**Review of IEP and other Bay-Delta modeling focused on hydrodynamics and fish.**

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## 1. Introduction

On May 24th and 25th, 2009, the Interagency Ecological Program (IEP) sponsored a workshop on modeling of the Delta, with a special focus on how hydrodynamic modeling of flows and of fish embedded in those flows could be useful to management of the San Francisco Bay Delta as well as to the design of new facilities to better achieve the goals of improved water supply reliability and ecosystem protection/restoration. The workshop was intended to serve as the foundation for a review by the IEP Science Advisory Group (SAG) of modeling activities directly sponsored by the IEP as well as other related efforts. The agenda for the workshop, a link to supporting materials, and links to most of the presentations that were given can be found at http://www.water.ca.gov/iep/archive/2009/archive-2009.cfm , 2009 Workshop 1. The agenda is attached as Appendix A.

As a basis for its review, the SAG was provided a set of questions that can be summarized as (a more detailed list of these questions is attached as Appendix B):

(1) What should be the role of the IEP with respect to hydrodynamic modeling?

(2) What is the state of current IEP modeling activities?

(3) Are available models being used appropriately and are model uncertainties and limitations made clear to policy-makers, managers and other stakeholders (e.g. the environmental community)?

This review differed from past IEP reviews, e.g. of delta smelt research (2006) or the Environmental Monitoring Program (2000). In this review, much of the modeling that is currently underway for the Bay-Delta is not supported by the IEP. Indeed, other than Pelagic Organism Decline (POD) research (MacWilliams and Gross) and an Individual Based Model (IBM) directed at striped bass life-cycle modeling, including bioenergetics, being conducted at Davis (Loge), the IEP itself currently supports little modeling. Some of the research that was described has been funded by CALFED (Kimmerer, Monsen), some by the water contractors (De George), some by other State agencies (Fringer), and some by DWR independent of IEP activities (Smith, Nam, Ateljevich), in these efforts have focused primarily on internal agency needs.

The review included presentations describing applications of the DWR Java-based Particle Tracking Model (PTM) that is based on the 1-D hydrodynamic model DSM2-Hydro (which is at its core the USGS model "4 Point"). DSM2-Hydro has been extensively calibrated and modified to give predictions that have excellent correspondence to available in situ observations. Of note is that one application involved the development and use of a new method to predict delta smelt salvage at the pumps using what DWR calls the "Potential Entrainment Index" (PEI). The PEI is simple in concept: use the 1-D PTM model to move particles around the Delta. The likelihood of entrainment is then based on delta smelt distributions as indexed by the 20-mm townet survey. As is the case with all organism-flow models, the effects of fish behavior can be substantial (e.g., Simons *et al* 2007; North et al. 2008, 2009); in the case of PEI, like all the models discussed at the workshop except that of RMA, behavior of delta smelt is neglected entirely. Perhaps more importantly, given the extremely sparse occurrences of delta smelt now being observed, it seems likely that the predictions of the PEI approach have large uncertainties that render the approach of limited use. For example, the late May (18-22) 2009 survey shows no delta smelt in the interior Delta and, accordingly, the PEI would likely indicate no risk of entrainment. In fact, delta smelt <u>did</u> appear in the salvage data for late May and early June 2009. The PEI modeling highlights a key requirement for any model that is to be used in the policy arena: it is critical to quantify the uncertainty of the model. It also highlights the critical need for new measurement technologies able to monitor where the smelt are and how they behave.

While the 1-D approach of DSM2 (and its components) has the advantage of computational speed, several very powerful multi-dimensional models are also currently being used or are being developed for use for various purposes on San Francisco Bay. No doubt this reflects the impressive gains in computational power that have been made in recent years. The multi-D models are TRIM3D, UnTRIM, and SUNTANS. All are based on fundamental numerical algorithms developed by Prof. Vicenzo Casulli of Trento, Italy, but diverge in implementation. TRIM3D has been used most on Bay-Delta applications (see e.g., Casulli and Cheng 1993; Gross *et al* 1999; Monsen *et al.* 2007). However, because it uses a regular Cartesian grid, it poorly represents small channels in the Delta. Nonetheless, it can provide important spatial detail in open water areas like Franks Tract or at complex junctions. It is notable that the original application of TRIM3D to the Delta was supported by the IEP as a grant to Stanford University. With support from CALFED through their Proposal Solicitation Package (PSP) process, Gross and Kimmerer (see Gross *et al.* 2009; Kimmerer et al. 2009) have applied TRIM3D to the Bay-Delta, including some of the adjacent coastal ocean, with a goal of producing a coupled physical-biological model like that described in North *et al.* (2008) or Simons *et al.* (2007). As presented at the workshop, once calibrated, this hydrodynamic model (TRIM3D) could be used to explore hypotheses relating physical processes to ecological processes and outcomes. In many ways, the collaborations that have used TRIM3D demonstrate how high quality physical modeling carried out in close collaboration with estuarine ecologists can be very effective in addressing complex questions about linkages between flows and fish ecology.

The newer TRIM model, UnTRIM, applied by MacWilliams and Gross to the Bay-Delta, uses an unstructured grid to overcome the lack of model resolution in the small channels, enabling the modeler to specify very fine spatial resolution in areas where it is needed. The high quality of calibration results for UnTRIM presented at the workshop made clear that this is an effective strategy. Importantly, while UnTRIM is a proprietary model, all of its core numerical methods have been published in the archival peer-reviewed literature (see e.g., Casulli 2009).

The third of this set of models, SUNTANS[1], which also features an unstructured grid, has been developed with support from the Office of Naval Research (ONR). From the outset, SUNTANS has been written to be used on highly parallel computers, reflecting the fact that such computers are becoming increasingly available and affordable (e.g., a 320 cpu machine purchased by Fringer in 2008 cost approximately $200,000). The application of SUNTANS to San Francisco Bay by a Stanford-Berkeley consortium[2] has been supported by the Coastal Conservancy to predict circulation and sediment transport processes that are important to evaluate effects of tidal wetlands on the system. The grid for this application (a request of the funding source) does not include the Delta, except as a large channel with approximately correct hydraulic characteristics. The status of SUNTANS as a calibrated model of the Bay-Delta is less complete than the TRIM models, in part an effect of the 2008-09 stoppages of bond-funded research. Unlike TRIM and UnTRIM, SUNTANS is an open-source, non-proprietary code.

For all of the 3-D models, the main parameter that can be adjusted for calibration is the bottom roughness; generally this is set to be depth dependent but otherwise spatially homogeneous (see e.g., Gross *et al.* 1999). Thus, once bottom roughness is specified, the quality of the model results depends primarily on the grid resolution (generally finer resolution is better) and on the quality of the bathymetry and how it is represented on the grid, as well as on the quality of the boundary forcing data used to drive the model. Even with the best resolution available, there remain uncertainties associated with 3-D models because they include models of turbulent mixing that can be quite inaccurate in the presence of density stratification or surface waves, both common features of flows in the Bay-Delta. Although these turbulence models are the subject of active research in the physical oceanography and engineering communities, most 3-D circulation modeling tends to adopt one of a small set of closely related turbulence models (see e.g. Umlauf and Burchard 2005). Finally, we note that one motivation for using 3-D models is to resolve detailed flow structure near junctions or the secondary circulation in a channel

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[1] http://suntans.stanford.edu/

[2] The consortium includes two of the SAG panel members, Powell and Monismith.

bend. To the best of our knowledge, there have been few data-model comparisons (and in even fewer the closure algorithms and rigor of the calibration were quantified) for these complex flows. Where such comparisons have been made (e.g., see Wang *et al.* 2009), the agreement between model and data is only fair. Thus, it should be recognized that even sophisticated 3-D models (and their beautiful color animations etc.) often have significant limitations. Nonetheless, these detailed models are very helpful in furthering our knowledge of the basic flow structure and helping refine data monitoring programs to capture key processes.

The panel also heard presentations from California Department of Water Resources (DWR) staff (Smith, Nam, Ateljevich) on DWR modeling efforts, research apparently not connected to specific IEP projects or goals, but rather reflecting the fact that the mission of the DWR modeling group is to support DWR planning and operations. This effort includes using and supporting the use of the 1-D network model DSM-2, and its associated particle tracking and water quality modules. It does appear that at various times DWR staff has supported IEP use of DSM2 (e.g., Nobriga *et al.* 2007). Some of DWR's efforts appear to have focused on maximizing the utility of DSM2 as a tool for addressing practical problems like optimizing exports while minimizing export losses of fish like delta smelt (Nam). DWR also is supporting an effort at Lawrence Berkeley National Laboratory to develop a new advanced 2-D model, REALM, that, among other advantages, would have the capability to adaptively re-grid itself where needed to minimize errors (Berger and Colella 1989). REALM is designed to address difficult time-dependent flows like those that might accompany a levee break. However, since REALM does not simulate vertical structure, it may not be well suited to compute flows down-estuary of the Delta where stratification and vertical velocity shear can be quite important (e.g., see Stacey *et al.* 1999). Like SUNTANS, REALM appears to be a work in progress.

There was a presentation of Metropolitan Water District (MWD) funded work by John DeGeorge of RMA involving 2-D finite element modeling of the effects of EC and turbidity on delta smelt distributions. The predictions of the RMA Bay-Delta model for EC look excellent, likely reflecting the effort expended during the preparation of the Delta Risk Management Strategy (DRMS) to improve the model. This highlights the importance of building new modeling efforts on previous ones. On the other hand,

turbidity modeling was done in a fairly simple fashion, not attempting to build in any information about processes like sediment re-suspension that can markedly affect turbidity. Likewise, the delta smelt behavior model was constructed empirically. This is a bold attempt to better understand smelt behavior using turbidity as a surrogate for fish location. The presenters were transparent in their assumptions and simplifications, and recommendations for more detailed field studies and algorithm improvements were made during the discussion. We note that a detailed review of this effort can be found in the CALFED Science program review of the Two Gates project conducted in August 2009[3].

The most impressive model applications presented at the workshop were those by MacWilliams and Gross using UnTRIM that were designed to infer the locations and rates of hatching of delta smelt by tracking them as passive particles using essentially an *ad hoc* data assimilation scheme. The comparison of modeled delta smelt distributions with 20-mm townet survey data indicates this method has promise. This example also demonstrated an important attribute of successful coupled physical-biological modeling in the Bay-Delta, i.e., interdisciplinary involvement. The research team included a fisheries scientist (Grimaldo) as well as significant participation by other IEP staff.

## 2. Why model?

Central to the evaluation of the IEP's modeling efforts is the need to understand why models are constructed and used. For the most part, models of the Bay-Delta system are used in an engineering approach, i.e., they are used to project how the design and operation of engineered facilities like the proposed Dual-Conveyance facility will affect system behavior. This is most easily done for the physical system, i.e. currents, temperatures and salinities, although much of the interest in and demand for such models lies in understanding how physical changes will affect water quality (e.g., DO, contaminant concentrations), fish populations or, more generally, ecosystem structure and function.

Modeling can also allow us to explore how changes in hydrology due to climate change will affect the system, again with the same caveats that physical variables are

[3] http://www.science.calwater.ca.gov/events/reviews/review_2gates.html

much easier to predict than the ecological responses. Finally, a far more challenging predictive task, one that would depend on having satisfactory models of key components of the food web and how they are connected, is that of forecasting how species shifts or introductions affect the overall ecological functioning of the system. Ecosystem models are now being developed (e.g., ECOPATH and ECOSIM) for the Bay-Delta to explain the pelagic organism decline as part of a collaboration between the IEP and UC Santa Barbara, National Center for Ecological Analysis and Synthesis[4]. To our knowledge, these food-web models are not linked to circulation models for the Bay-Delta. In predictive mode, models can also be used to hindcast previous conditions. Typically this is done to assess model fidelity, quantify uncertainties and thus the likelihood that model predictions will be (to some degree) accurate.

When not used to make specific engineering-type predictions, models can also be used to explore hypothesized linkages of forcing (e.g., flow) and responses (e.g., fish behavior, population dynamics, or water quality), suggesting relationships that can be explored through further analysis of data or by design of new data collection programs. Finally, models also can serve to link researchers from different disciplines, i.e. to provide a forum for interdisciplinary collaboration between fisheries biologists, social scientists and engineers.

It is clear that modeling to evaluate specific actions may be very different from modeling undertaken to improve fundamental understanding of system structure and function, and thus should require different kinds of expertise, i.e., the former may in many cases best be done by consultants tasked with addressing specific issues, while the latter may be better tackled by scientists and engineers focusing more on basic scientific inquiry.

## 3. State of modeling in the IEP

In light of the discussion above, we note several salient features of current IEP modeling:

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[4] Personal communications from Howard Townsend (NOAA) and Larry Brown (USGS)

(1) With some notable exceptions, existing modeling is largely focused on details and projections connected to specific management questions, e.g., changes in transport patterns due to facilities and operations proposed as part of the Two Gates project. Essentially all of the DWR work (which we recognize is not formally part of the IEP) falls in this category. One consequence of this mode of operation that is driven by immediate agency need is that the modeling effort is fragmented.

(2) As a corollary, there is little or no real portfolio of modeling research, i.e., of modeling for exploring linkages and understanding how hydrodynamic processes work in the system, much less for modeling biogeochemical or food web/fish population dynamics. In many respects, the emphasis on addressing only current problems and engineering fixes reflects the absence of a long-term strategy for modeling and thus weakens the potential value of what modeling is supported by the IEP.

(3) These different modeling efforts use different data sets, and simulate different periods, making inter-model comparisons or assessment of consistency in findings from different studies virtually impossible.

## 4. Recommendations

Based on the IEP Workshop and review of modeling of the Bay-Delta, which had a broader scope than solely evaluating IEP-supported modeling, we make the following recommendations about how hydrodynamic and hydrodynamics/fish modeling might be used most effectively by the IEP and its member agencies.

Our basic recommendations are:

(1) The IEP must adopt a set of best practices for modeling, focusing on model evaluation and data-model integration. This has three aspects. Firstly, model hindcasts, which are central to evaluating model performance, must be conducted using quantitative skill and predictive metrics (e.g., see Blumberg *et al.* 1999; Warner *et al.* 2005). The “Looks Pretty Good” metric that has been commonly employed in the past for Bay-Delta modeling has no part in meaningful science and engineering research. It must be banished! Secondly, hindcast models should be run with varied

calibration parameters to show sensitivity to inputs and quantify the uncertainty in predictive capability. Further, consideration should be given to comparative studies – how much of this uncertainty can be mitigated if the objective is to understand the relative differences between different possible management options. For example, the coupled physical-biological model of zooplankton in the St. Lawrence estuary described by Simons *et al.* (2007) showed that given a key swimming behavior, plausible but different values of swimming velocity produce very different population distributions. This kind of model evaluation enables focusing future research efforts and identifying robust results. Thirdly, where possible, and especially for large projects (e.g., the dual-conveyance concept), different models should be run over multiple scenarios. As noted in our review of the Workshop above, there is clearly no shortage of different models available on the Bay-Delta! Like parameter variation, the agreement and disagreement of different models (at least ones of near equal quality) with respect to results are critical to identify uncertainties. We recognize that our recommendations may require increased modeling effort and hence more cost. The best reply we can make is to remind everyone of the old comment that "There is never time to do it right, only time to do it over..." Finally, it is critical that policy makers understand what aspects of model results are robust and in what ways the models are uncertain. Thus, the IEP should <u>require</u> that any presentation of model results by its staff and contractors clearly state assumptions and likely uncertainties, i.e., describe the model "warts and all".

(2) A key role for the IEP is to facilitate interaction of modelers with IEP scientific staff involved with fisheries/biological data collection and interpretation. The IEP staff has the most knowledge about how data were collected, and thus its limitations, as well as the biology and ecology of the organisms of interest, i.e., the scientific issues and needs driving the modeling effort. This integrated understanding of the Bay-Delta's physical and ecological dynamics by the IEP's phenomenal institutional memory is critical if modeling is going to be used to make major investments in infrastructure or to design and implement large-scale experiments like Two Gates. Thus, no modeling of fish-flow interactions should be conducted by engineers, numerical modelers, or fisheries scientists working in isolation. The IEP needs to assign fisheries science

staff to modeling projects its partner agencies undertake. Similarly, it would be very useful if the management of DWR, the agency with by far the most modeling expertise, could support IEP hydrodynamics-fish projects with time committed by its staff to more fully integrate their modeling with that of other IEP partners.

(3) The theme that came through most clearly in the review was that modeling efforts, while generally individually strong, suffered from a lack of coordination and interaction. Indeed the comment from a number of the modelers was that they really appreciated the forum presented by the review as a place to discuss strategic choices about modeling and model structure. Moreover, a greater degree of interaction between the different modeling groups spread around the Bay and in Sacramento would benefit all involved as well as the IEP. Thus, we recommend forming three coordinated and interacting modeling working groups that IEP would support both financially and with staff time:

i. A physical modeling group focusing on hydrodynamics including integration with climate models as has recently been undertaken by the USGS in their CASCADE program. The purpose of this group would be to share model development activities among its participants, keeping all informed about what was currently being done and, reflecting rapid advances in computational technology, to help advise IEP and DWR on future directions such modeling might take. Such a group could work on developing specific larger projects such as the delta transport validation model/field program outlined last year by a group convened by Steve Culberson under the aegis of the CALFED Science Program and including many people who participated in the IEP review. Monismith (IEP SAG chair) could chair this group.

ii. A glaring hole in current modeling efforts is modeling of physical-biological interactions at lower trophic levels. By this we mean the Nutrient-Phytoplankton-Zooplankton (NPZ) type models which can be simple ones like that Batchelder *et al.* (2002) have developed to model

the California Current Ecosystem as part of GLOBEC[5], or more complicated models like that of Chai *et al.* (2002), originally developed for large systems like the Equatorial Pacific, but currently being adapted by R. Dugdale and his research group at SFSU-RTC for use in addressing the question of ammonium effects on primary production. We heard little about these models at the workshop. These kinds of models are critical to understand how broad biogeochemical processes operate at the base of the food web and can be affected by (e.g.) water project operations or treatment plant discharges. It would be valuable to consider funding development/application of such models, but as a starting point in the near-term, we recommend development of a second modeling group, possibly chaired by Tom Powell, and certainly including Dugdale's group as well as Cloern and Lucas at the USGS. This group could meet as soon as possible to discuss the state of such models for the Bay-Delta.

iii. The third group we recommend forming would be one looking specifically at integration of fish biology and biology of other organisms at higher trophic levels (e.g., zooplankton, clams and other benthic organisms with pelagic larvae, etc.) and flow. As seen in the Two Gates review, this can involve connecting models of fish behavior with flow, or as in the delta smelt IBM developed recently by Kenny Rose and Wim Kimmerer, a comprehensive model including behavior in addition to a complete life cycle of the organism of interest. The broad purpose of this working group would be to recommend steps to advance the state of knowledge and integrated modeling of species of Bay-Delta interest. This group could be co-chaired by someone like Kenny Rose, Elizabeth North (UMCES-

[5] Global Ocean Ecosystems Dyamics - http://www.globec.org/

HPL), Jim Cowan (LSU), or Larry Crowder (Duke) and someone local like Wim Kimmerer or Frank Loge.

It is critical that the three modeling groups not work in isolation but that they are coordinated and complementary. This will require coordination by IEP and probable joint meetings or joint membership by some participants. Finally, each modeling group would be tasked to produce a state-of-the-art review paper of their topic for the online journal in ca. 1 year. In addition, in consultation with IEP staff and management, as well as the Delta Science program, these modeling groups should work with the IEP and the SAG to develop a longer term modeling strategy/plan that reflects agency needs and evolving computational capabilities. This consortium should work with to insure that activities are focused on integration of physics, biogeochemistry and fish models.

(4) A "clearinghouse" should be created to collect in one place the available high quality data sets of bathymetry, standard forcing for different types of water year, and data sets that are particularly good for model calibration/validation. While consideration of data needs was not part of the May 2009 review, the discussion of available data necessarily points to the gaps in available data. As discussed in a letter in July 2009 to the CALFED director from the Bay-Delta hydrodynamics modeling community (attached as Appendix C), an informal appraisal of currently existing data sets strongly points to the need for new data collection efforts, notably ones focusing on Delta-scale Lagrangian transport measurements.

(5) Our last recommendation is more specific: Physical models of the Bay-Delta must include connection of the model to the Bay and to the adjacent coastal ocean. As highlighted in recent work by the NCEAS working group on ocean-estuary coupling, variability in biota of the SF Bay-Delta estuary as well as in key biogeochemical processes can be driven by changes in the coastal ocean. This is especially critical for understanding the effects of climate change.

This last recommendation brings to mind a practical problem that, while outside the scope of our review, should be addressed: Computational power should not limit the selection of model, duration of simulations and spatial and temporal resolution to what can be accomplished with a desktop machine, albeit one with several multiple

core processors. Given the scale of projects for which these models are run, and the present and future demand for modeling, we believe that establishing a Bay-Delta Computing Center with a large-scale parallel processing capability would be a valuable investment. This undertaking would require that codes be adapted or developed to use such a machine. We note that several of the codes we heard described (e.g., SUNTANS and REALM) already have this capability. One could imagine such a center functioning like a 21st century version of the Bay Model in Sausalito or, more closely, like the National Center for Atmospheric Research (NCAR) in Boulder, CO, albeit in a way that is specifically focused on Bay-Delta problems.

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