CMARP: HYDRODYNAMICS MONITORING AND RESEARCH

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1. Monitoring objectives for hydrodynamics

The monitoring of hydrodynamic variables should be aimed at providing data that is useful for interpreting or using other biological and geochemical data particularly in connection with understanding physical effects on ecosystem functions and processes, environmental compliance, and with the planning and operation of engineered facilities; i.e., with all aspects of adaptive management of the Bay/Delta estuary. The monitoring program should provide:

- A description of the physical state of the estuary, particularly salinity and water levels throughout.
- Hydrodynamic data needed to calibrate, verify and operate circulation models of various complexities. These models in turn will provide a way of "monitoring" the movement of passive organisms and chemicals through the system. Used in real time, with active assimilation of real-time hydrodynamic data, as in weather forecasting, these models will also provide information for guiding operations. These models will also be used to hindcast flow patterns and salinities that may also be used to help interpret other monitored quantities, e.g. phytoplankton concentrations.
- In conjunction with suitable biological and/or geochemical data, to estimate fluxes through key cross sections of the Bay/Delta of salt, sediments, organic carbon, contaminants, organisms. These data can be used in the formulation of budgets of these quantities for evaluation of effects of CALFED actions on the system.
- Data indicating changes in bathymetry resulting from sediment inputs from the rivers, its redistribution throughout the system, and from CALFED (or other) actions.

2. Conceptual Model

Introduction

Hydrodynamic processes in the Bay/Delta system move organisms, salt, contaminants, and sediments from place to place and control many aspects of the physical environment of the system. As a consequence, they influence virtually all aspects of the biology and geochemistry of the Bay/Delta. Because the basic laws that govern hydrodynamics are well known (turbulence and sediments aside), rates of transport and mixing, sediment re-suspension, and of vertical redistribution of properties and organisms can be predicted, in principle, using numerical and analytical means. Hence in any consideration of hydrodynamics there is a natural emphasis on the ability to accurately predict physical properties like salinity and current distributions. Indeed, a substantial portion of the historical effort on Bay/Delta hydrodynamics has focused on the development of numerical models to predict salinities and transport. Accordingly, in discussing hydrodynamics we emphasize the conjunctive use of modeling and observation to monitor and describe the physical Bay/Delta system.

Monitoring and research on Bay/Delta hydrodynamics focuses on knowing or computing:

(1) Tidally varying and short-term tidally averaged currents, depths, flows, sediment concentrations, salinities, and temperatures for all or part of the system. This constitutes the basic physical state of the estuary. These variables are most readily computed and/or observed.

(2) Patterns and rates of transport of scalars other than salt (e.g. phytoplankton or dissolved copper) and, perhaps most importantly, particles with and without behavior (e.g., larval fish or copepods). This represents, often in a complex fashion, the integration of currents over spatial scales of tens of kilometers and over temporal scales of days to weeks. For example, as a fish egg (e.g.) moves through the Delta into Suisun Bay it can sample the entire range of hydrodynamic conditions ("habitats") existing in the system, i.e., from well-mixed riverine conditions with little tidal variation to stratified estuarine channels with strong tidal variations in current speed, sediment concentration, and salinity. In a like fashion, it is the integrated dynamics of salt transport that determines the spatial structure of the salinity field and how it depends on flow, e.g., the X2-flow relation. Prediction of transport for timescales longer than a tidal period is significantly more difficult because small errors on the tidal timescale may add up to a large error on the roughly one week timescale of many transport

processes. Observational description is complicated by the fact that single point (known as Eulerian) measurements can be totally misleading; instead, to know where things are moving, it is necessary to either make measurements following the motion of marked parcels of fluid (known as Lagrangian measurements) using drogues or floats, or to have a dense array of fixed measurements.

(3) On longer (seasonal and beyond) timescales, sediment accumulation, erosion and redistribution. Sediment dynamics determine the evolution of the bathymetry (and hence the tidal currents etc.) and can play a significant role in the geochemistry of the estuary. Because the physics of sediment erosion and accretion are intimately tied to near-bed turbulence and to the rheology of the sediment bed, things that are not well known and that are difficult to measure, prediction of sediment behavior on these time scales cannot be done with much confidence (it is hard to even get the sign right).

Freshwater flow is a variable that directly connects the operation of California's water supply systems to valuable ecosystem processes and functions, most notably manifest as entrainment losses and X2-abundance relations. Quite justifiably, a premium has been and will continue to be placed on the prediction of system behavior. Desired predictions range from now-casts of salinity and transport that can be used to guide operations (e.g. gate closures or pumping strategies) to long-term evaluations of water supply availability given the need to meet environmental (salinity, flow, and/or temperature) constraints in the face of year-to-year hydrologic variations. Thus, a significant element of hydrodynamic monitoring should be directed at obtaining data that is useful for exercising hydrodynamic models in real-time, hindcast, or forecast modes as well as for calibration and verification purposes. In parallel, research activities that directly improve the predictive ability of Bay/Delta hydrodynamic models will be needed.

<u>Temporal variability</u>

Our conceptual model of the Bay-Delta hydrodynamics is one that operates on several time scales:

(1) Tidal time scale (ca. 1 day): Tides control vertical mixing and through sediment resuspension, the light field and the presence of particles upon which chemical transformation, perhaps mediated by microbes, may take place. On tidal timescales, passive organisms can be moved back and forth between a shallow shoal to a deeper channel, or from the Sacramento River to the San Joaquin through Threemile Slough. Lateral shears in tidal currents caused by depth variations can lead to rapid dispersion on the tidal timescale. In the Delta, flow splitting at channel junctions can also lead to rapid spreading of materials throughout the Delta on the tidal timescale.

Density stratification and thus gravitational circulation strength can vary tidally due to variations in turbulent mixing. One particularly important form of this variation is known as SIPS (Simpson ref) = Strain Induced Periodic Stratification. SIPS results when, in the presence of a longitudinal salinity gradient, vertically sheared ebbs carry fresher water over saltier water, thus stabilizing the water column. By contrast, on floods the tendency is to carry saltier water over fresher water, a condition that enhances vertical mixing. Thus a pattern of tidally increasing and decreasing stratification can be observed. During spring tides, turbulent, tidal mixing dominates and little stratification develops. During neaps, when turbulent mixing is weaker, density stratification can persist through entire tidal cycles and thus intensify over several tidal cycles, leading to a state that can be termed "runaway stratification". The transition between these two states, which have very different physics, appears to be governed by a parameter known as Ri_x, a Richardson number based on tidal mixing and the tendency to create stratification. Thus, as observed, transitions between stratified and periodically stratified water columns accompany spring-neap variations as well as changes in outflow. In fact, it appears that these transitions are more strongly controlled by tides than by freshwater flow.

Finally, given typical diurnal winds in the region, there can also be tidal time-scale current and particularly surface wave field variations. These will primarily lead to diurnal sediment concentration variations

(2) Fortnightly spring-neap cycles: Residual circulation patterns, water levels and mean sediment concentration are all strongly modulated by spring-neap variations in the tides. For example, for low riverflows, subtidal flows associated with filling and emptying of the Delta (by as much as a foot) can be quite important and lead to net flow from the Bay at times when the mean water balance for the Delta indicates the opposite to be true. Subtidal variations in flows, concentrations etc. are responsible for much of the net movement of materials through the system. Thus an important conceptual distinction

between mean flows and tidal flows is that tidal motions generally cause a cloud of marked particles (e.g. fish eggs) to disperse, whereas it is the rectified effects of tides, including mean discharge, that cause net movement of the centroid of the cloud. An important subtlety for transport is that the net motion of the cloud is not solely determined by the residual Eulerian current field (what is measured by an array of current meters), but also by the phasing and spatial variations of tidal currents, an effect variously known as wave transport or Stokes drift.

Besides residual currents determined by tidal variations in bottom stress, a principal contributor to net (subtidal) transport downstream of X2 is gravitational circulation. Indeed, the Entrapment Zone model/hypothesis that guided much IEP work for the last 20 years is largely based on a conceptual model of transport that only involves gravitational circulation. Not surprisingly, gravitational circulation is observed to be strongly modulated by spring-neap variations in tidal mixing. Indicative of the strong connection between tidal and subtidal variability, intensification of gravitational circulation at neap tides and with relatively small values of X2 appears to be associated with intensification of tidally varying stratification which greatly reduces the frictional resistance of the water column to the pressure gradient associated with the longitudinal salinity gradient.

Finally, to a first approximation, the timescale for changes in river flow to change the salinity field is observed to be roughly two weeks. This is based on the X2-Q relation given in Kimmerer and Monismith (1992) that connects X2 on a given day to both flow and X2 the previous day. This timescale is not what one would observe were mean advection to dominate, but may be indicative of the importance of dispersive salt fluxes to the overall salt balance, and the way those fluxes may depend on the strength of the longitudinal salinity gradient.

(3) The year (and beyond): Seasonal variations in riverflows, pumping, gate operations, barrier installation and tides (solstices versus equinoxes) lead to variations in advective and dispersive processes in the Bay/Delta, and thus at first order, variations in the salinity field, i.e., in X2. Variations in X2 in turn lead to variations in the intensity and timing of gravitational circulation and hence of whatever net transport is supported by gravitational circulation. Driven by variations in sediment supply and in prevailing winds (summer vs. winter), sediment deposition/erosion and transport also vary on the year timescale. Sediment supply may be largely the result of a few intense episodes (i.e., floods). Integration of these annual variations in sediment behavior over several years is what produces changes in bathymetry.

In summary in all of the above we emphasize the central challenge to monitoring, describing, and predicting the physical state of the estuary: rectification of more easily measured/calculated "fast" processes is what leads to the more difficult to measure/calculate "slow" evolution of fields of interest. As a consequence, virtually any description of the physics of the Bay/Delta must implicitly take account of tidal variations in flows etc.

<u>Spatial variability</u>

Hydrodynamic processes also vary along the axis of the system. In the eastern Delta and upstream mean flows dominate. Dispersion mechanisms are relatively well known, although the effects of secondary flows that develop due to channel curvature can complicate matters. At low flows thermal stratification can develop in these reaches. In the western Delta and downstream towards the ocean, tides are more important, esp. in dry (low outflow) conditions. At the same time, mean advection due to riverflow is generally lessened because channel cross-sections are larger than in the rivers.

Besides the straightforward difference between riverine and tidal motions, other spatial differences include

- The complex topology of the Delta may greatly enhance longitudinal dispersion of what would be expected for the relatively prismatic channel sections of the Delta. In particular, it is likely that splitting of tidal flows as they pass through the multiplicity of channel junctions extent in the Delta is the main contributor to dispersion in the Delta. Particular topographic features like the shallows on the western side of Franks Tract or the set of openings to the main channels that exist for Sherman Lake may also be important.
- In Suisun Bay, the existence of three main flow paths: the shipping channel, the combination of Suisun cutoff and the Reserve Fleet channel, and Montezuma Slough, along with the presence of shallow regions like Middle Ground and Roe Island provides the flow path variability needed to support tidally based longitudinal dispersion.

- The large shallow (<2m MLLW?) regions of the Delta, Suisun and San Pablo Bay are also expected to have very different sediment dynamics by virtue of the fact that windwaves greatly enhance resuspension in shallow regions over that experienced in the channels.
- One of the biggest source of spatial variations is not fixed to any particular location. The longitudinal salinity structure gives rise to a mean baroclinic pressure gradient that supports gravitational circulation downstream of X2. Upstream of X2, the pressure gradients that drive fluid motions are only due to variations in free surface elevation. Since surface pressure gradients affect the entire water column in the same way, little vertical current shear is observed in upstream of X2 whereas downstream the shear, especially as seen in tidally averaged velocities and in instantaneous velocities *around slack water, can be quite strong. When the mean flow toward the ocean is sufficiently weak, net mean upstream* flow can be observed at the bottom. It is this pattern that underlies the model of EZ (a.k.a. Estuarine Turbidity Maximum - ETM) that has been a guiding hypothesis for work carried out during much of the last 30 years. However, this picture neglects the complex bathymetry of Suisun Bay and the western Delta, where the two dimensional mean flow structure required by the EZ/ETM model is not likely to be observed, and, as seen in computations only, tidal dispersion may be strong. It also does not account for the dynamic nature of stratification, particularly its intensification at neap tides.
- In the relatively deep Central Bay region horizontal salinity gradients are weak but persistent stratification is observed. Here, bathymetry, particularly the sill/narrows combination near the Golden Gate, almost certainly controls (much like a weir controls water level) exchanges between the coastal ocean and the Bay. Pinole Shoal may also regulate upstream transport between Central Bay and the Suisun Bay/Western Delta complex. Numerous frontal systems can be casually observed, e.g. near the sill in Raccoon Strait or around the Golden Gate itself. Given the paucity of data for this region, little can be said definitively about its physics excepting a description of tidal motions only.
- *South Bay: Classically described as a well-mixed lagoon, South Bay can be strongly stratified in wet years like 1997-98* as well as homogeneous and eve hypersaline in dry years and at the end of summer. While physically connected to Central Bay, there is little information about how water is exchanged between these two subembayments, although, San Bruno Shoal has been identified as a possible topographic control on exchanges. Under most conditions (i.e., in the absence of persistent stratification) tidal dispersion dominates longitudinal mixing between the Bay Bridge and the Dumbarton Bridge. Like Suisun Bay and San Pablo Bay, the shallows of South Bay experience significant sediment resuspension because of wind waves.
- Marsh systems and inter-tidal mudflats: Lastly, the various marshes and inter-tidal mudflats have altogether different physics from the rest of the Bay. The marshes are regions of very high bottom roughness (the elements, plants, often emerge through the water surface), and hence flows there are dominated by friction. Variations in plant "density" (stems per area etc.) can lead to variations in friction that may be important for mean circulation. There are also complex networks of hierarchies of channels. Since this is the topic of one of the other CMARP groups, we will not discuss marshes further, except to note that, aside from recent work by USGS/UC Davis on the Napa marsh, they have received *little attention from the hydrodynamics community.*

<u>Sediments and Bathymetry</u>

The concentration of sediments in the water column represents a balance between erosion of sediment from the bed by turbulence and wave motions, deposition of sediments to the bed, and horizontal transport and redistribution of those sediments. In general, in most tidally influenced parts of the Bay/Delta, erosion and deposition are nearly in balance, with rates of net erosion or deposition controlled by the imbalance of these three processes.

Sediment deposition is dependent on the relative magnitudes of settling velocity and turbulence. Settling velocity increases as the size and density of the suspended material increases, primarily due to size changes of the suspended sediment flowing into the Bay during high flows and physio -chemical and biological flocculation. Aggregation of fine sediment, either by salt flocculation or biological flocculation has been postulated (Arthur and Ball 1979, Meade 1972), but in situ study of the physical characteristics of the suspended material is limited to the work of Krank and Milligan (1992), who used a floc camera to observe flocs for 11 hours in San Pablo Strait. Temporal and spatial variability of the physical characteristics of the suspended material (grain size, floc size, floc density, flocculation mechanism) determine settling rates and may affect the dynamics of sediment-associated contaminants. In the Bay, deposition is more likely at slack tide, in shallow water (where water velocities and turbulence are less than in the deeper channels), during neap tides (when turbulence is less than during spring tides), and during periods of high sediment influx from tributaries when turbulence can not support the suspended material.

Sediment resuspension (erosion) is dependent on the relative magnitudes of applied force on the bottom and erodibility. In the Bay, force is primarily applied by tidal currents and wind waves. Erodibility is determined by the size, consolidation, and biological binding of the bottom sediment. The applied force is greater during spring tides than during neap tides, during spring and summer when wind speed and wind waves are greatest, and in shallow water where wind waves affect the bottom most, where the wind fetch is greatest. Bottom sediment is most erodible during winter and spring when newly deposited sediment from winter runoff is finest and is relatively unconsolidated and is not biologically bound.

Wind-wave resuspension is at least as important for sediment and associated contaminant resuspension as is tidal hydrodynamics, but much more attention has been given to tidal hydrodynamics. Some wind-wave and sediment resuspension data has been collected in South Bay and Suisun Bay (Buchanan and others 1996, Lacy and others 1996, Ruhl and Schoellhamer written comm.), but there has been no comprehensive study to characterize the wave field and sediment resuspension in the subembayments of the Bay. The shear force applied by wind waves to the bed is sensitive to water depth and fetch and therefore varies spatially and temporally, typically varying diurnally during persistent summer winds.

Three significant cycles of variability of suspended material are the tidal cycle, spring/neap cycle, and annual cycle. The greatest concentrations of suspended matter during a tidal cycle are typically observed at slack after ebb tide because higher concentrations from shallow water are transported seaward during the ebb tide. About one-half the variance of suspended-solids concentration (SSC) is caused by the spring-neap cycle, and SSC lags the spring-neap cycle by about 2 days (Schoellhamer 1996). Relatively short duration of slack water limits the duration of deposition of suspended solids and consolidation of newly deposited bed sediment during the tidal cycle, so suspended solids accumulate in the water column as a spring tide is approached and slowly deposit as a neap tide is approached.

The annual cycle of sediment deposition and resuspension begins with large sediment influx during winter, primarily from the Central Valley, much of which deposits in San Pablo and Suisun Bays (Krone 1979). The first flush of sediment from the Central Valley watershed coincides with the first large runoff event of the winter, producing the greatest SSC. Subsequent runoff events that are larger have a smaller SSC (Goodwin and Denton 1991, Schoellhamer 1997). Wind increases during spring, causing wind-wave resuspension of the deposited sediment in shallow water and increasing SSC (Krone 1979, Schoellhamer 1996, 1997). The resuspended sediments are either transported out of the Bay or deposit where they are unlikely to be resuspended. As the wind continues during summer, fine sediments are winnowed from the bed and the bed sediment becomes coarser and less erodible (Krone 1979, Nichols and Thompson 1985). SSC tends to decrease during late summer and fall as the supply of erodible sediment decreases (Schoellhamer 1997).

Summary:

In summary, there is a temporal hierarchy of physical processes from tidal variations in mixing to inter-annual variations in salinity and sediment. Much of the temporal variability in the system is driven by spring-neap and annual variability in the tidal timescale processes like sediment resuspension, stratification development and phasing and strength of lateral shearing of tidal currents. Figure 1a sketches a the spatial variability as mapped onto the different geographic regions of the Bay, whereas figure 1b sketches them in terms of the different dynamical processes operant. Here the important distinctions are those of the importance of riverine flows, the presence of density gradients, and the possible importance of wind waves.

3. Monitoring Plan Elements

The plan for hydrodynamic monitoring must build on and add to the existing suite of physical variables that are measured. Furthermore whatever plan is adopted must be designed with integration of with models in mind. With these premises, we first discuss current monitoring activities and then propose additional monitoring elements designed to achieve the goals stated above. Proposed additions to hydrodynamic monitoring most notably include changes in the availability and means of using the data.

EXISTING MONITORING

Existing monitoring of hydrodynamic processes and variables can be divided into two categories: individual or recurring field studies; and, time series of variables like channel flow as recorded by the USGS UVMs (Ultrasonic Velocity Meters), water levels as recorded by NOS tide gauges, or salinities as measured by DWR stations required by D1485 for environmental standard compliance.

Time series data

There are significant spatial variations and annual, seasonal, diurnal, and semidiurnal oscillations in water height, flow, salinity, water temperature, and suspended sediment throughout the Delta and Bay system that are related to tides, fresh-water inflow, anthropogenic effects, and meteorological forcing. Several hydrodynamic parameters have been continuously monitored by various agencies at numerous sites for many years. The following is a brief description of the present continuous hydrodynamic monitoring activities:

Water Height (stage):

Time-series of stage data for the majority of the rivers that flow into the Delta are being collected primarily by DWR and USGS with some records beginning during the late 1800's. These data are primarily used for flood warning/control and computation of river flows. Stage data also are being collected throughout the Delta and Bay by DWR, USGS, and NOAA with some records beginning in the 1920's. These data are primarily used to monitor the tide, for flood warning/control, numerical model calibration and validation, and recently for the computation of Delta channel tidal flows.

Flows:

River flows are measured at numerous locations throughout the non-tidal affected water ways of the central valley primarily by DWR and USGS; some flow records begin during the late 1800's. Time series of measured tidal flows in the Delta were not available until the USGS began using acoustic technology in 1987. Since that time, the USGS has installed nine continuous tidal-flow monitoring stations in the Delta that use ultrasonic velocity meters (UVM) that are calibrated using a downward-looking acoustic Doppler current profiler (ADCP) flow measuring system. Flow data for four of these UVM stations are combined to provide an indirect measure of Delta outflow.

Salinity (specific conductance and temperature):

Several specific conductance and water temperature continuous monitoring stations are located throughout the Delta and Bay. Delta sites are primarily operated by DWR and USBR, and Bay sites by USGS and DWR. In the case of the Bay sites, the specific conductance data are used to calculate salinity which is generally recorded at two depths in order to monitor salinity stratification. Most of the Delta specific conductance stations are used to monitor saltwater intrusion into the Delta from the Bay, and the operations of the SWP and CVP.

Sediment:

The USGS has been monitoring suspended sediment inflow to the Delta from the Sacramento and San Joaquin Rivers since 1960; these are presently the only suspended sediment records upstream of the Delta. The monitoring of suspended sediment in the Delta just began this year at five sites using optical backscatterance (OBS) sensors; before this monitoring began by the USGS, there were no suspended sediment concentration data available for the Delta. The USGS began monitoring suspended sediment at two depths at five sites in the Bay using OBS sensors starting in 1991; the network has now expanded to eight sites.

Data accessibility:

The hydrodynamic data discussed above are accessible from various depositories, with some of the data being accessible from multiple depositories. Most of the data are accessible via the INTERNET.

The IEP file server, managed by Karl Jacobs (916-227-0435) of DWR, probably contains or provides access to the largest quantity of data for the Bay/Delta system. The IEP data base is accessible via the IEP home page at http://www.iep.ca.gov and contains hydrodynamic data as well as biological, water quality, and meteorological data. All of the data required to run the DSM2 hydrodynamic and water-quality models can be accessed from the server via the

Hydrologic Engineering Corps Data Storage System (HEC-DSS); i.e. time series of stage, Delta inflows, channel tidal flows, export rates, and salinity, and non time-series data such as timing of the operation of various flow gates, and installation and removal of temporary flow barriers. The IEP home page also has links to other Bay/Delta data bases.

DWR also maintains two other relevant Bay/Delta data bases. The California Data Exchange Center (CDEC) data base is primarily used for flood management and can be accessed at http://cdec.water.ca.gov. CDEC contains real-time and historical data on river stage and flow, and reservoir storage and releases. The data base also contains flow statistics for various stations. DAYFLOW, accessible via a link to the IEP home page at http://www.iep.ca.gov/dayflow, provides historical daily export rate and daily Delta inflow data. DAYFLOW also provides estimates of daily flows at key locations in the Delta, and estimates of Delta consumptive use .

The USGS maintains a data base for hydrodynamic data for the Bay and Delta which includes stage, Delta tidal flows including measured Delta outflow, salinity, water temperature, suspended sediment, and meteorological data. The data can be accessed by contacting the data base manager Rick Oltmann (916-278-3129) for access via telnet; the creation of a INTERNET home page for access to the data base is planned for this year. ADCP velocity profile data are not accessible through the data base but can be obtained by contacting Jon Burau (916-278-3127). River flow and stage data measured by the USGS (real time and historical) for non-tidal effected sites can be accessed via the USGS California District home page at http://water.wr.usgs.gov. Additional hydrodynamic and biological data for the Bay can be accessed through "Access USGS" at http://sfbay.wr.usgs.gov/access/ including real-time model simulation results for the Bay.

Real-time and historical stage and velocity data collected by NOAA at several locations throughout the Bay can be accessed via http://www.opsd.nos.noaa.gov. NOAA presently has five upward-looking ADCPs operating in the Bay and providing real time velocity profile data as part of their Physical Oceanographic Real-Time System (PORTS).

Recurring studies

In addition to the State Board required compliance monitoring (which includes a number of shore sites and monthly boat runs) the USGS, USBR, DWR, COE, and collaborators at Stanford University and UC Davis, have conducted a series of short-duration (a few months), often large-scale (lots of equipment), process-oriented (hypothesis testing) hydrodynamic monitoring studies. Over the years these studies have evolved from ingenious and often arduous single tidal cycle measurements using anemometer-like instruments to studies that involve a large network of simultaneously-deployed self-contained equipment that operate unattended for periods of up to three months. Although the objectives of these studies differ from a typical monitoring program (data collected to identify long term [annual] trends and to detect dramatic changes), these studies have produced a large quantity of hydrodynamic data (typically time series of sea level, currents, salinities, and turbidity) that have been used to understand how the plumbing of the system works at tidal to seasonal timescales. A chronologically ordered list of these studies, including a brief description, is given as attachment H1.

NEW MONITORING

Salinity monitoring

A set of bottom salinity/temperature sensors should be deployed along the axes of the northern channel of San Francisco Bay and in the Delta to accurately define X2 (as discussed originally by Schubel et al). Each salinity station would be deployed, recovered and re-deployed on approximately 3 month cycle. Each station would cost approximately $x to install and $y to maintain. Real time telemetry might also be possible, although it would certainly be more expensive.

Fluxes

Although the transport of salinity, sediment, toxics and biota within the Bay and Delta system is fundamentally Lagrangian (goes with the flow), the flux of any parameter of interest past a given location is useful in understanding where things have come from, where they are stored and where they are going. For example, typical questions might be: Are fish, zooplankton, sediment, or any measurable parameter of interest, moving towards the pumps during certain hydrology,s and/or reservoir release and pumping scenarios? What are the exchanges between embayments or between areas in the Delta?

From a physical standpoint, the instantaneous flux of a given substance through a cross-section is determined by computing the integral over the area of the concentration of that substance times the velocity perpendicular to that area. In principle, this requires that the velocity and concentration be known at all points in the cross section. Moreover, since the depth varies, computation of this integral also requires that the depth be known. The simplest flux to compute is that of volume of fluid, i.e., flow. Other quantities that might be of interest are the flux of salt, the flux of organic carbon, or the flux of sediment. Given that budgets are usually formulated for periods of days and longer, the time average of the flux, i.e., its subtidal variation, is of more interest than instantaneous values.

To *estimate* fluxes, an ADCP, an autonomous profiling CTD (also equipped with Chl*a* fluorometer, an obs, and whatever other sensors may become available in the future) should be deployed at several key stations in the Bay-Delta. The methods by which this profile data is converted to fluxes and the associated problems are discussed in attachment H2. These hydrodynamics stations might also be equipped with autonomous samplers for other water quality parameters. Bearing in mind CALFED's focus on the region upstream of Carquinez Strait. The list should include:

a) Highest priority: Chipps Island/Mallard Slough – this station would connect the Bay and Delta.
b) Carquinez Strait – this station connects Suisun Bay with the rest of the Bay. Data from here could be used to drive a model of Suisun Bay and Delta alone (as is currently done). This station would need to be carefully designed given the substantial boat traffic through the region.
c) The Golden Gate (or just outside) – This could be piggybacked with the PORTS ADCP. This data is essential for hydrodynamic modeling of the whole Bay. There are significant engineering issues associated with this region and the CTD profiler might be replaced with 3 sensors in the water column (CTD+) which would be considerably cheaper and more robust.
d) Rio Vista - fluxes from the Sacramento
e) Jersey Point – fluxes from and to the San Joaquin
f) A location to be determined in the Southern Delta

The interior Delta stations probably do not require profilers, but instead single samples might suffice. The cost of the installation would vary depending on what was required, but would involve capital costs for instruments and engineering of roughly $150K each. Maintenance/servicing costs would need to be determined. Note that several of the stations currently include UVMs. Recent USGS work has been aimed at replacing the UVMs with ADCPs which might also be calibrated to flow.

Flow monitoring specific to CALFED actions:

Once a preferred alternative is selected by CALFED, new flow monitoring stations will need to be installed to monitor the effects of the new Delta plumbing on the hydrodynamics of the Delta. The existing UVM flow network will continue to provide valuable flow monitoring data prior to, during, and after re-plumbing; however, additional key locations will need to be monitored. For example, if water is diverted from the Sacramento River near Hood, a flow monitoring site should be installed on the Sacramento River downstream of the diversion point to monitor the quantity of water left in the Sacramento River, and the flow into Sutter and Steamboat Sloughs. The Sutter and Steamboat Sloughs flow would be determined by differencing the flows from the new station with the flows from the present UVM station on the Sacramento River upstream of Delta Cross Channel. Additional flow monitoring sites will be selected as a result of the chosen configuration. Other locations of interest include the Mokelumne downstream of the confluence of its north and south forks.

Assuming that set-back levees in conjunction with wide shallow flow planes will be created as part of a through Delta plan, velocity and flow data will need to be monitored in the flow planes to investigate sedimentation (deposition/erosion, contaminants) and biological questions. Other such re-plumbing modifications, such as operable flow control barriers, flooding islands, etc. will probably require some type of similar hydrodynamic monitoring.

Each new UVM station would cost about $50K to install and $36K/year to operate and maintain. These costs could be reduced if the UVMs were replaced by new side-looking ADCPs which can also be calibrated to flow. The USGS is currently investigating this option, which should cost roughly $20K per installation plus $20K/year to operate.

Shallow water data stations

Standard hydrodynamic data are required for shallow water regions like Honker Bay, Sherman Lake, or Franks Tract. Given the paucity of data in these regions we have no idea of the predictive skill of hydrodynamic models there or in general how shoal salinities are related to conditions in near by channels. Given the emphasis of CALFED on shallow water habitat, it is essential that routine monitoring of physical processes there be undertaken. At a minimum some version of the USGS shallow water package (ref) – an S4 current meter, a CTD with OBS, an altimeter to measure sediment elevation changes, and possibly a chlorophyll fluorometer to measure phytoplankton biomass – should be deployed at several stations in the shallows of Suisun Bay and the Delta. Each of these stations would cost ca. $50K for new instruments plus the annual cost of maintenance. They could be configured to telemeter their data in real time as well.

Sediments

Several methods can be used to monitor deposition and resuspension; selection of a method depends upon the purpose of the monitoring. Time series data provides excellent temporal resolution and good accuracy but poor spatial resolution. Time series data can be used to determine trends, determine the factors that affect SSC and to estimate their magnitudes. Remote sensing of SSC provides good spatial resolution but less accuracy and poor temporal resolution. A calibration curve for remotely sensed images the USGS developed for the Bay had a standard error of prediction of 52 mg/L, compared to a mean standard error of prediction of 14 mg/L for water year 1995 SSC monitoring data. Sediment traps can be used to collect samples of suspended material. Direct measure of sediment resuspension can possibly be measured by measuring the turbulent fluctuations of vertical velocity and sediment concentration. Under more controlled settings, resuspension can be measured with sea flumes deployed on the bed of the estuary and deposition can be measured by a small video camera filming deposition in a quiescent settling chamber. Both these methods can be used to determine erosion and deposition coefficients used in numerical models.

Continuation of existing sediment monitoring in the Delta and Suisun Bay (presently funded by CALFED) and in the rest of San Francisco Bay (presently funded by the U.S. Army Corps of Engineers as part of the RMP, Buchanan and Schoellhamer 1998) should be supported as it will provide information on an ecologically important state variable (Cloern 1987), linkage between watershed/Delta/Bay (Porterfield 1980, Goodwin and Denton 1991, Schoellhamer 1997), long-term trends (Jaffe and others 1996, Oltmann 1996), seasonal and annual variability (Krone 1979, Schoellhamer 1996, 1997), sediment supply needed for habitat restoration and levee improvement (Oltmann 1996), effect of habitat restoration on sedimentation, contaminant transport (Domagalski and Kuivila 1993, Flegal and Sanudo-Wilhelmy 1993, Luoma and others 1995, Schoellhamer 1997), entrapment mechanisms (Schoellhamer and Burau 1998), budgets of sediment and sediment-associated constituents (LTMS 1996), and factors that affect sediment transport (Krone 1979, Schoellhamer 1996 and 1997, Schoellhamer and Burau 1998). The data also will be valuable for any future sediment modeling effort. The cost of the current sediment network is roughly $600K/year.

Bathymetry

Channels can fill by several meters in a few years, so bathymetric data must be gathered periodically to maintain accurate topography. Many of the channels are gauged for stage and flow velocity to derive flow rates. If cross-sectional area is changed near the gages, the flow rates change accordingly. To maintain accuracy, cross-sectional measurements of channel topography should be checked periodically. We note that using flow and bathymetric data to predict movement of large bars in the Delta will be a sensible engineering approach for assessing the effects of proposed mitigation projects.

We recommend that multi-beam sonar surveys of various areas of the Bay be done as a part of routine monitoring of the Bay. The particular activities we envisage are:

- To check for large-scale/long timescale erosion/deposition, the entire Bay should be surveyed once every 5-10 years at a cost of $100K to $200K each time.
- Specific areas, including key Bay/Delta channels should be surveyed more frequently particularly after floods. Cost unknown.
- Channels and shallows near and within Delta islands flooded as part of CALFED should be surveyed at least annually if not more regularly

Given the size and complexity of the Delta, it is likely that the Delta will probably be surveyed by various agencies collecting data relevant to their interests. In this case, topographic data should be distributed in a format common to hydrographic surveying.

Modeling

Because there exists considerable temporal and spatial variability in the currents and water properties of the Bay/Delta, it is unlikely that hydrodynamic field measurements alone will ever be dense enough in space and time to describe the circulation and mixing properties adequately. For example, computing the surface area extent at any time of waters having a specified salinity range is virtually impossible observationally, yet is trivial to do with a numerical model. Therefore, numerical models are needed to fill in gaps in data collection and to interpret sparse observations. Models also are needed to investigate management questions relating to physical or operational changes in the bay/delta.

Although, traditionally, modeling has not been viewed as monitoring, modeling technology and computer systems recently have advanced to such a degree that large volumes of hydrodynamic modeling data, usually in a graphical form, can be delivered to decision makers and the public in near real time in much the same way as measured data. The USGS in collaboration with NOAA have demonstrated a highly successful real-time hydrodynamic modeling system for San Francisco Bay that delivers hourly maps of the horizontal current patterns in the bay to a public site on the world-wide web (WWW) (see http://sfports.wr.usgs.gov). A similar real-time modeling system, that combines a 1-D (or possibly 2-D or 3D) model of the delta and a 3-D model of the bay, would be invaluable for assisting with delta operational decisions and for use by bay and delta biological monitoring programs (e.g. to guide in selecting sampling dates and locations).

An important element of a real-time modeling system would be the use of formal data assimilation techniques. For example, one such approach. "nudging" is used in meteorology to adjust (or nudge) the results of a numerical weather prediction so that they bets match observations, and also don't render the model unstable. There is a growing use of such models in oceanography as well, including a recent application by Rutgers in which data streams from a diverse monitoring network are assimilated into a model of coastal circulation in the New York Bight. In this example, the model forecasts have been used to guide field sampling programs; in the case of the Bay/Delta, they would be used to help guide biological sampling programs, as well as to guide operations.

Ideally, the model used would be three dimensional and cover all of the Bay at relatively high spatial resolution. In effect it would be a computational replacement for the Corps of Engineers Bay Model. Current efforts at Stanford with a 2D/3D model of the Delta spanning the same domain as existing 1D models and having 50m resolution reveals the inherent challenge: Given 1998 hardware and a single fast processor, the code runs at about real-time speed, i.e., one day of simulation takes roughly one day of computation. Thus, besides improving accessibility of delta hydrodynamic information, e.g. Clifton Court gate operations, cross-channel gate operations, and barrier installations, it will be necessary to improve computational efficiency by creating a code that can be effectively used on a network of fast workstations. This programming paradigm is currently being pursued at several places including UC Berkeley. The hardware itself is not prohibitively expensive: a machine consisting of 32 top of the line Pentium II CPUs costs approximately $100K and offers the prospect of a 32 times speed up over the single CPU model.

Finally, numerical simulations of tidally varying flows from a real-time delta model could be time-averaged on a tidal cycle basis to develop complete distributions of net flows in delta channels. These distributions could be plotted on maps, delivered to the WWW (with one day lag time), and saved for future reference. Similarly, the bay portion of the modeling system could be used to produce maps of both tidal and net (residual) currents, salinity (showing X2), and gravitational circulation. These modeling data would be meant to supplement measured monitoring data and would be very helpful in assessing the hydrodynamic effects of any CALFED actions.

The cost of this effort would include $100K+ of capital cost of the computers, plus networking and possibly upgrading other hydrodynamic data monitoring to be available in real time to the modeling computer. It would also require implementation of the chosen assimilation scheme, modifying the circulation code of choice to run on a parallel computer, and finally operation. These activities would probably occupy at least 2 PhD level engineer/scientists plus a programmer at ca. $150K/y each, and should be done by an agency and university in partnership rather than by an agency or university alone.

4. Needed Research

The principal aims of the research program should be to:

- Resolve key issues regarding the hydrodynamic functioning of the Delta, and thus determine the limits of one and two dimensional transport models in the Delta. This will improve the predictive ability of Delta models, and will help address several controversies related to Delta hydrodynamics.
- Establish and understand the dynamical basis of transport through and around the system, especially given that Lagrangian and Eulerian averages may well be different. This is fundamental to understanding how the system functions physically, and thus to understanding how physical transport affects estuarine ecosystem functioning. It will also help define how 3D modeling must be done so as to accurately predict transport.
- Understand the physical functioning of existing shallow water areas and how they interact with adjacent wetlands and marshes, as well as with nearby channels. Given the major role shallow areas play in CALFED plans, and the paucity of data for estuarine and delta shallows, it seems imperative that research efforts be directed towards this goal.
- Establish calibration of key cross-sections for flux computations. This means empirically determining how to use limited (point measurements) of flux to compute area and tidally averaged values.
- Determine how Ocean-Bay exchanges are regulated by river flow and tides. A number of Bay/Delta fish species must either enter or exit the Bay through the Golden Gate, something that has been postulated to be hydrodynamically mediated.
- Identify physical mechanisms for concentrating organisms in the low salinity zone. Recent work on the physics of the low salinity zone suggests that the assumed ETM circulation pattern is not present, yet concentrations of organisms are observed nonetheless. Given the challenges of making adequate Lagrangian measurements, this will require conjunctive use of field observations and numerical modeling.
- Establish the material properties of Bay sediments and how they behave in the waters of the Bay/Delta
- Develop and validate the operation of the 1D/2D/3D (dimensionality to be determined) real-time, data assimilating hydrodynamic model for parts or all of the Bay/Delta

<u>Delta hydrodynamics</u>

Specific issues that will be need to be addressed to make necessary improvements in modeling the Delta and to confidently predict changes in flow regime that might accompany CALFED actions include:

- Determining how net transport (Lagrangian) through major cross-Delta connections like Threemile Slough and Georgiania Slough depends on different hydrodynamic/hydrologic conditions, particularly for low flows and high exports.
- Resolving the hydrodynamic basis and accuracy (or limitations) of QWEST and of Carriage Water. These are indicators of Delta hydrodynamics and represent respectively the extent of mean transport towards the pumps and the outflow required to meet salinity standards. The utility of these flowrates in managing Delta flows is contingent on the extent to which their underlying premises and assumptions are valid. These are both likely to be tied into the dynamics and net dispersion associated with the major cross Delta connections. Thus, addressing these issues will require a mixture of modeling and direct observation with drifters of Lagrangian motions indicative of the paths taken by passive particles like fish eggs.
- Determining how residence time in shallows like Franks Tract, Sherman Lake, or Prospect Island depends on tidal and flow conditions. This could be done using tracers like SF_6 (Clark ref.), or with naturally occurring chemical markers (Paulsen thesis), and would be coupled with Eulerian measurements like those recently (1997-98) carried out in Honker Bay by Jessie Lacy and Jon Burau.
- Quantifying the extent (degree of completeness) of cross-sectional mixing in channels, as well as the effects of large and small channel junctions, channel sinuosity, and of channel curvature on mixing. This will enable us to assess the accuracy of transport predictions made using simple but efficient models of Delta hydrodynamics like DSM2 that assume cross-sectional homogeneity. This would entail the combining Eulerian hydrographic measurements with measurements

of mixing of fluorescent dyes, as has been done the past two years by the USGS in their South Delta studies. These observations would be supported by three-dimensional modeling.

Despite the large modeling effort and recent USGS field studies, the complex dynamics of the Delta, particularly the interplay of mixing and transport processes remain poorly understood. What is needed is the not only data collection and modeling, but a serious effort and fitting these efforts into some analytical framework that gives a correct picture of how the Delta functions. Thus, we view a comprehensive synthesis of past and proposed work as essential to better understanding how the Delta functions.

Shallow water dynamics

A major question pertaining to the dynamics of the shoal and shallow regions of the Bay/Delta is the effects of winds. Although wind-driven currents are generally weaker than tidal ones, wind-generated waves probably plan an important role in sediment resuspension and vertical mixing. Moreover, from the standpoint of circulation modeling, windwaves are known to significantly enhance the effective bottom roughness felt by tidal flows. Thus we recommend a series of field experiments aimed at describing the wave field in a shallows like Honker Bay or Grizzly Bay, and its effect on circulation and sediments. This entails directly measuring windwaves, something that has only been done once before in the Bay to our knowledge.

Given the importance of "lakes" produced by breaching levees to the CALFED program, it will also be important to describe wind-driven waves and flows in a weakly tidal area such as Franks tract, where wind-induced circulation may provide the majority of flushing of the "lake". Similar methodologies to that used in the Bay shallows would probably work, although (again) introduced tracers like SF6 might provide important Lagrangian information.

Finally, there is the issue of how shallow regions interaction with marshes and their associated network of channels. Clearly field experiments and modeling will need to be pursued to address the dynamics of this interaction and to develop predictive tools for use in planning restoration actions. Further discussion of these issues is left to the shallow water section elsewhere in this report.

Transport processes and flow structure in Suisun Bay and beyond

Suisun Bay has received the most observational attention and is probably the best understood of all of the parts of San Francisco Bay. Nonetheless, we still lack a quantitative understanding of many fundamental issues specific to Suisun Bay and the low salinity zone (the region around X2). First and foremost, there is the issue of the ETM/EZ – there are clearly aggregations of organisms in this region, yet recent observations seem to refute the classical EZ mechanism (which does seem to work in the Chesapeake). Thus, in order to test the hypothesis that this aggregation has a physical basis, we recommend that field work emphasizing Lagrangian and Eulerian measurements be done in conjunction with detailed modeling. We envisage use of tracers like SF6 to extend Lagrangian measurements over the entire spring-neap cycle. The modeling effort required here is somewhat different from what one would do for longer term transport studies in that the emphasis would be on dissecting the physical processes operant in Suisun Bay, and perhaps identifying key places for making field measurements.

We imagine that a comprehensive effort of this kind, modeled on past EZ studies would address the suite of questions past work has raised:

- How much of the upstream and downstream transport of materials through Suisun Bay is via the northern set of channels (Suisun Cutoff + Mothball Fleet) as opposed to the more southern shipping channel?
- For various hydrological scenarios, what are residence times in Honker and Grizzly Bay, and how do they interact with each other?
- What effects does the operation of the Montezuma slough tide gate have on transport and dispersion in Suisun Bay.
- What are the roles of smaller channels (e.g. Spoonbill slough or the channel adjacent to Snag Island) in mixing and transport?
- What is the role of bathymetry on exchange flows through Carquinez Strait and in the Benecia region?
- What are the dynamics of the exchange of Bay/Delta waters with the coastal ocean through the Golden Gate? Given the logistics involved in this part of the Bay, quantifying and understanding flows through the Golden Fate will require a major field study taking several years. While this region is technically outside the CALFED region is clear from a number

of perspectives, e.g. modeling, recruitment of organisms from and to the ocean, it appears to be a key piece of the puzzle regarding the way many biological resources of the Bay/Delta vary from year to year. We view this as a high priority activity.

Finally, as with the Delta work discussed above, we take it to be essential that the various field activities be synthesized into an accurate working picture of how the northern reach of San Francisco Bay moves and disperses organisms and materials.

Fluxes

A research program should be established that addresses the spatial and temporal variability at each specific prospective sampling location. First, depending on the site, the spatial variability in the currents and parameters of interest should be documented using profiling equipment at regular intervals across the cross section. If the prospective site is strongly tidally affected these preliminary studies should be conducted over as many tidal cycles as is practically possible to uncover possible ebb/flood asymmetries in the velocity and concentration distributions. Finally, depending on the variability observed in the tidal cycle measurements, a network of ADCPs should be deployed for several months at a time to monitor the spatial variations in the residual current field. Based on analysis of these data the minimum appropriate level of instrumentation needed to accurately monitor the flux through a given section could be determined.

Correctly "removing" the tidal signal from the raw flux data through some sort of averaging or filter requires the data must accurately represent tidal timescale variations without ebb/flood bias. Since the tides can be thought of as a summation of sinusoidal signals that vary at roughly daily and twice daily frequencies, adequately resolving tidal timescale variability routinely requires sampling at hourly intervals. Hourly sampling makes it virtually impossible to routinely compute fluxes of many biological parameters of interest, therefore research into decreasing the total required sampling effort ought to be an integral part of any monitoring program aimed at computing fluxes in the Bay/Delta.

Sediments

The three most important data gaps regarding sediment deposition and resuspension that need additional study are quantification of 1) physical characteristics of suspended material; 2) material properties of Bay/Delta sediment beds, and 3) wind-waves and sediment resuspension in the shallows.

Any attempt to construct a budget of sediment or a sediment-associated contaminant would require knowledge of sediment sources and sinks. The annual recycling of sediment by resuspension and deposition, however, is probably one to two orders of magnitude greater than the annual inflow or outflow of sediment (LTMS 1996), so such a budget probably would be relatively insensitive to an improved estimate of the external (to the Bay) sources and sinks. The last comprehensive study of sediment supply to the Bay was conducted by the USGS in the 1950s (Porterfield 1980) and changes in sediment supply from the Central Valley (Oltmann 1996) and urbanization of local watersheds have altered sediment supply to the Bay. Sediment flux through the Golden Gate would be extremely difficult and probably infeasible to measure accurately.

There are other data gaps that can be eliminated with additional studies. Measurements of bottom shear stress and resuspension would help quantify the resuspension process. Processing of remotely sensed images in real time would help to define the spatial variability of SSC that could be used by sampling programs. A seasonal coring program could help us understand seasonal deposition and resuspension cycles. Jaffe and others (1996) are using historical bathymetric surveys to study deposition and erosion patterns (decadal time scale) in San Pablo and Suisun Bays and these could be extended to Central and South Bays.

Sampling protocols

Sampling the physical, chemical, and ecological constituents of an estuary is complicated by variability at many time and space scales that can bias trend analysis of data. Using predicted tides to schedule sampling of suspended-solids concentration (SSC) and sediment-associated pesticides during flood pulses at Mallard Island produced more accurate results than random sampling (Jennings and others 1997). SSC varies with the fortnightly spring/neap cycle, so sampling the estuary over a period of several days can produce an inaccurate portrayal of the spatial distribution of sediment (Schoellhamer 1996) and sediment-associated contaminants (Schoellhamer 1997). SSC in shallow water can be very different than SSC in deep channels due to cycles of deposition and resuspension and the location and timing of sample collection can greatly affect results (Ruhl and Schoellhamer, unpub. data, 1998).

Ecological and water-quality sampling is time-consuming and expensive, so the number of samples that can be collected is limited. Proper selection of sampling times and locations that also considers the goals of the sampling program can reduce or eliminate the possibility of the sampling design biasing results. Additional research is required to determine the optimal number and timing of discreet samples which best reflect the temporal and spatial variability of the estuary and meet project specific goals.

Modeling

Delta Modeling--One-dimensional delta models already have been used extensively to examine the impacts of delta flows on CalFed alternatives. It is likely they will continue to play an important role in studies into the foreseeable future. We view there being four important tasks required to improve modeling of the Delta:

1. In conjunction with the field program discussed above and through the use of two and three dimensional modeling, we must assess whatever limitations might exist for using a one dimensional model like DSM2 for transport predictions. The issues include where and for what conditions is the 1D model appropriate? What features of Bay/Delta flows can be described or predicted using a 1D model? When and where are lateral and vertical variations in flow and salinity significant? How do we develop/predict the parameters necessary to incorporate non-channel elements like shallow water areas into 1D models?
2. Assuming that the 1D model is generally suitable for transport predictions, it must be mated to a 3-D bay model for use in developing the real-time modeling system of the entire bay/delta estuary discussed above.
3. To improve the accuracy of delta models, however, a new detailed, comprehensive, and high resolution (10m) bathymetric data set should be collected, ideally with multi-beam sonar (see above under monitoring).
4. New calibration and validation of Delta models using new hydrodynamic flow data is recommended. This work must include a determination of various error measures and of sensitivities of computed results to calibration parameters. Using new Lagrangian data, error reporting should include measures of the ability to predict transport over a period of time long enough to move materials across or through the Delta. Findings from the calibration/validation should be made widely available through an interagency publication and should thoroughly address the applicability and accuracy of computational results.
5. Finally, we feel certain that analyses of some of the proposed "Through-Delta" modifications to the delta will require at least a 2D if not 3D model. Moreover, for real-time purposes, 2D/3D models may have adequate speed especially given continued advances in computing power. Thus development and testing of a 2D/3D delta models should be continued in parallel with the refinements to the existing 1-D models. In reality, these two classes of model are complementary: informed with results from the 2D/3D model as well as field data, 1D models might be constructed that give accurate predictions for long-term simulations of system behavior such as might be required to evaluate the water supply impacts of various CALFED actions.

Bay Modeling-

A new 3-D model of the bay portion of the estuary has been under development by the IEP and is nearly ready for applications. At the same time, TRIM3D has been applied to the whole Bay by Ralph Cheng at the USGS, and to the South Bay by Ed Gross at Stanford. Both the USGS and Stanford applications includes calibration to current meter data; the Stanford application also include validation of intertidal transport by comparison to USGS salinity transect data (see:). To apply either TRIM3D or the IEP model to the northern reach requires completion of several tasks:

1. An appropriate domain must be chosen for 3D modeling. This requires determining what part of the Bay is of interest and locating open boundaries far enough away from the region of interest to allow the model to be realistically constrained, but not overly controlled, by the boundary data, which must be supplied. This choice will require model execution as well careful selection of open boundaries for which good data can be found. Note that several of the monitoring and research activities described in this section would provide such data.
2. The model must be calibrated and validated with field data from a range of hydrologic conditions. Because of river flows, harmonic constants for Suisun Bay can vary by 10% in the channels and perhaps more in the shallows. Thus, calibration should be done for specified periods of time for which suitable field data exist using actual real not

harmonically derived data. As part of this activity, the degree to which scalars (a must) and momentum are conserved by the code. Conservation of scalars like salt is a must, whereas exact conservation of momentum is not necessarily important because bottom friction, the sole calibration parameter in a 3D model, represents a variable momentum sink. However, momentum conservation may be important when the water column is stratified and bottom friction is weakened. It should be recognized that for codes with state-of-the-art advection schemes and capable of providing good resolution of bottom bathymetry (probably about 100m) the quality of calibration may be limited by our present inability to model turbulence in stratified flows.

3. In application, the model should be used to hindcast data sets other than that used for calibration, to model details of flows observed in the field (see above), and as a component of the real-time modeling system discussed above. The latter application will require study of the best means for using different types of data available, and for determining which data might be most useful to making accurate predictions. A careful study of the different types of assimilation schemes available will be required.
4. To obtain the necessary efficiency to model large sections of the Bay at adequate spatial resolution, research will need to be conducted into methods of making existing circulation codes run efficiently on moderate parallel machines (ca. 32 processors). This involves dealing with issues of parallel programming paradigms as well as choices of numerical methods that are well-tailored to parallel machines.
5. The modeling system will require a high degree of graphics capability, i.e., attention should be given to making model output as easily accessible as possible to as broad a community of end users as possible. To make the code useful to fisheries biologists, geochemists, and system ecologists, particle-tracking, sediment, and biological/chemical modules should be added to the model.

Once operational, this replacement for the physical Bay Model will be used to carry out studies aimed at improving or developing our understanding of the physics of Suisun Bay (X2, EZ, etc.) and of the lower estuary (recruitment of species by gravitation circulation, etc.). Moreover as has been shown in the Chesapeake (ref.s), 3D circulation models can be particularly valuable for providing information about particle motions over many tidal cycles, something that is fundamental to all of what we have written above about the importance and monitoring of hydrodynamic processes.

5. Indicators

The proposed use of single station currents, depths and limited concentration/number density to infer fluxes make these measurements constitute a form of hydrodynamics indicator. In this way inferred mass fluxes like, DAYFLOW and QWEST are also indicators respectively of net river flow out of the Delta (and hence fluxes into the Bay) and flow across the Delta towards the pump (and hence fluxes towards the pumps). X2 is an indicator of the overall salinity structure of the Bay/Delta. Finally water level at the Golden Gate is a general indicator of the tidal hydrodynamic forcing of the system.

6. Linkages

Hydrodynamic processes affect many aspects of the ecological functioning of the Bay/Delta, with direct connections generally stronger at the lowest trophic levels. Virtually all elements of the hydrodynamics program have natural linkages to other CMARP elements. Particular linkages we see as being strongest and most obvious include:

- X2-fish relations: A number of the postulated mechanisms for X2 dependence of species abundance have physical underpinnings, especially several like Crangon Fransiscorum that may involve the effects of gravitational circulation on recruitment, or with the dynamics of the low salinity zone .
- Shallow water habitat: Hydrodynamic and sedimentary processes are clearly fundamental determinants of the physical character of shallow water habitat, both in terms of defining current conditions and in influencing the creation of suitable habitat via restoration program elements.
- Contaminants: Contaminant geochemistry is tied to both transport and sediments.
- System productivity - As stated above, lower trophic levels have been identified as being substantially regulated by physical processes. For example, the regulation of primary production by benthic grazing is strongly influenced by the presence or absence of stratification. Primary production can also be controlled by the length of time phytoplankton

cells remain in regions conducive to growth, e.g. shallows or the photic zone in the channel. Finally, the importance to the overall food web of microbial processing of organic matter input into Suisun Bay may well be determined by the residence time of organic particles in Suisun Bay.

In order to pursue these linkages, it is vital that the monitoring of hydrodynamic processes focus on what is important in the end for the biology and geochemistry, as was done in the IEP's EZ studies of 1995-97. This requires that consideration be given to hydrodynamic processes at an early stage in any research or monitoring activity in which physical processes like transport might be important, and that scientists and engineers versed in hydrodynamics be active participants in many of the monitoring and process studies of that CALFED undertakes.

Attachment H1: Summary of hydrodynamics studies

Instrument abbreviations are as follows (listed alphabetically): (AA - Price AA current meter, Aandera - Savonius rotor current meter, AD - Sontek Acoustic Doppler velocity meter, ADP - Sontek Acoustic Doppler Profiler, ADCP - RD Instruments Acoustic Doppler Current Profiler, CTD - Conductivity, Temperature, Depth sensor, D - Alpha-Omega depth/temperature sensor, Endeco - ducted impeller current meter, OBS - Optical Backscatter Sensor, S4 - Interocean velocity meter.)

Study: Current measurement at the Golden Gate
Location: Golden Gate
Time: 1914
Agency: USGS
Principal Investigator: Gilbert
Parameters measured: currents
Equipment used: AA.

Study: Current measurement in North Bay
Time: 1956-1969
Location: North Bay
Agency: Unknown
Principal Investigator: R.W. Carter (analyzed by Peterson et. al. 1975)
Parameters measured: currents, salinities.
Equipment used: AA, salinometer.

Study: Drifters in San Francisco Bay
Time: 1970-1971
Location: Throughout Bay including near-shore ocean.
Agency: USGS
Principal Investigator: T.J. Conomos
Parameters measured: Drifter release and recovery positions.
Equipment used: Buoyancy adjusted drifters

Study: Circulatory study (primarily for navigation).
Location: 97 different location throughout the bay.
Time: 1979-1980
Agency: NOAA - USGS
Principal Investigator: R.T. Cheng
Parameters measured: currents, sea level, temperature, electrical conductivity.

Equipment used: many Endeco, and Aanderaa meters.

Study: Shallow water current meter study
Time: 1985
Location: South Bay.
Agency: USGS
Principal Investigator: J.W. Gartner
Parameters measured: currents
Equipment used: 1 Endeco, 1 Aanderaa, 1 S4 and 1 General Oceanics velocity sensor.

Study: Velocity profile measurement in Carquinez Strait
Time: 1986
Location: Wickland Oil pier.
Agency: USGS
Principal Investigator: M.R. Simpson
Parameters measured: Velocity profile.
Equipment used: 1 ADCP.

Study: Salinity profiling program ("Running with the tide")
Time: 1985-1986
Location: North Bay.
Agency: IEP (USBR, USGS, DWR)
Principal Investigator: J. Arthur
Parameters measured: Conductivity, temperature, turbidity, depth profiles.
Equipment used: Seabird CTD profilers.

Study: South San Francisco Bay circulation and mixing study
Time: 1987
Location: South Bay.
Agency: USGS, UCD, USBR
Principal Investigator: J. Cloern
Parameters measured: Conductivity, temperature, turbidity, depth profiles, Chlorophyll a.
Equipment used: Seabird CTD Profilers.
Study: Roe Island circulation study
Time: 1986
Location: Several channels near Roe Island.
Agency: IEP
Principal Investigator: B. Mortenson
Parameters measured: Currents, sea level and salinity.
Equipment used: 3 Endeco,s.

Study: Turbulence and bottom boundary layer experiments in South Bay
Time: (1) 10/94, (2) 2/95, (3) 5/96, (4) 6/96, (5) 10/97, (6) 1/98, (7) 5/98, (8) 7/98.

Location: South Bay
Agency: USGS
Principal Investigator: J. Gartner (data collection), R. Cheng (analysis), G. Tate (GEOPROBE data collection), D. Cachione (GEOPROBE data analysis)
Parameters measured: Current profiles, sea level, salinity, turbidity.
Equipment used: (1) 5 ADCP's, 3 CTD's, 1 GEOPROBE.
Equipment used: (2) 3 ADCP's, 3 CTD's, 2 OBS's, 1 GEOPROBE.
Equipment used: (3) 2 ADCP's, 2 CTD's, 2 OBS's.
Equipment used: (4) 3 ADCP's, 3 CTD's, 3 OBS's, 1 S4.
Equipment used: (5) 2 ADCP's, 3 CTD's, 3 OBS's, 1 LISST (particle size analyzer).
Equipment used: (6) 2 ADCP's, 3 CTD's, 3 OBS's, 1 LISST.
Equipment used: (7) 2 ADCP's.
Equipment used: (8) 2 ADCP's, 3 CTD's, 3 OBS's, 1 LISST.

Study: Lower Sacramento River salinity intrusion study
Time: 1987-1993
Location: Sacramento River channel markers 14, 18, 22.
Agency: USCOE
Principal Investigator: G. Nichol
Parameters measured: Currents, sea level and salinity.
Equipment used: 6 S4,s.

Study: Delta outflow measurement
Time: 1988
Location: Chipps-Mallard Island.
Agency: USGS
Principal Investigator: L. Smith
Parameters measured: Current profiles.
Equipment used: 1 ADCP.

Study: ADCP deployments
Time: (1) March-November 1988, (2) March-April 1990, (3) October-November 1990, (4) December 1990-June 1991
Location: (1) Carquinez Strait, (2) Carquinez Strait, (3) San Pablo Bay, (4) Carquinez Strait.
Agency: USGS
Principal Investigator: M. Simpson
Parameters measured: Current profiles.
Equipment used: 1 ADCP.

Study: Cohesive sediment study
Time: 1990
Location: Carquinez Strait.
Agency: USGS, Australian Institute of Marine Science

Principal Investigator: R. Cheng
Parameters measured: Current profiles and CTD-OBS profiles
Equipment used: 1 ADCP, Seabird CTD profilers, nephelometers.

Study: Carquinez Strait flux study
Time: 1990
Location: Carquinez Strait.
Agency: USGS
Principal Investigator: P. Smith
Parameters measured: Current profiles and CTD-OBS profiles
Equipment used: 1 ADCP, Seabird CT Profilers.

Study: Entrapment zone studies
Time: 1993-94-95-96
Location: Suisun Bay.
Agency: USGS
Principal Investigator: J. Burau
Parameters measured: Current profiles, sea level, salinity, turbidity.
Equipment used (1993): 4 ADCP's, 7 CT's, 1 CTD.
Equipment used (1994): 5 ADCP's, 3 CT's, 4 CTD,s.
Equipment used (1995): 4 ADCP's, 8 S4,s, 1 CT, 15 CTD,s, 14 OBS,s.
Equipment used (1996): 3 ADCP's, 6 S4,s, 6 CTD,s, 3 OBS,s.

Study: Suisun Cutoff Turbulence study
Time: 1994
Location: Suisun Bay.
Agency: USGS
Principal Investigator: J. Burau (data collection), S. Monismith & M. Stacey (analysis)
Parameters measured: Current profiles, sea level, salinity.
Equipment used: 3 ADCP's, 1 CT, 5 CTD,s.

Study: Honker Bay
Time: 1997-1998
Location: Suisun Bay.
Agency: USGS - Stanford
Principal Investigator: J. Burau (data collection), S. Monismith & J. Lacey (analysis)
Parameters measured: Current profiles, sea level, salinity.
Equipment used: 4 ADCP's, 9 S4,s, 13 CTD,s, 11 OBS, 8 D,s.

Study: Napa-Sonoma Marsh
Time: 1997-1998
Location: Suisun Bay.
Agency: USGS - UCD

Principal Investigator: J. Burau (data collection), G. Schladow & J. Warner (analysis)
Parameters measured: Current profiles, sea level, salinity.
Equipment used: 1 ADCP, 3 ADP,s, 2 AD,s, 10 S4,s, 13 CTD,s, 11 OBS, 8 D,s.

Study: South Delta VAMP flow and tracer-dye
Time: spring 1997
Location: South Delta
Agency: USGS
Principal investigator: R. Oltmann
Parameters measured: velocity and stage (tidal flows computed at six sites); dye concentration (monitored at nine sites)
Equipment used: 6 ADCPs, automatic water samplers

Study: South Delta VAMP flow and tracer-dye
Time: spring 1998
Location: South Delta
Agency: USGS
Principal investigator: R. Oltmann
Parameters measured: velocity and stage (tidal flows computed at seven sites); dye concentration (monitored at ten sites)
Equipment used: 6 ADCPs, 1 S4, automatic water samplers

Study: Sacramento-San Joaquin River confluence flows
Time: fall 1998
Location: Western Delta
Agency: USGS, DWR
Principal investigators: R. Oltmann and J. Burau
Parameters measured: velocity andstage (tidal flows computed at nine sites); salinity.
Equipment used: 6 ADCPs, 10 S4, 6 CTDs

Attachment H2: Computing Fluxes

The first difficulty in tidally averaged flux computation is basically a signal-to-noise problem where one tries to extract a small net quantity, which is in this case our desired signal, by removing a (usually) much larger tidal fluctuation, the "noise" for the purposes of this discussion. If the ratio of signal/noise is small, as it often is in the Bay and Delta, then the required accuracy of the measurements is increased making the computation of the net flux more difficult (if not impossible). For example, in the case of the mass flux (Delta inflows), the signal to noise ratio is large on the eastern fringes of the Delta because tidal influence is minimal in this part of the Delta, making the calculation of net quantities relatively easy from a temporal standpoint. On the other hand, as one nears the ocean, the ratio of the net flows to the tidal flows decreases and it becomes increasingly difficult to calculate the net flows and therefore the net flux of anything moving with the water. As an example, net Delta outflow in the summer low flow period is on the order of 5,000 cfs, whereas the tidal flows during this period are roughly 200,000, 300,000, and 600,000 cfs at Rio Vista, Chipps Island, and Carquinez Strait, respectively, giving signal to noise ratios of 0.025, 0.017, and 0.008. These signal to noise ratios are a worst case for these locations because the net flows reach their minima during this period. During periods when Delta outflow is high (say 200,000 cfs) these ratios (1.0, 0.67, 0.33, at Rio Vista, Chipps Island, and Carquinez Strait, respectively) are much larger for the same tidal flows making it easier to compute the net flows.

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In addition to temporal variability, the degree of cross-sectional inhomogeneity in the current and concentration distributions, to a large degree, determines whether or not fluxes can be practically computed. If, for example, the currents and concentrations are perfectly homogeneous throughout a given cross section, then the flux can be computed simply as the product of a single measurement of the current, a single measurement of the concentration made anywhere in the cross section (preferably near the shore) multiplied by the cross sectional area, which requires that the depth be measured.

Narrow, straight, prismatic channels are likely to be the most spatially homogenous whereas cross sections with considerable variation in depth or cross sections near contractions, expansions or near bends are more likely to have spatially inhomogeneous velocity and concentration fields. For example, in this system, the relatively narrow prismatic channels typical of the eastern Delta are the Bay's closest approximation of homogenous conditions and therefore it is likely that fluxes may be reasonably computed from a single measurement of the velocities and concentrations within the cross section. In most locations, particularly in the Bay, however, the velocity and concentration distributions will likely be spatially variable. Accurately measuring fluxes where the cross sectional variability is large may require a prohibitively large number of sampling locations in the cross section. The minimum spatial coverage needed to calculate accurate fluxes is therefore site specific and determining the required coverage is a necessary research activity prior to the establishment of any flux-based monitoring program.