- ## X2 Workshop Notes

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Introduction

On March 11, 1998 the Interagency Ecological Program (IEP) and the Bay-Delta Modeling Forum sponsored a day-long workshop on X2. Held at the Contra Costa Water District (CCWD) building in Concord, the workshop was attended by approximately 100 people from the IEP and related agencies, consulting firms, and stakeholders.

X2 is defined as the distance along the main channel (usually in km) from the Golden Gate Bridge to the point where the salinity on the bottom is 2 psu. Following a series of workshops led by Jerry Schubel and described in the report Managing freshwater discharge to the San Francisco Bay/ Sacramento-San Joaquin Delta Estuary: The Scientific Basis for an Estuarine Standard [1] , X2 was proposed by the Environmental Protection Agency (EPA) as a basis for regulating freshwater inflows to San Francisco Bay. While the EPA standards were never implemented, the 1994 Bay-Delta Accord explicitly includes X2 standards [2] .

As stated in an e-mail from the workshop's organizers, the background for the workshop is as follows:

"... It [X2] is being used to manage flow conditions in the estuary on the basis of relationships between X2 and abundance or survival of a number of estuarine-dependent species. The use of X2 for this purpose has engendered a good deal of confusion, particularly regarding the distinction between the 2-psu isohaline as it represents the habitat defined by the low-salinity zone (or Entrapment Zone) of the estuary, and the position of the 2-psu isohaline as an index of overall flow conditions.

Uncertainty also exists in the bay-delta community about whether recent changes in the estuarine food web have resulted in a deterioration of some of the X2 relationships. The purpose of this workshop is to define more clearly the nature of X2 (both as a description of habitat and as an index of estuarine condition), to identify likely causes of the relationships and fruitful avenues of research to ascertain those causes, and to describe the changes that have occurred in the relationships. We will also examine some of the policy implications of the X2 standard. The output of the workshop will be a consensus document on the above issues with accompanying technical discussions of the key issues."

With this background, the objectives of the meeting were to:

1. Refine our knowledge of X2 and its hydrodynamic and biological implications.
2. Provide stakeholders with a consensus statement about the value (or lack thereof) of X2 and the relevance and biological significance of the relationships of abundance to X2.
3. Clarify points of misunderstanding or technical disagreement.
4. Build on the Estuarine Ecology Team's discussion of probable mechanisms underlying the X2 relationships.

Presentations

The workshop began with a series of talks in the morning by Wim Kimmerer, Bruce Herbold, Jon Burau, Bill Bennett, and BJ Miller. Each of these presentations is reviewed below. The morning talks were followed after lunch by a sometimes lively, free-ranging question and answer session with questions from the audience directed to a panel consisting of all of the morning speakers, except BJ Miller who was replaced by Tom Mongan.

Wim Kimmerer: X2 review: Introduction and review of X2 and the Schubel workshops

Wim began his presentation by reviewing the genesis of X2 as a possible flow standard in the Bay/Delta system. He pointed out several important features of X2:

- It is a tidally averaged variable.
- It is an open-water concept, not necessarily applicable to marshes.
- It was selected to be an index of estuarine conditions.
- It is correlated with a number of variables and effects, including changing physical/chemical processes, habitat, and abundance of organisms at all trophic levels (but not all organisms).
- To date, there has not been much success at separating the effects of inflows from those of outflow, i.e., entrainment effects are weakened when X2 is downstream in Suisun Bay rather than in the delta.

Wim reminded the audience of how X2 came to be used during the Schubel workshops, which were originally convened to discuss positioning of the postulated Entrapment Zone (EZ). After very little discussion, Jim Arthur and Doug Ball's EZ concept was rejected as a basis for standards and instead attention was focused on the low salinity habitat (around 2 psu) that was thought to characterize the EZ. Although concomitant analysis of X2-abundance relationships showed many strong relationships between X2 and abundance/productivity, the Schubel group did not recommend standards but instead suggested that it was important to maintain the natural variability of the salinity field as indicated by the "natural" (historic) variability of X2.

Bruce Herbold: X2 standard development

Bruce introduced his presentation by remarking that it was in essence a summary of several presentations he had given over the past few years discussing the EPA's rationale for their proposed X2 standards. Bruce's talk included several salient points:

- Freshwater flows are difficult to connect to fish behavior, at least in the Western Delta and Suisun Bay, because tidal motions are generally (much) stronger. However, residual flow patterns that may lead to entrainment in the pumps are directly related to freshwater flows.
- The number of days X2 was at or downstream of Chipps Island within a given water year type has generally decreased over the last 50 years. [3]
- Careful attention was given by the EPA as to how monitoring and compliance with an X2 standard should be done, i.e., the conversion of a standard requiring a sequence of monitoring stations to one using data from existing sites, as well as permitting several options for compliance (equivalent flow etc.).

- Year type, although often convenient, compresses real hydrological variability, e.g., '97 was classified as a "wet" year, yet the rain essentially stopped in January.
- X2 doesn't limit exports directly and so may not protect against entrainment, something the State Board is considering in its deliberations.

Bruce completed his presentation by noting that a triennial review of standards (and data?) is required. If we have implemented X2 standards and we continue to see declines, we will have to return to the drawing board, because the problem will not be one of habitat, but instead "something else like food limitation."

Jon Burau: Physical conditions in the low salinity zone - why flow has little direct effect during low flow

Jon's discussion of his work over the last few years on Suisun Bay and the Western Delta illustrated a blend of field observations and numerical modeling. He made the following important points:

- Contrary to a widely-held view, the Western Delta is not a river; transport there is the combined result of advection (residual currents) and dispersion mostly due to tides. The relative importance of residual flows and dispersion of course depend on flow rate.
- The density gradient that results from the longitudinal salinity gradient is important to hydrodynamics and thus to transport. The exact nature of the linkage depends on the interaction of turbulent mixing by the tides with the stratification that develops (see Monismith et al 1996 4). X2 is significant because it sets the strength of this gradient and the upstream limit of gravitational circulation.
- On a more direct level, ADCP data from Suisun Bay reveal a mean flow picture that is different from that hypothesized to maintain the ETM (Estuarine Turbidity Maximum), a better term for describing what has been known as the Entrapment Zone (this distinction was also made during the Schubel workshops). However, Jon (and Wim) prefer to refer to it as the LSZ (low-salinity zone), since: (1) the turbidity maximum isn't always found there; and (2) there is no agreement as to the location, significance, and nature of the ETM 5 . A revised picture emphasizes the importance of local topographic features like the rapid shoaling of the main channel near Benicia as well as the connection of channels to shallow high turbidity regions like Grizzly Bay.

Wim Kimmerer: Fish-X2: Update and analysis of time trends 6

Besides reviewing some background to X2-fish relations (e.g., the near co-occurrence of X2 and the abundance of Eurytemora), Wim's presentation aimed at addressing three technical issues:

The statistical significance of some X2-abundance relations has decreased in the past few years. Mysids showed the largest change, with essentially no relation between X2 and abundance after 1987. This change may reflect changes in trophic dynamics resulting from the arrival of Potamocorbula and the subsequent decline of phytoplankton blooms in Suisun Bay. In contrast, significant relationships still exist for several of the species analyzed by Jassby et al (1995), including Crangon franciscorum and longfin smelt. Wim hypothesized that lower trophic levels responded directly to Potamocorbula, and hence may no longer exhibit X2 dependence, whereas higher trophic levels still depend on X2, albeit in some cases more weakly than before Potamocorbula's establishment.

1. The use of log transforms in formulating these relationships;

Several good reasons exist for using log rather than linear relationships: the variance is more homogeneous (presumably making for more robust statistical interpretation); there is concern for populations at low abundance levels where extinction may occur; and finally, biological populations (like the stock market?) grow in multiples (i.e., logistically).

1. The formulation of statistical relations based only on the range of flow rates than can be controlled by operation of the water projects;

There is some argument as to whether or not regulations should only be based on abundance variations occurring for flows that can be controlled, perhaps because different mechanisms might function at low and high flows. Wim argued that regressions can only be used to evaluate trends and not to make predictions. Moreover, tests of two-segment fits for existing X2 abundance relations did not show substantial differences between low and high flows. In any event, since we don't yet have specific causal relations to explain any observed X2 abundance relations, prudence (and possibly limited data) dictates that we choose the simplest relations.

Wim concluded by saying that the X2-fish relations have not changed sufficiently to warrant being scrapped; nonetheless, the uncertainties point to the need to understand the basis of those relationships

Bill Bennett: Causes of the X2-Fish Abundance relationships: How does freshwater flow regulate fish populations

The tone of Bill's talk was set by the following quote with which he prefaced his talk: "...the full details of the mechanism of regulation of population density have probably never been worked out even for one species..." 7 Nonetheless, in a very general way, Bill outlined an approach to working out what regulates the population of a given organism that includes:

- Monitoring the population (catch/unit effort, abundance)
- Identifying likely mechanisms (density dependence, stock-recruitment, environmental factors)
- Developing life history tables (e.g., what life stage contributes most to mortality)
- Using observation/experimentation to develop and test hypotheses

In his talk, Bill illustrated this approach as it applies to relating fish abundance to X2. As a starting point, one must recognize that the fish species of interest in the Bay-Delta system widely differ in their life histories; thus, it is clear that "X2 represents a single indicator for many factors averaged over many scales." To emphasize this point, Bill presented a table (figure 1 in a 1997 EET report 8 on X2-abundance relations) of species and mechanisms by which X2 might influence abundance to some degree.

Discussing Bay and X2/Delta species separately, Bill briefly reviewed some possible mechanisms of importance:

- For Crangon franciscorum, starry flounder, and Pacific herring their reproductive strategies require them to transit the Golden Gate, suggesting outflow and gravitational circulation (which has been hypothesized to depend on the longitudinal density gradient and hence outflow) should be important factors. Passage across Potato Patch Shoal may be problematic 9 . However, for C. franciscorum, "many believe" that habitat space may be limiting rather than recruitment rate.
- For X2/delta fish, there appear to be two pathways for effects: habitat/trophic effects (access/extent of shallow water, food, exotics, toxics); and hydrodynamic (retention, transport, entrainment).
- For short-lived X2/delta fish effects on early life history are more likely to drive population dynamics.

Bill's discussion of particular examples of these last two points illustrated the complexities involved in connecting a single variable, X2, to abundance:

1. It has been shown that Sacramento splittail has higher year class success when the Yolo Bypass is flooded, something that coincidentally is more likely in wet years when X2 is relatively farther downstream on average.
2. Gravitational circulation (the strength of which depends on X2, and on position relative to X2) has been hypothesized to transport organisms upstream against the mean flow driven by outflow, and so allow them to remain in the ETM. Recent data taken by Bill and Wim show that larval fish and zooplankton can use vertical migration to selectively use the vertically variable tidal currents to accomplish the same end [10] .

3. Bill's dissertation research [11] showed that even after the arrival of Potamocorbula, and the subsequent low standing stocks of phytoplankton and zooplankton, captured larval and juvenile striped bass were not starving. Although there was clear evidence of substantial liver damage associated with pesticide exposure in 1988-90, a big drop in pesticide use and a concomitant drop in liver damage in 1991 did not result in higher young of the year indices. Because a single factor like X2 "can alternate in importance between and among years," it can be difficult to distinguish the effects of changes in such a factor on target populations. Nonetheless, "...because X2 can represent the influences of many of these factors, it is an extremely useful index."

Focusing on delta smelt, Bill discussed how its life cycle and the timing of different life stages might be used to test more carefully for X2 effects by looking at mortality at each life stage. For example, egg-juvenile mortality accounts for 33% of the variability in the log of the Midwater Trawl Index (MWT) whereas the MWT Index is essentially independent of juvenile-adult mortality. Egg-juvenile mortality in turn is significantly correlated with the presence of X2 upstream of Collinsville ($R2 = 0.55$), the percent of inflow diverted ($R2 = 0.39$), and with the abundance of inland silversides ($R2 = 0.20$). More detailed analysis suggests that the effects of inland silversides are separate from those of X2. While diversions and X2 position also seem to have separate effects, the fact that the two variables are related suggest that further work is needed to look at this question.

Bill finished his talk by addressing the question, "Is X2 useful?" His answer had two parts:

1. "X2 is a useful indicator of population abundance for many species. Indeed, that so many constituents of [the] estuarine food web are associated with X2 is a unique and fortunate finding (i.e., this is why Jassby et al were published in Ecol. Applications.)"
2. The "actual mechanisms vary and currently we don't know all [of the] mechanisms or how they interrelate."

BJ Miller: Policy implications of the X2 standard.

BJ introduced his presentation by posing the question, "Why is X2 important to water users?" His gave two answers:

1. X2 affects water supplies. Most of the CALFED alternatives produce little water but cost lots of money, so potential reductions in supply due to X2 regulations are of concern.
2. While water users understand the importance of X2 to environmental protection and improvement, given point 1, water users have agreed that X2 needs critical re-examination.

BJ made the following arguments in support of the view that the formulation of X2-based regulations needs to be reexamined. Firstly, after 1986 most X2-abundance relationships, except those for C. franciscorum and splittail, have broken down or weakened. Secondly, those relations could originally have been expressed in terms of delta inflow, "which could have produced requirements that did not influence export much if at all." Thirdly, X2 must meet the "adult fish test," i.e., any actions taken must be aimed at improve stocks of adult fish, rather than larval and juvenile fish alone.

Rather than use log-log [12] or log-linear plots to test for changes in X2 (or flow) abundance relations, BJ plotted several abundances as functions of X2 and of delta inflow, and argued that by simple inspection of these plots, one can conclude that [13] :

- Crangon--the relationship still looks pretty good
- longfin smelt--used to be good, not so good anymore, much lower abundance for lower X2
- delta smelt--never had one, don't have one now
- splittail--still looks good
- striped bass 38 mm--never had one, don't have one now
- striped bass year 3--never had one, don't have one now
- striped bass MWT--used to be good, not so good anymore, much lower abundance for lower X2
- striped bass survival--still a relationship, but no data past 1993.

Supporting his second point, BJ redisplayed these data using Delta inflow rather than X2 as the independent variable. This lead him to pose the question, "How much do observed relations depend on large inflows vs. small inflows?" [14] , [15]

His last point, that of adult fish, was predicated on three ideas: (1) The average person doesn't care out about larval fish, a point BJ reinforced with the entertaining image of a fisherman posing with a string of recently caught larval fish; (2) The connection between pre-adult and adult stages is not well established. Good juvenile-adult relationships are needed if we insist on focusing regulatory, research and monitoring energies on juveniles rather than adult fish; (3) "The CVPIA and other regulatory mandates call for increases in populations of adult fish."

Lastly BJ outlined a course of action that included the following:

- More workshops such as this one, including "outside experts" to help resolve the various biostatistics/fisheries issues that have been at the core of many of the X2/flow debates of recent years
- Determining for which species an "X2-like" relationship is valid (or not), as well as understanding the mechanisms that underlie that relationship (if one exists)
- Evaluating actions that could increase abundance of target species, in particular looking at both water project operational requirements and ecosystem improvements like requirements for flooded vegetation.

He concluded by stating that linked actions for ecosystem improvement are not possible with "surrogate requirements such as X2."

Panel Discussion

Following lunch, a panel consisting of the above speakers, with Tom Mongan substituting for BJ Miller, responded to a series of question posed by the audience. The principal issues that arose were:

1. X2 could serve as an example of "adaptive management" in the sense that CALFED uses the phrase to mean adjusting regulations in response to observed changes in the system (or the lack thereof). Among other things, this requires that we continue to track X2-fish relations (WK 16), and perhaps most importantly, that we recognize that X2 is an index of a variety of mechanisms affecting a variety of species (BH), something that may be taken to be the main point made in Jassby et al (1995). However, using an index like X2 will not necessarily be as efficient for single species like delta smelt or winter run salmon for which more specific actions like particular detailed regulations on pumping might be more efficient (BH).
2. The challenge of using X2 to help manage the flow is complicated due to continuing changes in the estuary like variations in contaminant distributions, or invasions by introduced species, particularly, P. amurensis. Taking this to one limiting view, one can argue - because of food web changes apparently driven by P. amurensis, X2 is no longer a good index for management of the Bay-Delta system (TM). In the parlance of "adaptive management" one would argue that the adaptive action should be not to continue setting flow standards using X2! Alternatively, one could argue that while X2 is currently the best indicator (predictor) of ecosystem health, CALFED is free to consider other indicators (Gary Bobker), in which case we still need to understand the implications of the change from a pelagic/planktonic food web to one dominated by the benthos.
3. The viability of adaptive management seems to be predicated on having hypothesized (or understood) mechanisms by which the management actions might accomplish stated goals, e.g. increasing the abundance of delta smelt. One set of hypotheses for X2 has been developed by the IEP Estuarine Ecology Team, and it may prove useful to test it experimentally for some specific organisms like Crangon (which may not be important overall) for which the X2-abundance (or flow-abundance) relations are strong, or to look at an intercomparison of longfin and delta smelt (BH). This may require a substantial financial investment as well as a more substantial involvement of university researchers (BH, BB).

Summary and Comments

The morning presentations packaged together nicely data, analyses, points of view, and problems that give a fair view of the current status of X2 as a regulatory tool. In contrast, the afternoon Q&A session served to remind one of the degree to which the Bay-Delta community, as represented by those in attendance at the workshop, diverges in its understanding of the basis of X2 as well in its utility. For example, it was surprising to me to hear questions from the engineering community about specific features of the salt field that would be important if X2 regulations were strictly given in terms of X2. However, given that the EPA proposal provided three different ways of satisfying the standard, one of which involves flows directly, operational concern that X2 is different from X2 inferred from surface salinity measurements seems a waste of time.

More fundamentally, the tone of the questioning and discussion, well exemplified by BJ's presentation, highlights one of the major challenges of any policy formulation in the Bay-Delta system: Water is so valuable that the uncertainty/natural variability in aquatic population response to X2 makes X2 regulations a difficult pill to swallow. BJ's point that the cost of new facilities designed to increase water harvest essentially makes the marginal cost of water for environmental protection quite substantial is well taken. From an engineering standpoint, one always wants to optimize extraction of a resource or minimize cost to achieve a given goal like protection. Thus, if restoration/protection goals are articulated taking the X2-abundance relations given in Jassby et al. to be predictive in the same way that a stage-discharge relation (also empirically determined) is predictive, disputes will naturally arise. As Bill took great pains to point out, the difficulty with the expectation of predictability is that population dynamics generally don't work that way.

The primary issue is one of trying to manage broadly rather than specifically: X2 can be taken as an important measure of system hydrology (as can flows on the fortnightly or longer time scale). If hydrology is thought to be important biologically, one approach would be to try to make the behavior of X2 look as much as possible like it would do "naturally," with "natural" defined as some level of water development (a policy-based decision). Somewhat like the "Field of Dreams" philosophy - i.e., build it and they will come - this presumes that by restoring some aspect of the physical environment to some previous state which was better ecologically (e.g. which supported larger populations of native fishes), one will see ecological restoration (defined as some specific goals cf. CALFED). It should be pointed out that this is exactly the guiding rationale for increasing shallow water habitat in the Delta, notwithstanding the lack of anything like the X2-abundance relations to connect acres of shallow water habitat to (e.g.) abundance of Delta Smelt. If we adopt this approach with X2, we must be satisfied with the very loose level of control it accords. Specifically, the results may take a long time to manifest themselves. This point was made repeatedly during the shallow water habitat workshop in late June, particularly by Si Simensted, who was arguing for decades for the development of littoral/shallow water habitats in restored wetlands/marshes.

The alternative is to try to manipulate the system in detail, as one might operate a sewage treatment plant, or design an airplane. Certainly from an engineering standpoint, it is much more tractable to pursue the latter strategy, i.e., to consider pump operation strategies or the construction of facilities aimed at preventing specific problems like entrainment. The results are immediately measurable, i.e., fewer Delta Smelt entrained, and, adaptation of the design (facility or policy) more easily done to achieve an optimal solution. Which mode of operation provides a better return on resources (water, capital) invested seems to be a fundamental issue that was only tangentially addressed in the workshop.

Nonetheless, based on the workshop proceedings and on previously published work, I think some answers can be given to the questions posed for the afternoon workshop:

1. Is it possible to devise an experimental test of the success of X2? Yes, if one is willing to wait sufficiently long to see the results, and if one designs limited, focused experiments on hypothesized connections between X2 and abundance, e.g., X2 downstream means intensified gravitational circulation through the Golden Gate, which equates to better recruitment of things like Crangon (or Dungeness crab) into the Bay. This approach means a continued focus by the IEP on "studies" (research) in addition to monitoring, and most likely an enhanced role for university researchers. It also means continuous, careful, biostatistical analysis of the data. We should not be debating log vs. linear plots. Perhaps one should say that we need consensus by a group of statisticians; it shouldn't really matter what BJ Miller or I think about the statistical significance of X2-striped bass relationships.

2. Is X2 any better as a standard than X1 or X3? From a statistical standpoint, there is no real difference given the self-similarity of the salinity distributions observed in Northern SF Bay. From a physics standpoint there is not much difference although if you were choosing between X2 and X6 or X0.5 there are real differences in flow structure. From a biological standpoint, Bill and Wim's X2 studies may show that X2 (like Ball and Arthur's earlier EZ work) is a good reference position for looking at the spatial structure of ETM (LSZ) populations. However, this all begs the question of why all the action at or around X2 given Jon's observations that show convincingly that the ETM (LSZ) does not function in the way hypothesized by Ball and Arthur (which, by the way, was a very useful hypothesis for guiding subsequent work).

3. Is X2 more or less useful than outflow for use as a standard or conceptual tool for understanding the estuary? Since X2 and flow are tightly linked at timescales of a fortnight or more, X2 has only proven to be more useful as a standard in the sense that it could be promulgated, and thus was useful in breaking the logjam that had developed over flow regulation. Conceptually, on the other hand, it is

different since it determines the strength of the density gradient that drives gravitational circulation, it measures where one finds habitat at a given salinity, and it thus determines where that habitat is positioned relative to the pumps. Jon provided a useful view of the difference--X2 is good for describing things related to the salt field in Suisun Bay and the western delta whereas flow is good for describing things where the currents it drives are comparable to those driven by the tides, e.g. somewhat upstream of Suisun Bay at low flows and possibly down in San Pablo Bay at high flows. Other variables, like contaminant levels, the presence of exotic species, or even, one might argue, the operation of the Montezuma Slough tide gates might be found to be important at times and for particular species.

4. What needs to be done next? In terms of actions, there seems to be some interest in focusing some attention on species like Crangon or longfin smelt that exhibit a robust X2-abundance relation, and for which hypotheses exist as to possible mechanisms behind those relations. This might involve some workshop activity summarizing what is known, etc., but more likely requires designing new experiments and/or monitoring. From the standpoint of data analysis, careful examination of X2-abundance relations should be an ongoing activity, carried out by people who are skilled at the necessary biostatistics. I doubt that the X2-Q-time relationship needs re-evaluation, but it would not hurt, especially given the additional data that would be available for the high flows we have seen in the past few years [17] .

Finally, bluntly put, the workshop failed to accomplish the latter 3 of its 4 major objectives, which, in retrospect, were probably too ambitious. In particular, little progress was made on the second and fourth objectives, i.e., there was no consensus achieved about the current value of X2. This is hardly surprising given that the earlier Schubel workshops lasted 8 days in total, included a good deal of work outside the workshop, and, in the end reached a set of conclusions that were not unanimously adopted.

Owing to the large size of the meeting, and a lack of direction in the afternoon discussion, it is hard to argue that much was accomplished in the latter part of the workshop. To be successful, this type of discussion probably needs to be steered somewhat by the firm hand of the moderator, which can easily raise the collateral issue of whose agenda is subtly or not so subtly being put forward. To his credit, Randy Brown was suitably neutral in his moderation of the afternoon session. As a recommendation, I would think that a group of the size of the Estuarine Ecology Team might be better suited to carry on the real group work needed to address the stated objectives of the workshop, with a large town meeting like the X2 workshop used to inform the community as to what the smaller group was engaged in or about what conclusions to which they had arrived. In that respect, public presentation of the EET X2 matrix might have been a more useful activity after the morning talks.

Overall, I don't regret having attended the workshop. However, for myself, the exercise of preparing these notes has helped me to reflect upon what was presented and said. Although it would be expensive in terms of IEP staff time, I would recommend that anyone who attends a workshop like this be required to develop their own view of what was accomplished. This would serve two goals--first, the number of workshops and their total of attendees would drop, and secondly, those who do attend will better profit from their time spent listening to presentations and discussion. I note that this is not unlike the approach we employ in teaching university students!

Acknowledgments

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A Summary of the Current State of the X2 Relationships

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On March 11, 1998 the Interagency Ecological Program (IEP) and Bay-Delta Modeling Forum sponsored a workshop at the Contra Costa Water District (CCWD) to present and discuss several aspects of the X2 standards and relationships between abundance of aquatic organisms and X2 (the "fish-X2" relationships). This report is a summary of my presentation at the workshop, borrowing heavily from those of other presenters in an attempt to summarize the current state of these issues. I update the relationships with the most recent data, and discuss several of the salient issues that came up before and during the workshop.

The overall workshop is discussed in a separate report by Stephen Monismith (this issue).

X2 is defined as the distance in kilometers up the axis of the estuary to where the tidally-averaged near-bottom salinity is 2 psu (practical salinity units). It was developed as an indicator of the physical response of the estuarine ecosystem to changes in freshwater flow. For a concept that is relatively straightforward, X2 has engendered a surprising amount of disagreement and misunderstanding. The workshop was convened to increase the general level of understanding of these issues, discuss key areas of disagreement, and attempt to build on previous attempts by the Estuarine Ecology Team (EET) and others to identify probable mechanisms underlying the relationships.

X2 is now being used, in a somewhat altered form, to manage the estuarine ecosystem. The water costs of this management may be high in dry years. Furthermore, we do not know whether an "Isolated Transfer Facility" would improve conditions in the estuary enough to justify relaxing the X2 standard. Therefore, intense interest exists among stakeholders in ways to reduce the water costs of the X2 standard while providing adequate protection of the estuarine ecosystem and key species.

A Brief History of X2

Although the idea of using a 2 psu isohaline for ecosystem management arose in the late 1980's, it received its major impetus in a series of workshops from 1991 through 1992, organized by the San Francisco Estuary Project and moderated by Jerry Schubel (see Schubel 1993, Kimmerer and Schubel 1994). An important basis for these workshops was the recognition that freshwater flow had measurable effects on the abundance of estuarine-dependent species (Turner and Chadwick 1972, Stevens 1977, Armor and Herrgesell 1985, Hatfield 1985).

In the Schubel workshops the concept of X2 was defined as an alternative description of flow conditions in the estuary. The relationships between X2 and abundance of several estuarine species were developed (Jassby et al. 1995). The report of the workshops (Schubel 1993) made several recommendations, the principal one being that X2 be used as an index of estuarine condition.

The daily numerical value of X2 was determined by interpolation using data from continuous monitoring stations maintained by the U.S. Bureau of Reclamation and the Department of Water Resources (Jassby et al. 1995). These stations sample 1 meter below the surface, in about 10 meters of water between the shoreline and the ship channels; near-bottom sensors on some of these instruments had not provided enough data to use in interpolation. The measurements were converted to salinity and corrected to bottom salinity assuming a constant stratification of 0.24 psu determined from grab sample data for surface and bottom salinity. Stratification did not depend on outflow except at extremely high values. Gaps in the data were filled using a time-series regression that included the log of net delta outflow and the previous day's value of X2. For times when X2 was seaward of the Martinez sensor, values were calculated using the same equation; thus values for X2 in Carquinez Strait and seaward (<56 km) are merely estimates and based on recent field experience (Kimmerer 1998) these may be very inaccurate. The final time series consisted of daily values from 1968 to 1992. Values for earlier and later years have been filled in using the time-series regression model.

Estimates of X2 now being used in management are based on the same time-series regression developed in the Schubel workshops. This analysis was never intended to be the underpinning of a system of legal requirements for California's water system, but as an exploration of what form a standard might take. To my knowledge the analysis has never been repeated by other researchers, nor has it been updated to reflect a longer series of data or more appropriate (i.e., near-bottom) data.

Participants in the Schubel workshops had expected to recommend particular values of X2 as standards based on analysis of the available data. This was not possible because the fish-X2 relationships were monotonic, with no optimum or leveling-off point. This meant that more flow should produce more fish, at least up to, and sometimes including, the extreme flows of 1983. Therefore particular values for X2 could not be selected using only scientific analyses, and societal factors had to be brought to bear. Workshop participants therefore left the selection of particular values of X2 to other forums.

It is worth noting that participants in the Schubel workshops agreed that whatever standard was developed on the basis of whatever relationships, these would apply only if the plumbing of the water projects remained the same. The participants expected that major changes in water project configuration would result in substantial but unpredictable changes in these relationships.

The next step in development of standards was made by the Environmental Protection Agency (EPA) on the basis of three principles: (1) the standard should account for water availability on a continuous basis rather than by discrete water year types; (2) the standard should be set by comparison with conditions existing at a time when the biological populations of the estuary were considered "healthy"; and (3) the standard should use salinity at existing monitoring stations rather than interpolated values of X2.

Using these principles, EPA developed a "sliding scale" by which X2 was dependent on the availability of flow to the watershed and the level of development in the watershed, represented by calendar year. This gave a relationship in which the value of X2 could be set based on precipitation including recent history, and on a selected year representing level of development. The year ultimately written into the standard was 1971.5. The sliding scale ensures that the amount of water used to control X2 is proportional to the amount available in the watershed.

In designing the new standard, EPA replaced the actual value of X2 with the frequency with which 2 psu salinity was exceeded at three control points where conductivity sensors had been in place: Collinsville, Chipps Island, and Roe Island. This modification eliminated the need for accurate estimates of X2, and therefore the recommendation of the Schubel workshops (that sensors be put in place to monitor X2), was not taken. Furthermore, this modification made the use of the "g model" of the Contra Costa Water District more suitable in management than the X2 equation, since the g model predicts salinity at a site rather than the movement of a salinity value.

The State Board adopted the X2 standard following the signing of the Bay-Delta Accord in 1994. A provision of the Accord was that there would be a triennial review of the standard, but to date no formal review has occurred. This may be partly due to the high flows that have occurred in all years since 1994, resulting in little impact of the standard on operations.

X2 and the Low Salinity Zone

I use X2 to mean the distance up the axis of the estuary to the 2 psu isohaline; I call the region of the estuary where the salinity is around 2 psu the "Low-salinity Zone" (LSZ). Several terms have been used to describe this region including "Entrapment Zone," "Null Zone," and "Estuarine Turbidity Maximum" (ETM). However, the region where salinity is around 2 (say, 1-6) psu is not always an Entrapment Zone (Burau 1998); since stratification is weak in Suisun Bay, it is not always a Null Zone (Burau 1998); and only sometimes is it an ETM. The term Low-Salinity Zone implies no mechanisms and is unequivocally related to a certain salinity range.

X2 is an index of estuarine conditions and it responds to flow (Figure 1). However, a large array of other variables are, or may be, correlated with flow (Table 1). The mutual relationships among these variables make it difficult or impossible to use statistical analyses of annual data to determine which is a better predictor of variation in fish abundance, or if any has a direct causal link. To unravel the relationships requires understanding of the biology of the individual species in the context of the physical conditions in the estuary. This is discussed further below. However, it is important to recognize that on statistical grounds, other variables may be just as good as X2 in predicting abundance.

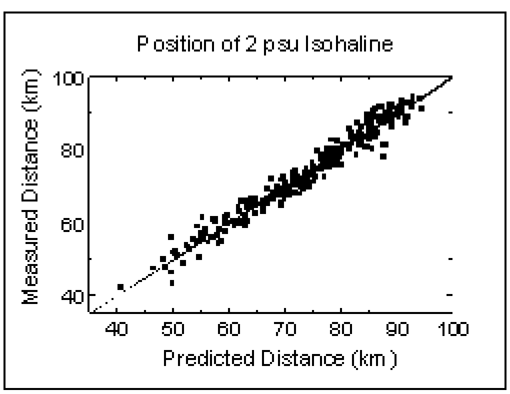

Figure 1. Relationship of X2 to net delta outflow (DWR Dayflow model output). The model is a time-series model containing the log of monthly mean outflow and X2 in the previous month.

Table 1. Variables Related to Freshwater Flow into the San Francisco Bay-Delta Estuary and River System. *

Flow Variables	
Sacramento River, San Joaquin River, tributary flow	Cause
Delta inflow and outflow	Cause
Inundation of flood plains and flood-control bypasses	Cause
Physical/chemical variables	

Nutrient and organic carbon supply rate	Data
Sectionally-averaged seaward residual circulation	Cause
Residence time	Inferred
Distance up estuary to 2 psu salinity "X *2*"	Data
Distance up estuary to any salinity	Inferred
Steepness of longitudinal density gradient	Data
Stratification seaward of LSZ	Inferred
Gravitational circulation seaward of LSZ	Inferred
Habitat Variables	
Area of inundated river-margin habitat	Inferred
Temperature (weak effect)	Data
Dilution or mobilization of river-borne contaminants	Suspected
Area or volume encompassed by two salinity values	Inferred
Location of low-salinity zone and associated species	Data
Biological Variables	
Abundance or survival of numerous species	Data
Transport of young anadromous fish into bay	Suspected
Entrainment of young into bay	Suspected
Proportional entrainment in export pumps	Inferred

** The table indicates whether the relationship is known from a clear causative link, known from data analysis, inferred from other information, or suspected.*

X2 is clearly useful in describing some physical characteristics of parts of the estuary unlikely to be affected directly by freshwater flow. Two factors are important here: the dispersive nature of the estuary, and the qualitative difference between fresh and brackish water regions of the estuary.

The further seaward one goes in the estuary, the more the hydrodynamics is influenced by tide and the less by flow. At Chipps Island in a low-flow period, tidal flows are about 50 times greater than net freshwater flow. Although the tidal flows are bidirectional, tidal trapping and asymmetry in tidal currents in different channels of the delta and Suisun Bay produce intense mixing that is the predominant mode for transport of some substances under these conditions. Generally tidal dispersion can be expected to dominate the net flux of substances that have a strong gradient (e.g., salt), while the net flow due to freshwater input would be expected to transport substances with little gradient (e.g., chlorophyll before 1987, Jassby and Powell 1994). As flow increases, the boundary between dominance by tidal mixing or by net flow moves seaward.

The LSZ also marks a boundary between the tidal-freshwater region of the estuary and the brackish region. In the freshwater region stratification is slight and ephemeral. Seaward of the LSZ, stratification and therefore gravitational circulation are possible, although they are common only in deep water, given the tidal energies and horizontal salinity gradients typical in this system (Burau 1998). Furthermore, at the LSZ the flora and fauna of the estuary change from a freshwater assemblage to an assemblage characteristic of brackish water, and further seaward to an assemblage characteristic of more saline water (Kimmerer and Orsi 1996).

An Update of the Fish-X2 Relationships

The fish-X2 relationships have been updated through March 1998 (Figure 2). Data for fish and bay shrimp are annual values, since these species reproduce on an annual basis. Data for chlorophyll, a measure of phytoplankton biomass, and for planktonic species, are monthly or survey means to reflect the shorter generation times of plankton. Below I discuss the features observed in each of the relationships, including results of exploratory data analysis done on some of the species. Regression statistics are given in Table 2.

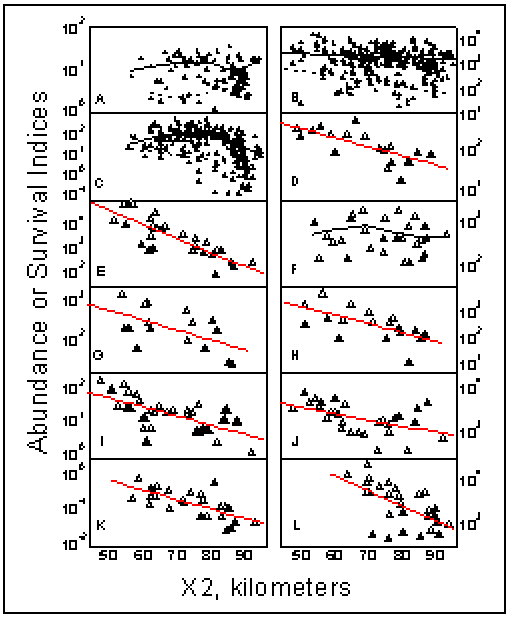

Figure 2. The fish-X2 relationships. Open symbols and solid lines, data before 1988; closed symbols and dashed lines, data from 1988 on; solid lines only include all the data. A, chlorophyll, monthly means; B, Eurytemora affinis abundance, survey means, with post-1988 data for March-June only; C, Mysid abundance (Neomysis mercedis until 1992, then also Acanthomysis spp.), survey means for May and later and for temperature over 18°C; D, Crangon franciscorum; E, Longfin smelt; F, Delta smelt; G, Pacific herring; H, Starry flounder; I, Sacramento splittail; J, American shad; K, striped bass survival index (ratio of summer young-of-the-year abundance index to egg abundance estimate); L, striped bass midwater trawl index. Data from IEP monitoring, provided as annual abundance indices except raw data were used for A-C. Curved lines in A and F are locally-weighted regressions drawn to capture the general trend in the data without fitting a chosen model; the curved line in C is a second-order polynomial regression. To account for zeros in the data, abundance indices for starry flounder were incremented by 10, and those for splittail by 1, before log-transformation.

All data were log-transformed before analysis (see below). Linear models were generally fit by ordinary least-squares methods, after examination of residuals for departures from assumptions. When apparent outliers were present I used generalized linear models with robust fitting procedures (Venables and Ripley 1994). Residuals from modeled relationships of the higher-frequency data (lower trophic levels) were autocorrelated over a time scale of a few months. Since the data are not evenly spaced in time and contain numerous gaps, they are not suitable for time series analysis or any of the available methods of correcting for autocorrelation. Therefore I calculated confidence intervals using a conservative value for the number of data points that was 10-fold lower than the actual number of points (Figure 2 B, C).

For most response variables I examined the relationships up to 1987 and for the entire time series. For lower trophic levels, which had clearly changed, I examined the relationships separately for data up to 1987 and for 1988 and later. Except for the three representatives of lower trophic levels, the models did not change much when the post-1988 data were added (Figure 2, Table 2). Apparent weakening in some of the relationships (longfin smelt, starry flounder, and striped bass MWT index) did not result in substantial changes in either the fitted slopes or their confidence limits (Table 2), mainly because the increased number of data points reduced the error variance.Chlorophyll in samples taken from 0.5-5.6 psu salinity (1-10 mS/cm specific conductance; Figure 2A) were taken as the geometric mean of data from the IEP water quality and zooplankton monitoring programs. Chlorophyll has never had a relationship with X2, and the mean value decreased by about 5-fold after 1987. The data taken before 1988 (solid line and open symbols) show a decline at low X2 values that may be a seasonal effect: low values occurred in spring before the annual phytoplankton bloom.

The abundance of the copepod Eurytemora affinis (Figure 2B) had a significant but very weak relationship to X2 before 1988, along with a large, continuous decline in abundance between 1972 and 1987. The relationship with X2 after 1988 was steeper and stronger, with mean abundance about 10-fold lower than before 1988. Note that the values for 1988 and later include March-May only, since this copepod is now found in few or no samples in summer to fall each year. A straight line provided a good fit to both data sets (Table 2).

Mysids (Figure 2C) include Neomysis mercedis as well as Acanthomysis spp, introduced in about 1992 (Odlin and Orsi 1997). Data were truncated to include months after April and temperature above 18°C, since mysids are uncommon when the water is cooler. Before 1988 N. mercedis had a complex relationship to X2 and also varied seasonally, decreasing from a peak in late spring to a low in the fall. This relationship was fitted with a linear term in date within year, and a quadratic term in X2. The curved line in Figure 2C is for mid-July. After 1988 the seasonal trend remained but the relationship to X2 appeared linear; the dashed line is for mid-July (Table 2).

The bay shrimp Crangon franciscorum had a significant relationship with X2 that did not appear to change since 1988 (Figure 2D). The lowest and highest residuals around the X2 trend line were both observed after 1988.

Longfin smelt (Figure 2E) had the strongest relationship with X2 which weakened somewhat after 1988, with a decrease in abundance of about 5-fold but little change in slope. Delta smelt (Figure 2F) has no relationship with X2, and did not appear to decrease in abundance beginning in 1988. The contrast between these related species may be useful in unraveling the mechanisms underlying the relationship of longfin smelt to X2.

Table 2. Summary of parameters of fish-X2 relationships. Slopes are given with estimated 95% confidence limits.

Taxonomic Group	***Variable***	***Averaging Period***	***Pre-1988 N***	***Slope***	***All Data N***	***Slope***	***Post-1988 N***	***Slope***	***Remarks***
Phytoplankton	Chlorophyll	Month	114	--			46	--	No relationship
Eurytemora	Abundance (0.5-6 psu)	Survey	257	-0.006 0.0035			37	-0.022 0.011	
Calanoid Copepods	Abundance (>6 psu)	Survey	223	-0.013 0.004			109	-0.029 0.012	
Mysids	Abundance	Survey	158	Nonlinear			74	-0.024 0.018	
C. franciscorum	Abundance index	Mar-May	8	-0.025 0.019	18	-0.025 0.012			
Longfin smelt	Abundance index	Jan-Jun	19	-0.062 0.016	29	-0.059 0.017			
Delta smelt	Abundance index	Feb-Jun							No relationship
Pacific herring	Abundance index	Jan-Apr	7	-0.035 0.039	16	-0.026 0.022			1983 omitted; see text
Starry flounder	Abundance index	Mar-Jun	8	-0.031	18	-0.031			

				0.029		0.021	
Sacramento splittail	Abundance index	Feb-May	19	-0.038 0.017	29	-0.028 0.013	
American shad	Abundance index	Feb-May	19	-0.025 0.011	29	-0.015 0.010	Slope declined: increased abundance at high X2
Striped bass	Survival index	Apr-Jun	18	-0.022 0.012	25	-0.027 0.012	
Striped bass	Abundance index	Jul-Nov	19	-0.037 0.015	29	-0.035 0.018	

Pacific herring (Figure 2G) had a weak relationship with X2 before 1988: the 95% confidence limits of the slope included 0, with only 7 data points. This analysis was done with 1983 excluded because of the unusually low abundance. The relationship for the entire period, again excluding 1983, better predicts abundance, although since 1990 it has been lower than predicted by the relationship. Including 1983 requires a nonlinear fit to the data that is forced entirely by that one point. Thus, the relationship for herring is not very strong and very high flow appears to result in a decrease in abundance index.

Starry flounder had a similar weakening of a significant relationship, with a flatter slope than before (Figure 2H).

Both splittail (Figure 2I) and American shad (Figure 2J) vary with X2 and for both species the slope has flattened apparently because of higher abundance at high values of X2. The cause of any increase in abundance with high X2 is unknown, although the mechanism for the X2 relationship is better understood for splittail than for any other species (Sommer et al. 1997).

Two different variables for striped bass tell a slightly different story. Survival index from egg to summer townet index (Figure 2K) is related to X2, and the relationship has not changed. The midwater trawl index (Figure 2L), also related to X2, has fallen below the prediction in every year since 1988 when X2 was at or below 85 km. The difference between these can be interpreted as due to declining egg production because of declining abundance of large adults (Kimmerer 1997, Bennett and Howard 1997). This decline is accounted for in the survival figure, but not in the figure for abundance.

Some technical details

Several key issues bear on the interpretation of the fish-X2 relationships. I discuss these below using longfin smelt as an example. This species has the strongest relationship with X2 and also one of the longer time series of data.

Interpretation of relationships

Each of the relationships depicted in Figure 2 can be interpreted as follows: "On average, the abundance of species x increases by y% for each kilometer seaward movement of X2." The percentage increase y per kilometer seaward movement can be calculated from the slope b as: percent increase = 100 (10-b - 1). Thus, for example, the expected abundance of longfin smelt increases by 15% and that of starry flounder by 7% on a 1-km seaward movement of X2.

The prediction inherent in the relationships only holds if future conditions will continue as in the past, so intervening changes may lessen their predictive value. The prediction is for the average condition only, rather than for a particular future year. It can be assumed to work within a year, such that if X2 were at, say, 70 km over the course of the relevant time period (Table 2), then longfin smelt would be 72% more abundant than it would have been with X2 at 74 km. Of course, there is no way to test this directly.

Use of log-transformed data

One of the topics for discussion at the X2 workshop was the use of raw vs. log-transformed abundance data (Figure 3). Log- transformed relationships are familiar from other fields: e.g., the Richter scale, the pH scale, and decibels all involve a log transform. Although some people are not comfortable with the concept of "log fish," I argue that log-transformed data are more appropriate than linear data for several reasons, some general and some specific to the fish-X2 relationships.

Ecologists log transform abundance data for four main reasons, two statistical and two ecological. Commonly-used statistical techniques require that variances be homogeneous; that is, variance of the response variable must not depend on its mean value. This is usually not the case for abundance data, for which the variance is often positively related to the mean value. Log transformation often removes this heterogeneity. Modern, computer-intensive statistical techniques do not require the constraint of homogeneous variances, so this use of log transforms is less necessary than before.

The other statistical reason for using log-transformed data is that often an underlying relationship can be more closely modeled as a straight line, which makes fitting the model much simpler and more straightforward.

One ecological reason for using log transforms is that biological populations change by multiples. This means that models fitted to log-transformed data have parameters with unambiguous meanings. For example, if we fit a straight line to the time course of log-transformed abundance of striped bass in the fall, the slope of the line is the mortality rate. Similarly, the slope of the time course of log-transformed annual abundance of winter-run salmon gives the annual proportional loss to the population on an instantaneous basis. The time trend of abundance data that have not been log-transformed has no clear meaning.

Finally, we are more concerned about the populations at low than at high abundance. This is because populations have a higher probability of extinction at low abundance. Thus from a species-protection perspective, this is the part of the curve we should be concerned about. At the high end of the curve, we would like to produce as many of each species as we can, but nobody knows what a suitable target abundance index should be. Thus our fitted curve should emphasize proportional change, not absolute abundance, and a log-transformed curve is preferable.

Figure 3 shows the relationship between longfin smelt abundance index and X2, plotted on linear and log scales. The linear plot appears to show a step change in abundance, such that at high flow/low X2, abundance is high and variable, while at low flow/high X2 it is always low. This implies that there is no relationship of abundance index to X2 at low flow, but as the log-transformed figure shows, this is misleading. In fact the relationship appears to be the same throughout the range of X2, such that a seaward movement of 10 km in X2 results in about a 4-fold increase in abundance index on average. This increase is not apparent in the linear graph because it starts from a baseline that is very low on the arithmetic scale.

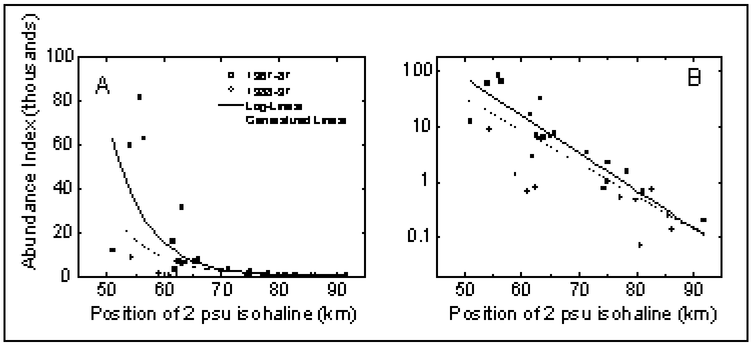

Figure 3. Longfin smelt. Comparison of relationships to X2 of raw (A) and log-transformed (B) data. Squares are pre-1988 and circles are post-1987 data. The darker line is calculated from a linear regression on log-transformed data, while the lighter line is from a generalized linear model with log link function, fit to the raw data.

In both plots of Figure 3, two lines have been drawn: one is the regression line based on log-transformed data, and the other is the fit of a generalized linear model (glm) with log link function and variance proportional to the mean squared (Jassby et al. 1995, Venables and Ripley 1994). The fitted lines have the same form but a somewhat different slope, with the log line having symmetrical residuals on the log scale, and the glm line having symmetrical residuals on the linear scale. However, both increase monotonically with decreasing X2, so both give the same information.

The only cases where we might be more interested in fitting a curve to the raw abundance indices are when the data contain a lot of zeros, or when the objective is an unbiased forecast of abundance under a specified set of conditions. This might be the case if, for example, the objective were to predict abundance in a fishery. However, that is not the objective for any of the fish-X2 relationships as they relate to setting standards for the estuary.

Using all or part of the data set

The fish-X2 relationships include a range of X2 values controllable by project operations, and a range that responds largely, but not entirely, to high flows during wet years. This has led to the "controllable range" shibboleth, which is this: we should use only the controllable range of X2 data in assessing the effect of project operations on fish abundance.

There are several arguments for using the entire set of data. First, relatively simple continuous functions are appropriate for data that do not contain step or other discontinuous functions. The fish-X2 relationships cannot contain discontinuous functions, as demonstrated by a simulation shown in Figure 4. I started with the assumption that the actual underlying response of a species such as Crangon franciscorum could be a step function, as shown by the line in Figure 4. Then I took the daily X2 values for March-May in each year and calculated a fraction of each day on which X2 would be seaward or landward of the assumed breakpoint of the step function. The tidal excursion in Suisun Bay is about 14 km, so the fraction seaward of the breakpoint was scaled linearly from 1 to 0 over 14 km, with a value of 0.5 at 68 km. Then I calculated the response based on the step, and averaged the values over the season.

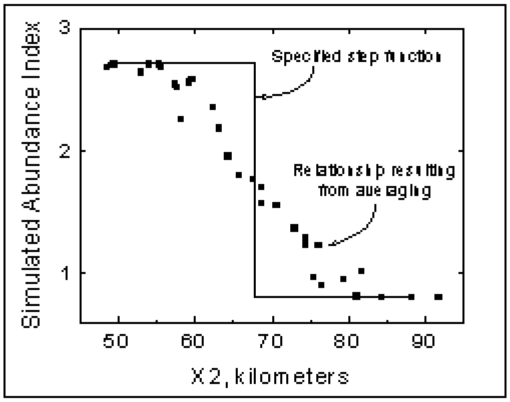

Figure 4. Results of a simulation illustrating the smoothing out of a postulated step function in response of a bay species (Crangon franciscorum used as an example) by temporal variability in X2 during the averaging period.

The average values calculated for each season (1967-1997) are plotted as points in Figure 4. The daily tidal excursion and seasonal variation in X2 have smoothed the step function into a continuous, nearly linear function. This suggests that either a straight line or some slowly-varying curved function would be most appropriate to fit to the fish-X2 relationships, irrespective of the shape of the underlying mechanism.

The second argument for using all the data is by analogy. Suppose we wanted to bet on a one-on-one game of basketball, and all we knew about the two players was that one had a larger shoe size than the other. The prudent gambler would always bet on the player with the larger shoe, reasoning that this person would probably be taller than the other player and therefore have an advantage in a game of basketball. However, this gambler would not expect to win this bet every time, and the closer the two shoe sizes are together, the smaller the odds in the gambler's favor.

This analogy has an exact parallel in understanding the meaning of the fish-X2 relationships. In neither case is it likely that the independent variable (shoe size or X2) exerts a direct influence on the outcome; both are surrogates for variables that probably do have an effect. In both cases, we use our knowledge of the overall relationship to make inferences about changes over a small range. In neither case do we expect to be able to predict the outcome of an individual event (game or year's abundance index), but we expect that on average, we will come out ahead by using the average relationship. In both cases, using all of the available data improves the ability to predict the likelihood of success in a given trial.

An additional argument is that, if somebody wants to use just part of the relationship to establish how abundance varies with X2, then that person should be obliged to demonstrate that the relationship is in fact different within that range than over the entire range. I have investigated this possibility by calculating piece-wise linear regressions for each of the significant fish-X2 relationships, assuming the "controllable range" to be landward of 68 km (corresponding to about 20,000 cfs delta outflow). In four cases the slopes of the two segments differed, but in three of those cases the slope was actually steeper in the low-flow range (Table 3).

Table 3. Statistics for Piece-wise Regressions Around the Controllable Range (68 km) for Annual Indices Except for delta smelt (no significant relationship) and Striped Bass Midwater Trawl Index (only one x2 value <68 km).

Taxonomic group	*Response Variable*	*Difference in Slopes**
C. franciscorum	Abundance index	-0.017 + 0.021
Longfin smelt	Abundance index	-0.002 + 0.03
Pacific herring	Abundance index	***-0.077 + 0.02***

Starry flounder	Abundance index	***-0.020 + 0.016***
Sacramento splittail	Abundance index	0.021 + 0.028
American shad	Abundance index	***0.050 + 0.043***
Striped bass	Survival index	***-0.024 + 0.009***

Difference in slopes is the slope of the controllable range minus the slope of the remaining range, given with 95% confidence limits.

The "Adult Fish" test

Concern has been expressed by some that the objective of restoration actions should be to restore populations of adult fish, not juveniles. About half of the fish-X2 relationships apply to juveniles. However, only for those species that are harvested are we concerned about adults; for other species (e.g., delta smelt) juvenile abundance is a more suitable and convenient measure of the status of the population than abundance of adults.

For those species that are harvested, the issue is whether density-dependent mortality occurs between the life stage measured and the life stage of interest. This is mortality that increases as the number of fish increases. Density dependence is very difficult to determine from field data, and for most species in the estuary it has not been detected. Survival of young striped bass from their first summer to the end of the first year of life appears to be density-dependent (Kimmerer 1997).

In the absence of a clear indication of density dependence, we can only assume that in any one year some fraction of the young fish will become adults, and that fraction will not change if there are more young fish. Therefore, if the fish-X2 relationship predicts more young fish with a seaward position of X2, then more adults are also expected. This assumption should be verified for those species with significant fisheries.

Investigating the Mechanisms

A great deal of interest was expressed by many participants at the X2 workshop in investigating the mechanisms underlying the fish-X2 relationships. I believe that there is now a general consensus that these relationships can be investigated only through a careful program of research. Although some investigators have pursued particular aspects of the relationships (e.g., Unger 1994, Kimmerer 1998) there is not now a comprehensive strategy for investigating them.

The motivation for pursuing these mechanisms varies, but an underlying theme among many stakeholders is that the X2 standard is too crude a tool for managing the estuary, and since it is so expensive in terms of water, it should be made more efficient. This could be done by limiting the time period over which X2 is adjusted, or by employing other, more efficient measures to accomplish the same ends.

It is somewhat ironic that, in this age of "ecosystem management," there is such strong interest in species-specific management. X2 is one of the few examples of ecosystem management in aquatic ecosystems. Perhaps the interest in management at higher than the species level is not as strong as the economic interest in protecting the estuarine system parsimoniously as to water.

The Estuarine Ecology Team wrote an essay on the likely mechanisms (EET 1996; text portion available at http://wwwiep.water.ca.gov/eet/x2fish.html), basing its conclusions on knowledge of the biology of the various species. Unfortunately, because of time constraints and a lack of funding or mandate to write a scientific paper on this topic, the EET chose not to attempt to back its consensus opinions with citations or evidence, so it remains merely a statement of consensus of the group.

The EET's report examined the likely mechanisms by which X2 or any of its covariates (Table 1) could influence species abundance, and then looked at each species to determine which of these causal linkages were likely to operate. Mechanisms were divided into those that were very likely, moderately likely, and unlikely, based on current knowledge about the location and seasonal patterns of movement and development of each species. For each species, several mechanisms were considered the most likely. Although these differed among species, several were labeled as important for more than one species. These included physical habitat space including spawning habitat, residence time, food production, and co-occurrence of the species with food.

The mechanisms selected as important can be used to develop hypotheses to be used in a research plan. These hypotheses would then be tested using an appropriate combination of data analyses, field and laboratory studies, and modeling. This will not be easy, and it will not be cheap, given the complexity of this ecosystem and the likelihood that different factors interact on different time scales to influence species abundance (Bennett and Moyle 1996).

Not all possible mechanisms should be investigated. For example, it is equally specious to look for a direct causal link between delta inflow and Pacific herring, as between X2 and splittail. We do know a few things, one of them being that causal mechanisms probably operate in the regions where the species are found.

The original motivation of the EET was to use its conclusions to devise a research program to investigate the mechanisms further. It has not done this yet. Given the interest in this topic, several members of EET and others are developing a research plan to address this need.

Conclusions

The deterioration of the X2 relationships for lower trophic levels is a concern. However, most of the fish and bay shrimp seem to have maintained their relationships with X2, although abundance of longfin smelt has declined. The lack of major changes in most of the fish and shrimp is a major ecological puzzle, since most of these fish and shrimp rely on the lower trophic levels for food. It suggests caution in predicting future abundance patterns from X2, but also suggests that the X2 relationships are fairly robust to significant perturbations to the system.

The next step should be to develop and implement a program of research into mechanisms. Future workshops can be convened to discuss results of such investigations.

Finally, I believe it is time for researchers and managers in the Bay-Delta arena either to accept the concept of X2 as an indicator of estuarine response to flow, or find and publish a legitimate reason not to use it. The fish-X2 relationships are robust, they are real, and they are generally consistent with one another. Arguments for amendment (in either direction) of the X2 standard should be based not on the relationships themselves, but on either the selection of a target year for use in the sliding scale, development of a standard that is as protective but more conducive to effective water management, or refinement of the standard through investigation of the mechanisms, their time and space dependence, and their probable response to CALFED rehabilitation activities.

Recommendations

1. The flow-X2 relationship should be recalculated using all available data. This calculation should be updated on an annual basis.
2. The fish-X2 relationships should continue to be updated annually, new ones should be identified, and any revisions to the overall trends should be announced.
3. A major effort should be undertaken to determine the mechanisms underlying the X2 relationships.

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