CALFED Bay-Delta Program Environmental Water Account
Summary of the Annual Delta Smelt Technical Workshop, Santa Cruz, CA, August 18-19, 2003

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Introduction

Technical workshops are held annually to assess and advance the state of science used in support of the CALFED Environmental Water Account (EWA). This report describes the third such workshop held to examine the status of knowledge of delta smelt, a threatened fish species that is one of the targets of EWA operations.

This year's workshop differed in format and participation from previous workshops (e.g., see Brown and Kimmerer 2001, 2002). In contrast to the usual practice of combining presentations with discussions on key issues, we organized this workshop around the development of several models of delta smelt biology, and in particular focused on an individual-based simulation model. The idea behind this approach was twofold: to force a systematic look at the key issues in the life history of this fish; and to develop a model that might prove a useful tool for investigating EWA actions and other influences on delta smelt. Thus, this workshop focused on the long term, in that model development and use will occur over the next several years.

The workshop also capitalized on the nearly simultaneous release of a draft review paper[1] on delta smelt biology written by Dr. Bill Bennett of the Bodega Marine Laboratory. Although the paper could not be made available in time for review by workshop participants, much of the information in the paper had already been discussed in previous forums, so the content of the paper provided a useful starting point for the discussion in the workshop.

This summary focuses not on the chronology of the discussion at the workshop, but on the key issues relevant to modeling, and on the outcomes. We describe the state and content of the various models, with an emphasis on future model development and use. We also discuss several aspects of delta smelt biology addressed at the workshop, with an emphasis on points of disagreement and potential mechanisms for resolution.

Key points of agreement in the workshop were:

1. Knowledge of delta smelt biology is sufficient for modeling purposes, and would benefit by the organization that a model brings to bear.
2. It is worthwhile to proceed to develop all of the models discussed here.
3. It would be impossible to evaluate the population-level effects of EWA without some sort of model at the population level.
4. The workshop was successful in making progress toward a common

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[1] This paper is one of several "white papers" commissioned originally by the CALFED Ecosystem Restoration Program, and recently re-energized by the Science Program, to describe the state of science in a number of key areas. Each of these papers can be more accurately described as a review paper, containing the analyses and opinions of its authors, rather than a "white paper", which is defined as a statement of government policy. See http://science.calwater.ca.gov/white_papers.shtml

understanding of delta smelt biology.

5. Valuable information is becoming available from the culture studies, but needs to be reported to maximize its utility.
6. The participants would continue to work as a team.

Key points where workshop participants did not agree, or agreed that the knowledge is incomplete or inconsistent.

1. The degree and importance of density dependence.
2. The importance of 2-year-old fish to population dynamics and persistence.
3. The nature of the relationship of delta smelt abundance to flow/X_2

Participants included members of the academic, regulatory, and stakeholder communities. Key participants included Dr. Kenny Rose and Dr. Jim Cowan, both of Louisiana State University, and both on the EWA Review Panel. Rose led the discussion of the modeling approaches, and is developing the first version of the individual-based model. The Appendix lists participants in the workshop.

Background

The Environmental Water Account has been operating on the basis of reasonably complete knowledge of water flows and costs, regulations, and the number of fish salvaged at the export pumping plants. Protection of delta smelt using EWA water has taken the form of reductions in export flow at times determined using a decision tree (see Models, below) based on agency scientists' understanding of the biology and movement patterns of delta smelt. Although extensive analysis and gaming have been used to design and refine the EWA, the target of EWA actions has generally been reduction in take. To date there has been no quantitative assessment of the likely results of alternative decision trees, or of potential population-level effects of EWA actions. Both needs can be filled only through some sort of modeling.

The scientific and management community in the CALFED arena has embraced the use of conceptual models as a means of making assumptions, beliefs, and expectations explicit. However, there has been a certain amount of intertia in extending these conceptual models into simulation models, and there are two reasons why it might be opportune to do this now. First, the amount of data and knowledge on delta smelt seems sufficient to at least attempt to build simulation models; and second, we have the expertise and a limited amount of funding to get an initial modeling effort off the ground.

Because of the role of delta smelt as a focus of management, both the modeling and the presentation of analyses of delta smelt biology are subject to intense scrutiny and review. In such an environment, mistrust can arise when some parties are not informed of developments, and are not involved in decisions about what needs to be done. Therefore, a key objective of this year's workshop was to build trust among various participants and stakeholders. Such trust can develop from creating a transparent process, collaboration, and on-going communication. It is essential for the results of future analytical and modeling efforts to become part of the commonly-held conceptual model of delta smelt and, in particular, of how EWA actions may benefit delta smelt.

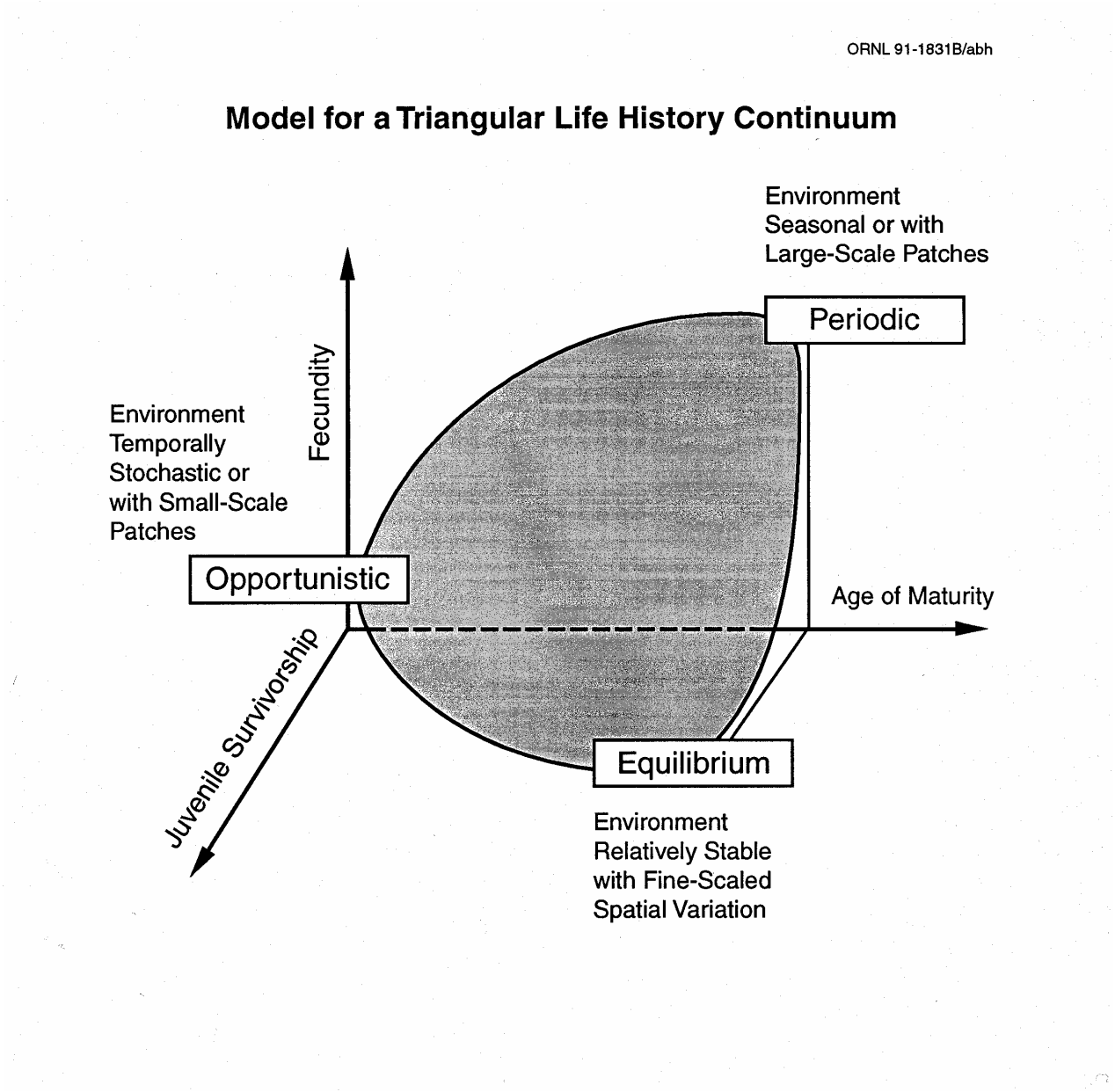

Figure 1. Model of fish life-history strategies based on demographic tradeoffs and selection in response to environmental variation. Alternative strategies are labeled according to interpretations of the environmental conditions and life-history responses. From Winemiller and Rose 1992 Fig. 6..

Life history and ecology of delta smelt

Rose described an analysis by Winemiller and Rose (1992) in which species of fish were arrayed within a triangle whose apexes defined extremes of life history in terms of fecundity, juveinle survivorship, and age at maturity (Figure 1). This is useful because if delta smelt can be placed on a particular point on this diagram, inferences can be drawn about their life history from other

species near the same point. Most of the panel members considered delta smelt to be "opportunistic" in that they mature early and have low fecundity and (presumably) low juvenile survivorship. This would be expected if their environment is unpredictable and they capitalize on favorable conditions when they occur. However, Herbold pointed out that their habitat (essentially the low-salinity zone) is always present, and except for changes in temperature their habitat is not as variable as it may appear to us. Nevertheless, the triangular ordination is based on aspects of life history which appear to be correctly applied to delta smelt, regardless how the apexes are named. .

Model of fish life-history strategies based on demographic tradeoffs and selection in response to environmental variation. Alternative strategies are labeled according to interpretations of the environmental conditions and life-history responses. From Winemiller and Rose 1992 Fig. 6.

Most of the material on delta smelt life history is described in the review paper (Bennett in prep.). Here we discuss only the issues that are key to the modeling, or that evoked controversy or discussion about modeling approaches.

Spawning: The spawning season is regulated by water temperature (15-20°C). Extended spawning seasons, with 60 or more days with water temperature of 15°C–20°C, may lead to enhanced year class success. This temperature relationship may have important management implications. It could help managers understand if and when delta smelt require additional conservation measures and targeted efforts (e.g., EWA or environmental water).

During wet years, the fish spawn over a wide area, including the Napa River. During dry years, they spawn mostly in the North and South Delta. DFG midwater trawl surveys over the past two years, which collect pre- and post-spawning adults, show that different spawning locations have different apparent success rates (we did not discuss how this was determined).

Bridges reported that in the laboratory the fish typically have poor egg quality in the first 2 cohorts, then excellent survival, and then poor survival in the last cohort(s). Length and maturity are correlated, but laboratory studies have seen small (16 mm) fish deposit eggs and large (80 mm) fish without ripe eggs. Late (and hence small) individuals who hatch in June catch up in size with the other earlier hatching fish, but we do not know whether or not these fish spawn or delay spawning. More data are needed to track cohorts separately and learn about their relative population contributions.

In the laboratory smelt spawned preferentially on gravel, but the substrate used in the delta is unknown and to date only one delta smelt egg has been recovered from the field. Time to hatching is a function of temperature, at 4 and 18 days at 20 and 10°C, respectively. Laboratory hatch rates were between 40-60% but are probably lower in the field. Abundant data exist about size variations in delta smelt, including length at hatch, length at first feeding, and size-dependent feeding success. At 20°C the average delta smelt hatches out at 4.6 mm.

Growth: Growth rate as size at age can be based on cultured fish or on field-collected fish

through the use of otoliths. Otoliths of cultured fish look very different from those of wild fish, suggesting that growth patterns are not very similar. Multiple approaches may be helpful to

estimate growth rates, including a bioenergetics approach. During the fall and winter, it may be possible to track lipid composition to better understand how the year class fares during lean winter conditions. The analyses of liver condition by Teh on fish collected in 1999 (in Bennett in prep.) suggests poor condition, indicative of low feeding rate, in many of the fish in spring and fall. This approach should also be able to shed light on conditions for growth.

Importance of age-2 fish: Delta smelt typically live one year, but approximately 3-4% of individuals live two years. Two-year-old fish have 3-5 times the fecundity of 1-year-old fish. These fish could be important for carrying the population over through years of poor year-class strength. However, there is no direct evidence that 2-year-old fish contribute more to spawning during years following poor recruitment than during other years.

Cohort analysis: Bennett (in prep, Figure 25) identified cohorts in the data for 1999 by back-calculating birth dates using otoliths. These results suggest that early and late cohorts were less successful than cohorts spawned in the middle of the spawning season, and that the earliest cohort was most abundant at the export salvage facilities. Cowan suggested that estuarine fish typically have the greatest population contribution from cohorts from the middle of the spawning season. Note that this appears to be consistent with information from the laboratory described above.

X_2 relationship: Several years ago Herbold (unpublished) presented an analysis of the relationship of delta smelt fall midwater trawl index to X_2 (or freshwater flow) in which abundance was only high when X_2 was in Suisun Bay (i.e., between 56 and 75 km) for a large fraction of February-June. This relationship is the implied basis for management of delta smelt using flow. The problem with the analysis is that the relationship is clearly not linear, but rather that when conditions are favorable with regard to X_2, delta smelt may be abundant or not, but they are not abundant when X_2 is unfavorable. This kind of relationship can be analyzed using regression quantiles or a corner test. (N.B. A corner test using data through 2002 does not support an X_2 effect, see Figure 2. Regression quantiles have not been applied to these data).

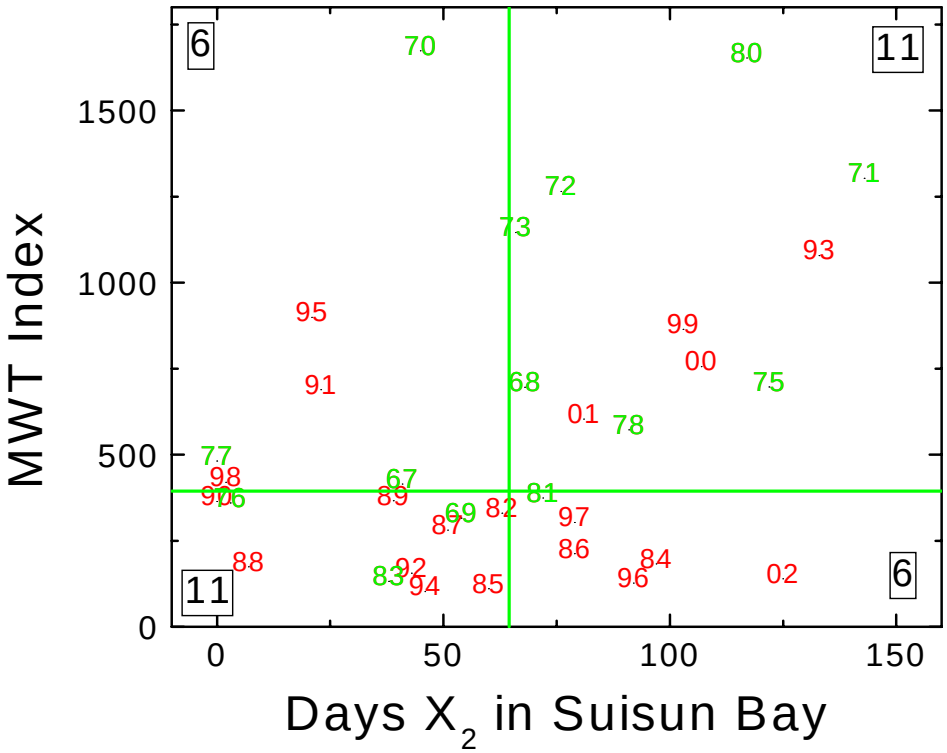

Figure 2. . Midwater trawl index vs. days in February-June when X2 is in Suisun Bay. Numbers indicate years, and lines indicate medians for each axis. The boxed numbers in the corners indicate the number of points in each quadrant. A corner test using these data gave a chi-square value of 1.88 (1 df) and p=0.17.

Population size: For several reasons population size estimates have not been readily accepted by the biological community (Herbold 1996). Kimmerer presented abundance estimates for delta smelt based on spring-summer 20-mm surveys, summer tow-net surveys, and fall mid-water trawl surveys. These estimates were based on assumptions of constant volume sampled per tow and 100% net efficiency, as assumed for striped bass (Kimmerer et al. 2000). Egg production was also estimated using mean fecundity (Figure 3). Fleming pointed out an error in the volume estimates, in that the 20mm survey and townet survey use the same technique and should have the same volume sampled, which would lower the townet abundance estimates by about 70% (this has not been corrected in Figure 3).

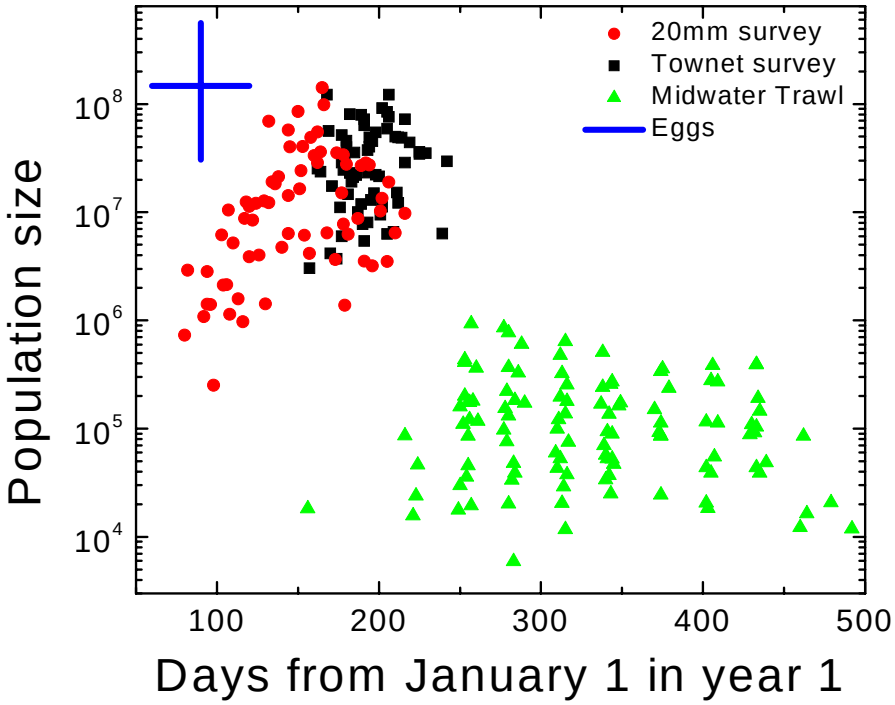

Figure 3. Abundance estimates based on three sampling surveys. For each survey abundance was calculated as the mean catch per unit volume in all samples, multiplied by the total volume in the sample area (delta and Suisun Bay). Volume filtered was estimated as 192 m3 for the 20mm and townet surveys, and 7000 m3 for the midwater trawl. Egg abundance was estimated as the mean fecundity (3200 eggs per female) times the proportion females (assumed 50%) times the abundance of adults estimated as the MWT abundance after day 365. Vertical bar for eggs represents the 10th and 90th percentiles of estimated egg abundance, and the horizontal bar the estimated spawning period.

Several inconsistencies appear in Figure 3. First, the mortality between the egg and the most abundant juvenile stage appears to be too low; in most fishes mortality decreases as the fish age (see Fig. 4 in Bennett in prep.). Second, abundance in the 20mm survey actually increases over time, which seems anomalous, although it is probably caused by increasing vulnerability of the fish to the net as they grow. Third, a sharp drop in abundance between summer and fall suggests either a huge (and unlikely) mortality event in late summer, or a gradual recruitment of fish into vulnerability to the fall midwater trawl, as noted above for the 20mm survey. This could be addressed by looking at length distributions in the same data set; if length does not change over time, probably the smaller fish are not being collected efficiently. However, there was no such discontinuity between summer and fall sampling for striped bass (Kimmerer et al. 2000).

Another approach to determining abundance was to compare abundance estimates based on net tows, as above, with those based on salvage at the export pumping facilities. The salvage estimates were made by simply assuming the salvage abundance (per unit volume) represented that in the population, so the population size could be estimated by expanding by the volume of habitat, taken to be the delta and Suisun Bay. The expectation was that the salvage estimate of population size would approach the net estimate when the population was well into the delta and therefore most vulnerable to entrainment in the export facilities. However, the salvage

estimate was nearly always much lower than the estimate from net sampling, and the ratio of the two was unrelated to X_2. This result contrasts sharply with that of a similar analysis of striped bass (Kimmerer et al. 2001), and may suggest that delta smelt are poorly sampled by the salvage facilities. (N.B. Since this applies to both facilities it is unlikely to arise through predation in Clifton Court Forebay; could it suggest that delta smelt go through the primary louvers at the fish salvage facilities?)

Density dependence: This is controversial for most fish species, particularly those affected by diversions or other mortality factors. The controversy arises because killing fish before the density-dependent life stage has little effect on abundance after density dependence has had its effect (e.g., Kimmerer et al. 2001). Density dependence must exist at some level because fish populations sustain themselves over long periods of time during changing conditions. The difficulty lies in determining when it occurs (i.e., which life stage), which processes are responsible for it (e.g., reproduction, food limitation, predator attraction), and how to quantify it. Density dependence can be episodic, varying with time, space, and environmental conditions, as well as population levels.

Density dependence in delta smelt between the summer and fall is supported by an analysis showing that a Beverton-Holt model fits the data better than a straight line, either for data in the pre-decline period or after the decline (Bennett in prep. Fig. 18). There was some discussion about whether the data were good enough to support this analysis. As with most fish, there are sources of error in the data including measurement error and process error, including variation in density-independent processes, that tend to obscure any density dependence. This does not mean it is absent, but that it is difficult to detect and to assign to a life stage.

The group agreed that this issue will not easily be resolved, and that multiple modeling approaches may be the best way to proceed. Because the delta smelt summer townet index has been low since 1983 (Fig. xx in Bennett in prep.), the fish are not likely experiencing much density dependence. Short-term model predictions (1- 3 years) without density dependence will therefore likely be reasonable at current population densities. The models can then be used to determine how small or infrequent the effect of density dependence could be and still maintain a population, in a sort of reverse engineering approach to the problem.
Mortality: The preliminary IBM framework uses mortality estimates from Bennett (in prep.). Obtaining survivorship/size-frequency distributions may offer another good approach. If the panel accepts Kimmerer's recent abundance estimates, we can back-calculate mortality rates from those abundance values. Taking the abundance values at face value, though, suggests an increasing mortality rate with age, which is contrary to expectations based on many species of fish.

In theory, we want to derive a mortality rate for each size- and year-class, based on salinity, outflow, and other environmental conditions. The challenge is to couple mortality to these physical conditions. Mortality due to predation levels off above a certain size, so constant predation mortality might be a reasonable assumption for adults. The group discussed scaling mortality curves according to turbidity under the assumption that predation was largely visual. Cech reported that experiments are ongoing at his laboratory on the influence of turbidity on visual predation. The refuge effect of turbidity has been demonstrated for other fish elsewhere. Nevertheless there was no consensus that this effect on mortality was understood well enough to be included in the model.

There was relatively little discussion of mortality due to entrainment at the water export facilities. However, it was recognized that power plants with flow-through cooling can impose significant mortality if they are close to the fish habitat. In the San Francisco Estuary we have two such plants, one at Pittsburg and one at Antioch, both well within the region of maximum abundance of delta smelt in many months.

Modeling

The first step in a modeling exercise is to identify questions we expect to answer. In the case of delta smelt, these questions arise both from a need to understand the basic biology of the species, and from a need to evaluate the effectiveness of specific management activities. The principal questions that modeling may help to answer are:

1. How does smelt abundance vary?
2. What are principal controls on abundance?
3. What is the probability of extinction?
4. How important are controlled vs. uncontrolled factors?
5. What can be done to protect delta smelt?
6. How effective is EWA for that purpose?

Although these questions were intended to stimulate and focus the modeling discussion, it is important to recognize that a model has certain limitations, no matter how sophisticated. First, a simulation model is tautological: although models can surprise even their developers, the outcome of a modeling effort represents only the combined effect of the inputs. Second, features that are not put in the model are not there; although this may seem trivial, it is a common experience for modelers to be asked about features of model behavior as if it contained relationships or functions that the modeler did not put in. Third, a model has many parameters and functions, and may therefore produce sensible output for the wrong reasons. Fourth, a model of a fish or other biological population has almost no chance of capturing all of the important sources of variability, so model behavior should be compared with the prototype only in terms of form and pattern, rather than actual numerical output.

Varieties of models discussed

Four modeling approaches discussed in the workshop are complementary in terms of their scope, resolution, time scale, and purpose. Listed by time scale from shortest to longest, these are:

1. The decision tree used to decide EWA actions, here called the "Fleming model". This is a simple model of movement of smelt in the Delta, based on expert opinion, with a mechanism by which new information can be used to refine the decision tree.
2. A particle tracking model is being used to assess the influence of export pumping in the delta, and to track the movement of early smelt larvae. This project is being funded by the Interagency Ecological Program (IEP) and is being conducted by Nobriga, Kimmerer, and Bennett.
3. An individual-based model (IBM) was the principal topic of discussion, because it is a

new model and requires considerable detailed biological information as input.

4. Matrix models can be used to evaluate probability of extinction and long-term projections of population trajectories under alternative assumptions about changes in vital rates (e.g., birth, mortality). Bennett is applying a matrix approach (in prep.).

The decision tree is not a population model and its approach lacks an evaluation of population level effects. Rather, the decision tree is a model of concern that provides biologists and operators with insight on how to manage EWA with real-time recommendations. The decision tree is a qualitative model based on assumptions of temperature limits, spawning windows, and an index of vulnerability based on proximity to export pumps. The decision tree is adequate for weekly, daily, and real-time management forecasts, whereas the IBM's strengths lie in predicting probabilistic, long-term changes. The IBM could be used to assess the consequences of alternative decision trees over a long time period (multiple years). Although the IBM has good temporal resolution it would not be an appropriate use of this model to try to evaluate short-term (weeks) consequences of applying the decision tree. Short-term responses of the delta smelt population should continue to be examined and predicted using decision trees, expert opinion, and possibly particle-tracking models. However, it is essential that these approaches continue to be informed by progress on understanding delta smelt biology, both through the use of the other models and through new research and analyses.

The particle tracking model was brought up only as an additional modeling effort, since it is already underway. However, output of the PTM will likely be useful as input to the IBM, particularly in estimating the transition probabilities between spatial boxes (see below).

The IBM was the centerpiece of the discussion. A key aspect of developing this model, which Rose mentioned on several occasions, was that most management actions would be entered in the model as changes in mortality. That is, there would not be explicit features in the model that would map directly to EWA, export flow, or other managed variables. Two reasons were given for this choice. First, this would minimize the tendency (seen in a lot of other modeling efforts) of managers and others to think of the model as the population, and infer more from the model output than is actually there. If input to the model were in the form of increased or decreased mortality, rather than, say, changes in export flow, screening, or handling practices, there would be less tendency to use the model to compare these alternative practices whose actual effects on mortality would have to be estimated. Second, the real purpose of the model is to put various sources and magnitudes of mortality in the population context; this enables the users to quickly conduct analyses that might consider, for example, estimates of changes due to EWA. In other words, given an estimate (perhaps an upper bound) of the decrease in mortality due to EWA, the model would be used to examine the population consequences.

Matrix models are a relatively simple, defensible way to explore long-term consequences of changes in population vital rates. These models are very simple in that they describe transitions between stages or ages as single numbers, i.e., survival or fecundity. Although functions (e.g., density dependence) and stochasticity can be added, the simplest versions of these models are still instructive in exploring the long-term consequences of changes in these vital rates. These models are useful for estimating probability of extinction. Required inputs include fecundity and average survival, both of which can be estimated from available data. The matrix model will help

us discover relative responses to population changes in vital rates, and is a useful approach because it does not require a lot of data or parameters. We can use this stage-based matrix modeling approach to roughly gauge EWA effects, but it is not ready for management applications.

It is important to clearly define life stages and regional boxes for the matrix approach. The model should identify a consistent way to define age because pre- and post-census can confound age and size. Rose and Bennett agreed to get together to work on assumptions, generate preliminary results, and then simulate the matrix model.

IBM design

The IBM is a widely accepted approach in which individual fish are tracked and their growth, development, fecundity, and mortality are simulated. The principal advantages of an IBM over cohort and other models are: 1) the conceptual basis for the model is clear; 2) nonlinear transformations do not distort the distribution of population parameters as they do in cohort models; and 3) conditions resulting in different trajectories for different individuals, such as through movement between regions of high and low growth rate, are accurately and easily depicted. The principal disadvantage of an IBM is the need to include aspects of individual behavior or physiology that are unknown and in some cases need to be inferred by comparing model results to the prototype at a more aggregated level.

Rose highlighted his initial efforts to code a preliminary IBM model, using data provided by Kimmerer (based on IEP monitoring) and Bennett. Although the preliminary model is coded in Fortran, there is no restriction on the language used or on the approach used to organize data input or analyze output. This modeling initiative is not limited by technical computing capabilities, but by scientific data, interpretation, and agreement on assumptions about model functions and parameters.

The model program itself is largely a bookkeeping exercise. Most of the programming effort goes into keeping track of individual model fish. Adding or changing functions controlling life history is relatively simple. The model runs as a series of nested loops, with the longest time scale the outer loop, and loops across individuals at the core (Figure 4). Different life stages can be modeled at different time scales. Generally it is neither necessary nor desirable to simulate the entire population of fish; rather, the model fish may number in the thousands, and can be seen each to represent some number of real fish.

Table 1 summarizes the choices made for model design at the workshop. Below we provide a summary of the discussion related to those choices.

Time and space scales: Selecting time and spaces scales is somewhat subjective and based on expert opinion. A daily time step is in a way easiest to model, particularly when modeling movement of fish between spatial boxes; a longer time step may distort that movement pattern. The number of spatial boxes can be set equal to the number of areas in which fish are exposed to substantially different conditions, and in which measurements are adequate to see the

difference. Thus, if two boxes in the model have the same outcomes (as far as the corresponding measurements can tell), they might as well be collapsed. (N.B.: This is not the case for a particle tracking model, which is a special case of an IBM. In that case, movement

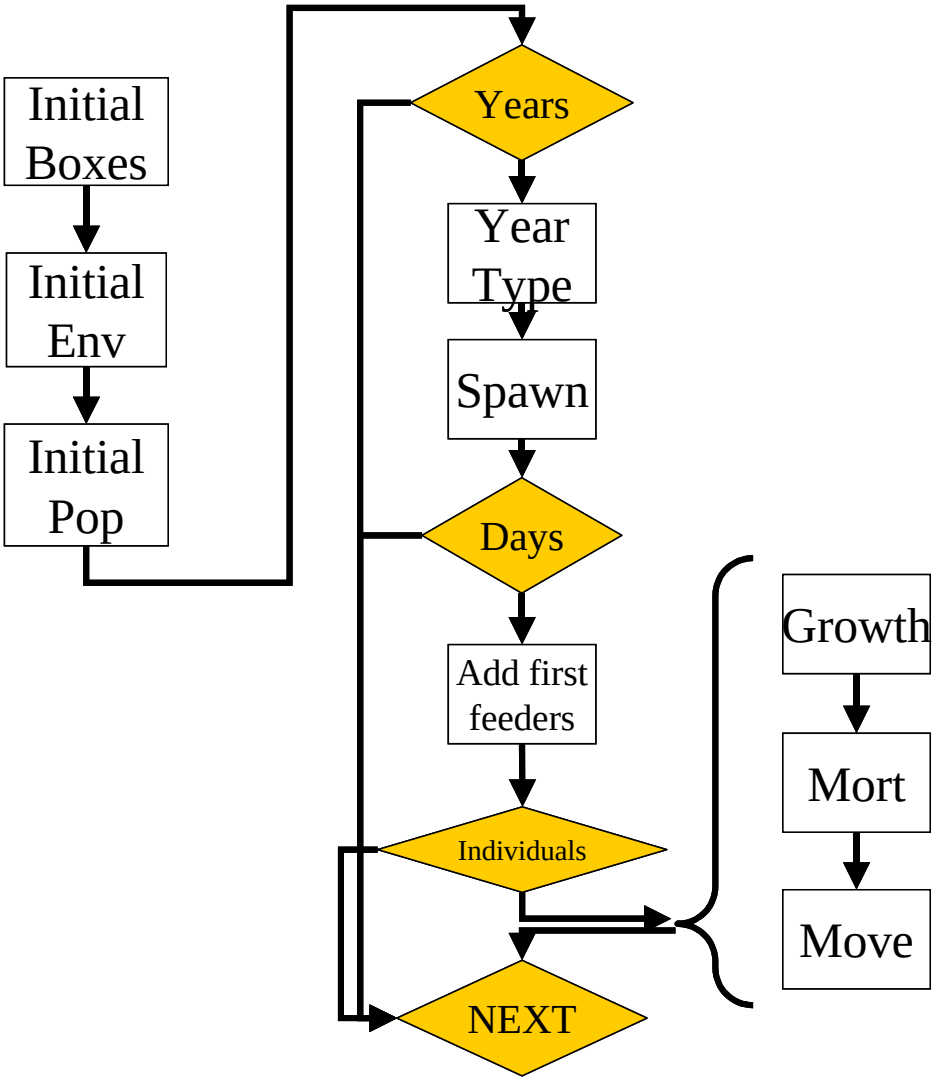

Figure 1. Flow diagram for the model. Diamond shapes indicate loops within the program.

occurs between adjacent cells in a highly detailed physical description of the system on a very short time scale. Aggregating time and space scales will result in numerical diffusion of particles, distorting the movement patterns).

The five boxes (Table 1, Figure 5) were selected to represent fundamentally different locations with regard to expected vital rates of delta smelt. The number of boxes can be changed as data become available that suggest differences. The two delta boxes represent spawning and early rearing habitat, but in the southern delta box only, the fish are exposed to additional mortality

risk due to entrainment in export pumping facilities. The northern border of the south delta box was placed just north of the San Joaquin River west as far as Big Break (See Figure 5), because the area around the confluence of the two rivers was not considered to have much exposure to the pumps.

Suisun Bay is divided into a north and south region too, because field observations have shown that the habitat in the northern part of the bay is substantially more favorable for young fish than that in the southern part (Bennett et al. 2002).

The group decided against dynamic boundaries for the boxes, mainly because that could result in the boxes becoming too small and the fish being too dense within the smaller boxes. Instead, conditions in the boxes will be determined from the response of those conditions to changing flow. For example, there are known relationships of flow to salinity at certain stations, and these can be used to determine conditions within the box. This may change growth and mortality parameters for the fish. Given the high quality of zooplankton abundance and distribution data, the group suggested cross-referencing zooplankton information with assumed salinity ranges. The group agreed to add food responses and zooplankton availability as a parameter check, but Rose warned that food can be tricky. (N.B. Functional responses of planktivorous fish are not well known and depend on environmental conditions including species composition of prey, so feeding rates cannot be predicted from food concentration.)

Environmental conditions: There was some discussion about whether to use historical flow conditions or synthetic sequences of high- and low-flow periods. The final decision was to use the latter for flexibility, but the time periods should be months rather than years. Temperature will be daily values for the same time periods as selected for flow (is that right?), and salinity will be calculated from flow.

Movement between boxes is governed by probabilities which can depend on environmental conditions. In the model, movement is determined by drawing a random number from a uniform distribution; if the random number is less than the probability of movement, the fish moves. The trick is to determine the probability that a fish in one box will move to another, which is one of the more difficult tasks for the larger fish.

Yolk-sac larvae probably move with the water, so the particle tracking model can be used to estimate the probability of movement. However, the location of the eggs is unknown, and therefore the initial position of the newly hatched larvae must be inferred from the distribution of larvae in the field, or spawning and post-spawning adults. Unfortunately there is no sampling at the moment that determines the distribution of early smelt larvae. (N.B. The zooplankton monitoring program samples for mysids with a 505 μm mesh net and should collect fish larvae; although they have not been counted they should be in the samples, which we believe are retained).

As the fish grow they become increasingly competent at maintaining position and less likely to go with the flow. Movement patterns are affected by the distributions of salinity and temperature. The model will deal with these by size class:

5-15mm larvae: The group did not identify a way to distinguish the movement of these fish from earlier or later larvae.

15-25mm post-larvae: After delta smelt develop their swim bladder (approx. 15-20 mm), they can stay remarkably well in one location. Movement is largely correlated with temperature. During a wet year, delta smelt larger than 15 mm are broadly distributed, but in low-flow years the fish are confined to a small region, usually in the lower Sacramento River. The available data on these fish, from the 20mm survey, need to be examined to develop a description of these movement patterns for use in the model.

Juveniles: Forty years of bi-weekly and monthly summer/fall distribution data exist, allowing for a good description of distribution under different flow conditions. Rose will develop the distribution probabilities to approximately match real-data patterns.

Spawning adults: The model can ignore post-spawning migration because most fish die soon after spawning. The model currently assumes that 95% of the population dies, and 5% magically appears post-spawning in Suisun Bay. The group agreed that this approach to completing the modeling life cycle captures the desired parameters, even if it does not accurately reflect reality.

The group agreed that Fleming, Nobriga, or others would review historical data to identify ways to categorize years to produce a limited number of movement categories relevant to delta smelt, based on actual data and different flow scenarios. The preferred approach is to categorize all of this historical data and develop parameters to enter into the model. If modeled movement still seems inaccurate, the group can back-track and re-visit assumptions.

Spawning: The IBM currently assumes that during low-flow years, each female probabilistically deposits 90% of her eggs in the North Delta and 10% in the South Delta. During a wet year, eggs are evenly distributed among three boxes (33% each). The model assumes that 60% of the eggs are deposited on one spawning day, with the other 40% appearing 2-weeks later. Potential triggers for spawning include day, temperature, outflow, salinity range, and lunar cycles. Temperature will have a cutoff value to stop spawning above ~18-20°C. Size-frequency distributions for spent fish from the spring midwater trawl can be combined with length-fecundity relationships to estimate eggs produced.

The initial model does not include variability in fertilization success, and egg development is modeled for each day based on the temperature for that day, with no memory of previous days (other than the extent of development to date).

Mortality: Initially the model will be simple, with box-specific mortality parameters related to operations. Additional complexity can always be added to mortality or growth functions, but we want to use only solid data because these modifications can can have substantial effects on model results. The group discussed major mortality assumptions and agreed that, although delta smelt grow based on different conditions in different parts of the system, the model will assume that they die at the same rate (except for diversions, operations). In other words, predation pressures are the same in each box.

Density dependence: This will be modeled as an input parameter that the user can vary from none to an extremely high amount. Carrying capacity could be bounded by the pre- and post-decline high abundances, assuming there was a downward shift in carrying capacity. In addition, density dependence could be in the model as a conditional or episodic factor.

Testing the model: The model should first re-generate patterns in various indices, starting with the relationship between X_2 and the fall midwater trawl index (but see above on this topic). Second, it could output expected salvage and compare that with actual salvage, which should be higher in dry years and lower in wet years (see above on this too). There should be a rough proportionality within years between abundance of life stages (at the appropriate time) and salvage of those life stages. Third, the distribution of post-larvae, either in or out of the delta, could be used as a testing parameter. Fourth, the relationships between successive life stages could be explored. Finally, the abundance estimates presented above could be used to constrain the model output.

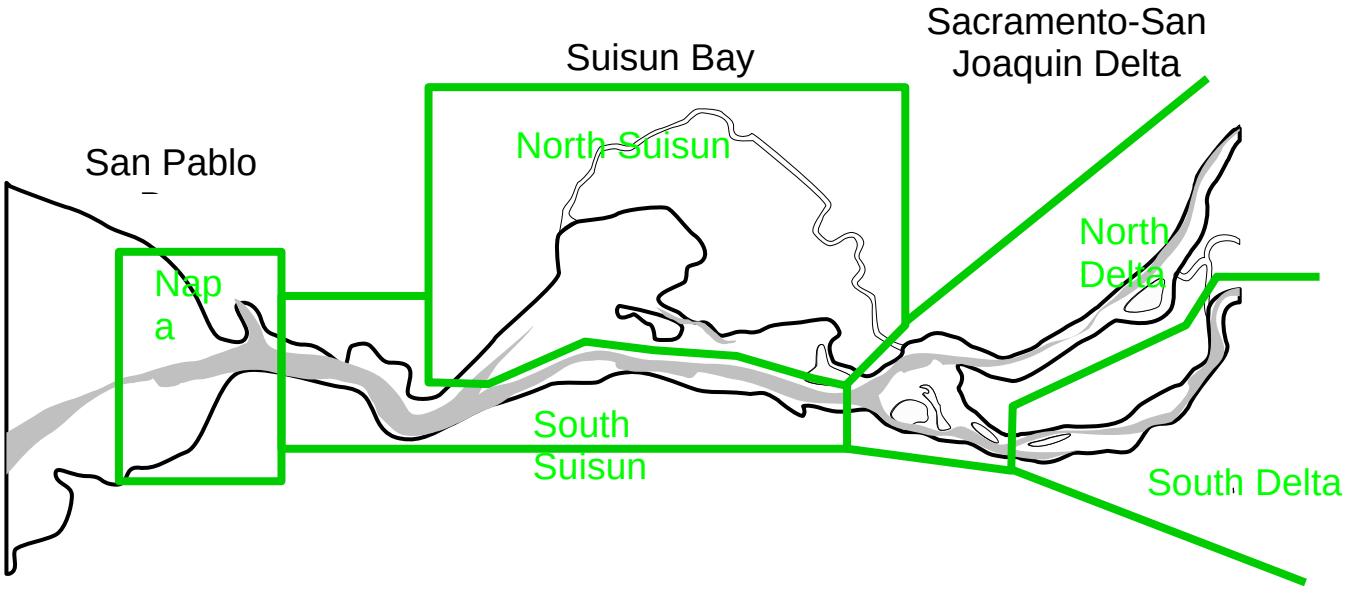

Figure 5. Map of Suisun Bay and the western Delta showing boundaries of spatial boxes used in the model.

Next steps

The principal issues to be addressed in coming months are: 1) what the group agreed on; 2) what to do in the next 5-7 months; and 3) what to do in the longer term. The group did not really address the latter, so we have taken some liberties and anticipate, and welcome, comments on our suggestions for the longer term. To accomplish this work it will be necessary to form a project work team, which has been initiated by setting up a reflector at smelt@water.ca.gov. This

reflector is open to anybody who is interested; contact either of the authors to be added to the reflector.

Agreements: Four different modeling approaches were identified, and we agreed to pursue all of them:

1. The “Fleming model”, or decision tree used to operate EWA for delta smelt, will continue to be revised, refined, and tested.
2. The particle tracking model is being used by Nobriga, Kimmerer, and Bennett to investigate how flow patterns in the delta may influence movement of early larval stages of the smelt. Funding is from IEP and this will continue through next year.
3. Matrix models presented by Bennett should be continued.
4. The individual-based model presented by Rose will be developed further and its utility tested.

Next steps: Most of the items identified as next steps do not require additional funding, although a few of them may be helped by some funds. These were the things we agreed should be done by about the end of 2003 to March 2004. I have taken some liberties here, flagged below. The next steps include modeling activities, data analysis, and research, some of which will require additional funding.

1. Matrix model: complete some initial analyses (Bennett with some help from Rose)
2. IBM: develop initial working model (Rose)
3. PTM: continue developing map of probabilities based on flow/export scenarios (Kimmerer, Nobriga)
4. Data analysis: BJ Miller offered a data analyst at no cost to the project. However, it was/is not clear what analyses could simply be turned over to an individual, and we did not go down the list of potentially useful analyses.
5. Develop field research plan and proposal to Science Program (Bennett and others). Although we talked a lot about what field research might be needed, we did not come close to developing a research plan. This is usually best done in the context of a proposal since it focuses attention on what needs to be done, why, and when.
6. A substantial amount of very useful data is being developed by Bradd Bridges and his colleagues at the UC Davis culture facility. This information needs to be provided in the form of papers or in some other way be made directly available to the rest of the research community. We did not discuss details of this, but some of this information was summarized by Brown and Kimmerer (2002).
7. Analyze year types. BJ Miller offered to do this and has done so, and his draft is in Appendix II.

Future steps: We discussed in general terms what might be a suitable course of action once the above steps have been taken. In particular, what progress needs to be made with the modeling, and how can we do it? These are my impressions based on our discussions but also on subsequent thoughts. Some of these ideas will need to be developed as part of the proposal.

1. Continue to develop matrix models. This could be done in the context of the proposal described above.
2. Continue to develop the IBM. After initial development it is unrealistic to expect this to happen without further funding. One way to do this would be to fund a 2-year post-doc position with some funding provided to Rose as advisor.
3. Continue with PTM and decision tree model; this will continue at least through 2004 (PTM) or as long as the EWA is in existence (decision tree). No additional funding needed unless extensions to these efforts are needed.
4. Get a better handle on spawning and on distribution and abundance of yolk-sac larvae. This will require an additional research or monitoring effort.
5. Institute a field sampling program to get delta smelt for analyses requiring specific handling, e.g., otolith and histopathology. DFG biologists indicated that sampling to obtain delta smelt for these purposes is incompatible with the 20mm survey, mainly because of workload. To prevent jeopardizing either set of samples, a separate sampling program is required, perhaps using IEP boats and personnel. For this program to succeed, DFG must commit to notifying the sampling team as soon as they learn that delta smelt are abundant.
6. Broaden the scope of the analysis of individual fish, particularly of otoliths, to include different age classes sampled at different locations and times, and during different hydrologic conditions. We did not discuss whether to continue with the analysis of histopathology and DNA markers. A talk at the subsequent AFS conference by Kathy Kuivila showed that abundance of delta smelt overlaps substantially with high concentrations of pesticides and herbicides. Although these concentrations were not individually high enough to cause acute mortality, the suggestion from this and the DNA work of Susan Anderson was that there are enough indications of toxic problems that this should at least continue to be monitored at some level.

Ultimately, the activities described here could be seen as part of a research program on delta smelt, in which modeling, analysis, and research would be tightly linked and each would inform the others. The small size of the research community concerned with delta smelt means that this is possible. The importance of this fish to management means that the scientific activities need to be as efficient as possible, and this seems like the way to do it.

Since there is such close attention to the biology and management of this fish, this research will continue to be conducted under intense scrutiny. Under these conditions, there is a need to balance demands on the research community for answers to specific questions and participation in workshops and symposia, against the need for time (both calendar and clock) to do the work necessary to make progress. The final answer to optimal management of delta smelt will never be available - rather, over time we should anticipate that the answers the research community is able to provide will be increasingly reliable. This indicates a need to educate managers about what this kind of work takes and why additional research will probably always be useful.

Several offers were made of small amounts of funding to help this process along. This is very encouraging, but we did not discuss what this would be used for. These sources of funding would probably best be used for specific analyses or model development leading to a specific

product. On the other hand, some of the larger-scale activities will require more funds than are likely to come from these sources, and Science Program representatives stated that this initiative has strong Program support, but could not commit to any funding. There was a suggestion that matching funds could be developed, or that gap funding could be provided from the various alternative sources.

The research program was estimated to cost on the order of a million dollars, based on previous experience. A postdoc for 2 years would cost about $180,000, based on our experience with IEP. It might be helpful, therefore, to begin to identify the kinds of projects that could be supported by more modest sources of funding, but still contribute to the overall goal of better understanding delta smelt biology and management.

Table 1: Initial design parameters for the Individual-Based Model	
Temporal Scale	- Daily time step - March 1 to February 28 - Can simulate one year to 100 years
Spatial Scale	- Entire Bay-Delta system area of estuarine habitat used by delta smelt - Five fixed (not dynamic) boxes: (1) South Delta (2) North Delta (3) South Suisun Bay (4) North Suisun Bay (5) Napa River
Biological individuals and populations	- All individuals are created equal - Fecundity (size on March 1 determines maturity, size, fecundity, etc.)
Environment	- Two flow types (low- and high-outflow months); synthetic years from sequences of these - Daily water temperature and salinity - Volume in the spatial box (read in but not used yet. Because delta smelt inhabit the top surface layer of water, we may want to change this total water volume parameter to reflect only the top-layer environment of the water column)
Bookkeeping	- Follow egg cohorts of each female - Sample model individuals from aggregated first feeders from each day and box - Follow "super individuals" - Allows us to follow a fixed number of model individuals - Track fish movement between boxes
Initial Conditions	- Begin with spawning - All females on March 1 to determine number of first feeders each day - 1 to 1 sex ratio - Maturity - Temperature (should be a factor, but ignored in the current, simplified version) - Fecundity is a function of length - 60% eggs on day of spawning and 40% 2 weeks later (same box) - During low-flow periods: 90% North Delta 10% South Delta - During high-flow periods: 33% in each box location - Development: Larvae (5-15 mm), post larvae (15-25 mm), YOY juveniles (25 mm to age 1), adults (1, 2, 3, and maturity) - Feeding stages/growth (bioenergetics, prey encounter, etc.) - Specify growth rate (GR, mm/day) - GR depends on life stage, geographic box, year type (high/low flow) - educated guesses - Variation of GR is normally distributed - Instantaneous mortality rates as opposed to finite mortality rates - Movement is difficult to model, but multiple approaches exist (e.g., particle tracking models, tagging studies, stable isotopes data). - Simple 4-dimensional relationships with a probability of moving each day (high/low). Five probabilities exist (move to each of the other four boxes or stay in original box.

	- Model movement assumptions use 5x5 matrices, calculated each day, for each life-stage, for each year-class. - Density dependence entered by choice of the user

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Appendix I: List of Participants
(Partial draft - need to be completed

Russ Bellmer, USFWS
Bill Bennett, UC Davis
Bradd Bridges, UC Davis
Randy Brown, CALFED Science Program
Joe Cech, UC Davis
Pat Coulston, CDFG
Jim Cowan, LSU
Kevin Fleming, CDFG
Bruce Herbold, USEPA
Zach Hymanson, CALFED Science Program
Wim Kimmerer, Romberg Tiburon Center, SFSU
Rhonda Lucas, California Farm Bureau Federation (?)
BJ Miller, State Water Contractors
Joe Miyamoto, EBMUD
Matt Nobriga, DWR
Ryan Olah, USFWS
Victoria Poage, USFWS
Kenny Rose, LSU
Rick Sitts, MWD
Kane Totzke, Kern County Water District

Appendix II

(Ref Excel file: BJ Miller Delta Smelt Water Years.XLS)
DRAFT
CATEGORIZING WATER YEARS FOR THE DELTA SMELT MODELS
September 8, 2003

As you may recall, at the conclusion of the delta smelt modeling workshop I volunteered to assemble, with the help of others, some of the data needed to develop the two models for delta smelt. This represents the first installment, the categories of water years.

I attempted to produce about 10 categories, following suggestions made at the workshop.

There are a number of ways to categorize. This is only one. Perhaps this will inspire others to come up with different ways to categorize. Please do not hesitate to comment.

I measured water year types using Delta inflow because inflow seemed to be of the most practical significance to Delta smelt. I used total Delta inflow rather than segregating it into particular river inflows because such segregation would produce too many categories. I segregated the annual flows into monthly flows to get some idea of patterns during the year. I used real years instead of making up inflows so that, if we wanted weekly or even daily flows, we would have them from historical records.

I eliminated years before 1970 for two reasons: Oroville, the last major reservoir, was built in the late 1960s, and the delta smelt FMWT data only go back to 1969.

I ordered those years by total annual inflow and looked for groupings. I found four, of average annual inflows of about 10,000 cfs, 20,000 cfs, 40,000 cfs, and 60,000 cfs. I eliminated 1977 and 1983 as unlikely extremes. To avoid confusion with other wet and dry year classifications, I labeled the four groups A through D, with D being the group with lowest inflow.

I graphed all the years in each group and looked for patterns that might be relevant to delta smelt. I noticed three general patterns:

> “normal” years with sort of a bell-shaped curve that peaked in the winter months.
>
> “flat” years in which there was not much of a bell-shaped curve
>
> “peaked” years in which one or two months had really high flows, relative to the annual total.

I fooled around with ways to quantify those patterns and eventually came up with two statistics for each year, the ratio of October-November flows to October-March flows (“flatness”) and the ratio of the maximum month to the total annual (“sharpness”). It turns out that these two statistics correlate with the number of days that Suisun Bay and Delta water temperature is between 15 and 20 degrees. The equation is

Days (between 15-20 deg) = 98.2 – 8.93*(sharpness) – 120.4*(flatness)

with an R2 of 0.33 and p values of 0.07003(flatness) and 0.01 (sharpness).

I tried finding relationships between days between 15 and 20 degrees and other, later inflows, ones during the time temperature is in the 15 to 20 degree range, but had no luck.

Within each of the four categories of annual Delta inflow, I subcategorized years according to each year's value of sharpness and flatness, each value weighted by the above coefficient. The accompanying flatness/sharpness graphs, one for each category A through D, show the results. I designated years between flat and sharp as "major" and outlying years as "minor." There were only two D (dry) years, so I just averaged their monthly inflows.

Those of you who are musically inclined probably see where I am going with these names. Mnemonically, the 10 categories are Ab, A#, Bb, B#, Bmaj, Bmin, Cb, C#, Cmaj, and D.

I averaged monthly flows within each of these 12 categories to produce the years shown on the accompanying graphs. However, the "sharp" category presented a problem because the maximum month's inflow, whose ratio with the annual average defined "sharpness," did not occur in the same month in each of the "sharp" years. Averaging would tend to dampen out the sharpness, which was the salient characteristic of that subcategory. Therefore, I examined monthly inflow patterns in each of the "sharp" subcategories and chose a single year that had a pattern of importance to delta smelt.

The analysis and resulting graphs of monthly flows for each category is shown in the accompanying Excel workbook.

I have the following questions about these categories:

Is there another way to categorize years that better suits our purposes?

Given the way I categorized years, should some categories be eliminated or consolidated?

Does the way I categorized years lend itself to characterizing delta smelt movement, especially the downstream migration of juveniles?

Thanks in advance for your comments.

BJ
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