

Report on the CALFED Science Program Workshop “Defining a Variable Delta to Promote Estuarine Fish Habitat”

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Executive Summary

On June 11, 2007 the CALFED Science Program hosted a workshop titled “Defining a Variable Delta to Promote Estuarine Fish Habitat.” The Workshop included six technical presentations followed by an audience participation/panel discussion. This workshop was inspired by the Variable Delta Hypothesis (VDH), which was originally outlined in the Public Policy Institute of California report “Envisioning Futures for the Sacramento-San Joaquin Delta” (www.pplic.org). Prior to the workshop, the VDH was informally being simplified into a notion of a Delta system with variable salinity. However, the VDH encompasses more than salinity. It is based on the premise that (1) increasing the variability of estuarine habitat will improve conditions for native estuarine fishes (and the introduced sport fish striped bass), and (2) increased expanses of aquatic habitat with more variability are likely on the way, and we should attempt to manage that variability to achieve positive benefits for native species. The VDH can be stated as *increasing the variability (or heterogeneity) of the Delta’s geometry, which comprises both regional scale plan forms and local scale channel morphology, will lead to water residence time diversity that will improve habitat conditions for desirable fishes and other organisms.* A Delta with more variability in habitat gradients, it is argued, will provide more habitat that is suitable for desired species and less habitat that is suitable for undesirable invasive species like *Corbula amurensis* (overbite clam), *Corbicula fluminea* (Asiatic freshwater clam), and *Egeria densa* (Brazilian waterweed).

There was agreement among the presenters that greater variability in environmental conditions in the Delta might be good for currently desired estuarine fishes like delta smelt and striped bass, and other desirable organisms like waterfowl and invertebrates that are important as fish food. All of the presenters agreed that a focus simply on salinity variability is inappropriate; that habitat variability had to include a broad range of attributes. There was also general agreement that dendritic channel geometry would promote more variability in water residence time, salinity gradients, and other water quality attributes than the current channelized, interconnected geometry of the Delta. However, there was no consensus as to what the necessary environmental gradients and their scales of variability should be.

There is so little known regarding if or how the VDH would work because past studies, conducted on an essentially geometrically static Delta, provide few clues. Therefore,

further scientific research is needed to enhance our understanding of the opportunities and challenges for estuarine fish restoration, as system geometry evolves through either natural or anthropogenic means. Moreover, it was recognized that aquatic ecosystems do not operate in a vacuum, and thus there is a need to fully incorporate terrestrial ecologists and terrestrial wildlife issues into discussions of aquatic system restoration to provide a more holistic restoration plan.

There are predictions of the VDH that are testable, but several panelists and audience members cautioned that we do not have a level of understanding that would inform a full-scale system-level manipulation in the near-term. Existing simulation models could be used to test the water residence time and salinity responses to different combinations of channel geometry and hydrologic change. Some of this work is underway as part of the Delta Risk Management Strategy, but additional work, including examining salinity responses to specific geometric restoration concepts is needed. Unfortunately, the ecological responses to these changes are much less predictable so field and laboratory testing of predictions is desirable though such research cannot be completed as quickly as hydrodynamic and water quality modeling. It was suggested that the Science Program's Proposal Solicitation Process represents a good opportunity for focused learning about aspects of the VDH. For instance, laboratory and microcosm tests of clam responses to various salinity challenges, or field evaluations of existing dendritic marsh systems in Suisun Marsh or the Cache Slough complex could be undertaken with the goal of developing mathematical models of how these systems develop and respond to variation in habitat attributes.

One limitation is that at this point, none of these studies can be completed in time to inform the Delta Vision process under its current schedule. It is possible, but unlikely that natural catastrophic changes to the estuary will occur before a research program designed to vet the testable aspects of the VDH could be completed. However, there is an urgent need to embed the notion of a variable environment into long-term restoration planning, and there is a lot of opportunity to increase scientific understanding over the next 10-15 years during implementation of a new DeltaVision. In considering whether to incorporate the VDH into its scenarios, the Blue Ribbon Task Force will need to rely on expert opinion and alternatives that are flexible as new information becomes available.

Introduction

On June 11, 2007 the CALFED Science Program hosted a workshop titled “Defining a Variable Delta to Promote Estuarine Fish Habitat.” This workshop was inspired by the Variable Delta Hypothesis (VDH; author’s phrase), which was originally outlined by Lund et al. (2007). This report synthesizes my understanding of the VDH; it is not a transcript of the workshop. This report is partly an overview of the workshop presentations and the opinions of the presenters. Statements based on presented material are clearly referenced as such; speaker names and slide numbers are cited. All presentations are posted on the Science Program website along with this report. I also drew on published literature for some sections of the report.

It was recently estimated that there is an approximately two in three chance of catastrophic levee failure in the Delta by 2050 (Mount and Twiss 2005). Mount and Twiss’ risk analysis was based on trends of increasing sea level and continued land subsidence in Delta islands that occur in a seismically active and flood prone region. A major social and economic impact of multiple levee breaches in the Delta would be salt water intrusion, which could severely degrade water quality for agriculture and municipalities. Because of this risk, salinity has been a central focus in discussions of future environmental variability in the Delta (Lund et al. 2007).

To stimulate discussions about long-term planning for the Delta, Lund et al. (2007) described alternative long-term water management strategies that range from attempting to maintain the status quo to abandoning the Delta as a water supply. Their first order economic analyses of these strategies indicated that options which allow for significant landscape and hydrodynamic change, while accommodating at least some water supply functionality, represent the best options for achieving the dual objectives of protecting California’s water supply and preserving the estuary ecosystem.

The VDH can be stated as *increasing the variability (or heterogeneity) of the Delta’s geometry, which comprises both regional scale plan forms and local scale channel morphology, will lead to water residence time diversity that will improve habitat conditions for desirable fishes and other organisms.* Lund et al. (2007) provided lists of aquatic and terrestrial plants and animals they considered important players in the ecology and human uses of the San Francisco Estuary. The list includes species they termed both desirable and undesirable. The terms desirable and undesirable are not scientific terms. Rather, they reflect the current perception about which species are (1) economically important, (2) important from a biodiversity conservation frame of reference, or (3) provide food web support for desirable species. The undesirable species are species that limit productivity of desirable species. Key desirable species include Chinook salmon (*Oncorhynchus tshawytscha*), delta smelt (*Hypomesus transpacificus*), and striped bass (*Morone saxatilis*). Key undesirable species include overbite clam (*Corbula amurensis*), Asiatic freshwater clam (*Corbicula fluminea*), and Brazilian waterweed (*Egeria densa*).

Associated with the VDH is the idea that the appropriate conditions will come about as the result of the establishment of a more heterogeneous physical habitat than currently exists. Another key assumption of the VDH is that overbite clam (*Corbula amurensis*) currently benefits from stable brackish water conditions in the estuary that represent muted variability relative to historical conditions, and that Asiatic freshwater clam (*Corbicula fluminea*) and Brazilian waterweed (*Egeria densa*) benefit from stable freshwater conditions in the Delta. This assumption stems from invasion biology theory, which posits that long-term success of invasive species is more likely in systems that have been highly altered by humans (Moyle and Light 1996). The purpose of the June 11 workshop was to establish the state of science supporting the VDH.

The workshop included six technical presentations (Table 1). Note that some presentation titles varied from what had been printed in the public announcement for the workshop (http://science.calwater.ca.gov/pdf/workshops/SP_workshop_variable_delta_public_notice_061107.pdf). The technical presentations were followed by an audience participation/panel discussion facilitated by Dr. Ron Ott. The workshop was webcast live. The webcast archive can be seen in its entirety (<http://www.visualwebcaster.com/event.asp?regd=y&id=40345>).

Table 1. Summary of speakers and topics at the Variable Delta Workshop

Speaker	Affiliation	Presentation
Ms. Tara Smith	Department of Water Resources	Animation of salinity in the estuary with a 1995 level of development
Dr. Greg Gartrell	Contra Costa Water District	Trends in hydrology and salinity in Suisun Bay and the western Delta
Dr. Peter Moyle	UC Davis	Towards a more heterogeneous Delta
Dr. Jan Thompson	U.S. Geological Survey	Clams – where, how, and can we limit the damage?
Mr. Jon Burau	U.S. Geological Survey	Variable Delta – a hydrodynamic perspective (geometry, geometry, geometry)
Dr. Wim Kimmerer	San Francisco State University	What are the big knowns and unknowns for a variable Delta?

Historical setting

During the latter 19th century through the early 20th century, the Sacramento-San Joaquin Delta was converted, beginning with the process of agricultural reclamation, from a large tidal marsh system with a dendritic (branching) channel network into a water conveyance/flood control system with many channel connections that move water efficiently (Burau, slide 4). The current system configuration is highly dispersive because channel lengths are often less than tidal excursion distances (Burau, slide 25);

this tends to homogenize water quality throughout much of the Delta. Further, the canal-like shape of most Delta channels (Burau, slide 19) efficiently transports water and substances dissolved in water (e.g., salt), but provides little habitat heterogeneity for aquatic plants and animals (Burau, slide 20).

The State and federal water projects use reservoir releases to maintain a hydraulic barrier against oceanic salinity intrusion to support human consumptive uses of Delta water (Gartrell, slides 9 and 22). The amount of water storage capacity available to create a hydraulic salinity barrier increased dramatically through the 20th century, with the greatest increase in reservoir storage occurring from about 1945 through about 1975 (Smith, slides 8-9; Gartrell, slide 8). However, human demand for fresh water upstream of the Delta also increased dramatically. Central Valley agricultural land use increased about three-fold during the 20th century (Smith, slides 4 and 6; Gartrell, slide 7), and urban land use increased about 10-fold, with rapid increases in Sacramento Valley urban land use beginning in the early 1960s (Smith, slide 5) followed by rapid increases in San Joaquin Valley urban land use beginning in the latter 1970s (Smith, slide 7). There are two major inflow factors that affect salinity variability in the Delta. First, the increase in reservoir storage flattened the hydrograph by changing the timing of flows into the Delta (Kimmerer 2002), reducing the amount of flows in naturally high flow periods (normally winter/early spring months) and increasing the flows into the Delta during naturally lower flow periods (normally summer/early fall months). Second, the increased upstream usage reduced the quantity of water available for flows into the Delta. Other important factors that have affected the salinity variability include export and in-Delta diversions and return flows (drainages and discharges from farms), and higher specific conductance¹ in the San Joaquin River which is due primarily to drainage and discharge flows from farming in the San Joaquin watershed (Letey et al. 2002).

Analyses of diatom assemblages from sediment cores in Suisun Marsh have been used to reconstruct paleosalinity trends in San Francisco Estuary (Byrne et al. 2001). These data cannot discern seasonal variation in salinity, but they do represent multidecadal trends in average salinity conditions. The data show high variability in the mixtures of freshwater and marine diatoms over the past 3,000 years (Gartrell, slide 14). During the recent past (~ 150 years), percentages of freshwater diatoms are among the lowest for the 3,000 year time series and percentages of marine diatoms among the highest. This suggests relatively saline conditions in the estuary during the period of European colonization (Gartrell, slide 15).

In the early 20th century, the C&H Sugar Company used the Delta and Suisun Bay as a source of freshwater for its sugar refineries. They required fresh water of about 50 mg/liter chlorides, which is less than 0.1‰ (parts per thousand) oceanic salinity. For reference, ocean water is typically about 33‰ or about 330 times more salty. The distance into the estuary that C&H staff had to travel oscillated among seasons and years based on variation in river flows, but seldom exceeded 25 miles from the town of

¹ Specific conductance is the measure of the ability of a water sample to conduct electricity. It is therefore a measure of the water's ionic content and activity that approximates total dissolved solid content and is a surrogate for salinity.

Crockett on the Carquinez Strait (Gartrell, slide 17). Dr. Gartrell also estimated what the travel distances would have been for the C&H operations had they occurred during 1965-1976 and 1994-2005 (Gartrell, slide 17). During the latter periods, travel distances would have exceeded 25 miles more frequently. A change in the seasonal cycle is also apparent. In the latter two time periods, water storage and diversion has caused the seasonal transition from minimum to maximum expected travel distances to water less than 50 mg/liter chloride to happen more quickly than in the early 20th century. This suggests that there is less fresh water in the estuary now than there was 90 years ago (Gartrell, slide 18). These trends were corroborated using other data sources and methods (Gartrell, slides 27-36).

In most of the estuary, specific conductance has a pronounced seasonal cycle with typical minima in February through April and maxima in September and October (Smith, slides 17-18 and 20). However, in the San Joaquin River above Prisoner's Point, and the south Delta, the seasonal cycle in specific conductance is greatly muted and specific conductance is virtually always less than 1,000 microseimens/centimeter (about 0.6‰) (Smith, slides 21 and 23-24). Note that in this part of the system, salts in agricultural return water contribute to the specific conductance. During the previous 20 years or so, there has been a trend toward higher fall salinity in the estuary (Gartrell, slides 24-25; Feyrer et al. 2007).

Ecological setting

How are drinking water salinity variation and ecological salinity variation different?

True estuarine organisms and anadromous fishes can survive considerable salinity variation (Thompson, slide 15; Kimmerer, slide 11). In contrast, drinking water providers need the salinity of Delta water to stay as far under 1‰ as possible. This is an issue because under current operations it is typical for the confluence of the Sacramento and San Joaquin rivers to exceed 2‰ during fall (Gartrell, slide 11). Because of the tides, this slightly saline water from the western Delta frequently encroaches into areas where drinking water supplies are diverted – particularly the southern Delta intakes for the Contra Costa Water District diversions, which have salinity standards of 150-250 mg/L of chloride (less than 1‰).

The ecological salinity indicator used in the San Francisco Estuary is X_2 , which represents the approximate upstream limit of estuarine conditions. This is the distance in kilometers from the Golden Gate Bridge to the location in the estuary where the average salinity at the bottom of the water column is 2‰ (Jassby et al. 1995). During periods of very low freshwater inflow, X_2 may enter the western part of the Delta, more than 80 km from Golden Gate Bridge. During very wet periods, it may be pushed into San Pablo Bay, less than 50 km from Golden Gate Bridge. The geographic distribution of numerous organisms is generally associated with X_2 (Jassby et al. 1995; Bennett et al. 2002; Dege and Brown 2004; Kimmerer, slide 11). Note that organisms residing mainly upstream of X_2 are freshwater forms or life stages (Thompson, slide 16) even though some of the water upstream of X_2 is much too salty for drinking water. The San

Francisco Estuary's biological changeover point at salinities near 2‰ is similar to that of east coast estuaries, which generally have a turnover from freshwater forms to brackish water forms where salinities average 2-4‰ (Bulger et al. 1993).

Why are invasive species a problem for native fish and striped bass?

The VDH stems from the desire to control invasive species that act as 'ecosystem engineers' (Moyle, slide 6; Kimmerer, slide 14). Ecosystem engineers are species that dominate a system, may change its physical structure, and change the way the system functions. The following paragraphs describe the known and suspected ecosystem impacts of overbite clam (Moyle, slide 8), Asiatic freshwater clam, and Brazilian waterweed (Moyle, slide 7). There are other potential ecosystem engineers that could invade the Delta in the near future, particularly the quagga mussel (*Dreissena bugensis*).

Overbite Clam: The overbite clam was first reported from San Francisco Estuary in 1986 and it was well established by 1987 (Carlton et al. 1990). Prior to the overbite clam, there were periods of relatively low clam biomass in the upper estuary because the Asiatic freshwater clam colonized Suisun Bay during high flow periods and the native marine clam *Mya arenaria* (also known as *Macoma balthica*) colonized Suisun Bay during prolonged (> 14 month) low flow periods (Nichols et al. 1990). Thus, there were periods of relatively low clam grazing rates while one species was dying back and the other was colonizing. The overbite clam invasion changed this formerly dynamic clam assemblage. Since 1987, the overbite clam, which is tolerant of a wide range of salinity (Thompson, slide 15) is always the dominant clam species in the brackish water regions of the estuary.

The overbite clam precipitated major changes in the estuarine food web (Kimmerer, slide 19). Starting about 1987-1988, major step-declines were observed in the abundance of phytoplankton (Thompson, slide 8) and the copepod *Eurytemora affinis* due to grazing by the clam (Kimmerer et al. 1994). The influence of overbite clam grazing on phytoplankton extends into the Delta (Kimmerer and Orsi 1996; Jassby et al. 2002) beyond the clam's typical range, presumably due to tidal dispersion of phytoplankton-depleted water (Thompson, slide 9). Northern anchovy abandoned the estuary's low-salinity zone coincident with the overbite clam invasion, presumably because the sharp decline in planktonic food items made occupation of low-salinity waters unprofitable for this marine fish (Kimmerer 2006). There was also a major step-decline in mysid shrimp in 1987-1988, presumably due to competition with overbite clam for phytoplankton (Orsi and Mecum 1996). The mysid shrimp had been an extremely important food item for larger fishes like longfin smelt and juvenile striped bass; its decline resulted in substantial changes in the diet composition of these species (Feyrer et al. 2003). The population responses of longfin smelt and juvenile striped bass to winter-spring outflows changed after the invasion of the overbite clam. Longfin smelt relative abundance was lower per unit outflow post-clam (Kimmerer 2002). Young striped bass relative abundance stopped responding to outflow altogether (Sommer et al. 2007). One hypothesis to explain these changes in fish population dynamics is that lower prey abundance reduced the system carrying capacity (Kimmerer et al. 2000; Sommer et al. 2007).

Diving ducks, white sturgeon and splittail are known predators of the overbite clam. The overbite clam has a higher food uptake rate than the Asiatic freshwater clam, so it bioaccumulates toxic selenium at higher rates (Lee et al. 2006). It also has a lower clearance rate than planktonic crustaceans, which further contributes to its high selenium accumulation (Stewart et al. 2004). Stewart et al. (2004) showed that overbite clam selenium concentrations exceed the levels known to cause reproductive effects in higher trophic animals. Thus, there is concern that overbite clam predators are at high risk of reproductive impairment (Linville et al. 2002; Stewart et al. 2004; Thompson, slide 3). One recent study with a low sample size did not find evidence of selenium effects on the reproductive success of a diving duck called the lesser scaup, *Aythya affinis* that preys on overbite clam (Fox et al. 2005). Several dose-response relationships between food-borne selenium and negative health effects for splittail have been published (Teh et al. 2004). However, there has not been a determination of whether wild splittail are reproductively impaired by selenium.

Asiatic Freshwater Clam: The Asiatic freshwater clam invaded the Sacramento River in 1945 (Hanna 1966). Since it was introduced before comprehensive ecological monitoring programs were initiated, it is unknown whether there were major ecological changes associated with its introduction, although it is known that it was present in sufficient numbers to cause mechanical problems with the pumps at Tracy in 1952 and to be ubiquitous in Central Valley Project irrigation canals in 1946. Like the overbite clam it exerts strong grazing pressure on phytoplankton, particularly in heavily colonized shallow-water habitats (Lucas et al. 2002; Lopez et al. 2006; Thompson, slide 24). Adult Asiatic freshwater clams also can tolerate brackish water (Thompson, slide 15). However, Asiatic freshwater clams did not historically suppress annual spring-summer phytoplankton blooms throughout the upper estuary like overbite clams do in the brackish water zone today (Thompson, slide 10). It is unknown if the Asiatic freshwater clam populations have increased or decreased coincident with the introduction of the overbite clam. It is also unknown whether they are capable of reducing phytoplankton biomass at a larger scale today than they did historically. It will be necessary to develop numeric models to examine the importance of the different percentages of shallow-water habitat that is available to both clams and how these habitat differences might change the mass of phytoplankton that each species is capable of consuming.

Brazilian Waterweed: Brazilian waterweed is a freshwater plant commonly sold in the aquarium trade (Moyle, slide 7). Its date of introduction to the Delta is unknown, but it was abundant enough to become a boating nuisance by the late 1980s (CDBW 2001). Between the early 1980s and the early 2000s, its distribution spread from the central Delta to most of the Delta (except the north Delta) (Brown and Michniuk 2007). In mesocosm experiments, Hauenstein and Ramirez (1986) noted a dramatic decrease in Brazilian waterweed growth at salinities $>4\text{‰}$ and no growth of roots or stems at $\geq 10\text{‰}$. They did not find Brazilian waterweed at field sites where salinity was $>5\text{‰}$. In the Delta, Brazilian waterweed growth rates are positive throughout the year, but growth is most rapid during spring (Pennington and Sytsma 2006). The only limitations on Brazilian waterweed growth in the Delta seem to be (1) high water velocities which

physically prevent rooting, and (2) light, which is controlled by depth and turbidity. In clear water, Brazilian waterweed can grow to depths of 6 m (Anderson and Hoshovsky 2000). Water clarity has increased in the Delta over the past several decades (Jassby et al. 2002). The primary hypotheses to explain the increase in water clarity are (1) reduced sediment supply due to dams in the watershed (Wright and Schoellhamer 2004), (2) sediment washout from very high inflows during the 1982-1983 El Nino (Jassby et al. 2005), and (3) biological filtering by submerged aquatic vegetation (Brown and Michniuk 2007). The nearshore fish assemblages in areas infested with Brazilian waterweed have a high proportion of nonnative centrarchids (largemouth bass and sunfishes) and extremely low proportions of native fish and young striped bass (Grimaldo et al. 2004; Nobriga et al. 2005; Brown and Michniuk 2007). This suggests that the centrarchids are competitively dominant or exert a strong predatory influence on native fishes and striped bass, which are not adapted to coexist with them (Brown 2003; Nobriga et al. 2005; Nobriga and Feyrer 2007). Further, the increasing water clarity in the Delta has decreased pelagic fish habitat suitability (Feyrer et al. 2007; Nobriga et al. in press) suggesting an indirect link between Brazilian waterweed proliferation and open-water habitat quality for fishes like delta smelt.

What are the arguments for embracing the Variable Delta Hypothesis?

This section describes the conjectural basis for the VDH. The VDH is based on the premise that (1) increasing the variability of estuarine habitat will improve conditions for native estuarine fishes (and the introduced sport fish striped bass) (Lund et al. 2007), and (2) because increased expanses of aquatic habitat with more variability are likely on the way, we should attempt to manage that variability to achieve positive benefits for native species. Current projections are that major landscape and hydrodynamic changes are likely in the Delta in the coming decades due to changing climate, sea level rise, seismic and flood risk, and human development (Mount and Twiss 2005; Lund et al. 2007; Moyle, slides 11-14). These changes are likely to create a more heterogeneous land and waterscape and would have an unknown mix of positive and negative impacts on fishes and other organisms (Moyle, slides 15 and 17). Assuming the best way to deal with change is to plan for it, the potential benefits of controlled system changes are that they may increase the resilience of the Delta to changes stemming from sea level rise, earthquakes, and flooding while increasing the options for restoration of desirable species (Lund et al. 2007).

Dr. Moyle reiterated a salinity-based VDH first outlined by Lund et al. (2007). He argued that areas subjected to a salinity range of 0-12‰ for 1-2 years with the salinity lows and highs sustained for 4-5 months at a time would be unfavorable to overbite clam and Brazilian waterweed, while favoring desirable species adapted to the historical pattern of fluctuating Delta salinity regimes (e.g., delta smelt, longfin smelt, striped bass, mysid shrimp, splittail, and tule perch) (Moyle, slides 19-20).

Moyle and Burau also argued that there is a geometric or landscape aspect to the VDH. This aspect proposes that restoration that mimics the system's natural dendritic channel

structure will generate variability in water residence time that will, in turn, generate variability in salinity gradients and other water quality attributes. This small scale variability might allow fish to find and exploit microhabitats appropriate for successful completion of their life cycles (Burau, slides 28-29; Moyle, slides 21 and 25). In discussing landscape change, Moyle argued that Suisun Marsh will inevitably become more brackish as sea level rises. This assertion is of concern to waterfowl managers because Suisun marsh is currently an important habitat for migratory ducks and geese. A saltier marsh would not support the same community of birds and other organisms as the current system, which is largely managed as a low-salinity marsh that is protected by levees from intrusion of the brackish water in its sloughs. This concern emphasizes the need to recognize and plan for a broad spectrum of ecological change in the Delta in the future. Change or increasing variation in one kind of habitat that might favor some desirable species might also cause problems for other desirable species.

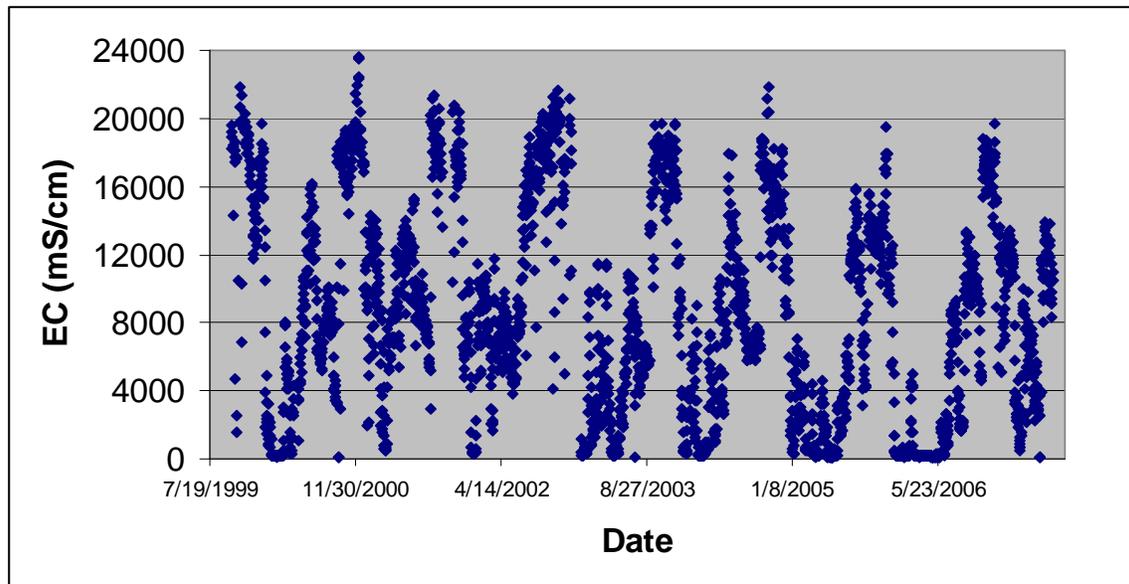
What is the state of scientific knowledge about the Variable Delta Hypothesis?

The VDH is not a true scientific hypothesis because it is not fully testable. Rather, it is a working hypothesis on which to base a strategy for native fish and striped bass restoration that might be implementable in the context of society's need to accommodate landscape and hydrologic change. No aspect of the VDH has been formally tested.

All of the presenters agreed that a focus simply on salinity variability is inappropriate; that habitat variability had to include a broad range of attributes. As an example, the overbite clam has a wide range of salinity tolerance (Thompson, slide 15). There is a salinity monitoring station at Port Chicago in Suisun Bay, which is within the 'permanent' range of overbite clam (Thompson, slide 12). The salinity at Port Chicago currently varies over values similar to those suggested by Moyle (slide 19), ranging seasonally between freshwater and >10‰ (Figure 1). When examining Figure 1, note that specific conductances less than about 2,000 mS/cm are roughly equivalent to salinities < 1‰ and specific conductances greater than about 16,000 mS/cm are generally about 10‰ or more. This suggests that the overbite clam easily survives salinities seasonally ranging from 0-12‰. Although survival over longer periods of high and low salinity as suggested by Moyle cannot be determined, it is known that overbite clams survive long periods of time in tidal reaches where salinities on the ebbing tides are at or near zero in the water column. It is also unknown if extending the freshwater period to kill overbite clams would allow Asiatic freshwater clams to establish higher populations in Suisun Bay. Thus, the dynamics of clam-phytoplankton interactions under different salinity regimes are not currently predictable. Therefore, the food web responses of fishes feeding on clams or competing with them for food are likewise not currently predictable.

As a second example, Dr. Gartrell pointed out that it is unlikely a salinity regime similar to that depicted in Figure 1 can be achieved in the Delta (given its current geometry). Initial studies indicate that 4-5 months with close to zero net outflow would be needed to get the salinity that high and then an additional 4-5 months of low outflow would be needed to keep the salinity elevated, leaving very little time for a freshwater phase.

Figure 1. Specific conductance at Port Chicago from summer 1999 through spring 2007. Data taken from the California Data Exchange Center (<http://cdec.water.ca.gov/>). Blank and zero values have been removed.



Workshop Synthesis

What did we learn from the Variable Delta Workshop?

There was agreement among the presenters that variable environmental conditions might be good for currently desired estuarine fishes like delta smelt and striped bass, and other desirable organisms like waterfowl and invertebrates that are important as fish food. All of the presenters agreed that a focus simply on salinity variability is inappropriate; that habitat variability had to include a broad range of attributes. There was also general agreement that dendritic channel geometry would promote more variability in water residence time, salinity gradients, and other water quality attributes than the current channelized and interconnected geometry of the Delta. However, there was no consensus as to what the environmental gradients and their scales of variability should be.

There is so little known regarding if or how the VDH would work because past studies, conducted on an essentially geometrically static Delta, provide few clues. Therefore, further scientific research is needed to enhance our understanding of the opportunities and challenges for estuarine fish restoration, as system geometry evolves through either natural or anthropogenic means. Moreover, it was recognized that aquatic ecosystems do not operate in a vacuum, and thus there is a need to fully incorporate terrestrial ecologists and terrestrial wildlife issues into discussions of aquatic system restoration to provide a more holistic restoration plan.

There are predictions of the VDH that are testable, but several panelists and audience members cautioned that we do not have a level of understanding that would inform a full-scale system-level manipulation in the near-term. Existing simulation models could be

used to test the water residence time and salinity responses to different combinations of channel geometry and hydrologic change. Some of this work is underway as part of the Delta Risk Management Strategy, but additional work, including examining salinity responses to specific geometric restoration concepts is needed. Unfortunately, the ecological responses to these changes are much less predictable so field and laboratory testing of predictions is desirable though such research cannot be completed as quickly as hydrodynamic and water quality modeling. It was suggested that the Science Program's Proposal Solicitation Process represents a good opportunity for focused learning about aspects of the VDH. For instance, laboratory and microcosm tests of clam responses to various salinity challenges, or field evaluations of existing dendritic marsh systems in Suisun Marsh or the Cache Slough complex could be undertaken with the goal of developing mathematical models of how these systems develop and respond to variation in habitat attributes.

One limitation is that none of these studies can be completed in time to inform the Delta Vision process. It is possible, but unlikely that natural catastrophic changes to the estuary will occur before a research program designed to vet the testable aspects of the VDH could be completed. However, there is an urgent need to embed the notion of a variable environment into long-term restoration planning, and there is a lot of opportunity to increase scientific understanding over the next 10-15 years during implementation of a new DeltaVision. In considering whether to incorporate the VDH into its scenarios, the Blue Ribbon Task Force will need to rely on expert opinion and alternatives that are flexible as new information becomes available.

References Cited

- Anderson, L, Hoshovsky, MC. 2000. *Egeria densa*. in Bossard, C. C., J.M. Randall, and M. C. Hoshovsky. Invasive Plants of California's Wildlands. University of California Press. Berkeley, CA.
- Bennett, WA, Kimmerer, WJ, Burau, JR. 2002. Plasticity in vertical migration by native and exotic fishes in a dynamic low-salinity zone. *Limnology and Oceanography* 47:1496-1507.
- Brown LR. 2003. Will tidal wetland restoration enhance populations of native fishes? *San Francisco Estuary and Watershed Science* 1: <http://repositories.cdlib.org/jmie/sfews/vol1/iss1/art2>.
- Brown, LR, Michniuk, D. 2007. Littoral fish assemblages of the alien-dominated Sacramento-San Joaquin Delta, California, 1980-1983 and 2001-2003. *Estuaries and Coasts* 30:186-200.
- Bulger, AJ, Monaco, ME, Nelson, DM, McCormick-Ray, MG. 1993. Biologically-based estuarine salinity zones derived from a multivariate analysis. *Estuaries* 16:311-322.
- Byrne, R, Ingram, BL, Starratt, S, Malamud-Roam, F. 2001. Carbon-isotope, diatom, and pollen evidence for late Holocene salinity change in a brackish marsh in the San Francisco Estuary. *Quaternary Research* 55:66-76.
- California Department of Boating and Waterways. 2001. Environmental impact report, *Egeria densa* control program. California Department of Boating and Waterways, Sacramento, California. Available: <http://dbw.ca.gov/PDF/EIR/eir.pdf> (12 May 2005).
- Carlton, JT, Thompson, JK, Schemel, LE, Nichols, FH. 1990. Remarkable invasion of San Francisco Bay (California, USA) by the Asian clam *Potamocorbula amurensis* I. Introduction and dispersal. *Marine Ecology Progress Series* 66:81-94.
- Dege, M, Brown, LR. 2004. Effect of outflow on spring and summertime distribution and abundance of larval and juvenile fishes in the upper San Francisco Estuary. *American Fisheries Society Symposium* 39:49-66.
- Feyrer, F, Herbold, B, Matern, SA, Moyle, PB. 2003. Dietary shifts in a stressed fish assemblage: consequences of a bivalve invasion in the San Francisco Estuary. *Environmental Biology of Fishes* 67:277-288.

- Feyrer, F, Nobriga, ML, Sommer, TR. 2007. Multi-decadal trends for three declining fish species: habitat patterns and mechanisms in the San Francisco Estuary, California, USA. *Canadian Journal of Fisheries and Aquatic Sciences* 64:723-734.
- Fox, GA, MacCluskie, MC, Brooke, RW. 2005. Are current contaminant concentrations in eggs and breeding female lesser scaup of concern? *The Condor* 107:50-61.
- Grimaldo, LF, Miller, RE, Peregrin, CP, Hymanson, ZP. 2004. Spatial and temporal distribution of native and alien ichthyoplankton in three habitat types of the Sacramento-San Joaquin Delta. *American Fisheries Society Symposium* 39:81-96.
- Hanna, GD. 1966. Introduced mollusks of western North America. *Occasional Papers of the California Academy of Sciences* 48.
- Haunstein, E, Ramirez, C. 1986. The influence of salinity on the distribution of *Egeria densa* in the Valdivia River Basin Chile. *Archiv Fur Hydrobiologie* 107:511-520.
- Jassby, AD, Cloern, JE, Cole, BE. 2002. Annual primary production: patterns and mechanisms of change in a nutrient-rich tidal ecosystem. *Limnology and Oceanography* 47:698-712.
- Jassby, AD, Kimmerer, WJ, Monismith, SG, Armor, C, Cloern, JE, Powell, TM, Schubel, JR, Vendlinski, TJ. 1995. Isohaline position as a habitat indicator for estuarine populations. *Ecological Applications* 5:272-289.
- Kimmerer, WJ. 2002a. Physical, biological, and management responses to variable freshwater flow into the San Francisco Estuary. *Estuaries* 25:1275-1290.
- Kimmerer, WJ. 2002b. Effects of freshwater flow on abundance of estuarine organisms: physical effects or trophic linkages? *Marine Ecology Progress Series* 243:39-55.
- Kimmerer, WJ. 2006. Response of anchovies dampens effects of the invasive bivalve *Corbula amurensis* on the San Francisco Estuary foodweb. *Marine Ecology Progress Series* 324:207-218.
- Kimmerer, WJ, Cowan, JJ, Jr., Miller, LW, Rose, KA. 2000. Analysis of an estuarine striped bass (*Morone saxatilis*) population: influence of density-dependent mortality between metamorphosis and recruitment. *Canadian Journal of Fisheries and Aquatic Sciences* 57:478-486.
- Kimmerer, WJ, Gartside, E, Orsi, JJ. 1994. Predation by an introduced clam as the likely cause of substantial declines in zooplankton of San Francisco Bay. *Marine Ecology Progress Series* 113:81-93.

- Lee, BG, Lee, JS, Luoma, SN. 2006. Comparison of selenium bioaccumulation in the clams *Corbicula fluminea* and *Potamocorbula amurensis*: a bioenergetic modeling approach. *Environmental Toxicology and Chemistry* 25:1933-1940.
- Letey, J, Williams, CF, Alemi, M. 2002. Salinity, drainage, and selenium problems in the western San Joaquin Valley of California. *Irrigation and Drainage Systems* 16:253-259.
- Linville, RG, Luoma, SN, Cutter, L, Cutter, GA. 2002. Increased selenium threat as a result of invasion of the exotic bivalve *Potamocorbula amurensis* into the San Francisco Bay-Delta. *Aquatic Toxicology* 57:51-64.
- Lopez, CB, Cloern, JE, Schraga, TS, Little, AJ, Lucas, LV, Thompson, JK, Burau, JR. 2006. Ecological values of shallow-water habitats: implications for the restoration of disturbed ecosystems. *Ecosystems* 9:422-440.
- Lucas, LV, Cloern, JE, Thompson, JK, Monsen, NE. 2002. Functional variability of habitats within the Sacramento-San Joaquin Delta: restoration implications. *Ecological Applications* 12:1528-1547.
- Lund, J, Hanak, E, Fleenor, W, Howitt, R, Mount, J, Moyle, P. 2007. Envisioning futures for the Sacramento-San Joaquin Delta. Public Policy Institute of California (www.ppic.org).
- Matern, SA, Moyle, PB, Pierce, LC. 2002. Native and alien fishes in a California estuarine marsh: twenty-one years of changing assemblages. *Transactions of the American Fisheries Society* 131:797-816.
- Mount, J, Twiss, R. 2005. Subsidence, sea level rise, and seismicity in the Sacramento-San Joaquin Delta. *San Francisco Estuary and Watershed Science* 3: <http://repositories.cdlib.org/jmie/sfew/s/vol3/iss1/art5>.
- Moyle, PB, Light, T. 1996. Biological invasions of fresh water: empirical rules and assembly theory. *Biological Conservation* 78:149-161.
- Nichols, FH, Thompson, JK, Schemel, LE. 1990. Remarkable invasion of San Francisco Bay (California, USA) by the Asian clam *Potamocorbula amurensis*. II. Displacement of a former community. *Marine Ecology Progress Series* 66:95-101.
- Nobriga, ML, Feyrer, F. 2007. Shallow-water piscivore-prey dynamics in the Sacramento-San Joaquin Delta. *San Francisco Estuary and Watershed Science* 5: <http://repositories.cdlib.org/jmie/sfew/s/vol5/iss2/art4>.
- Nobriga, ML, Feyrer, F, Baxter, RD, Chotkowski, M. 2005. Fish community ecology in an altered river delta: spatial patterns in species composition, life history

strategies and biomass. *Estuaries* 28:776-785.

- Nobriga, ML, Sommer, TR, Feyrer, F, Fleming, K. In press. Long-term trends in summertime habitat suitability for delta smelt, *Hypomesus transpacificus*. San Francisco Estuary and Watershed Science.
- Orsi, JJ, Mecum, WL. 1996. Food limitation as the probable cause of a long-term decline in the abundance of *Neomysis mercedis* the opossum shrimp in the Sacramento-San Joaquin estuary. Pages 375-401 *In* Hollibaugh, JT (ed) San Francisco Bay: the ecosystem. American Association for the Advancement of Science. San Francisco, CA.
- Pennington, T, Sytsma, M. 2006. Life history of *Egeria densa* in the Delta: factors controlling production and fragment viability. Report to the Calfed Bay-Delta Authority Contract # ERP-02-P18.
- Sommer, T, Armor, C, Baxter, R, Breuer, R, Brown, L, Chotkowski, M, Culberson, S, Feyrer, F, Gingras, M, Herbold, B, Kimmerer, W, Mueller-Solger, A, Nobriga, M, Souza, K. 2007. The collapse of pelagic fishes in the upper San Francisco Estuary. *Fisheries* 32(6): In press.
- Stewart, AR, Luoma, SN, Schlekot, CE, Doblin, MA, Hieb, KA. 2004. Food web pathway determines how selenium affects aquatic ecosystems: a San Francisco Bay case study. *Environmental Science and Technology* 38:4519-4526.
- Sweetnam, DA. 1999. Status of delta smelt in the Sacramento-San Joaquin Estuary. *California Fish and Game* 85:22-27.
- Teh, SJ, Deng, X, Deng, D-F, Teh, F-C, Hung, SSO, Fan, TW-M, Liu, J, Higashi, RM. 2004. Chronic effects of dietary selenium on juvenile Sacramento splittail (*Pogonichthys macrolepidotus*). *Environmental Science and Technology* 38:6085-6093.
- Wright, SA, Schoellhamer, DH. 2004. Trends in the sediment yield of the Sacramento River, California, 1957-2001. *San Francisco Estuary and Watershed Science* 2: <http://repositories.cdlib.org/jmie/sfews/vol2/iss2/art2>.