production models (Schaefer 1954; Beverton and Holt 1957; Pella and Tomlinson 1969; Fox 1975; Ault and Olson 1996). Dividing Equation I2 by $W(a,t)$ produces the weight-specific growth rate and equivalency between the Chapman-Richards equation and the bioenergetic modeling framework (Kitchell, Stewart, and Weininger 1977; Jobling 1994; Houde 1996):

$$\frac{1}{W(a,t)} \cdot \frac{dW(a,t)}{dt} = \lambda W(a,t)^{m-1} - \eta W(a,t)^{n-1} = (C - E - U) - R \qquad (I3)$$

where C is consumption, E is egestion, U is excretion, and R is respiration or total metabolic costs. The consumption term is configured to contain prey-dependence. As such, Equation I3 captures fundamental individual growth principles into an ensemble population weight equation, thus providing a coherent means to link animal growth, survivorship, recruitment, and spatial movement into a robust population dynamics system of equations (Ault et al. 1998).

Mortality and Survivorship: The population model should be designed to encompass the range of trophodynamic interactions relevant to the scope of dredging activities. We link natural mortality to metabolic growth and current status as compared to an optimal metabolic state which in turn links to recruitment via fecundity at age. Thus, population size depends on metabolic (weight) status through both mortality and reproduction. The conservation law for the population that formalizes this connection follows Ault and Olson (1996):

$$dN(a,t)=\frac{\partial N(a,t)}{\partial a}da+\frac{\partial N(a,t)}{\partial t}dt=-Z(a,t)N(a,t)dt \tag{I4}$$

where $N(a,t)$ represents cohort abundance for individuals aged a at time t, and $Z(a,t)$ is the instantaneous rate of total mortality. Animal mortality is driven by two variables: population abundance (uncontrolled) and water/sediment volume dredged (controlled) following Wainwright et al. (1992). The dredge entrainment mortality impact model derives from the basic mortality model (Baranov 1918; Ricker 1954a,b; Beverton and Holt 1957):

$$N(a,t)=N(a,0)e^{-Z(a,t)} \tag{I5}$$

Total mortality, Z, is usually thought to be comprised of both fishing, F, and natural, M, mortalities (i.e., $Z = F + M$). Fishing mortality is anthropogenically forced and is normally modeled as $F = q{\cdot}f{\cdot}s$, where f is nominal fishing effort, s is selectivity, and q is the catchability coefficient. Natural mortality M includes all population- and community-forced mortality (e.g., predation, starvation, cannibalism, disease, etc.). The abundance equations are coupled to the metabolic growth equations through the instantaneous total mortality rate $Z(a,t)$, which is the sum of time-dependent natural mortality $M(a,t)$, fishing mortality $F(a,t)$, and dredge entrainment mortality $D(a,t)$. Natural mortality is computed as the base nominal rate $\tilde{M}(a,t)$ modulated by current size-at-age relative to an optimum:

$$M(a,t)=\tilde{M}(a,t)\left\{1-\delta\left[\frac{W(a,t)-W^{o}(a)}{W^{o}(a)}\right]\right\} \tag{I6}$$

$W^{o}(a)$ is the a-th cohort's optimal weight when resources are not limited, and δ is a metabolism-dependent death rate coefficient that indicates suboptimal growth equates with higher natural mortality. The form of the natural mortality Equation I6 reflects the degree of metabolic stress a cohort endures, implying larger fish at a given age are, on average, less susceptible to the forces of "natural" mortality.

It is relatively simple to show that the effects of mortality are "intrinsically linear" so that dredging mortality, or the mortality associated with entrainment, is an additive linear component of total mortality:

$$Z(a,t)=M(a,t)+F(a,t)+D(a,t) \tag{I7}$$

where D is the instantaneous rate of entrainment mortality. The additive rates of mortality can be thought of as competing risks of mortality, where the individual forces are competing for the life of the animal. The entrainment process has two phases which may result in mortality of animals that encounter the intake flow fields: (a) probability of entrainment by the dredge gear, and

(b) probability that animals at size L die, given they encounter the gear. These probabilities are heavily dependent on the mean and probability distributions associated with the quantity and areal extent of nominal dredge effort, the availability of the life stages to the gears, and the selectivity of the gears relative to the various life stages. Using this framework, the instantaneous rate of entrainment mortality can be computed as:

$$D(a,t) = f_d \cdot q(a) \cdot s(a,t) \cdot a(a,t) \tag{I8}$$

where f_d is nominal dredge effort; q is the catchability coefficient or the fraction of the unit stock affected per unit of nominal dredge effort; $s(a,t)$ is selectivity at age a and time t; $a(a,t)$ is the availability to the dredge gear. It is assumed that the selectivity will affect the various life stages differentially and is a fraction that ranges from zero to one (Figure 3). The availability to the gear will depend upon the local mobility and escape ability of the affected species. This makes it possible to rewrite the rate of change of population abundance as:

$$\frac{dN}{dt} = -Z(a,t)N(a,t) = -\left[M(a,t) + F(a,t) + D(a,t)\right]N(a,t) \tag{I9}$$

Conceptually, it is relatively simple to characterize key ontogenetic life stages (larvae, juveniles, and adults). Larvae (including eggs) are restricted to the planktonic phase of life. Juveniles are those recruited animals up to the age of first reproductive maturity. Adults are the mature segment of the stock (Figure 2). The entrainment process will affect the continuous age distribution of the stock in a differential manner which will be assessed through analysis of existing empirical data specific to the population or populations of focus (Figure 3).

Reproduction: The "recruitment" boundary condition at age $N(a=0,t)$ is the birth or population growth term. The actual number of newborn $R(0,t)$ is computed "annually" by summing birth rate per age/size group over the number of mature females for all ages such that:

$$R(0,t) = N(0,t) = \sum_{j=L_m}^{L_\lambda} \beta\left[f\left(W_j|a,t\right)\right] \cdot \theta\left(L|a,t\right) \cdot N\left(L|a,t\right) \tag{I10}$$

L_m is length of first maturity, and birth rates or fecundity β are assumed to be a function of cohort weight dependent on age, female population fraction θ at age, and cohort abundance N at age/size. In practice, empirical estimates of stock spawning biomass and egg production are typically functions of individual size, fecundity, age of maturity, and the age distribution of the population as modified by individual nutritional status and population density. The choice of the recruitment function greatly influences the resultant population dynamics variability over time.

Indicator Variables: A stock assessment indicator variable is a quantitative measure that reflects the status of a population subjected to fishing or other environmental changes (Ault, Bohnsack, and Meester 1998). Because fishes integrate aspects of the coastal ocean environment over their lifetime, a robust measure of population "health" or status can provide a sensitive indicator of direct and indirect stress on the stock, and perhaps on the regional marine ecosystem (Fausch et al. 1990).

FISHFATE will be configured to assess at least two fishery management decision-making end-points, yield-per-recruit (YPR) and spawning potential ratio (SPR). Fishery management endpoints are relatively robust measures of potential yields and recruitment. As such, they help to focus on the biological (size) and fishing (intensity) controls for managing current and future fishery production. Because biomass *B(a,t)* is the product of numbers-at-age multiplied by weight-at-age from the size of first capture L' to the maximum size in the stock L_λ, yield in weight Y_w from a given species is calculated as:

$$Y_w(F, L', t) = F_f(t) \int_{L'}^{L_\lambda} B(L|a,t)\,dL = F_f(t) \int_{L'}^{L_\lambda} N(L|a,t) \cdot W(L|a,t)\,dL \tag{I11}$$

YPR is then calculated by scaling yield to average recruitment from the right-hand side of the above equation. Spawning stock biomass (SSB) is a measure of the stock's reproductive potential or capacity to produce offspring, ultimately realized at the population level as successful cohorts or year classes which reflect population resiliency and stability. Spawning stock biomass is obtained by integrating over individuals between the minimum size of first maturity, L_m, and maximum reproductive size (here assumed to be the maximum size L_λ) in the stock:

$$SSB(t) = \int_{L_m}^{L_\lambda} B(L|a,t)\,dL \tag{I12}$$

Spawning potential ratio (SPR) is a management endpoint that measures a stock's potential capacity to produce optimum yields on a sustainable basis. SPR is a fraction expressed as the ratio of exploited spawning stock biomass in relation to the equilibrium unexploited SSB:

$$SPR = \frac{SSB_{exploited}}{SSB_{unexploited}} \tag{I13}$$

SPR estimates are compared to the U.S. Federal standards which currently define 30 percent SPR as the "overfishing" threshold. In these analyses it is reasonable to ask what changes in the YPR and the maximum sustainable yield proxies (catch-per-unit-effort, population size or biomass, average length, average weight, and spawning potential ratio) can be expected by changing size of first capture L' and fishing mortality F. What pattern of dredging and fishing will produce the greatest yield to the fishery and the fewest impacts? What is the probability that the change will actually occur? What is the probability that the change can be detected? The objective of these analyses is to balance growth and mortality to maximize yields and, as a result, provide advice on the optimum level of biomass that maximizes stock productivity while at the same time minimizes the probability of a recruitment failure.

Density-Dependent and Spatial Population Effects: Density-dependent effects may be incorporated into the model in the areas of growth, mortality, and fecundity:

$$\frac{dN}{dt} = b(N)N - d(N)N + I(N)N - E(N)N \tag{114}$$

where *b(N)* is the per capita birth rate, *d(N)* is the death rate, *I(N)* is the immigration rate, and *E(N)* is the emigration rate. Most traditional models assume the effects of emigration and immigration are equivalent and thus cancel each other out, having no net effect on the population or its dynamics; so, inclusion of these terms can account for fluxes in stock biomass.

Another important role for visualization is the ability to track the evolution of the coupled system through time and space to see how and why the system evolves to a given endpoint. The time scales for redistribution of populations range from tidal cycles and diel cycles through to seasonal, annual, and multiyear cycles. In a spatially structured context, the model could incorporate the spatial dynamic multistock production model form of Ault et al. (1998):

$$\frac{dN_1(a,t,x)}{dt} = f\left[N_1, N_2\right] + \frac{\partial}{\partial x}\left(\chi N_1 \frac{\partial \lambda}{\partial x}\right) + \frac{\partial}{\partial x}\left(D_{N_1} \frac{\partial N_1}{\partial x}\right) \tag{115}$$

where N_1 is the predator population, N_2 is the prey population, χ is a taxis coefficient, $\partial\lambda/\partial x$ is the detected environmental gradient, D_{N_1} is a coefficient of population diffusion, and *a*, *t*, and *x* are dimensions in age, time, and space, respectively. Equation 115 reflects three forces of population change per unit time: (a) the net population dynamics-community relationship, (b) directed movement (or taxis) along an environmental gradient, and (c) undirected random movement of the population. As such, it provides a basis of formal bioenergetic linkages to the environment and prey populations in dimensions of both space and time. The proposed framework allows a logical and concise extension of the nonspatial population model to a spatially explicit context. It is also suitable for making formal linkages to hydrodynamic and, ultimately, fate-and-transport models to assess the full range of impacts associated with dredge operations and their relationship to the concept of environmental windows.